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Orographic effects on the northwestern Pacific monsoon: Role of air-sea interaction

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[1] Orographic effects on northwestern Pacific climate are investigated with atmospheric and coupled ocean-atmosphere general circulation models. In response to the removal of global orography, both models simulate a widespread decrease of summer rainfall over the Asian Continent. Over the subtropical northwestern Pacific, however, the response is opposite between the atmospheric and coupled models during spring and early summer. Sea surface temperature (SST) cooling is responsible for these differences between the atmospheric and coupled response. The SST cooling is triggered by winter stationary wave response to the mountain removal and amplified during spring by the wind-evaporation-SST feedback, altering the atmospheric response through summer. These results illustrate the importance of air-sea interaction and provide useful guidance for interpreting paleoclimate changes in response to the uplift of the Tibetan Plateau and Rift Valley of Africa. **Citation:** Okajima, H., and S.-P. Xie (2007), Orographic effects on the northwestern Pacific monsoon: Role of air-sea interaction, *Geophys. Res. Lett.*, *34*, L21708, doi:10.1029/2007GL032206.

1. Introduction

[2] Mountains are an important forcing for the earth climate system and Asian-Pacific climate in particular. In winter, the Tibetan Plateau, standing in the way of the midlatitude westerlies, excites stationary waves and substantially modulates the extratropical storm tracks downstream over East Asia, the North Pacific and beyond [*Held et al.*, 2002; *Inatsu et al.*, 2002; *Nigam and DeWeaver*, 2003]. In summer, intense solar heating makes the Tibetan Plateau a massive elevated heat source that drives the Asian summer monsoon [e.g., *Yanai and Li*, 1994]. (The heating effect of the Plateau is also manifested in the diurnal cycle and in a narrow rain band on the steep-rising south slope of the Himalayas [*Xie et al.*, 2006]). The summer Plateau heating generates a baroclinic response, with a gigantic low pressure system in the lower troposphere that helps the monsoon rain band advance inland. In atmospheric general circulation models (GCMs), the removal of the Plateau results in a reduction in strength [e.g., *Hahn and Manabe*, 1975] and delay in onset [*Xie and Saiki*, 1999; *Chakraborty et al.*, 2002] of the Asian summer monsoon. Removing the mountains causes the summer monsoon rain band to displace southward.

[3] By design, studying orographic effects with atmospheric GCMs assumes that the ocean, and sea surface temperature (SST) in particular remain unchanged in response to the removal of mountains. This assumption is generally invalid as orographic changes in atmospheric circulation modify the SST distribution by changing ocean circulation and/or surface heat flux. SST changes, especially those in the tropics, are almost certain to affect precipitation and feedback on atmospheric circulation. Indeed, *Kitoh* [2004] show that the precipitation response over the summer northwestern Pacific to the removal of global mountains is very different between atmospheric and coupled ocean-atmosphere GCMs, suggesting that SST changes are the cause of the differences. *Kitoh* [2004] study points to the need to consider oceanic changes in studying the role of orography in climate formation but it does not investigate how the oceanic changes take place and interact with the atmospheric changes. His study is also limited to the summer monsoon season whereas changes in other seasons may affect summer climate through interaction with slow oceanic changes.

[4] The present study examines the response of the subtropical northwestern Pacific to the removal of global mountains by using a coupled GCM, and extends *Kitoh*'s [2004] study in two important ways, by using a different GCM and studying the mechanisms for the differences between the atmospheric and coupled response. Specifically, we would like to address the questions of whether *Kitoh* [2004] results are sensitive to the choice of model and what causes the SST changes that modify summer rainfall over the northwestern Pacific. We show that air-sea interaction plays a critical role in the summer northwestern Pacific response to orographic forcing and somewhat surprisingly, the changes in winter atmospheric circulation are the important trigger for the air-sea interaction. We choose to focus on the northwestern Pacific both because the coupled and atmospheric simulations display large differences there and because of its climatic importance. The mid-summer onset of the northwestern Pacific monsoon brings major changes in East Asian climate [*Ueda and Yasunari*, 1996] but the mechanism for this abrupt onset remains unclear. Perturbing the system with orographic forcing can shed light on this problem.

[5] The rest of the paper is organized as follows. The next section briefly describes the models and experimental

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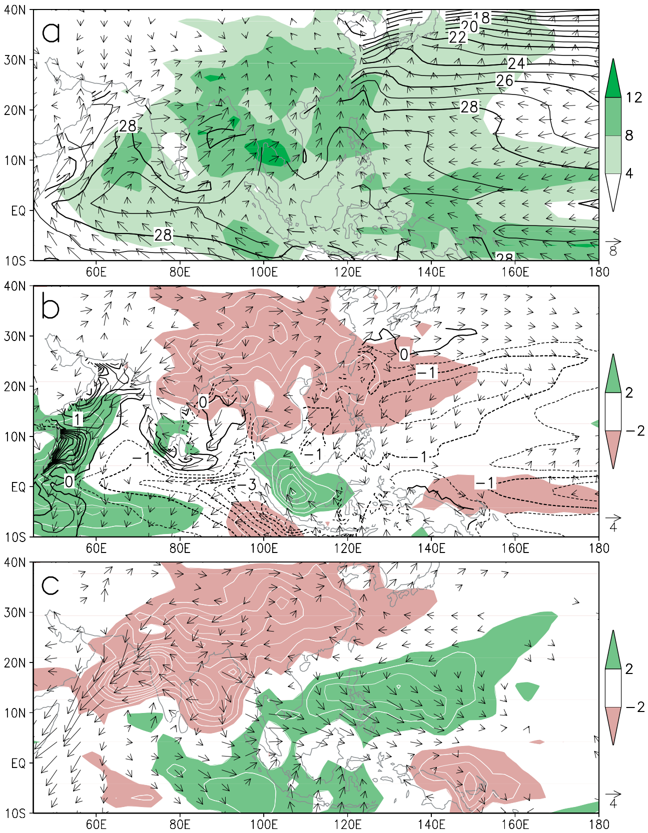

Figure 1. (a) May–July climatology of SST (black contours in °C), surface wind (vectors in m s^{-1}), and precipitation (color shade in mm day^{-1}) in the CTRL simulation. Same as Figure 1a but for changes in response to the mountain removal in (b) the coupled and (c) stand-alone atmospheric GCMs. White contour interval is 2 mm day^{-1}.

design. Sections 3 and 4 presents the results. Section 5 is a summary and discusses the broad implications.

2. Methods

2.1. Model

[6] The atmospheric GCM is developed at the Center for Climate System Research of University of Tokyo and the National Institute for Environmental Studies. It is a global spectral model with a package of physical parameterizations for convection, cloud, radiation, turbulent mixing, and land surface. We set the horizontal resolution at T42, with 20 sigma levels in the vertical. A detailed description of the model and its performance can be found in *Numaguti et al.* [1995].

[7] The ocean component is the Modular Ocean Model version 3.1, developed at the Geophysical Fluid Dynamics Laboratory [*Pacanowski and Griffies*, 2000]. The horizontal resolution is 1° × 1°. There are 25 vertical levels with a 10 m spacing in the upper 100 m. The ocean model covers the entire global tropics, with the poleward boundaries set at 32°S and 32°N, respectively. There is a 5° wide sponge layer for each of the poleward boundaries, where water temperature and salinity are restored to the observed climatology [*Levitus*, 1982]. Thus, air-sea interaction in the extratropics and its potential influences on tropical climate are beyond the scope of this study.

[8] The atmosphere and ocean models exchange wind stress, heat and fresh-water fluxes every two hours. Prior to the coupling, the atmosphere and ocean models are spun up separately for 2 and 20 years, respectively with the observed monthly climatology as boundary conditions.

2.2. Experimental Design

[9] We first conduct the control (CTRL) run with the realistic land-sea distribution and orography. We then remove land orography globally in the coupled GCM (the FLAT run hereafter). In lowering the mountain heights to the sea level, we keep land surface conditions, such as roughness, albedo, and vegetation, the same for easy comparison. The initial conditions are the same between the CTRL and FLAT runs. Both experiments are integrated for 60 years and the last 50-year results are averaged into monthly climatology for analysis. Interannual variability is left for future studies.

[10] To investigate what triggers the oceanic changes in the FLAT run, two stand-alone atmospheric experiments are conducted, one with realistic orography (aCTRL) and the other without mountains (aFLAT). Both are forced by the observed SST [*Levitus*, 1982]. For these atmospheric GCM experiments, the last 3 out of a total of 5 years results are analyzed.

3. Summer Response

[11] The coupled model simulates the salient features of Indo-western Pacific climate (Figure 1a) [*Okajima*, 2006]. During May–July, a large warm pool forms from the tropical eastern Indian Ocean to the western Pacific. Precipitation covers the warm pool as well as the tropical and subtropical Asian continent from India to China and Japan. Strong southwest monsoon prevails over the tropical North Indian Ocean and South China Sea. These wind and precipitation patterns are typical of the observed Asian summer monsoon. The easterly trade winds and zonal rain band associated with the intertropical convergence zone over the western Pacific are also simulated.

[12] Figure 1b shows the FLAT-CTRL differences, representing the coupled response to the removal of global orography. Without orography, the Asian summer monsoon is greatly weakened. Rainfall decreases over the entire Asian-western Pacific monsoon region, accompanied by a gigantic anticyclonic circulation in the difference field over a large subtropical region from Central Asia to the northwestern Pacific. As the south limb of this anticyclone, the southwesterly winds relax from the Arabian to South China Sea.

[13] The atmospheric GCM response without SST changes (Figure 1c) is generally similar to the coupled one over the Asian continent; the removal of the Tibetan Plateau prevents the monsoon rain from advancing inland [*Hahn and Manabe*, 1975]. Large rainfall differences are found over the subtropical northwestern Pacific where the aFLAT-aCTRL response features increased rainfall and surface cyclonic circulation while the FLAT-CTRL response

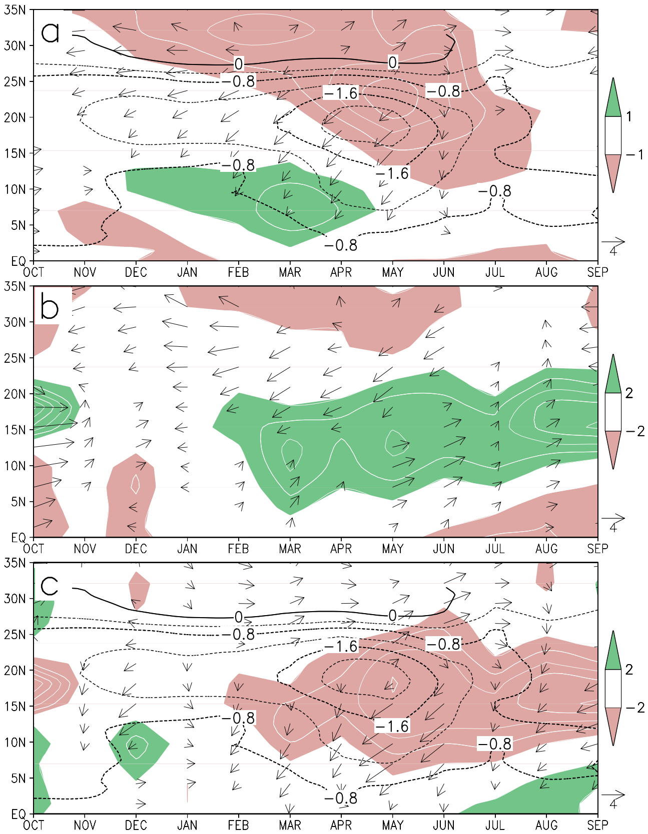

Figure 2. Time-latitude diagrams of SST (black contours in °C), surface wind velocity (vectors in m s^{-1}), and precipitation (color shade in mm day^{-1}) changes in response to the mountain removal, all averaged in 120°E–160°E: in (a) the coupled runs, (b) the direct atmospheric response as represented as the aFLAT minus aCTRL difference, and (c) the indirect response as presented as Figure 2a minus Figure 2b. White contour intervals are 1 mm day^{-1} for Figure 2a, and 2 mm day^{-1} for Figures 2b and 2c.

is characterized by a slight reduction of rainfall and anticyclonic circulation. Over a broad subtropical region from the eastern Bay of Bengal to the western Pacific, the southwest monsoon strengthens in aFLAT-aCTRL but weakens in FLAT-CTRL. The nearly opposite response between the atmospheric and coupled response to orographic forcing is due to the SST response over the northwestern Pacific as represented by the FLAT-CTRL difference (Figure 1b). Negative SST changes weaken atmospheric convection over the South China Sea and western Pacific in FLAT-CTRL. Large SST anomalies are also found over the equatorial Indian Ocean, which *Okajima* [2006] shows is due to the Bjerknes feedback between the ocean and atmosphere. We limit the scope of this paper to the investigation of anomalies over the subtropical northwestern Pacific. The aforementioned anomalies over this region are largely similar to those reported by *Kitoh* [2004], suggesting that the results are not very sensitive to models.

[14] The subtropical northwestern Pacific atmosphere displays abrupt changes in the second half of July, from dry to wet conditions. Our CTRL run simulates this northwestern monsoon onset at around mid-July. The removal of mountains cools the northwestern Pacific and delays this onset by about a month (not shown), in support of *Ueda and Yasunari*'s [1996] hypothesis about the role of warm SST in triggering the onset of convection over the region.

4. Indirect Effects

[15] We proceed to examine air-sea interaction mechanisms with the following method. First we represent the direct orographic effects on the atmosphere in the absence of SST changes as the aFLAT-aCTRL difference. Then, we diagnose how this direct atmospheric response triggers air-sea interactions. We define indirect effects as "FLAT-CTRL minus aFLAT-aCTRL", or the coupled response with the direct effects subtracted. Indirect atmospheric anomalies thus constructed are induced by SST anomalies.

[16] Figure 2 tracks how the indirect response to the orography removal develops in time and space over the northwestern Pacific and how it forces SST anomalies. The direct effects of removing orography include easterly anomalies during winter in the subtropics north of 20°N (Figure 2b), representing a northward advance of the boundary between the northeast trades and the prevailing midlatitude westerlies. This northward displacement of the trade-westerly boundary is part of winter-time stationary waves induced by the Tibetan Plateau [e.g., *Held et al.*, 2002] and consistent with a reduction in storm track rainfall around 35°N. In response to the intensified trades, negative SST anomalies begin to develop around 20°N in winter, amplify and expand southward in spring (Figure 2a). The northwestern Pacific cooling reaches a maximum in excess of −2°C during April-May and then decays as the direct effect of the intensified trades begins to wane. The indirect SST effect on subtropical precipitation is most pronounced during the summer half of the year when the SST is warm enough to support atmospheric convection (Figure 2c). Here we note that the SST changes are forced not by simultaneous wind changes during spring/summer but by those a season ahead in winter. Thus, the ocean acts as a memory mechanism recording the winter changes and unleashing their effects through summer. The SST effect is large enough to reverse the sign of the precipitation response over the northwestern Pacific during spring and early summer (Figure 2a).

[17] Figure 3 shows the indirect SST effects on surface circulation and precipitation during spring when the SST anomalies are at the maximum. The subtropical northwestern Pacific cooling suppresses atmospheric convection, exciting an anomalous anticyclonic circulation near the surface. As a result, the northeast trades accelerate over the southern half of the SST cooling, intensifying surface evaporation and causing the subtropical SST cooling to propagate equatorward (Figure 2c). This equatorward propagation of the coupled SST and wind anomalies is typical of the wind-evaporation-SST (WES) feedback. The wind changes affect not only surface heat flux but also ocean circulation. Figure 4a shows the horizontal distributions of FLAT-CTRL anomalies of sea surface height (SSH), a proxy for the thermocline depth, and the upper 100 m mean ocean current anomalies in spring. In response to the

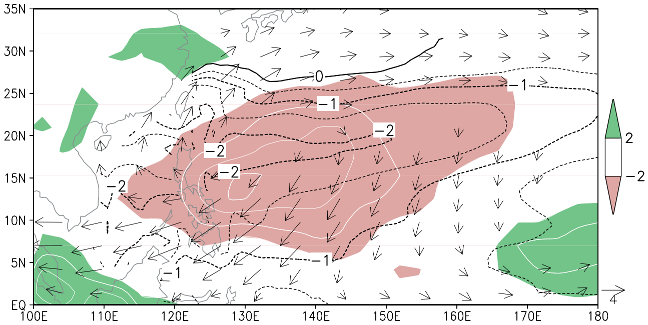

Figure 3. Indirect orographic effects for March to May: SST (black contours in °C), precipitation (color shade with white contours at intervals of 2 mm day^{-1}), and surface wind velocity (vectors in m s^{-1}).

cyclonic wind curls, the thermocline shoals over the northwestern Pacific. To infer the effect of the thermocline shoaling on SST, Figure 4b shows the vertical-meridional section of temperature and current anomalies. The subsurface cooling is greatest around 13°N below 100 m while the surface cooling is displaced northward and centered around 18°N. Over this SST cooling maximum, surface currents are northward advecting warmer water from the south, and the vertical velocity is downward. Thus, ocean advection is a negative feedback for the surface cooling over the northwestern Pacific. The thermocline feedback (an indirect effect) is negative for the following reason: a surface cooling induces anticyclonic wind curls, forcing the thermocline to deepen and prevent further cooling [*Yamagata*, 1985].

[18] The heat budget analysis for the ocean mixed layer (not shown), confirms the above inference. Surface heat flux is the dominant term, with the vertical advection/mixing as an opposing effect. Among the heat flux components, the latent flux dominates.

5. Discussion

[19] We have carried out experiments with atmospheric and coupled GCMs to investigate orographic effects on subtropical northwestern Pacific climate. Consistent with earlier atmospheric GCM studies using prescribed SST, summer precipitation weakens over the Asian monsoon region. The response over the subtropical northwestern Pacific, however, is very different depending on whether the ocean is interactive. In response to the global orography removal, precipitation increases and cyclonic circulation anomalies form over the northwestern Pacific in the atmospheric run with fixed SST. In coupled runs where SST is allowed to change, the precipitation response over the northwestern Pacific is subdued or even opposite in sign during summer as the direct orographic effect (resulting in increased rainfall) is countered by the effect of a SST cooling. The northwestern Pacific cooling begins in winter in response to the intensified northeast trades as part of the stationary waves induced by the removal of the Tibetan Plateau. The SST cooling intensifies and propagates equatorward due to the WES feedback. The thermocline shoals in the northwestern Pacific in response to positive wind curls but the subsurface cooling is not the primary cause of the SST cooling, which is instead due to wind-induced changes in surface evaporation. Thus, air-sea interaction via surface heat flux adjustment is important for subtropical northwestern Pacific climate.

[20] Our results have important implications for detecting the climate response to the tectonic uplift of the Tibetan Plateau and Great Rifts of Africa from 20 to 50 million years before the present [*Sepulchre et al.*, 2006]. The land-sea distribution has remained more or less the same since then. Our coupled experiments suggest that over the subtropical northwestern Pacific including the South China Sea, increased SST and precipitation and intensified southwest winds are expected to result from the rise of the Tibetan Plateau. This is opposite to the prediction based on atmospheric model simulations with fixed SST. Synthesis of SST, precipitation and wind proxies is necessary to test the coupled model prediction for the subtropical northwestern Pacific response to the mountain uplift and shed light on the role of air-sea interaction.

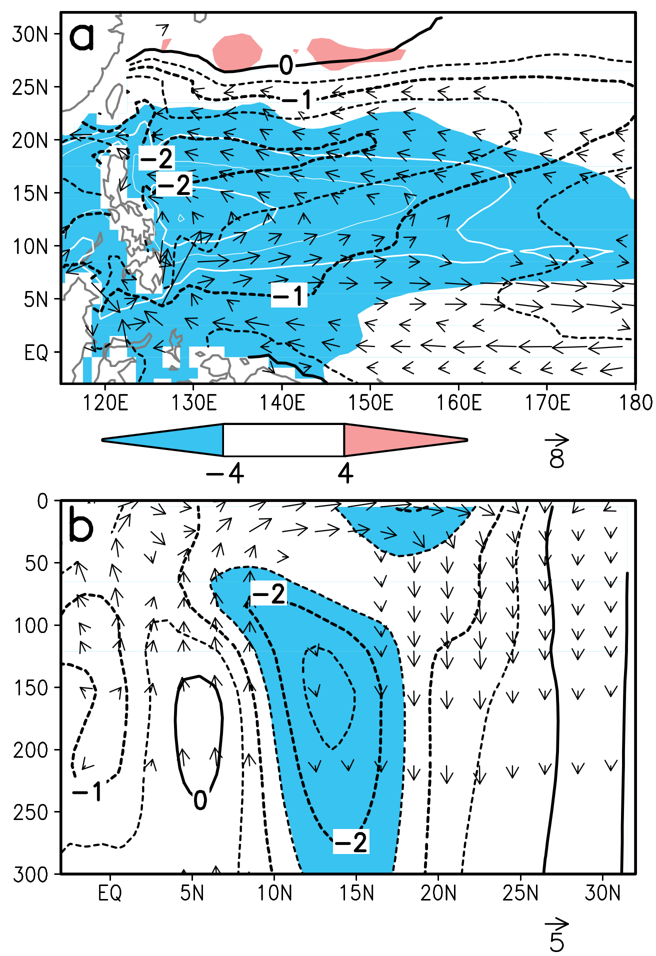

Figure 4. Ocean response to the orography removal during March–May: (a) SST (black contours at intervals of 0.5°C), SSH (color shade with white contours at intervals of 4 cm), and the 100 m averaged ocean current velocity (vectors in cm s^{-1}) and (b) ocean temperature (contours in °C; shade < −1.5°C), the meridional and vertical velocity (vectors in cm s^{-1} with the vertical velocity scale changed for clarity), zonally averaged between 135°E–145°E.

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