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Numerical study of natural sea salt aerosol and its radiative effects on climate and sea surface temperature over East Asia

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HIGHLIGHTS

- Vertical temperature anomalies by sea salt change precipitation over East Asia.
- Changes in SST by sea salt promote an extra force from atmosphere to ocean.
- East Asian summer circulation is weakened by sea salt aerosol.
- Climatic feedbacks will be attenuated under the fixed SST condition.

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ABSTRACT

A regional climate model, RIEMS-POM, was used to study the direct radiative forcing (DRF) of sea salt on precipitation, sea surface temperature (SST) and summer circulation over East Asia with aerosol dataset from GOCART. The simulations predicted negative DRFs of −0.87 W m^{-2} at the surface and −1.40 W m^{-2} at the top of the atmosphere by sea salt. Results from the simulations suggest the forcing of sea salt produces a slight positive temperature anomaly and a reduction in precipitation over Southern China, accompanied by an opposite trend north of 40°N in Northern and Northeastern China. The tendency of wetting in North and drying in South by sea salt was mainly determined by the wind field, the vertical motion, as well as the local evaporation anomalies. The impacts of sea salt on SST suggest that the net surface shortwave radiative flux and the changes in convective cloud are important in forming the decreased SST throughout the year, while the northward oceanic heat transport anomaly and the other heat flux anomalies contribute relatively smaller. The feature by sea salt on SST imposes an extra force from the atmosphere to the ocean. The sea salt could also diminish the land-sea temperature contrast (LSTC) in summer and therefore the climatological summer circulation over East Asia, leading to reduced precipitation in Southern China. All these climatic feedbacks, such as LSTC and precipitation anomaly, will be attenuated when the SST is fixed.

1. Introduction

Atmospheric aerosols contain species of both anthropogenic and natural origins, and play an important role in shaping the Earth's climate system (Liao et al., 2004). Many previous studies have assessed the impact of anthropogenic aerosols, such as black carbon, sulfate, and nitrate (IPCC, 2013). However, the impact of natural aerosol species, including sea salt, must also be assessed due to its importance on climate (Yue and Liao, 2012).

Sea salt is a natural aerosol worthy of special consideration, due to its great amount in surface emissions and its complicated optical properties. The high oceanic emissions of sea salt was found between 40° and 60° in both hemispheres, according to the study of Chin et al. (2002), by using a global aerosol transport model

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(specifically the Goddard Chemistry Aerosol Radiation and Transport model, GOCART). The global sea salt emission rate is significantly larger than that of anthropogenic aerosol species (Chin et al., 2009). Many studies had reported a sea salt burden ranging from 3.8 to 18.9 Tg yr^{-1} globally (Haywood et al., 1999; Chin et al., 2002; Liao et al., 2004). On the other hand, sea salt is hygroscopic and once in the atmosphere, is subjected to transport, and dry and wet scavenging (Yue and Liao, 2012). Consequently, although sea salt particles are removed quickly from the atmosphere, they often grow into larger sized particles in ambient relative humidity (RH), resulting in a stronger radiation extinction (Chin et al., 2002; Yue and Liao, 2012). This property heavily influences radiation transfer, and therefore the Earth's energy budget.

Recent studies using numerical and observational methods have shown that tropospheric aerosols have a significant potential to change the temperature and precipitation in East Asia (Xu et al., 2001; Menon et al., 2002; Ramanathan et al., 2005; Lau et al., 2006), due to direct (IPCC, 2013), indirect (Twomey, 1991), or semi-direct (Hansen et al., 1997) effects. In contrast to anthropogenic aerosol components, sea salt is the leading aerosol contributor to the global mean radiation balance, especially over the oceans (Haywood et al., 1999). This leads to a strong influence on the formation and lifetime of clouds (Kaufman et al., 2005). Haywood et al. (1999) showed that the direct radiative forcing (DRF) of sea salt can reach up to -1.51 W m^{-2} at the top of the atmosphere (TOA) and -1.55 W m^{-2} at the terrestrial surface (under the low sea salt burden assumption); in contrast, under the high burden condition, the DRF of sea salt can be respectively as high as -5.03 W m^{-2} and -5.17 W m^{-2}. One of the biggest uncertainties affecting the calculation of sea salt DRF is its optical properties. The optical properties of sea salt particles change with particle size, which can be highly variable due to its hygroscopicity (Kaufman et al., 2005). Not only over oceans, sea salt also influences the radiation balance over the continent. Solar radiation scattering due to sea salt DRF could ultimately influence temperature and precipitation (Haywood et al., 1999; Zakey et al., 2008; Yue and Liao, 2012). Using a GCM, Yue and Liao (2012) found that the change in global mean surface temperature caused by sea salt was -0.55 K. The resulting decrease in both surface latent heat flux (LH) and sensible heat flux (SH), further influences hydrological cycle, resulting in a decrease of -0.04 mm day^{-1} for precipitation and an increase of 0.13% in the total cloud amount. Additionally, sea salt has a significant effect on temperature and rainfall on regional scale, particularly in high sea-salt oceanic areas (Zakey et al., 2008). However, great uncertainties still remain, especially on a regional scale.

In the past decades, the radiative effect of sea salt is mainly calculated by GCMs, and the relatively coarse grid used in this type of model has limited research into the climatic effects of sea salt. This study is concerned with East Asia, an area which typifies the macro-topography of the Pacific Ocean and Euro-Asian continent that so complicates climatic studies (Wu et al., 2012). The study aims to explore how sea salt DRF influences climate and sea surface temperature (SST) in East Asia with a newly developed regional model system RIEMS-POM (specifically the Regional Integrated Environment Model System – the Princeton Ocean Model). The numerical model and the experimental design are presented in the next section. Section 3 gives the model results of sea salt distributions, radiative forcing and the climatic feedbacks. A summary and conclusions are given in Section 4.

2. Model and numerical experiments

2.1. Model description and methodology

The radiative effects of sea salt in East Asia were investigated by using the latest version of RIEMS-POM with the sea salt concentrations from the GOCART model.

RIEMS was developed by the Key Laboratory of Regional Climate-Environment for Temperate East Asia (RCE-TEA) (Han et al., 2010, 2013; Li et al., 2014) and was based on the nonhydrostatic core of MM5 3.7, the Fifth-Generation Penn State/NCAR Mesoscale Model (Grell et al., 1995). A modified Column Radiation Model (CRM), based on the work of Kiehl et al. (1996), and a widely used land surface scheme, the Biosphere-Atmosphere Transfer Scheme (BATS 1e) (Dickinson et al., 1993), were introduced into RIEMS. The RIEMS model also contained the Medium-Range Forecasts (MRF) planetary boundary layer scheme of Hong and Pan (1996) and the Grell cumulus parameterization (Grell, 1993).

The new development in RIEMS was coupling with a regional ocean model, POM, which was developed by Blumberg and Mellor (1987), and modified by Fang et al. (2010, 2013). POM was a three-dimensional primitive equation, free-surface, sigma-coordinate, Arakawa-C grid staggering oceanic general circulation model. At every coupling step, the net heat fluxes (including the net LH, the net SH, and the net longwave and shortwave radiative fluxes) and the momentum fluxes will be transported from the atmosphere to POM. As a result, a new SST calculated by POM will then feedback to atmosphere and be used as the SST boundary for RIEMS. Previous studies have investigated the performance of this coupled model in East Asia (Fang et al., 2010, 2013; Zhao, 2013), and found a great improvement in simulations of monsoon and water vapor transport.

The GOCART is driven by realistic global wind analyses (Chin et al., 2002, 2009). The GOCART aerosol distributions have been found to be in excellent agreement with satellite observations and sun photometer measurements globally and regionally for anthropologic species or natural dust (Chin et al., 2002; Lau et al., 2006). By comparisons with the site-based observations in Supplementary Fig. 1, good agreement still exist for locations where sea salt seems to be the dominant aerosol compound. However, as a result of the anthropologic activities especially over areas near the continent, the agreement might be relatively weaker. Yet, the aerosol data from GOCART has been widely used in aerosol radiative effect assessments and is suitable for usage here (Ramanathan et al., 2005; Lau et al., 2006).

2.2. Experiments design

This study covered East Asia, with a horizontal resolution of 60×60 km^2. The NCEP/NCAR reanalysis data, with a horizontal resolution of $2.5^\circ \times 2.5^\circ$ and 4 times daily, is applied to provide initial and boundary conditions for the RCM. In addition, the oceanic boundary of weekly NOAA optimum interpolation SST data was also used for the RCM when the POM is disabled. The simulation covers the period 2000–2007, after a spin-up time of two years. This spin-up period begins after an initial spin-up of 30-year in POM to get a stabilized ocean. The initialization methodology used was similar to that in Fang et al. (2010, 2013) and Nabat et al. (2014).

Two groups of experiments were carried out to quantify the radiative effects of sea salt. The first group used the coupled model, which included two experiments. One anomaly experiment (labeled ALL) includes sea salt aerosol and three other major anthropologic aerosol species, i.e., black carbon, organic matter, and sulfate, with the external mixture assumption. The other baseline experiment (labeled NSS) is identical to ALL, except for the exclusion of sea salt. The difference between ALL and NSS was taken to represent the impact of sea salt. The second group was identical to the first, except for the only usage of the atmosphere model RIEMS. Similar with Group 1, the two experiments in Group 2 were labeled