Simulation of the effects of sea-salt aerosols on cloud ice and precipitation of a tropical cyclone

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1 | INTRODUCTION

Aerosols can act as cloud condensation nuclei (CCN), affecting cloud lifetime, cloud droplet radius, cloud liquid water path, and cloud albedo indirectly (Twomey, 1977; Rosenfeld et al., 2008). While the effects of aerosols on local weather phenomena, for example, tropical cyclone (TC) systems, are highly uncertain (IPCC, 2014), it is believed that aerosols cause cloud droplet radii to decrease, leading to the suppression of cloud droplet collisions (e.g., Andreae et al., 2004; Li et al., 2008; Lin et al., 2011; Yoon et al., 2016). Furthermore, aerosols modify the microphysical processes and thermodynamic structure of a TC and may subsequently affect TC intensity and precipitation. For example, increase in anthropogenic aerosols may lead to decrease in warm cloud precipitation and enhancement of the transport of water vapor to the upper atmosphere (Rosenfeld et al., 2007; Qu et al., 2017); increase in anthropogenic aerosols at the TC periphery lowers TC intensity (Wang et al., 2014). At the TC periphery, increase in CCN suppresses cloud droplet collision efficiency and lowers TC intensity (Carrio and Cotton, 2011), while increase in aerosol concentration results in weaker TCs; conversely, increase in aerosol concentration in the eyewall area results in stronger TCs (Herbener et al., 2014). Anthropogenic aerosol emissions may change ice microphysical processes and decrease stratiform precipitation rate (Jiang et al., 2016). When CCN concentration is high, cloud water content increases together with the number of small cloud droplets, resulting in more rapid evaporation of cloud water at the TC periphery (e.g., Lee et al., 2009; Khain et al., 2010). Deposition growth of ice crystals
may be enhanced by increased evaporation of cloud water, while CCN may also modify updrafts or downdrafts and affect the release of latent heat. Together, these processes may impact the transport of cloud water and vapor to the upper atmosphere, which is associated with ice microphysics (e.g., Khain et al., 2005; Wang, 2005). Therefore, cloud ice and ice microphysical processes may be indirectly affected by activated CCN (Tao et al., 2012).

Effects of giant aerosols, such as sea-salt or dust may be different from those of anthropogenic aerosols. Because the radius of the initial particle is larger, giant aerosols can form larger cloud droplet embryos (Johnson, 1982; Feingold et al., 1999; Jiang et al., 2019; Luo et al., 2019). Dust aerosols as CCN can change cloud droplet number concentration and diameter (Zhang et al., 2007). Dust aerosols from the Sahara Desert suppressed the activity of a TC over the Atlantic Ocean by introducing stable, dry air into the TC system (Dunion and Velden, 2004), while higher dust aerosol burden over the North Atlantic Ocean inhibited the development of disturbances into hurricanes (Bretl et al., 2015). Twohy et al. (2017) found that dust aerosols lofted by a convective system over the eastern Atlantic Ocean enhanced ice nucleating particle concentrations in the upper troposphere. Sea-salt aerosols, which have a giant particle radius and high hygroscopicity, can accelerate the formation of rain drops (Rosenfeld et al., 2012). Hoarau et al. (2018) pointed out that simulations with two-moment schemes produce TCs with more enhanced convective asymmetries than those produced by one-moment schemes. Sea-salt aerosols play a critical role in TC simulation; because of the scavenging and consumption of interstitial CCN a two-moment scheme without explicit sea-salt emission produces TCs with lower intensity (Hoarau et al., 2018). The effect of sea-salt aerosols on cloud is one of the most uncertain components of the aerosols–climate problem (Meskhidze et al., 2013). Although previous studies have investigated the effects of anthropogenic aerosols or dust aerosols on a TC (e.g., Dunion and Velden, 2004; Rosenfeld et al., 2007), the role of sea-salt aerosols on cloud ice and precipitation of TC has yet to be determined. Therefore, this study focuses on the impact of sea-salt aerosols on cloud ice and precipitation of TC with the Weather Research and Forecasting model with chemistry (WRF-Chem), which is a fully coupled chemistry model. Model configuration and simulation design are explained in Section 2. Simulation results and impact of sea-salt aerosols on TC precipitation and cloud ice are presented in Section 3. Section 4 presents a summary of results and discussion.

2 | MODEL CONFIGURATION AND SIMULATION DESIGN

The WRF-Chem model version 3.5.1 is a nonhydrostatic, fully compressible and fully coupled atmosphere and chemistry model. It has coupled physical and chemical processes such as transport, wet/dry removal, aqueous chemistry, gaseous chemistry, and interaction between aerosols and radiation; its time integration schemes use second- and third-order algorithms (Grell et al., 2005), and is suitable for the investigation of aerosols effects. Air pollution and primary aerosols including sea-salt aerosols are discharged into the atmosphere; secondary aerosols are produced after scavenging and chemical reactions; finally, aerosols activate as CCN when their radii exceed the critical threshold value at the corresponding supersaturation. To focus on the variation of cloud ice in the simulations, pressure at the top of the model domain was set to 20 hPa. The model had 52 nonuniform vertical layers; 18 were in the upper atmosphere; 12 were below an altitude of 1 km as the number of lower levels is crucial for simulation of the lower atmosphere. The terrain-following dry hydrostatic pressure was used as the vertical coordinate. We used two nested domains (Figure 1a); D01 had a horizontal resolution of 9 km and 336 × 256 grid points; D02 had a horizontal resolution of 3 km and 424 × 406 grid points. Data from D02 were used to assess the effects of sea-salt aerosols. We performed the simulations from 0000 UTC on August 20, 2017 to 0000 UTC on August 23, 2017; the first 24 h was used as the model spin-up. Initial and boundary conditions were taken from the National Center for Environmental Prediction Final Operational Model Global Tropospheric Analyses dataset at 1° resolution (NCEP-FNL http://rda.ucar.edu/datasets/ds083.2). Cumulus parameterization is optional for simulations with a resolution of 9 km because it may introduce more uncertainty in the coupled microphysical and radiative effects of aerosols in WRF-Chem. Following Wang et al. (2014) in which two nested domains (resolutions of 9 and 3 km) and no cumulus parameterization were used to investigate the coupled microphysical and radiative effects in WRF-Chem, the cumulus parameterization scheme was not used in this study.

This section summarizes the key physics and chemistry schemes used in the model. The Morrison microphysical scheme (Morrison et al., 2005) is a two-moment bulk microphysical scheme that includes ice microphysical processes, such as deposition, riming, and transformation, and involves five types of hydrometeor (cloud water, rain, cloud ice, snow, and graupel). Deposition growth of cloud ice mainly depends on supersaturation and the presence of ice crystals. At present, parameterization of aerosols activated as ice nuclei is absent in WRF-Chem. Characteristics of natural ice nuclei are a function of temperature in the Morrison scheme. The Modal Aerosol Dynamics Model for Europe and the Secondary Organic Aerosol Model are the driver modules of aerosols (Ackermann et al., 1998; Schell et al., 2001) in WRF-Chem. Aerosol size distributions are calculated according to three lognormal modes: the Aitken,
accumulation, and coarse modes. The dry radius size ranges for Aitken, accumulation, and coarse modes are 0.015–0.053 μm, 0.058–0.27 μm, and 0.80–3.65 μm, respectively (Liu et al., 2012). Sea-salt aerosols with wet radii exceeding the threshold value at the corresponding supersaturation are activated as CCN. Aerosols activated as CCN determine cloud droplet number and size. Moreover, aerosols participate in chemical processes and are subject to wet/dry removal. Concentrations and properties of CCN are predicted from online calculations of aerosol number and properties, such as radius and hygroscopicity, by WRF-Chem.

Sea-salt aerosols have a larger radius and a higher hygroscopicity than other aerosols, and are produced at the sea surface. Sea-salt aerosolization takes place during the bursting of whitecap bubbles and is parameterized as a function of sea-surface wind speed (Gong et al., 1997a; 1997b). Sea-salt flux density can be expressed as

$$dF/dr = 1.373W_{10}^{0.41}r^{-A}(1 + 0.057r^{3.45}) \times 10^{1.19\exp(-B)}$$ (1)

where $dF/dr$ is in particles m$^{-2}$ s$^{-1}$ μm$^{-1}$, $A = 4.7(1 + \Theta r)$, $B = (0.433 - \log r)/0.433$, $C = -0.017r^{-1.44}$, $W_{10}$ is the sea-surface wind speed, $r$ is the radius of the sea-salt aerosols, and $\Theta$ is a parameter to adjust the shape of the submicron size distribution. In the model, number concentration emission flux is converted into mass concentration emission flux. Sea-salt aerosols are treated as sodium chloride, which has high hygroscopicity, in WRF-Chem. Some of the sea-salt aerosols can be activated as CCN after dry deposition or wet deposition (scavenging). Water vapor condenses on to CCN, affecting cloud droplet number concentration, mixing ratio and cloud microphysical processes, such as collection and collision.

We simulated TC Hato, which developed over the northwestern Pacific Ocean in August 2017 and became a supercyclone. Two numerical simulations were conducted to assess the effects of sea-salt aerosols on cloud ice and precipitation of Hato. Sea-salt emission flux parameterized following Gong et al. (1997b) was used in the Ctl simulation; sea-salt emission flux used in the Low simulation was one-tenth that in Ctl. The difference between Ctl and Low was used to indicate the effects of sea-salt aerosols. Results from a third simulation in which sea salt emission flux was doubled are not presented because results were consistent with those from Ctl and Low. In this paper, we examine the effects of sea-salt aerosols by analyzing simulation data from 0000 UTC on August 21, 2017 to 0000 UTC on August 23, 2017. When a TC approaches land, anthropogenic aerosols may trigger new convective activity at the TC periphery (Khain et al., 2005; Jiang et al., 2016). However, during the simulation period, the TC center is far from the Chinese mainland; therefore few anthropogenic aerosols can interact with the TC after dry and wet scavenging.

**FIGURE 1** (a) Two nested domains used in simulations. Horizontal resolutions of the domains were 9 km (D01) and 3 km (D02), (b) observed and simulated tracks, (c) time dependence of maximum sea surface wind speed. The Ctl simulation is marked by the purple line, the low simulation is marked by the green line, and the observations are marked by the black line.
3 | RESULTS

Simulated tracks and maximum sea surface wind speed are consistent with best track data provided by the China Meteorological Administration TC database (http://tcdata.typhoon.org.cn/zjljsj_zlhq.html) (Figure 1), demonstrating that WRF-Chem is able to reproduce the TC adequately. Aerosols have little influence on overall TC track and intensity. Hato’s precipitation is asymmetrical and generally lies to the left of the cyclone track (Figure 2). Precipitation in the eyewall is larger in Ctl than that in Low throughout the simulation period. Simulated track, intensity, and precipitation distribution are in good agreement with observed values.

Figure 3 shows condensation rate, which comprises cloud water production rate and rate of water vapor condensing on CCN. It must be noted that TC is an asymmetry system. While height–radius plots are generally unable to depict the temporal evolution of asymmetrical cyclones, such as Hato. However, we can compare the two simulations directly based on height-radius plots. The area of higher precipitation in the eyewall of Hato is present in Ctl throughout the simulation period (Figure 2). Thus, height–radius plots are used for directly comparing results from Ctl and Low. Condensation mainly occurs within the eyewall and below an altitude of 5 km. Maximum condensation rate exceeds $0.5 \times 10^{-6}$ g g$^{-1}$ s$^{-1}$, and condensation rate in Ctl is higher than that in Low. Latent heat released by condensation can increase vertical motion. Vertical wind speed is higher in Ctl than in Low, indicating that sea-salt aerosols promote vertical motion (Figure 4f). Maximum condensation rate occurs at an altitude of around 5 km, while highest vertical wind speed occurs at an altitude of approximately 12 km. Although condensation is the process that releases the largest amount of latent heat, many microphysical processes also release latent heat and contribute to vertical motion. This includes the collection of rainwater by snow, which releases a maximum amount of latent heat at an
Many previous simulations show that maximum vertical wind speed occurs at altitudes of 8 to 13 km (Rosenfeld et al., 2007; Liu et al., 2012; Hazra et al., 2013). Enhancement of vertical motion promotes convective activity. Thus, precipitation is larger in Ctl than in Low, especially in the eyewall area (Figure 5a). Precipitation peaks at a horizontal distance of 30–60 km from the TC eye. Peak precipitation in Ctl (about 13 mm/h) is nearly 120% that in Low (about 11 mm h). Furthermore, we divided precipitation into convective and stratiform precipitation using the method of Sui et al. (2007). In agreement with Yang et al. (2018), we found that convective precipitation generally occurs in the inner core while stratiform precipitation is in the rain band (figure not shown), indicating that the method of Sui et al. (2007) is applicable to the different regions of a TC. Stratiform precipitation accounts for larger than 78% of the total precipitation region. Convective precipitation divided by the method of Sui et al. (2007) generally occurs in the inner core region and stratiform precipitation exists in the rain band region (figure not shown). The distribution is consistent with the conclusion presented by Yang et al. (2018). The method is suitable to apply on the different regions of TC. Figure 5b shows that sea-salt aerosols increase convective precipitation, which means that sea-salt aerosols enhance TC convective activity. Convective precipitation is always associated with warm microphysical processes such as cloud water autoconversion into rain (Sui et al., 2007). Figure 5b shows that sea-salt aerosols increase convective precipitation, indicating that sea-salt aerosols can enhance warm microphysical processes and TC convective activity.

Increase of vertical motion in Ctl not only promotes precipitation, but also favors water vapor transport to the upper atmosphere, enhancing deposition growth of cloud ice. Figure 6 shows that deposition growth rate is higher in Ctl than in Low, and that the maximum is located at an altitude of approximately 12 km. Thus, in the rain band, there is more cloud ice in Ctl than in Low, and the difference between the cloud ice mixing ratio in Ctl and that in Low reaches 8 g/kg. Depositional growth is the main microphysical source for cloud ice (Tao et al., 2012). Cloud ice mixing ratio is determined by advection, vertical motion, microphysical source, sink microphysical process, sedimentation, and other terms such as cloud ice autoconversion into snow; cloud ice autoconversion is a sink for cloud ice and is at a maximum at an altitude of approximately 12 km in Hato. In the eyewall, cloud ice mixing ratio in Ctl is smaller than that in Low. We infer that, compared with the Low simulation, vertical motion in Ctl is larger and transports more cloud ice from the eyewall to the rain band. Changes in cloud ice and
4 | DISCUSSION

Using WRF-Chem, we examined the effects of sea-salt aerosols on TC precipitation and cloud ice by conducting simulations using two different values of sea-salt aerosol emission intensity. Sea-salt aerosols may promote the condensation process, and enhance vertical motion and precipitation. Enhanced vertical motion leads to increases in deposition growth rate of cloud ice and cloud ice mixing ratio.

Both sea-salt aerosols and anthropogenic aerosols impact a TC by acting as CCN. Anthropogenic aerosols can trigger convection at the TC periphery (Khain et al., 2010) and decrease the radii of cloud droplets; this could reduce collision efficiency and the number of cloud droplets that can be lifted to the altitude where freezing occurs. Eventually, extra convection is generated at the TC periphery, which lowers TC intensity (Rosenfeld et al., 2007). Sea-salt aerosol spans over a wide range (from nm to mm) and high hygroscopicity, and are produced under high wind speeds; they create favorable conditions for the deposition growth of cloud ice by enhancing condensation and increasing vertical motion; cloud ice mixing ratio and TC precipitation are subsequently increased. Thus, sea-salt aerosols influence TC through mechanisms and microphysics that are different from those associated with anthropogenic aerosols.

The use of an ocean coupled model including the influence of sea surface temperature on atmosphere could improve prediction of TC intensity (Bender and Ginis, 2000). Ocean–atmosphere coupled models show that sea spray evaporation increases TC intensity (Bao et al., 2000); TC intensity may also be influenced by oceanic mesoscale eddies (Jullien et al., 2014); TCs may be intensified by enhanced latent heat transport into the inner core because of the formation of a stable boundary layer over the cold sea surface in the right rear quadrant of the TC (Lee and Chen, 2014). In this study, we mainly focused on the effect of sea-salt aerosols as CCN on TC using a model that was not coupled with an ocean model. Future research should consider using a coupled ocean model to investigate the effect of sea-salt aerosols on TCs.

Compared to warm seawater, cold seawater decreases sea-salt aerosol production. Therefore, it is more realistic to include the effect of sea surface temperature in the parameterization of sea-salt aerosol production, which is included in the new formula of Grythe et al. (2014). The spectral distribution of sea-salt aerosol production derived using this formula is similar to that derived from the parameterization of Gong et al. (1997a; 1997b), which is used in this study; production rates given by Gong et al. (1997a; 1997b) are slightly lower than those given by Grythe et al. (2014).

As our results show, sea-salt aerosols may modify the microphysical processes of a TC, affecting TC stratiform
precipitation. Notwithstanding, effects of aerosols on TC precipitation, intensity, and microphysical processes are complex, because of the nonlinear interactions between aerosols and the thermodynamics, hydrometeors, and microphysical processes of a TC. Parameterization of aerosols acting as ice nuclei is absent in WRF-Chem, but is crucial for the consideration of heterogeneous freezing and deposition growth of ice crystals. Ice nucleation is parameterized in the Morrison microphysical scheme that was used in this study. Hence, results from this study may differ from those that use models that include aerosols as ice nuclei.

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