Comparing surface wind stress and sea surface temperature biases over the tropical and subtropical oceans in subsets of CMIP6 models categorized by frozen hydrometeors-radiation interactions

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Abstract

We evaluate the simulations of surface wind stress (TAU) and sea surface temperature (SST) over subtropical and tropical Pacific and Atlantic oceans in subsets of CMIP6 models that are categorized by frozen hydrometeors-radiation interactions. The CMIP6 models are divided into two subsets with combined (SON1) and separated (SON2) radiative properties of cloud ice and falling ice (snow) and compared to the set with cloud ice radiative effects only (NOS). There is evidence that these hydrometeors-radiation interaction treatments induce different atmospheric dynamic responses that influence the surface properties. Excessive westerly TAU and meridional TAU divergence away from convective zones are reduced significantly in SON1 and SON2 relative to NOS against QuikSCAT observations; while the differences between SON2 and SON1 are small. SON2 reduces cold SST biases over north oceans and equatorial zones drastically (1 to 2 K), and warm biases (up to 1 K) off the coasts of America and zonal TAU biases are reduced relative to NOS. Unlike SON2, SON1 improves SSTs mainly over south of Pacific Ocean and limited areas over the tropical belts relative to NOS although TAU is reduced drastically as in SON2, implying that other factors play a role in degrading the SST simulations in SON1 relative to SON2. SON2 outperforms NOS and SON1 in the seasonal cycles of SST mean biases and mean absolute biases averaged over the equatorial area, north ocean, and South Pacific against ERSST observations. Despite the significant improvements in TAU and SST simulations, SON2 models still exhibit non-trivial biases over south and north flanks of equatorial zones. These results suggest that there are direct linkages of TAU with SST changes resulting from the hydrometeors-radiation interactions in SON2, but not in SON1, relative to NOS, implying that a separated treatment of cloud ice and falling ice radiative properties in climate models is preferred.

1. Introduction

The tropical and subtropical surface wind stress (TAU) (Roquet et al 2011, Lee et al 2013) drives the changes in ocean circulation that produce anomalous sea surface temperatures (SSTs) (Bjerknes 1969, Wang et al 2014). TAU and SST are two critical elements of the tropical atmosphere-ocean coupled system because SST distributions are mostly driven by near-ocean TAU while SST changes influence the tropical atmospheric circulation. Most coupled global climate models (GCMs) such as those in the 5th phase of Coupled Model Intercomparison Project (CMIP) (CMIP5; Taylor et al 2012) still have difficulties in simulating realistic SST
climatology (e.g., de Szoeke and Xie 2008, Li and Xie 2012, 2014, Li et al 2014, 2015) and TAU (e.g., Lee et al 2013). Extensive efforts have been made to mitigate SST and TAU biases (Luo et al 2005, Chikira 2010, Zhang and Song 2010, Li et al 2015, 2016). Recently, impacts of falling ice radiative effects (FIREs) on tropical radiative fluxes and circulation are found evidently important in the CMIP5 (Li et al 2012, 2015, 2016) and 6th phase of CMIP (CMIP6) models (Gettelman and Morrison 2015, Kodama et al 2015, Chen et al 2018, Michibata et al 2019, Li et al 2020b, 2022). Most GCMs in CMIP5 and CMIP6 do not include FIREs but only cloud ice radiative effects (Jiang et al 2012, Li et al 2012), while in reality radiation interacts with all frozen hydrometeors (Waliser et al 2009, 2011, Li et al 2013).

Li et al (2020a) examined the impacts of FIREs on surface wind stress, SSTs, radiation fields and precipitation by comparing two subsets of CMIP6 models used in the present-day climate simulations, one with FIREs (referred to as SON), and the other without FIREs (referred to as NOS). The overall performance of TAU and SST simulations in multi-model ensemble mean (MMM; combined NOS with SON) of CMIP6 models was improved compared to CMIP5, but the improvement was limited and trivial. They also found that SON subset did not exhibit expected systematic improvements from NOS subset compared to previous single GCM sensitivity studies carried out by Li et al (2015, 2016). In Li et al (2015), the surface wind stress and SST biases are reduced drastically in experiments with inclusion of FIREs relative to exclusion of FIREs.

The puzzling results also appear in radiation fields and surface precipitation when comparing CMIP6 SON with NOS groups (Li et al 2020a, Li et al 2020b, 2022) further categorized the SON group of models into two subgroups based upon treatments of frozen hydrometeors-radiation interactions; one with combined frozen hydrometeors radiative properties (SON1) and the other with separated cloud ice and falling frozen hydrometeors radiative properties (SON2). They found that SON2 significantly improves tropical precipitation biases including double intertropical convergence zone (ITCZ) (Li et al 2020a) and radiation (Li et al 2022) biases against SON1 and NOS in CMIP6 models. Their findings motivate us to further evaluate simulated surface wind stress and SST between NOS, SON1 and SON2 subgroups against observations in the context of tropical atmosphere-ocean interactions induced by hydrometeors-radiation interactions. Annual-mean spatial patterns and seasonal cycles of mean bias (MBs) and mean absolute biases (MABs) over the entire study domain (240°W–0°, 40°S–40°N), equatorial zones (200°W–100°W, 5°S–5°N), north Pacific and Atlantic oceans (240°W–0°, 15°N–40°N), and south Pacific trade-wind regions (160°E–120°W, 30°S–0°S) will be examined to understand the linkage of TAU with SST changes. The previous study by Li et al (2020a) only examined the annual-mean spatial patterns of NOS, SON and CMIP6 MMM. As in Li et al (2020a), the Indian ocean is excluded from the analysis due to its strong seasonal reversal controlled by the thermal effect of the Tibetan Plateau (Abe et al 2013, He et al 2019).

In section 2, we briefly describe the stratiform cloud schemes used in CMIP5 and CMIP6 models, including treatments of frozen hydrometeors (cloud ice and falling ice) radiative properties in the SON1 and SON2 subgroups and observational TAU and SST data products. In section 3, we present and discuss the results, and in section 4, the summary and discussion are given.

2. Model output and reference datasets

2.1. CMIP5 and CMIP6 model output

Following Li et al (2020a, 2020b), the CMIP5 (Taylor et al 2012) and CMIP6 (Eyring et al 2016) historical scenario simulations are used. For the purpose of intercomparisons between this study and Li et al (2020a, 2020b), we chose the same periods of 1970–2005 of CMIP5 and 1970–2014 of CMIP6 simulations. The chosen models must have zonal surface wind stress (TAUU), meridional surface wind stress (TAUV) and SST data available in their ensemble members designated r1i1p1f1 or r1i1p2f1 in CMIP6 and r1i1p1 or r1i1p2 in CMIP5. To be consistent with Li et al (2020a, 2020b, 222), the same 28 CMIP5 models (see table 1 of Li et al 2020a) multi-model mean is used, denoted as CM5. Outputs from 23 CMIP6 models are used, denoted as CM6.

2.2. Radiative treatments of frozen hydrometeors

Based on how the radiative effects of frozen hydrometeors are treated, outputs from 23 CMIP6 models are divided into three groups. One without FIREs is denoted as NOS. SON1 subgroup models use the combined cloud ice and falling ice mass to compute radiative properties of frozen hydrometeors from the stratiform cloud scheme in atmospheric component (HadGEM3–GA7.1) of the HadGEM3–GC3.1 Earth System Model (Wilson and Ballard 1999, Abel and Boutle 2012, Walters et al 2017, Mulcahy et al 2018, Williams et al 2018), denoted as GA71. The models in SON1 subgroup include UKESM1–0–LL, SAM0–UNICON, EC–Earth3–Veg, ACCESS-CM2, and HadGEM3–GCM31–LL GCMs. To compute radiative properties of frozen hydrometeors, the SON2 subgroup models use separated cloud ice and falling ice contents from a prognostic two-moment stratiform cloud scheme (MG2, Gettelman and Morrison 2015) in the CESM2 atmospheric component of CAM6. The
models using MG2 include E3SM-1-0, CESM2-WACCM, CESM2-WACCM-FV2, CESM2, and NorESM2-MM GCMS, as well as TaiESM1 with MG1 (Gettelman et al. 2010), which uses a diagnostic falling ice approach as in CESM1-CAM5 cloud microphysics scheme.

SON represents the sum of SON1 (5 models) and SON2 (6 models) ensembles. NOS represents the ensemble of 12 NOS models with diverse cloud microphysics schemes [see Supplementary Information (SI) table S2 and S3].

2.3. Reference datasets
2.3.1. Surface wind Stress
The surface wind stress reference dataset is the Scatterometer Climatology of Ocean Winds (SCOW: http://cioss.coas.oregonstate.edu/scow/), which is based on the measurements from the QuikSCAT scatterometer from September 1999 to October 2009 (Risien and Chelton 2008). The data are gridded at 2° × 2°. Lee et al. (2013) stated that the multidecadal variability in CMIP models is much smaller than the biases in climatology. This means that the QuikSCAT climatology is a reasonable reference data set to evaluate CMIP model biases averaged over a multidecadal period.

2.3.2. Sea surface temperature
The Extended Reconstructed Sea Surface Temperature (ERSST) version 5 dataset for the period of 1970–2014 is used (data source: https://www1.ncdc.noaa.gov/pub/data/cmb/ersst/v5/), the same period as CMIP6 output. The slightly shorter CMIP5 output does not change the conclusion of this study. ERSSTv5 is a global monthly dataset derived from the International Comprehensive Ocean–Atmosphere Dataset release 3.0 SST on a 2° × 2° grid with spatial completeness enhanced using statistical methods (Huang et al. 2017, 2018a, 2018b).

2.3.3. Atmospheric vertical velocity
The monthly mean vertical velocity data are from the 5th European Center for Medium–range Weather Forecast (ECMWF) reanalysis (ERA5; Hersbach et al. 2020). The ECMWF model, called Integrated Forecasting System (IFS), uses a pressure based vertical coordinate system. The vertical velocity in pressure coordinate (ω) is given by the Lagrangian derivative of pressure. Negative values of ω indicate upward motion. The model has a horizontal resolution of 0.25° × 0.25° with 137 pressure levels from 1000 hPa to 1 hPa. The available data of 1979–2014 are used.

Both the reference data and the GCM output are re-mapped onto a common 2° latitude by 2° longitude horizontal grid-box prior to analysis. Land grid points within the study domain are excluded.

3. Results
3.1. Annual mean surface wind stress biases
We examine geographic distributions of surface wind stress components (TAUU and TAUV) in different subgroups, including SON1, SON2, and NOS, for (1) annual mean biases against QuikSCAT (left columns of figures 1–2), (2) differences between the subgroups (middle columns of figures 1–2 with pooled t-test (95%) for examining statistical significance of the differences, and (3) changes in annual mean absolute bias (MAB) between two groups (Group A–Group B) with positive value (right columns of figures 1–2) indicating improvement from the first group (Group A) compared to the second group (Group B) against observations. Please refer to SI in Li et al. (2020a) for the TAUU and TAUV biases of individual models.

Li et al. (2014) showed that exclusion of FIREs in CESM1 leads to overactive deep convection over Tropical Western Pacific (TWP), ITCZ and South Pacific Convergence Zone (SPCZ), resulting in weaker surface easterlies and meridional divergent flows away from the ITCZ and SPCZ and over the trade–wind regions between the ITCZ and SPCZ and excessive TAUU over north Pacific with cold SST biases. Shown in figure 1, CMIP6 NOS also shows strong westerly biases of TAUU over the entire domain, in particular, over the trade–wind regions in Pacific and Atlantic (figure 1(c)) against QuikSCAT. These biases are mitigated significantly in SON1 (figure 1(a)) and SON2 (figure 1(b)) as illustrated in figure 1(g) for SON1 and figure 1(h) for SON2 from NOS at 95% confidence level (figures 1(d), (e)), respectively. There are some sporadic areas of systematic differences between SON1 and SON2 but not as apparent as those between NOS and SON2 (figures 1(e) and (h)) or between NOS and SON1 (figures 1(d) and (g)) except for north and south flanks of ITCZ (figures 1(f) and (i)).

NOS subgroup simulates stronger TAUU with meridional divergence anomalous away from ITCZ and SPCZ both in Pacific and Atlantic oceans (figure 2(c)) against QuikSCAT observations, which is consistent with that found in Li et al. (2015). The TAUU biases in both SON1 and SON2 are reduced significantly (figures 2(d) and (e)). The improved TAUU in both SON1 (figure 2(g)) and SON2 (figure 2(h)) from NOS appears over north/south flanks of ITCZ and, in particular, off the west coasts of North and South America. SON1 shows a
slightly better performance than SON2 over middle-east section north of ITCZ both in Pacific and Atlantic Oceans (figure 2(i)).

3.2. Annual mean surface wind stress vector and sea surface temperature biases

The annual-mean wind stress vector biases and total vector differences among the subgroups are shown in figure S4. The surface wind stress vectors in NOS show stronger biases (figure S4(c)), which are contributed by much weaker TAU speed (i.e., opposite in direction to prevailing winds) in the trade-wind regions and stronger TAU speed over the mid-latitudes dominated by westerly surface wind stress than those in SON1 (figure S4(d)) and SON2 (figure S4(e)), while there are no systematic differences in TAU speed between SON1 and SON2 (figure S4(f)). The wind stress vector differences between the subgroups are highlighted in figures 3(a)–(c) with t-test at 95% confidence level. The t-test highlighted surface wind vectors are more significantly different between SON1 (SON2) and NOS than between SON1 and SON2 over the trade-wind regions.
Shown in figures 4(a)–(c), SSTs in NOS are underestimated over most of the study domain, in particular, over north-west Pacific and Atlantic Oceans up to $-1.5$ K $-2$ K, but overestimated off the west coast of South America extending to middle section of ITCZ up to $2$ K (figure 4(c)). Similar to NOS, SON1 also produces cold SST biases (up to $-2$ K) over north oceans with reduced warm SST biases over the trade-wind regions and off the coast of north America continent (figure 4(a)). Unexpectedly, the SST bias patterns in SON1 are more similar to those in NOS rather than in SON2, with almost the same magnitudes of cold SST biases as in NOS over north-west Pacific and equatorial zones (figures 4(c), (d), (g), (h)). In SON2, the cold SST biases are mitigated drastically in concert with reduced biases in TAU (figures S4(b), (e)) over north of 15°N south of 15°S oceans. However, positive SST biases are found over north and south flanks of ITCZ and off the west coasts of Pacific and Atlantic Oceans in SON2 compared to those in SON1 and NOS.

In summary, we found that the patterns of weaker TAU are associated with those of warm SSTs over the trade-wind regions, while those of stronger TAU are associated with those of cold SSTs over north-west and south-west of domains, which are evidently found in NOS and SON1. The SST biases are reduced from NOS (and SON1) to SON2 except for the north and south flanks of ITCZ. However, comparison of SON1 with NOS does not indicate reduced SST biases in concert with reduced TAU biases over tropical oceans except north of 15°N and south of 15°S. Comparison of NOS with SON2 indicates that there is a strong link between surface wind stress biases and SST biases. This link can be explained by the sensitivity tests presented in Li et al (2015). They found that model without falling ice radiative effects produced weaker TAU, reducing upper ocean turbulent
water mixing, leading to warm SST on the flanks of the ITCZ over south trade-wind regions and stratus cloud regions off the west coasts of north and south America. While over north oceans, this model tends to enhance storm over mid-latitudes, producing stronger TAUU and cold SST in winter over the storm tracks.

3.3. Ranking models by regional mean absolute biases in SSTs

Figure 5(a) and table S4(a) shows the mean absolute biases (MABs) of SSTs averaged over the whole domain, equatorial zones, north ocean and south Pacific trade-wind regions for groups of NOS, SON1, SON2, SON, CM5 and CM6. For all four regions, the MABs of SON2 (red colored bar) are lower than those of both SON1 and NOS, while NOS (dark blue) has higher MABs than SON1 (purple colored bar). CM5 (CMIP5 MMM) has the highest MABs among all groups/subgroups. For all regions, we found that the area-averaged MABs all indicate that the reduced SST MABs from CM5 to CM6 are attributed to SON2, which has the lowest MABs with magnitudes of about a half of NOS and CM5.

Shown in figure 5(b) and table S4(a)) are MABs averaged over the whole domain for individual CMIP6 models and groups/subgroups, which are ranked from left to right for the highest to lowest MABs. Only the individual models within subgroups of NOS, SON1 and SON2 are discussed. There are some consistent results among the regions, especially for some NOS models. In summary, we found:

- For the whole domain, in terms of the lowest MABs, top five best performance models, ranked in order of ascending bias, are from SON2 models. Four of five models with the highest MABs are from NOS. Most of the NOS models have large MABs on the left-hand side of rankings, while the rest of SON2 and SON1 models are widely spread in the middle of rankings.

- For equatorial region, shown in figure 5(c), the top five best performance models are spread rather evenly from each subgroup. Four of five models with the highest MABs are from NOS models.

- For the north ocean region (figure 5(d)), the top five models with the smallest MABs are from SON1 and SON2 subgroups. The bottom five models with the largest MABs are mostly from NOS model.

- For the South Pacific trade-wind region (figure 5(e)), the best model is from SON2, followed by three NOS models and one SON1 model. The bottom five models are four NOS model along with one SON1 model.

3.4. Seasonal cycle of the mean and absolute SSTs biases

In this section, we examine the seasonal cycles of SST monthly mean biases (MBs) and MABs averaged over three regional domains defined in the previous section against ERSST for subgroups of models (NOS, SON, SON1, SON2, CM5 and CM6) and for individual models (shown in SI figure S1 (available online at stacks.iop.org/ERC/4/055009/mmedia)).
3.4.1. Equatorial zones

Shown in Figure 5(a) are the seasonal cycles of group mean biases (MBs) of SSTs averaged over the equatorial zones. All the groups (NOS, SON, SON1, SON2, CMIP5 (CM5) and CMIP6 (CM6)) show too cold SSTs relative to ERSST observations for all seasons. The reduction in SST MBs for SON2 relative to NOS (and SON1) occurs throughout the entire seasonal cycle. The MBs in SON2 are reduced drastically (more than 0.4 K) compared to NOS and SON1. From January–July, the MBs are reduced from NOS by up to four times, but the MBs for the rest of the year are similar between SON1 and SON2 (from ~0.4 K to ~0 K).

Consistent to that in MBs (figure 6(a), the seasonal cycle of MABs in SON2 are reduced by 0.4 K relative to those of NOS and SON (figure 6(b)), ranging from 0.4 K to 0.1 K throughout the entire annual cycle with the maximum difference appearing in March–April. The reduction of SST MBs and MABs in SON2 over the entire seasonal cycle matches well with the reduced annual-mean meridional surface wind stress divergence anomalies in SON2 versus NOS (figure S4(e)), but this is not seen in SON1 (figure S4(d)).

3.4.2. North Pacific and Atlantic Oceans

Over the north Pacific and Atlantic Oceans, all the subgroups (SON1 and SON2) and the groups (NOS, SON, CM5 and CM6) show too cold SSTs relative to ERSST observations for all seasons (figures 6(c) and (d)) with a
peak magnitude up to $-1.5$ K in SON1, except for the October–December period of SON2, relative to ERSST observations. The negative MBs in SON1 are larger than those in NOS by about $0.05$–$0.3$ K during January–August but nearly identical from September to December. SON2 has very small MBs, with reduced MBs for the entire seasonal cycle by up to four times from January–July relative to SON1 and NOS. The negative SST MBs for all subgroups over entire seasons are consistent with annual mean westerly surface wind stress anomalies (figures S4(a)–(c)), which enhance westerlies on $15^\circ$N–$40^\circ$N latitude belt by stirring colder upper ocean water through turbulent mixing and lead to annual mean cold SST biases. However, the improved surface wind stress in SON1 versus NOS does not impact the SST MB annual cycle.

The seasonal variations of MABs in SON1 and NOS are very similar to each other ($0.7$ K $\sim 1.1$ K) as shown in figure 6(d), implying that systematic cold biases in the averaging domain, while SON2 has the smallest MABs throughout the seasonal cycle with magnitudes of $0.5$ K $\sim 0.8$ K. The SON2 MABs are reduced by $0.4$ K relative to SON1 and NOS throughout the entire annual cycle, which is likely responsible for the improved performance in SON and CM6 relative to CM5.

3.4.3. South Pacific trade wind regions
Over the south Pacific Ocean, shown in figure 6(e), all the groups (NOS, SON, CM5 and CM6) and subgroups (SON1 and SON2) show too warm SSTs with positive MBs relative to ERSST observations for the entire annual cycle with magnitudes of up to $1.3$ K except in March with a slightly cold MB in SON2. SON1 has similar large warm SST MBs as NOS (up to $1.3$ K), appearing during October to April with minimum MBs ($0.3$ K) during May–June. SON1 has smaller positive MBs than NOS by $0.2$–$0.4$ K throughout the annual cycle. On the other hand, SON2 shows negligible MBs during February–June and positive MBs up to $0.6$ K (November) but these MBs are still smaller than those in NOS and SON1 for the rest of the year. The differences in MBs between SON2 and SON1 are as large as $0.5$ K during January–April. The improved SST MBs for SON2 versus NOS over the entire annual cycle is consistent with reduced annual mean westerly surface wind stress biases in the trade-wind regions (figures S4(a)–(c)) and annual mean SST (figure 4). The improved surface wind stress in SON1 versus NOS does, however, not yield the same amount of reduction of SST MBs as in SON2 versus NOS.

For this region, the seasonal variations of SST MBs for all group and subgroups (figure 6(f)) are rather similar to those of SST MBs (figure 6(e)) due to the fact that SST biases are mostly positive over the region except for SON2.

Figure 6. (a) Group sea surface temperature (SST) bias against ERSST observation (model–ERSST) for groups of models (NOS, SON, SON1, SON2, CMIP5 (CM5) and CMIP6 (CM6) averaged over equatorial zone ($200^\circ$W–$120^\circ$W, $5^\circ$S–$5^\circ$N). (b) Same as (a) but for absolute bias (|model–ERSST|). (c)–(d) same as (a)–(b) but for area average over north oceans ($240^\circ$W–$0^\circ$, $15^\circ$N–$40^\circ$N). (e)–(f) Same as (a)–(b) but for south Pacific trade-wind regions ($160^\circ$W–$120^\circ$W, $30^\circ$S–EQ). The time average is 1970–2005 for CMIP5 models while over 1970–2014 for CMIP6 models.
We examined subtropical and tropical oceanic surface wind stress (TAUU and TAUV) and sea surface temperatures (SSTs) against their respective observations (QuikSCAT and ERSST) over the Pacific and Atlantic oceans between groups of CMIP6 models that are categorized based on different treatments of falling ice radiative effects (FIREs): (1) treating the radiative effects of all the frozen hydrometeors with a single ice particle diameter (SON1); (2) treating radiative properties of floating cloud ice and falling ice separately with their respective masses and particle diameters (SON2) and (3) without FIREs included at all (NOS).

We found that the differences in TAU between SON2 and SON1 subsets are small and the biases are significantly reduced from NOS over the entire study domain. We also found that the spatial patterns of SST biases in NOS are similar to those of SON1 with cold SST biases over north Pacific (figure 4(c)) and warm El Niño and Southern Oscillation (ENSO)-like SST biases over eastern basins off the west coasts of north and south America continents. SON1 has smaller SST biases off the west coast of California compared to NOS and SON2. While SON2 mitigates the SST biases in NOS significantly in the whole domain, there are still too warm SSTs over the north and south flanks of ITCZ, which might be caused by too strong TAUV biases. The coherent reductions in TAU and SST biases in SON2 are parts of hydrometeor-radiation-circulation coupling related to the falling ice radiative effects (see Li et al 2022 for radiation bias comparisons of the same CMIP6 subgroups), which has been identified using the fully coupled CESM1-CAM5 (Li et al 2014). However, this is not the case in SON1. Although TAU improves drastically in SON1 and SON2 against NOS, the tropical SST biases in SON1 are barely improved against NOS except for south of 15°S latitudes. SON1 has similar cold SST biases over equatorial zones and north oceans, which is consistent with NOS despite the improved surface wind stress. The above results suggest that the biases in TAU and SST over tropical oceans presented in Li et al (2016) are well connected in SON2 (relative to NOS), but not for SON1 versus NOS comparisons.

From the above mentioned, one may wonder whether or not there are substantial differences in hydrometeor-radiation-circulation coupling between SON1 and SON2. In Li et al. (2014), they showed the differences in the vertical profiles of radiative and latent heating rates between experiments with FIREs and without FIREs. However, there are no such outputs from the CMIP6 data port to perform a similar analysis. Instead, we examine the vertical profiles of vertical motion (ω; hPa day⁻¹) averaged over deep convective zones (figures 7(a), (b)) and trade wind subsidence regions (figures 7(c), (d)) because vertical velocity can be approximated as the ratio of the total diabatic (radiative plus latent) heating and vertical gradient of potential temperature if the horizontal advection is small. This assumption is more likely valid over deep convective zones than over trade wind subsidence regions. The difference in the implied diabatic heating between SON1 and SON2 also depends on their vertical gradients of potential temperature. Figure 7 shows that there are more significant differences in vertical velocity between SON2 and NOS than between SON1 and NOS in both regions. The mean vertical velocity in SON2 is much closer to the ERAS5 (Hersbach et al 2020) than either NOS or SON1. The subsidence in SON2 (figure 7(c)) is stronger than in SON1 although both are associated with strong trade wind surface wind stress.

It is puzzling that SON1 shows an improved surface wind stress simulation, compared to NOS, even though both SON1 and NOS have very similar vertical velocity profiles. This implies that there may be a disconnection in changes between the dynamics in the atmosphere and surface wind stress in SON1 relative to NOS in both deep convective zones and subtropical trade wind regions. This is not the case in SON2 relative to NOS, in particular, SON2 shows that stronger subsidence is associated with stronger trade wind surface wind stress. Possible uncertainties in SON1 may be attributed to (a) the drag coefficient adjustment to reducing surface wind stress biases, and (b) the upper ocean currents in response to air-sea interactions such as surface wind stress. These uncertainties need to be explored and addressed in future studies, which is out of the scope of this study.

We further compared SST mean absolute biases (MABs) of groups (CM5, CM6, NOS and SON) and subgroups (SON1 and SON2) for the whole domain, equatorial area, north ocean, and South Pacific trade wind regions. For the whole domain, SON has the lowest MABs, followed by SON2, while for the rest of area averages, SON2 has the lowest MABs, followed by SON. The rest of groups/subgroup are ranked as follows, in order from low to high magnitudes of MABs, SON1, CM6, NOS and CM5. CM6 is influenced by SON1, offsetting the large reduction of MABs in SON2 versus NOS. All model groups (NOS and SON) and subgroups (SON1 and SON2) show improvements relative to CM5 except for NOS over the South Pacific trade wind region.

Finally, we examined the seasonal cycles of monthly SST mean biases (MBs) and MABs averaged over the equatorial area, north ocean, and South Pacific trade wind regions against ERSST observations. Over the equatorial zones and north Pacific and Atlantic Oceans, all the groups (NOS, SON, CM5 and CM6) and subgroups (SON1 and SON2) show too cold SSTs relative to ERSST observations for all seasons; while the
opposite is true for the South Pacific trade-wind regions. There are consistent reductions in SST MBs relative to NOS for SON2 and SON throughout the entire seasonal cycle for all three regions. This is also true for SON1 with smaller bias reduction for the equatorial zones and South Pacific trade-wind regions. Over the north oceans, the biases in SON1 are higher than those of NOS for the January-August period. Comparing SON1 with SON2, the magnitudes of regionally-averaged mean bias reduction are much higher in SON2 (up to four times) than those in SON1 except for September-December of the equatorial zones and June-September of the north oceans. The MAB reductions are consistent with those of mean bias reductions except that SON has slightly smaller MABs than SON2 for a few months due to offsetting between SON1 and SON2.

In summary, we found that in SON2, the MBs and MABs of the annual-mean spatial patterns and annual cycles of monthly-mean SST are reduced drastically compared to NOS and SON1. SON1 does not show the improvement of as in SON2 even though the TAU biases are reduced relative to NOS. However, SSTs and TAU in SON2 still exhibit non-trivial biases over south and north flanks of deep convective zones. The limited improved SST performance in CMIP6 relative to CMIP5 is mainly due to offsetting by the degradation of SON1. The findings from this study indicate that SON2 models produce more realistic TAU and SST than SON1 models when compared to NOS. We acknowledge that the improvements of TAU and SST in SON2 cannot solely be due to MG2 scheme, but may have been contributed by other improved physical processes, which are needed for our future study. Nevertheless, the results of the present study imply that with more models including a separated treatment of cloud ice and falling ice radiative properties (SON2), it might be possible to bring to a consensus between the state-of-the-art climate models.

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Figure 7. (a) Annual mean differences of domain area average vertical motion profiles (Omega: hPa hr⁻¹) against ERA5 reanalysis and (b) same as (a) but for biases against ERA5 between CMIP6 models excluding effects of falling ice (NOS), with combined frozen hydrometeors AG71 (SON1) and with separated frozen hydrometeors MG2 (SON2) taken from Pacific ITCZ (EQ–15°N; 180–120° W). (c)–(d) same as (a)–(b) but for south Pacific Trade wind region (5°S–30°S; 140°W–100°W). The time period over 1980 to 2014 is used.
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Data availability statement

No new data were created or analysed in this study.

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