Summertime circumglobal Rossby waves in climate models: Small biases in upper-level circulation create substantial biases in surface imprint

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Abstract. In boreal summer, circumglobal Rossby waves can promote stagnating weather systems that favor extreme events like heatwaves or droughts. Recent work highlighted the risks associated with amplified Rossby wavenumber 5 and 7 in triggering simultaneous warm anomalies in specific agricultural breadbaskets in the Northern Hemisphere. These type of wave patterns thus pose potential risks for food production, as well as human health, and other impacts. The representation of such summertime wave events and their surface imprints in general circulation models (GCMs) has not been systematically analyzed. Here we validate three state-of-the-art global climate models (EC-Earth, CESM, and MIROC), quantify their biases and provide insights into the underlying physical reasons for the biases. To do so, the ExtremeX experiments output data were used, which are (1) historic simulations (1979 – 2015/2016) of a freely running atmosphere with prescribed ocean, and experiments that additionally nudge toward the observed (2) upper-level horizontal winds in the atmosphere, (3) soil moisture conditions, or (4) both. The nudged experiments are used to trace the sources of the model biases to either the large-scale atmospheric circulation or surface feedback processes. We show that while the wave position and magnitude is represented well compared to ERA5 reanalysis data. During high amplitudes (> 1.5s.d.) wave-5 and wave-7 events, the imprint on surface variables temperature, precipitation and sea level pressure is substantially underestimated: typically, by a factor of 1.5 in correlation and normalized standard deviations (n.s.d.) for near-surface temperature and mean sea level pressure. As for the precipitation, it's still a factor of 1.5 for n.s.d. but 2 for correlation. The correlations and n.s.d. for surface variables do not improve if only the soil moisture is prescribed, but considerably increased when the upper-level

35   atmosphere circulation is nudged. The underestimation factors are corrected almost entirely. When applying both soil moisture prescription and the nudging of upper-level atmosphere, both the correlation and n.s.d. values are quite similar to only atmosphere component is nudged experiments. Hence, the near-surface biases can be substantially improved when nudging the upper-level circulation providing evidence that relatively small biases in the models' representation of the upper-level waves can strongly affect associated temperature and rainfall anomalies.

40   **1 Introduction**

The past decade has witnessed a series of unprecedented boreal summer weather extreme events around the globe such as the 2010 Russian heatwave, 2012 North American heatwave, and the record breaking heatwaves of 2015, 2018 and 2019 in Europe (Barriopedro et al. 2011; Kornhuber et al. 2019; Krzyżewska and Dyer 2018; Wang et al. 2014; Huntingford et al. 2019; Xu et al. 2021). Some of these events also happened simultaneously with other types of extremes such as the persistent

45   Russian heatwave and Pakistan flood in 2010 July and August (Lau and Kim 2012; Martius et al. 2013). These persistent weather extremes can have disastrous impacts on human health and societies such as wide spread crop failure, infrastructure damage and properties loss, especially when they are defined as compound events (Zscheischler et al. 2018). Quasi-stationary Rossby waves are often connected with such persistent summer extremes. For instance, Recurring Rossby Waves Packets (RRWPs) can lead to high-impact persistent surface weather extremes such as cold spells in winter and hot spells in

50   summer (Röthlisbergera et al. 2019). Several other studies have also identified that amplified circumglobal waves favor the occurrence of weather extremes in certain regions (Screen and Simmonds 2014; Kornhuber et al. 2020). Specifically, in summer wave-5 (Ding and Wang 2005; Kornhuber et al. 2020) and wave-7 (Kornhuber et al. 2019, 2020) have preferred phase positions and thereby favor simultaneous extremes in major bread-basket regions (Kornhuber et al. 2020).

55   Several mechanisms can promote quasi-stationary Rossby waves including strong convective forcing from monsoons (Di Capua et al. 2020), extratropical sea surface temperature anomalies (McKinnon, et al., 2016; Vijverberg, et al., 2020), soil moisture anomalies (Teng and Branstator 2019), waveguide effects (Hoskins and Ambrizzi 1993)(Hoskins and Ambrizzi 1993), and wave-resonances (Petoukhov et al. 2013, 2016; Kornhuber et al. 2017; Thomson and Vallis 2018). Recent work by Di Capua et al. (2020) found that the latent heat release from Indian Summer Monsoon initiates a circumglobal

60   teleconnection pattern, which reflects a wave-5 type pattern in the northern mid-latitudes. Extratropical sea surface temperatures (SSTs) can interact with atmospheric waves creating quasi-stationary atmospheric Rossby waves favorable for e.g. hot days in the eastern United States (McKinnon et al. 2016). Moreover, waves can be excited by reduced soil moisture and then maintained by waveguides in the Northern Hemisphere mid-latitudes (Teng et al. 2019), which could result in high-amplitude wave events occurring more often. Quasi-Resonant Amplification (QRA) theory suggests that synoptic scale

65   Rossby waves can be trapped within the mid-latitude waveguides, where they can get amplified given suitable forcing conditions (Petoukhov et al. 2013). Since the wave's energy is not lost via meridional dispersion, waves tend to propagate

over long longitudinal distances and can sometimes form circumglobal wave pattern (Hoskins and Ambrizzi 1993; Branstator 2002b; Teng and Branstator 2019).

70 Climate models are important tools for process understanding and assessment of future climate risks. However, most of previous studies that link specific circumglobal Rossby wave patterns to regional extreme events are based on reanalysis/observational data. Although some have analyzed waves in models, their focus is not on summer and, also, they have not explored the phase-locking behavior of amplified, quasi-stationary Rossby waves (Garfinkel et al. 2020; Wills et al., 2019). Also, most studies have not analyzed waves above wave number 6. Some studies by Branstator et al. (2002 &

75 2017) have looked into models but focus on seasonal means and/or winter. Thus, a multi-model validation study of quasi-stationary Rossby waves in boreal summer is still lacking. Another key issue here is the general underestimation in atmospheric blocking (Davini and D'Andrea 2020) and the errors in processes that maintain blocking and in atmospheric circulation representations, this hinders the model reliabilities in their prediction skills for future projections(Scaife et al. 2010; Shepherd 2014). A recent study by Davini and D'Andrea (2020) analyzed the representation of both winter and

80 summer time blocking frequencies in models from the Coupled Model Intercomparison Project Phase 3 (CMIP3, 2007), CMIP5 (2012), and CMIP6 (2019). Although biases in CMIP6 models were reduced by a factor of 0.5 compared to CMIP3 models in some key regions like Europe, the biases still remain: 1: even CMIP6 models cannot truthfully produce wintertime blocking frequencies in Europe, 2: CMIP models are not able to capture the obserbved strong and significant increase in summertime blocking activities over Greenland (Davini and D'Andrea 2020).

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Thus, to have confidence in future projections of extreme summer weather, a proper validation of state-of-art climate models in their representation of circumglobal Rossby waves in summer is essential. Both the upper-level dynamical characteristics, in terms of amplitude and phase position, is important, but also the waves' impact on surface weather. Here we systematically validate the representation of summertime Rossby waves in three state-of-the-art climate models, focusing on

90 wave-5 and 7, their phase-locking behavior and surface anomalies. Further, we use specific nudging experiments, that remove the bias in only one or two components of the model, to understand the origin of model biases.

This paper aims at addressing following questions:

1: Can models capture the key characteristics of high-amplitude circumglobal waves in summer?

95 2: What are the near-surface temperature, rainfall, and mean sea level pressure anomalies from such waves and how do they compare to observations?

3: Do potential model biases originate from the atmospheric circulation or land surface-feedbacks?

2 Data and Methods

2.1 ExtremeX experiment

We use output data from three Earth System Models (ESM) that participated in the ExtremeX modeling experiment (Wehrli et al. 2021, in review): European Community Earth System Model in version 3.3.1 (EC-Earth 3.3.1; Döscher et al. 2021, in review), Community Earth System Model in version 1.2 (CESM1.2; Hurrell et al. 2013), and Model for Interdisciplinary Research on Climate version 5 (MIROC5; Watanabe et al. 2010). CESM and MIROC are the versions used for the CMIP5 (CMIP5;Taylor et al., 2012), whereas EC-Earth is the latest 3rd generation model used for CMIP6 (Eyring et al. 2016).The ExtremeX modeling experiments were designed to disentangle the influence from atmospheric dynamics vs. soil moisture feedback on extreme events such as heatwaves, droughts, and other extremes. By nudging either the upper-level atmosphere or soil moisture state, or both, the individual effects can be compared across different models. Details on the experimental set-up and atmospheric nudging approach are described in a recent study where five individual heatwaves in the period of 2010 – 2016 were examined (Wehrli et al. 2019).

2.2 Model data output

Here we use four out of five sets of simulations from ExtremeX, which are all run in Atmospheric Model Intercomparison Project (AMIP) (Gates et al. 1999) style with prescribed monthly mean SSTs and sea-ice, but differing in whether the other components are free or controlled. The experiments are run with: (1) interactive atmosphere and soil moisture as reference (AISI), (2) nudged atmosphere (mostly above 700 hPa) but interactive soil moisture (AFSI), (3) prescribed soil moisture with nudged atmosphere (AFSF), and (4) prescribed soil moisture without nudging the atmosphere (AISF). The experiment period spans from January 1979 to December 2016 for both EC-Earth and CESM and till December 2015 for MIROC. Overall output is provided 6 hourly on different model grids (in longitude x latitude): EC-Earth (512 x 256), CESM (288 x 192), and MIROC (256 x 128). There are five ensemble members for runs AISI and AISF for the whole period. However, for runs AFSI and AFSF, only one run for each experiment was used. All model and reference data are regridded to the same resolution (256 x 128) for comparisons.

2.3 ERA5 Reanalysis data

For the study period 1979 to 2016 summer months June, July, and August (JJA), weekly meridional wind data at 250 hPa (v250), near-surface temperature (t2m), and mean sea level pressure (mslp) are taken from ERA5 reanalysis data (Hersbach et al. 2020). As for precipitation (prcp), the land only data is from WATCH Forcing Data applied to ERA5 which is bias-corrected based on Climate Research Unit (WFDE5_CRU) (Cucchi et al. 2020). Also, weekly t2m data is detrended to its climatological mean (1979 – 2016) values of that week.

2.4 Extracting circumglobal waves and phase-locking analysis

130   High amplitude wave events are selected based on the Fourier transformation analysis of weekly-mean v250 averaged over 35N to 60N, both in ERA5 and models analogous to previous studies (Kornhuber et al. 2019, 2020). Wave events are identified as those weeks with wave amplitudes higher than 1.5 standard deviations (s.d.) of the climatology calculated from 494 weeks (38 years times 13 summer weeks per year) for ERA5. As for AISI and AISF runs, since they both have 5 ensemble runs, thus the weeks are as follows: EC-Earth (494 x 5), CESM (494 x 5) and MIROC (481 x 5). For AFSI and
135   AFSF runs, only one member is used for each model. Then, the composite surface imprints of near-surface temperature, precipitation, and mean sea level anomalies were obtained from those wave events period. The probability density functions for phase positions are obtained for higher wavenumber waves 5 to 8 for the weeks with identified high-amplitude events.

2.5 Model bias definition

To isolate the source of the model biases in surface imprint anomalies to either the upper-level atmosphere or to the land
140   surface component, we define the total bias (B_tot), bias from atmosphere (B_atm), bias from land-atmosphere interactions (B_land), and the remaining residual bias (B_res).

In the AISI experiment, both the atmosphere and land surface component are allowed to interact and evolve freely, and this experiment thus defines the total bias:

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B_tot = AISI – ERA5

When prescribing soil moisture in AISF, we assume that the land bias is removed and only the bias from the atmosphere acting upon near-surface variables remains. Thus:

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B_atm = AISF – ERA5

In contrast, when nudging the upper-level atmosphere, the upper-level circulation pattern is constrained in the model and thus the bias arises from land-atmosphere interactions.

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B_land = AFSI – ERA5

When nudging both the upper-level atmosphere and soil moisture, the model biases are expected to be strongly reduced with only a residual bias remaining:

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B_res = AFSF – ERA5

3 Results

3.1 Climatology of summertime Rossby waves

165 We first assess whether the climate models are able to represent the mean state in terms of wave amplitude and variability for wavenumbers 1-10. Figure 1 compares wave spectra for wavenumber 1 to 10 from the AISI experiment with those of the ERA5 data. Overall, the wave amplitudes, regardless of wave numbers and models, are reasonably well reproduced with errors ranging from 5% (wave-10) to 12% (wave-3) in the differences of the model climatology compared to ERA5 data. This also applies to the variance in wave activity as given by the whisker bars for each model at different wavenumbers. For

170 all models the wave amplitudes and variabilities follow the same behavior with increasing values from wave number 1 to 5 and decreasing values till wave-10 thereafter. ERA5 shows the peak for both the wave amplitude and variance at wavenumber 5, which might suggest a systematic bias in the models, or alternatively it might be an under-sampling in ERA5.

3.2 Wave phase-locking behaviors

175 We use the 1.5 s.d. above the mean wave amplitude as a threshold to define high amplitude wave events, following Kornhuber et al (2020), to analyze phase-locking behavior of high amplitude waves 4-8. The phase positions of high amplitudes events are shown in Fig.2. It is clear that ERA5 data have inherent phase-locking properties, especially for wave 5 and 7, which is consistent with the work from Kornhuber et.al (2019) where a different reanalysis data NCEP-NCAR (Kalnay et al., 1996) was used. Also, in the NCEP-NCAR reanalysis data, waves 6 and 8 don't really show a preferred phase

180 position. In our experiments, across all three models, strong phase-locking behavior (a single symmetrical peak in the probability density function) can clearly be observed for wave-7. For wave-5, two models (CESM and MIROC) show phase locking that is comparable to ERA5, but EC-Earth underestimates the peak in the probability density function.

As for wave 6 and wave 8, ERA5 shows no phase-locking for these waves, but only a mild preference for some phase
185 positions. The models capture this, with only MIROC showing fairly pronounced phase-locking behavior for wave 6.

3.3 High-amplitude wave events and their surface imprint

Let's recall that when summertime amplified circumglobal Rossby waves get stuck in their favorite positions, especially for wave-5 and wave-7, they pose risks for the prolongations of simultaneous surface warm anomalies. As we find that the preferred phase position of circumglobal waves 5 and 7 is reasonably well represented in models, we next analyze high-

190 amplitude events (i.e. exceeding 1.5 s.d.) in more detail. The wave event occurrence is calculated as the number of weeks

selected as high amplitude wave event divided by the total number of weeks then times one hundred percent. Then we obtained the occurrences for JJA wave-5 and wave-7 events during 1979 to 2016 for ERA5 are 8.1% and 7.1%. The values are quite comparable to the results calculated from the models: 7.7% (EC-Earth), 8.0% (CESM), and 7.9% (MIROC) for wave-5, whereas the occurrences are 8.1% (EC-Earth), 7.8% (CESM), and 8.0% (MIROC) for wave-7. Figure 3 and 4 show

195   the upper-level circulation (v at 250 hPa) and near-surface temperature anomaly (t2m), precipitation anomaly (prcp), and sea level pressure anomaly (mslp) signals during such high-amplitude events in ERA5 (a) and the 3 climate models (b-d). All the anomalies are calculated as the differences between the selected event period and the full period summertime climatology means. Here we present the associated surface anomaly imprints during those high amplitude waves-5 and wave-7 events across all models for the AISI experiment with free-running atmosphere and soil moisture modules (Fig. 3 & Fig. 4).

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Additionally, to quantify the bias of all models and visualize how close the models are to the ERA5 reanalysis data, a Taylor Diagram (Taylor 2001) is constructed for both wave-5 (Fig.5) and wave-7 (Fig.6). A Taylor Diagram presents three key statistics in a single plot: the Pearson correlation between the observed and modeled spatial pattern; centered Root Mean Square Error (RMSE), the centered RMSE of the modeled field; and the normalized spatial standard deviation of the

205   modeled field. Thus,v250 during the wave-5 and wave-7 events, as well as t2m, prcp, and mslp anomalies from the different model experiments with respect to ERA5 reanalysis data are plotted in the Taylor Diagram.

During the wave-5 events, all models are able to capture the upper-level circulation mean patterns with v250 field correlations 0.86 (EC-Earth), 0.95 (CESM), and 0.88 (MIROC) (Fig.5 & Table A1). This is consistent with our findings

210   from Fig. 1 and 2. In terms of magnitude of the wind speed anomalies, CESM and MIROC have similar strengths compared to ERA5 data, whereas the signal from EC-Earth is weaker. The n.s.d. for EC-Earth is 0.70, for CESM is 1.04. and for MIROC is 1.24 taking ERA5 data as references. This also holds true for surface temperature imprints for wave-5 event, as all models are able to reproduce the patterns found in ERA5 data, such as the continental-scale patterns of positive and negative signals for central North America (+), western Europe (-), and central Europe (+). But their strength is weaker in

215   EC-Earth, especially for eastern Eurasia. However, when moving to the near-surface temperature anomalies, the correlations reduce greatly for EC-Earth (0.55) and MIROC (0.48), but not so much for CESM (0.81). As for the precipitation, all model correlations are below 0.50 with MIROC being the lowest (0.18), 0.46 for EC-Earth, and 0.43 for CESM. The correlation values for sea level pressure in models vary from 0.52 (MIROC), 0.58 (EC-Earth) to 0.80 (CESM).   As for the multi-model mean (MMM) s.d., there is a decline from v250 (0.99) to the surface variables t2m (0.71), pr (0.63), and mslp (0.69). Both

220   reanalysis data and models show strong positive anomalies in sea level pressure in the eastern basin of the Atlantic Ocean (west coast of Europe) during wave-5 event (Fig.3)

As for the wave-7 events, field correlations in Table A1 show that the upper-level circulation patterns match well compared to ERA5 data: 0.84 (EC-Earth), 0.84 (CESM), and 0.82 (MIROC). Again, this confirms the previous statement of models'

225   satisfactory performance in producing correct upper-level circulation patterns during high amplitude wave events. The t2m correlations in models are 0.70 (EC-Earth), 0.63 (CESM), and 0.53 (MIROC). The hot anomalies in t2m are quite pronounced in the regions of central North America, western Europe, northern Europe and central Eurasia. All models are able to show the hot t2m anomalies in these regions but all have weaker positive and negative anomalies than ERA5 with n.s.d. values being 0.62 (EC-Earth), 0.61(CESM), and 0.67 (MIROC) (Table A2). The large-scale precipitation anomaly

230   patterns in EC-Earth relate better to WFDE5_CRU data for North America, whereas in both CESM and MIROC there is more noise. The MMM precipitation anomalies correlation is 0.32. The large-scale patterns of sea level pressure during wave-7 events match relatively well with ERA5 data with MMM correlation value 0.63 In contrast to wave-5 having strong positive anomalies in sea level pressure at the eastern side of the Atlantic Ocean (west coast of Europe), during wave-7 event strong negative anomalies are found at the same location. Also, positive mean sea level pressure anomalies are found during

235   wave-7 events (Fig.4) at the east coast of North America, whereas the location shows negative anomalies during wave-5 events.

One common finding from both wave-5 and wave-7 events is that the models have relatively minor bias (n.s.d. ≥ 0.75) in upper-level circulation, but substantial bias in t2m, prcp, and mslp anomalies. All models substantially underestimate the

240   magnitude of t2m, prcp, and mslp anomalies associated with wave-5 and wave-7 events, typically by a factor of 1.5 (Table A4).

3.3 Investigating sources of model biases

Next, we systematically assess the origin of the biases in the upper-level wind and surface fields as shown in Fig 3 and 4. As defined in the methods section, the bias maps were computed as the differences between the selected variables' anomalies in

245   the models and in the reanalysis data ERA5 during high amplitude wave-5 and wave-7 events. It has to be noted that the biases that we refer to in surface variables are the biases of the anomalies instead of the absolute bias of the models. Here we present and describe the EC-Earth bias maps only. Equivalent plots for the other 2 models, with qualitatively similar outcomes, can be found in Fig. B1 to Fig. B4.

250   Here, we also employ the different nudged experiments: AISF (soil moisture prescription), AFSI (upper-level atmosphere nudging), and AFSF (nudging both) (see data section above for details). Overall, when nudging both atmosphere and soil moisture, the residual bias B_res is, as expected, negligible. This is true for both wave-5 and wave-7 events in all models and all analyzed variables (Fig.7 & Fig.8).

255   By nudging the atmosphere, the bias from the atmospheric part (B_atm) is (of course) almost completely removed for the v250 anomaly across all models (see Fig. 7(a), B_land). More interestingly, Fig. 7(b) shows that most of the EC-Earth t2m

anomaly bias is also removed when we nudge the upper-level atmosphere. Thus, the total bias (B_tot) in t2m is almost completely explained by the upper-level atmospheric bias (B_atm), and the land-atm bias (B_land) is negligible (Fig 7(b)).

260 Similarly, for wave-7 events, Fig. 8 (b) confirms our finding that nudging the upper-level atmosphere alone reduces the bias in surface temperature dramatically. Therefore, the total bias (B_tot) in t2m can be explained almost fully by B_atm, and again the land contribution to the bias is minor (Fig.8(b)). Specifically, with the aid of a Taylor Diagram (Fig.6 (b) & Fig.6 (d)), there is a clear separation and improvement comparing atmospheric nudged run AFSI to control run AISI and soil moisture nudged run AISF. The t2m bias still remains substantial when nudging the soil moisture. The actual n.s.d and

265 RMSE values for v250 in AFSI are 1.0 and 0.10, compared to that of AISI run 0.8 (n.s.d.) & 0.55 (RMSE). Fig. 6 also exhibits that CESM and MIROC have similar characteristics, with substantial t2m and mslp being removed by upper-level atmospheric nudging. Still in EC-Earth, for t2m , n.s.d. improves from 0.62 to 1.1 and mslp from 0.74 to 1.0. Fig. 6(c) also shows improvement in the spatial pattern correlation for prcp with 0.39 for the free running AISI run compared to 0.80 in the AFSI run. Another interesting observation obtained from comparing wave-5 and wave-7 Taylor Diagrams is that the models

270 are more clustered for all variables for wave-7 compared to wave-5.

This shows, that free-running EC-Earth (AISI) has a relatively minor bias in v250 (blue square in Fig 7(a)) with a correlation of ~0.9, RMSE of ~0.5 and n.s.d. ~0.7. In other words, the pattern is very similar with a bit underestimated strength in terms of wind speed. Still the bias in t2m (B_tot, blue square in Fig 5 (b)) is substantially larger with correlation of ~0.6, RMSE

275 ~0.9, and n.s.d ~0.6. Thus, the surface temperature imprint is underestimated with about a factor 1.7 (n.s.d ~0.6). This substantial bias in t2m is almost completely removed when nudging the upper-level wind field, i.e. removing the relatively minor bias in v250. This is given by the blue triangle in Fig 5(b) (AFSI) showing a correlation of 0.94, RMSE of 0.36 and n.s.d. of 1. As can be seen in Fig. 5, the other models behave qualitatively in a similar way, with a substantial bias in near-surface temperature being almost completely removed when the relatively minor bias in upper level wind is removed.

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Errors in precipitation anomalies are not fully removed when nudging upper-level circulation. Fig. 5 (c) shows some reduction in the overall magnitude of errors in precipitation and the field correlation improves with almost a factor of 2 from 0.46 to 0.81(Fig.5(c)). However, for the bias in sea surface pressure anomalies, the errors are almost completed removed (Fig.5(b)).

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In general, nudging the soil moisture doesn't affect the upper atmospheric flow. It can, however, in AISF runs reduce some errors across models for t2m and prcp variables. The same conclusion stands for AISF and AFSI runs for prcp and mslp. The observations are complex and location specific as one component within a climate model might be tuned in such a way that it compensates for biases in other components. If so, nudging only one component might not necessarily reduce the overall

290 biases, in this case, prescribing only soil moisture part.

4 Discussion

Large atmospheric circulation patterns, especially amplified wave-5 and wave-7 circumglobal Rossby waves, play an important role in climate variability and can trigger and maintain some extreme events in summer. In this study, we demonstrate that amplified circumglobal Rossby waves, with focus on the characteristics of boreal summer wave-5 (corr.

295   0.90) and wave-7 (corr. 0.83), are well captured in different climate models in terms of their climatology, variability, and phase-locking behaviors. Both amplitude and week-to-week variability, in terms of standard deviations, are reasonably well reproduces in all models for all relevant wave numbers. The MMM n.s.d. for v250 are 0.99 and 0.91 during wave-5 and wave-7 events, showing that the wave-amplitudes are well-captured. Although the upper-level wind flows are satisfactorily reproduced across all models, their associated surface meteorological imprints (surface temperature and precipitation) during

300   wave-5 and wave-7 high amplitude wave events is too weak. The MMM n.s.d. are 0.71 & 0.63 for t2m and 0.63 & 0.74 for pr in wave-5 and wave-7 events respectively. These model biases can be largely corrected by nudging the upper-level atmosphere. For instance, the n.s.d. for surface temperature field during high amplitude wave-5 (wave-7) events increase from 0.71 (0.63) to 0.99 (1.06), for precipitation from 0.63 (0.74) to 1.05 (1.04), and for sea level pressure from 0.69 (0.72) to 0.97 (1.0). The same scale reduction in errors are not observed when prescribing the soil moisture. This implies that a

305   small bias in the upper atmospheric levels can result in big biases in surface weather conditions and related extreme events. A full analysis of the underlying reasons is outside the scope of this paper, but here we discuss some potential mechanisms. First, nudging zonal (u) and meridional (v) winds in the upper-atmosphere constrains the large-scale vertical wind component (ω) which is a key input for cloud parameterization schemes. In models, large-scale vertical wind is primarily defined by divergence in the horizontal wind fields, ensuring mass conservation, and thus nudging u and v will also

310   effectively nudge ω. Likewise, biases in u and v will propagate in ω and can then have a strong (non-linear) impact on the amount of clouds in models (Satoh et al. 2019; Rio et al., 2019). Regions with anomalously high pressure due to the circumglobal wave, will have pronounced subsidence in ERA5 but this can be disturbed in the models. As a consequence, the models are likely to have more hazy cloud conditions as compared to clear-sky conditions in ERA5. This would impact the surface by reduced short wave radiation and hence less pronounced warm anomalies. Potentially, also limitations in the

315   cloud parametrization schemes could exacerbate this, with models having difficulties reproducing clear sky conditions (Lacagnina and Selten 2014). As the resolution for GCMs often don't allow sub-grid scale convective systems and their associated clouds to be resolved. It is also highlighted that particularly in mid-latitude continents, climatological biases in both clouds and precipitation persist in major GCMs (Rio et al., 2019). One study specifically focused on clouds and radiative fluxes in EC-Earth and revealed that there are too many clouds in EC-Earth that are optically thick but too little

320   clouds that are optically thin (Lacagnina and Selten 2014). Thus, a small bias in upper atmosphere wind field propagates via vertical wind (ω) and cloud scheme, into surface biases in climate models. While previous work has indicated that soil moisture can have pronounced effects on circumglobal waves (Koster et al. 2016; Teng et al. 2019), our analyses show that adjusting for soil moisture biases (by prescription) has little effect on the representation of circumglobal waves nor their

surface imprint. Or, at least not on the anomaly these events produce. These differences could arise from different time-scales and/or experiment set-ups. Earlier studies focused mainly on monthly to seasonal mean responses while ours analyzed weekly timescale. In addition, in Teng et al., (2019), they prescribed soil moisture as zero at specific locations, whereas in our soil moisture prescription experiments the soil moisture was prescribed with values from running the land component driven by atmospheric fields from reanalysis in the model offline, which thus represent much smaller forcings.

Recent work has shown that the individual extreme events can be examined in the climate models, but anomalies or bias-corrections should be applied for the analysis (Wehrli et al., 2019). Similarly, in our study, we defined the wave-5 and wave-7 events, then the surface variables anomalies against their climatological means are compared between ERA5 and the models for different experiments.

Our findings have implications for climate model projections of persistent summer weather extremes in the key affected regions. Kornhuber et al (2020) identified hotspots that are affected by summertime amplified wave-5 patterns (Central North America, Eastern Europe, and Eastern Asia) and wave-7 (Western Central North America, Western Europe and Western Asia). These regions are sensitive to simultaneous heat extremes, and to exacerbate the situation, some identified regions are also considered as global breadbasket regions. On average the reduction in crop production is 4% during wave-5 or wave-7 that persist more than 2 weeks in summer events and on a regional level up to 11% (Kornhuber et al., 2020). In our study, for wave-5 and wave-7 events, all the aforementioned key regions are identified in our three models for near-surface temperature positive anomalies. This allows us to have more confidence in the state-of-art climate models, not only for the accurate representation of upper-level atmospheric circulation, but also for the correctness of the associated hotspots at the surface. Since the strength of the near-surface temperature anomalies is underestimated, the climate models are likely to underestimate heatwaves as well. A potential way to adjust for this is to establish statistical links between upper-level atmosphere slow to near-surface temperature based on observational data, i.e. an emergent constraint. Then use this statistical link to adjust the effect of upper-level atmospheric circulation changes in climate models under future scenarios for heatwave risks. In addition, it will be important to assess how the large circulation pattern and strength change under future greenhouse gas forcing that can lead to changes in the extreme events.

5 Summary and Conclusions

Our validation study shows that upper-level wave characteristics are reasonably well reproduced in three GCMs in historic AMIP runs with MMM of n.s.d. for wave-5 and wave-7 events being 0.99 and 0.91. Both the climatology and phase-locking behaviors are captured in models for wave number 5 and 7, as the MMM correlation values are 0.90 and 0.83. Surface temperature anomalies are associated with the amplified wave-5 and wave-7 patterns but have weaker anomalies as

355 compared to ERA5 reanalysis data. The MMM n.s.d. for surface temperature field during high amplitude wave-5 and wave-7 events increase from 0.71 and 0.99 to 0.63 and 1.06 just by nudging upper-level atmosphere

In summary, for the surface meteorological variables, we find that:

- Overall, v250 is the most accurate and precipitation is poorly estimated among all variables for both wave-5 and
360   wave-7 events.
- Prescribing soil moisture does not add much improvements for the anomalies in t2m and prcp. In the case of v250 and mslp, it even made the representation of wave-5 and wave-7 events worse. This is likely due to model tuning issues.
- Nudging the upper-level atmosphere indicates that this is the prime origin of surface anomaly biases. We observe
365   significant improvements from AISI in AISF runs and AFSI runs across all models and all variables.

The bias in model surface imprints for amplified waves events mainly originates from smaller biases in the atmospheric circulation component of the model for the mid latitude. The soil moisture feedback also explains some bias but this is minor compared to the atmospheric part. Our study suggests that climate models can be used to study present and future wave
370 characteristics, but that care should be taken when analyzing the associated surface extremes.

375 *Code and data availability.* The code and data can be made available by the authors upon request.

Author contributions. FL, DC and FS designed the analysis with input from KK. FL ran the EC-Earth3 simulations with technical help from FS, WM, PLS, and TR. HS ran the interactive and atmosphere nudged simulations with MIROC5. DT and HK ran the soil 460 moisture nudged simulations with MIROC5. KW ran the CESM1.2 model simulations with
380 technical support by Mathias Hauser. FL analyzed the results from all models. All authors contributed to the discussion of results. FL prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

385   *Acknowledgements.* EC-Earth3 simulations were contributed by VU Amsterdam and KNMI. The MIROC5 simulations were
contributed by NIES Japan and University of Tokyo. CESM1.2 simulations were contributed by ETH Zurich. FL, DC and
FS acknowledge VIDI-award from Netherlands Organization for Scientific Research (NWO) (Persistent Summer Extremes
"PERSIST" project: 016.Vidi.171.011). KK was partially supported by the NSF project NSF AGS-1934358.KW and SIS
acknowledge funding from the European Research Council (ERC) ("DROUGHT-HEAT" project, Grant 617518). HS was
390   supported by the Integrated Research Program for Advancing Climate Models (JPMXD0717935457). The MIROC5
simulations were performed by using Earth Simulator in JAMSTEC and the NEC SX in NIES. WM is supported through the
Swedish strategic research area ModElling the Regional and Global Earth system (MERGE). The authors would like to
thank Mathias Hauser and Emanuel Dutra for their help in the discussions for the preparation of soil moisture prescription
data and the applications in the models.

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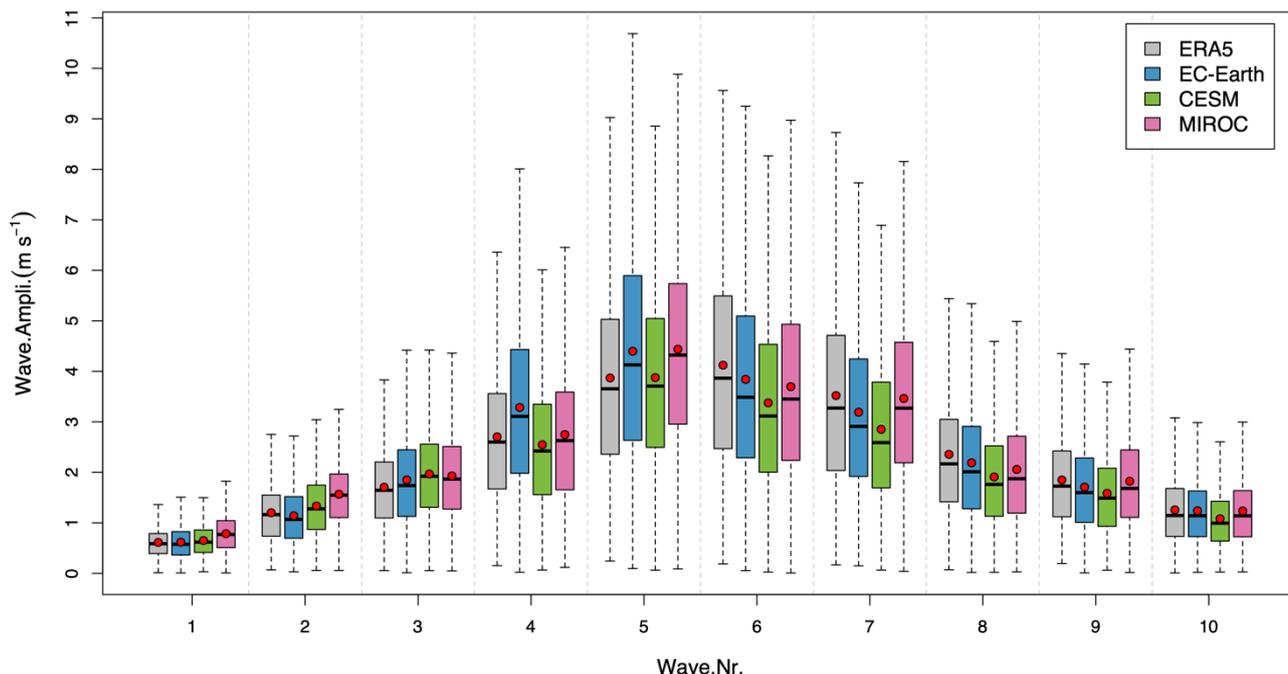
Figure 1: Boxplot for wave amplitudes in AISI climatology runs for climate models EC-Earth, CESM, and MIROC, as well as reanalysis data ERA5 for the period of June, July, and August in 1979-2015/2016. Red dots indicate the mean, and thick black lines represent the median. The lower hinge of each box is Q1 quartile (25th), and the upper hinge for Q3 quartile (75th). The upper bar represents maximal value whereas the lower bar represents minimal value. The outliers are not shown in the plot.
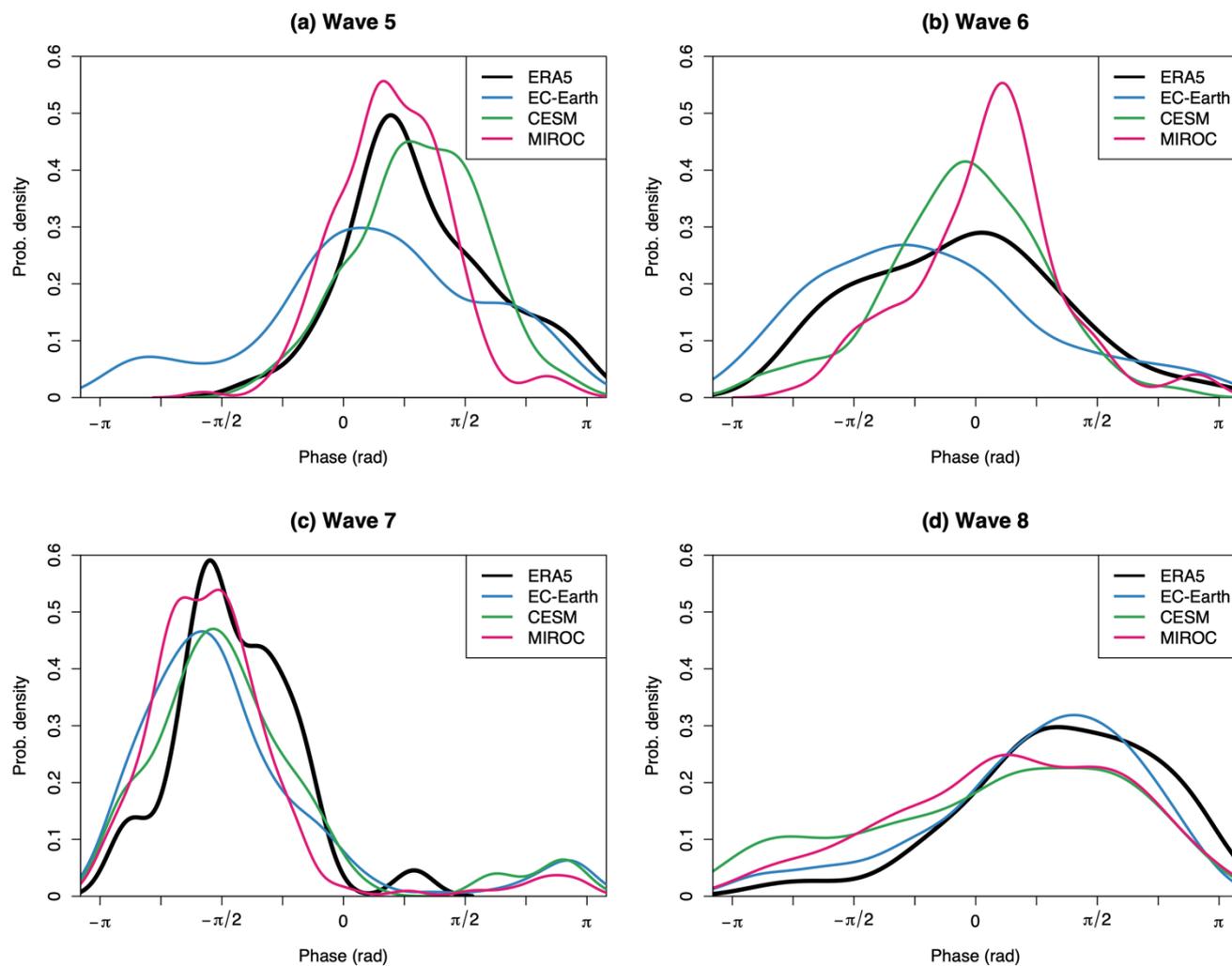
Figure 2: Phase-locking of Rossby waves for JJA ERA5 and model waves 5-8 in control run AISI for high wave amplitude events (> 1.5 s.d.): (a)-(d), Probability density functions of the phase positions of waves 5-8 in ERA5, EC-Earth, CESM, and MIROC during JJA for the period of 1979-2015/2016 (wave 5 (a), wave 6 (b), wave 7 (c), wave 8 (d)).

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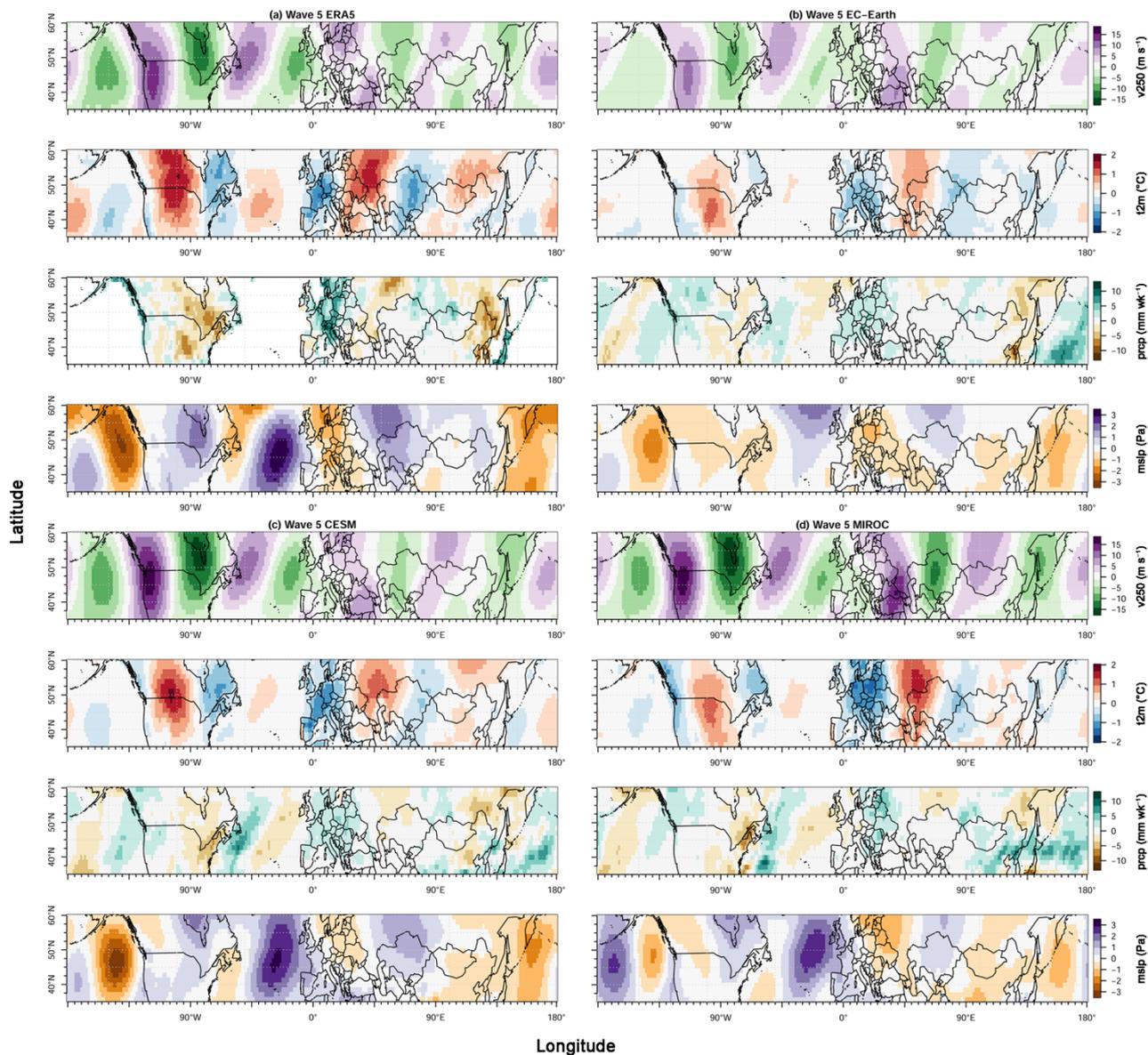
Figure 3: Composite anomaly plots of weeks with high-amplitude waves-5 events for meridional wind velocity at 250hPa (v250), near-surface temperature (t2m), precipitation (pr), and seal level pressure (mslp) in ERA5 (a), EC-Earth (b), CESM (c) and MIROC (d) based on control runs AISI.

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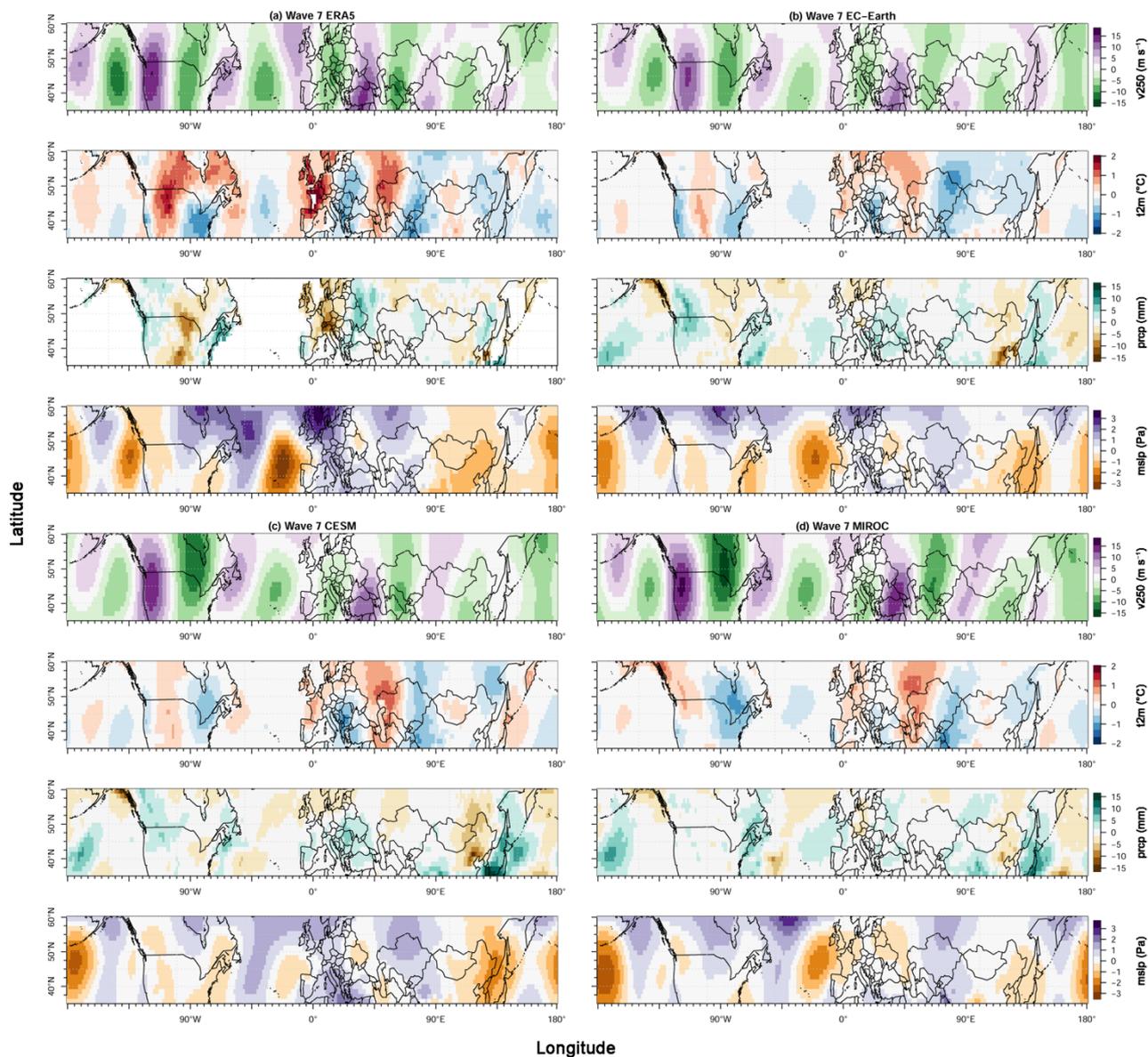
Figure 4: Composite anomaly plots of weeks with high-amplitude waves-7 events for meridional wind velocity at 250hPa (v250), near-surface temperature (t2m), precipitation (pr), and seal level pressure (mslp) in ERA5 (a), EC-Earth (b), CESM (c) and MIROC (d) based on control runs AISI.

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(a) wave 5, v250

(b) wave 5, t2m

(c) wave 5, prcp

(d) wave 5, mslp
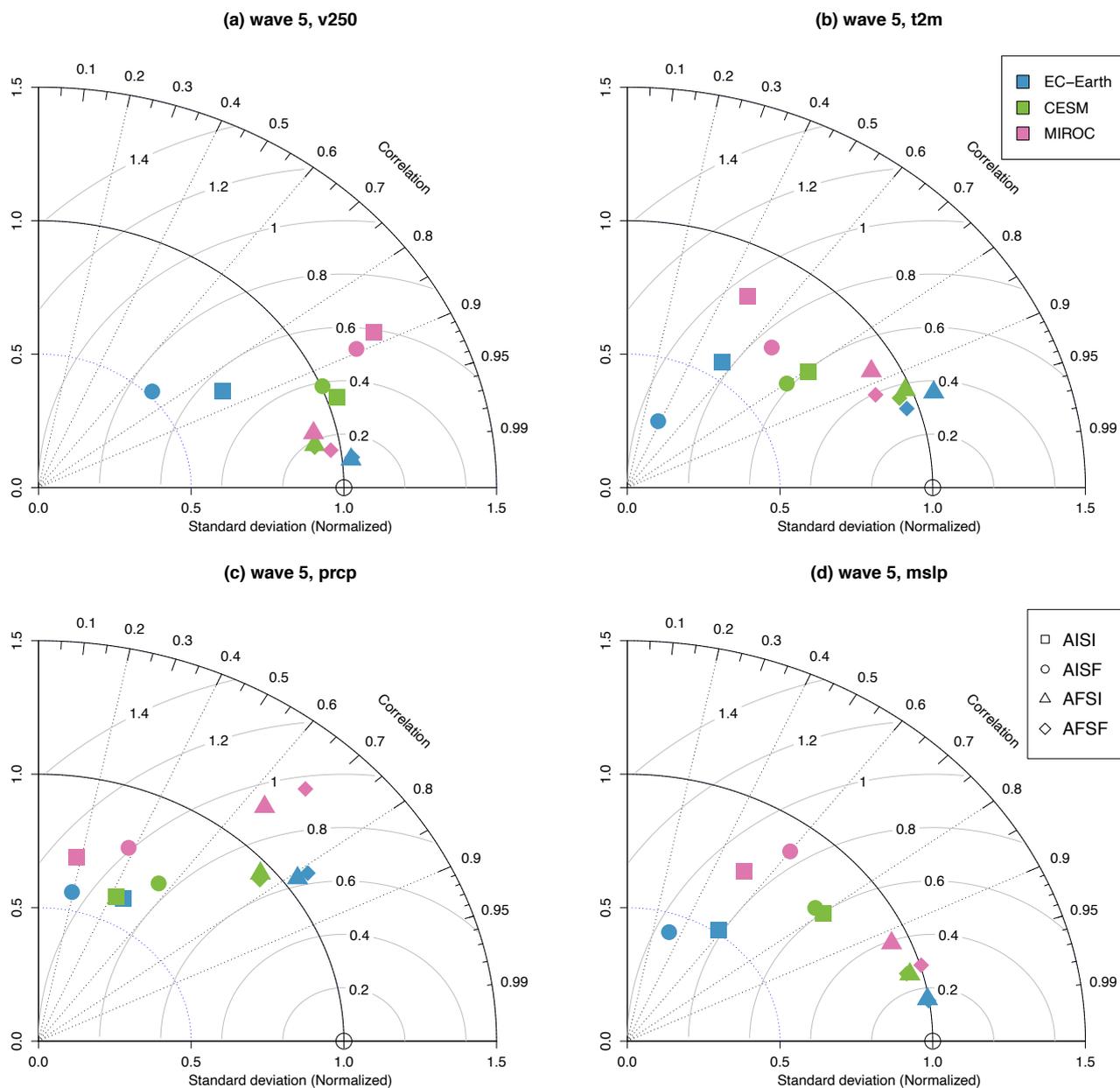
Figure 5: Taylor Diagram for all experiments in models compared to ERA5 for wave-5 events. For a) V250, b) t2m, c) prcp, and d) mslp, the Taylor diagram presents for each model and each experiment, three statistics: the Pearson correlation (dashed lines); the RMS error (grey contours); and the normalized spatial standard deviation (solid black contours).

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(a) wave 7, v250

(b) wave 7, t2m

(c) wave 7, prcp

(d) wave 7, mslp
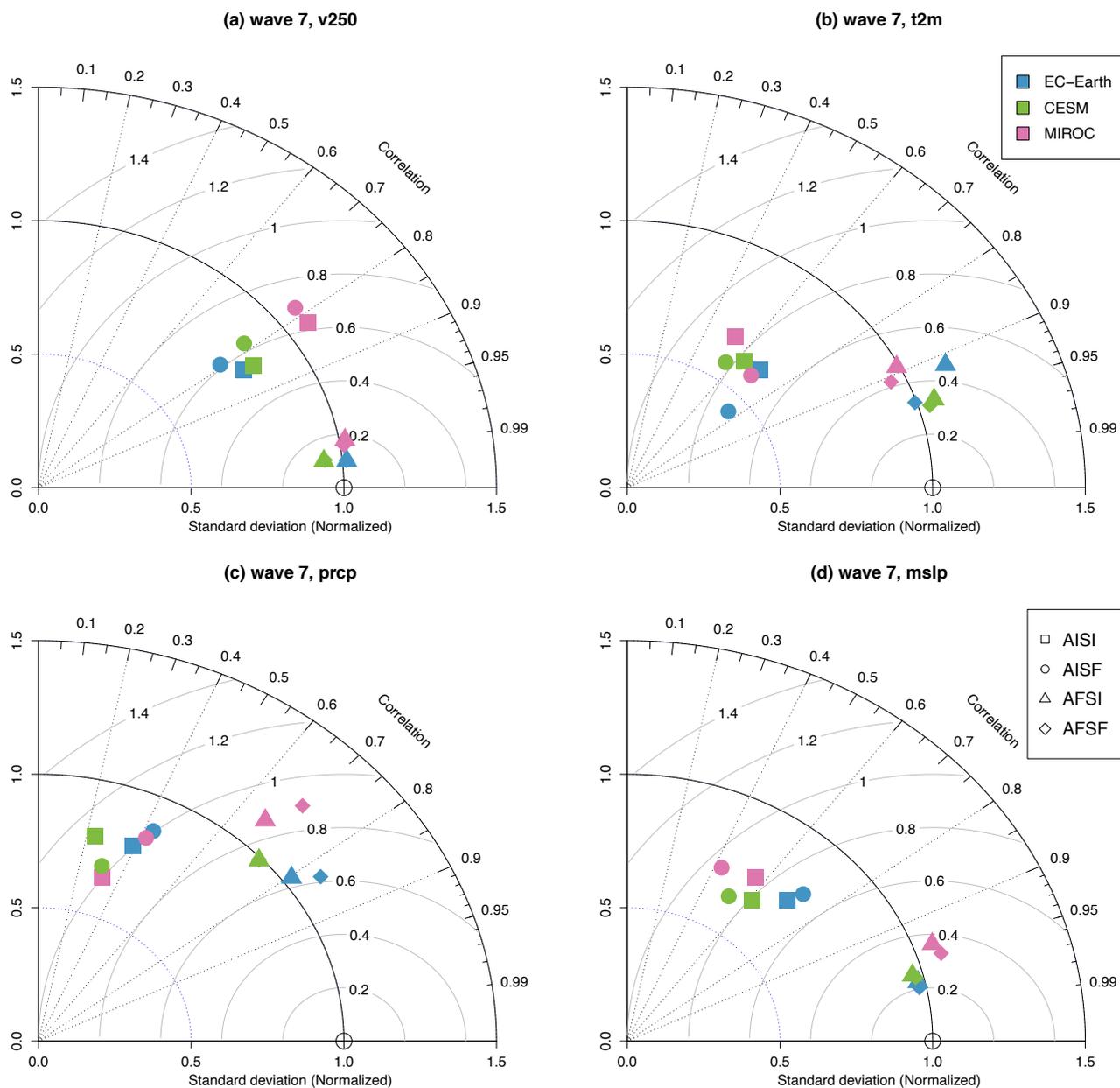
Figure 6: Taylor Diagram for all experiments in models compared to ERA7 for wave-5 event. For a) v250, b) t2m, c) prcp, and d) mslp, the Taylor diagram presents for each model and each experiment, three statistics: the Pearson correlation (dashed lines); the
550 **RMS error (grey contours); and the normalized spatial standard deviation (solid black contours).**
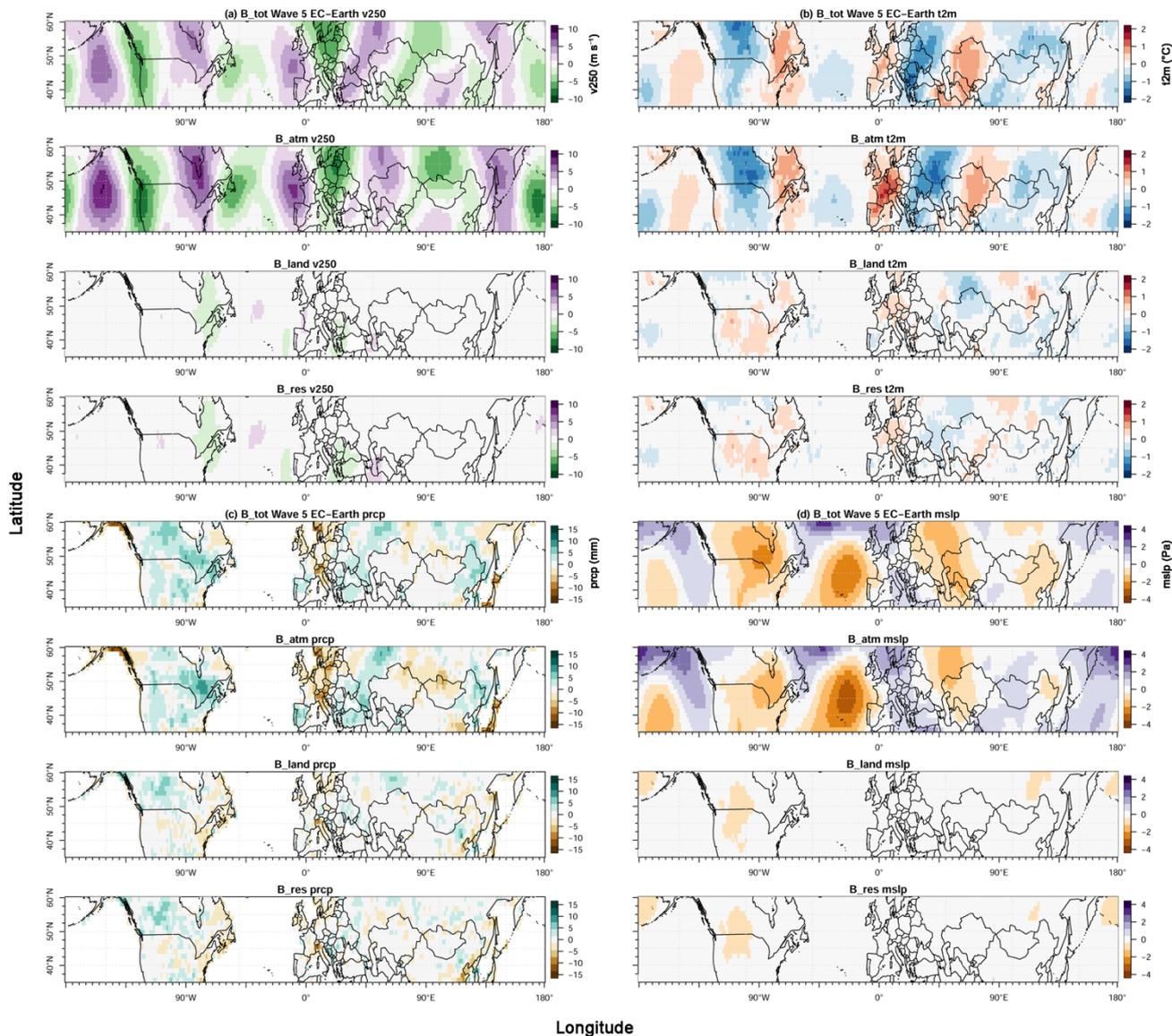
Figure 7: Bias plots for high-amplitude wave-5 events in different experiments for EC-Earth. Total bias(B_tot), atmospheric bias(B_atm), land-atmosphere interaction bias (B_land) and residual bias(B_res) for meridional wind velocity at 250hPa (a), surface temperature (b), precipitation (c), and seal level pressure (d).
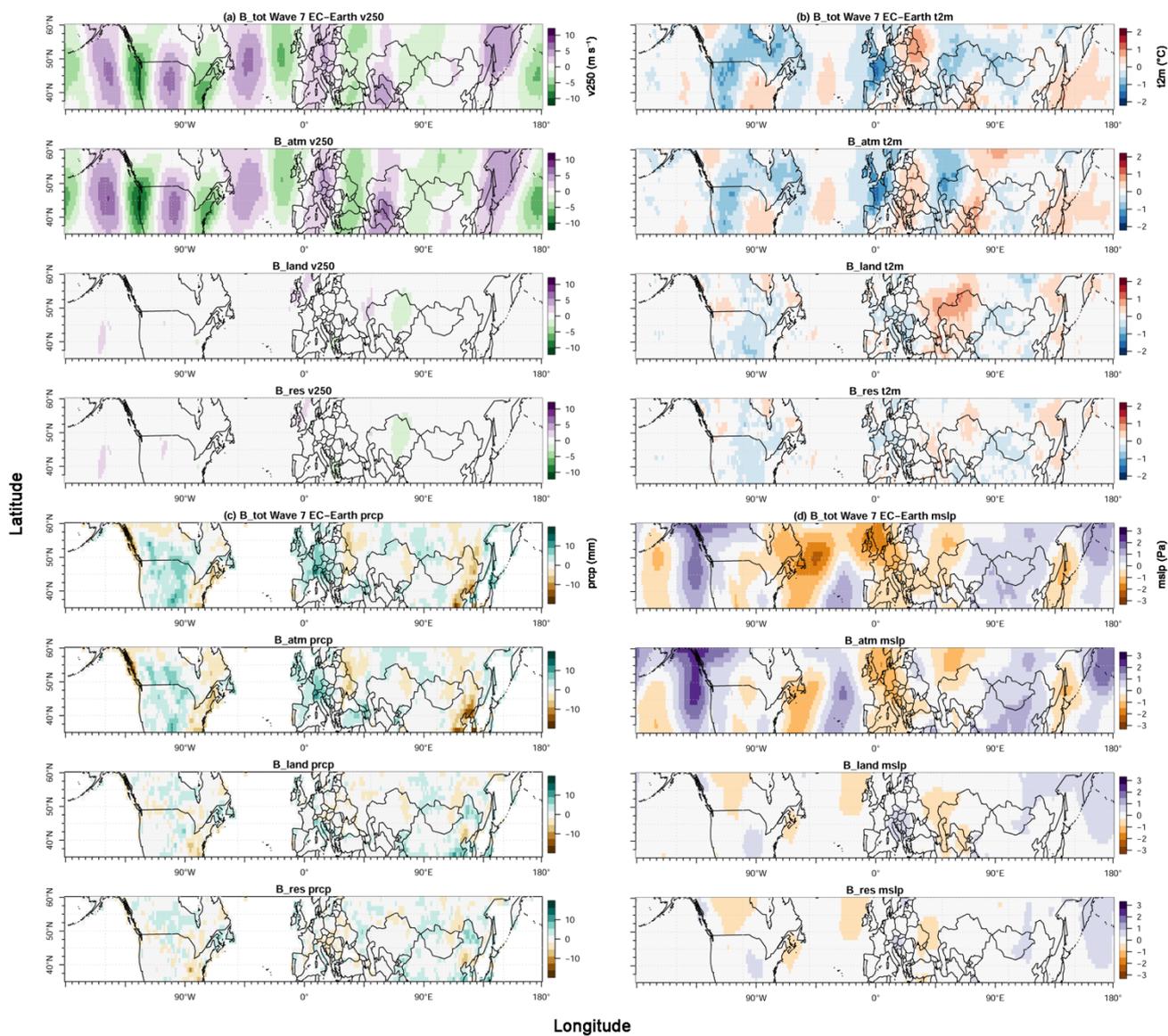
Figure 8: Bias plots for high-amplitude wave-7 events in different experiments for EC-Earth. Total bias(B_tot), Atmospheric bias(B_atm), Land-Atm interaction bias(B_land) and residual bias(B_res) for meridional wind velocity at 250hPa (a), surface temperature (b), precipitation (c), and seal level pressure (d).

Appendix

Wave5	v250				t2m				prcp				mslp			
Model	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean
AISI	0,858	0,945	0,884	0,896	0,552	0,806	0,481	0,613	0,460	0,427	0,179	0,355	0,584	0,801	0,515	0,633
AISF	0,719	0,926	0,895	0,847	0,375	0,801	0,669	0,615	0,192	0,554	0,377	0,374	0,317	0,777	0,600	0,565
AFSI	0,995	0,985	0,975	0,985	0,942	0,928	0,878	0,916	0,812	0,756	0,645	0,738	0,987	0,965	0,921	0,958
AFSF	0,994	0,986	0,989	0,990	0,951	0,936	0,920	0,936	0,814	0,768	0,679	0,754	0,988	0,964	0,959	0,970
Wave7	v250				t2m				prcp				mslp			
Model	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean
AISI	0,837	0,839	0,819	0,832	0,703	0,629	0,528	0,620	0,388	0,236	0,323	0,316	0,704	0,613	0,566	0,628
AISF	0,791	0,780	0,780	0,784	0,757	0,565	0,693	0,672	0,431	0,301	0,420	0,384	0,723	0,522	0,429	0,558
AFSI	0,995	0,994	0,984	0,991	0,915	0,950	0,890	0,918	0,804	0,729	0,668	0,734	0,974	0,967	0,939	0,960
AFSF	0,995	0,994	0,988	0,992	0,947	0,955	0,909	0,937	0,832	0,728	0,700	0,753	0,979	0,970	0,952	0,967

570 **Table A1: Summary of Model Taylor Diagram correlation values.**

Wave5	v250				t2m				prcp				mslp			
Model	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean
AISI	3,510	5,168	6,203	4,960	0,292	0,382	0,424	0,366	1,746	1,729	2,027	1,834	0,586	0,916	0,847	0,783
AISF	2,584	5,012	5,805	4,467	0,139	0,338	0,367	0,281	1,646	2,054	2,262	1,987	0,492	0,906	1,016	0,805
AFSI	5,133	4,584	4,608	4,775	0,553	0,509	0,472	0,511	3,024	2,779	3,322	3,042	1,138	1,096	1,075	1,103
AFSF	5,158	4,576	4,826	4,853	0,499	0,494	0,459	0,484	3,135	2,731	3,723	3,196	1,141	1,085	1,148	1,125
Wave7	v250				t2m				prcp				mslp			
Model	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean
AISI	4,162	4,344	5,585	4,697	0,310	0,304	0,334	0,316	2,526	2,510	2,064	2,366	0,818	0,734	0,818	0,790
AISF	3,894	4,467	5,574	4,645	0,219	0,285	0,292	0,265	2,775	2,190	2,669	2,545	0,877	0,700	0,792	0,790
AFSI	5,250	4,864	5,276	5,130	0,570	0,530	0,496	0,532	3,278	3,150	3,537	3,322	1,076	1,063	1,170	1,103
AFSF	5,245	4,883	5,240	5,123	0,498	0,520	0,476	0,498	3,532	3,154	3,928	3,538	1,076	1,072	1,188	1,112

Table A2: Summary of model standard deviation values.

Wave5	v250				t2m				prcp				mslp			
Model	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean
AISI	2,675	1,695	2,942	2,437	0,446	0,319	0,498	0,421	2,302	2,425	2,924	2,550	0,956	0,687	1,025	0,889
AISF	3,610	1,927	2,600	2,712	0,497	0,343	0,397	0,412	2,671	2,251	2,530	2,484	1,093	0,724	0,995	0,937
AFSI	0,542	0,944	1,140	0,875	0,187	0,209	0,257	0,218	1,771	1,822	2,490	2,027	0,189	0,303	0,450	0,314
AFSF	0,586	0,908	0,740	0,745	0,160	0,197	0,212	0,190	1,793	1,767	2,468	2,009	0,187	0,305	0,330	0,274
Wave7	v250				t2m				prcp				mslp			
Model	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean	EC-Earth	CESM	MIROC	Model Mean
AISI	2,838	2,813	3,263	2,971	0,380	0,397	0,442	0,407	3,076	3,395	2,988	3,153	0,785	0,872	0,928	0,862
AISF	3,174	3,267	3,582	3,341	0,376	0,420	0,372	0,389	3,062	3,152	2,878	3,031	0,785	0,949	1,04764	0,927
AFSI	0,527	0,638	0,935	0,700	0,231	0,167	0,237	0,212	1,988	2,262	2,558	2,269	0,250	0,306	0,510	0,355
AFSF	0,536	0,645	0,829	0,670	0,166	0,155	0,215	0,179	1,908	2,206	2,560	2,224	0,226	0,304	0,483	0,338

575 **Table A3: Summary of model RMSE values.**

Wave7	v250			t2m			prcp			mslp		
Model	corr	std	rmse	corr	std	rmse	corr	std	rmse	corr	std	rmse
AISI	0,832	0,907	0,574	0,620	0,631	0,812	0,316	0,744	0,991	0,628	0,717	0,783
AISF	0,784	0,897	0,645	0,672	0,530	0,777	0,384	0,800	0,953	0,558	0,717	0,842
AFSI	0,991	0,991	0,135	0,918	1,063	0,423	0,734	1,044	0,713	0,960	1,002	0,323
AFSF	0,992	0,990	0,129	0,937	0,994	0,356	0,753	1,112	0,699	0,967	1,010	0,307
Wave5	v250			t2m			prcp			mslp		
Model	corr	std	rmse	corr	std	rmse	corr	std	rmse	corr	std	rmse
AISI	0,896	0,994	0,488	0,613	0,705	0,811	0,355	0,634	0,882	0,633	0,685	0,778
AISF	0,847	0,895	0,544	0,615	0,542	0,794	0,374	0,687	0,859	0,565	0,704	0,820
AFSI	0,985	0,957	0,175	0,916	0,985	0,420	0,738	1,052	0,701	0,958	0,965	0,274
AFSF	0,990	0,973	0,149	0,936	0,933	0,366	0,754	1,105	0,695	0,970	0,983	0,240

Table A4: Summary of Multi-Model Mean Taylor Diagram values.

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ERA5 s.d.	v250	t2m	prcp	mslp
wave 5	4,990	0,519	2,893	1,144
wave 7	5,177	0,501	3,181	1,101

Table A5: Summary of ERA5 standard deviation values.

585
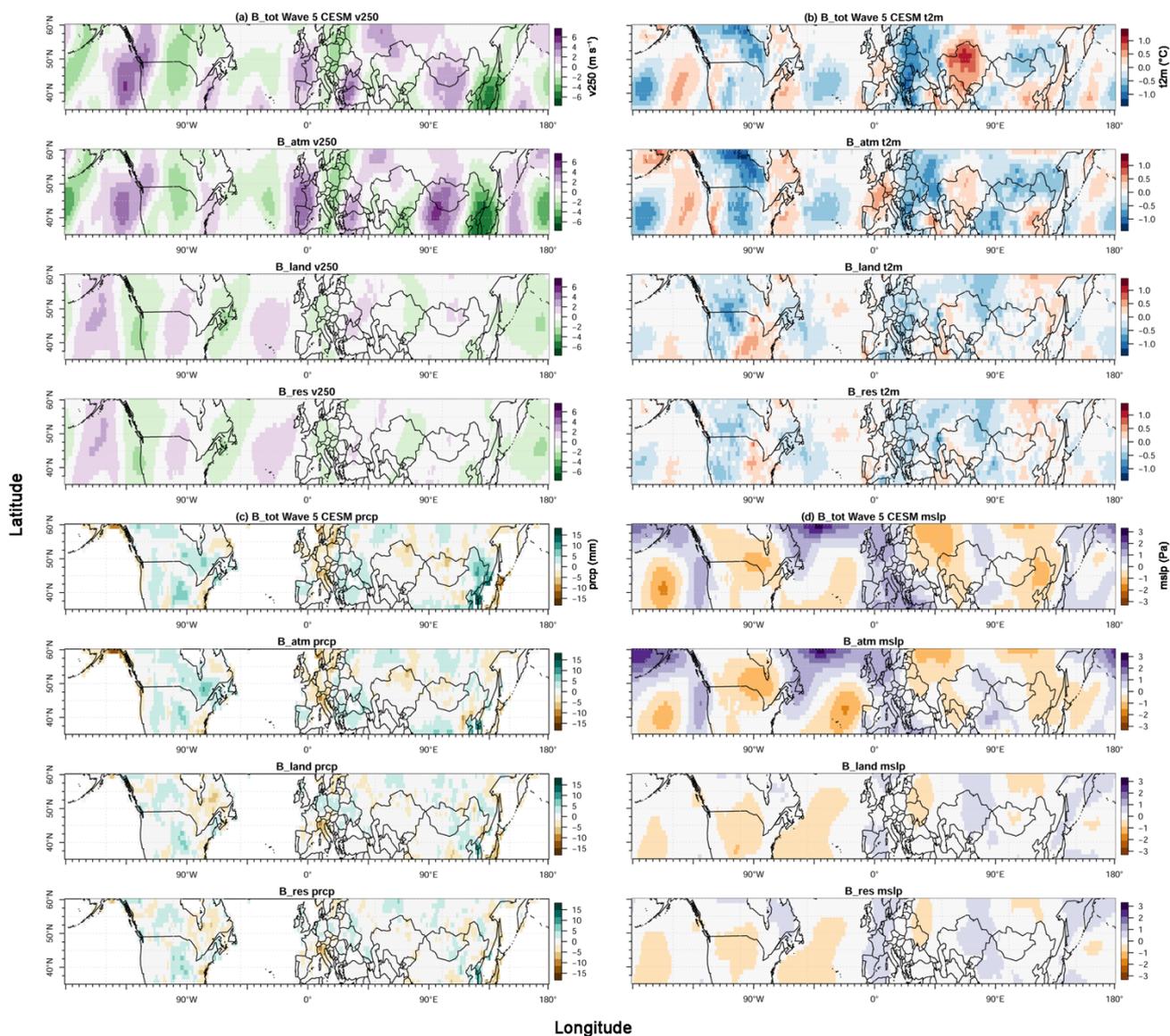
Figure B1: Bias plots for high-amplitude wave-5 events in different experiments for CESM. Total bias(B_tot), atmospheric bias(B_atm), land-atmosphere interaction bias (B_land) and residual bias(B_res) for meridional wind velocity at 250hPa (a), surface temperature (b), precipitation (c), and seal level pressure (d).

590
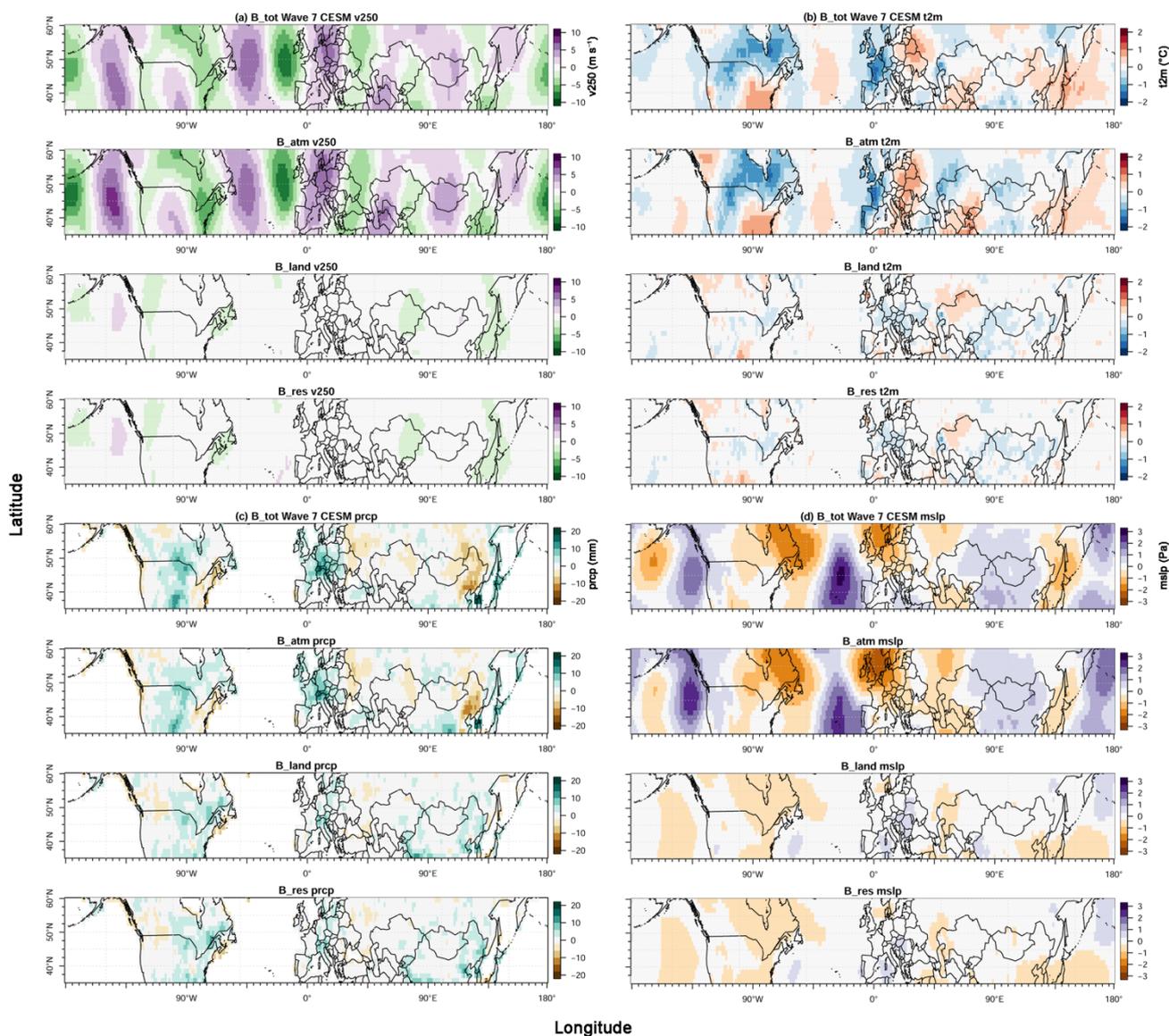
Figure B2: Bias plots for high-amplitude wave-7 events in different experiments for CESM. Total bias(B_tot), Atmospheric bias(B_atm), Land-Atm interaction bias(B_land) and residual bias(B_res) for meridional wind velocity at 250hPa (a), surface temperature (b), precipitation (c), and seal level pressure (d).
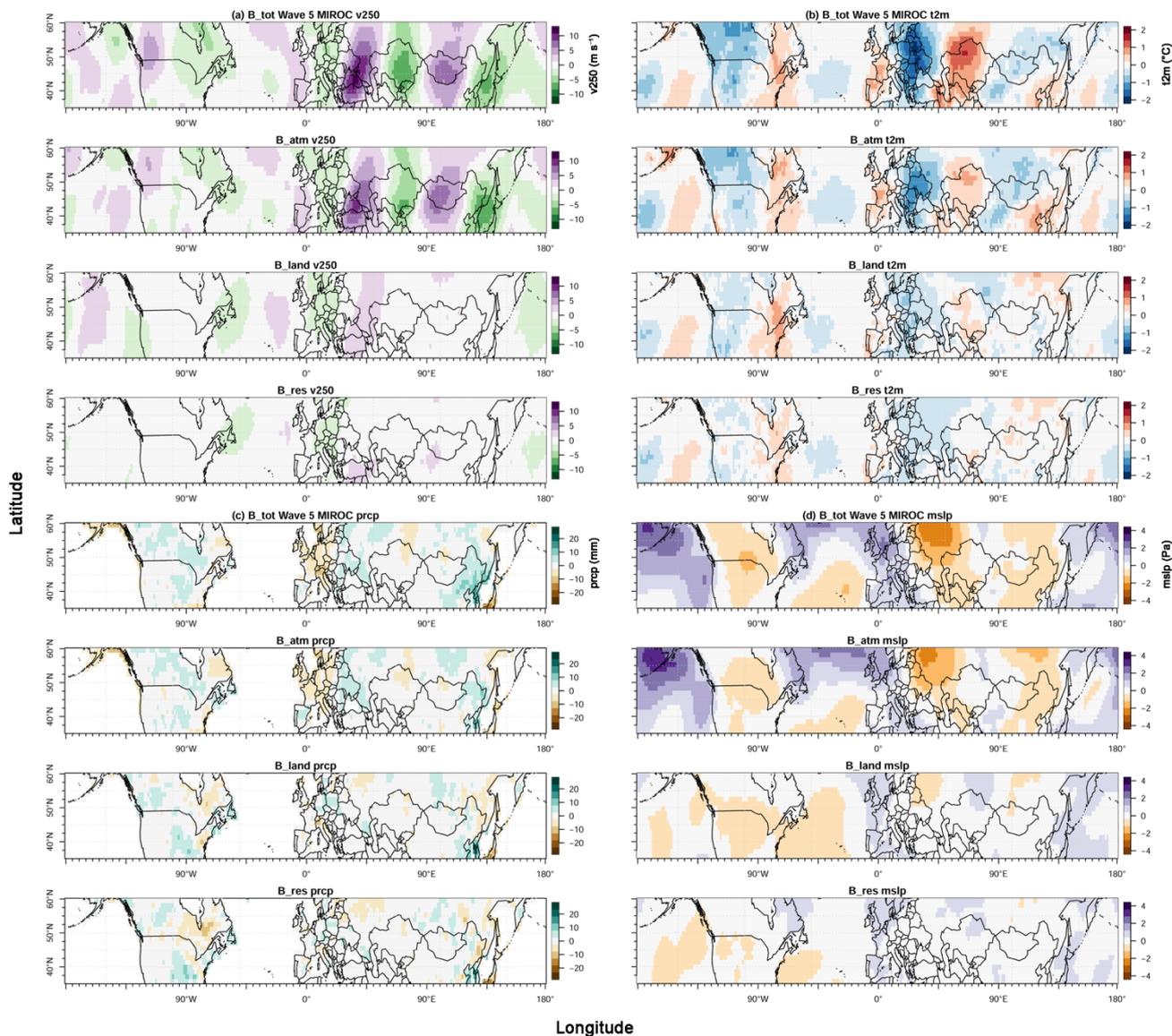
Figure B3: Bias plots for high-amplitude wave-5 events in different experiments for MIROC. Total bias(B_tot), atmospheric bias(B_atm), land-atmosphere interaction bias (B_land) and residual bias(B_res) for meridional wind velocity at 250hPa (a), surface temperature (b), precipitation (c), and seal level pressure (d).
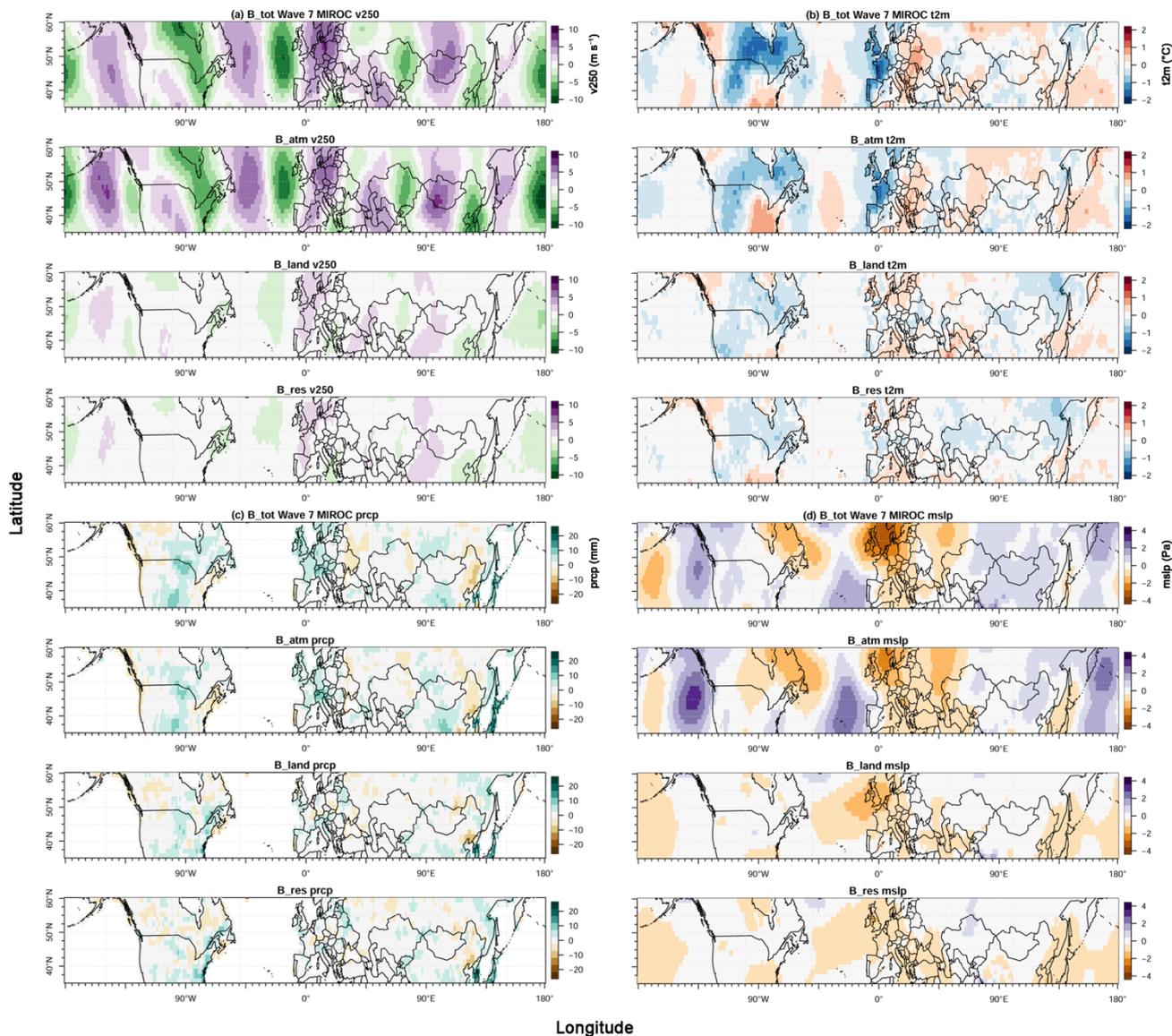
Figure B4: Bias plots for high-amplitude wave-7 events in different experiments for MIROC. Total bias(B_tot), Atmospheric bias(B_atm), Land-Atm interaction bias(B_land) and residual bias(B_res) for meridional wind velocity at 250hPa (a), surface temperature (b), precipitation (c), and seal level pressure (d).