https://doi.org/10.5194/egusphere-2022-1499
Preprint. Discussion started: 20 January 2023

Atmospheric response to wintertime Tibetan Plateau cold bias in climate models

Alice Portal[1,2], Fabio D'Andrea[2], Paolo Davini[3], Mostafa E. Hamouda[4,5], and Claudia Pasquero[1,3]

[1]Department of Earth and Environmental Sciences, Università di Milano - Bicocca, Milan, Italy
[2]Laboratoire de Météorologie Dynamique/IPSL, École Normale Supérieure, PSL Research University, Sorbonne Université, École Polytechnique, IP Paris, CNRS, Paris, France
[3]Consiglio Nazionale delle Ricerche, Istituto di Scienze dell'Atmosfera e del Clima (CNR-ISAC), Torino, Italy
[4]Astronomy and Meteorology Department, Faculty of Science, Cairo University, Cairo, Egypt
[5]Institute for Atmospheric and Environmental Sciences, Goethe University Frankfurt, Frankfurt am Main, Germany

Correspondence: Alice Portal (a.portal@campus.unimib.it)

Abstract. Central Asia orography sets important features of the winter climate over East Asia and the Pacific. By deflecting the mid-latitude jet polewards it contributes to the formation of the Siberian High and, on the lee side, to the advection of dry cold continental air over the East Asian coast and the Pacific Ocean, where atmospheric instability and cyclogenesis thrive. While the mechanical forcing by the orography is assessed by a number of modelling studies, it is still not clear how near-surface temperature over the two most prominent orographic barriers of the Central Asian continent, namely the Tibetan and Mongolian plateaux, influences the winter climate downstream. Moreover, a well known issue of state-of-the art climate models is a cold land temperature bias over the Tibetan Plateau related with the difficulty in modelling land processes and land–atmosphere interaction over complex orography. Here we take advantage of the large spread in representing near surface temperature over the Central Asia plateaux among climate models taking part in the Coupled Model Inter-comparison Project, Phase 6 (CMIP6) to study how temperatures over these regions impact the atmospheric circulation. Based on composites of the CMIP6 models' climatologies showing a cold bias over the Tibetan Plateau, we find that negative temperature anomalies over Asian orography intensify the East Asia winter monsoon and, by enhancing the low-level baroclinicity in the region of the East China Sea, reinforce the southern flank of the Pacific jet. The results of the CMIP6 composite analysis are supported by the response of an intermediate-complexity atmospheric model to a similar pattern of cold surface temperatures over the Central Asia plateaux; we also distinguish the relative influence of the Tibetan and the Mongolian Plateau surface conditions. Thereby, based on the intensification of the East Asia winter monsoon in models characterised by a cold land temperature (bias) over Central Asia plateaux, we prospect that advances in the modelling of the land energy budget over this region may improve the simulation of the mean climate over the Asia / Pacific sector, together with the reliability of climate projections and the performance of shorter term forecasts.

Short non-technical summary. The differences between climate models can be exploited to infer how specific aspects of the climate influence the whole Earth system. This work analyses the effects of a negative temperature anomaly over the Tibetan Plateau on the winter atmospheric circulation. We show that models with a colder-than-average Tibetan Plateau present

https://doi.org/10.5194/egusphere-2022-1499
Preprint. Discussion started: 20 January 2023

a reinforced East Asia winter monsoon and we discuss the atmospheric response to the enhanced transport of cold air from the continent toward the Pacific Ocean.

1 Introduction

The impact of orography on the extratropical circulation was proposed by the analytical studies of Charney and Eliassen (1949) and Bolin (1950), while Smagorinsky (1953) first discussed the matching of orographic and thermal forcing by land-sea contrast in order to explain the longitudinal variations of the mid-latitude westerlies. Manabe and Terpstra (1974) and Hahn and Manabe (1975) analysed the impact of the Tibetan Plateau on the Asian climate by running an atmospheric general circulation model (AGCM) with and without mountains. They proved that the elevation of central Asia is essential to reproduce the position and strength of the low-level winter anticyclone known as the Siberian High and for the maintenance of the South-East Asia summer monsoon, which, due to the intense uplift from orography, extends from the Indian sector as far as East Asia. The regional dryness and humidity of the aforementioned winter and summer circulation patterns and their association with orography were examined by Broccoli and Manabe (1992).

More recently, starting with Sato (2009), the influence of lower-range mountain chains on the Asia and Pacific climate was investigated, and their role was considered separately from that of the Tibetan Plateau. This applies in particular to the mountain chains extending north east of Tibet. Similarly to White et al. (2017), we denote the orography between approximately 20 to 40 N and 62 to 120 E as the Tibetan Plateau or TP, and that between approximately 38 to 60 N and 65 to 140 E as the Mongolian Plateau or MP.

In the cold season the Asia / Pacific circulation is dominated by the East Asia winter monsoon, which consists in north-westerly advection of cold dry continental air from Siberia over the Asian coast and the Pacific Ocean (Zhang et al., 1997; Chan and Li, 2004). The strong winter thermal emission of the TP land and of the air column above generate a tropospheric heat sink over the Plateau (Yanai et al., 1992; Yanai and Wu, 2006; Duan and Wu, 2008) that reinforces the Eurasian mid-tropospheric thermal high (Shi et al., 2015). Moreover, the presence of TP and MP orography reduces the westerlies upstream and enhances the north-westerly winds over East Asia and the Pacific (Shi et al., 2015; Sha et al., 2015). On the lee side of the plateaux, the cold advection strengthens the thermal contrasts and increases the baroclinicity, which in turn fuels the Pacific jet stream downstream, over and east of the East China Sea (Shi et al., 2015; White et al., 2017). Notwithstanding the lower elevation and extension of the MP compared to the TP, the MP is more relevant for the winter circulation because of its ideal position - in terms of impinging low-level winds and meridional potential vorticity gradients - for acting as a source of Rossby waves (Held and Ting, 1990; White et al., 2017).

Conversely, the warm season circulation is driven by the East Asia summer monsoon, modulating rainfall over land and ocean (Yihui and Chan, 2005). This is sustained in strength and extension by the atmospheric uplift produced by Asia orography, which constitutes a tropospheric summer heat source (Yanai et al., 1992; Hahn and Manabe, 1975; Ye and Wu, 1998). The summer monsoon is mostly controlled by the presence of the TP which, among other things, reinforces the monsoonal circulation and the associated precipitation along the east coast of Asia, with the MP playing only a marginal role (see Figures 6, 9, 10 in Sha et al., 2015).

Considering the importance of the Central Asia orography for the climate of the Asia / Pacific sector, it is not surprising to find examples in literature where orographic surface and near-surface conditions (contributing to the tropospheric heat sources or sinks, Yanai et al., 1992) have an impact on the atmospheric conditions downstream. Indeed, evidence is found on the relevance of spring and summer temperatures over Asian orography for the successive atmospheric conditions far downstream (see Wu et al. (2015) for a review and Xue et al. (2021, 2022) for recent work on the impact of spring TP land initialisation in subseasonal-to-seasonal predictions). In the extended winter season (October–March) the presence of anomalous snow cover changes the tropospheric energy budget through an increase of the surface albedo, enhancing the reflection of shortwave radiation and the cooling of the land surface and the atmosphere (Yeh et al., 1983). Analyses on the dynamical influence of Tibetan Plateau snow cover indicate that it is relevant for the atmospheric circulation at intraseasonal time scales (Li et al., 2018) and, when anomalies are persistent, it can modulate interannual variability (Chen et al., 2021; Clark and Serreze, 2000) and long-term projections (Liu et al., 2021). Contrarily to the extensively discussed impact of autumn Siberian snow cover on the winter circulation (e.g. Cohen et al., 2014; Garfinkel et al., 2010; Henderson et al., 2018), the dynamical role of anomalous surface conditions over the Tibetan and Mongolian plateaux has been poorly investigated, notwithstanding its potentially high impact on East Asia. In a more idealised context, winter positive thermal forcing over mid-latitude land - as in a climate with a reduced winter land-sea thermal contrast caused by the faster warming of continents with respect to oceans - was analysed by Portal et al. (2022). It was there shown that the atmospheric response to idealised warming over East Asia (including the orography) dominated over a pattern of similar intensity imposed in North America. A possible explanation for this is that, because the high orographic elevation of the Asian forcing acts as a heat source directly in the mid troposphere, it was more effective in producing a large hemispheric response than the equivalent low-level forcing over the North American continent (Hoskins and Karoly, 1981; Trenberth, 1983; Ting, 1991).

Recently, output from the CMIP6 showed a significant multi-model mean (MMM) bias in the region of the TP over multiple seasons. Priestley et al. (2022) detect a strong deviation from the reanalysis for summer temperature and, based on the modified thermal gradients in the low troposphere, hypothesise a role of the TP land on the baroclinicity and cyclogenesis downstream. Along the same lines, Peng et al. (2022) and Fan et al. (2020) find a cold TP bias in winter for the MMM near-surface temperatures; the improvements in the transition from Phase 5 to Phase 6 of the CMIP are limited (Lun et al., 2021; Hu et al., 2022). These last studies also highlight the presence of a wide inter-model spread in year-round TP temperatures among the CMIP6 climate models, which comes with the difficulties in representing surface energy fluxes over complex orography characterised by seasonal variations in snow cover (e.g. Su et al., 2013; Chen et al., 2017; Li et al., 2021).

Although the reason for the emergence of the cold Tibetan Plateau temperature bias in many state-of-the-art climate models is examined in some detail by Chen et al. (2017), the dynamical consequences of the cold bias are yet to be explored. Hence, the aim of the present paper is to analyse the implications of cold Central Asia orography winter conditions on the large-scale circulation on the lee side of the mountains. To do this we take advantage of the large temperature spread detected over TP and MP among CMIP6 models to construct a multi-model realisation of the cold bias (the “cold TP composite”), over which

https://doi.org/10.5194/egusphere-2022-1499
Preprint. Discussion started: 20 January 2023

we conduct an analysis of the Pacific sector atmospheric circulation, more specifically of the East Asia winter monsoonal circulation. The results obtained from the multi-model study are further tested with an intermediate-complexity Atmospheric General Circulation Model (AGCM) forced by land-surface temperature patterns similar to the CMIP6 "cold TP composite". Finally, to shed light on the role of the Mongolian Plateau in the atmospheric response to cold land over Central Asia orography, we consider a separate AGCM experiment where MP forcing is opposed to a widespread TP and MP forcing.

The two approaches (CMIP6 compositing and AGCM idealised simulations) are described in the Methods, the outcomes and their mutual consistency are examined in the Results and a final summary and discussion considering previous literature is provided in the Conclusions.

2 Methods

2.1 CMIP6 simulations

We use CMIP6 historical runs for years 1979–2008 and we compute the January-February climatology over the whole period; the January and February months are referred to as *winter* throughout the paper. As in Clark and Serreze (2000) the results for an extended winter taking into account the transition months (e.g. October–March) are weaker in intensity, hence are not reported. We select one member per climate model from the CMIP6 dataset, as specified in Table 1, giving a sample of 37 historical simulations. Based on an index of Tibetan Plateau temperature (i.e. the climatological weighted-area average on near-surface temperature in the black box of Figure 1(b) over the period 1979–2008), the six simulations with temperature below one standard deviation from the CMIP6 multi-model mean form the "cold TP composite" (see models in bold in Table 1). The composite fields are shown in terms of the anomalies from the climatology of the CMIP6 multi-model mean (MMM), with significance computed according to a permutation test repeated 1000 times over the 37 model realisations, considering the 95% confidence level (Wilks, 2011). Note from Table 1 that in the "cold TP composite" multiple models from the same institutions are chosen; the same selection, but based on a single model per institution, produces similar results (not reported).

Wind components and air temperature at levels between 1000 and 700 hPa are extracted from the CMIP6 archive and used in the analysis. Turbulent surface heat fluxes, surface temperature (skin temperature or SST for open ocean) and near-surface temperature (usually 2-meter air temperature) are also used. Due to the lack of availability of daily frequency fields for a large subset of the CMIP6 models, the analyses on the "cold TP composite" are based on monthly-mean variables condensed in model climatologies. Moreover, we report that surface latent heat flux in KIOST-ESM, meridional wind and temperature advection in CAS-ESM2-0, zonal wind, temperature advection and Eady growth rate in FGOALS-f3-L are excluded from the analysis because of the inaccessibility of some datasets from the servers providing the CMIP6 archive.

2.2 Idealised experiments

To confirm the causal link between the results obtained from compositing on CMIP6 models we run idealised experiments using an 8-level AGCM developed at the International Centre for Theoretical Physics (ICTP), known as SPEEDY for Sim-

https://doi.org/10.5194/egusphere-2022-1499
Preprint. Discussion started: 20 January 2023

plified Parametrization, primitivE-Equation DYnamics. The model is spectral on the sphere, with triangular truncation at total wavenumber 30 (T30) and a Gaussian grid of 96 by 48 points, and includes simple parametrisation of moist processes (Molteni, 2003). Despite the low horizontal and vertical resolution, SPEEDY displays an adequate performance for the analysis of large-scale features of the climate system (Kucharski et al., 2006, 2013). SPEEDY is run in perpetual-winter mode (200 January months and 200 February months) with prescribed sea-surface temperatures (SSTs), sea-ice cover (SIC) and land-surface temperatures (LSTs). Two type of simulations are considered:

- a *control integration* where SST and SIC are equal to the 1979–2008 HadISST climatologies (Rayner et al., 2003). The LST corresponds to the climatology obtained from a SPEEDY ensemble run with a freely evolving LST scheme and with prescribed climatological SIC and evolving SSTs 1979–2008 from HadISST. Details on SPEEDY's LST scheme are available in the Appendix B of Portal et al. (2022);
- two *cold integrations* with SST and SIC as in the *control*, and with LST forcing corresponding to the significant anomaly of surface temperature from the "cold TP composite" within 60–140 E and 20–60 N ("TP+MP experiment") or within 60–140 E and 38–60 N ("MP experiment"), interpolated onto SPEEDY's grid (Figure 3(a,e,i)).

The responses of "TP+MP" and "MP" forcing visualised in the Results correspond to the climatological difference "*cold integration - control integration*".

2.3 Diagnostics

We introduce some diagnostics used in the analysis of the results.

- Temperature advection is

  $$-\boldsymbol{u}\cdot\nabla T = -\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right),$$

  where $\boldsymbol{u} = u\hat{\mathbf{i}} + v\hat{\mathbf{j}}$ is the horizontal wind composed by the zonal and meridional component and T is the temperature.
- The Eady growth rate corresponds to

  $$\sigma = 0.31\,f\,\frac{du}{dz}\mathcal{N}^{-1},$$

  where f is the Coriolis parameter, z is the geopotential height and $\mathcal{N} \equiv \sqrt{(g/\theta)\,d\theta/dz}$ is the Brunt-Väisälä frequency with θ potential temperature and g Earth's gravitational acceleration.
- The meridional eddy momentum flux (MEMF) is the product of the 2–6 day Fourier filtered wind components $u^{\mathrm{HF}}v^{\mathrm{HF}}$.

Among these, the temperature advection and the Eady growth rate are computed using mean climatological variables, giving the *temperature advection by the mean flow* and the *Eady growth rate of the mean state*. The climatological MEMF is computed on high-pass filtered daily fields averaged over the total time span of the model simulations.

https://doi.org/10.5194/egusphere-2022-1499
Preprint. Discussion started: 20 January 2023

3 Results

The representation of winter (January-February) near-surface temperatures by CMIP6 models in the historical period 19792008 shows a strong inter-model spread (Figure 1(a)). The spread generally grows with latitude: the largest amplitude is attained around and poleward of the 60° N latitude circle, with a maximum over the Atlantic and Pacific Oceans likely due to the inter-model variability in winter sea-ice cover. An additional hot-spot can be easily identified in the mid-latitude continents over the Tibetan Plateau (cf. temperature spread and green/yellow boxes over orography in Figure 1(a)). Since the atmospheric response to deep mid-latitude heat sources or sinks is specially strong (Trenberth, 1983), and, on top of this, the winter mid-latitude circulation is known to be highly sensitive to East Asia surface conditions (e.g. Portal et al., 2022; Cohen et al., 2001), in the following we study the dynamical features of a "cold TP composite" obtained by averaging over a model selection based on a TP temperature index (see Methods). The index (one value per CMIP6 model) is the area-weighted spatial and temporal average of near-surface temperature over a region characterised by large temperature spread and high elevation within the Tibetan Plateau domain (black box in Figure 1(b)).

Some relevant surface variables from the "cold TP composite" are presented in Figure 2. The near-surface temperature map features an intense cold anomaly on the orography of Central Asia, peaking over the TP and extending north-eastwards to the MP. Significant surface anomalies are also found elsewhere in the North America / North Atlantic sector (not shown), but, since the focus is on Asian orography and its downstream impacts, regional surface signals that are unlikely to interact with the Asia / Pacific sector are not presented nor discussed. By comparing the surface and near-surface temperature patterns over the TP (cf. Figure 3(a) and Figure 2(a)) we notice that the land-surface temperature anomaly is stronger in intensity than the near-surface anomaly, and conclude that in the "cold TP composite", as described by Chen et al. (2017), land has a cooling effect on the atmosphere above. This feature is corroborated by negative anomalies of surface sensible and latent heat flux in a region where the MMM fluxes are - on average - weakly positive (Figure 2(b,c)), representing a reduced latent and sensible warming of the atmosphere by the land surface. The signal in sensible heat flux is strong over the center of the TP, the latent heat flux term is significant elsewhere over TP and MP.

In the "cold TP composite" anomalous snow amount is detected in correspondence of the strongest sensible heat flux anomalies (not shown), but, since the anomalies are not significant, this is unlikely to explain by its own the surface temperature pattern. Chen et al. (2017) decompose the surface energy budget over the TP and show that the processes causing cold biases are physically interlinked, involving anomalous snow cover enhancing the surface albedo with negative effects on the low-level water vapor content and the downward longwave radiation, which ultimately result in a cooling of the surface. The existence in CMIP6 models of a variety of schemes for land, snow and atmospheric boundary layer and of the mutual interaction between these over complex orography, is at the origin of the wide inter-model spread. Furthermore, based on the results of Figure 3 and of Liu et al. (2022), the anomalies do not appear to be driven by the circulation upstream of the TP.

The temperature and wind conditions of the CMIP6 "cold TP composite" at 850 hPa are shown in Figure 3(a–d). We note that the negative thermal anomaly is shifted north eastward of the most elevated area of the Tibetan Plateau - represented by grey patching - and reinforces the thermal cooling induced by the uplift over MP orography, shown in Figure 11 of Sha et al.

https://doi.org/10.5194/egusphere-2022-1499
Preprint. Discussion started: 20 January 2023

(2015). East of this region the westerly zonal winds (i.e. Pacific jet) are reinforced. At the same time, southward wind over East China and northward wind over the ocean give rise to a cyclonic anomaly over the Asian coast and reinforce the East Asia winter monsoon. The advection of cold air downstream of the TP (Figure 4(a), see Methods for details on the computation) is supported both by the negative temperature anomaly on the orography and, to the east, by the reinforcement of the north-westerly wind (Figure 2(b,d)). These conditions are responsible for intensified meridional temperature gradients east of the TP and along the Pacific coast which enhance the baroclinicity (see positive anomalies in the Eady growth rate west and east of the chinese coastline, Figure 4(b)). Since the Eady growth rate (definition in Methods) measures the environmental conditions favourable to instability, we expect the strengthening of the jet at the entrance of the Pacific basin (Figure 3(c)) to be induced by more synoptic disturbances breaking and depositing zonal momentum in the mean westerly flow. Moreover, cyclogenesis is high to the east of the TP and over the East China Sea from mid winter (Priestley et al., 2020; Schemm et al., 2021). In the CMIP6 composite we cannot verify the relation between the transient eddies and the mean flow due to the unavailability of daily frequency data. Nonetheless, the analysis of the eddy feedback on the zonal flow is presented in the discussion of the idealised "TP+MP experiment", which generally confirms the results of the CMIP6 composite analysis and supports the hypothesis that the jet is strengthened by enhanced eddy momentum deposition.

One might wonder why strong surface heat flux anomalies are present over the Pacific basin (Figure 2(b,c)). In the "cold TP composite" the strengthening of the Pacific jet over and downstream of the East China Sea (Figure 3(c)) extends down to the near-surface level (not shown) and intensifies the advection of cold air masses over the ocean (Figure 4(a)), reinforcing the surface sensible heat flux (Figure 2(b)) The release of heat thus exerted into the lower layers of the atmosphere restores the low-level baroclinicity (Hotta and Nakamura, 2011; Papritz and Spengler, 2015), with a positive feedback on the local generation of synoptic eddies, hence on the strength of the Pacific jet. Papritz and Spengler (2015) propose a dominant role of the surface latent heat flux for maintaining the tilt of the isentropic slopes (i.e. baroclinicity) to the east of the mid-latitude continents. In this case we observe no significant latent heat flux anomaly over the East China Sea, whereas towards the center of the Pacific there is a decrease in the latent heat flux which suppresses the fueling of the jet east of 150 E (cf. Figure 2(c) and Figure 3(c)). The origin of the negative latent heat flux is unknown, but may be related to a subtropical or tropical Pacific signal emerging from the selection of CMIP6 models (Figures 2(a–c), 3(b–d)).

To support the existence of a causal relation linking the cold Asian orography and the enhancement of the East Asia winter monsoon we run an idealised experiment using the model SPEEDY (a perpetual winter simulation with prescribed surface temperatures, for details see Section 2). The response of SPEEDY to "TP+MP" forcing - a surface cooling over central Asia orography (Figure 3(e)) resembling the pattern of the "cold TP composite" (Figure 3(a)) - in terms of air temperature, zonal wind and meridional wind at 850 hPa is shown in panels (f–h) of Figure 3. As in the CMIP6 composite, we find a cold anomaly to the north-east of the TP, with enhanced north-westerly winds downstream of the topography advecting excess cold air onto East Asia and over the Pacific (Figure 5(a)). The striking similarity between composite and "TP+MP experiment" (cf. panels (b–d) and (f–h) in Figure 3) proves that also in the "cold TP composite" the circulation anomalies in the Asia / Pacific sector are generated by the cold surface temperatures over Asian orography. Differences in low-level wind are still detected over the Pacific: in the composite the significant strengthening of the jet terminates at about 160 E, while it extends zonally to the

https://doi.org/10.5194/egusphere-2022-1499
Preprint. Discussion started: 20 January 2023

whole Pacific basin in the "TP+MP experiment" (not shown); the positive meridional wind signal over the North Pacific is also different, with a strong positive signal extending from 20 to 70° N in the CMIP6 composite (Figure 3(d)), and a weak positive signal limited to the high latitudes in the SPEEDY experiment (Figure 3(h)). Nonetheless, these discrepancies do not undermine the analogy between the two cases, in that they are located far relatively from the TP region and might be related to the presence of additional signals emerging from the selection of CMIP6 models, such as Pacific tropical and subtropical forcing and cold North America land temperatures.

In the "TP+MP experiment" the increase of eddy momentum deposition in the Pacific jet is evident from the map showing the divergence of the meridional eddy momentum flux (MEMF, Figure 5(c), see Methods). The increase in low-level baroclinicity to the east of the Chinese coast (Figure 5(b)) favours the development of transient eddies which shift the MEMF convergence equatorwards. Such environmental conditions are supported by the cold advection from the orography over the East China Sea (Figure 5(a)). In the "cold TP composite" the positive signal in baroclinicity is stronger and localised closer to the coast (Figure 4(b)); nevertheless it is consistent with the pattern of jet intensification in Figure 3(c), also stronger and more localised then in the "TP+MP experiment".

In the papers by White et al. (2017) and Sha et al. (2015) the winter NH circulation is shown to be more impacted by the MP than by the TP due to the former's latitudinal position and interaction with the Pacific low-level jet (Held and Ting, 1990). We briefly consider the role of the former by running the so-called "MP experiment", where the cold anomalies over the Tibetan Plateau are removed (south of 38 N), leaving a residual negative temperature signal over the Mongolian Plateau (Figure 3(i)). The low-level response to "MP" forcing shows cold anomalies limited to high mid latitudes (Figure 3(j)) and cold advection centered over Japan (Figure 5(d)). Since the baroclinicity is also enhanced at higher latitudes with respect to the "TP+MP experiment" (cf. panels (b) and (e) of Figure 5), MP cooling strengthens the Pacific jet on its poleward flank (Figure 3(k)), coherently with the changes in MEMF convergence (Figure 5(f)). Although the results support the relevance of the MP for the climate of the Pacific sector, TP surface forcing is necessary to have consistency with the "cold TP composite". The latter is in fact fundamental to obtain a strengthening of the baroclinic conditions over East Asia and of the Pacific jet to the east of the Chinese coast, i.e. for the overall intensification the East Asia winter monsoon.

4 Conclusions

By comparing a selection of CMIP6 historical simulations - the "cold Tibetan Plateau (TP) composite" - with an idealised AGCM simulation we show how cold temperatures over Central Asia orography influence the winter atmospheric circulation over East Asia and the North Pacific. Colder than average Asian plateaux strengthen the tropospheric heat sink and intensify the East Asia winter monsoon, leading to stronger north-westerly winds and cold advection downstream of the orographic features. Over the East China Sea, the enhancement of the advection of cold northerly air from the continent and of the surface heat flux from the ocean contribute to the intensification of the low-level baroclinicity. The idealised experiment shows that low-level baroclinic conditions over the East China Sea favour the development of transient atmospheric perturbations which

https://doi.org/10.5194/egusphere-2022-1499
Preprint. Discussion started: 20 January 2023

deposit additional eddy momentum on the mean zonal flow, reinforcing the equatorward flank of the Pacific jet (Hoskins et al., 1983; Hoskins and Valdes, 1990).

Building on previous literature that investigates the relative role of the Tibetan and Mongolian Plateaux on the downstream winter climate by removing or adding regional orography (Shi et al., 2015; Sha et al., 2015; White et al., 2017), we apply a similar approach to surface temperature forcing. A second set of idealised simulations is presented where cold anomalies are confined to the region with Mongolian orography. The response still consists in a strengthening of the zonal winds over the Pacific, however shifted northward with respect to the experiment with extended surface cooling, due to weakened advection of cold air to the east of the Tibetan Plateau. We conclude that the TP region is fundamental for setting the ideal conditions for the intensification of the East Asia winter monsoon, as detected in the CMIP6 models contributing to the "cold TP composite". Still, changes in the Mongolian Plateau land temperature are relevant to understand future projections of the winter season over the Pacific sector (Xu et al., 2016).

CMIP6 climate models are often affected by a cold surface and near-surface temperature bias in the Tibetan Plateau region (Peng et al., 2022; Fan et al., 2020) and show limited improvements despite the massive model developments of the recent years (e.g. across CMIP phases, Bock et al., 2020; Lun et al., 2021; Hu et al., 2022). Chen et al. (2017) decompose the surface energy budget over the TP and show that the processes causing cold biases involve anomalous snow cover with a cascade of consequences on surface albedo, low-level water vapor content and downward longwave radiation, which ultimately result in a cooling of the surface. This work suggests that deviations from the observed land temperature over high Central Asia plateaux foster significant large-scale circulation biases on the lee side of the orography. Specifically, a strengthening of the East Asia winter monsoon, affecting the highly inhabited eastern coast of China and the Pacific jet, is found in models characterised by colder-than-average temperatures over Central Asia plateaux.

Based on these findings, advances in the representation of surface processes over complex orography are expected to reduce temperature and circulation biases and to improve the modelling of the mean climate downstream of the Central Asia plateaux. Stronger inter-model coherence would also reinforce the confidence in climate projections for the next decades. Similarly, approaches such as the "emerging costraints" (Hall et al., 2019) applied to the feedback between surface temperatures over orography and the local energy budget, may be useful to reduce the uncertainty of the above mentioned projections. On a different time scale, works analysing subseasonal-to-seasonal forecasts over East Asia find a significant influence by surface anomalies over the Tibetan Plateau (e.g. Li et al., 2018; Xue et al., 2021), implying that shorter-term operational forecasting could also benefit from advances in the modelling of land–atmosphere interaction over Central Asia plateaux.

Data availability. The CMIP6 dataset is publicly available at https://esgf-node.llnl.gov/projects/cmip6/. Download information on the AGCM "SPEEDY" can be found at the link https://www.ictp.it/research/esp/models/speedy.aspx.

Author contributions. All authors conceived the study and contributed to the interpretation and discussion of the results. A. P. performed the analyses and wrote the paper.

Competing interests. No competing interests are present.

Acknowledgements. A. P. is thankful to Gwendal Rivière for insightful discussion and advice.

https://doi.org/10.5194/egusphere-2022-1499
Preprint. Discussion started: 20 January 2023

References

Bock, L., Lauer, A., Schlund, M., Barreiro, M., Bellouin, N., Jones, C., Meehl, G., Predoi, V., Roberts, M., and Eyring, V.: Quantifying progress across different CMIP phases with the ESMValTool, Journal of Geophysical Research: Atmospheres, 125, e2019JD032 321, 2020.

Bolin, B.: On the influence of the earth's orography on the general character of the westerlies, Tellus, 2, 184–195, 1950.

Broccoli, A. J. and Manabe, S.: The effects of orography on midlatitude Northern Hemisphere dry climates, Journal of Climate, 5, 1181–1201, 1992.

Chan, J. C. and Li, C.: The east Asia winter monsoon, in: East Asian Monsoon, pp. 54–106, World Scientific, 2004.

Charney, J. G. and Eliassen, A.: A numerical method for predicting the perturbations of the middle latitude westerlies, Tellus, 1, 38–54, 1949.

Chen, X., Liu, Y., and Wu, G.: Understanding the surface temperature cold bias in CMIP5 AGCMs over the Tibetan Plateau, Advances in Atmospheric Sciences, 34, 1447–1460, 2017.

Chen, Z., Wu, R., and Wang, Z.: Impact of Autumn-Winter Tibetan Plateau Snow Cover Anomalies on the East Asian Winter Monsoon and Its Interdecadal Change, Frontiers in Earth Science, 9, 569, 2021.

Clark, M. P. and Serreze, M. C.: Effects of variations in East Asian snow cover on modulating atmospheric circulation over the North Pacific Ocean, Journal of Climate, 13, 3700–3710, 2000.

Cohen, J., Saito, K., and Entekhabi, D.: The role of the Siberian high in Northern Hemisphere climate variability, Geophysical Research Letters, 28, 299–302, 2001.

Cohen, J., Furtado, J. C., Jones, J., Barlow, M., Whittleston, D., and Entekhabi, D.: Linking Siberian snow cover to precursors of stratospheric variability, Journal of Climate, 27, 5422–5432, 2014.

Duan, A. and Wu, G.: Weakening trend in the atmospheric heat source over the Tibetan Plateau during recent decades. Part I: Observations, Journal of Climate, 21, 3149–3164, 2008.

Fan, X., Miao, C., Duan, Q., Shen, C., and Wu, Y.: The performance of CMIP6 versus CMIP5 in simulating temperature extremes over the global land surface, Journal of Geophysical Research: Atmospheres, 125, e2020JD033 031, 2020.

Garfinkel, C. I., Hartmann, D. L., and Sassi, F.: Tropospheric precursors of anomalous Northern Hemisphere stratospheric polar vortices, Journal of Climate, 23, 3282–3299, 2010.

Hahn, D. G. and Manabe, S.: The role of mountains in the south Asian monsoon circulation, Journal of the Atmospheric Sciences, 32, 1515–1541, 1975.

Hall, A., Cox, P., Huntingford, C., and Klein, S.: Progressing emergent constraints on future climate change, Nature Climate Change, 9, 269–278, 2019.

Held, I. M. and Ting, M.: Orographic versus thermal forcing of stationary waves: The importance of the mean low-level wind, Journal of Atmospheric Sciences, 47, 495–500, 1990.

Henderson, G. R., Peings, Y., Furtado, J. C., and Kushner, P. J.: Snow–atmosphere coupling in the Northern Hemisphere, Nature Climate Change, 8, 954–963, 2018.

Hoskins, B. J. and Karoly, D. J.: The steady linear response of a spherical atmosphere to thermal and orographic forcing, Journal of Atmospheric Sciences, 38, 1179–1196, 1981.

Hoskins, B. J. and Valdes, P. J.: On the existence of storm-tracks, Journal of Atmospheric Sciences, 47, 1854–1864, 1990.

Hoskins, B. J., James, I. N., and White, G. H.: The shape, propagation and mean-flow interaction of large-scale weather systems, Journal of Atmospheric Sciences, 40, 1595–1612, 1983.

Hotta, D. and Nakamura, H.: On the significance of the sensible heat supply from the ocean in the maintenance of the mean baroclinicity along storm tracks, Journal of Climate, 24, 3377–3401, 2011.

Hu, Q., Hua, W., Yang, K., Ming, J., Ma, P., Zhao, Y., and Fan, G.: An assessment of temperature simulations by CMIP6 climate models over the Tibetan Plateau and differences with CMIP5 climate models, Theoretical and Applied Climatology, 148, 223–236, 2022.

Kucharski, F., Molteni, F., and Bracco, A.: Decadal interactions between the western tropical Pacific and the North Atlantic Oscillation, Climate dynamics, 26, 79–91, 2006.

Kucharski, F., Molteni, F., King, M. P., Farneti, R., Kang, I.-S., and Feudale, L.: On the need of intermediate complexity general circulation models: A “SPEEDY” example, Bulletin of the American Meteorological Society, 94, 25–30, 2013.

Li, J., Miao, C., Wei, W., Zhang, G., Hua, L., Chen, Y., and Wang, X.: Evaluation of CMIP6 global climate models for simulating land surface energy and water fluxes during 1979–2014, Journal of Advances in Modeling Earth Systems, 13, e2021MS002 515, 2021.

Li, W., Guo, W., Qiu, B., Xue, Y., Hsu, P.-C., and Wei, J.: Influence of Tibetan Plateau snow cover on East Asian atmospheric circulation at medium-range time scales, Nature communications, 9, 1–9, 2018.

Liu, A., Huang, Y., and Huang, D.: Inter-model Spread of the Simulated Winter Surface Air Temperature over the Eurasian Continent and the Physical Linkage to the Jet Streams from the CMIP6 Models, Journal of Geophysical Research: Atmospheres, p. e2022JD037172, 2022.

Liu, L., Zhang, W., Lu, Q., and Wang, G.: Variations in the Sensible Heating of Tibetan Plateau and Related Effects on Atmospheric Circulation Over South Asia, Asia-Pacific Journal of Atmospheric Sciences, 57, 499–510, 2021.

Lun, Y., Liu, L., Cheng, L., Li, X., Li, H., and Xu, Z.: Assessment of GCMs simulation performance for precipitation and temperature from CMIP5 to CMIP6 over the Tibetan Plateau, International Journal of Climatology, 41, 3994–4018, 2021.

Manabe, S. and Terpstra, T. B.: The effects of mountains on the general circulation of the atmosphere as identified by numerical experiments, Journal of Atmospheric Sciences, 31, 3–42, 1974.

Molteni, F.: Atmospheric simulations using a GCM with simplified physical parametrizations. I: Model climatology and variability in multi-decadal experiments, Climate Dynamics, 20, 175–191, 2003.

Papritz, L. and Spengler, T.: Analysis of the slope of isentropic surfaces and its tendencies over the North Atlantic, Quarterly Journal of the Royal Meteorological Society, 141, 3226–3238, 2015.

Peng, Y., Duan, A., Hu, W., Tang, B., Li, X., and Yang, X.: Observational constraint on the future projection of temperature in winter over the Tibetan Plateau in CMIP6 models, Environmental Research Letters, 2022.

Portal, A., Pasquero, C., D’Andrea, F., Davini, P., Hamouda, M. E., and Rivière, G.: Influence of Reduced Winter Land–Sea Contrast on the Midlatitude Atmospheric Circulation, Journal of Climate, 35, 2637–2651, 2022.

Priestley, M. D., Ackerley, D., Catto, J. L., Hodges, K. I., McDonald, R. E., and Lee, R. W.: An overview of the extratropical storm tracks in CMIP6 historical simulations, Journal of Climate, 33, 6315–6343, 2020.

Priestley, M. D., Ackerley, D., Catto, J. L., and Hodges, K. I.: Drivers of biases in the CMIP6 extratropical storm tracks. Part 1: Northern Hemisphere, Journal of Climate, pp. 1–37, 2022.

Rayner, N., Parker, D. E., Horton, E., Folland, C. K., Alexander, L. V., Rowell, D., Kent, E. C., and Kaplan, A.: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, Journal of Geophysical Research: Atmospheres, 108, 2003.

https://doi.org/10.5194/egusphere-2022-1499
Preprint. Discussion started: 20 January 2023

Sato, T.: Influences of subtropical jet and Tibetan Plateau on precipitation pattern in Asia: Insights from regional climate modeling, Quaternary International, 194, 148–158, 2009.

Schemm, S., Wernli, H., and Binder, H.: The storm-track suppression over the western North Pacific from a cyclone life-cycle perspective, Weather and Climate Dynamics, 2, 55–69, 2021.

Sha, Y., Shi, Z., Liu, X., and An, Z.: Distinct impacts of the Mongolian and Tibetan Plateaus on the evolution of the East Asian monsoon, Journal of Geophysical Research: Atmospheres, 120, 4764–4782, 2015.

Shi, Z., Liu, X., Liu, Y., Sha, Y., and Xu, T.: Impact of Mongolian Plateau versus Tibetan Plateau on the westerly jet over North Pacific Ocean, Climate Dynamics, 44, 3067–3076, 2015.

Smagorinsky, J.: The dynamical influence of large-scale heat sources and sinks on the quasi-stationary mean motions of the atmosphere, Quarterly Journal of the Royal Meteorological Society, 79, 342–366, 1953.

Su, F., Duan, X., Chen, D., Hao, Z., and Cuo, L.: Evaluation of the global climate models in the CMIP5 over the Tibetan Plateau, Journal of climate, 26, 3187–3208, 2013.

Ting, M.: The stationary wave response to a midlatitude SST anomaly in an idealized GCM, Journal of the atmospheric sciences, 48, 1249–1275, 1991.

Trenberth, K. E.: Interactions between orographically and thermally forced planetary waves, Journal of Atmospheric Sciences, 40, 1126–1153, 1983.

White, R., Battisti, D., and Roe, G.: Mongolian mountains matter most: Impacts of the latitude and height of Asian orography on Pacific wintertime atmospheric circulation, Journal of Climate, 30, 4065–4082, 2017.

Wilks, D. S.: Statistical methods in the atmospheric sciences, vol. 100, Academic press, 2011.

Wu, G., Duan, A., Liu, Y., Mao, J., Ren, R., Bao, Q., He, B., Liu, B., and Hu, W.: Tibetan Plateau climate dynamics: recent research progress and outlook, National Science Review, 2, 100–116, 2015.

Xu, M., Xu, H., and Ma, J.: Responses of the East Asian winter monsoon to global warming in CMIP5 models, International Journal of Climatology, 36, 2139–2155, 2016.

Xue, Y., Yao, T., Boone, A. A., Diallo, I., Liu, Y., Zeng, X., Lau, W. K., Sugimoto, S., Tang, Q., Pan, X., et al.: Impact of initialized land surface temperature and snowpack on subseasonal to seasonal prediction project, phase i (ls4p-i): organization and experimental design, Geoscientific Model Development, 14, 4465–4494, 2021.

Xue, Y., Diallo, I., Boone, A. A., Yao, T., Zhang, Y., Zeng, X., David Neelin, J., Lau, W. K., Pan, Y., Liu, Y., et al.: Spring Land Temperature in Tibetan Plateau and Global-Scale Summer Precipitation–Initialization and Improved Prediction, Bulletin of the American Meteorological Society, 2022.

Yanai, M. and Wu, G.-X.: Effects of the Tibetan plateau, in: The Asian Monsoon, pp. 513–549, Springer, 2006.

Yanai, M., Li, C., and Song, Z.: Seasonal heating of the Tibetan Plateau and its effects on the evolution of the Asian summer monsoon, Journal of the Meteorological Society of Japan. Ser. II, 70, 319–351, 1992.

Ye, D.-Z. and Wu, G.-X.: The role of the heat source of the Tibetan Plateau in the general circulation, Meteorology and Atmospheric Physics, 67, 181–198, 1998.

Yeh, T., Wetherald, R., and Manabe, S.: A model study of the short-term climatic and hydrologic effects of sudden snow-cover removal, Monthly Weather Review, 111, 1013–1024, 1983.

Yihui, D. and Chan, J. C.: The East Asian summer monsoon: an overview, Meteorology and Atmospheric Physics, 89, 117–142, 2005.

https://doi.org/10.5194/egusphere-2022-1499
Preprint. Discussion started: 20 January 2023

Zhang, Y., Sperber, K. R., and Boyle, J. S.: Climatology and interannual variation of the East Asian winter monsoon: Results from the 1979–95 NCEP/NCAR reanalysis, Monthly weather review, 125, 2605–2619, 1997.

https://doi.org/10.5194/egusphere-2022-1499
Preprint. Discussion started: 20 January 2023

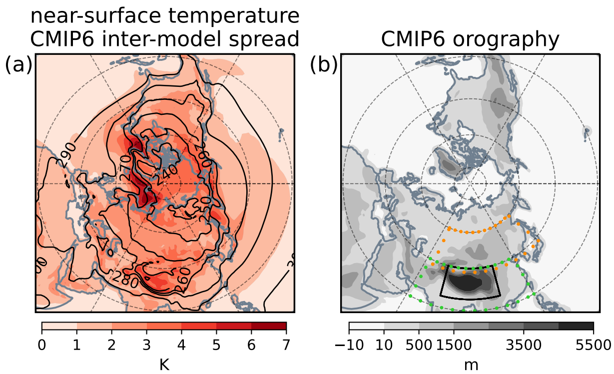

Figure 1. (a) The near-surface temperature spread in CMIP6 historical 1979–2008 for Jan-Feb, with the MMM field in contours, and (b) the MMM orographic elevation. The black box in panel (b) is used to compute the Tibetan Plateau index for near-surface temperature; the "cold TP composite" presented in Figures 2–4 is based on such index. The dotted boxes in panel (b) indicate the mountainous regions here named Tibetan Plateau or TP (green) and Mongolian Plateau or MP (orange)

https://doi.org/10.5194/egusphere-2022-1499
Preprint. Discussion started: 20 January 2023

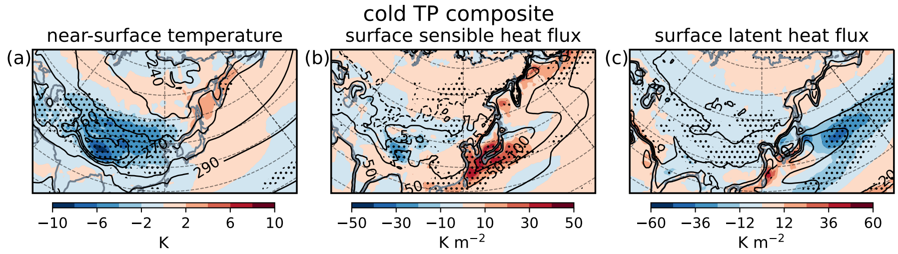

Figure 2. From the "cold TP composite" the anomalies of (a) near-surface temperature, (b) sensible and (c) latent surface heat flux (stippling above the 95% significance level). The respective MMM climatologies are displayed in contours (cl=[±5,+25,+50,+100,+200,+300] K m^{-2} for the heat fluxes)

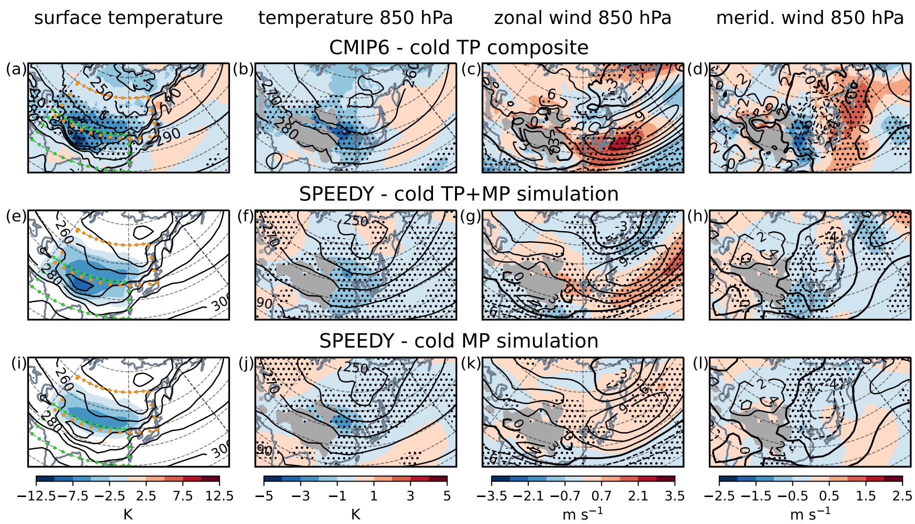

Figure 3. The "cold TP composite" anomalies of (a) surface temperature and 850-hPa (b) air temperature, (c) zonal wind, (d) meridional wind. The respective MMM climatologies are displayed in contours. The response of the model SPEEDY to "TP+MP" and "MP" surface-temperature forcing (panels (e,i)) in terms of 850-hPa (f,j) temperature, (g,k) zonal wind, (h,l) meridional wind; the control run is shown in contours. Stippling indicates that the anomalies exceed the 95% significance level. Green and orange dotted boxes in panels (a,e,i) indicate the mountainous regions named TP and MP, respectively. Grey shading masks orography exceeding 1400 m

https://doi.org/10.5194/egusphere-2022-1499
Preprint. Discussion started: 20 January 2023

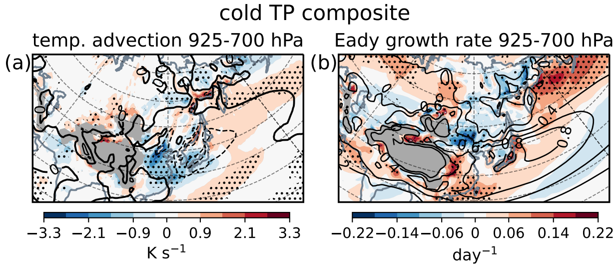

Figure 4. The "cold TP composite" anomalies of (a) temperature advection by the mean flow ($\boldsymbol{u} \cdot \nabla T$) averaged over the pressure-levels 925 to 700 hPa, (b) Eady growth rate between 925 and 700 hPa, and the respective MMM climatologies in contours (ci=4e-5 $\mathrm{K\,s^{-1}}$ for temperature advection, stippling above the 95% significance level). Grey shading masks orography exceeding 1400 m

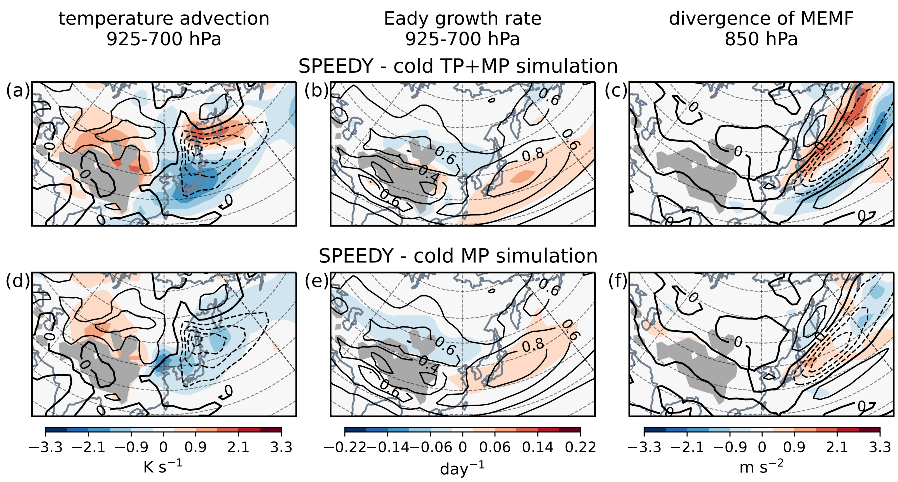

Figure 5. The response of the model SPEEDY to "TP+MP" and "MP" surface-temperature forcing in terms of (a,d) temperature advection by the mean flow ($\boldsymbol{u} \cdot \nabla T$) averaged over the pressure levels 925 to 700 hPa, (b,e) Eady growth rate between 925 and 700 hPa, (c,f) divergence of the meridional eddy momentum flux (MEMF) at 850 hPa; the control run is shown in contours (ci=4e-5 $\mathrm{K\,s^{-1}}$ for temperature advection, ci=3e-6 $\mathrm{m\,s^{-2}}$ for MEMF divergence). Grey shading masks orography exceeding 1400 m

https://doi.org/10.5194/egusphere-2022-1499
Preprint. Discussion started: 20 January 2023

Table 1. List of CMIP6 climate models

Model Name	Member Id.	Institution
ACCESS-CM2	1	Australian Research Council Centre of Excellence for Climate System Science & Commonwealth Scientific and Industrial Research Organisation (AUS)
ACCESS-ESM1-5	1	Commonwealth Scientific and Industrial Research Organisation (AUS)
BCC-CSM2-MR	1	Beijing Climate Center (CHN)
CAS-ESM2-0	2	Chinese Academy of Sciences (CHN)
CESM2	2	National Center for Atmospheric Research, Climate and Global Dynamics Laboratory (USA)
CESM2-WACCM	1	as above
CIESM	1	Department of Earth System Science, Tsinghua University (CHN)
CMCC-CM2-SR5	1	Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici (ITA)
CMCC-ESM2	1	as above
CNRM-CM6-1	1	Centre National de Recherches Meteorologiques & Centre Européen de Récherche et de Formation Avancée en Calcul Scientifique (FRA)
CNRM-CM6-1-HR	1	as above
CNRM-ESM2-1	1	as above
CanESM5	1	Canadian Centre for Climate Modelling and Analysis (CAN)
CanESM5-CanOE	1	as above
EC-Earth3-CC	1	EC-Earth consortium (visit https://ec-earth.org/consortium/)
EC-Earth3-Veg	1	as above
EC-Earth3-Veg-LR	1	as above
FGOALS-f3-L	1	Chinese Academy of Sciences (CHN)
FIO-ESM-2-0	1	Qingdao National Laboratory for Marine Science and Technology & First Institute of Oceanography (CHN)
GFDL-CM4	1	National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory (USA)
GFDL-ESM4	1	as above
GISS-E2-1-G	1	Goddard Institute for Space Studies (USA)
HadGEM3-GC31-LL	1	Met Office Hadley Centre (GBR)
HadGEM3-GC31-MM	1	as above
INM-CM4-8	1	Institute for Numerical Mathematics (RUS)
INM-CM5-0	1	as above
KACE-1-0-G	1	National Institute of Meteorological Sciences/Korea Meteorological Administration (KOR)
KIOST-ESM	1	Korea Institute of Ocean Science & Technology (KOR)
MIROC-ES2L	1	Japan Agency for Marine-Earth Science and Technology & Atmosphere and Ocean Research Institute & National Institute for Environmental Studies & RIKEN Center for Computational Science (JPN)
MIROC6	1	as above
MPI-ESM1-2-HR	1	Max Planck Institute for Meteorology (DEU)
MPI-ESM1-2-LR	1	as above
MRI-ESM2-0	1	Meteorological Research Institute (JPN)
NESM3	1	Nanjing University of Information Science and Technology (CHN)
NorESM2-LM	1	NorESM Climate modeling Consortium (visit https://www.noresm.org/consortium/)
TaiESM1	1	Research Center for Environmental Changes (TWN)
UKESM2-0-LL	1	National Institute of Meteorological Sciences/Korea Meteorological Administration (KOR)

Models in bold were selected for the “cold Tibetan-Plateau” composite