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RESEARCH ARTICLE - HYDROLOGY

# Value addition in coupled model intercomparison project phase 6 over phase 5: global perspectives of precipitation, temperature and soil moisture fields

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**Abstract**
This study establishes the improvements in the sixth phase of the Coupled Model Intercomparison Project (CMIP6) simulations as compared to its previous version, CMIP5. First, the historical simulations are compared with the reanalysis products from the 5th generation European Centre for Medium-Range Weather Forecasts (ERA5). Quality improvement in CMIP6 is assured through its correspondence with ERA5 in terms of mean, standard deviation and mean bias. Global fields of three hydrometeorological variables, i.e. temperature, precipitation and soil moisture, are considered from multiple General Circulation Models. Among the three variables, maximum improvement is noticed in case of soil moisture followed by precipitation, especially in the tropical belt. In case of temperature, the mean bias has reduced by ± 3 °C across the parts of North America, Africa, and South Asia. Better reliance on the CMIP6 motivates for a trend analysis to peek into the future. The results indicate a significant increasing trend for precipitation in the temperate, polar and sub-polar regions, whereas a significant increase in temperature is noticed almost all across the world with highest slope in the polar and sub-polar regions. Furthermore, soil moisture shows a significant trend that can be grouped continent-wise, e.g. Africa, Central and South Asia exhibit an increasing trend, whereas North and Central America and Northern parts of South America exhibit an overall decreasing trend. Apart from underlining the better reliance on CMIP6, the findings of this study will also be useful across different parts of the world for many climate related studies using CMIP6.

**Keywords** CMIP6 · CMIP5 · ERA5 · Historical simulations · Future projections · Trend analysis

## Introduction

Impact of climate change in the global resources and its management options highly rely on the projections of the climate models. Uncertainties associated with such projections often act as a limiting factor towards devising reliable measures for management of the available resources (IPCC 2012). The Coupled Model Intercomparison Project (CMIP) organized under the auspices of the World Climate Research Programme's (WCRP) Working Group on Coupled Modelling (WGCM) is one of the foundational elements of climate studies, as it coordinates the design of the global climate model simulations and projections (https://www.wcrp-climate.org/wgcm-cmip). A new generation of a more federated structure of CMIP (encompassing many individually designed MIPs instead of a centralized activity involving a large number of experiments), the 6$^{th}$ phase of CMIP, referred to as CMIP6, with comparatively complex model running scenarios, is expected to provide more reliable and detailed climate projections (Eyring et al. 2016; Stouffer et al. 2017). This phase differs from the previous generations in many aspects, such as finer spatial resolutions and introduction of improved parameterizations for different processes involving biogeochemical cycles, ice sheets and cloud microphysics (Eyring et al. 2019).

Since the availability of CMIP6 model outputs, several studies have attempted to analyse the uncertainty associated with different climatic variables at both regional and global scale. Fan et al. (2020a) analysed the historical performance

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by comparing the model outputs with observed data available from the University of East Anglia Climatic Research Unit (CRU) and the University of Delaware Air Temperature (UDEL), and the future changes in global surface air temperature. The results indicate that most of the CMIP6 models reproduce the spatial pattern of temperature climatology reasonably well, however the results vary with region and the model considered. Hermans et al. (2021) and Sung et al. (2021) studied the future changes in mean sea level and sea surface temperature. The analysis reveals that the estimated trend in global sea level rise is larger for CMIP6 simulations as compared to the observed data. Pendergrass (2020), Wang et al. (2020), and Zhu and Yang (2021) have compared the outputs of precipitation from CMIP5 and CMIP6 and analysed the future change in global monsoons projected by CMIP6 models. Their results indicate that most of the models in CMIP6 had a better performance in terms of the spatial distribution of the inter-decadal precipitation as compared to CMIP5. Deng et al. (2020) analysed the recent trends (1980–2019) in near surface wind speed using the reanalysis data and CMIP6 model simulations. Liu et al. (2020a, b) studied the future change in global potential evapotranspiration and compared the multi-model simulations obtained from CMIP5 and CMIP6. The projections show higher values of potential evapotranspiration in the future using the CMIP6 model simulations, possibly as CMIP6 simulates stronger warming for a given scenario. Liu et al. (2021) used soil moisture and precipitation simulation from CMIP6 models and evaluated the global fraction of stored precipitation in surface soil against offline simulations. Qiao et al. (2022) compared the shallow and deep soil moisture simulations from CMIP6 models with multiple reanalysis datasets. Fan et al. (2020b) and Kim et al. (2020) evaluated the ability of the CMIP6 models to simulate the climate extremes defined by the Expert Team on Climate Change Detection and Indices (ETCCDI). Their results indicate that the skill of CMIP6 models is similar to those of CMIP5 models, indicating limited improvements in model skills for climate extremes. However, notable improvement is observed in reproduction of extreme precipitation intensity by CMIP6 models. Cook et al. (2020), Hirabayashi et al. (2021), Ukkola et al. (2020), and Wang et al. (2021) have attempted to study the future change in drought and flood characteristics based on the projections of CMIP6. In case of drought events, the results indicate a progressive worsening of conditions and a marked increase in the future. The exposure to flooding is projected to be proportional to the warming and the threat may increase with the increase in population. All the above-mentioned studies have been carried out at global scale and show a distinctive difference in simulations made by CMIP5 and CMIP6 considering primary, secondary and tertiary hydroclimatic variables. Different studies have also attempted to analyse the CMIP6 model outputs at regional scale also (e.g. Almazroui et al. 2020a, b; Chen and Yuan 2021; Gusain et al. 2020; Jiang et al. 2020; Y. Liu et al. 2020a, b; Narsey et al. 2020; Sante et al. 2021). The regions (climatic variables) considered in these studies are Africa (temperature), India (monsoon rainfall), China (climatic extremes), Europe (precipitation extremes) and Australia (monsoon rainfall). Most of these studies have contrasted the model outputs from CMIP5 and CMIP6 and analysed the future projections under different Shared Socio-economic Pathways (SSPs).

As evident from the findings of the above-mentioned studies, both at global and regional scale, different generations of CMIP led to substantial progress in climate modelling. However, the extent of improvement depends on the variable and region considered. Precipitation, temperature and soil moisture are the three crucial hydrometeorological variables that help to maintain the atmospheric and land surface balance in terms of water and energy, and significantly affects the hydrologic cycle both at global and local scales (Huntington 2010). Thus, a global assessment with finer resolution is warranted to understand the value addition in CMIP6. Most of the previous studies involving precipitation fields using CMIP6 simulations are either carried out for specific regions or analyse the model uncertainty associated with annual precipitation (Zhu and Yang 2021). Similar assessment is made for the temperature related studies also (Fan et al. 2020a). Assessment of soil moisture fields using CMIP6 simulations is also limited. It may also be noted that most of the studies have carried out a comparison between the 5th and 6th phase of CMIP using the raw GCM data. However, it is established that the coarse resolution of the GCMs (CMIP5) prevents the models from appropriately capturing the local forcings, such as complex topography and land surface heterogeneity (Sylla et al. 2012). Regional Climate Models (RCMs) are used to dynamically downscale GCMs to produce fine-scale and improved regional climate information. Given the advancements in the CMIP6, such as finer horizontal resolution and improved parameterizations of different processes, it is may be useful to carry out a global assessment of improvement in the simulations of aforementioned variables with respect to CMIP5 outputs after downscaling, available from COordinated Regional Climate Downscaling Experiment (CORDEX). This helps to reveal the global perspectives of quality improvement along with its spatial variation, if any. A vital next question is how these variables are going to change in the future for different climate change scenarios, designated by SSPs. An assessment towards this will also be useful for identification of the regions that are more sensitive to climate change. This forms the motivation of this study.

The objective of this study is to carry out a global assessment of the historical simulations and future projections provided by CMIP6 with respect to CMIP5 model outputs.

It may be noted that the GCM outputs from two different phases of MIPs (CMIP5 and CMIP6) can be directly compared to assess the relative quality of different simulated variables. However, the quality of GCM outputs from CMIP5 is further improved after downscaling through CORDEX (henceforth CORDEX-CMIP5). Thus, the GCM outputs from the CMIP6 are compared with both CMIP5 (raw data) and CORDEX-CMIP5 (dynamically downscaled data). Three hydrometeorological variables, namely precipitation, temperature and soil moisture, are considered for the analysis. Firstly, the reanalysis products from 5th generation European Centre for Medium-Range Weather Forecasts (ECMWF), referred to as ERA5, are considered as the reference for the comparison of both CMIP6 and CORDEX-CMIP5 model outputs during the historical period. Secondly, the future projections following three different SSPs, namely SSP1-2.6, SSP2-4.5, and SSP5-8.5, are used to reveal the regions showing significant increasing/decreasing trend along with the number of models in agreement for the different hydrometeorological variables.

## Materials and methods

The outputs from the two phases of CMIP, namely CMIP6 and CMIP5, along with a reanalysis product ERA5 are utilized in this study. Outputs from multiple GCMs are available from both the phases of CMIP, however in this study simulations and projections from five GCMs are used for the analysis. The reason for selecting these GCMs is as follows: (a) availability of data for all the three variables (precipitation, temperature, and soil moisture) for both the historical and future period following three different SSPs and (b) availability of the CORDEX data developed by using the outputs from the 5th phase of CMIP. The time period for historical simulations from the CMIP6 models is 1850–2015. The same from CMIP5 is 1850–2005. The starting and ending year of the data availability varies based on the GCMs considered. Next, single pressure level monthly data from ERA5 is available for the time period of 1979–present. Thereby, the overlap period from all the three data sources, i.e. from 1979 to 2005, is considered as the historical period for the assessment. The time period for the future analysis is considered from 2021 to 2100 as provided by CMIP6. It may be noted that the horizontal resolution of the data varies from model to model, and thereby, all the datasets are re-gridded to 0.25°×0.25° (horizontal resolution of ERA5) to carry out a comparative analysis.

The overall analysis is carried out in two stages. Firstly, the reliability of the GCM simulations participating in different generations of CMIP is established by comparing their model outputs with the reanalysis product in terms of different statistics (e.g. mean, variance and mean bias). Secondly, the future projections from the latest phase of CMIP under different climate change scenarios are used to analyse the future trend of temperature, precipitation, and soil moisture across the globe. Details on all the three data sources (CMIP6, CMIP5, and ERA5) along with the methods used for analysis are provided as follows.

### CMIP6 simulations

CMIP started twenty years ago providing the comparison between a few early GCMs performing experiments using coupled models. Over the years, it has evolved into a major research activity, introducing a new era of climate science research, with different phases/generations of CMIP. The recent phase of CMIP, i.e. CMIP6, is set to address three broad areas; the response of the Earth system to the forcings, origin and consequences of systematic model bias and assessment of future climate change given the climatic variability, predictability and uncertainty in the scenarios. This phase has a more improved conceptualization consisting of three major elements: (i) a handful of common experiments, the Diagnostic, Evaluation and Characterization of Klima (DECK), and the CMIP historical simulations; (ii) common standards, coordination, infrastructure and documentation that will facilitate the distribution of model outputs and the characterization of the model ensemble; and (iii) an ensemble of CMIP-Endorsed Model Intercomparison Projects (MIPs) that will be specific to CMIP6 (Eyring et al. 2016). In this recent phase, the Scenario Model Intercomparison Project (ScenarioMIP) is a primary source that provides multi-model climate projections based on alternative scenarios that are directly relevant to societal concerns regarding climate change mitigation, adaptation, or impacts (O'Neill et al. 2016). These climate projections are driven by a new set of emissions and land use scenarios, referred to as the SSPs, produced with integrated assessment models based on new future pathways of societal development and related to the previously used Representative Concentration Pathways (RCPs). One major improvement in the CMIP6 scenarios is a better exploration of possible baseline "no climate policy" outcomes.

Output from multiple GCMs is available under the CMIP6 (URL: https://esgf-node.llnl.gov/search/cmip6/). The details on the GCMs used for the analysis are provided in Table 1. The reason for selecting these GCMs is the availability of data for both the historical and future period for all the three SSPs, namely SSP1-2.6, SSP2-4.5, and SSP5-8.5, and for all the three variables. Furthermore, the data for the historical period are available from different MIPs, however, in this case, the outputs from High Resolution MIP, which mainly focuses on the regional phenomena are utilized.

**Table 1** Details of the GCMs, participating in CMIP6 and CMIP5, and CGMs/RCMs combinations in CORDEX-CMIP5

| Model name | | Name of the institute | RCM (CORDEX-CMIP5) |
|---|---|---|---|
| CMIP6 | CMIP5 | | |
| CNRM-CM6-1 | CNRM-CM5 | National Centre for Meteorological Research, France | Rossby Centre regional atmospheric model (RCA4) |
| EC-Earth3 | EC-Earth | EC-Earth Consortium, Europe | |
| HadGEM3-GC31-HM | HadGEM2-ES | Met Office Hadley Centre, UK | |
| MPI-ESM 1-2-HR | MPI-ESM-LR | Max Planck Institute for Meteorology, Germany | |
| IPSL-CM6A-HR | IPSL-CM5A | Institute Pierre Simon Laplace, France | |

### CMIP5 simulations

The 5th phase of CMIP, i.e. CMIP5, is the previous phase of CMIP for which model outputs are available since 2011. CMIP5 has notably provided a multi-model context for assessing the mechanisms responsible for model differences, examining climate predictability on decadal time scales and determining why similarly forced models produce a range of responses. In order to capture the local forcing RCMs are extensively used to dynamically downscale GCMs. The outputs from the climate models are used to drive the RCMs that provide simulations and projections at a finer spatial scale. The CORDEX builds a foundation of previous downscaling intercomparison projects to provide a common framework for downscaling activities around the world (Giorgi et al. 2009). The outputs from different GCMs provide driving conditions for the RCMs. In this study, both raw GCM data from CMIP5 (URL: https://esgf-node.llnl.gov/search/cmip5/) and CORDEX data developed by using the outputs from CMIP5 (CORDEX-CMIP5; URL: https://esgf-data.dkrz.de/search/cordex-dkrz/), are utilized for the comparative assessment against CMIP6. The details on the different GCMs and RCMs are provided in Table 1. It may be noted that these RCMs are driven by the same GCMs, however, with a different version as available in CMIP5. Furthermore, the data from each RCM may not be available for all the fourteen domains. The RCM used in this study provides the downscaled data for eight domains, namely Africa, Arctic, Central America, Europe, Middle East North Africa, North America, South America, and South Asia.

### ERA5 reanalysis data

ERA5 is the latest climate reanalysis product by ECMWF that provides an estimate of a large number of atmospheric, land and oceanic climate variables at different temporal scales. This reanalysis product combines vast amounts of historical observations into global estimates using advanced modelling and data assimilation systems. We used a single pressure level data at monthly scale (URL: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5). As mentioned before, three hydrometeorological variables, namely, precipitation, temperature and soil moisture are used in the analysis. It is important to note that the total soil moisture content, as obtained from ERA, is available for four layers and the data are summed over all the layers and then analysed.

### Comparison between CMIP6, CMIP5, and CORDEX-CMIP5 in the historical period

The data obtained from the five GCMs participating in CMIP6 models, CMIP5 models, and GCMs-RCMs combinations participating in CORDEX-CMIP5 models are utilized to obtain the multi-model ensemble for each of the three variables. Next, the data from the historical period (1979–2005) are utilized to evaluate two sample statistics, namely, mean and variance for each data source individually, to study the reliability of climate model outputs with respect to the reanalysis product. Lastly, the mean bias is evaluated by calculating the difference between the mean values of the climate model outputs (CMIP6, CMIP5, CORDEX-CMIP5) and the reanalysis product (ERA5). A positive bias indicates that the climate model is overestimating the mean value for a particular variable over the period of 1979–2005 and a negative bias indicates that the climate model is underestimating the mean value.

### Trend analysis for future

Trend analysis is carried out separately for the model outputs obtained from each GCM (five) considering CMIP6 models, for the future period (2021–2100). The nonparametric Mann–Kendall (M–K) test is used to detect the statistically significant trends (95% confidence level). This test was introduced by Mann (1945) and then expanded/modified by Kendall (1975). In this test, the rank of the data is used instead of actual values, which makes the computation less sensitive to the distribution of data. This test is also less sensitive to the nonlinear trends, abrupt breaks, and inhomogeneity in the data. Additionally, the Sen's slope estimator is used to evaluate the value of the slope for the grids with a significant trend as identified form the M–K test. It is also a nonparametric estimator first outlined by Theil (1950) and later expanded upon by Sen (1968). It may be noted that for a particular grid, outputs from all the GCMs may not show a significant trend. For instance, considering a specific grid, it might be possible that three GCM outputs are showing significant increasing trend and the two GCM outputs are showing an insignificant trend. Thereby, the number of models in agreement, that is the number of GCMs that show the presence of a similar significant trend, for a particular grid, is identified along with the average value of the slope.

## Results

### Comparison of CMIP6, CMIP5, and CORDEX-CMIP5 model outputs for the historical period

The maps displaying the climatology of precipitation on the surface, which includes both liquid and solid phases from all types of clouds (both large-scale and convective), as obtained from the different phases of CMIP (CMIP6 and CMIP5) and reanalysis product (ERA5), are shown in Fig. 1. The climatology is presented in terms of basic statistics, namely mean and standard deviation, for the historical period (1979–2005). The mean value of precipitation is shown in varying shades of green and blue with the regions receiving higher mean precipitation represented in blue, like majority of the regions lying in the tropical belt. Given that the ERA5 datasets are developed by combining observed records from various sources, these datasets can be considered to provide/represent the ground reality during the historical period. The climatology maps indicate that, in general, the outputs from the two phases of CMIP capture the spatial pattern of precipitation, in terms of mean and standard deviation, very well with respect to the ERA5 products. Figure 1 also shows the mean bias of CMIP simulations with respect to ERA5 to specifically identify the regions with improved historical simulations considering the two phases of CMIP. This value is obtained by subtracting the reanalysis values (ERA5) from CMIP simulations. In the figure, the greenish shade indicates that the bias is very low (close to zero), whereas the positive bias is shown in shades of blue and negative bias is shown in shades of red. It may be to noted, that the simulations made by the CMIP6 model outputs better match with the ERA5 values as compared to both CMIP5 and CORDEX-CMIP5 model outputs, especially for the tropical belt.

Next, the maps showing the climatology of near-surface air temperature (at 2-m height), as obtained from the outputs of the two phases of CMIP and ERA5 reanalysis product are shown in Fig. 2. As before, the climatology is represented in terms of the basic statistics during the historical period. The regions with mean temperature close to 0 °C are shown

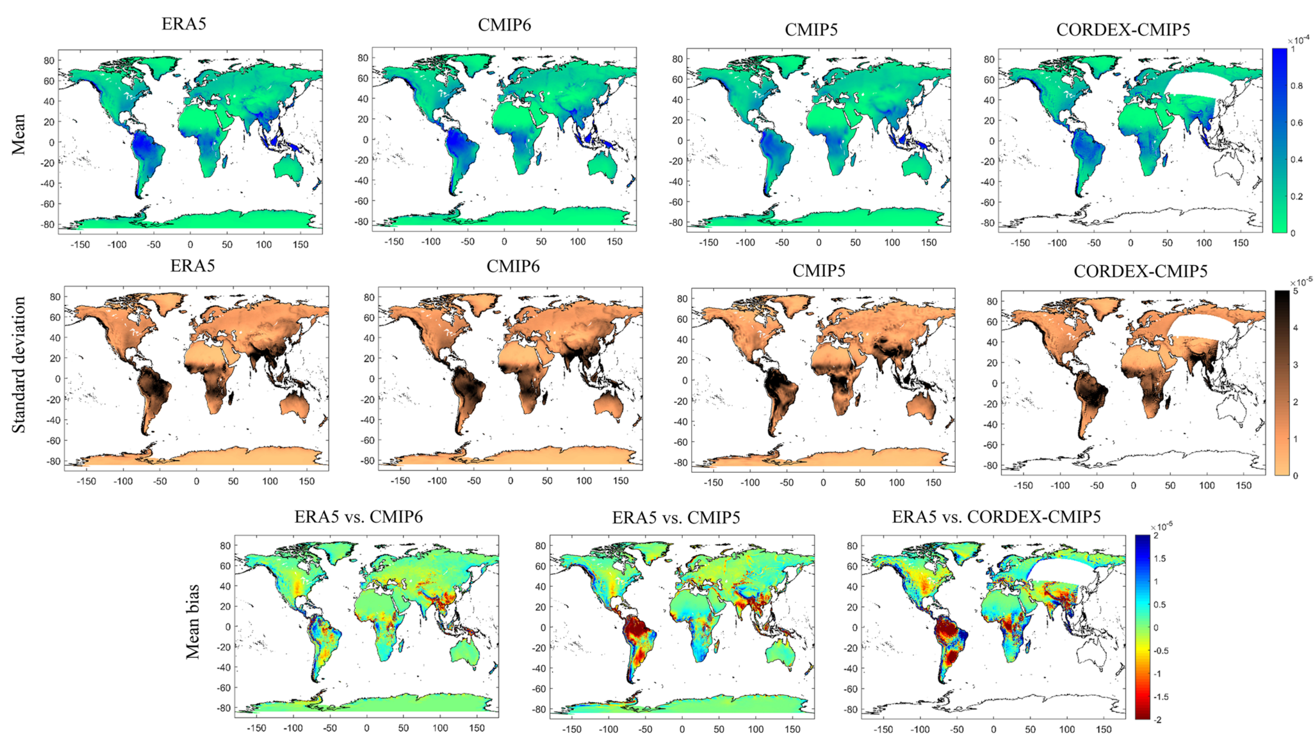


**Fig. 1** Comparison of precipitation data (in kg/m$^2$s, historical) obtained from CMIP6, CMIP5, and CORDEX-CMIP5 with the ERA5 data considering the time period of 1979–2005 and multi-model ensemble from 5 GCMs/RCMs

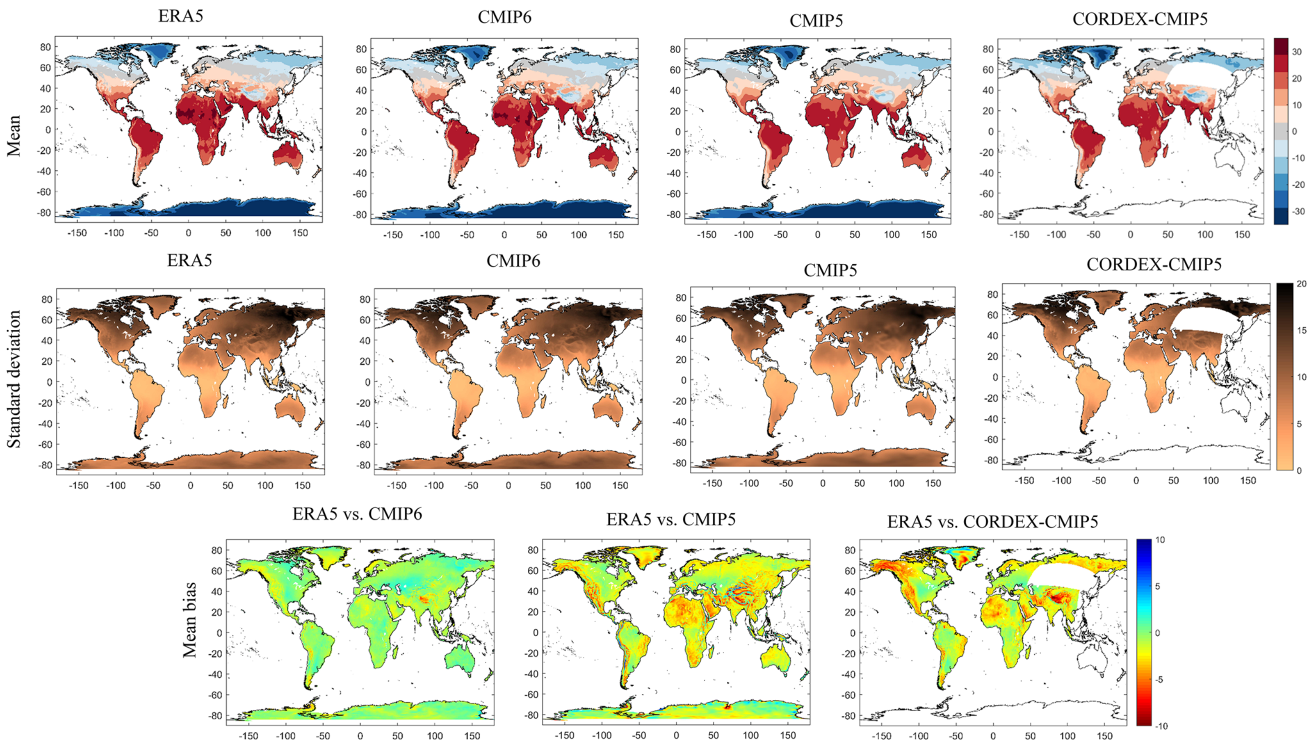


**Fig. 2** Comparison of temperature data (in °C, historical) obtained from CMIP6, CMIP5, and CORDEX-CMIP5 with the ERA5 data considering the time period of 1979–2005 and multi-model ensemble from 5 GCMs/RCMs

in grey. The regions with comparatively cooler climate with mean temperature less than − 5 °C are shown in different shades of blue and the regions with mean temperature higher than 5 °C are shown in different shades of red. The results indicate that the mean temperature is very well captured by CMIP6, CMIP5, and CORDEX-CMIP5 with respect to ERA5 reanalysis data during the period of 1979–2005. This is true for the tropical regions with humid climate, hot/cool dry climate and mild/cold mid-latitude climate. Next, the mean bias, obtained by comparing the climate model outputs and the reanalysis product, indicates that the CMIP6 has higher efficacy for the simulation of near-surface temperature as compared to CMIP5 and CORDEX-CMIP5 models. The mean bias is close to zero for most of the regions in case of the CMIP6 model outputs.

Lastly, comparing the mean soil moisture obtained from the reanalysis product (Fig. 3) with the different soil categories shows that the mean value is highest for the regions (parts of Africa and South America) falling in the Oxisol (heavily weathered and are rich in iron and aluminium oxides with only trace nutrients due to heavy tropical rainfall and high temperatures) category. Next, the Aridisol (dry soils forming under desert conditions which have fewer than 90 consecutive days of moisture during the growing season) and Entisol (recently formed soils that lack well-developed horizons) categories mainly covering the parts of Africa, South Asia, and Australia show the lowest soil moisture content as expected. The temperate, polar and sub-polar zones mainly fall under the Alphisols (soils with aluminium and iron and have horizons of clay accumulation that form in regions with enough moisture and warmth), Mollisols (soft, deep, dark fertile soil formed in grasslands and some hardwood forests), Inceptisols (young soils that have subsurface horizon formation), and Gelisols (permafrost soils with permafrost within 2 m of the surface or gelic materials and permafrost within one metre) categories. The mean soil moisture is comparatively higher in these regions. These regions are shown in different shades of green and blue. It is interesting to note that CMIP6 model outputs provide very similar values of soil moisture as in ERA5 during the historical period. Thereby, it may be concluded that the ability of CMIP6 models to simulate the data for the historical period has not only improved for the primary hydrometeorological variables like precipitation and temperature, but also for the secondary hydrometeorological variables like soil moisture, for which the spatial pattern is accurately captured, with respect to the reanalysis product, in the historical period. Thus, the better performance of CMIP6 during the historical period provides more reliance on the projections provided for the future period.

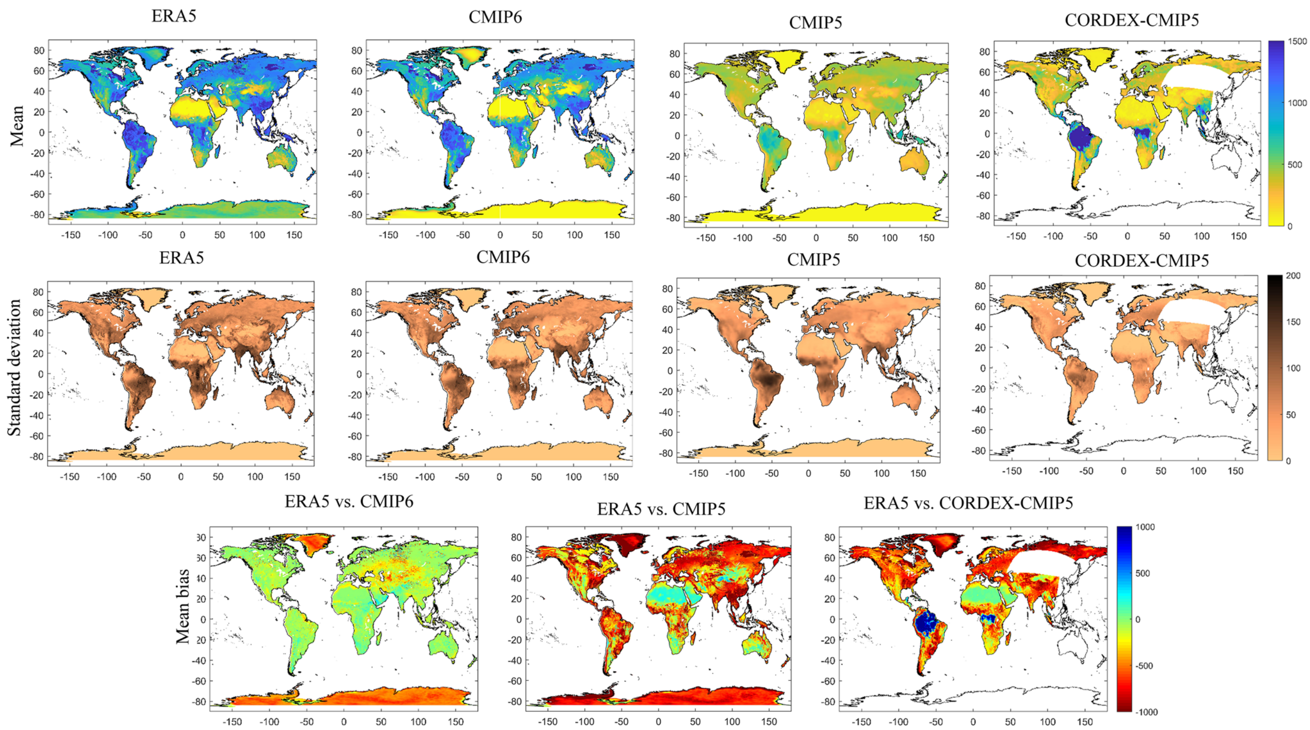


**Fig. 3** Comparison of soil moisture data (in kg/m$^2$, historical) obtained from CMIP6, CMIP5, and CORDEX-CMIP5 with the ERA5 data considering the time period of 1979–2005 and multi-model ensemble from 5 GCMs/RCMs

## Trend analysis for the future period considering the CMIP6 model outputs

The CMIP6 model projections (5 GCM outputs) are used to assess the future change in precipitation for 80 years (2021–2100). Figures 4, 5, and 6 show the model average slope and the number of models in agreement that show a significant trend in future for precipitation, temperature and soil moisture, respectively. The colour varies from grey to purple, where grey signifies that one model shows a significant trend and purple signifies that all the models show a significant trend. It may be noted that the grids where all the models show insignificant trend are also shown in purple, as all the models agree to the same outcome.

Figure 4 shows the average slope for the grids with the significant trend for precipitation where shades of blue are used to show the positive (increasing) trend and shades of red are used to show the negative (decreasing) trend. The grids for which all the models show insignificant trend are shown in white. Results for all three scenarios, namely SSP1-2.6, SSP2-4.5, and SSP5-8.5, are shown. Trend analysis for precipitation reveals that the model agreement decreases moving from SSP1-2.6 to SSP5-8.5, i.e. for severe warming scenarios the model agreement is comparatively lower. Most of the regions showing significant change in precipitation over the period of 2021–2100 shows an increasing trend except certain regions in Europe, South America, and South Africa.

Trend analysis of temperature indicates that most of the regions are showing an increasing trend in future (Fig. 5). This observation was established from the previous phases of MIPs also. By addressing the issue of Earth system response to the forcings, it may be expected that these projections will provide a more realistic picture of how the future will look like. Increase in temperature is considered as an important indicator of climate change and given its role in the hydrologic cycle, precise projections will lead to better management of resources in the future. Contrary to precipitation for severe warming scenarios (SSP5-8.5), the model agreement is higher as compared to SSP1-2.6, especially considering the regions lying in the Southern hemisphere.

Lastly, trend analysis of soil moisture for the future period reveals some interesting findings. Given that the variation of soil moisture is a complex process, the CMIP6 model outputs obtained from the different GCMs vary from one to another leading to fewer number of models to agree at many regions unlike precipitation and temperature (Fig. 6). It may be noted that almost all the regions show a significant change in the spatio-temporal distribution of soil moisture in the future with the significant increase/decrease in trend varying from region to region.

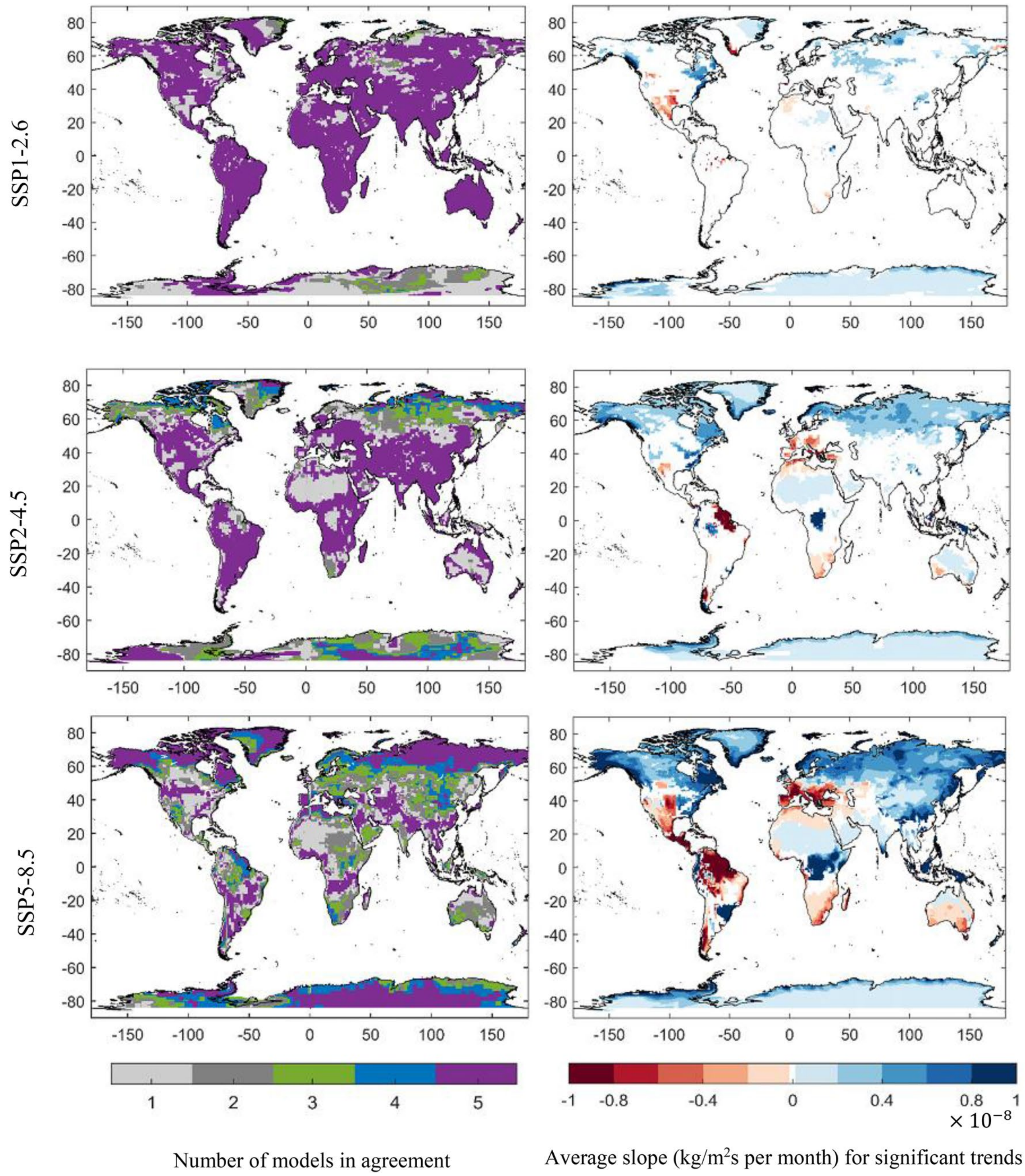


**Fig. 4** Trend analysis for precipitation data (in kg/m$^2$s) considering the time period of 2021–2100 and 5 GCM outputs. The left column shows the model agreement. Purple colour designates that all the 5 GCMs are in agreement either to exhibit a significant trend or an insignificant trend. Rest of the colours designate the number of GCMs that show significant trend. In the right column, the insignificant trend are shown in white and the model average value of the significant slopes

## Discussion

### Historical changes and future projections for precipitation

Considering the global climatic field, both mean and standard deviation of precipitation are on the higher side in the tropical belt which is governed by multiple interacting climatological processes. Given the complexity associated with the precipitation pattern and distribution within this region it is interesting to note that CMIP6 very well captures the climatology for three distinct regions. These are: (i) the regions that are constantly moist with persistent rainfall throughout the year, e.g. northern parts of South America, (ii) the regions that receive monsoon rainfall, i.e. the regions where precipitation in the driest month is less than 6 cm and

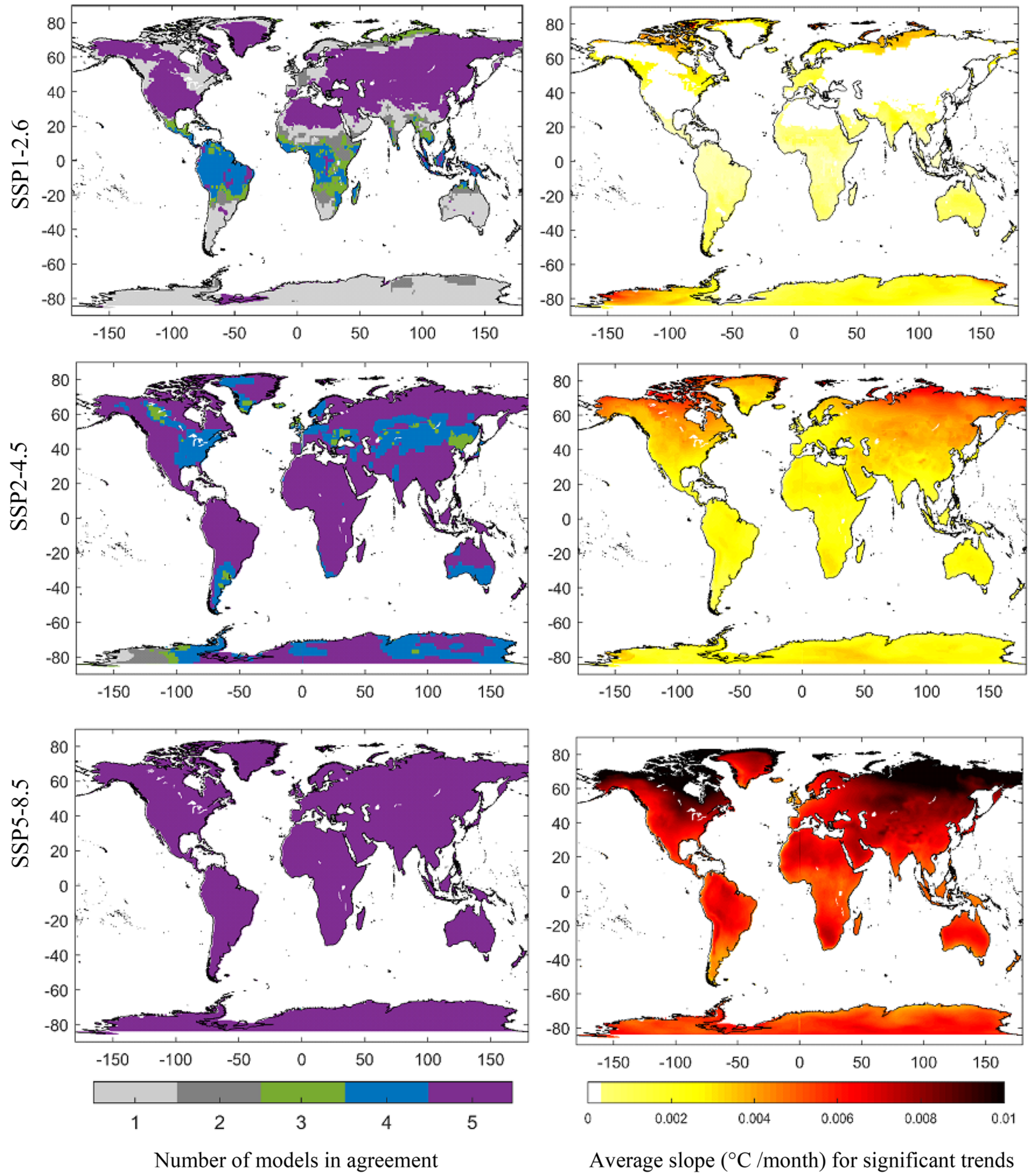


**Fig. 5** Trend analysis for temperature data (in °C) considering the time period of 2021–2100 and 5 GCM outputs. The left column shows the model agreement. Purple colour designates that all the 5 GCMs are in agreement either to exhibit a significant trend or an insignificant trend. Rest of the colours designate the number of GCMs that show significant trend. In the right column, the insignificant trend are shown in white and the model average value of the significant slopes

total annual precipitation exceeds 125 cm, e.g. South Asia, and (iii) the regions with the dry season in winter, i.e. the regions where 70% or more of annual precipitation falls in summer, e.g. northern parts of America (Fig. 1). Comparing the climatic model outputs with reanalysis product in terms of mean bias, these values are very low over almost all the parts of the globe including regions with infrequent rain, light seasonal rain, moderate rain every month and heavy seasonal rain. Exceptions include some regions with highland climate, e.g. small patches across North America, South America, and South Asia. However, considering CMIP5, the mean bias is very high in the parts of Africa, South America, and South Asia. It may be noted that the rainfall variability in these regions is also very high. Studies, like Gusain

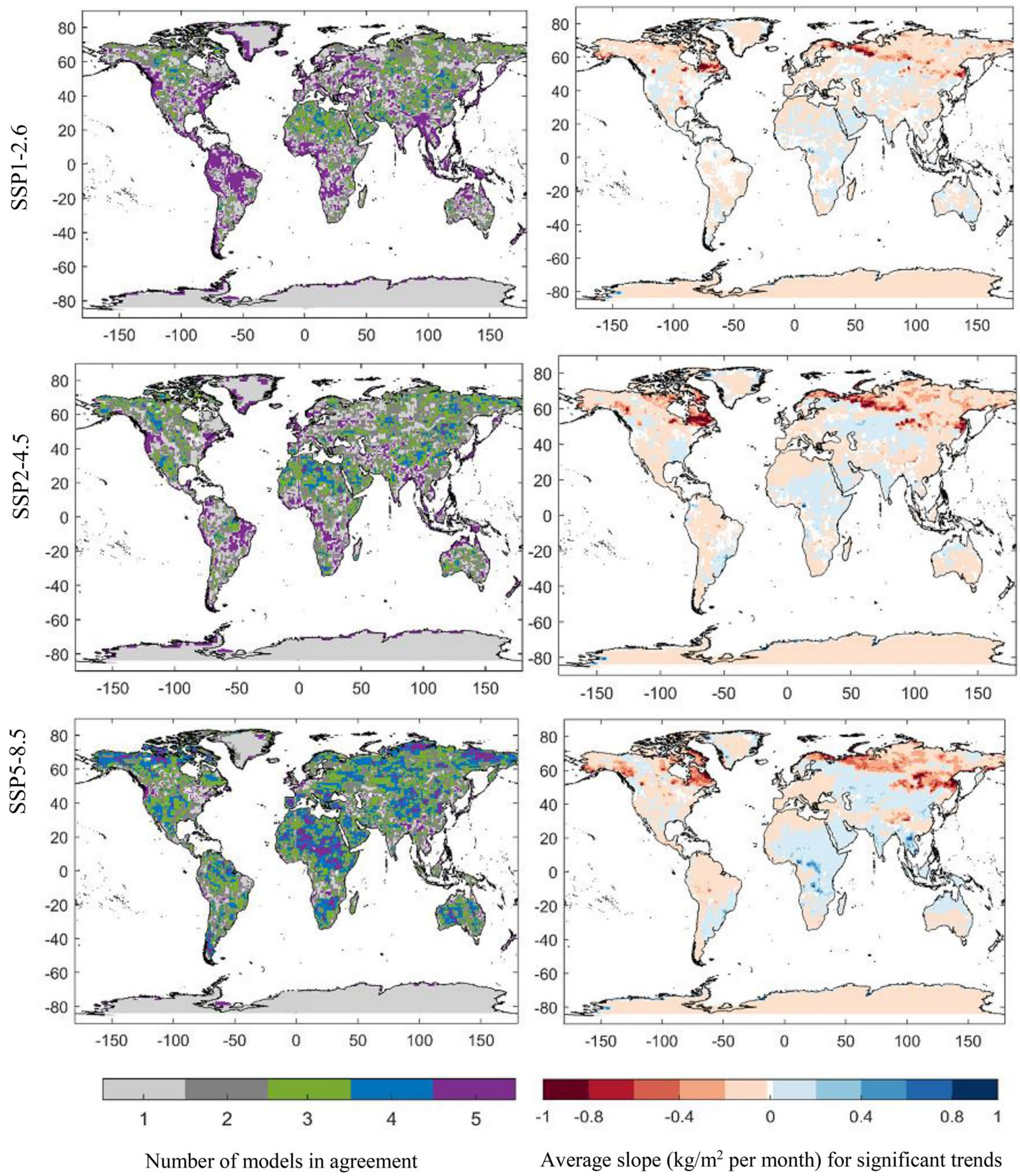


**Fig. 6** Trend analysis for soil moisture data (in kg/m$^2$) considering the time period of 2021–2100 and 5 GCM outputs. The left column shows the model agreement. Purple colour designates that all the 5 GCMs are in agreement either to exhibit a significant trend or an insignificant trend. Rest of the colours designate the number of GCMs that show significant trend. In the right column, the insignificant trend is shown in white and the model average value of the significant slopes

et al. (2020); Jiang et al. (2020); Zhu and Yang (2021), have also established that the individual models in CMIP6 better simulate the spatial distribution of precipitation as compared to CMIP5, especially for East and South Asia and North and South Africa. The results indicate that after dynamical downscaling (CORDEX-CMIP5) improvement may be observed for the North American and European regions (Fig. 1). However, for certain parts of Africa and South East Asia, the mean bias is higher considering CORDEX-CMIP5 as compared to raw CMIP5 model outputs. Studies have shown that the geographic distribution of precipitation, especially in regions with strong seasonal variability are strongly affected by boundary conditions and the statistics may not be always be improved by the downscaling

(Dosio et al. 2015; Nikiema et al. 2017). Overall, the CMIP6 provides an improved simulation of precipitation almost all over the world that is perhaps due to improved parameterization of various physical processes like Walkers circulation, low clouds in tropical belt, position of the atmospheric jet in the Southern hemisphere, thickness of thermocline layer, to name a few.

The analysis of the projected data reveals that the rate of change in precipitation increases with the severity of the scenario (from SSP1-2.6 to SSP5-8.5) in terms of the magnitude of the slope and the spatial extent of the change. In case of SSP1-2.6, no significant trend can be observed. However, for some of the regions in the temperate, polar and sub-polar regions, with light seasonal rainfall, one or two model outputs show an increasing (significant) trend. In case of SSP2-4.5, the rate of change in precipitation slightly increases for almost all the regions. The regions with cold mid-latitude climate, where either 70% of annual precipitation falls during the summer months or the rainfall is consistent throughout the year, shows an increasing trend with the number of models in agreement lying between 2 and 4. Similar observations are made for regions with infrequent rainfall (parts of Africa and Australia) also, however, only 1 model supports this observation. In case of SSP5-8.5, a wide range of results is noticed, especially for the tropical belt. Parts of Central America with heavy seasonal rainfall and heavy rainfall every month shows a negative trend (high value of average slope), whereas the parts of Africa with the same rainfall pattern shows a positive trend (high value of average slope). The number of models that agree to this observation mostly lies between 2 and 4. Some parts of Europe with moderate rain every month show a decreasing trend but most of the regions in the temperate, polar and subpolar regions show an increasing trend with an agreement of more than 3 models. The results clearly indicate a long-term change (increase/decrease) in precipitation for many regions with an above average model agreement (three or more models show the same result as designated by the colours green, blue and purple in Fig. 4) for most of the regions.

## Historical changes and future projections for temperature

Unlike precipitation, the standard deviation of surface temperature is higher in the temperate, polar and sub-polar regions, where the mean monthly temperature, in general, is lower than 10 °C. Within the tropical belt, similar observations are made for the regions with high altitude climate, where the mean temperature is lower than 0 °C. For certain regions in the polar belt, where the temperature is above 10 °C for less than four months in the year, and the coldest month is below −37 °C, the standard deviation lies within the range of 15 to 20 °C. For the parts of South Asia and Northern America with highland and mid-latitude climate, the mean bias is negative and the same for the hot dry and cold mid-latitude climate for parts of North America and Central Asia is positive. In case of CMIP5, the bias lies in the range of − 10 to 10 °C, with most of the regions showing negative mean bias that is, the model is underestimating the value of monthly temperature. The model error is highest across the parts of South Asia and North America with highland and mid-latitude climate. In the tropical belt also, where the standard deviation is comparatively low, the model underestimates the value of temperature mostly by 5 °C. Similar observations that the CMIP6 models could capture the spatial patterns and temporal variations of surface temperature as compared to reanalysis data is also made by Fan et al. (2020a). Comparing the findings from CMIP5 and CORDEX-CMIP5, it may also be noted that considering the regions of Africa and South America, some improvements are observed after dynamically downscaling. Studies have identified some major gaps in the previous phases on CMIP including CMIP5, one of them being the response of the Earth system to changes in forcings (Stouffer et al. 2017; Eyring et al. 2019). Most of the climate models simplify this issue and utilize single metrics like equilibrium climate sensitivity which may lead to higher model bias. One of the three broad questions addressed in CMIP6 is how the Earth system responds to such forcings. Different techniques have been integrated into the models to deal with such issues like adjustments in sea surface simulations, modified simulation of tropical and subtropical low clouds, modified simulation of land surface/cloud schemes leading to improved simulations for most of the regions around the globe (Stouffer et al. 2017).

Considering the future analysis, in case of SSP1-2.6, it may be observed that almost all the regions in the southern hemisphere along with the tropical belt shows an increasing trend. An agreement of 1 to 4 models is noticed with the highest value of average slope for the regions with *tropical humid* and *hot and dry* climate. Referring back to the climatology of temperature, based on the historical period, the mean monthly temperature is also highest for these regions. Next, in case of SSP2-4.5, the results indicate an increasing trend for the entire globe. For most of the regions, all the model outputs show an increasing trend with the highest value of the slope for the temperate, polar and sub-polar regions. It may be noted that the standard deviation, during the historical period, is highest for these regions. All the other regions show a more or less similar rate of change in temperature. For SSP5-8.5, similar observations are made with an agreement from almost all models and the value of the slope for the increasing trend is higher as compared to SSP1-2.6 and SSP2-4.5 for almost all the regions. Similar to the precipitation, the highest increase is observed for the regions with a cold mid-latitude climate. The analysis also reveals that in case of SSP1-2.6, most of the models show an insignificant trend for the above-mentioned regions. However, both SSP2-4.5 and SSP5-8.5 indicate a significant increasing trend in these regions. Thereby, the rate of change in temperature as well as the spatial pattern of change for the future period varies with the climate change scenario considered for the analysis.

## Historical changes and future projections for soil moisture

Similar to precipitation, the results indicate that the standard deviation is highest in the tropical belt, which consists of the regions with the highest or near to highest mean monthly soil moisture. Comparing the mean bias obtained for the outputs from the two phases of CMIP, it is noticed that the performance of the CMIP6 models is much better as compared to CMIP5 and CORDEX-CMIP5 models (Fig. 3). All the model outputs successfully capture the spatial pattern of mean soil moisture in the historical period however the mean values are not captured properly by the CMIP5 models. Both the regions with low mean soil moisture like the northern part of Africa and regions with high mean soil moisture like South America and parts of Africa are successfully captured by the CMIP6 simulations. However, the mean bias for CMIP5 and CORDEX-CMIP5 model outputs are high (either positive or negative) for almost all the domains. Most of the regions show negative bias except for the regions with high soil moisture which shows positive bias.

Finding for the future analysis are summarized as follows: in case of SSP1-2.6, most of the regions falling under the category of Inceptisols (young soils that have subsurface horizon formation) and Gelisols (permafrost soils with permafrost within two metres of the surface or gelic materials and permafrost within one metre) show a decreasing trend. For most of these regions, 3 models are found to be in agreement. Other regions falling in the category of Alfisols (soils with aluminium and iron and have horizons of clay accumulation that form in regions with enough moisture and warmth) and Vertisols (inverted soils that are clay-rich and tend to swell when wet and shrink upon drying, often forming deep cracks into which surface layers can fall) show an increasing trend and the number of models in agreement varies between 1 and 3. The value of the slope for the grids with a significant trend does not change much between SSP1-2.6 and SSP2-4.5 but the spatial extent of the regions showing significant trend increases. In case of SSP5-8.5, most of the regions in Africa, Central Asia, and South Asia show an increasing trend with more than 50% of models in agreement. On the other hand, most of the regions in North and Central America show a decreasing trend that is agreed by 2–3 models. Considering the polar and sub-polar regions, most of the models show a decreasing trend in soil moisture, especially for the regions falling under Spodosols (acid soils with organic colloid layer and typical soils of coniferous and deciduous forests in cooler climates) category. Given the complexity associated with the secondary hydrometeorological variables like soil moisture, it is expected that the model agreement will be comparatively low. However, the improved simulation of soil moisture in CMIP6, as compared to its previous phases, during the historical period increases the reliance on the future projections. A more careful quantification of the radiative forcings for the different specified forcing factors might be a primary reason for the improved simulation in the CMIP6 models.

## Conclusions and recommendations

The sixth phase of CMIP (CMIP6) addresses some of the major drawbacks persistent with the climate models which throttle the advancement of climate studies. The CMIP6 models provide GCM outputs for the historical simulations and future projections, considering different SSPs, at various spatio-temporal scale. Given the advancements in the CMIP6 models, it will be useful to analyse the improvement in the historical simulations of different hydrologic variables at global scale and the future change in these variables for different climate change scenarios. Following specific conclusions can be drawn from the analysis:

- Assessment of three hydrometeorological variables, namely precipitation, temperature and soil moisture, indicates that the outputs from the CMIP6 models very well capture the climatology of the variables in terms of monthly mean and standard deviation. For precipitation and soil moisture, the standard deviation is highest for the tropical regions, whereas for temperature the standard deviation is highest for the temperate, polar and sub-polar regions.
- When comparing the outputs from the two phases of CMIP with the ERA5 reanalysis product, the results indicate very low mean bias in case of the CMIP6 model outputs. The simulations for the tropical belt has remarkably improved for all the three variables. The precipitation climatology is very well captured for the regions of Africa, South America, and South Asia by the CMIP6 model outputs. The mean bias for parts of the above-mentioned regions with heavy seasonal rainfall and heavy rainfall every month (regions with comparatively complex climatology) is almost four times considering CORDEX-CMIP5 as compared to CMIP6. For temperature, the mean bias across the parts of North America, Africa, and South Asia lies within the range of − 5 to 5 °C in case of CORDEX-CMIP5, whereas the same for CMIP6 has been reduced to − 2 to 2 °C for most of the regions.

- Maximum improvement is noticed for soil moisture in the CMIP6 model outputs. Simulation of soil moisture is indeed a challenging task as the variation of soil moisture is associated with many climatic factors in complex ways and its spatio-temporal variability is very high. Given all the uncertainties associated with such simulations, the mean bias is promisingly low in the CMIP6 model outputs. As against CMIP5 and CORDEX-CMIP5, the climatology is very well captured across the northern parts of Africa and regions with high mean soil moisture, such as parts of Africa and South America. The improved ability of the CMIP6 models to simulate primary and secondary hydrometeorological variables provides more reliance on the projections provided for the future period.
- Trend analysis for the future projections shows a significant change in the magnitude and spatial distribution of the three hydrometeorological variables. The rate and spatial extent of change increase with the severity of the scenario (from SSP1-2.6 to SSP5-8.5) with more number of models in agreement. Highest value of slope, for regions showing significant positive trend of precipitation and temperature, is noticed in the temperate, polar and sub-polar belt. In case of the worst scenario, i.e. SSP5-8.5, precipitation shows a negative trend (model average) across the parts of Central America, whereas the parts of Africa with similar rainfall pattern shows a positive trend. Certain parts of Europe show a decreasing trend, however, most of the regions in the temperate, polar and sub-polar regions show an increasing trend. The number of models in agreement lies between 2 and 5 for all the above findings. For temperature, in case of SSP5-8.5, all the five climate models show an increasing trend with the highest rate of change across the regions with cold mid-latitude climate, i.e. parts of Asia and North America.
- Soil moisture shows a significant increasing/decreasing trend in almost all parts of the world, for all the three climate change scenarios, and these results can be strongly associated with the basic properties of soil, such as temperature, texture and moisture condition. In case of the worst SSP5-8.5 scenario, most of the regions in Africa, Central Asia, and South Asia show an increasing trend, whereas most of the regions in North and Central America shows a decreasing trend. The number of models in agreement is bit less (between 2 and 4), which is expected as the complexity associated with the variation of soil moisture is very high.

Overall, the simulations provided by CMIP6 model outputs during the historical period exhibit an improvement over the previous generation as these outputs successfully capture the mean and standard deviation over the climatological scale. The reduced model error (with respect to reanalysis product, ERA5) provides greater reliance on the future projections from CMIP6. Specifically, the vastly improved efficacy of CMIP6 in capturing the climatology of precipitation and soil moisture for regions with high variability (tropical belt) gives more confidence in the utilization of these model outputs for climate studies. However, it may be noted that the reliability of the above-mentioned conclusions is dependent on the reliability of the reanalysis product (ERA5). Considering the future projections (SSP5-8.5), all the three hydrometeorological variables are showing significant change considering the time period of 2021–2100. Furthermore, the regions identified as more sensitive to climate change (significant change in the future with a comparatively higher rate of change in the hydrometeorological variables) need to be further studied to develop efficient water resource management policies. Additionally, the analysis may be extended to tertiary hydrometeorological variables, like floods and droughts, and at a finer temporal scale which will give a better insight into the capability of the climate models to capture the extremes.

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**Availability of data and materials** The data that support the findings of this study are available from; https://esgf-node.llnl.gov/search/cmip6/, https://esgf-node.llnl.gov/search/cmip5/, https://esgf-data.dkrz.de/search/cordex-dkrz/ and https://www.ecmwf.int/en/forecasts/datasets/ reanalysis-datasets/era5. These datasets are freely available. It was accessed by the authors in April 2021.

**Code availability** The codes required for the analysis are written in MATLAB R2018a (version 9.4). These codes can be made available on request.

## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Ethics approval** Not applicable.

**Consent to participants** Not applicable.

**Consent for publication** Not applicable.

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