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Spurious Drifts in the ITCZ Location and Associated Atmospheric Circulation in Decadal Climate Predictions

Rashed Mahmood[1], **Makus G. Donat**[2,3], **Bo Christiansen**[1], **and Francisco J. Doblas-Reyes**[2,3]

[1]National Center for Climate Research (NCKF), Danish Meteorological Institute, Copenhagen, Denmark, [2]Barcelona Supercomputing Center (BSC), Barcelona, Spain, [3]Catalan Institution for Research and Advanced Studies (ICREA), Barcelona, Spain

Key Points:

- Drift in initialized climate predictions causes spurious shifts in the location of the Intertropical Convergence Zone
- These spurious shifts also affect the large-scale atmospheric circulation including the location of jet streams
- The drift is larger in full-field initialized models but anomaly-initialized models show large biases from the beginning

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

R. Mahmood,
rama@dmi.dk

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Author Contributions:

Conceptualization: Rashed Mahmood, Makus G. Donat, Bo Christiansen, Francisco J. Doblas-Reyes
Data curation: Rashed Mahmood
Formal analysis: Rashed Mahmood
Funding acquisition: Makus G. Donat
Writing – original draft: Rashed Mahmood, Makus G. Donat
Writing – review & editing: Rashed Mahmood, Makus G. Donat, Bo Christiansen, Francisco J. Doblas-Reyes

Abstract Decadal predictions are affected by initialization shocks and drift, typically diagnosed in ocean circulation or temperature. It is not known, however, to what extent the drift can affect atmospheric dynamics. Here we investigate how the drift causes spatial shifts in the location of key large-scale atmospheric circulation features such as the Intertropical Convergence Zone (ITCZ). The asymmetrical changes in surface temperature (with warmer southern and cooler northern hemisphere) with increasing forecast times cause southward shifts in the location of ITCZ, the subtropical jets and tropical precipitation patterns. Such changes are larger in full-field initialized models, however, the anomaly-initialized models show large biases in their ITCZ location from the beginning. These artificial changes in the location of large-scale circulation patterns pose important challenges to initialized climate predictions, potentially undermining the ability of current prediction systems to predict changes in climate aspects for which atmospheric circulation is an important driver.

Plain Language Summary Decadal climate predictions suffer from various issues related to differences between the observed climate and that represented by models. When initializing the models close to observations, this mismatch causes the models to drift toward their own climate as the forecast time increases. We show here that such drift can artificially change the location of the atmospheric circulation systems and the associated precipitation patterns during model simulations. These spurious shifts in the location of atmospheric circulation patterns point to important limitations in current decadal prediction systems, affecting their suitability to predict regional climate conditions and extremes.

1. Introduction

Initialized climate predictions are designed to provide accurate and reliable climate information on subseasonal to decadal timescales (e.g., Meehl et al., 2021). Since these model simulations are carried out by starting the model from climate states close to observations, these simulations are expected to better represent the internal climate variability and the forced model response than the uninitialized climate projection simulations (Doblas-Reyes et al., 2005, 2013; Smith et al., 2007). Therefore, climate information from these simulations is highly desirable for applications in various socio-economic sectors, such as better adaptation planning and designing resilient infrastructures and reducing risks of mal-adaptations.

Decadal climate predictions are simulations generally performed for the next 10 years (Boer et al., 2016) and sometimes extended up to 20 or 30 years after initiation (Düsterhus, & Brune, 2024; Mahmood et al., 2025). As the initialized predictions have gained significant interest among both the climate science community and the users, several modeling centers now provide regular forecasts (issued once a year) for the next decade after initialization (Hermanson et al., 2022). However, these prediction systems must be evaluated routinely for testing the accuracy and maintaining confidence in the forecasts as the methods of initialization as well the prediction systems are continuously evolving over time. For this, retrospective forecasts (also known as "hindcasts") are carried out by initializing the models every year during a period when observations are available. These retrospective forecasts are then evaluated using both deterministic and probabilistic skill metrics (e.g., Delgado-Torres et al., 2022).

The skill of the initialized prediction systems in predicting climate over multi-annual and decadal timescales has remained challenging, though some recent studies claim high skill of the forecasts on decadal timescales (Smith et al., 2020; Tsartsali et al., 2025). While the climate predictions have shown success in predicting certain aspects of global climate and added value with respect to historical simulations for some variables over a number of regions (e.g., Athanasiadis et al., 2020; Delgado-Torres et al., 2022; Nicolì et al., 2025; Smith et al., 2020; Yeager et al., 2018, 2022), these prediction systems are, however, affected by initialization shocks and subsequent climate drift (e.g., Bilbao et al., 2021; Kröger et al., 2018; Mahmood et al., 2025; Polkova et al., 2023). Furthermore, it is difficult to assess the statistical significance of the added value from initialization (e.g., Christiansen et al., 2023). Previous studies have reported drift in the Atlantic Meridional Overturning Circulation (AMOC) and surface temperatures resulting from initialization shock (e.g., Mahmood et al., 2025; Polkova et al., 2023). This can lead to large-scale temperature asymmetries (Mahmood et al., 2025) that can plausibly be expected to affect atmospheric dynamics, causing changes in large-scale circulations and the associated climatic conditions (such as the location or intensity of precipitation) (e.g., Roldán-Gómez et al., 2025). Such circulation changes in response to ocean temperature drift can plausibly be expected but have not yet been studied.

For example, it remains unknown how climate drift affects the location of circulation features such as the Intertropical Convergence Zone (ITCZ) and precipitation patterns in initialized climate predictions. Similarly, how the initialization methods influence such changes in global circulation and precipitation patterns still needs to be explored. In this study we intend to fill this knowledge gap by analyzing the changes in the location (and intensity) of large-scale atmospheric circulation and precipitation patterns related to the model drift after initialization and model biases in 11 decadal prediction systems contributing to the Coupled Model Intercomparison Project Phase 6 (CMIP6) decadal climate prediction project component A (DCPP-A; Boer et al., 2016) that use either full field or anomaly initialization methods.

Prediction experiments such as DCPP-A, with a large ensemble size, provide unprecedented opportunities for comprehensive evaluations of the retrospective forecasts. While many studies evaluating decadal predictions focus on finding added skill from initialization in these prediction systems (e.g., Athanasiadis et al., 2020; Delgado-Torres et al., 2022; Nicolì et al., 2025; Smith et al., 2020), much less attention has been devoted to understanding the changes in large-scale circulations induced by the initialization shock and subsequent model drift (e.g., Bilbao et al., 2021; Mahmood et al., 2025; Meehl et al., 2022; Polkova et al., 2023). We are not aware of previous studies that have explored how drift affects changes in the location of large-scale atmospheric circulation and the associated precipitation patterns. Understanding whether the issues related to model drift after initialization are present in, for example, global circulation and the precipitation patterns is important in order to further highlight the current discrepancies in these prediction systems and to emphasize the need for improved systems.

2. Data and Methods

The CMIP6 DCPP-A experiment consists of a large number of simulations contributed by several global modeling centers (Boer et al., 2016). We use monthly surface temperature, precipitation and zonal wind data from 11 decadal prediction systems (see Table S1 in Supporting Information S1). For most of the DCPP-A systems used here, an ensemble of 10 members is used while for some models only 8 or 9 members were available at the time of performing the analysis. For one model (i.e., CanESM5) a twenty-member ensemble is used. Different methods have been used to initialize the predictions, with some systems using full-field initialization, while others used anomaly-initialization methods. Note that for the BCC-CSM2-MR decadal predictions we were not able to obtain relevant information about the initialization method used.

All DCPP-A systems produce simulations up to 10 years after initialization; therefore, the last forecast year used here is year 10. For annual means, we use calendar years (January–December), which require discarding the first two or 3 months of data after initialization for the models initializing the predictions in November or October of the previous year. A total of 54 initializations are used, corresponding to the first forecast years from 1961 to 2014. To quantify the drift in the different climate variables, we analyze here annual mean differences between the first and last forecast years from all initialized predictions. We focus here on decadal timescales and investigate drift in temperature, large scale circulation, and precipitation patterns based on annual averages, and therefore do not take into account the fast adjustments during the first steps after initialization (e.g., Hermanson et al., 2018). The statistical significance of the mean difference is estimated based on two tailed Student's *t*-test after taking into account serial correlation using lag-1 auto-correlation.

We estimate the location of ITCZ based on annual mean precipitation centroids of the area between 20°S and 20°N. Since ITCZ has a strong seasonal variation in its location, the annual mean is not representative of its location throughout the year. Therefore we also analyze the ITCZ location and shifts during the

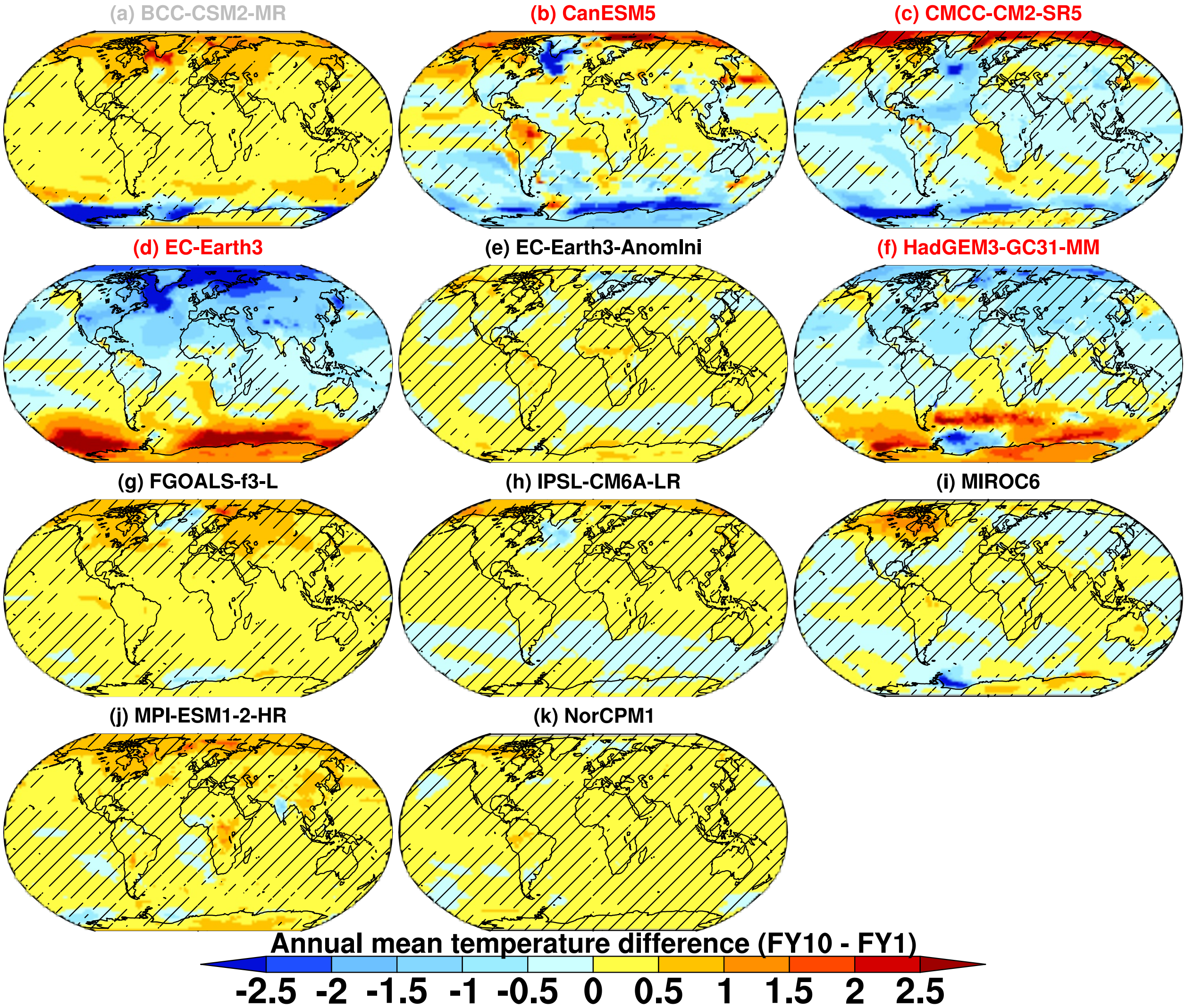

Figure 1. Climatological annual mean temperature difference between forecast years 1 and 10 (K). Hatching indicates regions where the differences are not significant at the 95% confidence level. A two-tailed Student's *t*-test is applied, after taking into account serial correlation, to estimate the significance of the mean differences. The red colored titles are for the models that are initialized using full-field initialization methods and the black colored titles indicate models that are initialized using anomaly initialization methods. The gray colored title indicates that the information about the initialization method could not be found for the model.

June–July–August (JJA) and December–January–February (DJF) seasons, when the ITCZ is at the northern and southern extremes of its annual range. Monthly mean precipitation from the European Center for Medium-Range Weather Forecast's fifth-generation global reanalysis (ERA5; Soci et al., 2024; Copernicus Climate Change Service, 2023) is used to estimate the observed ITCZ location.

3. Results

We first analyze the drift in surface air temperature in each of the prediction systems by comparing climatological means of the first and final forecast years (Figure 1). All prediction systems show temperature differences between the first and the last (tenth) forecast year in some regions, although the magnitude and spatial distribution vary among models. The largest temperature differences are found over polar regions in particular for those prediction systems that use full-field initialization methods (Figure 1). In several prediction systems, these temperature differences are asymmetrical between the Northern and the Southern hemispheres. In particular over the polar regions, some models (BCC-CSM2-MR, CanESM5, CMCC-CM2-SR5) show warming in the Arctic while cooling in the Antarctic region. Other models, in particular EC-Earth3 and HadGEM-GC31-MM, show that the later forecast years tend to be warmer in the Southern hemisphere and cooler in the Northern hemisphere. Over

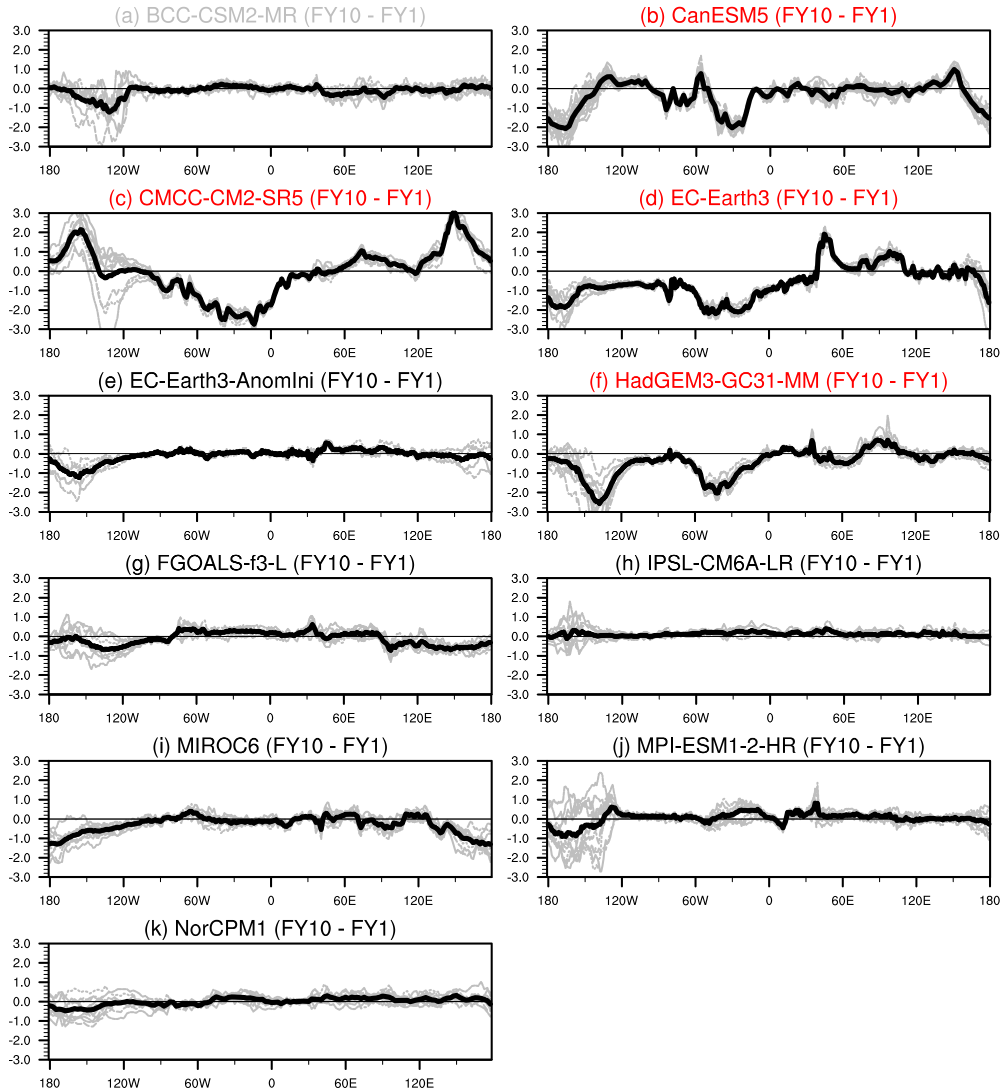

Figure 2. Change in the annual mean location of ITCZ (degrees) between forecast year 1 and 10 averaged over all initializations. The thick black line is ensemble mean while the thin gray lines represent change in individual ensemble members. The title colors are the same as in Figure 1.

the tropical Atlantic region several models show opposing temperature differences with cooling in the tropical north Atlantic and warming in the south Atlantic (e.g., Figure 1). This is likely related to less northward heat transport in later forecast years compared to the first forecast year due to drift in simulated AMOC toward lower mean state (Figure S1 in Supporting Information S1). The models that are anomaly-initialized show relatively smaller temperature differences, with statistically non-significant changes over most regions (Figure 1). Note that some small differences in temperature between forecast years 1 and 10 could be due to the nine year difference in their averaging periods when characterizing drift from all initializations. Therefore, we also analyzed temperature differences during the same averaging period (1970–2014, i.e. the period i.e. common to all initializations: 1970 being forecast year 10 of the 1960 initialization and forecast year 1 of the 1969 initialization) for both forecast years (Figure S2 in Supporting Information S1). We found overall similar results when using this climatology period with small positive temperature differences in anomaly-initialized predictions becoming even less significant while the full-initialized predictions show very similar differences as in Figure 1.

The asymmetrical changes in temperature can then lead to southward shifts in the mean location of the ITCZ (Figure 2) and precipitation patterns more broadly (Figure S3 in Supporting Information S1). These changes are strongest over ocean regions, in particular in the four models with full field initialization. The largest shifts occur in the tropical Atlantic where all four full-field initialized models show southward shifts in the ITCZ location in later forecast years (Figure S4 in Supporting Information S1). The models that are initialized using anomaly initialization do not exhibit a strong shift in the location of ITCZ between the different forecast years over most regions. However in the Pacific, some of the anomaly-initialized models also show shifts in the ITCZ location, though these changes are relatively smaller compared to the changes in full-field initialized models (Figure 2). We also performed similar analysis during the extremes of the seasonal cycle (i.e., winter and summer seasons). For the full-field initialized predictions the drift is dominated by the boreal winter season while in the anomaly-initialized predictions the differences between summer and winter is considerably small (see Figures S5 and S6 in Supporting Information S1). Nevertheless, all prediction systems exhibit model biases relative to the ERA5 reanalysis in the ITCZ latitude over the tropical Atlantic irrespective of the initialization method (Figure S4 in Supporting Information S1). For example, the observed ITCZ (based on annual mean precipitation) is located at around 2–2.5°N, while the models tend to differ in the mean ITCZ location. In several models the ITCZ is located south of the equator, which is in contrast with the northern hemispheric location of the ITCZ in the reanalysis reference. For the full-field initialized models the ITCZ location is initially closer to the reanalysis (i.e., in the first few forecast years). It then drifts toward the models' own attractor during the subsequent forecast years. No discernible drift in the ITCZ location is found in the anomaly-initialized systems, although the biases are also high in several of these prediction systems for all forecast years, including the first forecast year. The interannual variability of the model ensemble mean ITCZ latitude is smaller than the observed variability. These results therefore highlight general model deficiencies in representing the location of ITCZ in both the full-field and anomaly-initialized prediction systems. This implies that, although decadal predictions show skill in predicting precipitation in some low-latitude regions such as the western Sahel (e.g., Delgado-Torres et al., 2022), this skill may be reduced owing to the biases and drift in the ITCZ location, suggesting that the prediction skill may improve if the models could simulate these features in the correct locations.

For the models showing a southward shift in ITCZ location in the tropical Atlantic region we find that such changes are highly correlated with the temperature gradient in the tropical Atlantic (Figure 3). In particular for the four full field-initialized models (i.e., CanESM5, CMCC-CM2-SR5, EC-Earth3, and HadGEM3-GC31-MM) there is a strong correlation between the changes in sea surface temperature in the tropical Atlantic and the changes in the ITCZ location. These results suggest that the models that show larger drift in SST gradient also show stronger spatial shifts in ITCZ while the models with no drift in SST gradient also do not show a shift in the ITCZ. These findings are consistent with previous studies suggesting southwards shift of ITCZ location due to warmer SST model biases in the southern hemisphere (e.g., Lee et al., 2022).

The ITCZ location is important as it drives global circulation through convection powering the Hadley circulation, which itself connects with the Ferrel cell of the large-scale extra-tropical atmospheric circulation. Any drift in the ITCZ location would therefore plausibly affect these large-scale circulations including the upper air westerly winds (e.g., McGee et al., 2018; Watt-Meyer & Frierson, 2019). Indeed, we find that the westerly winds at 250 hPa level are also shifted southwards in later forecast years as compared to the first forecast year (Figure 4). Similar to the changes in temperature and ITCZ, zonal wind changes are also largest in the models that use the full-field initialization method (Figure 4). Notably, the strongest changes are in the location of subtropical jets over Africa and Asia with strengthening toward south of the climatological means in the later forecast years. The anomaly-initialized models show small and generally not significant differences between the forecast years except for MIROC6, which may be related to the full-field initialization of the atmospheric component of this model (Polkova et al., 2023; Tatebe et al., 2019). Any unrealistic changes in the temperature and the large-scale circulation would induce model errors that would accumulate and grow over the simulation period, rendering the subsequent predictions farther away from the mean observed climate.

The CMIP6 DCPP-A simulations are made up to 10 forecast years after initialization. However, the drift in at least some of these prediction systems can potentially continue for a much longer period than the 10 forecast years. For example, using the EC-Earth3 model, Mahmood et al. (2025) showed that the drift in near-surface air temperature and AMOC continued after forecast year 10 and stopped only after ∼22 years of initialization. Similarly Düsterhus and Brune (2024) showed that the AMOC drift in their 20-year hindcasts with the MPI-ESM-LR model does not stabilize throughout the 20-year simulations, though it significantly reduced toward the end of the hindcasts. Therefore, it is likely that the ITCZ location also continues drifting after forecast year 10 in the full-field initialized prediction systems. To test this, we take advantage of the 30-year hindcast experiment produced with the EC-Earth3 model using full-field initialization (Mahmood et al., 2025). Indeed, the ITCZ location

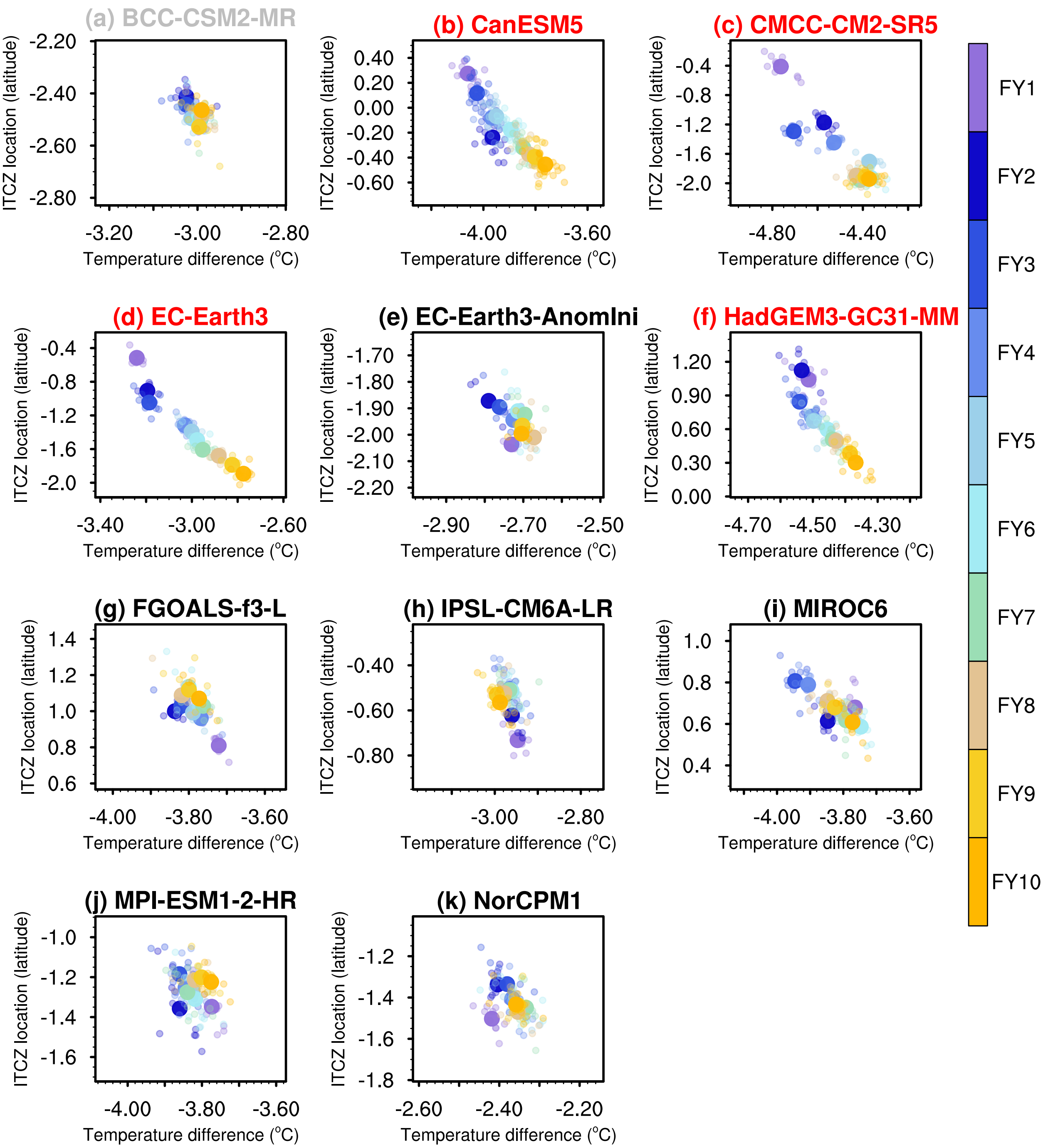

Figure 3. Comparison between annual mean location of ITCZ and the difference in sea surface temperature (°C) in tropical Atlantic regions (North Atlantic: 0–25°N, 80°W–15°E) and (South Atlantic: 0–25°S, 60°W–15°E). The temperature difference is computed as South Atlantic minus North Atlantic. ITCZ is averaged for the longitudes (80°W–15°E). Small dots represent individual ensemble members while the larger dots represent the ensemble mean. The title colors are the same as in Figure 1. Please note the different data ranges for *x* and *y* axes across the different panels. The colors represent progression of the forecast years from FY1 to FY10.

continues to shift southwards after forecast year 10 and stabilizes when the changes in SST gradients become small (Figure S7 in Supporting Information S1). However, we also note here that such changes in ITCZ location (and tropical Atlantic SST gradients) are much larger during the first decade and smaller in the second decade. As expected, we do not find significant differences during the third decade after initialization between forecast years since the drift in surface temperature and AMOC stabilizes during this decade. These results highlight further that

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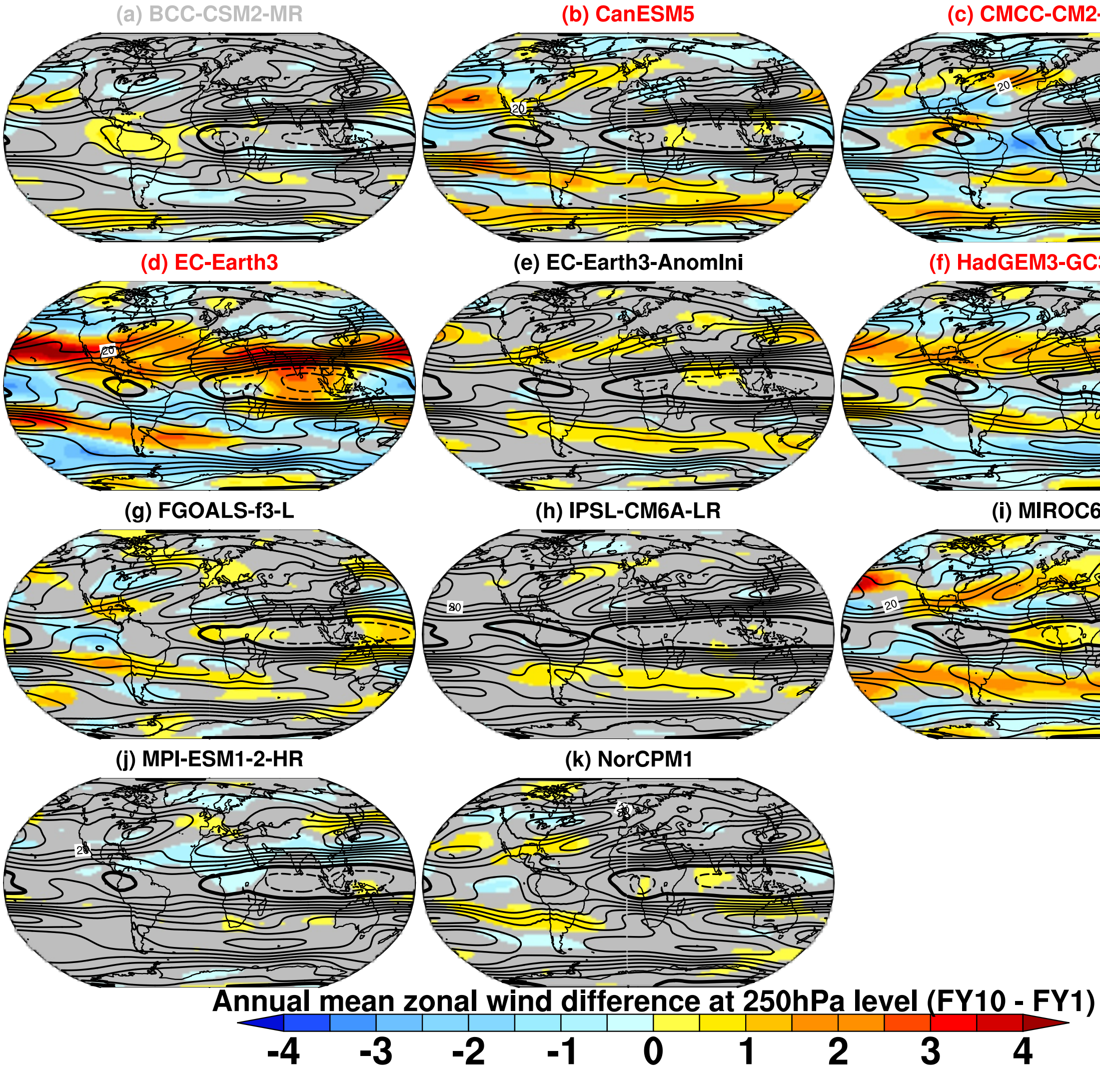

Figure 4. Climatological annual mean difference of zonal wind (m/s) at 250 hPa between forecast years 1 and 10 in color. Gray color indicates regions where the differences are not significant at the 95% confidence level. A two-tailed Student's *t*-test is applied, after taking into account serial correlation, to estimate the significance of the mean differences. The contours indicate climatological mean values of zonal wind for the first forecast year with negative values indicated by dashed line contours and 0 by the thick solid contour; contours from −10 m/s to 45 m/s in steps of 5 m/s. The title colors are the same as in Figure 1.

the climate drift in initialized predictions induces spurious changes in the circulation patterns during the evolution of the drifting forecasts and is not limited to the first 10 forecast years.

4. Discussion and Conclusions

In this study we analyzed spatial shifts in large-scale atmospheric circulation associated with the drift in ocean circulation and surface temperatures in initialized climate predictions. We focused here on initialization-related drift in surface temperature, precipitation and global circulations both in the full-field and anomaly-initialized decadal prediction systems. The drifts are found to be larger in the prediction systems using full-field initialization methods as compared to anomaly initialization, consistent with previous studies (e.g., Bilbao et al., 2021; Mahmood et al., 2025; Meehl et al., 2022; Polkova et al., 2023). The strong drift in full-field initialized predictions results in temperature asymmetries in the tropical Atlantic with cooler conditions in the north and warmer conditions in the south. As a consequence of the drift in SSTs, the ITCZ location is generally shifted southwards in later forecast years as compared to the first forecast years in the models that are initialized using a full-field initialization method. The largest drift in ITCZ is found over the tropical Atlantic and Pacific oceans. For the tropical Atlantic region, we found that the changes in the location of ITCZ are highly correlated with SST gradients in the tropical Atlantic. They are likely due to AMOC weakening as a result of the drift and less heat transport from the Southern to the Northern hemisphere in these prediction systems.

All prediction systems, irrespective of how they are initialized, show biases in the mean ITCZ location in the Atlantic region with most models simulating the ITCZ in the southern instead of northern hemisphere, which is where it is found in observations. Full-field initialization tends to reduce the location bias in the first forecast years, and the drift typically moves the ITCZ further away from the observed location (whereas in anomaly-initialized systems the location bias tends to be large from the beginning). Such spatial biases in the location of weather systems undermine the ability of the models to correctly simulate regional climate conditions and might prevent the models from correctly propagating the information in the initial conditions. Furthermore, the ITCZ being a major driver of global climate, any artificial changes in its location could then trigger spurious large-scale changes in global three-dimensional climate by, for example, changing the location of the westerly winds including the subtropical jets. For the models using full-field initialization, the subtropical jets intensify south of the mean flow in forecast year 10 compared to the first forecast year indicating southward shift of subtropical jets consistent with southward shift in ITCZ location.

These results point toward fundamental issues related to the initialization of climate model simulations and the resulting shocks and climate drifts. While using the full-field initialization can bring models' initial state closer to observations, this also leads to significant issues in representing the regional climate as the drift in the models induces spurious changes during the forecast evolution. Such signals can then propagate through the three dimensional dynamics and, therefore, some of the simulated changes may be the result of the interference of the drift in the forecasts and blur the desired response to internal variability or external climate forcings. In particular, the errors induced by the shifted location of the atmospheric circulation during the forecasts would be difficult to take into account during the post-processing methods aimed at reducing a posteriori the effect of the climate drift.

The drift in initialized climate predictions is generally corrected a posteori by removing forecast time dependent climatologies (e.g., Meehl et al., 2009) or by additional adjustments that also take into account the modeled forced response (Kharin et al., 2012). These common drift adjustment methods are typically performed at the local level at each grid cell individually, reducing some systematic errors in the climatological features and adjusting the model simulated trends. However, the shifting atmospheric circulation features with increasing forecast time would suggest that even if the climatological drift can be characterized at the local level, its causes can have a spatial component, which is not considered by current drift adjustment methods. Therefore, the drift-associated spatial shift of atmospheric circulation features pose a significant challenge for the generation of climate information because current adjustments do not ensure physical consistency of the fields. Fully adjusting for changes in certain climatological features would require to properly account for the more complex spatio-temporal aspects of the drift. Ultimately these results highlight the importance for achieving a physically balanced initialization that avoids the model drift, and for developing models that have reduced biases in key circulation features. Their combination will allow the predictions to start as close as possible from the observed state without causing drift.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

All CMIP6 data sets used in this study are freely available from WCRP data nodes (https://esgf-metagrid.cloud.dkrz.de/search). ECMWF precipitation is freely available from their website (Copernicus Climate Change Service, 2023).

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