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Current status and progress in the seasonal prediction of the Asian summer monsoon

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सार – दुनिया के सबसे अधिक आबादी वाले क्षेत्र के मानव जीवन परएशियाई ग्रीष्मकालीन मॉनसून (ASM) काफी प्रभाव डालता है। इसलिए, इसका ऋतुनिष्ठ पूर्वानुमान पृथ्वी विज्ञान में एक हाई-प्रोफाइल अनुप्रयोग है। संख्यात्मक मॉडल में क्षेत्रीय जलवायु पर वायुमंडल-महासागर परिवर्तनशीलता की जटिल अंतःक्रियाओं और इसके दूरस्थ प्रभाव को सटीक रूप से अनुकरण करने में समस्या के कारण क्षेत्रीय ASM परिवर्तनशीलता का पूर्वानुमान कौशल कॉफी समय से सीमित रहा है। यह अध्ययन वर्तमान स्थिति को अद्यतन करता है और ASM मौसमपूर्वानुमान प्रदर्शन में प्रगति का आकलन करता है। इस अध्ययन ने WCRP क्लाइमेट-सिस्टम हिस्टोरिकल फोरकास्ट प्रोजेक्ट (CHFP) और कोपरनिकस क्लाइमेट चेंज सर्विस (C3S) द्वारा संग्रहीत हिंडकास्ट डेटा में मॉडलों की दो पीढ़ियों के ऋतुनिष्ठ पूर्वानुमान कौशल का मूल्यांकन किया। अल नीनो-दक्षिणी दोलन (ENSO) और हिंद महासागर परिवर्तनशीलता से जुड़े प्रमुख टेलीकनेक्शन के प्रतिनिधित्व पर विशेष ध्यान दिया गया। यह पाया गया कि नवीनतम ऋतुनिष्ठ पूर्वानुमान प्रणाली (C3S) आमतौर पर पिछली पीढ़ी की प्रणालियों (CHFP) से बेहतर प्रदर्शन करती है, जो कि प्रेक्षित वर्षा जलवायु विज्ञान की पुनरुत्पादन क्षमता और ASM क्षेत्र में ऋतुनिष्ठ वर्षा की अंतर-परिवर्तनशीलता के पूर्वानुमान कौशल के संदर्भ में है। इसके अलावा,परिणामों से पता चला कि ASM केपूर्वानुमान कौशल में सुधार मॉडल में मॉनसून जलवायु विज्ञान और टेलीकनेक्शन के बेहतर प्रतिनिधित्व से उपजा है। ये विश्लेषण वायुमंडल-महासागर युग्मित मॉडलिंग की स्थिर प्रगति को उजागर करते हैं और ऋतुनिष्ठ ASM पूर्वानुमान में भविष्य में सुधार का वादा करते हैं।

ABSTRACT. The Asian summer monsoon (ASM) has a considerable impact on human lives in the most populated region in the world. Thus, its seasonal prediction is a high-profile application in Earth Science. However, the prediction skill of the regional ASM variability has long been limited due to a formidable difficulty in accurately simulating the complex interactions of the atmosphere-ocean variability and its remote influence on regional climate in numerical models. This study updates the current status and assesses progress in the ASM seasonal prediction performance. This study evaluated the seasonal prediction skill of two generations of models in hindcast data archived by the WCRP Climate-system Historical Forecast Project (CHFP) and Copernicus Climate Change Service (C3S). A special focus was put on the representation of the predominant teleconnections associated with the El Niño-Southern Oscillation (ENSO) and Indian Ocean variability. It was found that the latest seasonal prediction systems (C3S) generally outperform previous-generation systems (CHFP) in terms of the reproducibility of the observed precipitation climatology and the prediction skill of the interannual variability of seasonal precipitation over the ASM region. Furthermore, the results suggested that the improvement of the prediction skill of the ASM likely stems from the improved representation of the monsoon climatology and teleconnections in the models. These analyses highlight the steady progress of the atmosphere-ocean coupled modelling and promise future improvements in the seasonal ASM prediction.

Key words – Asian summer monsoon, Seasonal prediction, Atmosphere-ocean couple model.

1. Introduction

The Asian summer monsoon (ASM) is the most prominent seasonal variability on the globe. Its seasonal variability arises from the heat contrast between the land and ocean, associated seasonal evolution of convective activity and additional topographical influence (Boos and Kuang, 2013; Webster *et al*., 1998). The ASM is often subdivided in regional ASM monsoons, namely, South Asian, Southeast Asian, western North Pacific and East Asian monsoons, because of different seasonal characteristics and impacts on local climate (Wang and LinHo, 2002). Meanwhile, it is known that the regional monsoons interact with each other and share the interannual variability.

The socio-economies of Asian countries are greatly affected by the ASM (Ding, 2007; Wang, 2006). For instance, the Indian economy, in particular, rainfed agriculture depends on the year-to-year fluctuation of the monsoonal rainfall (Gadgil and Rupa Kumar, 2006). Thus, reliable outlooks of the seasonal monsoon have been anticipated and techniques for making them have been studied intensively for over a century (Blanford, 1984; Krishnamurti and Kumar, 2012; Kumar and Krishnamurti, 2012; Rajeevan *et al*., 2012; Webster *et al*., 1998; Wang *et al*., 2009).

Advances in atmospheric models and data assimilation systems in the 1990s offered a great opportunity for improved seasonal ASM prediction using atmospheric dynamical prediction, in addition to earlier statistical approaches. However, the atmospheric models adopted widely in the early stage, had a critical deficiency in the representation of atmosphere-ocean interaction, which is considered to be a pivotal process for the ASM variability and thus uncoupled atmospheric models had a limitation in predicting the interannual ASM variability (Krishna Kumar *et al*., 2005; Wang *et al*., 2005). The game-changer for seasonal ASM prediction was the introduction of atmosphere-ocean coupled models and improved ocean data assimilation systems in concert with emerging global ocean observations around the beginning of the 21st century (Stockdale *et al*., 1998; Saha *et al*., 2006; Zhu and Shukla, 2013; Takaya *et al*., 2017). Since then, an intensive effort has been made to improve the performance of coupled atmosphere-ocean prediction systems in predicting the ASM (Kim *et al*., 2012; Johnson *et al*., 2017; Rao *et al*., 2019).

In the past, a few international collaborations on the seasonal ASM prediction had been coordinated to provide a consensus view and prospects (Krishnamurti *et al*., 2006; Sperber *et al*., 2001; Rajeevan *et al*., 2012; Wang *et al*., 2009). Numerous studies have reported the skill assessment of the seasonal ASM prediction at each modelling centre (Chevuturi *et al*., 2021; Jiang *et al*., 2013; Kim *et al*., 2012; Takaya *et al*., 2017). However, a comprehensive evaluation of the skill of the seasonal ASM prediction in the latest systems from multiple major modelling centres and comparison with their predecessors have not been reported.

A newly launched initiative of the World Climate Research Programme (WCRP) Working Group on Subseasonal to Interdecadal Prediction (WGSIP) "Prediction capability" revisited the prediction capability of the monsoon as a part of its activity. The purpose of this paper is to update the current status and progress in the last decade of the seasonal ASM prediction using data archives of the seasonal hindcasts of multiple models with the aid of international research collaboration.

2. Data and methodology

We used two sets of hindcast data of multiple seasonal prediction systems freely available from the data archives, CHFP (Tompkins *et al*., 2017) and C3S (Brookshaw, 2017). The CHFP dataset was obtained from a data archive hosted by the Centro de Investigaciones del Mary la Atmósfera (CIMA; http://chfps.cima.fcen.uba.ar/). The C3S seasonal hindcast data were obtained from a data archive of C3S (https://climate.copernicus.eu/seasonal-forecasts). We evaluated hindcasts (retrospective forecast) for boreal summer (June-August) with approximately one month lead. Specifications of the hindcast data analysed in this study are summarised in Table 1. The CHFP archive includes models developed in the late 2000s, on the other hand, the C3S archive contains the latest models. Therefore, by comparing these two generations models, we can address the progress of the prediction capability in the past decade.

For the verification, we used monthly precipitation analysis of the Global Precipitation Climatology Project (GPCP) version 2.3 (Adler *et al*., 2018). We also used monthly SST analysis of the Centennial in situ Observation-Based Estimates (COBE-SST; Ishii *et al*., 2005). All the hindcast data and analysis data were interpolated to 2.5 × 2.5 degrees grids.

A temporal anomaly correlation coefficient between the ensemble mean prediction and the observation was used to evaluate the seasonal prediction skill. In order to compare the prediction skill of different models with different ensemble sizes, we adjusted the correlation skill to reflect the effect of the ensemble size on the prediction scores. Specifically, we assessed the expected temporal correlation coefficients with an ensemble size (C_{∞}) using Murphy's equation under the perfect model assumption

TABLE 1

Specifications of the seasonal prediction models analysed in this study

Data archive	Institution	Model/ system name	Model/system short name	Hindcast period	Ensemble size	Reference
CHFP	CAWCR	POAMA Version 2.4a	POAMA2a	1980-2009	10	Cottrill *et al*. (2013)
CHFP	CAWCR	POAMA Version 2.4b	POAMA2b	1980-2009	10	Cottrill *et al*. (2013)
CHFP	CAWCR	POAMA Version 2.4c	POAMA2c	1980-2009	10	Cottrill *et al*. (2013)
CHFP	CCCma	CMAM	CMAM	1979-2008	10	Scinocca *et al*. (2008)
CHFP	CCCma	CMAMlo	CMAMlo	1979-2008	10	Sigmond *et al*. (2008)
CHFP	CCCma	CCCma-CanCM3	CanCM3	1979-2008	10	Merryfield *et al*. (2013)
CHFP	CCCma	CCCma-CanCM4	CanCM4	1979-2008	10	von Salzen *et al*. (2013)
CHFP	ECMWF	ECMWF System 4	EC-Sys4	1981-2009	15	Molteni *et al*. (2011)
CHFP	JMA	JMA/MRI-CPS1	CPS1	1979-2009	10	Takaya *et al*. (2017)
CHFP	JMA	JMA/MRI-CPS2	CPS2	1981-2009	10	Takaya *et al*. (2018)
CHFP	Meteo France	ARPAGE	ARPAGE	1979-2007	10	
CHFP	Met Office	GloSea4L85	GloSea4	1989-2009	9	Fereday *et al*. (2012)
CHFP	Met Office	GloSea5	GloSea5	1996-2009	24	MacLachlan *et al*. (2015)
CHFP	MPI	MPI-ESM-LR	MPI-ESM	1982-2009	9	Baehr *et al*. (2015)
CHFP	NOAA	CFSv1	CFSv1	1981-2007	7	Saha *et al*. (2006)
CHFP	Univ. Tokyo, JAMSTEC, NIES	MIROC5	MIROC5	1979-2009	8	Watanabe *et al*. (2010)
C3S	CMCC	SPS3	SPS3	1993-2016	40	Sanna *et al*. (2017)
C3S	CMCC	SPS3.5	SPS3.5	1993-2016	40	Gualdi *et al*. (2020)
C3S	DWD	GCFS2.0	GCFS2.0	1993-2016	30	Fröhlich *et al*. (2021)
C3S	DWD	GCFS2.1	GCFS2.1	1993-2016	30	
C3S	ECMWF	System 5	EC-Sys5	1993-2016	25	Johnson *et al*. (2019)
C3S	JMA	JMA/MRI-CPS2	CPS2	1993-2016	10	Takaya *et al*. (2018)
C3S	Météo France	System 6	MF-Sys6	1993-2016	25	Dorel *et al*. (2017)
C3S	Météo France	System 7	MF-Sys7	1993-2016	25	Batté *et al*. (2019)
C3S	Met Office	GloSea6	GloSea6	1993-2016	28	Williams *et al*. (2017)
C3S	NOAA	CFSv2	CFSv2	1993-2016	24	Saha *et al*. (2014)

(Murphy, 1988). Using the expectation of the single member correlation skill C_1, the expectation of the correlation skill of the M-member ensemble mean hindcasts (C_M) is written as follows (Eqn. 9 in Murphy 1988).

$$C_M = \sqrt{M}\,C_1 / \sqrt{1+(M-1)C_1}. \tag{1}$$

According to Equation (1), the skill dependency on the ensemble size is relatively large, in particular, in a relatively small ensemble size (< 15). Based on Equation (1), the single member correlation skill C_1 can be estimated from C_M (correlation score with the available M-members). Moreover, C_∞ is given as $\sqrt{C_1}$ as a limit of $M \to \infty$ (Eqn. 1). In this way, we can compute C_∞ from

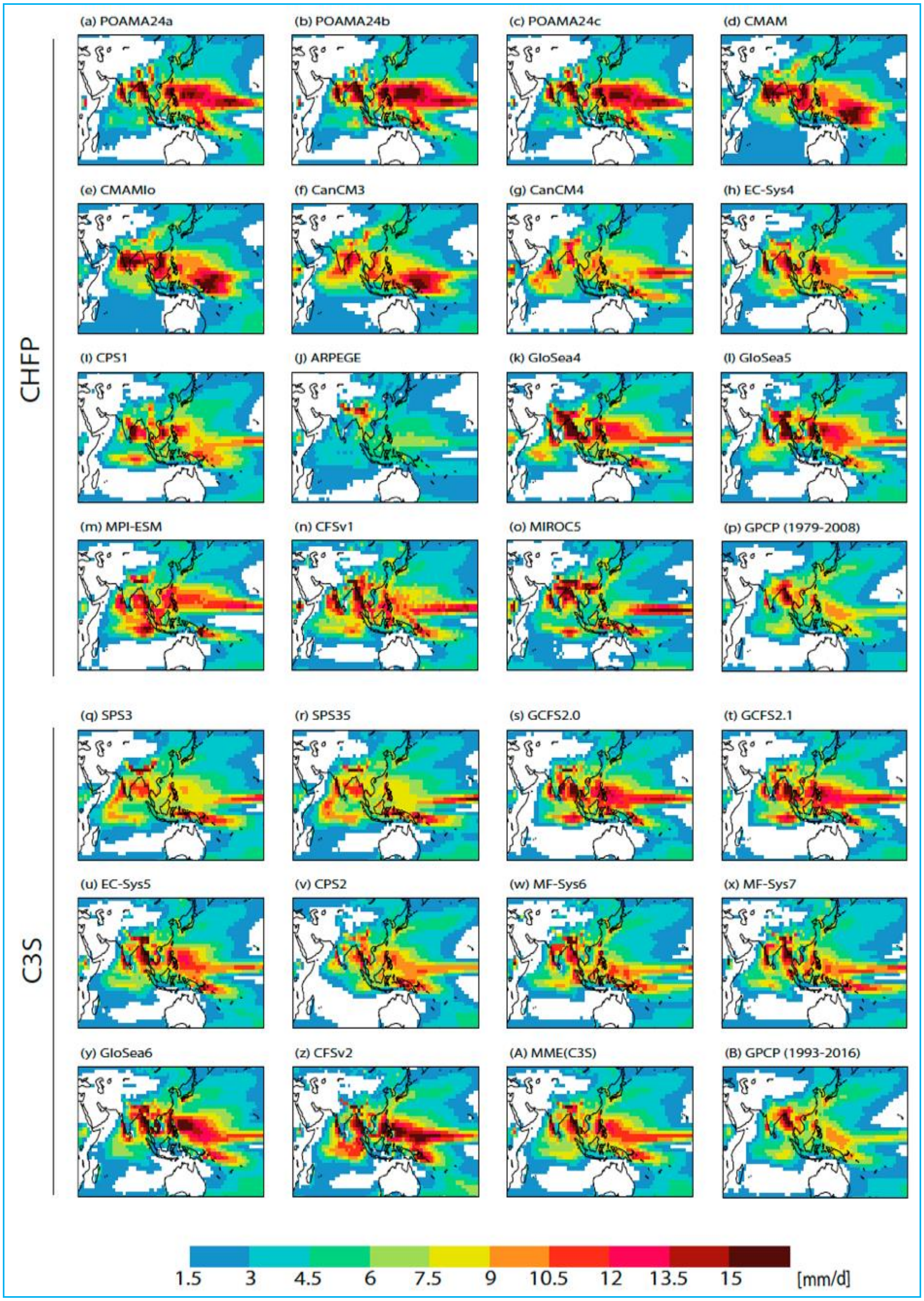

Fig. 1. The precipitation climatology during June-August in seasonal prediction models. The model names and averaging periods are listed in Table 1. The multi-model ensemble (MME) of the C3S models is a so-called poor-person ensemble, which is the simple multi-model average of the climatology of each model

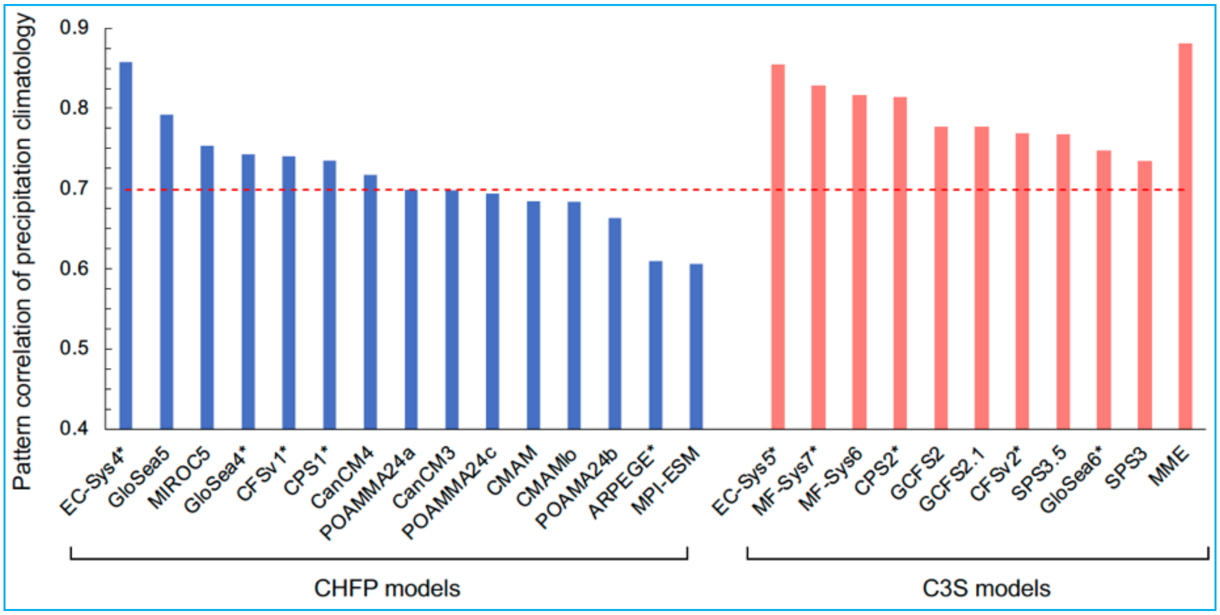

Fig. 2. Pattern correlations between the observed precipitation climatology and predicted climatology of each model over the ASM region (40° N-10° S, 40° E-180°). Analyzed periods vary depending on the data availability of each model (Table 1). The red dashed line indicates the median of the correlations of the CHFP models. The asterisks indicate the selected models for the comparison of the same operational centers

C_M. Please note that if C_M is negative, C_∞ cannot be computed, in such a case, we let $C_\infty = 0$ in the analysis of this study.

3. Results and discussion

3.1. *Representation of the climatological mean precipitation in boreal summer*

The representation of the mean climate is considered to be one of the important factors for producing the skillful seasonal prediction of the ASM (Lee *et al.*, 2010). Fig. 1 compares the climatological spatial distributions of predicted precipitation in each model during boreal summer (June-August). The lead time is about one month for all model predictions. Averaging periods (hindcast periods) vary depending on the data availability, however, the observed climatology does not change much for the different hindcast averaging periods of each model (Table 1). Thus, we can compare the model performance in representing the climatological precipitation. The seasonal prediction models capture the overall characteristics of the observed distribution such as a large amount of precipitation over the tropical Indian Ocean (Bay of Bengal) and the tropical western North Pacific east of Philippine and the South China Sea.

Fig. 2 presents pattern correlations between the observed precipitation climatology and predicted climatology of each model over the ASM region (40° N-10° S, 40° E-180°; Fig. 3). Throughout this study, we selected the broad region covering Asia as well as the Indo-western Pacific since the interannual precipitation variability over the region is closely associated with the large-scale monsoon variability. For computing the pattern correlation, we used the observed climatology corresponding to the hindcast periods of each model. Pattern correlations of the climatological precipitation over the ASM region exceed 0.8 in some models. We found that the latest models (C3S) have a higher ability to

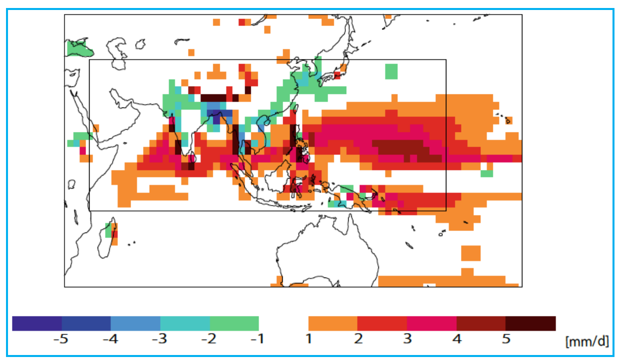

Fig. 3. A geographical bias of the MME-mean precipitation climatology in boreal summer during 1996-2016 in the latest C3S models (SPS3.5, GCFS2.1, EC-Sys5, CPS2, MF-Sys7, GloSea6, CFSv2). The MME mean climatology was computed as the average of the model climatology of each model. The MME mean climatology was compared to the climatology of GPCP v2.3 precipitation analysis. The box indicates the ASM region (40° N-10° S, 40° E-180°)

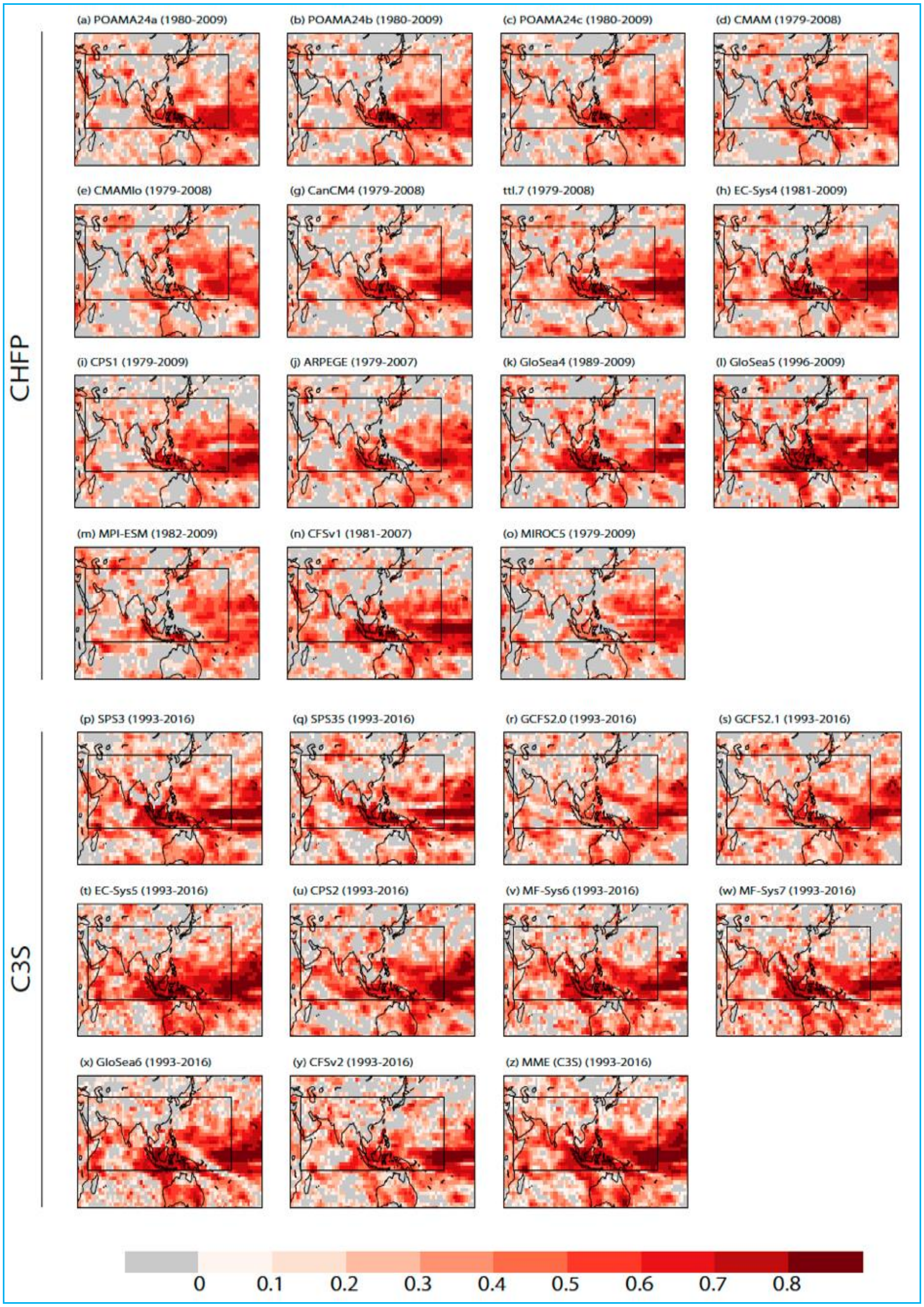

Fig. 4. Pointwise temporal correlations of June-August precipitation for (a-o) CHFP and (p-y) C3S models. The estimates of the correlation with the infinite ensemble size (C_∞) are presented. (z) C3S MME presents the correlation skill of the multi-model mean using all the available ensemble members, not the correlation with the infinite member

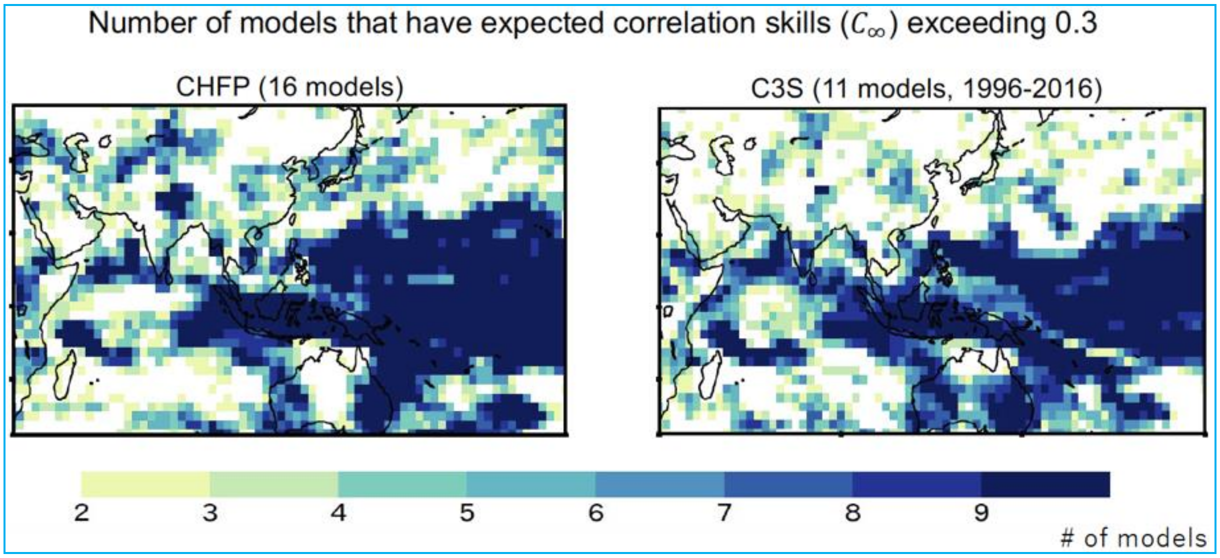

Fig. 5. Predictable regions of seasonal precipitation of the ASM. The number of models that have expected correlation skills (C_∞) exceeding 0.3

reproduce the climatological pattern of observed precipitation compared with the models a decade ago (CHFP). Almost all of the C3S models have higher pattern correlations than the median of correlations of the CHFP models. Since participating modelling centres are different for CHFP and C3S and the CHFP data archive include more recent models, it may not be fair to compare with each other. To make a fairer comparison, we compared five common operational centres in both the data archives, namely, the European Centre for Medium-Range Weather Forecasts (ECMWF), Japan Meteorological Agency (JMA), Meteo France, Met Office, National Oceanic and Atmospheric Administration (NOAA). We found that almost all the models present the increase of the pattern correlations except that the ECMWF models have comparable and high correlations in both the versions in CHFP and C3S. The result basically highlights a decade of progress in the model performance in replicating the precipitation climatology.

We also evaluated C3S model biases of the climatological precipitation in boreal summer during 1996-2016 (Fig. 3). We see a typical bias pattern in the C3S MME, for example, positive rainfall biases over the tropical western North Pacific and North Indian Ocean and negative rainfall biases around coastal East Asia and South Asia. This pattern is commonly seen in models of the Coupled Model Intercomparison Project Phase 5 (CMIP5) and Phase 6 (CMIP6) and persistently exists in seasonal forecasting models (Sperber *et al*., 2013; Rejeevan *et al*., 2012; Choudhury *et al*., 2022; Davis *et al*., 2017). This indicates that further model improvements are anticipated although we observed the steady progress in Fig. 3.

3.2. *Seasonal prediction skill of precipitation in boreal summer*

This study evaluated the prediction skill of June-August mean precipitation. Because some models have a small ensemble size of hindcasts in the CHFP and C3S archives, we investigated deterministic scores of the temporal correlation between the ensemble mean predictions and observations for each model. We compared temporal correlations after adjusting them considering the available ensemble size. Specifically, we computed expected correlations forthe infinite ensemble size following the equation (Eqn. 9) of Murphy (1988) as described in Section 2.

Fig. 4 displays the estimate of the temporal correlation skill with the infinite ensemble size for all the models of the CHFP as well as C3S data archives. Patterns of the correlation skill are roughly consistent among the models with higher correlations over the tropical Pacific and around the Maritime Continent than other regions. The higher correlations result from the stronger influence of ENSO on the seasonal precipitation variability (Wang, 2020). In contrast, correlations are relatively low over the continents, although there are some notable predictable regions. We will elaborate on remote drivers of the seasonal precipitation variability that bring the seasonal predictability of precipitation in Section 3.4. Fig. 5 highlights the potentially predictable regions, which include the tropical western North Pacific, the Maritime Continent, Arabian Sea, eastern and western Indian Ocean, Ganges region, south part of Indian Peninsula, Central China-Japan (Meiyu-Baiu region), coastal regions

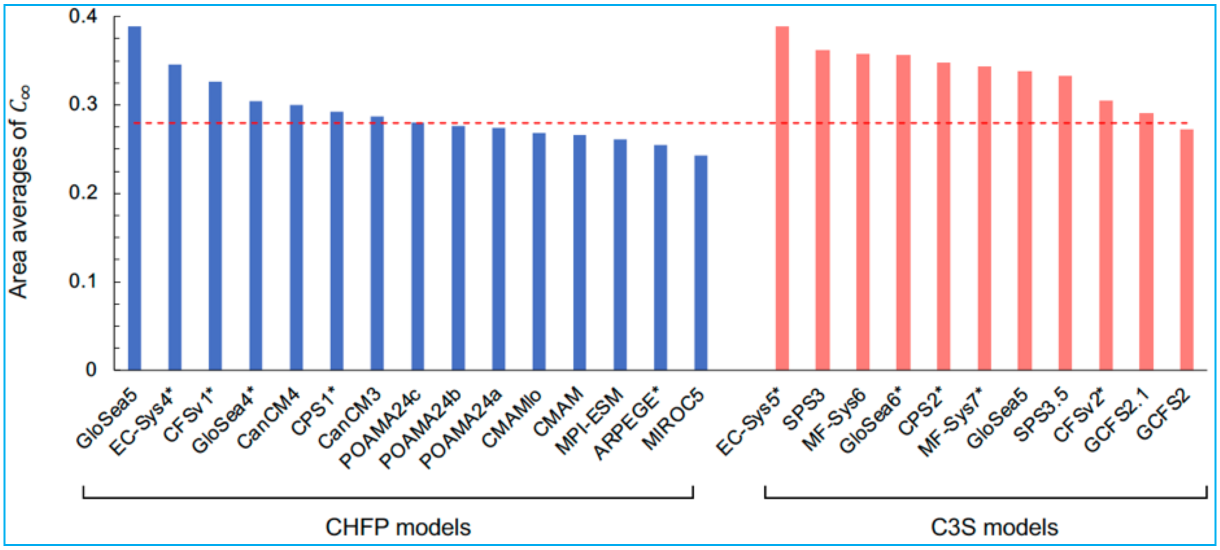

Fig. 6. Comparison of the estimated maximum prediction skill of the ASM precipitation during summer (June-August). The area average of temporal correlations (the estimated skill with infinite members) for June-August precipitation over the ASM region (40° N-10° S, 40° E-180°). The red dashed line indicates the median of the correlations of the CHFP models. The asterisks indicate the selected models for the comparison of the same operational centers

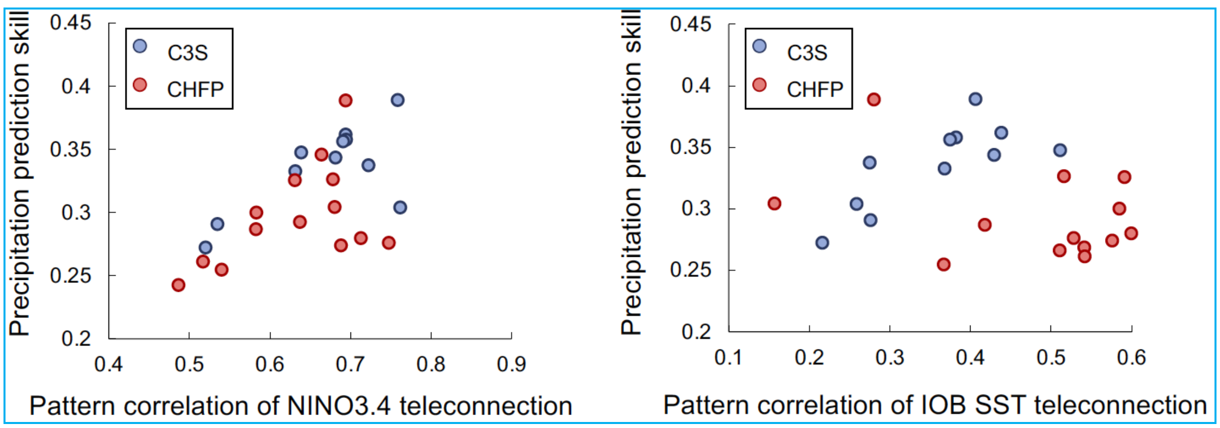

Fig. 7. Relationship between the ASM precipitation prediction skill and representation of the teleconnections. The *Y* axis indicates the area average of temporal correlations (the estimated skill with infinite members) for June-August precipitation over the ASM region (40° N-10° S, 40° E-180°). The X axis indicates the uncentered pattern correlation between the observed and predicted regressed patterns of June-August precipitation against (left) NINO3.4 (5° N-5° S, 170° W-120° W) and (right) Indian Ocean basin (20° N-20° S, 40° E-100° E) SSTs

of Indochina Peninsula. These results are consistent with the potential predictability and prediction skill highlighted by some previous studies (Martin *et al*., 2020; Rajeevan *et al*., 2012; Takaya *et al*., 2021; Wang *et al*., 2009). It is emphasised that, even in the latest (C3S) models, not all the models present a noticeable potential prediction skill over Asian land regions such as Central China (Meiyu region), Ganges region and coastal regions of Indochina Peninsula, indicating more improvements are anticipated for the further use of the seasonal ASM predictions over Asia.

Fig. 6 summarises the prediction skill (temporal correlations averaged in the ASM region) for June-August mean precipitation. The result indicates that the latest models (C3S) have a higher ability to predict the interannual variability of precipitation over the ASM region than the CHFP models that are previous generation models a decade ago. We found that almost all the C3S models have higher average correlations than the median of the CHFP models. Again, to make a fairer comparison, we compared five common modelling centres, namely, Meteo France, JMA, ECMWF, Met Office and NOAA.

We found that almost all of the models display higher averaged skill except for NOAA. Thus, the added value of C3S over CHFP is visible in this comparison as well.

3.3. *Relationship between the prediction skill and representation of the precipitation climatology and teleconnections*

Previous studies have identified the key drivers for the interannual variability of the ASM. They include ENSO (Wang *et al*., 2020), Indian Ocean-western Pacific Capacitor (IPOC; Xie *et al*., 2016; Kosaka *et al*., 2013) and Indian Ocean Dipole (or its atmospheric manifestation of the equatorial Indian Ocean oscillation; EQUINOO; Gadgil *et al*., 2004). For instance, monsoon season (June-September) precipitation over India is predominantly affected by SST in the equatorial Pacific (ENSO) and North Indian Ocean and South China Sea (IPOC) (Mishra *et al*., 2012). We performed a Singular Vector Decomposition (SVD) analysis similar to that was done by Mishra *et al*. (2012) and confirmed that ENSO and IPOC are two dominant coherent modes for the ASM precipitation in June-August (figure omitted).

Considering the dominant coherent modes, we attempted to relate the prediction skill of the ASM precipitation and representation of the teleconnections to the dominant coupled climate variability. In Fig. 7, the prediction skill of ASM precipitation is represented by the area average of temporal correlations (the estimated skill with infinite members) for June-August precipitation over the ASM region (Fig. 6). The representation of the teleconnections was assessed by the uncentered pattern correlation (*i.e*., without the spatial average of each field subtracted) between the observed and predicted regressed patterns of June-August precipitation against SSTs in (left) NINO 3.4 (5° N-5° S, 170° W-120° W) region and (right) Indian Ocean basin (IOB; 20° N-20° S, 40° E-100° E). In the left panel of Fig. 7, we see the moderate correlation between the prediction skill and the representation of the NINO3.4-SST (ENSO) teleconnections in both the C3S and CHFP models. It is noted that some CHFP models present lower pattern correlations of the ENSO teleconnection than C3S models. For the IOB-SST teleconnection (the right panel of Fig. 7), we see a moderate correlation in the C3S models, but no clear correlation is observed in the CHFP models. It is noteworthy that the results of C3S models, which generally have a better representation of the teleconnections and prediction skill, display better correspondence between the fidelity of the representation of the teleconnections and prediction skill. The result of the IOB-SST teleconnection supports a recent argument that the IOB SST is a key driver of the ASM precipitation variability, thus, an important source of the seasonal ASM predictability (Chowdary *et al*., 2019; Kosaka *et al*., 2013; Takaya *et al*., 2021). In short, the skill difference is, to some extent, attributable to the ability or lack thereof to represent the ENSO-rainfall teleconnection, implying that improving the representation of the atmosphere-ocean coherent variability and teleconnections to the key SST variability is instrumental for achieving better prediction skill of the seasonal ASM prediction. However, it is noted that, since the remote influence of ENSO and IOB may vary in a decadal timescale and may depend on the analyzed hindcast periods, further investigation may be required to conclude this point.

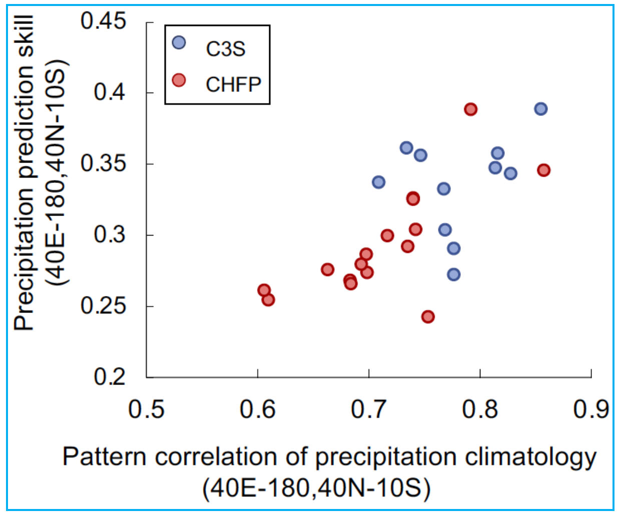

Fig. 8. Relationship between the ASM precipitation prediction skill and representation of the climatological distribution of June-August precipitation over the ASM region (40° N-10° S, 40° E-180°). The *Y* axis indicates the area average of temporal correlations (the estimated skill with infinite members) for June-August precipitation. The *X* axis indicates the pattern correlation between the observed and predicted climatological precipitation patterns for June-August

Lastly, we examined the relationship between the ASM precipitation prediction skill and representation of the climatological distribution of June-August ASM precipitation. In general, better representing the observed climatological states (reducing the model bias) is considered to be favourable for better representing the variability as well (Lee *et al*., 2010). As we saw in Sub-section 3.1, the latest models have a higher capability in replicating the observed climatological states. It is interesting to see how the models' representation of the climatology is associated with the prediction skill. Fig. 8 presents the relationship between the models' representation of the ASM precipitation climatology and the prediction skill of the ASM precipitation. Combining the CHFP and C3S models, it was found that the fidelity in replicating the ASM precipitation climatology is associated with the interannual prediction skill of the ASM precipitation. The C3S models have generally higher performance in both the measures. Thanks to the analysis using a large number of prediction models participating in the international comparisons, now we are able to affirm the importance of better representing the climatology for improving the seasonal prediction skill of the ASM.

4. Conclusions

This study has updated the current status and assessed progress in the prediction capability of the interannual ASM variability as a part of the WGSIP project "the Predictive Capability". We analysed a set of hindcast data provided from the WCRP Climate-system Historical Forecast Project (CHFP) and Copernicus Climate Change Service (C3S). These data archives are assets that enable us to evaluate and review the progress of the seasonal ASM forecasting in the past 20 years and to provide prospects for the future developments.

It was found that the latest C3S overall outperformed previous-generation systems (CHFP) in terms of replicating the observed climatology of the ASM precipitation and predicting its interannual variability. In other words, with the aid of a large number of the models, we witnessed the steady progress of the modelling for the seasonal prediction of the ASM. This study focused on the representation of the dominant coherent atmosphere-ocean variability and their teleconnections of the ASM. Our analysis highlighted the importance of better replicating teleconnections associated with the key drivers (the equatorial Pacific and tropical Indian Ocean) for improving the seasonal prediction of the ASM though primary regional circulation patterns with high predictability that play key roles in bridging those oceanic drivers with the ASM precipitation (Zhou *et al*., 2020). In addition, our results also suggested the importance of improving the model ASM climatology. In the 1990s, it was considered that the seasonal prediction of the ASM was difficult to make. However, with the steady model improvements, the state-of-the-art models now have improved capability in predicting the complex climate variability of the ASM and producing the meaningful forecasts.

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Author statement

All authors declare that the research was conducted in the absence of any commercial or financial relationships that may have an interest in the submitted work.

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