

Statistical-Dynamical Seasonal Forecasts of Central Southwest Asia winter precipitation*

MICHAEL K. TIPPETT

LISA GODDARD

ANTHONY G. BARNSTON

International Research Institute for Climate Prediction, Palisades, New York

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Abstract

Central Southwest (CSW) Asia recently experienced four years (winter of 1998-99 to 2001-02) of severe drought. Interannual precipitation variability in the region has been associated with East Asia Jet Stream variability and Western Pacific tropical convection. However, atmospheric general circulation models (AGCMs) forced by observed sea surface temperature (SST) poorly simulate the region's interannual precipitation variability. The statistical-dynamical approach uses statistical methods to correct systematic deficiencies in the response of AGCMs to SST forcing. Statistical correction methods linking model-simulated Western Pacific precipitation and observed CSW Asia precipitation result in modest, but statistically significant, cross-validated simulation skill over the period 1951-1998. The statistical-dynamical method is also applied to recent (winter 1998-99 to 2002-03) multi-model, two-tier December-March precipitation forecasts initiated in October. Tercile probability forecasts are produced using the ensemble mean forecasts and forecast error estimates. The statistical-dynamical forecasts show enhanced probability of below normal precipitation for the four drought years and capture the return to normal conditions in part of the region during the winter of 2002-2003.

May Kabul be without gold, but not without snow.

—Traditional Afghan proverb.

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1. Introduction

Prediction of climate anomalies on seasonal-to-interannual time-scales is practical in regions and seasons where predictable boundary conditions (e.g., land surface properties and sea surface temperature; SST) lead to predictable changes in seasonal weather statistics (Goddard et al. 2001). Temperature and precipitation anomalies directly affect society and are of particular interest. The outstanding example of predictable boundary conditions are SST anomalies associated with ENSO, and many areas of the world exhibit significant temperature and precipitation responses to these SST anomalies (Ropelewski and Halpert 1987; Mason and Goddard 2001).

A variety of methods are used to make seasonal forecasts. In the one-tier approach, coupled atmosphere-ocean models predict future boundary conditions and climate anomalies from present conditions. In the two-tier approach, SST is first predicted and that predicted SST is the basis for predicting climate anomalies. The prediction of Central Southwest (CSW) Asia winter precipitation anomalies given SST predictions is the general subject of this paper.

Dynamical and statistical methods can be used to describe the effect of SST on the climate system. However, both approaches have shortcomings. Dynamical models, in particular atmospheric general circulation models (AGCMs), are based on physical laws of nature but are unable to resolve all spatial and temporal-scales. Inaccurate AGCM parameterizations of unresolved processes such as convection lead to errors in predicting the climate response to SST anomalies. Statistical methods such as regression predict the climate response to SST anomalies based on the historical record. However, the shortness and quality of the climate record limit accuracy, and stationarity of the climate is a further complicating issue.

Recently dynamical and statistical methods have been combined to compute the climate response to SST forcing (Smith and Livezey 1999; Feddersen et al. 1999; Mo and Straus 2002; Tippett et al. 2003; Widmann et al. 2003). The statistical-dynamical approach is in the spirit of

model output statistics (MOS) where systematic errors of the dynamical model are identified and corrected. Multivariate MOS correction involves identifying model patterns that are related to observed patterns and replacing model patterns with observed ones. The MOS correction may effectively only make minor shifts or rotations of model output when model deficiencies are minor. In these cases, *local* model information is sufficient to perform the MOS correction. For instance, AGCM simulation of seasonal rainfall anomalies in the Northeast of Brazil is skillful, and model simulated precipitation over the Northeast of Brazil provides sufficient information for MOS corrections to improve details of model precipitation patterns. In other cases AGCM precipitation simulation deficiencies require using other model variables, for instance geopotential height, in the MOS correction (Landman and Goddard 2002). More severe AGCM errors may result in a complete failure of the model to reproduce large-scale teleconnection patterns seen in observations. If the model reproduces some component of the large-scale SST response, MOS corrections may be feasible. In these cases, use of spatially remote model variables and model variables other than the target variable may be required. An example is the use of spatially remote model simulated precipitation to estimate winter precipitation in the CSW Asia region (Tippett et al. 2003). The multi-model application of the statistical-dynamical method to wintertime precipitation over the CSW Asia region, with emphasis on forecast performance during the past five winters (1999-2003), is the subject of this paper.

Much of CSW Asia, including parts of Iran, Afghanistan, Turkmenistan, Uzbekistan, Tajikistan and Pakistan, has a semi-arid climate. The region lies beyond the usual reach of the Indian Monsoon, and instead receives most of its annual precipitation during winter and early-spring in the form of snow along the high elevation of the region (Martyn 1992). This precipitation, associated with eastward-propagating mid-latitude cyclones, displays considerable interannual variability. The recent drought (1999-2002) was the worst in fifty years and had a severe impact on agricultural production and livestock populations (Agrawala et al. 2001; Barlow et al. 2002).

An indication of the role of SST forcing in the recent drought is found in a modeling study where several AGCMs forced by observed SSTs reproduced features of the 1998-2002 drought (Hoerling and Kumar 2003). However, AGCM simulations of the period prior to the recent drought show little skill in simulating CSW Asia seasonal precipitation anomalies, and we must rely heavily upon the observational record to elucidate connections between CSW Asia precipitation and SST. The classical ENSO response does not include the CSW Asia region (Ropelewski and Halpert 1987, 1989). However, Mason and Goddard (2001) did find that enhanced frequency of above normal precipitation in Southwest Iran is associated with La Niña conditions which is in contrast with the work of Barlow et al. (2002) that linked the La Niña episode of 1998-2002 with the severe drought in CSW Asia. Barlow et al. (2002) also found that ENSO events with stronger Western Pacific SST anomalies were associated with precipitation patterns similar to those observed during the recent drought period, suggesting that details of the basin-wide ENSO pattern can effect different impacts over the CSW Asia region. The variation between one ENSO event and another could be expected to produce different atmospheric responses, and modeling studies have computed the sensitivity of the atmospheric circulation to the location of tropical heating (Sardeshmukh and Hoskins 1988; Ting and Sardeshmukh 1993; Hoerling and Kumar 2002; Barsugli and Sardeshmukh 2002). However, model deficiencies can obscure sensitivities in the observed physical climate system. Ting and Sardeshmukh (1993) highlight how slight differences in the mean circulation can strongly affect the extratropical response to tropical heating. Also in Kidson et al. (2002), cluster analysis of OLR data was used to classify different types of ENSO warm-events, identifying the western extent of SST anomalies as a distinguishing feature. However, in the same study, an AGCM was unable to differentiate between the climate responses associated with the different warm event SST types types.

An observation study by Lau and Boyle (1987) noted different circulation responses to western Pacific/Maritime Continent and central Pacific OLR anomalies, finding that Maritime continent

OLR anomalies had more effect on the circulation over Asia than did OLR anomalies in the central Pacific. A dominant feature of the wintertime circulation over Asia is the upper-tropospheric westerly jet stream over subtropical east Asia and the western Pacific, referred to as the East Asia Jet Stream (EAJS). Using composite analysis, Lau and Boyle (1987) found that enhanced EAJS strength was associated with enhanced Maritime continent convection. Maritime Continent convection influences the EAJS through the local Hadley circulation (Chang and Lau 1982; Chang and Lum 1985; Lau and Boyle 1987). Enhanced Maritime Continent convection leads to upper level divergence and southerly flow into the subtropical Northern Hemisphere. The resulting westerly flow near the EAJS exit region, due to Coriolis effect, intensifies the EAJS. Yang et al. (2002) found EAJS strength to be positively correlated with precipitation anomalies in the Maritime Continent and western Pacific regions. Additionally, they found EAJS strength to be uncorrelated with ENSO. They also found significant negative correlations between EAJS strength and precipitation anomalies on the east coasts of Asia and the United States, as well as southeast of the Ural mountains. A possible explanation for the association between EAJS strength and CSW Asia precipitation is that the dominant mode of variability of observed (Reanalysis) upper-level winds indicates EAJS strengthening is accompanied by a southward shift of the jet maximum and northeasterly flow anomalies over the CSW Asia region (Tippett et al. 2003). The negative correlation between EAJS strength and CSW Asia precipitation means that southwesterly flow anomalies over the CSW Asia region are associated with enhanced upslope precipitation.

Tippett et al. (2003) found that poor ECHAM 4.5 simulation of EAJS variability precluded using upper-level model winds as a predictor for CSW Asia precipitation. The difficulty some AGCMs have in simulating EAJS variability may be a factor in the poor simulation of CSW Asia precipitation. However, statistical corrections using ECHAM 4.5 precipitation in the Western Pacific and Maritime Continent region were shown to give statistically significant simulation skill (Tippett et al. 2003). In the present work we apply this method to the ECHAM 4.5 and four ad-

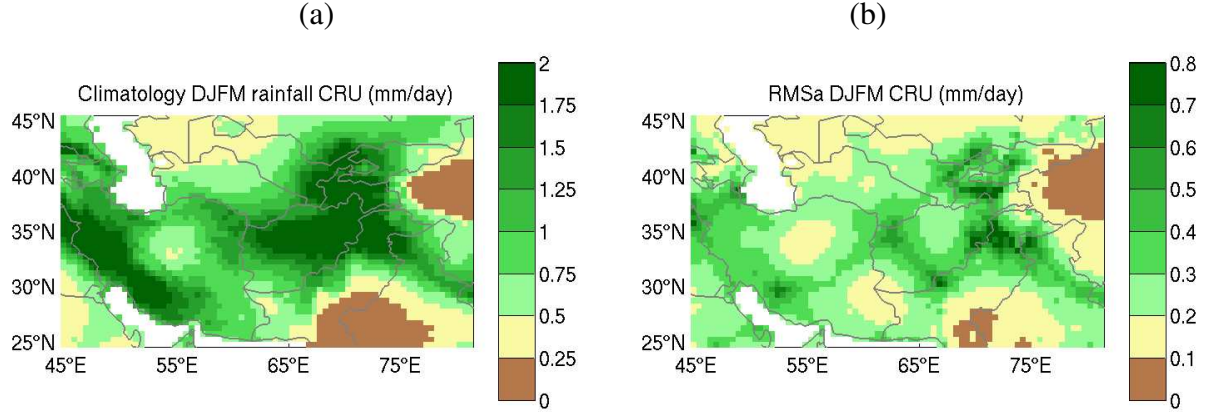


Figure 1. (a) Climatological and (b) root-mean-square anomaly of the DJFM precipitation 1951-1998 ($0.5^\circ \times 0.5^\circ$ resolution).

ditional AGCMs and obtain an estimate of simulation skill. We also use the corrections to make retrospective statistical-dynamical forecasts based on operational two-tier IRI AGCM forecasts of December-March (DJFM) precipitation anomalies for the last five years (1999-2003); the AGCM forecasts use SST predicted the preceding October. Simulation skill is used to estimate forecast uncertainty and produce probability forecasts.

2. Data and methods

a. Observations

Precipitation observations used to compute skill and statistical corrections are taken from the extended New et al. (2000) gridded dataset of monthly precipitation for the period of 1950 to 1998, giving 48 DJFM seasons. This dataset is based on station observations interpolated to a $0.5^\circ \times 0.5^\circ$ lat-lon grid. A low-resolution version of this dataset interpolated to a T42 grid is used for the calculations here unless otherwise noted.

DJFM CSW Asia climatological precipitation and its variability, shown in Fig. 1, are closely related to the elevation of the region. Climatological precipitation follows the principal mountain

ranges of the region: the Zagros, Himalaya, Karakorum, and Hindu Kush. Precipitation variability shown in Fig. 1(b) separates into two geographical regions. One accompanies the Zagros mountain range along the Southwest border of Iran. Another region of precipitation variability is found where the borders of Afghanistan, Pakistan and Tajikistan meet in the Hindu Kush mountain range. The correlation between box averages over the SW and NE regions is 0.34, suggesting only a weak statistical relation between the precipitation variability of the two regions over the entire period; both regions did experience drought during 1970-71 and 1999-2002. Neither region is significantly correlated with the NINO3 SST index (the average SST over the region 5°S to 5°N, 90°W to 150°W).

The CAMS-OPI precipitation dataset, which includes satellite observations, is used to examine qualitative precipitation features for the period 1999-2003 as shown in Fig. 2 (Janowiak and Xie 1999). The general features are of below normal precipitation beginning in DJFM 1999, continuing through 2001, weakening of the drought in some northern areas in 2002 and return to normal conditions in northern areas in 2003. However, as shown in Fig. 3, there are very few reporting stations in this region during this period, and the precipitation estimate relies heavily on satellite data. Uncertainties with the observational data limit forecast verification to qualitative aspects.

News reports and humanitarian aid information support these general features, including the enhanced wet conditions in the northern part of the regions during DJFM 2003 where flooding occurred. Station data available during the drought period and with sufficiently long records to compute 30-year (1961-1990) climatologies are shown in Fig. 4. The station data shows above normal precipitation in DJFM 1998 followed by 3 years of below normal precipitation. Station precipitation amounts were close to normal in DJFM 2002 and above normal in DJFM 2003.

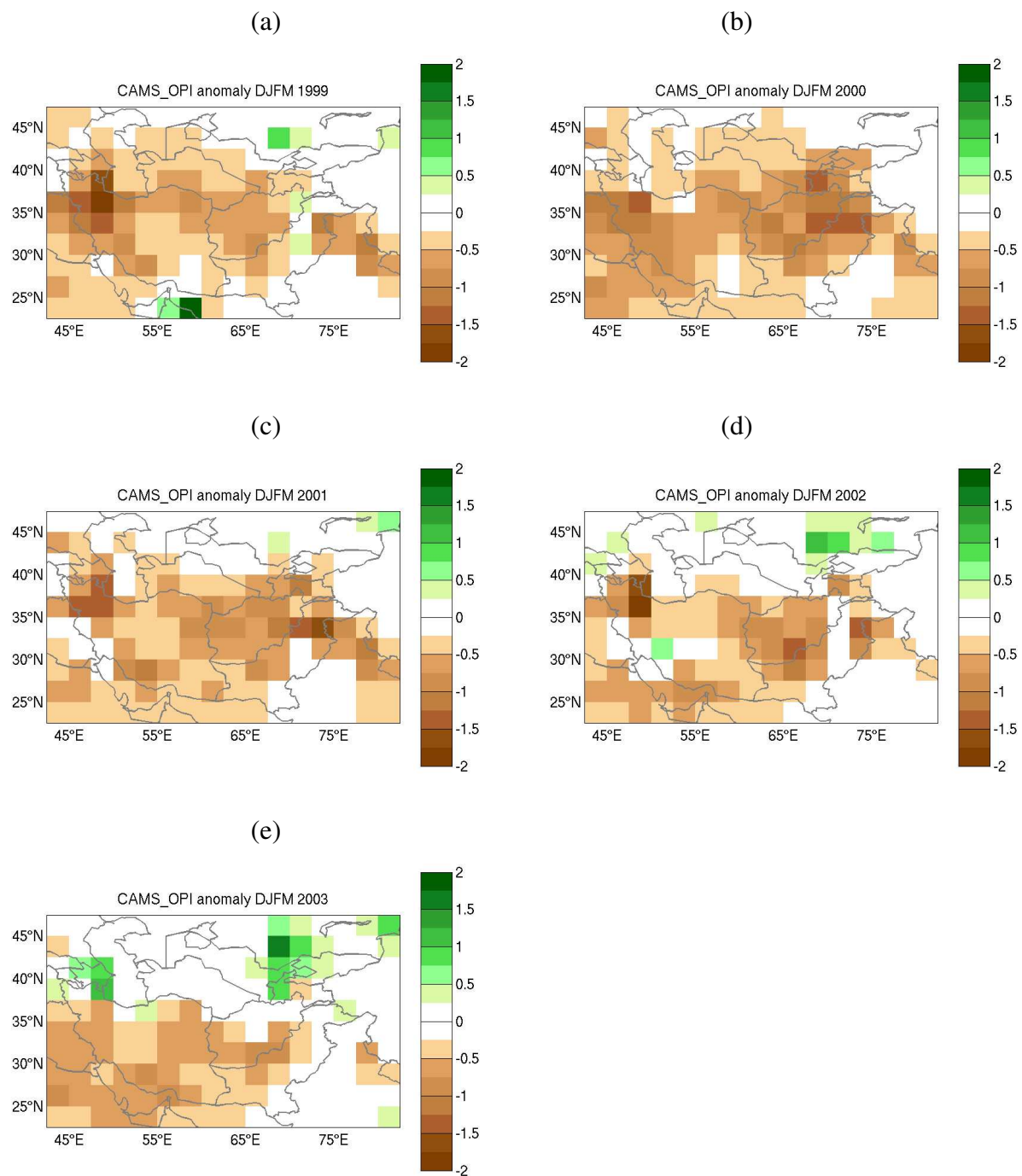


Figure 2. CAMS OPI anomalies (mm/day) for DJFM (a) 1999, (b) 2000, (c) 2001, (d) 2002 and (e) 2003.

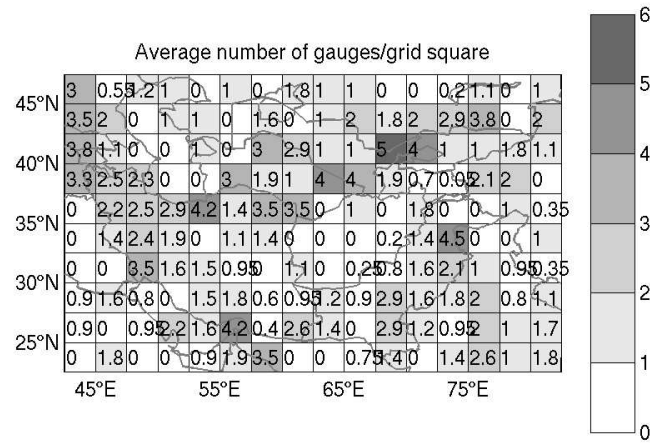


Figure 3. Average number of gauge data available per month per grid box in CAMS OPI data DJFM 1999-2003.

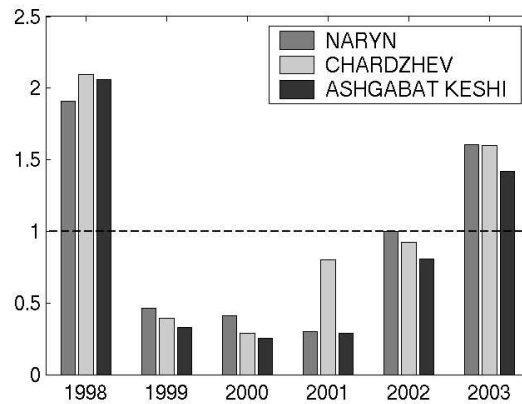


Figure 4. Fraction of normal DJFM precipitation at three stations: Naryn (Central Kyrgyzstan; 76E,41.43N), Chardzhev (Turkmenistan; 63.6E, 39.1N) and Ashgabat Keshi (Southern Turkmenistan; 58.33E,37.97N) for the period DJFM 1998-2003.

<i>Model</i>	<i>Resolution</i>	<i>Start</i>	<i>End</i>	Ens. Size
NCEP/MRF9	T42	DJFM 1966	DJFM 1998	10
CCM3	T42	DJFM 1951	DJFM 1998	10
ECHAM4.5	T42	DJFM 1951	DJFM 1998	24
COLA	T63	DJFM 1951	DJFM 1997	10
NSIPP	$2.5^{\circ} \times 2^{\circ}$	DJFM 1962	DJFM 1998	9

TABLE 1. AGCMs simulation periods and ensemble sizes used to computed corrections and estimate simulation skill.

b. Model simulations and forecasts

We examine the AGCMs used operationally at IRI: NCEP/MRF9, ECHAM4.5, COLA, CCM3.2, and NSIPP-1 (Livezey et al. 1996; Roeckner et al. 1996; Kinter et al. 1997; Hack et al. 1998; Bacmeister et al. 2000, respectively). The simulation skill of the AGCMs is estimated by performing long ensemble integrations forced by observed SSTs. The spatial resolution, simulation period and ensemble size for each model are shown in Table 1. Spatial maps of temporal anomaly correlation of model simulation and observation (Fig. 5) indicate little skill in the CSW Asia region with few correlations exceeding 0.3.

The IRI has been making two-tier real-time seasonal forecasts since 1995 and Net Assessment forecasts since 1997 (Mason et al. 1999; Goddard et al. 2003). SST conditions for the forecast period are first predicted, and then those predicted SST conditions are used as forcing for a set of AGCM integrations. AGCM initial conditions are taken from simulations forced by observed SST until the forecast start time. SST predictions are made using a combination of dynamical and statistical forecast models. The dynamical model is the coupled ocean-atmosphere model of the National Centers for Environmental Prediction (NCEP) covering the area from 30N to 25S, and 70W to 120E (Ji et al. 1998). Forecasts of the tropical Atlantic SST are made using the statistical canonical correlation analysis (CCA) model of CPTEC/INPE in Brazil, using the tropical Atlantic and Pacific SST fields as predictors (Repelli and Nobre 2003). Similarly, forecasts of the Indian

	1999	2000	2001	2002	2003
NCEP	•	•	•	•	•
CCM3	•	•	•	•	•
ECHAM4.5	•	•	•	•	•
NSIPP-1				•	•
COLA				•	•

TABLE 2. Availability of DJFM AGCM forecasts made Oct of the preceding year.

Ocean are presently done at the IRI using a CCA model, using the observed Indo-Pacific SST anomalies, and the forecasts of the Pacific SST field, as predictors. This Indian Ocean CCA model makes use of, among other things, the observed tendency for the Indian Ocean’s SST anomalies to approximately follow the ENSO-related SST anomalies of the tropical Pacific, with a lag time of about one season.

In the second step of the two-tiered forecasting approach, the predicted SST is used as a prescribed boundary condition for several atmospheric AGCMs. For the forecasts here, the AGCMs are forced with observed SST until the end of September and with forecast SST for the period Oct-Mar. Forecast DJFM seasonal anomalies are computed with respect to the time-mean of the given AGCM’s simulations over the period 1969 to 1998. The AGCMs and ensemble sizes are the same as those listed in Table 1. However, the availability of the AGCMs in forecast mode varies during the period as shown in Table 2; only the NCEP, CCM3 and ECHAM 4.5 models are available for DJFM 1999-2003. Moreover, the ECHAM 4.5 model forecasts for 1999-2001 were not available in real-time.

c. Correction Method

Statistical correction methods can compensate for model deficiencies by filling in details of large-scale teleconnection patterns found in nature but inaccurately or incompletely represented by models. Such methods have been used to correct model simulated precipitation anomalies (Smith and

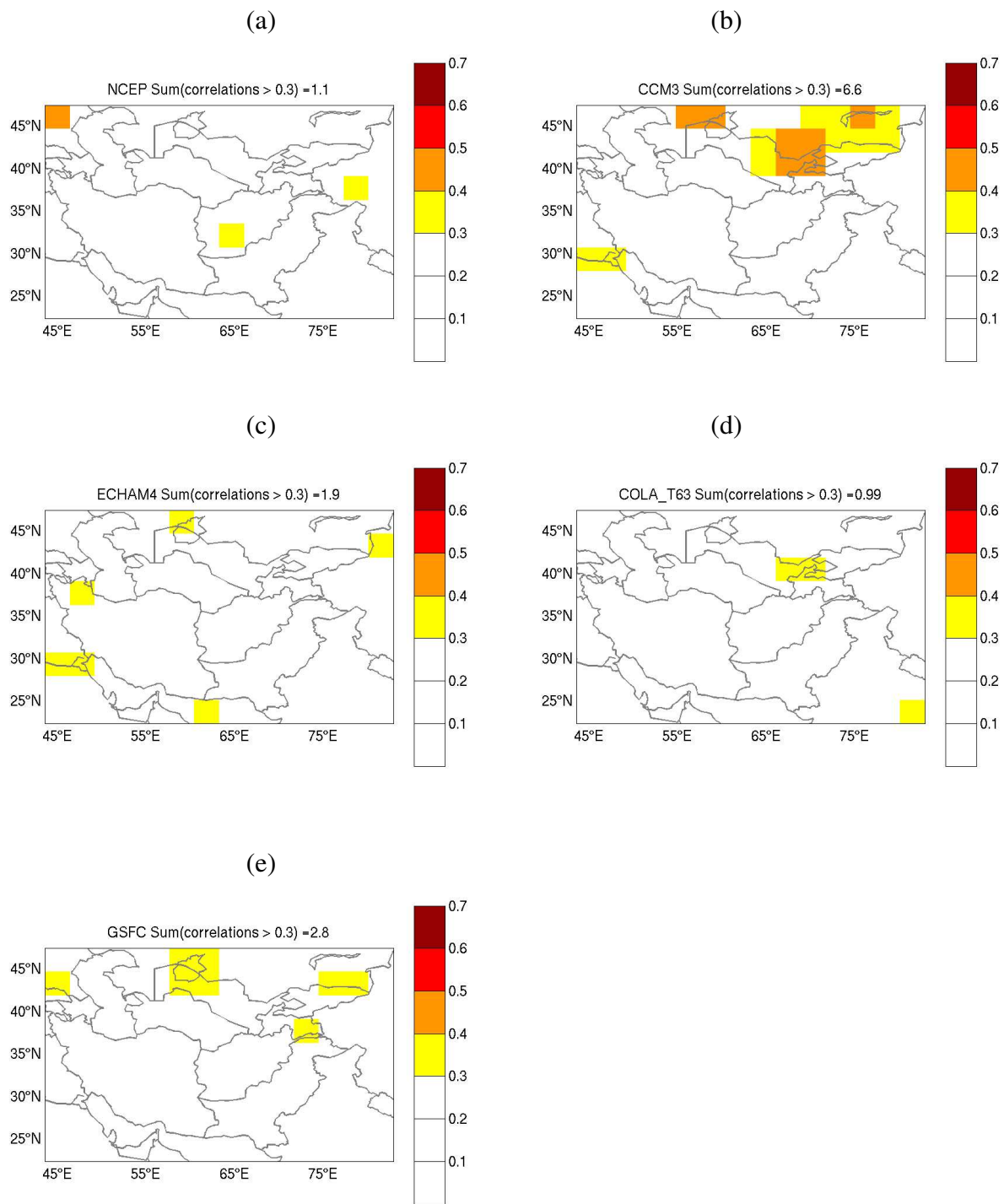


Figure 5. Anomaly correlation of DJFM observed precipitation with precipitation simulated by the (a) NCEP, (b) CCM3, (c) ECHAM 4.5, (d) COLA and (e) NSIPP AGCMs.

Livezey 1999; Feddersen et al. 1999) and seasonal forecasts (Mo and Straus 2002). Model precipitation has also been used as a predictor for statistical downscaling (Widmann et al. 2003). The fundamental idea of these methods is a multivariate (pattern) regression between model fields and observed anomaly fields. Prior to employing such a multivariate regression, separate principal component analyses (PCA) of model fields and observations are applied to reduce the number of degrees of freedom and decrease the effects of sampling error. Canonical correlation analysis (CCA) is the multivariate regression method used to identify model fields most highly correlated with observed precipitation anomaly patterns (Barnett and Preisendorfer 1987). The set of CCA correspondences between model and observation patterns is then used to predict observed precipitation anomalies from model outputs.

Previous work showed a relation between observed variations of the EAJS and observed CSW Asia precipitation with the observed 200 mb wind field being a good predictor of simultaneous observed CSW Asia precipitation (Tippett et al. 2003). However, examination of the ECHAM 4.5 and NSIPP simulated wind fields show that they exhibit different variability than do observed winds and are not good predictors of CSW Asia precipitation; the AGCM simulated winds are more highly correlated with ENSO than are observed (Reanalysis) winds. Wind fields from the other AGCMs were not available. Since Western Pacific upper atmospheric heating is related to EAJS variability it is reasonable that it might be directly related to CSW Asia precipitation. Previous work confirmed a relation between Western Pacific precipitation and observed CSW Asia precipitation and demonstrated that this relation is present in ECHAM 4.5 AGCM simulations forced with observed SST (Tippett et al. 2003). The statistical correction is made using model precipitation in the region 100°E to 130°W and 20°S to 20°N as the predictor. Here we apply the same method also to four other AGCMs. Maps of corrected simulation skill estimated with cross-validation in which three consecutive years are left out and the middle year used as the target, are shown in Fig. 6. Correction skill is limited to the northern part of the region from Turkmenistan

<i>Model</i>	<i>Grid points with $r > 0.3$</i>		<i>Average r over points with $r > 0.3$</i>	
	Uncorrected	Corrected	Uncorrected	Corrected
NCEP	3 pts.	25 pts.	0.35	0.4
CCM3	17 pts.	26 pts.	0.39	0.36
ECHAM4.5	6 pts.	22 pts.	0.32	0.38
COLA T63	3 pts.	28 pts.	0.33	0.38
NSIPP	8 pts.	28 pts.	0.35	0.43

TABLE 3. Number of grid points where the simulation anomaly correlation exceeds 0.3 and the average anomaly correlation at those points.

<i>Model</i>	<i>AGCM EOFs</i>	<i>Observation EOFs</i>	<i>CCA modes</i>
NCEP	5	3	1
CCM3	3	2	1
ECHAM4.5	2	3	1
COLA T63	2	3	2
NSIPP	4	4	3
SST	3	7	2

TABLE 4. Number of AGCM and observation EOFs and number of CCA modes used to construct the statistical corrections.

west through Uzbekistan, northern Afghanistan and Pakistan, Tajikistan and Kyrgyzstan. The number of grid points whose correlation exceeds 0.3, and their average correlation, are given in Table 3. EOF truncations and number of CCA modes are shown in Table 4. EOF and CCA truncations were chosen to maximize the sum of the cross-validated correlations exceeding 0.3 in the simulation skill estimates. The relatively low-dimension of the statistical correction lessens the risk of over-fitting the data in the regression.

d. Tercile probability forecasts

Seasonal forecasts are inherently nondeterministic and uncertain. Probabilistic forecasts provide a means of quantifying and communicating forecast uncertainty. Ideally, a seasonal forecast should

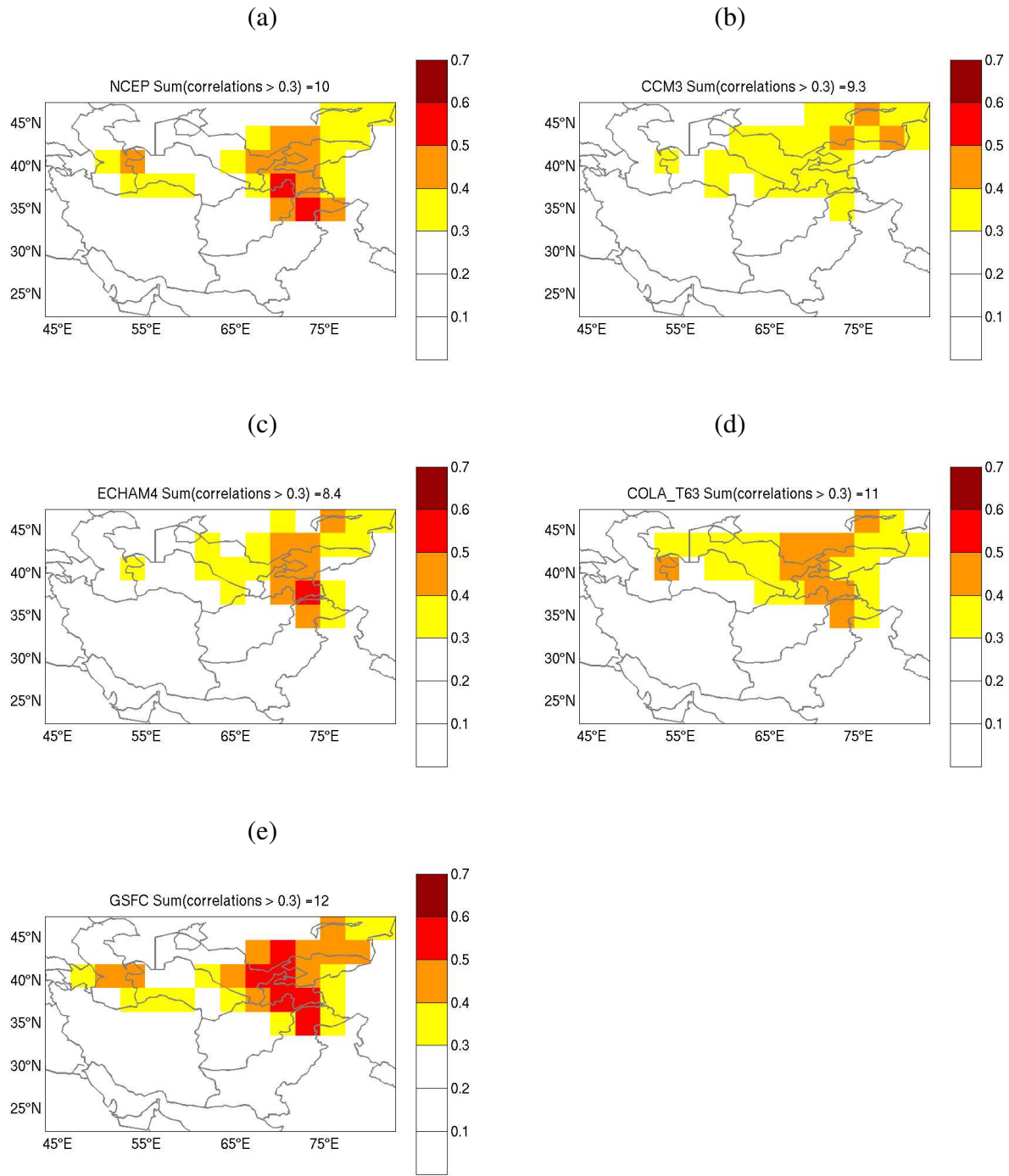


Figure 6. As in Fig. 5 but for the AGCM precipitation corrected using model Pacific precipitation.

consist of the probability distribution function (pdf) of possible outcomes given the present climate state. Then the probability of a particular event, for instance, the probability of precipitation exceeding a given amount, can be computed.

The historical record can be used to construct probability forecasts by looking at what occurred subsequent to states similar to the present one. This is the method of analogues. The shortness of the historical record necessitates that only a few parameters be used to select analogues—for instance, values of a single index. Then it is possible to compute relative frequencies of outcomes given conditions close to present ones. However, the crude selection process can result in a failure to distinguish between different phenomena.

Model-based forecasts are a means of circumventing the short record problem. The issue becomes how to construct probabilistic forecasts from deterministic models. Ensemble methods are essentially Monte Carlo methods of evolving an initial condition pdf into a forecast pdf. However, small ensemble size and model error make it difficult to use ensemble statistics directly. Model error often appears in the form of biases in ensemble statistics. Although the MOS correction is designed to correct errors in the ensemble mean, errors in the ensemble statistics such as overconfidence remain; these require separate treatment (Rajagopalan et al. 2002).

Here we use the historical record to estimate parametrically the forecast pdf (Kharin and Zwiers 2003). This approach limits us to stationary distributions. Furthermore we estimate only the distribution variance and assume that the pdf is Gaussian. More complex forecast uncertainty models can be formulated but the shortness of the climate record may make their use challenging. In the approach here, we decompose the observed climate variable C as the sum of a prediction M and an error E

$$C = M + E;$$

for instance, M is an ensemble-mean forecast, and E is the difference between ensemble-mean forecast and observation. Then, the expected correlation r between the observed climate C and the

ensemble mean M is

$$r = \frac{\sigma_M}{\sqrt{\sigma_E^2 + \sigma_M^2}} \quad (1)$$

where σ_M^2 is the prediction variance, σ_E^2 is the error variance, and we assume that the ensemble mean M and error E are independent. The assumption of forecast-independent error is usually unjustified, and furthermore implies that the correlation r is nonnegative. The forecast pdf is completely determined from the error variance σ_E^2 and the ensemble mean M if we assume that forecast errors are Gaussian and stationary. Probabilities of events in the below, normal and above categories can be computed from the parametric forecast pdf.

The correlation r and prediction variance σ_M^2 are computed at each gridpoint for uncorrected simulations and for leave-three-out cross-validated statistical-dynamical simulations. The error variance σ_E^2 at each gridpoint is then obtained by solving (1). Negative correlations are set to zero in (1), effectively forcing the error variance σ_E^2 to be unbounded. The probabilities coming from the different models are averaged equally. Models with relatively low skill will have a larger value of σ_E and consequently a wider forecast pdf and will contribute less to probability shifts. Forecast uncertainty may be underestimated as this procedure does not take into account error in the SST prediction.

3. Forecast Results

We now examine the probability forecasts obtained using the AGCM forecast precipitation over CSW Asia and those obtained using statistical-dynamical forecasts based on model precipitation over the Western Pacific. The forecast period 1999-2003 is independent of the period used to compute the model corrections. The statistical-dynamical calibration method is slightly different from that used in Tippett et al. (2003). There ECHAM 4.5 was forced by persisted SST, and the data used for the statistical correction came from a set of hindcasts also forced by persisted SST.

Such an approach has the potential to account for error due to systematic SST errors. Here the statistical correction is computed using AGCM simulations from observed SST which are less computationally costly than hindcasts.

We examine the SST forecast, AGCM-based precipitation forecast and statistical-dynamical precipitation forecast for each of the five winters 1999-2003. The observed and forecast SST are shown in Fig. 7. SST forecasts are made in the Oct preceding the target season. The uncorrected retrospective forecasts are shown in Fig. 8 and the corrected ones in Fig. 9.

a. DJFM 1999

In the first year of the drought, La Niña conditions prevailed in DJFM 1999, particularly in the Central Pacific. These cool conditions were also present in the forecast SST used to force the AGCMs (Fig. 7a). Also present in both observed and forecast SST were warm conditions in the Maritime Continent region. These warm conditions are correlated with local positive precipitation anomalies, which in turn are correlated with negative precipitation anomalies over CSW Asia. The statistical model used to predict Indian ocean SST produced weak cool anomalies while warm anomalies were actually observed there. The Oct 1998 AGCM ensemble mean forecasts of DJFM 1999 all show wet anomalies, and the tercile probabilities from the AGCM output (Fig. 8a) show enhanced likelihood of above normal precipitation along the southwest border of Iran and in the region northeast of Afghanistan. The corrected tercile forecasts (Fig. 9a) show enhanced likelihood of below normal precipitation in the region where there is skill.

b. DJFM 2000

In the second year of the drought, La Niña conditions continued in DJFM 2000, particularly in the Central Pacific. These cool condition were present to a much lesser extent in the forecast SST used to force the AGCMs, being mostly confined to the South American coast (Fig. 7b). Also present

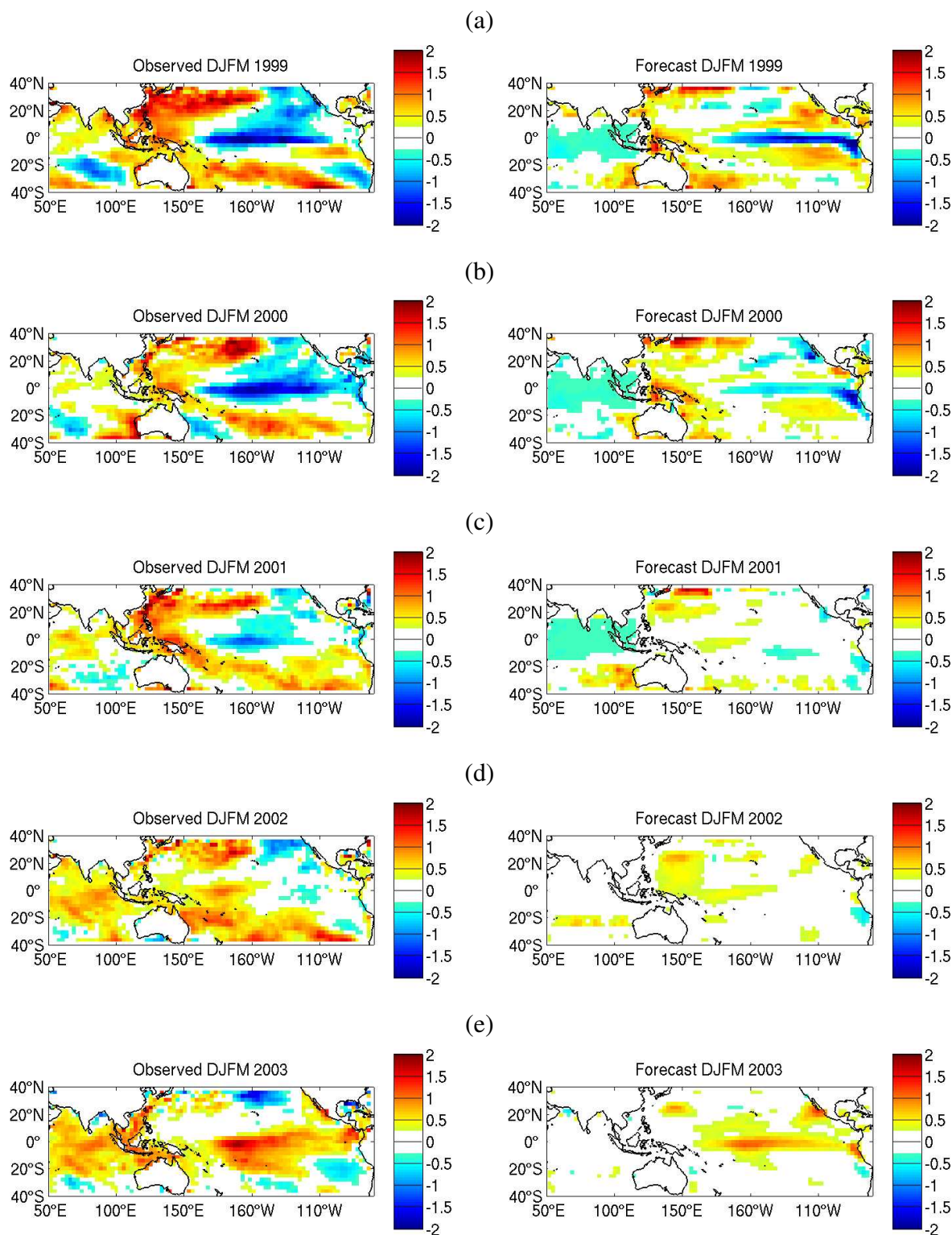


Figure 7. Forecast (right panel) and observed (left panel) SST anomalies for DJFM (a) 1999, (b) 2000, (c) 2001, (d) 2002, (e) 2003.

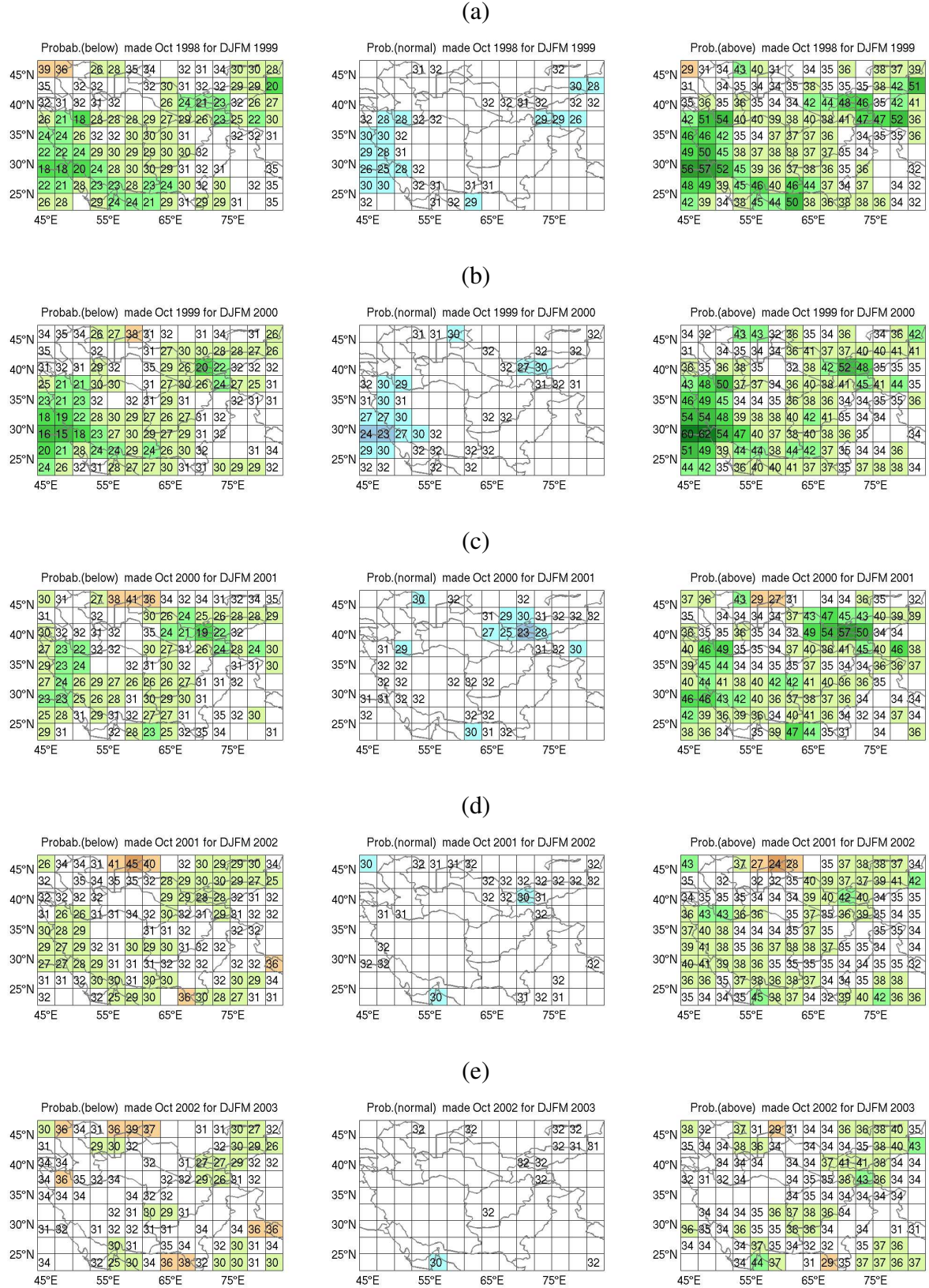


Figure 8. Forecast probabilities (in percent) obtained from AGCM output of below (left panel), normal (center panel) and above (right panel) categories for DJFM (a) 1999, (b) 2000, (c) 2001, (d) 2002, and (e) 2003.

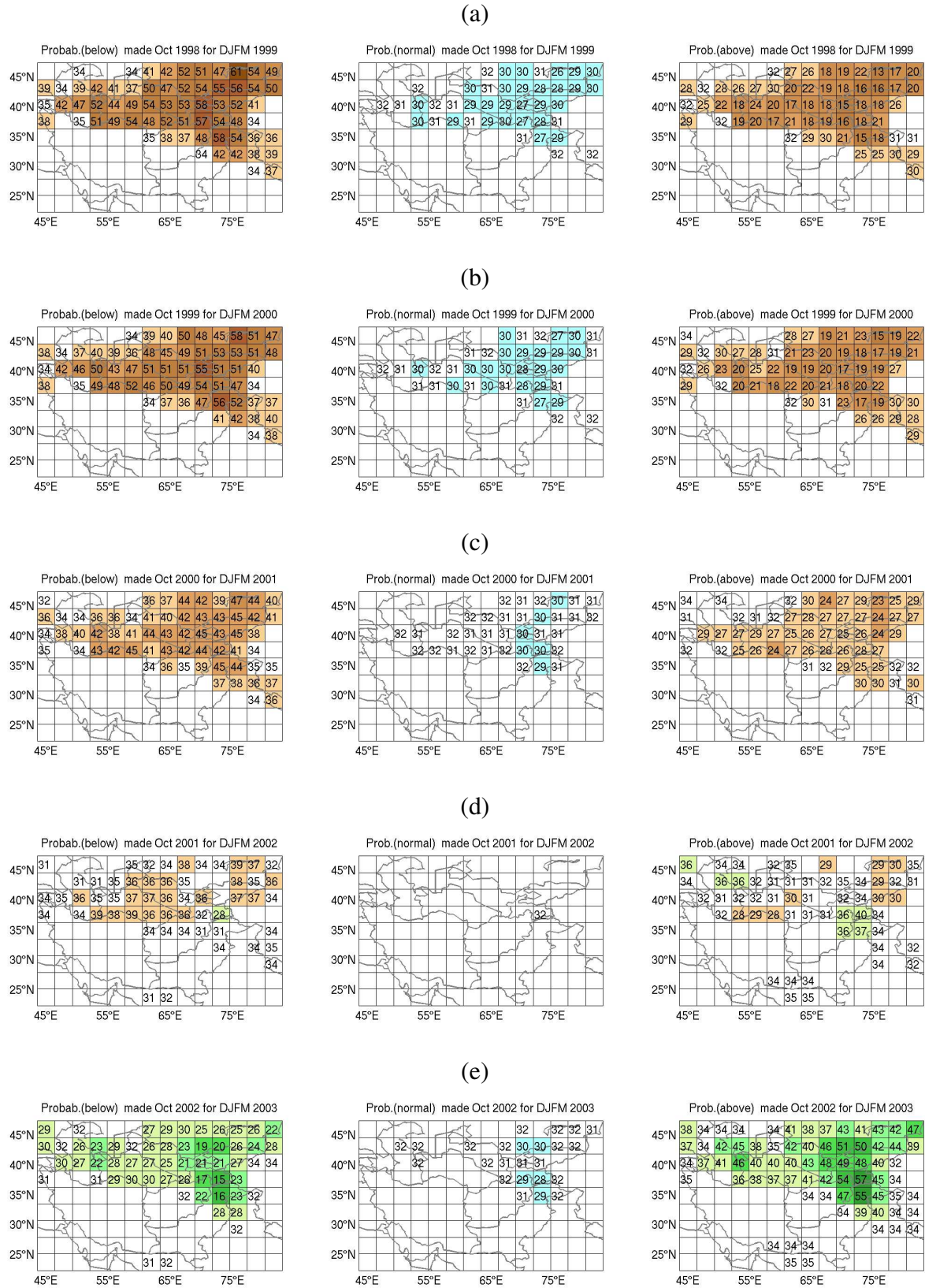


Figure 9. As in Fig. 8 but the forecast categorical probabilities from the statistical-dynamical forecasts.

in both observations and forecast were warm conditions in the Maritime Continent region. Again the statistical model used to predict Indian ocean SST produced weak cool anomalies while some warm anomalies were actually observed there.

The available models forecast wet ensemble mean anomalies resulting in the enhanced likelihood of above normal precipitation (Fig. 8b). The corrected tercile forecasts (Fig. 9b) show an enhanced likelihood of below normal precipitation in the region where the corrections have skill. In the southwest part of the region, including Iran where the correction have little skill, there was also severe drought.

c. DJFM 2001

Cool, although weaker, SST anomalies continued in the Central Pacific during DJFM 2001. These cool conditions were only weakly present in the forecast SST used to force the AGCMs (Fig. 7c). More importantly, missing from the forecast were warm SST conditions in the Maritime Continent region. Again the statistical model used to prediction Indian ocean SST produced weak cool anomalies while warm anomalies were actually observed there. The available AGCMs all forecast positive precipitation anomalies over CSW Asia (Fig. 8c). The statistical-dynamical forecasts using the NCEP and ECHAM 4.5 models indicated negative precipitation anomalies and the one using the CCM3 model indicated positive precipitation anomalies. The corrected tercile forecasts (Fig. 9c) show an enhanced likelihood of below normal precipitation. However, the shift toward below normal was weaker than in the previous two forecasts.

d. DJFM 2002

Warm SST anomalies were observed in DJFM 2002 in the central western Pacific, Maritime Continent and Indian Ocean. However, only very modest warm anomalies in the Central and Western Pacific were forecast (Fig. 7d). All AGCMs indicated wet anomalies in CSW Asia except the

COLA model which showed negative precipitation anomalies in the northern part of the domain. The uncorrected AGCM tercile probabilities indicate enhanced likelihood of above normal precipitation (Fig. 8d). The NCEP and COLA model statistical-dynamical forecasts indicated dry conditions, while those of the CCM3 and ECHAM 4.5 models showed positive precipitation anomalies; the NSIPP statistical-dynamical forecast indicated positive precipitation anomalies in north and negative precipitation anomalies in south. The weakness of the SST forcing is perhaps reflected in the lack of agreement in the AGCM forecasts. The resulting tercile forecast reflects the lack of consensus and shows a slight shift to dry conditions in most of the region with a slight shift toward wet in the northeast of Afghanistan and Tajikistan (Fig. 9d). While drought continued in many regions, drought conditions began to ease in March and April in the northeast, as suggested by the station data shown in Fig. 4.

e. DJFM 2003

Warm SSTs were observed in DJFM 2003 across the Central Pacific (a weak to moderate El Niño was beginning to decay), through the Maritime Continent and into the Indian Ocean. Forecast SSTs captured only the warm Pacific SSTs (Fig. 7e). AGCM forecast anomalies and tercile probabilities indicated wet conditions, much as they did during the drought (Fig. 8e). The statistical-dynamical forecasts are uniformly wet across models, and the tercile probabilities are shifted to the above normal category (Fig. 9e). Above normal precipitation was observed in the northern half of the region, and the drought of the previous years had ended.

4. Summary and Conclusions

Statistical-dynamical seasonal forecasts use statistical methods to correct systematic deficiencies in the response of atmospheric general circulation models (AGCMs) to predicted sea surface temperature (SST). The statistical correction is constructed here by applying a CCA regression between

AGCM simulations forced by observed SST, and the corresponding observations. This regression is then applied to AGCM forecasts forced by predicted SST in a two-tiered prediction system, outside of the regression training period. Simulation performance provides an estimate of forecast uncertainty that can be used to construct a parametric forecast probability density function and compute categorical probabilities.

We applied this method to winter (DJFM) precipitation in Central Southwest (CSW) Asia. Although observational studies relate the region's precipitation to tropical SST forcing with some success, AGCMs forced with observed sea surface temperatures simulate poorly the region's interannual variability. The CSW Asia response pattern is part of a large-scale pattern that includes ocean-atmosphere processes around the Maritime Continent. AGCMs do simulate precipitation variability in the Maritime Continent region reasonably well, and we base the statistical correction on model precipitation over the Maritime Continent region. This approach was previously used for the ECHAM 4.5 model using observed and persisted SSTs (Tippett et al. 2003). Here we have applied the method to ECHAM 4.5 and four additional AGCMs presently used at IRI for seasonal forecasting. We find that the correction of simulations forced by observed SST results in significant historical cross-validated skill.

We also applied the statistical-dynamical method to two-tier AGCM forecasts of the DJFM season made during the period 1999-2003; the AGCMs are forced with SST forecasts made the previous October. This period is independent of that used for developing the correction statistics and includes a severe multi-year (1999-2002) drought. Tercile probability forecasts were constructed using simulation skill as an estimate of forecast uncertainty. While the SST forecasts had errors, they usually had the correct anomaly sign in much of the critical region in the western tropical Pacific. In spite of these SST errors, the statistical-dynamical forecasts capture some of the general features of the 1999-2003 period. The statistical-dynamical forecast probabilities show enhanced likelihood of below normal precipitation during the drought years and enhanced likelihood

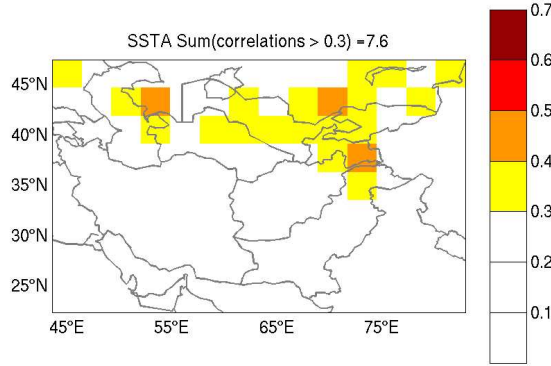


Figure 10. As in Fig. 5 but for the CCA-predicted precipitation using only simultaneous Pacific SST.

of above normal precipitation for DJFM 2003 when the northern part of the region experienced a return to normal and above normal conditions, including flooding.

The statistical nature of this approach leads to the question of whether there is benefit to using AGCMs or whether a purely statistical forecast using only the forecast SST would perform as well. We believe that statistical-dynamical approaches are potentially superior to purely statistical ones since AGCMs have the potential to produce nonlinear responses to SST forcing. Furthermore we expect AGCMs to improve in performance with time. Figure 10 shows that the estimated skill of a purely statistical CCA scheme using simultaneous observed SST as a predictor is slightly less than that of some of the corrected AGCMs. The difference in skill is modest and is, for the most part, not statistically significant. However, we can conclude that the statistical-dynamical method permits AGCMs to achieve skill levels comparable with, if not better than, purely statistical methods. Additionally since the detailed characteristics of each AGCM are different, using several models may improve the robustness of the forecast.

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