# Dynamical-Statistical Seasonal Forecasts. Central Southwest Asia winter precipitation*

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### Abstract

Central Southwest (CSW) Asia recently experienced four years (winter of 1998-99 through 2001-02) of severe drought. Atmospheric general circulation models (AGCMs) forced by observed sea surface temperature (SST) demonstrate little skill in simulating interannual precipitation variability in this region, although the region's interannual precipitation variability has been linked to remote forcings that include East Asia Jet Stream variability and Western Pacific tropical convection. The dynamical-statistical approach uses statistical methods to correct systemic 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 Dec-Mar (DJFM) 1951-1998. The dynamical-statistical method is also applied to recent (winter 1998-99 through 2002-03) multi-model, two-tier DJFM precipitation forecasts initiated in October. Tercile probability forecasts are produced using the ensemble mean forecasts and forecast error estimates. The dynamical-statistical 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 climate anomalies for a specific region and season given SST predictions, is the 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 limits 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 dynamical-statistical 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 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 failure of the model to reproduce completely 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 wintertime precipitation in the Central Southwest (CSW) Asia region (Tippett et al. 2003). The multi-model application of the dynamical-statistical 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 has a semi-arid climate with a substantial fraction of annual precipitation occurring during winter and early-spring, mostly in the form of snow. This precipitation is associated with eastward-propagating mid-latitude cyclones and falls along the slopes of the region's principal mountain ranges (Martyn 1992). The melting of this snow provides an important source of water during the summer. Interannual variability of precipitation is large in the region, and CSW Asia recently experienced four years (1999-2002) of the worst drought in fifty years, drastically reducing agricultural production and livestock populations (Agrawala et al. 2001; Barlow et al.

2002).

The feasibility of CSW Asia seasonal forecasts depends on the impact of predictable SST anomalies on the region's precipitation. The CSW Asia region is not noted as part of the typical ENSO signal (Ropelewski and Halpert 1987, 1989). Some, but not all, ENSO events seem to impact CSW Asia precipitation with El Niño events being associated with enhanced precipitation and La Niña events with decreased precipitation, although enhanced frequency of above normal precipitation in Southwest Iran is associated with La Ninña conditions (Mason and Goddard 2001). Barlow et al. (2002) stratified ENSO events based on the strength of their Western Pacific SST anomalies and found those with more vigorous anomalies are associated with SST and precipitation patterns similar to those observed during the recent drought period, even when the recent drought period is withheld from the calculation. The role of SST forcing in the recent drought is supported by a model-based study showing that several AGCMs forced by observed SSTs reproduced features of the 1998-2002 drought (Hoerling and Kumar 2003). Thus, the particular "flavor" of the extended La Niña episode of 1998-2002 appears to be linked to the severe drought in CSW Asia. In related work, Kidson et al. (2002) used cluster analysis of OLR data to separate ENSO warm-events into two types with associated SST anomalies of differing western extent. The warm-event type with extended Western Pacific SST anomalies appears to be associated with stronger circulation anomalies over the Asian region.

A physical mechanism connecting Western Pacific convection and SST anomalies with CSW Asia precipitation is the wintertime upper-tropospheric westerly jet stream over subtropical east Asia and the western Pacific, often referred to as the East Asia Jet Stream (EAJS). Yang et al. (2002) found EAJS strength to be inversely related with DJF CSW Asia precipitation anomalies; a strong (weak) EAJS is correlated with negative (positive) CSW Asia precipitation anomalies. Additionally, they found EAJS strength to be uncorrelated with ENSO. 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 which in turn is associated with negative CSW Asia precipitation anomalies. Associated with EAJS strengthening is a southward shift of the jet maximum and northeasterly flow anomalies over the CSW Asia region.

The difficulty some AGCMs have in simulating EAJS variability may be a factor in the poor simulation of CSW Asia precipitation (Tippett et al. 2003). Poor simulation of EAJS variability precludes using upper-level model winds as a predictor for CSW Asia precipitation. However, statistical corrections using ECHAM 4.5 model 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 additional AGCMs, obtain an estimate of simulation skill and apply the correction retrospectively to two-tier AGCM operational IRI forecasts of DJFM precipitation anomalies over 5 recent years (1999-2003) using forecast SSTs made in 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 December-January-February-March (DJFM) seasons. This dataset, based on station observations interpolated to a $0.5° \times 0.5°$ lat-lon grid, is here interpolated to a T42 grid.

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

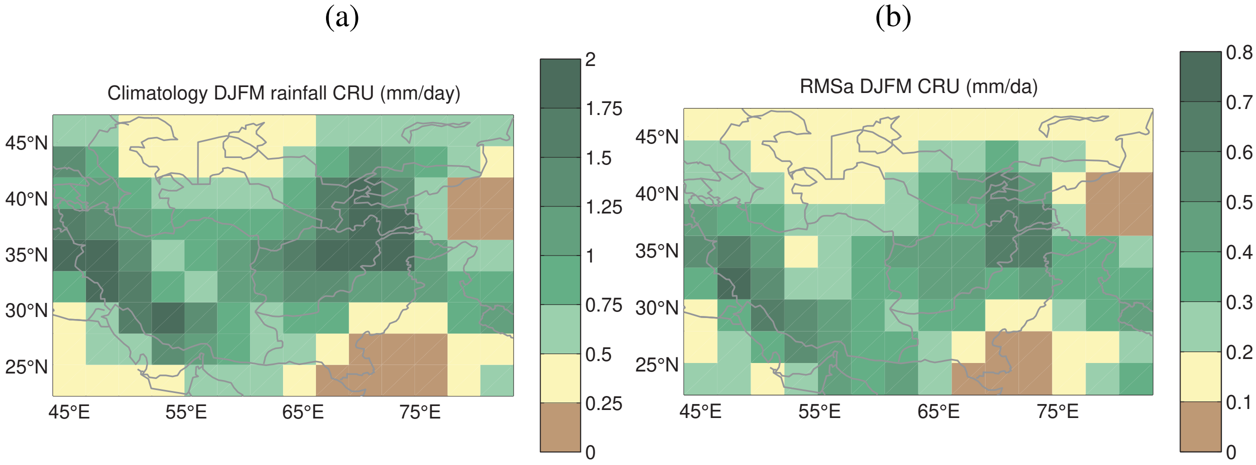


Figure 1. (a) Climatological and (b) root-mean-square anomaly of the DJFM precipitation 1951-1998.

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 index.

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 areas in 2002 and return to normal conditions in some 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

| *Model* | *Resolution* | *Start* | *End* | 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 | $2.5° \times 2°$ | DJFM 1962 | DJFM 1998 | 9 |

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

enhanced wet conditions in the northern part of the regions during DJFM 2003. 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. Precipitation amounts were close to normal in DJFM 2002 and above normal in DJFM 2003.

*b. Model simulations and forecasts*

We examine the AGCMs used operationally at IRI: NCEP/MRF9, CCM3.2, ECHAM4.5, COLA, and NSIPP-1 (Livezey et al. 1996; Hack et al. 1998; Roeckner et al. 1996; Kinter et al. 1997; Bacmeister et al. 2000). 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 is shown in Table 1. Spatial maps of temporal anomaly correlation of model simulation and observation shown in 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. 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

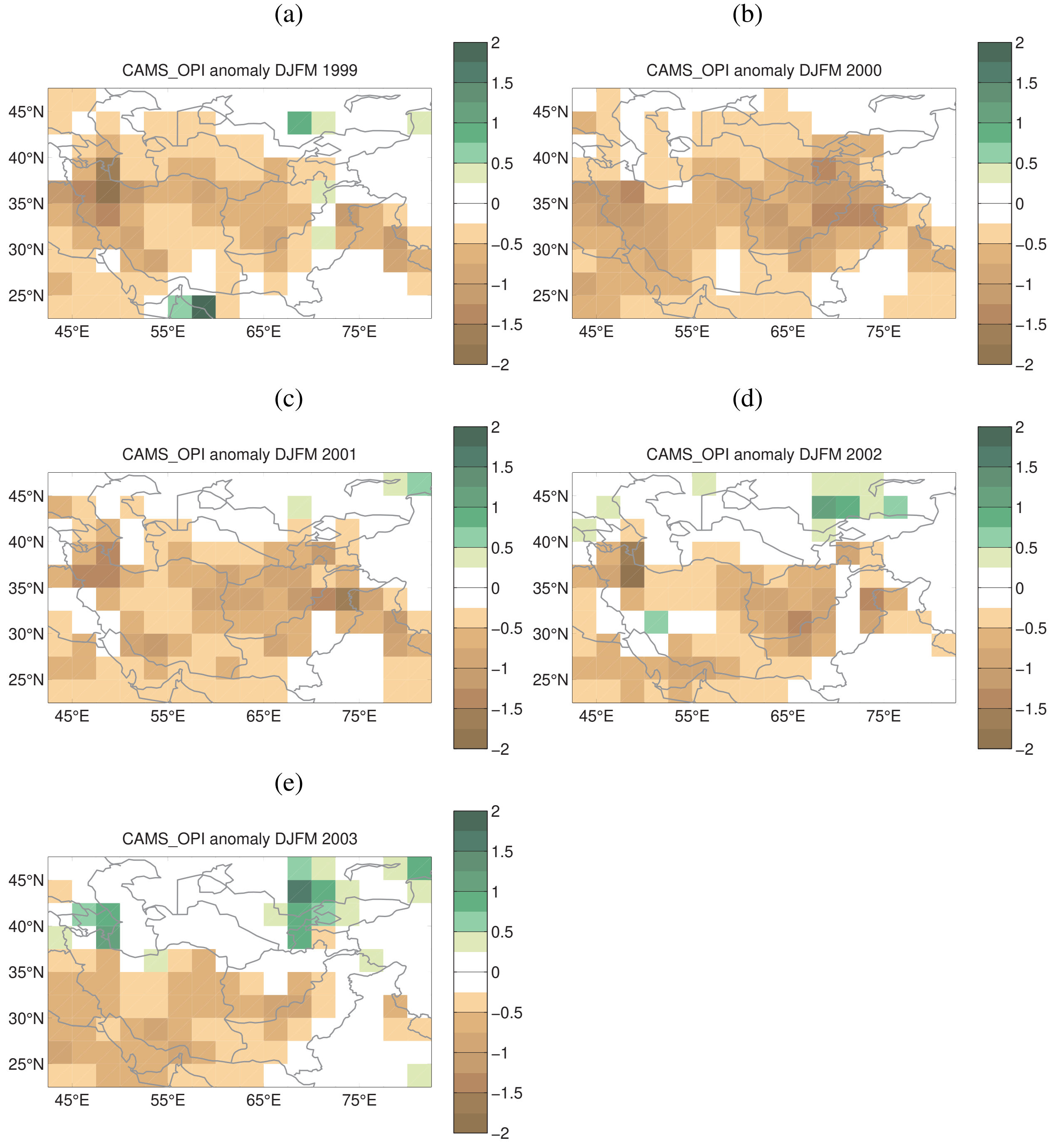


Figure 2. CAMS OPI anomalies (mm/day) for DJFM (a) 1999, (b) 2000, (c) 2001, (d) 2002 and (e) 2003.

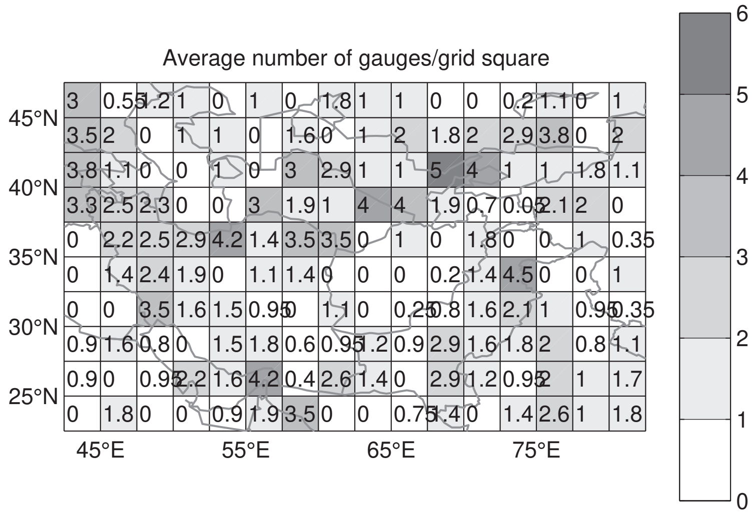


Figure 3. Average number of gauge data available per month per grid box in CAMS OPI data DJFM 1999-2003.

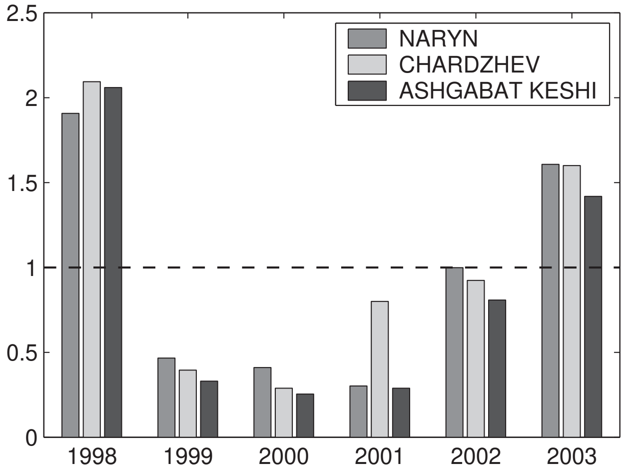


Figure 4. Fraction of normal DJFM precipitation at three stations: Naryn (76E,41.43N), Chardzhev (63.6E, 39.1N) and Ashgabat Keshi (58.33E,37.97N) for the period DJFM 1998-2003.

| | 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.

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. Similarly, forecasts of the Indian 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 simulations using 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.

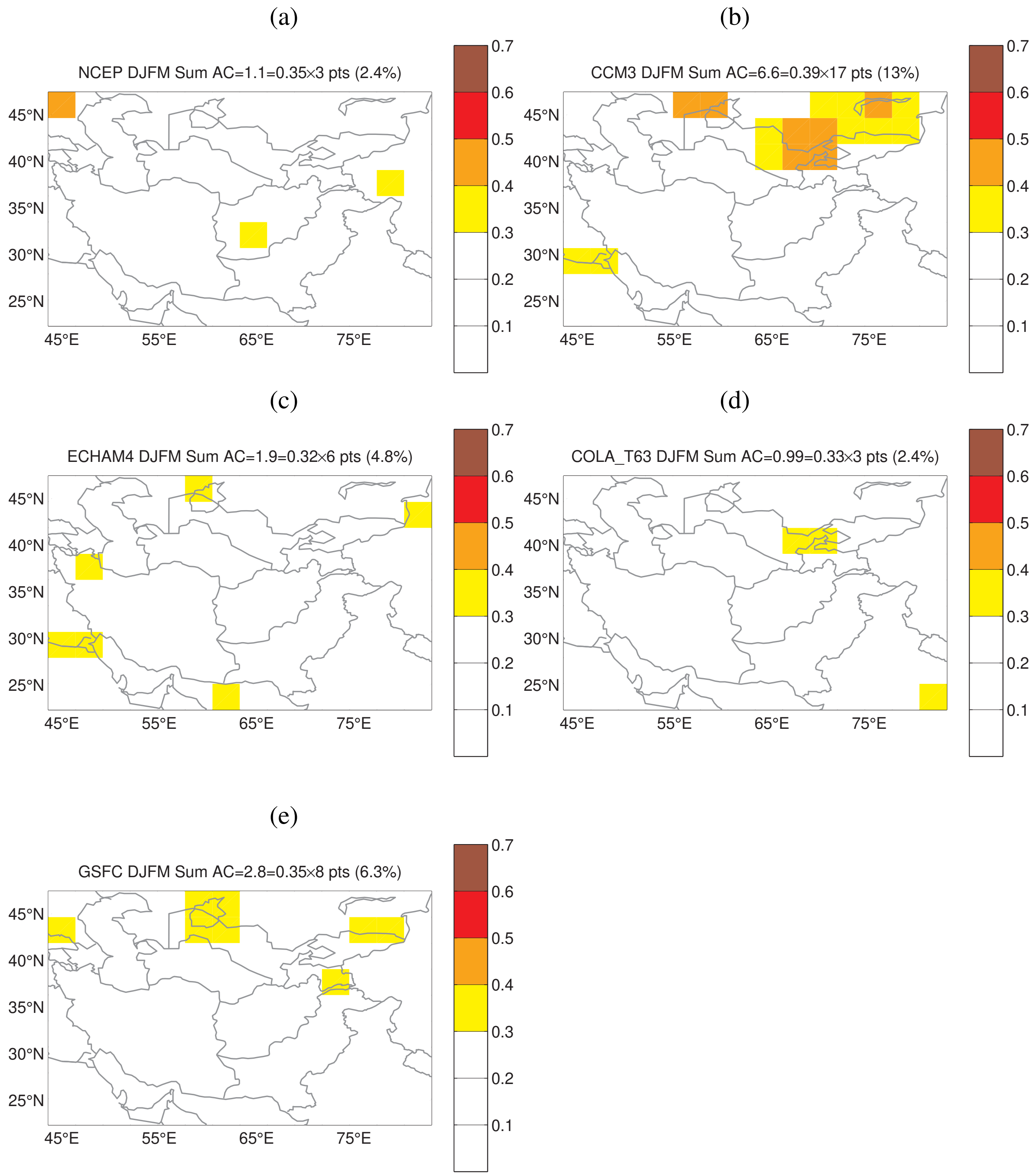


Figure 5. Anomaly correlation of DJFM observed precipitation with precipitation simulated by the (a) NCEP, (b) CCM3, (c) ECHAM 4.5, (d) COLA and (e) NSIPP AGCMs.

*c. Correction Method*

Statistical correction methods can compensate for model deficiencies by filling in details of large-scale teleconnection patterns found in nature but incompletely represented by models. Such methods have been used to correct model simulated precipitation anomalies (Smith and 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 a good predictors of CSW Asia precipitation; the AGCM winds are more highly correlated with ENSO than are observed (Reanalysis) winds. Wind fields from the other AGCMs were not available. Since Western Pacific heating is related to EAJS variability it is reasonable that it might be 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

| *Model* | *Correlation >* | | *Average correlation* | |
|---|---|---|---|---|
| | before | after | before | after |
| 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.

| *Model* | *Predictand EOFs* | *Predictor EOFs* | CCA modes |
|---|---|---|---|
| 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 predictor and predictand EOFs and number of CCA modes used to construct the statistical corrections.

predictor is model precipitation in the region 100°E to 130°W and 20°S to 20°N. Here we apply the same method to 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 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 is shown in Table 4. EOF and CCA truncations were chosen to maximize the sum of cross-validated correlations exceeding 0.3 in the simulation skill estimates.

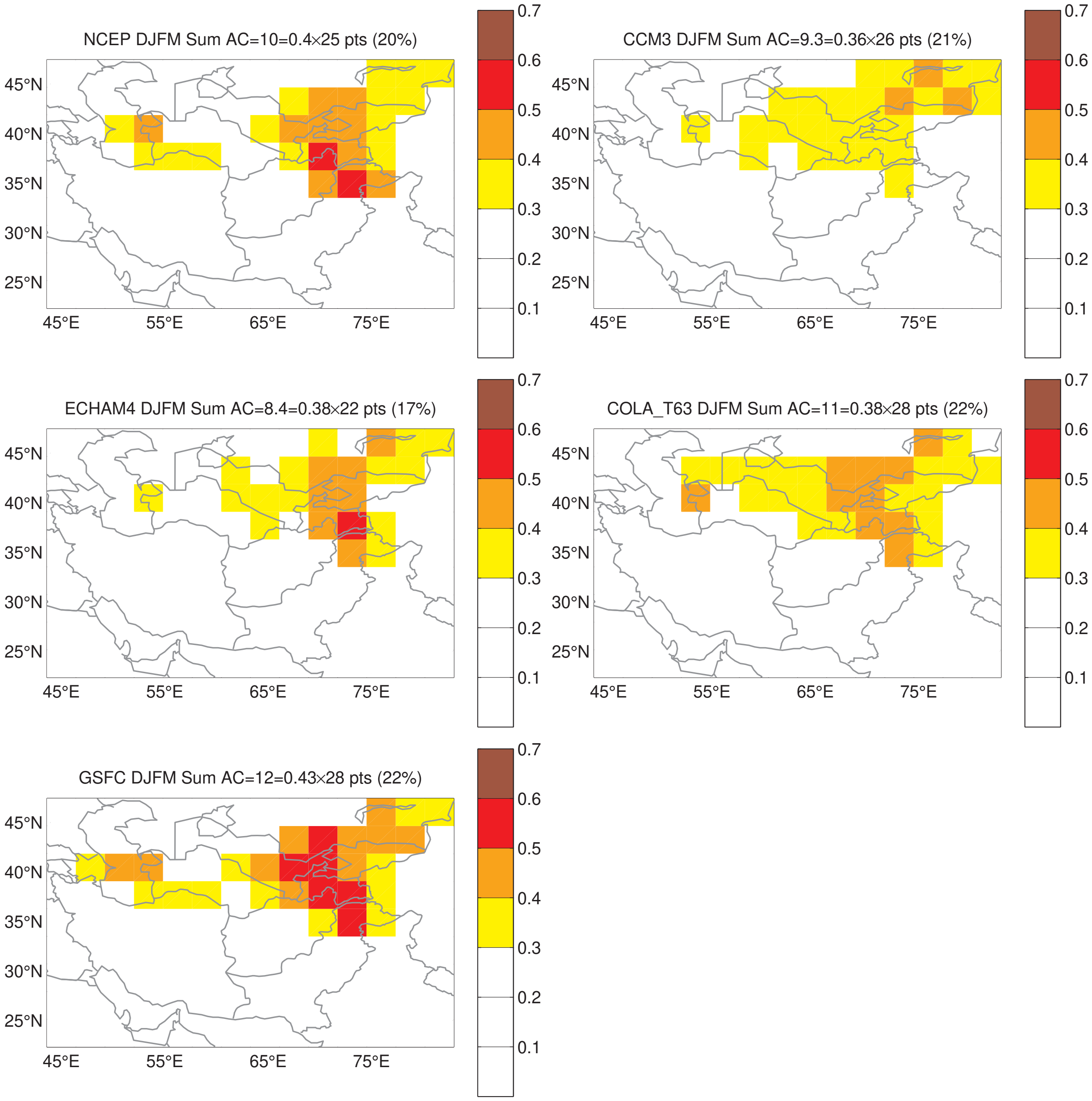


Figure 6. As in Fig. 5 but for the AGCM precipitation corrected using model Pacific precipitation.

*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 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 after states similar to the present state. 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 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 and 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 variance of the distribution and assume that it is Gaussian. Suppose that an observed climate variable $C$ is decomposed into a sum of a prediction $M$ and an error $E$

$$C = M + E\,;$$

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

$$r = \frac{\sigma_M}{\sqrt{\sigma_E^2 + \sigma_M^2}} \tag{1}$$

where $\sigma_M^2$ is the prediction variance, $\sigma_E^2$ is the error variance and we assume that the ensemble mean $M$ and error $E$ are independent. The assumption of forecast-independent error is is usually unjustified, and furthermore imples that the correlation $r$ is nonnegative. The forecast pdf is completely determined from the error variance $\sigma_E^2$ 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 $\sigma_M^2$ are computed at each gridpoint for simulations and leave-three-out cross-validated dynamical-statistical simulations. The error variance $\sigma_E^2$ at each gridpoint is then obtained by solving (1). Negative correlations are set to zero in (1), effectively forcing the error variance $\sigma_E^2$ to be unbounded. The probabilities coming from the different models are averaged equally. Models with relatively low skill will have a larger value of $\sigma_E$ 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 dynamical-statistical 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 dynamical-statistical 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 correct for error due to systematic SST errors. Here the statistical correction is computed using AGCM simulations which are less computationaly costly than hindcasts.

We examine the SST forecast, AGCM-based precipitation forecast and dynamical-statistical 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 continued in DJFM 1999, particularly in the Central Pacific. These cool conditions were also present in the forecast SST used to force the AGCMs. Also present in both observed and forecast SST are warm condition in the Maritime Continent region. These warm conditions are correlated with positive precipitation anomalies locally, 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 forecasts of DJFM 1999 all show wet anomalies, and the tercile probabilities from the AGCM output in Fig. 8 show enhanced likelihood of above normal precipitation along the southwest border of Iran and in the region northeast of Afghanistan. The corrected tercile forecasts in Fig. 9 show enhanced likelihood of below normal precipitation in the region where there is skill.

### *b. DJFM 2000*

In 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. Also present in

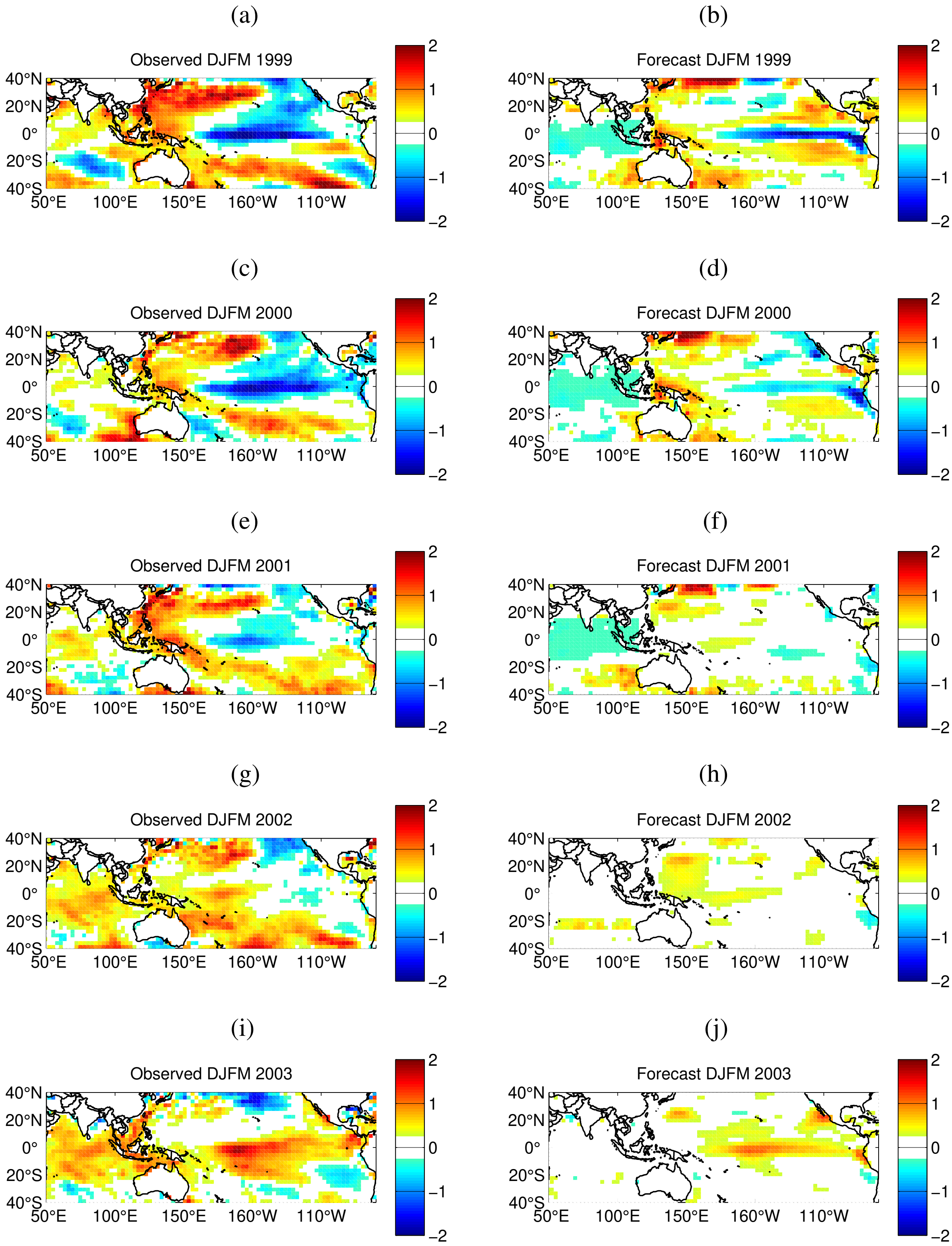


Figure 7. Forecast and observed SST anomalies.

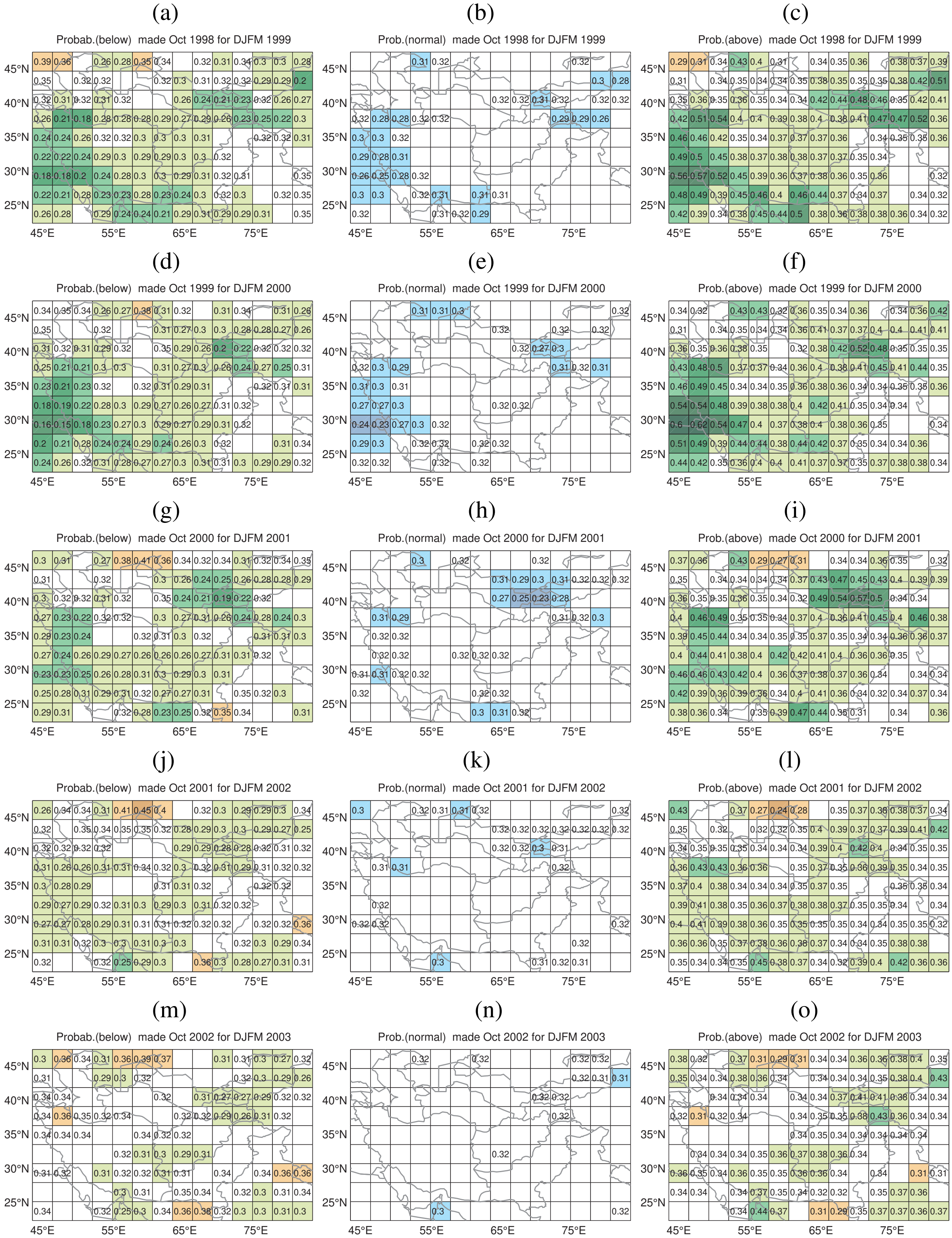


Figure 8. Forecast categorical probabilities obtained from AGCM output. (a)-(c) 1999. (d)-(f) 2000. (g)-(i) 2001. (j)-(l) 2002. (m)-(0) 2003.

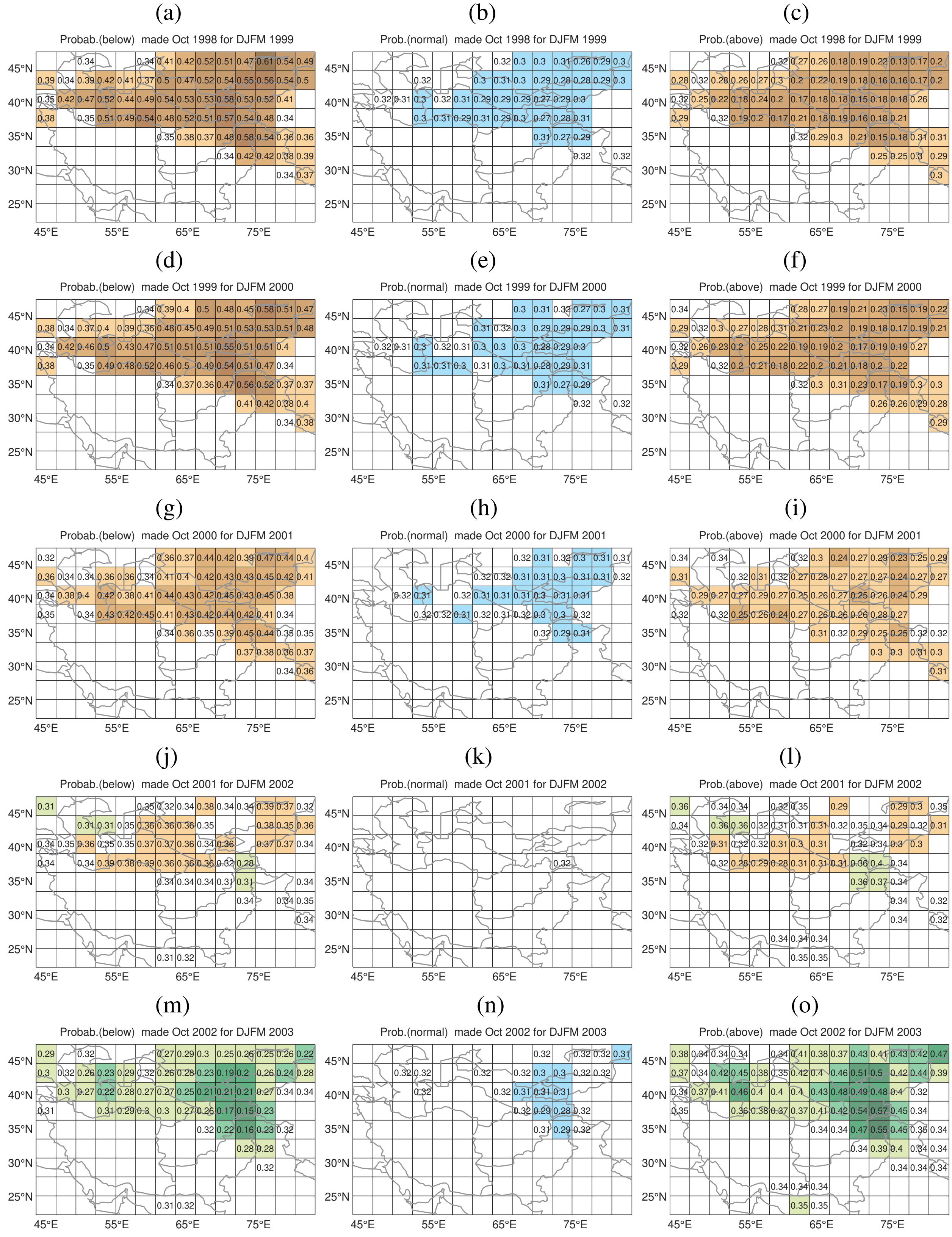


Figure 9. As in Fig. 8 but the forecast categorical probabilities from the dynamical-statistical forecasts.

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

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

### *c. DJFM 2001*

Cool, although weaker, SST anomalies continued in the Central Pacific during DJFM 2001. These cool condition were only weakly present in the forecast SST used to force the AGCMs, being mostly confined to the South American coast. More importantly, missing from the forecast are 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. On the other hand, the dynamical-statistical 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 in Fig. 9 show enhanced likelihood of below normal precipitation. However, the shift towards below normal was weaker than in the previous two forecasts.

### *d. DJFM 2002*

Warm SST anomalies were observed in DJFM 2002 in the central Pacific, Maritime Continent and Indian Ocean. However, only very modest warm anomalies in the Central and Western Pacific were forecast. All AGCMs indicated wet anomalies in CSW Asia except the COLA model which showed dry in the northern part of the domain. The NCEP and COLA model dynamical-statistical forecasts indicated dry conditions, while those of the CCM3 and ECHAM 4.5 models showed wet; the NSIPP dynamical-statistical forecast indicated wet in north and dry 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 slight shift to dry conditions in most of the region and a slight shift toward wet in the northeast of Afghanistan and Tajikistan. 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, through the Maritime Continent and into the Indian Ocean. Forecast SSTs captured only the warm Pacific SSTs. AGCM forecast anomalies and tercile probabilities indicated wet conditions, much as they did during the drought. The dynamical-statistical forecasts are uniformly wet across models, and the tercile probabilities are shifted to the above normal category.

## 4. Summary and Conclusions

Dynamical-statistical 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 by applying a CCA regression between observations and AGCM simulations forced by observed SST. This regression is then applied to AGCM forecasts forced by predicted SST in a two-tiered prediction system. 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 (Dec-Mar; DJFM) precipitation in Central Southwest (CSW)

Asia. Although observational studies relate the region's precipitation to tropical SST forcing with some sucess, 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 dynamical-statistical 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. In spite of errors in forecast SST, the dynamical-statistical forecasts capture some of the general features of the 1999-2003 period. The dynamical-statistical forecast probabilities show enhanced likelihood of below normal precipitation during the drought years and enhanced likelihood 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 estimate skill of a

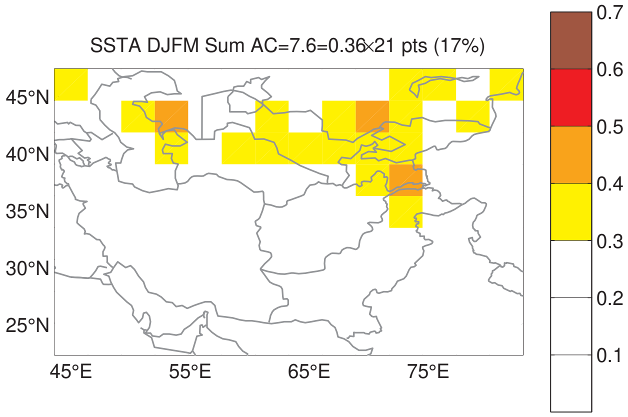


Figure 10. As in Fig. 5 but for the CCA-predicted precipitation using only simultaneous Pacific SST.

purely statistical CCA scheme using simultaneous observed SST as a predictor is slightly less that 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 dynamical-statistical method permits AGCMs to achieve skill levels comparable with, if not better then, purely statistical methods. Also since the response of the models varies, using several models increases sample size and may improve the robustness of the forecast.

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## REFERENCES


Agrawala, S., M. Barlow, H. Cullen, and B. Lyon, 2001: The Drought and Humanitarian Crisis in Central and Southwest Asia: A Climate Perspective. Technical report, IRI, Palisades, NY, available online at: http://iri.columbia.edu/outreach/publication/irireport/SWAsia/index.html.

Bacmeister, J., P. Pegion, S. Schubert, and M. Suarez, 2000: Atlas of seasona means simulated by the nsipp 1 atmospheric gcm. Technical Report NASA/TM-2000-104505, NASA, Vol. 17.

Barlow, M., H. Cullen, and B. Lyon, 2002: Drought in Central and Southwest Asia: La Niña, the Warm Pool, and Indian Ocean Precipitation. *J. Climate*, **15**, 697–700.

Barnett, T. P. and R. Preisendorfer, 1987: Origins and Levels of Monthly and Seasonal Forecast Skill for United States Surface Air Temperatures Determined by Canonical Correlation Analysis. *Mon. Wea. Rev.*, **115**, 1825–1850.

Chang, C.-P. and K. Lau, 1982: Short-Term Planetary-Scale Interactions over the Tropics and Midlatitudes during Northern Winter. Part I: Contrasts between Active and Inactive Periods. *Mon. Wea. Rev.*, **110**, 933–946.

Chang, C.-P. and K. Lum, 1985: Tropical-Midlatitude Interactions over Asia and the Western Pacific Ocean during the 1983/84 Northern Winter. *Mon. Wea. Rev.*, **113**, 1345–1358.

Feddersen, H., A. Navarra, and M. N. Ward, 1999: Reduction of Model Systematic Error by Statistical Correction for Dynamical Seasonal Predictions. *J. Climate*, **12**, 1974–1989.

Goddard, L., S. J. Mason, C. F. R. S. E. Zebiak, R. Basher, and M. A. Cane, 2001: Current approaches to seasonal-to-interannual climate prediction. *Int. J. Climatol.*, **21**, 1111–1152.

Hack, J., J. Kiehl, and J. Hurrell, 1998: The hydrologic and thermodynamic characteristics of the ncar ccm3. *J. Climate*, **11**, 1179–1206.

Hoerling, M. and A. Kumar, 2003: The Perfect Ocean for Drought. *Science*, **299**, 691–694.

Janowiak, J. and P. Xie, 1999: CAMS-OPI: A global satellite-rain gauge merged product for real-time precipitation monitoring applications. *J. Climate*, **12**, 3335–3342.

Ji, M., D. W. Behringer, and A. Leetmaa, 1998: An improved coupled model for ENSO prediction and implications for ocean initialization. Part II: The coupled model. *J. Climate*, **126**, 1022–1034.

Kharin, V. V. and F. W. Zwiers, 2003: Improved seasonal probability forecasts. *J. Clim.*, **16**, 1684–1701.

Kidson, J. W., M. J. Revell, B. Bhaskaran, A. B. Mullan, and J. A. Renwick, 2002: Convection Patterns in the Tropical Pacific and Their Influence on theAtmospheric Circulation at Higher Latitudes. *J. Climate*, **15**, 137–159.

Kinter, J., D. DeWitt, P. Dirmeyer, M. Fennessy, B. Kirtman, L. Marx, E. Schneider, J. Shukla, and D. Straus, 1997: The COLA atmosphere-biosphere general circulation model Volume: 1 Formulation. Technical Report 51, COLA, Calverton, MD.

Landman, W. A. and L. Goddard, 2002: Statistical recalibration of GCM forecasts over Southern Africa using model output statistics. *J. Climate*, **15**, 2038–2055.

Lau, K. M. and J. S. Boyle, 1987: Tropical and Extratropical Forcing of the Large-Scale Circulation: A Diagnostic Study. *Mon. Wea. Rev.*, **115**, 400–428.

Livezey, R. E., M. Masutani, and M. Ji, 1996: SST-forced seasonal simulation and prediction skill for version of the ncep/mrf model. *Bull. Amer. Meteor. Soc.*, **77**, 507–517.

Martyn, D., 1992: *Climates of the world*. Elsevier, 436 pp.

Mason, S. J. and L. Goddard, 2001: Probabilistic precipitation anomalies associated with enso. *Bull. Amer. Met. Soc.*, **82**, 619–638.

Mo, R. and D. M. Straus, 2002: Statistical-Dynamical Seasonal Prediction Based on Principal Component Regression of GCM Ensemble Integrations. *Mon. Wea. Rev*, **130**, 2167–2187.

New, M. G., M. Hulme, and P. D. Jones, 2000: Representing 20th century space-time climate variability. II: Development of 1901-1996 monthly terrestrial climate fields. *J. Climate*, **13**, 2217–2238.

Rajagopalan, B., U. Lall, and S. E. Zebiak, 2002: Categorical Climate Forecasts through Regularization and Optimal Combination of Multiple GCM Ensembles. *Mon. Wea. Rev.*, **130**, 1792–1811.

Roeckner, E., K. Arpe, L. Bengtsson, M. Christoph, M. Claussen, L. Dümenil, M. Esch, M. Giorgetta, U. Schlese, and U. Schulzweida, 1996: The atmospheric general circulation model ECHAM-4: Model description and simulation of present-day climate. Technical Report 218, Max-Planck Institute for Meteorology, Hamburg, Germany, 90 pp.

Ropelewski, C. and M. Halpert, 1987: Global and Regional Scale Precipitation Patterns Associated with the El Niño/Southern Oscillation. *Mon. Wea. Rev.*, **115**, 1606–1626.

—, 1989: Precipitation Patterns Associated with the High Index Phase of the Southern Oscillation. *J. Clim.*, **2**, 268–284.

Smith, T. M. and R. E. Livezey, 1999: GCM Systematic Error Correction and Specification of the Seasonal Mean Pacific-North America Region Atmosphere from Global SSTs. *J. Clim*, **12**, 273–288.

Tippett, M. K., M. Barlow, and B. Lyon, 2003: Statistical correction of Central Southwest Asia winter precipitation simulations. *Int. J. Climatology*, in press.

Widmann, M., C. Bretherton, and E. P. S. Jr., 2003: Statistical Precipitation Downscaling over the Northwestern United States Using Numerically Simulated Precipitation as a Predictor. *J. Climate*, **16**, 799–816.

Yang, S., K.-M. Lau, and K.-M. Kim, 2002: Variations of the East Asian Jet Stream and Asian-Pacific-American Winter Climate Anomalies. *J. Climate*, **15**, 306–325.