On North American Decadal Climate for 2011–20

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(Manuscript received 13 October 2010, in final form 24 February 2011)

ABSTRACT

The predictability of North American climate is diagnosed by taking into account both forced climate change and natural decadal-scale climate variability over the next decade. In particular, the ''signal'' in North American surface air temperature and precipitation over 2011–20 associated with the expected change in boundary conditions related to future anthropogenic greenhouse gas (GHG) forcing, as well as the ''noise'' around that signal due to internally generated ocean–atmosphere variability, is estimated. The structural uncertainty in the estimate of decadal predictability is diagnosed by examining the sensitivity to plausible scenarios for the GHG-induced change in boundary forcing, the model dependency of the forced signals, and the dependency on methods for estimating internal decadal noise. The signal-to-noise analysis by the authors is thus different from other published decadal prediction studies, in that this study does not follow a trajectory from a particular initial state but rather considers the statistics of internal variability in comparison with the GHG signal. The 2011–20 decadal signal is characterized by surface warming over the entire North American continent, precipitation decreases over the contiguous United States, and precipitation increases over Canada relative to 1971–2000 climatological conditions. The signs of these forced responses are robust across different sea surface temperature (SST) scenarios and the different models employed, though the amplitude of the response differs. The North American decadal noise is considerably smaller than the signal associated with boundary forcing, implying a potential for high forecast skill for 2011–20 North American climate even for prediction methods that do not attempt to initialize climate models. However, the results do suggest that initialized decadal predictions, which seek to forecast externally forced signals and also constrain the internal variability, could potentially improve upon uninitialized methods in regions where the external signal is small relative to internal variability.

1. Introduction

Physical factors determining the predictability of decadal climate over land include sensitivities to external radiative forcing, to local and remote surface boundary forcing, and to unforced variability associated with atmospheric noise. In this study, the contribution of these

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* The National Center for Atmospheric Research is sponsored by the National Science Foundation.

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DOI: 10.1175/2011JCLI4137.1

factors to decadal variability is estimated in the context of producing a probabilistic forecast of 10-yr averaged 2011–20 North American surface air temperature and precipitation. Our analysis of physical factors driving North American decadal variability also provides a framework for evaluating the initialized decadal predictions that are part of a coordinated suite of coupled model experiments under the Coupled Model Intercomparison Project phase 5 (CMIP5) (Meehl et al. 2009).

Key to evaluating decadal predictability of the terrestrial climate is identifying signals related to changes in external forcing and comparing those to the variability arising from processes internal to the climate system. We employ such a signal-to-noise analysis of decadal variability to quantify decadal predictability over North America, an approach conceptually similar to prior studies that assessed seasonal climate predictability (e.g., Kumar and Hoerling 1995; Rowell 1998). We first estimate the anthropogenically forced sea surface temperature (SST) and sea ice evolution for the next decade; subsequently, atmospheric general circulation models (AGCMs) are used to derive the climate responses to this decadal ''signal.'' The anthropogenic component of SST change over 2011–20 is estimated from the ensemble mean of CMIP3 (Meehl et al. 2007) coupled model projections. However, these projections have been shown to contain appreciable errors, especially in regional patterns of SST change (Shin and Sardeshmukh 2010). Moreover, such errors can lead to significant biases in the simulation of regional temperature and precipitation. Thus, we also construct estimates of the forced SST change using the temporal optimal detection method (Ribes et al. 2010), in which the temporal pattern of the forced response is derived from the CMIP3 simulations, but the spatial pattern of change is derived from observations. This strategy thus allows us to quantify the uncertainty in estimates of the decadal signal using large ensembles from multiple AGCMs.

In this approach, the assumption is made that the forced response can be reliably estimated from atmospheric models alone, rather than from fully coupled climate models. There are several lines of evidence supporting the merit of such an approach. Most (80%–90%) of the centennial-scale warming in land temperature has resulted from contemporaneous ocean warming and not from the direct impact of radiative forcing (Hoerling et al. 2006, 2008; Dommenget 2009; Compo and Sardeshmukh 2009). Similarly, the pattern and intensity of regional precipitation trends simulated in the ensemble of CMIP3 models for the period 1977–2006 has shown to be realistically reproduced in AGCMs forced by specifying the SST change occurring in the coupled models alone (Hoerling et al. 2010). Additionally, Northern Hemisphere atmospheric circulation trends during 1950–2000 are realistically simulated in atmospheric models forced only by SST variability, though a combination of changes in SSTs and direct atmospheric radiative forcing, especially related to stratospheric ozone depletion, is important in forcing Southern Hemisphere circulation trends (Deser and Phillips 2009).

The North American decadal ''noise,'' that fraction of decadal variability resulting from sensitivity to internal decadal SST variability and to atmospheric noise, is estimated using several additional suites of climate simulations. One set consists of an ensemble of multi-AGCM simulations forced by the observed SST and sea ice variations of the twentieth century [so-called Atmospheric Model Intercomparison Project (AMIP) simulations]. These simulations have the attribute of capturing the actual observed decadal variability of the ocean, if only for the short period of the climate record covered by instrumental observations. A second set is also used to estimate decadal noise consisting of the CMIP3 preindustrial control simulations of unforced coupled ocean–atmosphere models. In their aggregate ensemble size, these simulations yield nearly a tenfold increase in decadal samples versus the twentieth-century AMIP experiments.

A forecast of North American surface temperature and precipitation for 2011–20 that quantifies the implied predictability for the upcoming decade is generated. Efforts to predict the evolution of climate over the next several decades that take into account both forced climate change and natural decadal-scale climate variability are in their infancy, with only a few studies having investigated the impact of initializing climate projections. Two sensitivity studies found little additional predictability from initialization over that due to changes in external radiative forcing (Pierce et al. 2004; Troccoli and Palmer 2007). Three extended hindcast experiments provided some evidence for enhanced skill from initialization; however, the results depended on the initialization techniques, data, and model (Smith et al. 2007; Keenlyside et al. 2008; Pohlmann et al. 2009). Likewise, future 10-yr projections from these systems also come to somewhat different outcomes (Keenlyside and Ba 2010).

Our decadal forecast method differs considerably from the aforementioned studies in that we estimate the *statistics* of decadal North American climate that are consistent with various plausible scenarios of boundary conditions, whereas most other studies to date have followed an ensemble of integrations from a specific, observed initial state. Our forecast is thus constrained solely by the signal associated with the expected change in boundary conditions related to future anthropogenic greenhouse gas (GHG) forcing. A probabilistic decadal prediction is generated, the mean value of which is the anthropogenically forced signal, and the spread of which is due to internal decadal noise, forcing uncertainty, and model uncertainty. By framing our signal-to-noise analysis in the context of predictability for the upcoming decade's North American climate, we conclude that there exists a high potential skill for 2011–20 surface air temperature over the United States and Canada and for precipitation over Canada, even in prediction methods that do not involve initializing the climate system because the anthropogenic boundary-forced signals are found to be appreciably greater than the internal variability. By contrast, we conclude that initialized decadal predictions, which seek to forecast externally forced signals and also constrain the internal variability, could potentially improve upon uninitialized methods for forecasting U.S. decadal precipitation that exhibits a small externally forced signal compared to internal variability.

2. Datasets and methods

a. 2011–20 SST and sea ice scenarios

Three scenarios for the 2011–20 SST change (relative to 1971–2000) due to anthropogenic GHG emissions are generated (Fig. 1). One uses the 22-model average SST anomalies computed from the CMIP3 simulations (Meehl et al. 2007) subjected to the Special Report on Emissions Scenarios (SRES) A1B. We note that there is no appreciable difference in temperature responses through the first several decades of the twenty-first century among the CMIP runs using various emissions scenarios. The other two scenarios are derived by applying temporal optimal detection to observations, a method that permits detection of regional climate change by only giving a temporal pattern of change inferred from model simulations (Ribes et al. 2010). The latter can be inferred by smoothing temporal patterns of global averages or of spatial averages over a region of interest from forced climate models. Here we determine the temporal pattern of the forced response over 1901–2020 using the CMIP3 simulations, whereas the spatial pattern of change is derived from observations. In particular, the temporal pattern is generated by averaging global-mean surface air temperature over the 22 separate CMIP3 models for each year and further imposing a smoothing constraint as in Ribes et al. The temporal structure of the global air temperature resembles a linear increasing function during the first half of the twentieth century and an exponentially increasing function in later decades. A spatial pattern is computed by regressing observed SST upon the temporal pattern for 1901–2009, and the 2011–20 anomaly amplitudes are then derived from the temporal optimal for 2011–20. Given the observational uncertainty in estimating the spatial pattern of the centennial SST trend (e.g., Deser et al. 2010), two datasets—the NOAA Extended Reconstructed SST version 3b analysis (Smith et al. 2008) and the Hurrell analysis (Hurrell et al. 2008)—are used. All three SST scenarios of the anthropogenic change for 2011–20 exhibit widespread positive anomalies, with a maximum warming of about +0.5°C. The CMIP warming (Fig. 1, bottom), however, is generally greater than that based on observations (Fig. 1, top) and is characterized by a more uniform pattern of warming compared to observations. In particular, the anthropogenic signal of SST change estimated from observations has local minima in warming over the tropical east Pacific and the North Atlantic.

For Arctic sea ice, we use a single scenario that involves persisting the recent (2007–09) pattern of observed monthly sea ice concentration. This was a period of record low Arctic sea ice extent and concentration (see Fig. 1 in Kumar et al. 2010). Our use of 2007–09 sea ice concentrations for the 2011–20 period is consistent with the lower quartile range for summertime Arctic projections in CMIP3 simulations (Stroeve et al. 2007).

b. Climate model simulations

Three AGCMs are used: the fourth-generation National Center for Atmospheric Research Community Climate Model (CCM3) (Kiehl et al. 1998); the Geophysical Fluid Dynamics Laboratory Atmospheric Model, version 2.1 (GFDL AM2.1) (Delworth et al. 2006); and the NASA Seasonal-to-Interannual Prediction Project (NSIPP) model (Schubert et al. 2004). For analysis of the forced response to the three scenarios of SST change, the 2011–20 SST anomalies between 40°S and 60°N (Fig. 1) are added to the 1971–2000 climatological SSTs, and 50-yr integrations are conducted for each of the three models. These simulations provide 45 forecasts (five decadal means for each of three models and three SST scenarios) for 2011–20 that are consistent with the expected change in boundary conditions related to future anthropogenic greenhouse gas forcing. An additional 50-yr integration is performed for each of the three models in which the only boundary condition change is the sea ice scenario for 2011–20. The model-simulated anomalies for all scenarios are calculated with respect to control integrations forced by the repeating seasonal cycle of climatological SSTs and sea ice.

It is reasonable to expect that the boundary conditions for 2011–20 will also have an internal decadal component, which will also generate an atmospheric and terrestrial impact—a noise contribution adding to the uncertainty in decadal predictions. To estimate this component, a 40-member ensemble of the twentieth-century AMIP simulations (16 CCM3, 14 NASA, and 10 GFDL simulations) is also diagnosed. This ensemble average has been generated by combining simulations from the three AGCMs in which each was forced by the observed time history of ocean

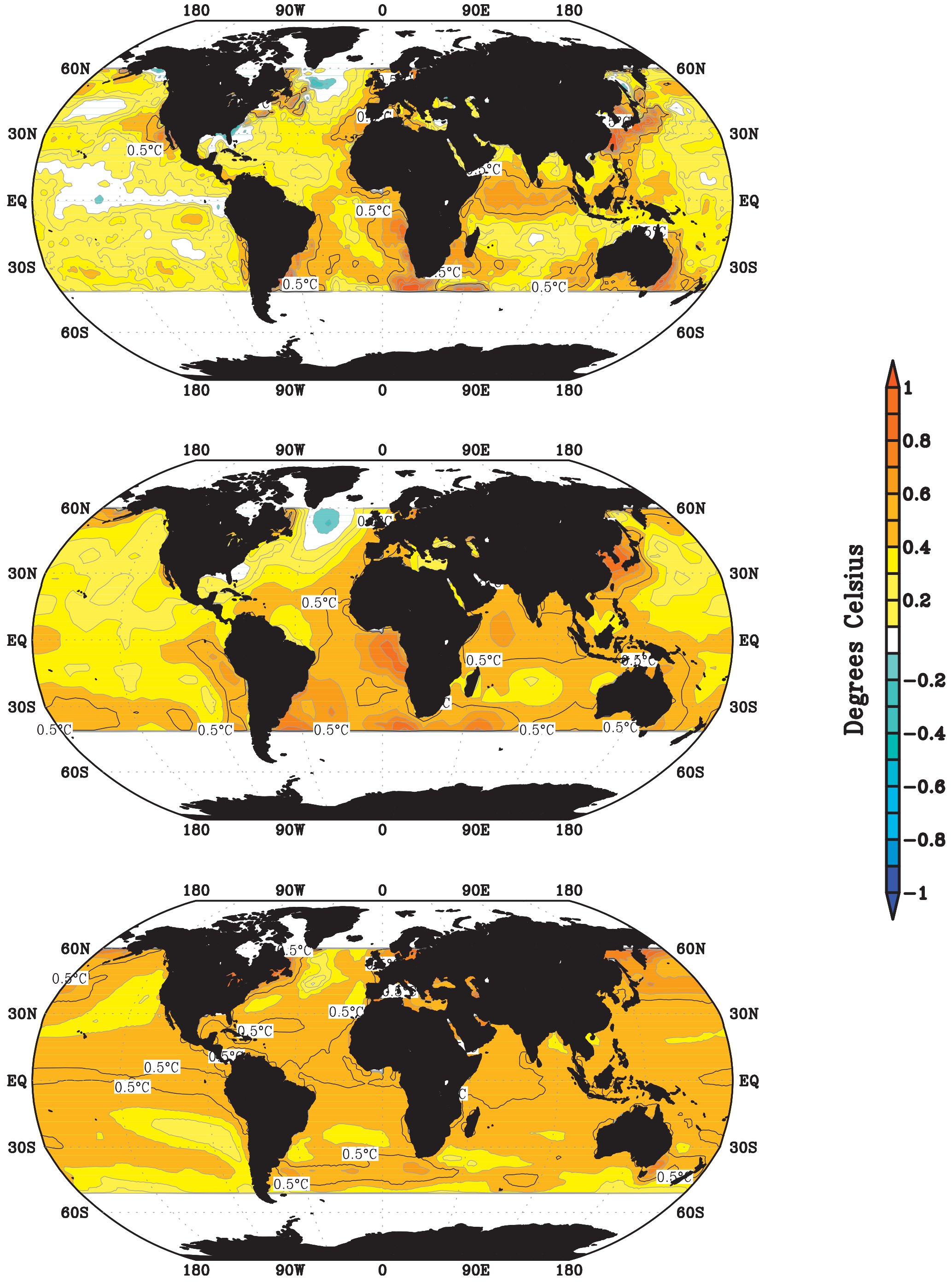

FIG. 1. Scenarios of the 2011–20 SST anomalies based on the method of temporal optimal detection applied to (top) the Hurrell et al. historical SST dataset, (middle) the NOAA historical SST datasets, and (bottom) the 22-model ensemble average of coupled model simulations forced by a business-as-usual (A1B) scenario of greenhouse gas change. All anomalies are relative to a 1971–2000 reference.

boundary forcing during 1902–2004. Using the method of temporal optimal detection, the annual surface temperature and precipitation of the model data are detrended (i.e., remove the anthropogenic signal) so as to estimate the impact associated with the natural, internal SST variability during the prior century. From this multimodel ensemble average, 94 consecutive running decadal-mean anomalies of North American surface temperature and

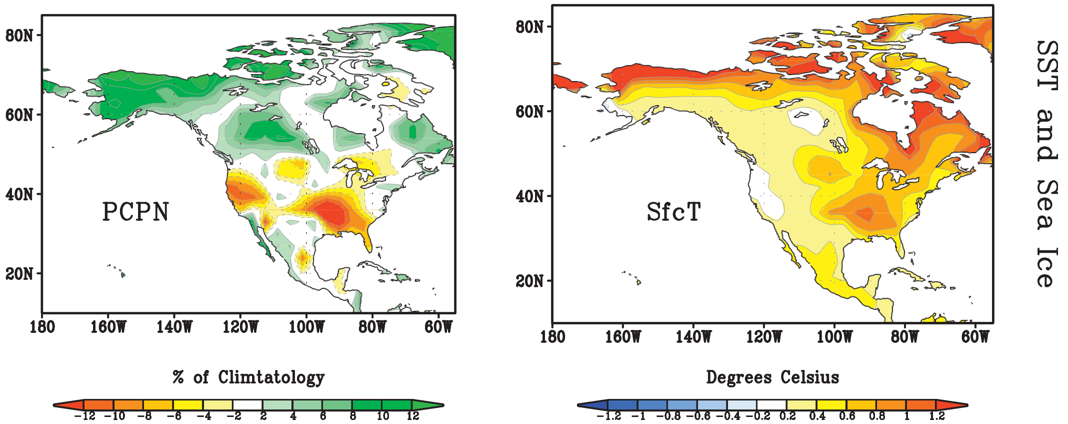

FIG. 2. Forced response of North American (left) precipitation (unit: % of annual climatology) and (right) surface air temperature (unit: °C) to the SST and sea ice scenarios for 2011–20. The forced response is the average of simulations using each of the three scenarios for anthropogenic changes in SSTs plus the response to the single scenario for changes in sea ice. The anomalies are based on the multimodel ensemble average of AGCM experiments, and are calculated relative to the models' 1971–2000 control climatologies.

precipitation during 1902–2004 are calculated and subsequently used to estimate North American decadal climate variability *forced* by internal decadal SST variability.

We use two different methods to determine the intensity of North American decadal variability arising from internal natural decadal-scale climate variability. One is based on the analysis of the twentieth-century AMIP simulations discussed above. The large ensemble of AGCM runs permits a diagnosis of the separate effects of purely atmospheric noise and of the impact by decadal SST/sea ice noise. The contribution of atmospheric noise is calculated from the spread in decadal anomalies occurring among individual runs of a particular model that have been otherwise subjected to identical ocean boundary forcing, and the contribution of decadal SST/sea ice noise was described in the previous paragraph. The sum of these two methods estimates the total internal decadal variability of the coupled system. In the second method, unforced, preindustrial control integrations of 21 separate CMIP3 models are diagnosed to provide an estimate of the internally generated decadal variability of North American climate. For each model, there is typically a multihundred year integration having preindustrial concentrations for greenhouse gases and aerosols. Nonoverlapping 10-yr averaged anomalies of North American surface temperature and precipitation are computed, resulting in approximately 800 samples of combined multimodel statistics available for analysis.

3. Results

a. *North American decadal signal*

The decadal signal in 2011–20 North American climate resulting from impacts of anthropogenic changes in SSTs and sea ice is shown in Fig. 2. The boundary-forced responses are calculated by averaging across model simulations using each of the three SST scenarios and the single sea ice scenario; the results are further averaged across the three different AGCMs. The average response is calculated by equal weighting the responses to each SST scenario and to the single sea ice scenario. The decadal signal is characterized by increased (decreased) precipitation over Canada and Alaska (the contiguous United States) with warming over all locations. The large warming signal over northern Canada and northern Alaska is mainly due to the impact of our scenario for depleted Arctic sea ice (not shown; see Fig. 3 in Kumar et al. 2010), whereas a warming signal elsewhere over North America results mainly from the region's sensitivity to global SST changes. Table 1 (left column) summarizes the forced responses for area averages calculated over two geographic regions: the contiguous United States and Canada/Alaska. For 2011–20 relative to the 1971–2000 mean, a warming signal of near +0.5°C occurs over both regions. The precipitation signals, expressed as percentage departures from the climatological annual totals, are characterized by a −2.1% drying over the contiguous United States and a +4.1% increase over Canada/Alaska.

Two factors contribute to uncertainty in our estimate of the decadal signals of North American climate for 2011–20. One is uncertainty in the prediction of the anthropogenically forced SST change itself. In Figure 3, the solid black curve illustrates the probability distribution function (PDF) of decadal anomalies based on all 45 forecasts, while colored curves indicate the estimated distributions for each SST scenario separately. The statistics of annual anomalies in temperature (top) and

TABLE 1. Decadal signals of contiguous U.S. and Canadian/Alaskan surface air temperature (TMP, °C) and precipitation (PPT, % of annual climatology) estimated from the forced responses to the 2011–20 SST/sea ice scenarios, the 2011–20 forecast uncertainty, and the 5%–95% confidence ranges. Remaining columns show the contributions to 2011–20 forecast uncertainty due to impacts of internal decadal SST variability and atmospheric (ATM) noise estimated from twentieth-century AMIP runs, and also the total internal decadal noise estimated from natural coupled ocean–atmosphere variability based on preindustrial CMIP3 simulations.

	2011–20 decadal signal	2011–20 forecast std dev	5%–95% confidence	Internal decadal SST std dev	ATM noise std dev	Decadal noise std dev
U.S. TMP (°C)	+0.48	0.27	−0.02/+0.93	0.15	0.15	0.20
Canada TMP (°C)	+0.49	0.28	+0.09/+0.98	0.11	0.13	0.31
U.S. PPT (%)	−2.1	3.6	−8.3/+3.4	2.7	2.4	3.6
Canada PPT (%)	+4.1	1.6	+1.8/+7.1	0.5	0.7	1.3

precipitation (bottom) are mostly insensitive to differences between the two observationally based SST forcing scenarios. By contrast, somewhat different statistics of decadal climate are generated in simulations using the CMIP 2011–2020 SST scenario, particularly for Canadian/Alaskan surface air temperature. The second factor concerns model uncertainty. We find the spread induced by different model sensitivities to be comparable to that resulting from scenario uncertainty (not shown). For both factors, however, the relatively small sample size of three SST scenarios and three models prevents a quantitative assessment of the uncertainty.

b. *North American decadal noise*

The estimate of noise based on the twentieth-century AMIP simulations, averaged across the three models, is summarized in Table 1 and indicates that atmospheric noise is a consequential source of decadal variability. This factor alone explains roughly 20%–30% of the total forecast uncertainty for our four predictands of 2011–20 conditions, although it should be noted that estimates of atmospheric noise derived from AGCMs may overstate their importance relative to that occurring in fully coupled systems (e.g., Barsugli and Battisti 1998).

The impact of decadal SST/sea ice noise is calculated from the variability of consecutive decadal averages of the multimodel ensemble means for the twentieth-century simulations (see section 2 for method details). Table 1 shows that the variability of North American decadal climate associated with the region's sensitivity to internal decadal SST/sea ice anomalies during the past century is comparable to that resulting from atmospheric noise alone. The PDFs for decadal anomalies forced solely by internal decadal SST variability are also plotted in Fig. 3 (dashed black curve). These reveal a considerably greater internal SST-forced variability for U.S. climate conditions than for Canadian climate conditions. We discuss these PDFs further in section 4 in the context of initialized decadal predictions.

It is possible that climate simulations spanning the relatively brief twentieth-century period may not adequately capture the range of internal decadal variability and that the decadal noise estimated thereby could be conservative. We have therefore also calculated the decadal variability of North American climate occurring in the long preindustrial simulations of the coupled ocean–atmosphere models of the CMIP3. The approximately 8000 years of model data undoubtedly captures a wider range of decadal SST/sea ice variability than was observed during the twentieth century alone. Nonetheless, the results, summarized in Table 1 (far right column), indicate that the internal variability calculated from the CMIP runs is quite similar to that estimated from the twentieth century AMIP experiments. The notable exception is for Canadian surface temperature for which the AMIP runs imply a total (atmosphere and ocean component) decadal standard deviation of 0.17°C compared to the appreciably greater 0.31°C standard deviation estimated from the CMIP runs.

c. *Predictability of North American climate for 2011–20*

The aforementioned analysis of decadal signal and noise provides an estimate for the predictability of North American climate conditions for the upcoming decade. Comparing the amplitude of the predictand signals (left side of Table 1) to the predictand noise (right side of Table 1) indicates that both U.S. and Canadian averaged surface temperature for 2011–20 is highly predictable, given that the anthropogenically forced change signal is roughly double the internal noise. A similar appraisal applies to the predictability of decadal Canadian precipitation, though low predictability is indicated for U.S. area-averaged precipitation for which the noise is nearly twice the amplitude of the anthropogenic signal. Of course, these estimates are drawn from a signal-to-noise analysis based on models with known biases, and thus may differ from the true predictability. Also, this analysis presumes the decadal noise is unpredictable, whereas initialized decadal prediction methods could constrain this noise component.

It is nonetheless instructive to consider the various attributes of a decadal prediction for North America in

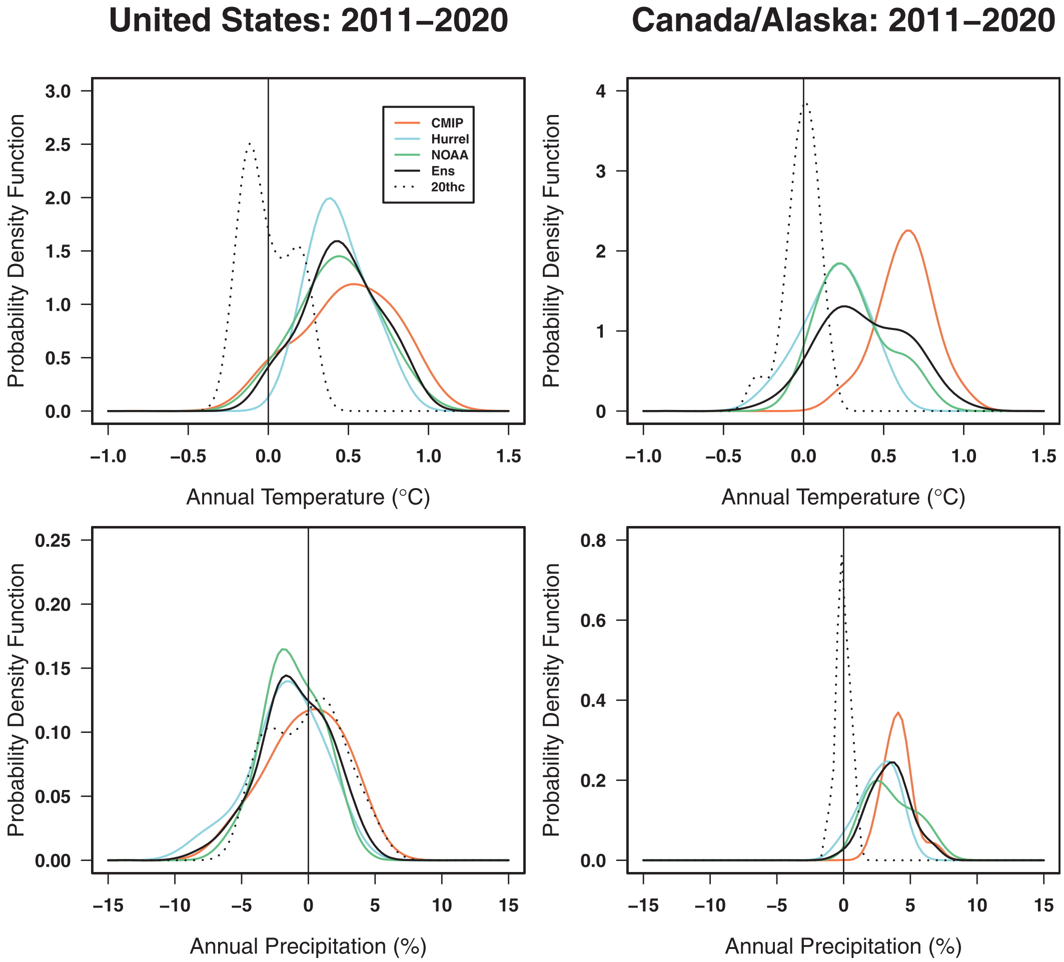

FIG. 3. Probability distribution functions for the 2011–20 SST-forced decadal anomalies of (left) contiguous U.S. (top) surface temperature and (bottom) precipitation and (right) Canada/Alaska surface (top) temperature and (bottom) precipitation. For each AGCM, five realizations of decadally averaged anomalies are computed for each of the three 2011–20 SST scenarios. The ensemble PDF (solid black curve) therefore consists of 45 samples, while the PDFs corresponding to each of the individual SST scenarios (solid colored curves) consist of 15 samples. PDFs for decadal anomalies forced by internal decadal SST variability (dashed black curve) are based on analysis of the detrended AMIP simulations of the twentieth century (see section 2 for details). Nonparametric PDFs are constructed using the Project for Statistical Computing R software program , which utilizes a kernel density estimation and a Gaussian smoother. Temperature anomalies (°C) and precipitation anomalies (% of annual climatology) are computed relative to a 1971–2000 reference.

which *only the impact of anthropogenic greenhouse gas forcing* is considered, while a specific trajectory of the internal variability is not predicted. We generate such a probabilistic decadal forecast by commingling the PDFs of the forced responses to our scenarios of anthropogenic changes in ocean boundary conditions with the decadal climate conditions resulting from natural, internal decadal SST variability during the twentieth century (PDFs, solid blue lines in Fig. 4). The combination yields 4230 samples (45 forced solutions commingled with 94 internal decadal solutions), and it is assumed that the North American anomalies resulting from natural decadal SST conditions and from the anthropogenic change component are linearly additive. By ranking the separate 4230 (45 × 94) predictions that make up the blue PDFs, the forecast relative to the 1971–2000 mean climate indicates a 94% and 98% probability for warmer-than-normal conditions over the United States and Canada, respectively; a 99% probability of wet conditions over Canada; and a 75% probability of dry conditions over the United States.

Also shown in Fig. 4 are the PDFs (dotted curves) of decadal anomalies due to internal variability alone based on the statistics derived from the roughly 8000 independent samples of 10-yr averages from the preindustrial CMIP3 simulations. In the absence of any constraint on the internal variations, the expected skill of the decadal

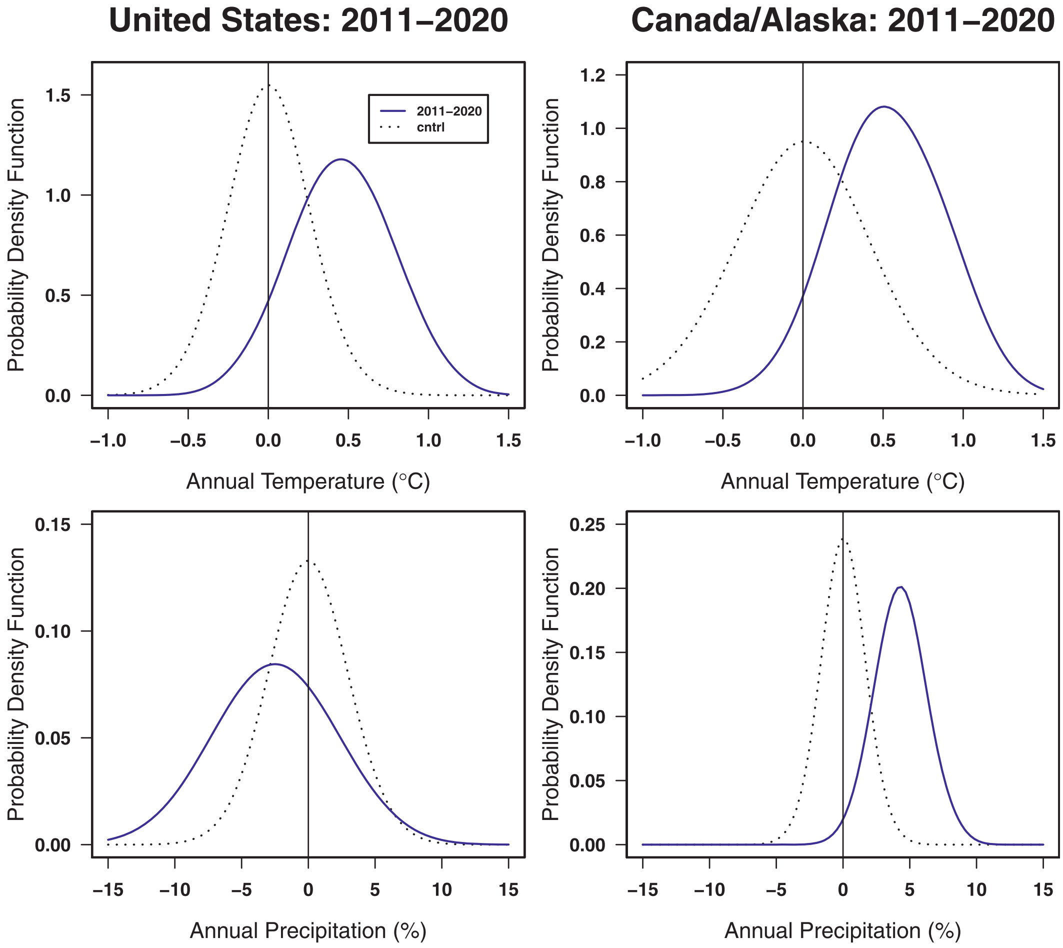

FIG. 4. Probabilistic forecasts (solid blue curves) for the 2011–20 decadal anomalies of (left) contiguous U.S. (top) surface temperature and (bottom) precipitation and (right) Canada/Alaska (top) surface temperature and (bottom) precipitation. The curves are based on commingling the PDFs of the forced responses to our scenarios of anthropogenic changes in ocean boundary conditions and the decadal climate conditions resulting from natural, internal decadal SST variability during the twentieth century. The combination yields 4230 samples (45 forced solutions commingled with 94 internal decadal solutions), and it is assumed that the North American anomalies resulting from natural decadal SST conditions and from the anthropogenic change component are linearly additive. PDFs were constructed as in Fig. 3, and all departures are relative to the 1971–2000 reference. Dotted-line PDFs illustrate the statistics of decadal climate anomalies derived from the roughly 8000 independent samples of 10-yr averages calculated from preindustrial CMIP3 simulations.

forecast can be inferred from the amplitude of the shift in the PDF due to the anthropogenic forcing relative to the spread of the PDF due to the decadal noise. It is evident that, with the exception of U.S. precipitation, appreciable skill would be expected from uninitialized prediction methods in which the sole predictor is the anthropogenic greenhouse gas forcing.

4. Concluding remarks

We have applied a signal-to-noise analysis to the predictability of decadal averages over North America. The ''decadal signal'' was estimated as the response to SST/sea ice forcing that results from impacts of anthropogenic changes in ocean surface boundary conditions. The ''decadal noise,'' the internally generated decadal variability of the ocean–atmosphere coupled system, was estimated from both atmospheric models driven by observed ocean boundary variations for the twentieth century and also from unforced coupled models simulating preindustrial climate variability. As a particular illustration of this analysis of decadal predictability, we constructed a 2011–20 North American temperature and precipitation probabilistic forecast that quantified the signal, the internal variability, and overall uncertainty.

Many challenges remain regarding decadal prediction (e.g., Hurrell et al. 2010). For instance, the possibility that forecast uncertainty will be high is implied by the large amplitude of the spread in our PDFs. While skill in decadal predictions based on uninitialized methods is expected (Lee et al. 2006), initialized decadal predictions hold the prospect for reducing uncertainty by actually discriminating among trajectories of future internal climate states (e.g., Hawkins and Sutton 2009; Keenlyside and Ba 2010). We note in particular that decadal U.S. temperature and precipitation associated with internal decadal SST variations exhibit an almost bimodal distribution, being either warm/dry or cold/wet (Fig. 3, dashed PDFs). We find this characteristic of simulated U.S. decadal conditions to be consistent with multidecadal periods in which North Pacific and North Atlantic SSTs reside in either warm or cold regimes during the twentieth century (not shown), which is a sensitivity consistent with the results of idealized SST anomaly experiments analyzed by Schubert et al. (2009) to examine U.S. drought-related SST forcing patterns. Our results suggest that initialized decadal predictions, which seek to forecast externally forced signals and constrain the internal variability, could particularly improve upon uninitialized CMIP methods in regions where the external signal is small compared to internal variability, such as for U.S. decadal precipitation. There is thus opportunity to sharpen the probability forecasts based on a skillful prediction of such internal multidecadal states of the oceans.

Acknowledgments. The authors thank Aurélien Ribes for his helpful discussions about the temporal optimal patterns, and Robin Webb and Tom Delworth for their comments regarding an earlier draft of the paper. The comments by three anonymous reviewers on an earlier draft of the paper are also gratefully acknowledged. Support for this work was provided by the NOAA Climate Program Office's Climate Variability Program.

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