Temperature Trends in the NARCCAP Regional Climate Models

MELISSA S. BUKOVSKY

National Center for Atmospheric Research, Boulder, Colorado

(Manuscript received 10 October 2011, in final form 9 February 2012)

ABSTRACT

The skill of six regional climate models (RCMs) in reproducing short-term (24-yr), observed, near-surface temperature trends when driven by reanalysis is examined. The RCMs are part of the North American Regional Climate Change Assessment Program (NARCCAP). If RCMs can reproduce observed temperature trends, then they are, in a way, demonstrating their ability to capture a type of climate change, which may be relevant to their ability to credibly simulate anthropogenic climate changes under future emission scenarios. This study finds that the NARCCAP RCMs can simulate some resolved-scale temperature trends, especially those seen recently in spring and, by and large, in winter. However, results in other seasons suggest that RCM performance in this measure may be dependent on the type and strength of the forcing behind the observed trends.

1. Introduction

Regional climate models (RCMs) should be able to capture large-scale temperature trends when forcing for these trends is included in the driving boundary conditions. This is logical, but it is only recently that the RCM community has tested its models' performances in this way, and examples are still not prevalent in the literature. Testing for skill in reproducing trends is a relatively recent phenomenon (e.g., Giorgi et al. 2004), while testing for general skill in regional climate models extends back much further (e.g., Dickinson et al. 1989). Proficiency in reproducing observed trends was recently included as one of six model performance metrics for weighting the RCMs participating in the ensembles-based predictions of climate changes and their impacts (ENSEMBLES) program (Christensen et al. 2010; Lorenz and Jacob 2010).

Trends may be unrelated to model mean bias, but they can certainly give information relevant to diagnosing the causes of model bias, and they may even unveil different types and characteristics of bias. This was the initial motivation for examining trends in the North American Regional Climate Change Assessment Program (NARCCAP) RCMs. However, if a model is reproducing observed trends, even over short periods, it is, in a sense, demonstrating its ability to simulate climate changes. Good performance then might give us more confidence in trends projected for the future (Giorgi et al. 2004; Tebaldi and Knutti 2007).

Here, I examine the performance of the NARCCAP (Mearns et al. 2009) reanalysis–driven RCMs in simulating observed 2-m temperature trends from 1980 to 2003. Over this short period, trends may be forced by many factors, for example, greenhouse gas concentrations, aerosol concentrations, sea surface temperatures (SSTs), land use changes, volcanic and solar activity, and the natural interdecadal variability of the climate system. How these factors influence trends and their simulation is also discussed.

2. Methods

The six NARCCAP RCMs driven by the National Centers for Environmental Prediction/Department of Energy Global Reanalysis 2 (NCEP-2; Kalnay et al. 1996) used here include the following:

- Canadian RCM (CRCM; Caya and Laprise 1999),
- Experimental Climate Prediction Center's version of the Regional Spectral Model (ECP2; Juang et al. 1997)
- Third-generation Hadley Centre RCM (HRM3; Jones et al. 2003),
- Fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model run by the Iowa State University modeling group (MM5I; Grell et al. 1993),

Corresponding author address: Melissa S. Bukovsky, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000.
E-mail: bukovsky@ucar.edu

DOI: 10.1175/JCLI-D-11-00588.1

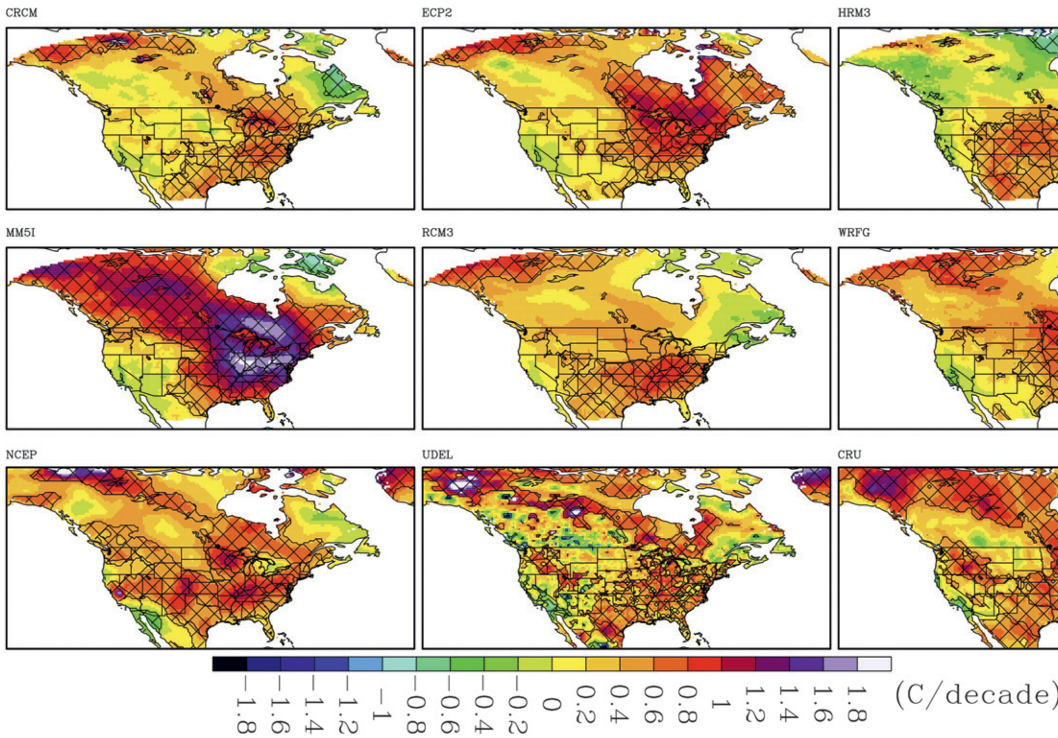

FIG. 1. DJF 2-m temperature trends during 1980–2003 from the six NARCCAP RCMs, NCEP-2, UDEL, and CRU (color fill, °C decade^{-1}). Hatching indicates where trends are statistically different from zero at the 0.01 level. Missing RCM data over land in the top-left and -right corners and along the bottom are outside of a given RCM's computational domain and only appear because of the chosen map projection and plot boundaries (values in each RCM's relaxation zone have also been removed).

- International Centre for Theoretical Physics RCM version 3 (RCM3; Giorgi et al. 1993a,b; Pal et al. 2007),
- Weather Research and Forecasting Grell model (WRFG; Skamarock et al. 2005).

One of two NARCCAP time slices is also utilized. It is produced by the atmospheric component of the Geophysical Fluid Dynamics Laboratory, version 2.1 (GFDL AM2.1; GFDL GAMDT 2004) global climate model (GCM) forced with observed SSTs and sea ice at the lower boundary. The second time slice is not available yet.

The NARCCAP RCMs all have a horizontal resolution of 50 km and have been regridded using bilinear interpolation to a 0.5° latitude/longitude grid for ease of comparison given that their projections vary. The CRCM and ECP2 are the only two models that include some form of nudging (a push toward the large-scale driving conditions in the interior of the domain). That particular feature is relevant to this study. Further details about NARCCAP and the RCMs can be found in Mearns et al. (2012) or online (at www.narccap.ucar.edu).

RCM-simulated 2-m temperature trends will be compared to observed trends in both the Climatic Research Unit (CRU; Mitchell and Jones 2005) and University of Delaware (UDEL; Willmott and Matsuura 1995) observationally based datasets, as well as their driver (NCEP-2). Multiple observations are used because all differ slightly, and this will give the reader a better sense of the uncertainty in the observations. For example, one will notice that the trends in UDEL are noisier than those in CRU due to differences in observation interpolation methodology.[1]

Trends are calculated using linear regression for each land-based grid box on seasonal averages. A Student's t test is used to determine if the trend at each point is significantly different from zero at the 0.01 level. If the time series at a given grid point is found to have a significant lag-1 autocorrelation at the 0.1 level, then the degrees of freedom for use in the significance test are adjusted appropriately (Zwiers and von Storch 1995).

A test is also performed to show where the trends are significantly different from trends in CRU at the 0.01 level using the Student's t test. The test is simply the difference between the slopes divided by the standard error of the difference between the slopes. This is used

[1] One might also notice the odd bull's-eye of cooling in Quebec in CRU. I have not yet found an explanation for this apparent inconsistency.

TABLE 1. Percentage of domain with trends that are statistically different from those in CRU.

	DJF	MAM	JJA	SON
CRCM	10.69	8.86	26.89	18.78
ECP2	12.10	12.69	26.68	15.69
HRM3	25.92	51.07	59.08	23.22
MM5I	26.66	36.12	53.25	19.08
RCM3	7.31	7.02	40.52	34.00
WRFG	11.14	30.69	49.98	32.01
NCEP-2	11.26	23.82	46.06	19.45
UDEL	11.21	12.71	28.15	14.37

to show a rough agreement/disagreement with CRU over the full domain (minus ocean areas). CRU is chosen over UDEL as a baseline for comparison in this metric because it contains a smoother trend field. This reduces dissimilarities caused by extraneous noise.

3. Results

a. Winter

December–February (DJF) temperature trends for 1980–2003 are shown in Fig. 1. Warming occurred over most of North America (NA) during this period, with areas of significant positive trends in eastern and northern NA and over the U.S. Rocky Mountains. Error in capturing DJF temperature trends is relatively small; most RCMs even capture, to some extent, the small region of cooling/minor warming near coastal California and the northern Baja peninsula. However, while NCEP-2, UDEL, and CRU all indicate statistically significant warming over 50%–60% of the domain, most of the models cover only 30%–40% of the domain, except ECP2 at about 51% and MM5I at 75%. This does not mean that they are warming at a pace that is significantly different than observed though. Four out of the six models and UDEL and NCEP-2 have trends that are statistically similar to those in CRU over 90% ± 3% of the region (see Table 1).

HRM3 and MM5I are less similar to CRU (75% ± 2%) and are exhibiting biases that will be seen in all seasons. Specifically, HRM3 has a cooling bias over the northern half of Canada, and MM5I has a strong warming bias in the trend that affects the whole domain. A more detailed discussion of the nature of these trends in bias, other biases not discussed here, and their impacts in climate change simulations for the NARCCAP RCMs is outside the scope of this short paper, but it will be more thoroughly detailed in forthcoming work.

b. Spring

Trends for March–May (MAM) are shown in Fig. 2. Explanations for near-term MAM trends are remarkably

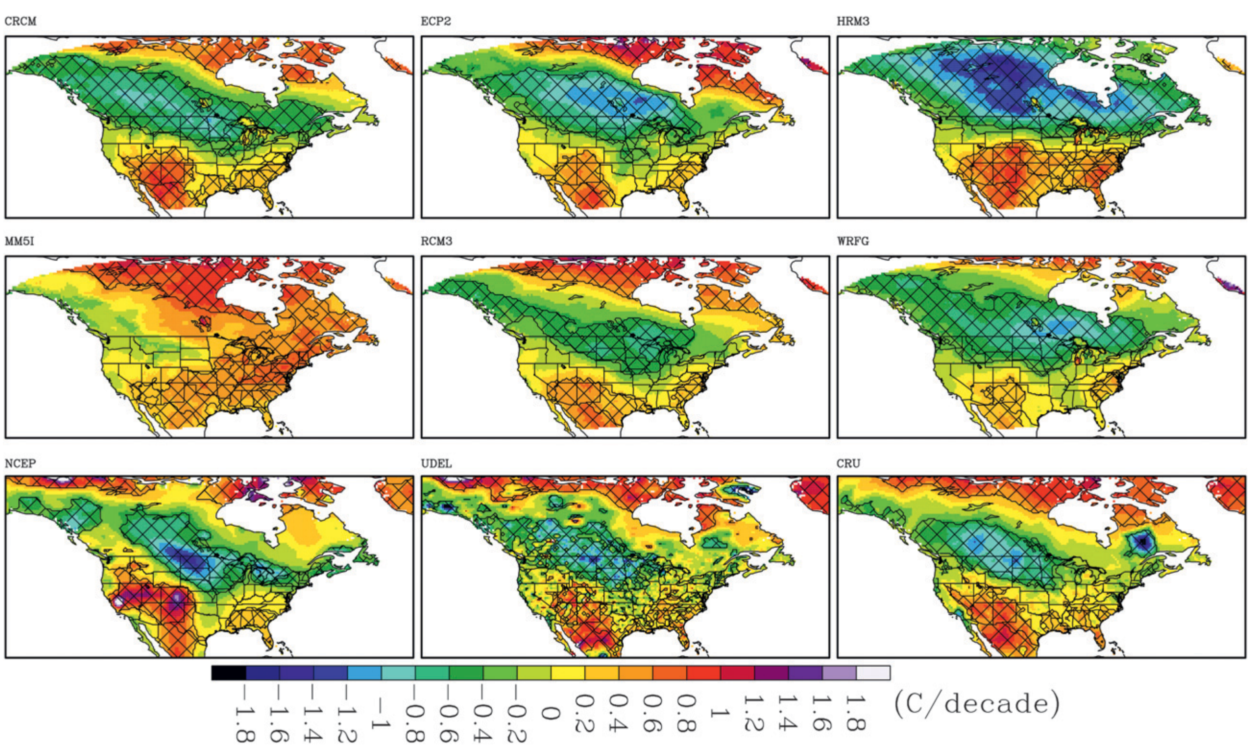

FIG. 2. As in Fig. 1, but for MAM.

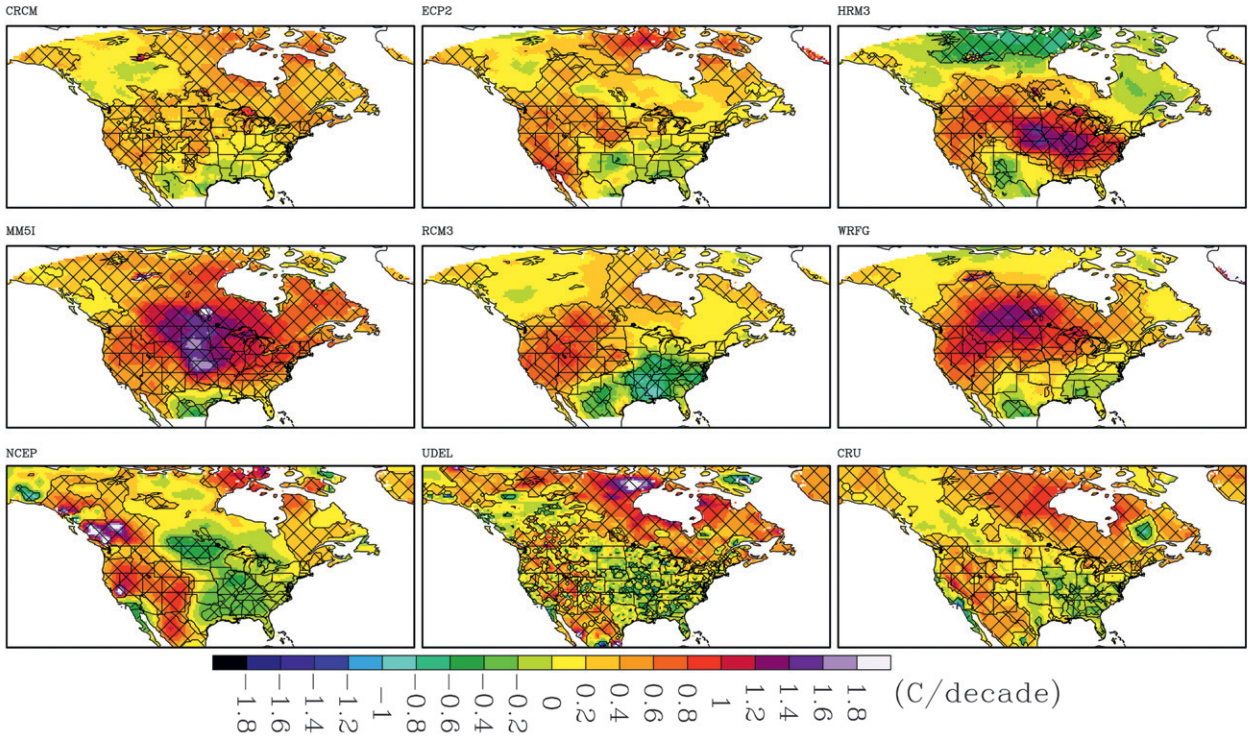

FIG. 3. As in Fig. 1, but for JJA.

neglected in existing literature, especially considering how strong the trends are. As illustrated in Fig. 2, there was a substantial swath of springtime cooling over this 24-yr period extending from southern Alaska to the Midwest, with warming in the Southwest and Southeast, and the Canadian Arctic. The cooling in MAM was pointed out in Trenberth et al. (2007, p. 250) in reference to global, seasonal plots of 1979–2005 trends. Trenberth et al. (2007) hypothesize that this cooling might be related to increasingly positive North Atlantic Oscillation (NAO) index values from the 1960s through the mid-1990s (decreasingly positive since). While this may be partially responsible for the pattern of DJF trends, it remains unclear how the NAO is impacting the MAM trends over NA, as discussion of the shoulder seasons is rather neglected in the literature. However, it is reasonable that the NAO plays a role here, as a strong winter NAO signal persists through the Northern Hemisphere cold season (November–April) and can have lasting impacts through the year (Hurrell et al. 2003; Thompson et al. 2003).

All of the models perform well in spring. The MM5I with its warming bias and HRM3 with its northern cooling bias also capture MAM trends in the context of their predispositions. RCM3 and CRCM exhibit trends that are significantly different from those in CRU over only 7%–9% of the domain. ECP2 and UDEL are significantly different from CRU over about 13% of the domain, and the other models range from 24% to 51% as shown in Table 1.

c. Summer

June–August (JJA) trends are shown in Fig. 3. JJA observations exhibit the well documented, but not causally agreed upon, ''warming hole'' (WH). The WH is the large swath of cooling/near-zero warming that extends from the Southeast northwestward into the Canadian plains. Potential reasons for it include an increase in the strength of the subtropical high over the West promoting more cold-air advection into the plains (Pan 2011), an increase in the strength of the low-level jet leading to an increase in cloud cover and precipitation over the Midwest and plains (Pan et al. 2004), and Pacific decadal variability (Wang et al. 2009), perhaps compounded by changes in the land surface (Diffenbaugh 2009). A contribution to the cooling in the Southeast from an increase in aerosols may also be a factor (Portmann et al. 2009 and references contained therein).

Performance in JJA is mixed. The RCMs do not clearly capture a WH. The two RCMs that use nudging, the CRCM and ECP2, do better. Their trends are significantly different from those in CRU over only approximately 27% of the domain, akin to UDEL at 28% (partly due to noise in the UDEL field). The other RCMs

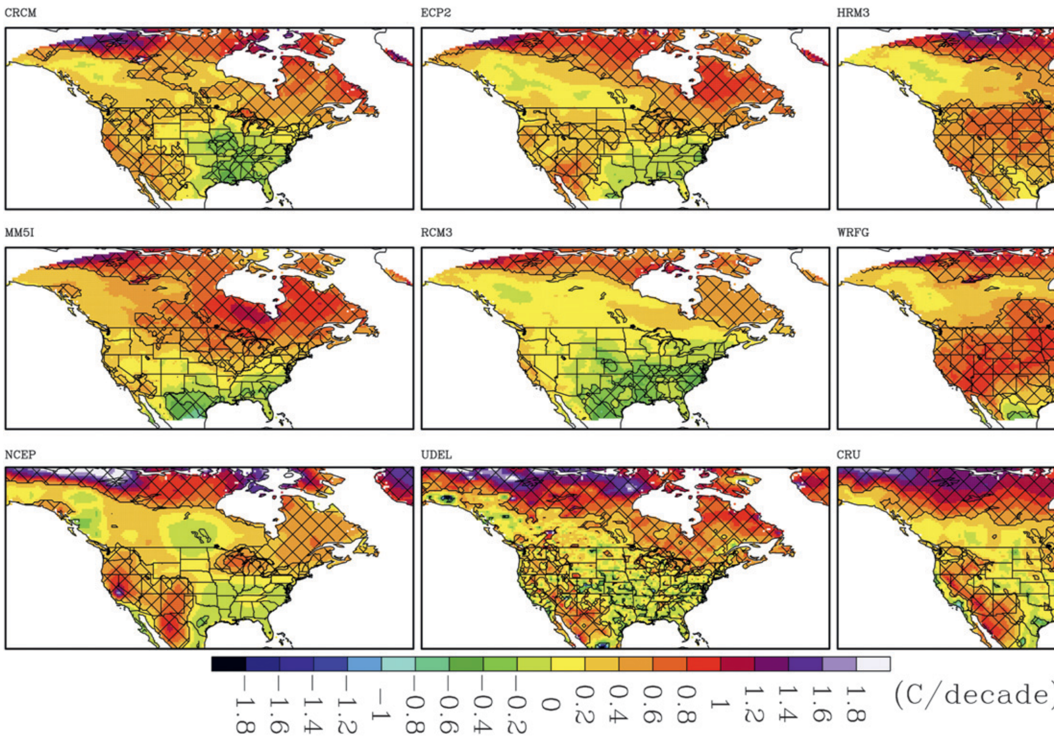

FIG. 4. As in Fig. 1, but for SON.

and NCEP-2 are significantly different from CRU over 40%–60% of the domain, with RCM3 performing best out of the nonnudged models in this season.

d. Fall

Observed trends in September–November (SON) are similar to those in JJA, as shown in Fig. 4, but SON trends may also be influenced by Atlantic multidecadal SST variability (Wang et al. 2009). Performance in SON is better than in JJA. Correspondingly, the RCMs' trends in SON are statistically similar to CRU over more of the domain (see Table 1). All RCMs are similar over about 66%–85% of the domain, with CRCM and ECP2 still performing best by this measure, in SON. This time, RCM3 is the most dissimilar.

4. Summary

It has been shown that the NARCCAP RCMs reasonably capture some observed trends in 2-m temperature when driven by reanalysis. However, it is clear that some RCMs cannot capture certain seasonal trends over portions of the NARCCAP domain. There are no clear, overarching tendencies toward over- or underestimating trends detected in this analysis that encompass all of the RCMs consistently across all seasons and regions. This is in contrast to the ENSEMBLES RCMs, which tended to produce trends over Europe that were weaker than observed (Lorenz and Jacob 2010).[2] Nevertheless, two RCMs do have notable biases in their trends: the MM5I has a strong widespread warming bias and the HRM3 has a strong cooling bias in the northern half of Canada.

5. Discussion

Differences in performance between seasons/regions may be the result of differences in the strength and type of trend forcing. In some areas, a failure to capture the observed trend may be a result of excluded or unresolved processes in the RCMs. For example, if the JJA WH in the plains is influenced by changes in land surface type and/or agricultural practices over time, as discussed in Diffenbaugh (2009), the RCMs would not capture this component of the trend, as the land surface characteristics are held constant with time. However, if the WH is forced by SST variability from outside the domain, one would expect the atmospheric-related effects to translate into the domain if they are present in the driver. Nonetheless, if this forcing is weak, given the large size

[2] Note that the ENSEMBLES simulations were forced by the 40-yr European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-40), not NCEP-2.

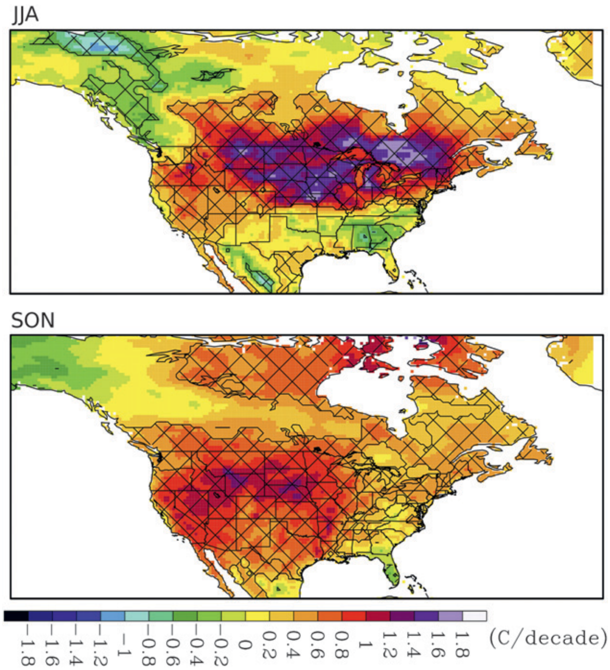

FIG. 5. (top) JJA and (bottom) SON 2-m temperature trends during 1980–2000 from the GFDL AM2.1 time-slice experiment. Hatching as in Fig. 1.

of the NARCCAP domain, then it may not translate well unless the RCM is nudged. As shown, the two nudged RCMs do perform best, though far from perfectly, in producing this phenomenon (Figs. 3, 4).

In contrast, the RCMs all capture the strong trends in spring (Fig. 2). This might imply that the atmospheric signal from the NAO (if that is indeed the cause) is stronger or better represented in the boundary conditions than the signal from the SST variability that might be forcing the WH.

Given the potential influence of SSTs in forcing the WH, the GFDL AM2.1 might be expected to produce trends that are closer to those observed in JJA and SON. It does not have to translate a signal through domain boundaries. However, this is not the case. It does, nevertheless, capture the cooling trend in the Southeast, like the RCMs. This is illustrated in Fig. 5.

One aspect of this study may aid in the attribution of one of the observed trends. As shown, all RCMs and the GFDL AM2.1 capture the SON WH in the Southeast, and most do in JJA as well (Figs. 3, 4). If this trend were, in fact, caused by an increase in aerosol content, then most RCMs would not capture this trend, at least not for the right reason. The RCMs do include aerosols; however, in all but two (CRCM and HRM3) this is done crudely. Specifically, most of the models use a climatologically realistic value in their radiation parameterizations that is constant in both time and space (i.e., there are no regions with more aerosols than others at any time in ECP2, MM5I, RCM3, and WRFG). Because of this homogeneousness, this could not be the cause of the Southeast cooling in all of the RCMs. The agreement among the models indicates that other mechanisms are likely in play in this region in reality.

Some of this discussion begs the question of whether examining trends in the regional models is a fair test. Obviously there is no straightforward answer to this question, as the answer depends on several complicating factors related to the processes included in the RCMs and the forcing behind the observed trends. Here, it is also interesting that where the models perform relatively well, they also tend to show the most intramodel agreement, conceivably indicating where trends are more strongly forced and have causal processes that the models are all able to simulate.

It should also be noted that observed trends are unlikely to be captured in a more realistic manner in the GCM-driven NARCCAP simulations, as the GCMs are not expected to contain the signals forcing these trends with the same temporal phasing. With GCM-driven simulations, multiple realizations would likely be needed in order to characterize the internal variability of the system and encompass the observed trend, as discussed in Giorgi et al. (2004).

Finally, there are potential implications for future projections and bias correction in this study, particularly where trends in bias (i.e., bias in the trends or RCM drift) are concerned. For example, the warming bias in the MM5I is present in the GCM-driven simulations also (not shown), and this bias may not be constant present to future, creating more or less warming artificially. Similarly, this could affect studies using current and future time series where the simulations have been bias corrected to the mean, not taking into account that the bias changes during the simulation period. Further examination of the NARCCAP simulations along these lines is underway.

Acknowledgments. The author wishes to thank Linda Mearns, the rest of the NARCCAP team, and the two anonymous reviewers for helping to shape this manuscript, and NARCCAP for providing the data used in this paper. NARCCAP is funded by NSF, DOE, NOAA, and the EPA ORD. This work was funded by EPA ORD Grant DW-49-92280601-1.

REFERENCES

Caya, D., and R. Laprise, 1999: A semi-implicit semi-Lagrangian regional climate model: The Canadian RCM. *Mon. Wea. Rev.,* **127,** 341–362.

Christensen, J. H., E. Kjellström, F. Giorgi, G. Lenderink, and M. Rummukainen, 2010: Weight assignment in regional climate models. *Climate Res.,* **44,** 179–194.

Dickinson, R. E., R. M. Errico, F. Giorgi, and G. T. Bates, 1989: A regional climate model for the western United States. *Climatic Change,* **15,** 383–422.

Diffenbaugh, N. S., 2009: Influence of modern land cover on the climate of the United States. *Climate Dyn.,* **33,** 945–958.

GFDL GAMDT, 2004: The new GFDL global atmosphere and land model AM2–LM2: Evaluation with prescribed SST simulations. *J. Climate,* **17,** 4641–4673.

Giorgi, F., M. R. Marinucci, and G. T. Bates, 1993a: Development of a second-generation Regional Climate Model (RegCM2). Part I: Boundary-layer and radiative transfer processes. *Mon. Wea. Rev.,* **121,** 2794–2813.

——, ——, G. de Canio, and G. T. Bates, 1993b: Development of a second-generation Regional Climate Model (RegCM2). Part II: Convective processes and assimilation of lateral boundary conditions. *Mon. Wea. Rev.,* **121,** 2814–2832.

——, X. Bi, and J. S. Pal, 2004: Mean, interannual variability and trends in a regional climate change experiment over Europe. I. Present-day climate (1961-1990). *Climate Dyn.,* **22,** 733–756.

Grell, G., J. Dudhia, and D. R. Stauffer, 1993: A description of the fifth-generation Penn State/NCAR Mesoscale Model (MM5). NCAR Tech. Note NCAR/TN-398+1A, 107 pp.

Hurrell, J. W., Y. Kushnir, G. Ottersen, and M. Visbeck, 2003: An overview of the North Atlantic Oscillation. *The North Atlantic Oscillation: Climatic Significance and Environmental Impact, Geophys. Monogr.,* Vol. 134, Amer. Geophys. Union, 1–35.

Jones, R. G., D. C. Hassell, D. Hudson, S. S. Wilson, G. J. Jenkins, and J. F. B. Mitchell, 2003: Workbook on generating high resolution climate change scenarios using PRECIS. UNDP, 32 pp.

Juang, H.-M., S.-Y. Hong, and M. Kanamitsu, 1997: The NCEP regional spectral model: An update. *Bull. Amer. Meteor. Soc.,* **78,** 2125–2143.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Lorenz, P., and D. Jacob, 2010: Validation of temperature trends in the ENSEMBLES regional climate model runs driven by ERA40. *Climate Res.,* **44,** 167–177.

Mearns, L. O., W. J. Gutowski, R. Jones, R. Leung, S. McGinnis, A. M. B. Nunes, and Y. Qian, 2009: A regional climate change assessment program for North America. *Eos, Trans. Amer. Geophys. Union,* **90,** 311, doi:10.1029/2009EO360002.

——, and Coauthors, 2012: The North American Regional Climate Change Assessment Program: Overview of phase I results. *Bull. Amer. Meteor. Soc.,* in press.

Mitchell, T. D., and P. D. Jones, 2005: An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *Int. J. Climatol.,* **25,** 693–712.

Pal, J. S., and Coauthors, 2007: Regional climate modeling for the developing world: The ICTP RegCM3 and RegCNET. *Bull. Amer. Meteor. Soc.,* **88,** 1395–1409.

Pan, Z., 2011: Dynamic and soil moisture feedbacks in regional climate change over the central U.S. *Proc. 25th Conf. on Hydrology,* Seattle, WA, Amer. Meteor. Soc., J11.3. [Available online at http://ams.confex.com/ams/91Annual/webprogram/Paper185712.html.]

——, R. W. Arritt, E. S. Takle, W. J. Gutowski Jr., C. J. Anderson, and M. Segal, 2004: Altered hydrologic feedback in a warming climate introduces a ''warming hole.'' *Geophys. Res. Lett.,* **31,** L17109, doi:10.1029/2004GL020528.

Portmann, R. W., S. Solomon, and G. C. Hegerl, 2009: Spatial and seasonal patterns in climate change, temperatures, and precipitation across the United States. *Proc. Natl. Acad. Sci. USA,* **106,** 7324–7329.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and J. G. Powers, 2005: A description of the Advanced Research WRF version 2. NCAR Tech. Note NCAR/TN-468+STR, 88 pp.

Tebaldi, C., and R. Knutti, 2007: The use of the multi-model ensemble in probabilistic climate projections. *Philos. Trans. Roy. Soc. London,* **365,** 2053–2075.

Thompson, D. W. J., S. Lee, and M. P. Baldwin, 2003: Atmospheric processes governing the Northern Hemisphere annular mode/North Atlantic Oscillation. *The North Atlantic Oscillation: Climatic Significance and Environmental Impact, Geophys. Monogr.,* Vol. 134, Amer. Geophys. Union, 81–112.

Trenberth, K. E., and Coauthors, 2007: Observations: Surface and atmospheric climate change. *Climate Change 2007: The Physical Science Basis,* S. Solomon et al., Eds., Cambridge University Press, 235–336.

Wang, H., S. Schubert, M. Suarez, J. Chen, M. Hoerling, A. Kumar, and P. Pegion, 2009: Attribution of the seasonality and regionality in climate trends over the United States during 1950–2000. *J. Climate,* **22,** 2571–2590.

Willmott, C. J., and K. Matsuura, 1995: Smart interpolation of annually averaged air temperature in the United States. *J. Appl. Meteor.,* **34,** 2577–2586.

Zwiers, F. W., and H. von Storch, 1995: Taking serial correlation into account in tests of the mean. *J. Climate,* **8,** 336–351.