Seasonal-to-Decadal Predictability and Prediction of North American Climate—The Atlantic Influence

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ABSTRACT

The question of the impact of the Atlantic on North American (NA) seasonal prediction skill and predictability is examined. Basic material is collected from the literature, a review of seasonal forecast procedures in Canada and the United States, and some fresh calculations using the NCEP–NCAR reanalysis data.

The general impression is one of low predictability (due to the Atlantic) for seasonal mean surface temperature and precipitation over NA. Predictability may be slightly better in the Caribbean and the (sub)tropical Americas, even for precipitation. The NAO is widely seen as an agent making the Atlantic influence felt in NA. While the NAO is well established in most months, its prediction skill is limited. Year-round evidence for an equatorially displaced version of the NAO (named ED_NAO) carrying a good fraction of the variance is also found.

In general the predictability from the Pacific is thought to dominate over that from the Atlantic sector, which explains the minimal number of reported Atmospheric Model Intercomparison Project (AMIP) runs that explore Atlantic-only impacts. Caveats are noted as to the question of the influence of a single predictor in a nonlinear environment with many predictors. Skill of a new one-tier global coupled atmosphere–ocean model system at NCEP is reviewed; limited skill is found in midlatitudes and there is modest predictability to look forward to.

There are several signs of enthusiasm in the community about using "trends" (low-frequency variations): (a) seasonal forecast tools include persistence of last 10 years' averaged anomaly (relative to the official 30-yr climatology), (b) hurricane forecasts are based largely on recognizing a global multidecadal mode (which is similar to an Atlantic trend mode in SST), and (c) two recent papers, one empirical and one modeling, giving equal roles to the (North) Pacific and Atlantic in "explaining" variations in drought frequency over NA on a 20 yr or longer time scale during the twentieth century.

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1. Introduction

The central theme throughout this paper is that of the "Atlantic" as a possible source of (potential) predictability or even actual seasonal prediction skill for North America (NA). We take this rather "restricted" point of view and stay away for the most part from other predictor areas, such as the Pacific or El Niño–Southern Oscillation (ENSO), even though ENSO could influence the Atlantic and may have delayed indirect effects on NA if the Atlantic, in turn, influences NA. In a nonlinear environment it may be a challenge to isolate the influence of a single factor like the Atlantic (or any other ocean, or other predictors), without considering all at once. The present paper thus has to be read in conjunction with the other papers presented at the Atlantic Climate Variability and Predictability (CLIVAR) meeting; see this special issue. The present paper also has a practical point of view as it was written by authors who are involved in preparing real-time seasonal forecasts over NA.

The working definition for the influence of the "Atlantic" on NA will not be precise. In most cases the Atlantic will be either Atlantic sea surface temperature (SST) or the atmosphere in the Atlantic area, most notably the North Atlantic Oscillation (NAO). The NA is most often represented by surface weather elements over NA. The time scale is seasonal, unless stated otherwise.

The question about the influence of the Atlantic on seasonal predictability over NA, when posed to practitioner-colleagues on that continent, leads to a few answers but only hesitantly so. The preoccupation with ENSO, the Pacific–North American pattern (PNA), and the Pacific has perhaps taken place at the expense of deep thoughts given to the role of the Atlantic, the Indian Ocean, or even the global continental lower boundary. This may be because the true predictability due to the Atlantic—however one defines "the Atlantic"—is low, or we, rightly or wrongly, believe it is low, or because insights are underdeveloped. One also has to admit that the role of midlatitude oceans in general is not well settled. So given the tame character of the tropical Atlantic (compared to Pacific ENSO), questions about the Atlantic are about as difficult to answer as questions about the influence of the extratropical Pacific. But since the Atlantic is downstream from NA, forecasters and researchers in NA may still favor the North Pacific over the Atlantic as a source of influence and skill. Indeed the extratropical Pacific has been studied a lot more than the Atlantic. Study of the Atlantic has been done mainly with an eye toward Europe. Study of the impact of the Atlantic in the Caribbean and Central America is less neglected, although even here the Pacific and ENSO are thought to be among the leading predictors.

Some answers by colleagues to the question of Atlantic influence on NA climate are listed below. The first three are mainly variations on the NAO theme. The fourth is about local effects and the fifth and sixth concern hurricanes and east coast storms.

(a) The NAO plays a clear role in U.S. weather and climate, perhaps as far west as the Rocky Mountains. This is a diagnostic statement. Clearly, if one defines the Atlantic as just the influence of the NAO, we have a large body of literature.

(b) In spite of being a leading mode (even in daily data), the NAO is actually not very predictable as an initial value problem. Already by week 2, skill in NAO prediction is quite small. Prediction skill for seasonal means at longer leads is marginal. Hence the NAO often gets mention in the negative as a "wildcard" for the seasonal forecast. For instance one might read: "Given that next winter is a Pacific 'warm event,' forecasters expect the southeast of the United States will be cold, unless the NAO is in its positive phase." Is it understood we do not know the phase of the NAO that far ahead of time? Is it an acceptable excuse? What is behind the somewhat limited prediction skill of the NAO?

(c) Both Canada and the United States have had some success using a tool called Optimal Climate Normals (OCN) in forecasting seasonal anomalies. OCN is essentially persistence of the average of the anomaly (relative to an official 30-yr climatology) over the last 10 yr. Other tools in use in Canada and the United States also attempt to harvest the trend signal. So where does this low-frequency variation come from? And why is 10 yr the optimal average? Many have referred to the low-frequency variations in the NAO as the source of skill in OCN, certainly along the east coast of NA. To be sure: not only the NAO, also the PNA and global change get mention, but the NAO gets prominent mention here due to its variations over the last several decades suggesting a trend and a possible connection to the global mean temperature as well as to the stratosphere.

(d) Local effects. Along the west coasts of continents, the role of (perhaps fairly local) SST anomalies is to enhance predictability of temperature. How about the east coasts?

(e) Atlantic Hurricanes that threaten NA originate, as tropical cyclones, in the (sub)tropical Atlantic, so a clear Atlantic "influence" of a very different nature is very real to NA. The number of hurricanes per season [June–November, but mainly August–October (ASO)] or other "net activity" measures display remarkable interannual variability including strong interdecadal variability. The main causes of these variations are several, and they are not all of Atlantic origin. Leaving the ENSO influence aside, the Atlantic appears to play a key role through interdecadal modulation. Predictability of statistics, such as total number of storms per season in the Atlantic basin, appears to be very high.

(f) If Atlantic hurricanes need consideration we should also mention east coast storms, especially in winter.

The paper is laid out as follows. In section 2 we review some of the literature. In section 3 we review seasonal prediction tools used in Canada and the United States for their seasonal forecasts, and the extent to which any of these have anything to do with the Atlantic. In section 4 and 5 we review covariability between the Atlantic and NA, as revealed in data, both simultaneously and at lead. For this we use global datasets 1948–present [National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalyses, monthly means, or longer averages] to do a number of new calculations. This includes comments on seasonality and an attempt to distinguish interannual from (inter)decadal time scales. Section 6 is devoted to Atlantic hurricanes. In section 7 we present a few results from the latest global coupled ocean–atmosphere model at NCEP. We end with conclusions.

2. Review of some literature

Because of arbitrary boundaries in the subject matter it is difficult to organize the literature on the influence of the Atlantic on NA. Much of the relevant literature is about more than just the Atlantic. Since Europe is the more obvious recipient of zonal wind variations across the Atlantic very few studies deal specifically with the impact of the Atlantic *on NA*. (We try to compensate for the latter in sections 4 and 5 with some new calculations.) The opposite, the influence of NA on the Atlantic, has been studied (Dickson and Namias 1976). We here present five sections on (a) NAO, (b) SST and Atmospheric Model Intercomparison Project (AMIP) runs, (c) (sub)tropical rainfall, (d) east coast storms, and (e) local effects. We do not separate empirical and model studies, just note here that empirical studies (e.g., Enfield 1996; Giannini et al. 2000) correctly identify and struggle with the relative role of the Atlantic and Pacific in explaining interannual variations over NA. In dynamical models, the problem is posed differently but the nonlinearity among signals (and noise) is a noted and infamous problem in disentangling the midlatitude response to say tropical SST from coupled atmosphere–ocean models in the midlatitude itself (Lau 1997; Lau and Nath 2001; Kushnir et al. 2002; Alexander et al. 2002). This topic remains under study.

a. NAO

If one limits the Atlantic influence to just the atmospheric component, the NAO, there are many studies, although not necessarily focused on the influence of the NAO *on NA*. Higgins et al. (2000), Bonsal et al. (2001), and Shabbar and Bonsal (2004) discuss all "dominant" factors influencing U.S. and Canadian weather and climate, and NAO is one of them. We leave aside the short-term weather aspects of the NAO (and all studies on blocking, zonal flow, etc.) except by noting that the NAO is very hard to predict, skill being low after 6 days (not shown), not much better than weather itself—this result would be consistent with Feldstein (2000). Interdecadal trends in the NAO in the direction of stronger westerlies across the ocean have received plenty of attention (Hurrell 1995; Gillet et al. 2003; Hurrell et al. 2003), because they may explain much of the long-term warming trend in Europe (and the United States) and the cooling in northeastern Canada during the last 30 yr (Shabbar et al. 1997). These studies tend to be naturally biased toward winter. Trends, due to the NAO or otherwise, are of interest in seasonal prediction (Huang et al. 1996) because the anomaly averaged over the last K years is a primary forecast tool. The attribution of the NAO trends to a specific cause is not universally accepted (Wunsch 1999), on the ground that an apparent trend may be produced by any red-noise process over a restricted portion of its record. Any further trend in the NAO index has been less obvious since 1995.

Although the NAO is the most important, popular, and least disputed teleconnection in the NH, it is not universally accepted, nor is there a strict definition. Even the synoptic view of what the NAO "really" is remains a modern topic of research (Benedict et al. 2004). One never sees the NAO in pure form in reality, not even when the index is extreme; see Fig. 1, which shows a 5-day mean height anomaly at a time of near-record-breaking negative NAO index. There is often a tendency in nature, as seen in Fig. 1, to break the NAO into separate western and eastern Atlantic patterns (Wallace and Gutzler 1981; Shabbar et al. 1997). Since the influence on NA is the issue, that distinction may be very relevant. Some lessons can be learned by studying a detailed seasonality of the first empirical "mode" (see section 4): a pure NAO across the entire ocean basin

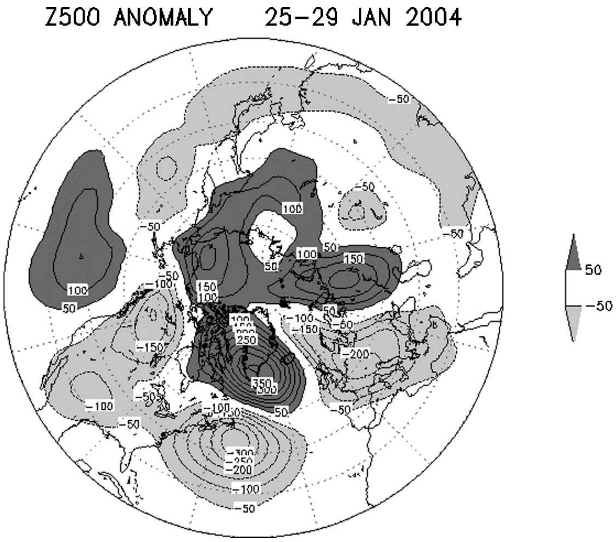

FIG. 1. Five-day mean Z500 anomalies over the NH centered at 30 Jan 2004. Units are gpm and the contour interval is 50 gpm. This situation has an extreme negative NAO index. Notice that a record large projection onto NAO does not imply in actuality a pattern that looks like the NAO at all longitudes.

may occur in some months, but modes with emphasis in either the west or east Atlantic in other (Barnston and Livezey 1987). The "NAO" is definitely seasonal; that is, the same stations cannot be used optimally for defining an NAO index in all seasons (Portis et al. 2001). To the extent that the NAO is related to the uncertainty in latitude for the Atlantic jet to settle in on, we must expect alternative positions, and indeed, in section 4, we report on an equatorially displaced NAO (ED_NAO).

To make the interpretation more difficult or rich, Hoerling et al. (2001) report on tropical impacts from both the Indian and Pacific Oceans on the NAO, especially on its trends. We should also mention stratospheric impacts on the NAO, or perhaps more specifically on the Northern Hemisphere "annular mode" (Thompson et al. 2002) (originally called the AO), which manifests itself very much like the NAO in the troposphere, but over a wider range of longitudes. Because trends are more dominant in the stratosphere than the troposphere, this connection may have forecast implications or give a physical basis to existing tools such as OCN (Huang et al. 1996). Another NAO modification via the stratosphere–troposphere connection may relate to stratospheric quasi-biennial oscillation (QBO) and stratospheric warmings (Thompson et al. 2002).

b. SST and AMIP

If one defines the Atlantic as the influence of the oceanic lower boundary condition in that sector, there are some (not many) GCM-modeling studies on the impact of prescribed SST on the seasonal atmosphere (sometimes reduced to the NAO); see Rodwell (2003) for a nice review. (Such studies have a bias toward winter and away from NA.) There are drawbacks to prescribed SST (often "AMIP" runs)—see list below at the end of section 2b—yet such runs have an appealing logic. For instance one can make multiyear GCM runs with globally varying observed SST (annual cycle plus anomalies) such that all oceans may provide a signal to the atmosphere. Additionally runs can be made with one ocean (or part of it) disabled, meaning that SST is just a climatological annual cycle only (no anomalies) in the disabled ocean basin. The difference should tell us about the impact of the SST anomalies in the disabled area. The assumption is that prescribed SST anomalies (SSTAs) adds to the atmospheric variance, so if one ocean is disabled the decrease of atmospheric variance tells how much this ocean contributes. One can alternatively compare long GCM runs with global climatological SST to GCM runs in which one ocean basin has been enabled. The analysis of variance (ANOVA) in combination with such AMIP runs makes logical sense and leads to a model-based definition of potential predictability (PP). This technique has been widely used to study ENSO in "Pacific only" versus SST in all oceans (Lau and Nath 1994; Hoerling and Kumar 2002), or to study tropical oceans' impacts versus global SST (but see the list of issues with AMIP at the end of this section).

We found few AMIP runs in which the role of the Atlantic is the focus, and especially its role in predictability over NA, but see Peng et al. (1995). The experiment that is tailored closest to our requirement was made by Conil (2003a,b) who used the Laboratoire de Météorologie Dynamique (LMD) model (version 3.3) for a 1950–94 seventeen-member AMIP run with global SST and sea ice (GLOBAL). This control run was compared to nine runs in which the Atlantic (north of 14°N) was disabled (NOATL), and nine runs in which only the Atlantic (ATL) had realistic SST and sea ice anomalies. Table 1 describes the standard deviation of seasonal Z500 over a Pacific–North American sector (Conil 2003a, his Table 3.5).

The area, designated "PNA" by Conil, used for the variance calculations is 20°–80°N, 145°E–80°W, which is North America plus much of the Pacific. The influence of the Atlantic on this PNA area is extremely weak. The best potential predictability in December–February (DJF) for the PNA area, close to 30%, is actually obtained when we disable the Atlantic, a pathetic result. This could in part be a flaw of the ANOVA technique that cannot account for destructive interference of signals, because it looks upon variance

TABLE 1. Standard deviation of seasonal mean Z500 in DJF over the PNA area in gpm for three multiple-membered AMIP runs. The SST forced variance (square of std dev) was calculated by Conil (2003a) as the variance of the ensemble means corrected for the spillover of internal variance. The potential predictability (PP) is defined as SST forced variance divided by total variance and given in percent.

	ATL	NOATL	GLOBAL
Total std dev	55.7	59.9	63.0
Internal std dev	54.8	50.3	55.4
External std dev	9.7	32.6	30.1
PP (%)	2.4	29.4	22.7

(the square of the signal) as additive. But it certainly does not point to the Atlantic as a major source of predictability over NA. [Conil's results for the North Atlantic and European atmosphere show modest predictability due to the Atlantic SST, as do results from Robertson et al. (2000), who (based on single runs over 30 yr) report a large increase in 500-mb height variance in the North Atlantic due to prescription of realistic SST in the Atlantic, with some or all of this impact coming from the tropical and, amazingly, the southern Atlantic.] At the time of final review we became aware of a paper by Sutton and Hodson (2005) describing a noticeable influence of the tropical Atlantic SST in a series of AMIP runs (global SST, Atlantic SST, only Atlantic subtropical SST, etc.) on summer climates in both North America (especially the Caribbean) and Europe. Their AMIP run indicates that subtropical Atlantic SST may be the agent, and mainly the low-frequency filtered component of it.

When studying AMIP runs and ANOVA, keep the following in mind:

1) We do not know SST perfectly ahead of time. AMIP yields an estimate of predictability, not actual prediction skill.
2) Variance is not (necessarily) additive when physics is nonlinear.
3) Prescribing SST is cutting the physics of atmosphere–ocean interaction. AMIP runs are known to have bad (even opposite) air–sea fluxes over many parts of the global oceans; see Bretherton and Battisti (2000).
4) In view of 2) one may question AMIP runs that do not include proper land surface treatment. That is, we may never know the impact of oceans in a nonlinear system until we can model the land properly (and vice versa).
5) Results are no better than the atmospheric model used. The LMD model used by Conil (2003a) had $4° \times 5°$ resolution.
6) Because of chaos, one needs (very) large ensembles. Studies like Robertson et al. (2000) have just two runs.

Not all of the above six items are uniquely AMIP/ANOVA problems. The nonadditivity of variance (second point) also applies as a handicap to empirical approaches, including the canonical correlation analysis (CCA) in section 5. The fifth point would apply to any models, including the coupled model in section 7.

In view of the third point, prescribed SST hindering the physics of air–sea interaction, there has been a development to prescribe SST only in areas where the ocean forces the atmosphere, such as the tropical Pacific, and using a simple mixed-layer ocean elsewhere (Bladé 1997, 1999; Delworth 1996; Saravanan 1998; Gallimore 1995; Wang et al. 2004). Often such studies describe the feedback from the oceans in midlatitude in general (Drijfhout et al. 2001; Barsugli and Battisti 1998) or for the North Atlantic specifically (Battisti et al. 1995; Bhatt et al. 1998; Deser et al. 2004; Deser and Blackmon 1993; Magnusdottir et al. 2004). The midlatitude response, feedback, or modification was summarized in a workshop report (Robinson 2000).

c. (Sub)tropical rainfall

Seasonal rainfall variation across (sub)tropical America appear to relate to Pacific SST with an important secondary Atlantic influence (Enfield 1996; Moron et al. 2001; Giannini et al. 2001a). The Atlantic SST is the primary influence during the early season [May–July (MJJ)] on precipitation in the Caribbean (Taylor et al. 2002; Enfield and Alfaro 1999), but during the height of the hurricane season the Pacific takes over (see section 6). Enfield et al. (2001) report on a trend in Atlantic SST, now called Atlantic Multidecadal Oscillation (AMO), which relates to modification of mainly summer precipitation over southern NA. Sutton and Hodson (2005) appear to confirm this finding by both empirical and modeling work. A similar mode is used in hurricane prediction (section 6). Giannini et al. (2001b) appear to have a different view on this as they report NAO trends conspiring with ENSO so as to cause trends in the Caribbean precipitation. The mode now called AMO was described much earlier in Kushnir (1994).

d. East coast storms

East coast winter storms in NA are impressive and a potential Atlantic influence suggests itself. Storms do shape the seasonal precipitation totals, but are seasonal totals over land related to predictable Atlantic interannual variation? Usually "weather" is looked upon largely as the noise component in "potential predictability" as defined empirically by Madden (1976), but persistent anomalous storm tracks would be part of short-term climate. Hartley (1999) and Hartley and Keables (1998) quote western Atlantic SST as a factor in high snowfall events in New England, but secondary to the more obvious NAO and storm tracks. Atlantic tropical storms are discussed in section 6.

e. Local SST effects

Along the west coasts of continents, the role of (perhaps fairly local) SSTAs is to enhance predictability and persistence of surface air temperature anomalies along the coast and inland over an *e*-folding distance of some 100 km (depending on orography this could be more/less) (see Van den Dool and Nap 1981, 1985). The skill one can harvest this way is actually quite high, albeit in a small area. Judging from a lack of literature, such effects do not occur, at least not to the same extent, along the east coasts. (Only a few islands have strong air temperature persistence.) This is because the prevailing winds are from the west. So the Atlantic SST does not appear to contribute to local effects and enhanced seasonal prediction skill for temperature along the east coast of NA, leaving an occasional sea-breeze event in Boston, Massachusetts, aside. Even the Gulf of Mexico appears to have little local influence through enhanced air temperature persistence (the Gulf may be too shallow to provide memory).

3. Review of seasonal forecast procedures

We here review prediction methods and tools used in Canada and the United States for their seasonal forecasts but with an emphasis on the following question: Which of these tools have anything to do with the Atlantic explicitly and/or the Atlantic as a cause of climate variability? The methods used, in no particular order, are (a) CCA (Barnston 1994; Shabbar and Barnston 1996; Johansson et al. 1998), (b) OCN (Huang et al. 1996; Zhang et al. 1996), and (c) two-tier or one-tier coupled atmosphere–ocean model (Kanamitsu et al. 2002; Saha et al. 2006 for the United States; Derome et al. 2001 for the Canadian models). These are the main tools always run and used in some fashion for U.S. and Canadian seasonal forecasts. In the United States there are also a handful of other tools of opportunity (ENSO composites), or warm-season tools based on soil moisture (Van den Dool et al. 2003). Tier-2 coupled models from other centers [International Research Institute for Climate Prediction (IRI) and Climate Diagnostics Center (CDC)] are also increasingly available for real-time forecasts.

Of the primary tools, CCA takes global gridded SST during the most recent four nonoverlapping seasons into account as predictor. So the Atlantic is included. But the general assumption is that most of the CCA skill over NA is mainly from the tropical Pacific. The need to analyze the attribution to certain ocean basins for real-time forecasts is not always apparent. [One exception we are aware of is a version of CCA, so-called ensemble-CCA, where forecasts based on each ocean (or other predictors) are prepared separately and looked upon as members of an ensemble (Lau et al. 2002).] CCA "modes" reflecting the Pacific influence may also have some projections in the Atlantic, spurious or otherwise. In section 4 some CCA modes are presented when the Atlantic is the only predictor.

The model version described in Kanamitsu et al. (2002) had atmosphere–ocean interaction only in the tropical Pacific and a two-tiered approach. The new coupled model in the United States [Coupled Forecast System (CFS); Saha et al. 2003, 2006] has a global ocean, is one-tiered, and has been implemented in August 2004—some early results (discussed in section 7) indicate modest prediction skill in Atlantic SST.

One of the main sources of skill in Canadian and U.S. seasonal forecasts is (or can be) harvested by a very simple tool called OCN (Huang et al. 1996; Zhang et al. 1996). This is basically persistence of the anomaly of the last K years for the same named season. This sort of tool works because the climate is not stationary and changes on a time scale considerably in excess of K years. We found $K = 10$ to be optimal for U.S. temperature. The trends being that important for forecasts for the next seasons out to 1–2 yr ahead, the question is, "What is the physical origin of these predictable trends?" Many have pointed to the NAO and its trends in the last 50 yr. This certainly appears to be contributing along eastern NA, especially in winter. It is also clear that the OCN-defined trends are related to similar trends in global SST, not only in the Atlantic, but also in the Pacific (Van den Dool 2003). Some trends turn around (like the AMO) so if OCN was based on just AMO its "skill" would be negative at a certain phase of the "cycle" (no periodicity implied). However, the 5-yr running mean skill of OCN for temperature has never been negative since 1960, so, indeed, there are apparently several components to trends over land. That a 10-yr average is optimal is a succinct statement about the power spectrum of all low frequencies relevant to NA temperature.

A posteriori verification for the period January–March (JFM) 1995–February–April (FMA) 2002 gives the skill of CPC seasonal temperature forecasts (see Table 2). The measure used is the Heidke skill score on

TABLE 2. Summary Heidke scores SS1 and SS2 of seasonal forecasts for 102 locations in the United States for all seasons during 1995–2002 and all leads combined. A random forecast is expected to score zero, a perfect forecast 100.

	SS1	SS2	Coverage (%)	
OFF	22.7	9.4	41.4	(Lead 0.5 through 12.5 months)
CCA	25.1	6.4	25.5	″
OCN	22.2	8.3	37.4	″
CMF	7.6	2.5	32.7	(Lead 0.5 through 3.5 months)

a scale from −50 to 100. SS1 is the Heidke score for areas where CPC makes a probability forecast that differs from the climatological probabilities (1/3, 1/3, 1/3) for the three classes used, the so-called non-CL forecasts, which cover typically 41% of the maps for the United States. SS1 thus applies to areas a priori identified as skillful. This identification is done by running methods retroactively on data from the 1950s to the present, and applying a skill threshold as follows: A local correlation less than 0.3 is thought to indicate no skill at that locale. SS2 is for the Heidke score for the entire map including non-CL areas (SS2 works out as SS2 = SS1 × coverage, where coverage is the percentage non-CL). See Van den Dool et al. (1999) for details on definitions etc. Numerically the Heidke score is about half the correlation (for low skill situations); that is, a Heidke score 25 corresponds to 50% correlation. The SS1 score in Table 2 at about 20 or better indicates we have indeed correctly identified places with a priori skill. [The Climate Model Forecast system (CMF) is the exception here.] The official (OFF) forecast has more skill than the tools, and also higher coverage, as it should. Among the tools, OCN appears to contribute the most over 1995–2002, emphasizing the role of trends in making seasonal predictions. It is especially the trend component of skill that may have some relationship to global oceans, including the Atlantic (see section 5).

Since 1998 the National Oceanic and Atmospheric Administration (NOAA)/CPC is also engaged in seasonal prediction of the total number of hurricanes (see discussion in section 6).

4. Covariability of Atlantic and NA—Diagnostic relations

In sections 4 and 5 we present some new calculations regarding the influence of the Atlantic on NA. This was done in part because while the literature is vast, it does not sufficiently focus on the question of the impact of the Atlantic *on NA*. The areal extent of the domains are as follows: (a) Atlantic SST: all ocean points north of the equator, between longitudes 100°W and 60°E, with the exclusion of Pacific points between equator–20°N and 100°–75°W, (b) Atlantic + NA atmosphere: all grid points north of equator between longitudes 130°W and 60°E, and (c) NA surface: all land points north of 10°N between 170° and 45°W, with the exclusion of Hawaii and Greenland. We keep the Atlantic atmosphere large enough so it could contain the NAO. The data used are the NCEP–NCAR reanalysis 1948–2003 (Kistler et al. 2001), except for temperature in section 4, which was taken from the Climate Anomaly Monitoring System (CAMS) dataset maintained at CPC.

In this section we present first a modal univariate analysis of Z500 across the combined Atlantic and NA atmospheric domain. This calculation is independent of what we may want to forecast over NA. The modes, obtained by "rotated" principal component analysis (PCA) (Barnston and Livezey 1987; Lau and Nath 1990; Peng et al. 2000) on seasonal mean Z500 over 1949–2003, have been organized into one plot so as to show the mode resembling the NAO the most in the same polarity for all four seasons (see Fig. 2). Note a problem with exact definitions. The pattern that looks the most like NAO (a judgment requiring a preconceived notion) is declared to be the NAO. In most seasons that is the first mode [in June–August (JJA) NAO is the second mode]. With the exception of summer we are nearly certain which mode is 'the" NAO. Although we have an NAO in all seasons, the NAO pattern does vary slightly with season, an observed fact that is somewhat violated when data at fixed stations are used to form time series of an NAO index.

In all seasons we also find an important second mode we name ED_NAO (see Fig. 3). In summer the ED_NAO explains 1% more variance than the NAO itself, but is a more distant second mode (in terms of explained variance) in all other seasons. Although the preferred anomalous jet runs from Newfoundland to Scotland (as in Fig. 2) there are clearly alternative latitudes, and ED_NAO (Fig. 3) represents a nodal line running from the Carolinas to the Iberian Peninsula. Physically there may well be a continuum of latitudinal positions where an NAO-like mode could settle, but in terms of explained variance (EV) we find only two dominant latitudes. The ED_NAO appears to look like the "East Atlantic Pattern" reported by that name as minor mode 6, 3, 8, and 4 in November through February only in Barnston and Livezey (1987). With the addition of 20 yr more data since 1987, the ED_NAO now seems much more important and year-round (and not particularly "east" in the Atlantic).

All calculations were repeated for data that have frequencies lower than one cycle per 10 yr removed. Re-

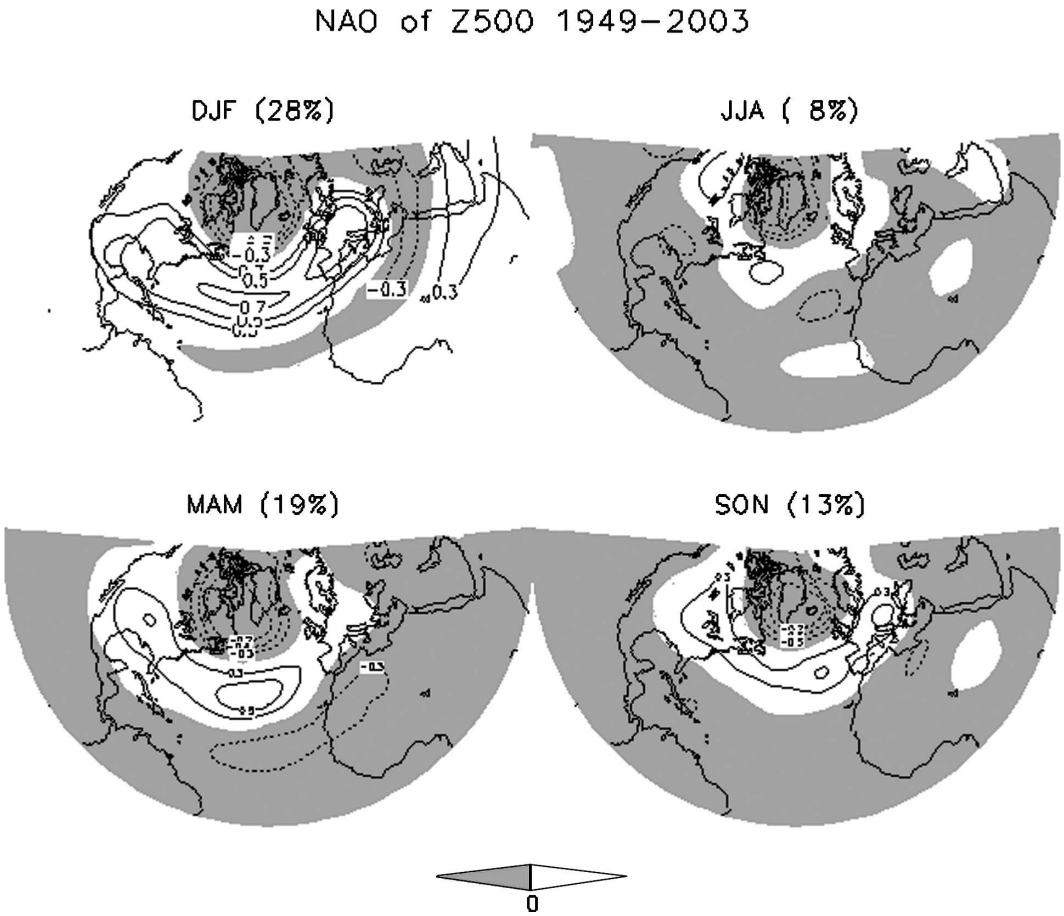

FIG. 2. The spatial pattern of the NAO in four seasons. Based on rotated PCA using NCEP–NCAR reanalysis for the years shown. The explained variance is shown in parentheses. Some postprocessing was done to achieve similar polarity in all seasons. Shown is the correlation between the time series of the NAO and the raw seasonal mean Z500 data. Contour interval 0.2; starting contour ±0.3 and negative values shaded. Negative contours are dashed. The NAO is generally mode 1, except in summer when it is mode 2.

sults for high-pass-filtered data for periods less than 10 yr (10%–20% less variance than total) are more or less the same as for the raw data.

From Figs. 2 and 3 collectively we see a considerable influence of the main Atlantic patterns on NA as far as circulation (Z500) is concerned. This is also true for surface conditions. Correlations between the NAO and ED_NAO time series and surface air temperature (T2m) over NA show noteworthy values in most seasons (see Fig. 4 for the NAO), and these correlations are not necessarily restricted to the eastern half of NA. Similar calculations for (ED_)NAO index versus NA *precipitation* show only small and scattered correlations and are probably not significant for the domain as a whole (not shown).

We redid the EOF analysis on monthly mean data for all 12 months for a more complete description of the annual variation. A breakup of NAO into east and west Atlantic pattern suggests itself in some months like January, while an ocean-spanning NAO can be seen in say December and February.

As a transition to section 5 we mention that a simultaneous CCA between Atlantic SST and Z500 in DJF reveals the somewhat famous tripole SST pattern thought to be associated with the NAO. But as with EOF on Z500 alone, two versions show up (not shown); the second CCA mode is associated with ED_NAO in the atmosphere.

5. Covariability of Atlantic and NA—Predictive aspects

(For the definition of the domains and the datasets see the first paragraph of section 4.) The EOF-type analysis in section 4 does not address cause and effect. We here move to time-lagged relations between two

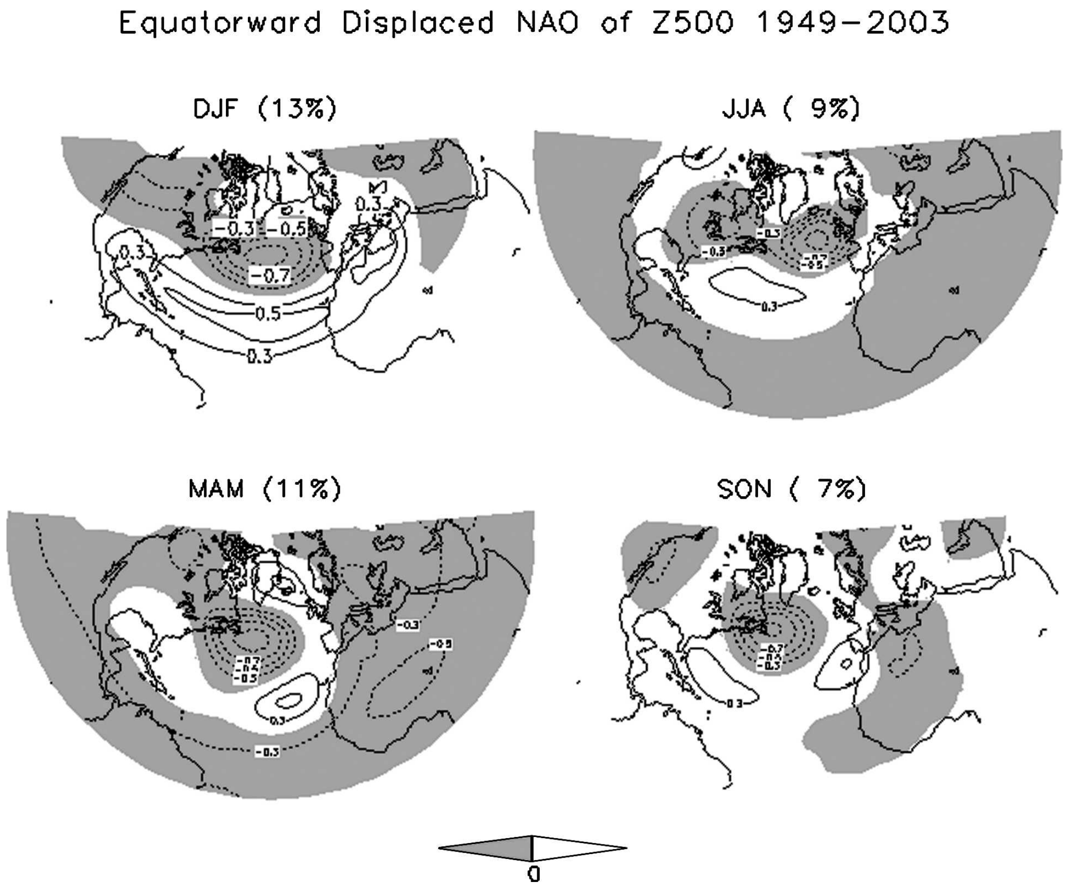

Fig. 3. Same as Fig. 2 but now for ED_NAO, generally mode 2 in a rotated PC analysis, except in summer when ED_NAO is mode 1.

fields of variables, which are, at the very least, suggestive of cause and effect. To this end we employ the CCA software used at CPC (Barnston 1994) and elsewhere (Johansson et al. 1998) for both research and for producing operational forecasts. This particular version of CCA is very close to maximizing the covariance between two datasets via singular vector decomposition (SVD; Bretherton et al. 1992; Lau and Nath 1994). For added realism and honesty, when quoting skill levels of the CCA, a full package of cross-validation was used. The number of predictor/predictand maps is large (too large for presentation). This is in part because it takes order-5 canonical modes to capture most of the covariance between the predictor and predictand datasets, and because there are four antecedent predictors seasons; see layout in Barnston (1994). Moreover, there are several predictors (SST, Z500, T2m, etc.) and we want to cover the entire annual cycle. Hence, in order to simplify matters for this paper we collapse the four predictor seasons into one, use a single predictor (SST in the Atlantic) and consider only the 1-month lead time (an example of a 1-month lead forecast: predict DJF T2m over NA from ASO SST in the Atlantic).

Figure 5 shows the first CCA mode between ASO SST and DJF T2m over NA. Zonal bands of positive Atlantic SSTA near 20° and 55°N, and negative SSTA near 40°N in the west Atlantic in ASO appear associated with warmth in the southwestern United States and northeasters Canada, as well as cold in central America and Alaska in the following DJF. The time series (full for SST; dashed for T2m) expresses both interannual and interdecadal variations but, interestingly, the latter dominates. The *R* value in the graph (73.6) refers to the correlation between the SST and T2m time series. The SST pattern of CCA mode 1 is not the pattern one gets when the ocean is forced by an atmosphere in pure NAO state, but rather looks like the "horseshoe" pattern discussed by Czaja and Frankignoul (2002). [Our CCA does produce the standard tripole SST and NAO for *simultaneous* SST and height fields, in agreement with Czaja and Frankignoul (2002)]. We will see the horseshoe pattern repeatedly below.

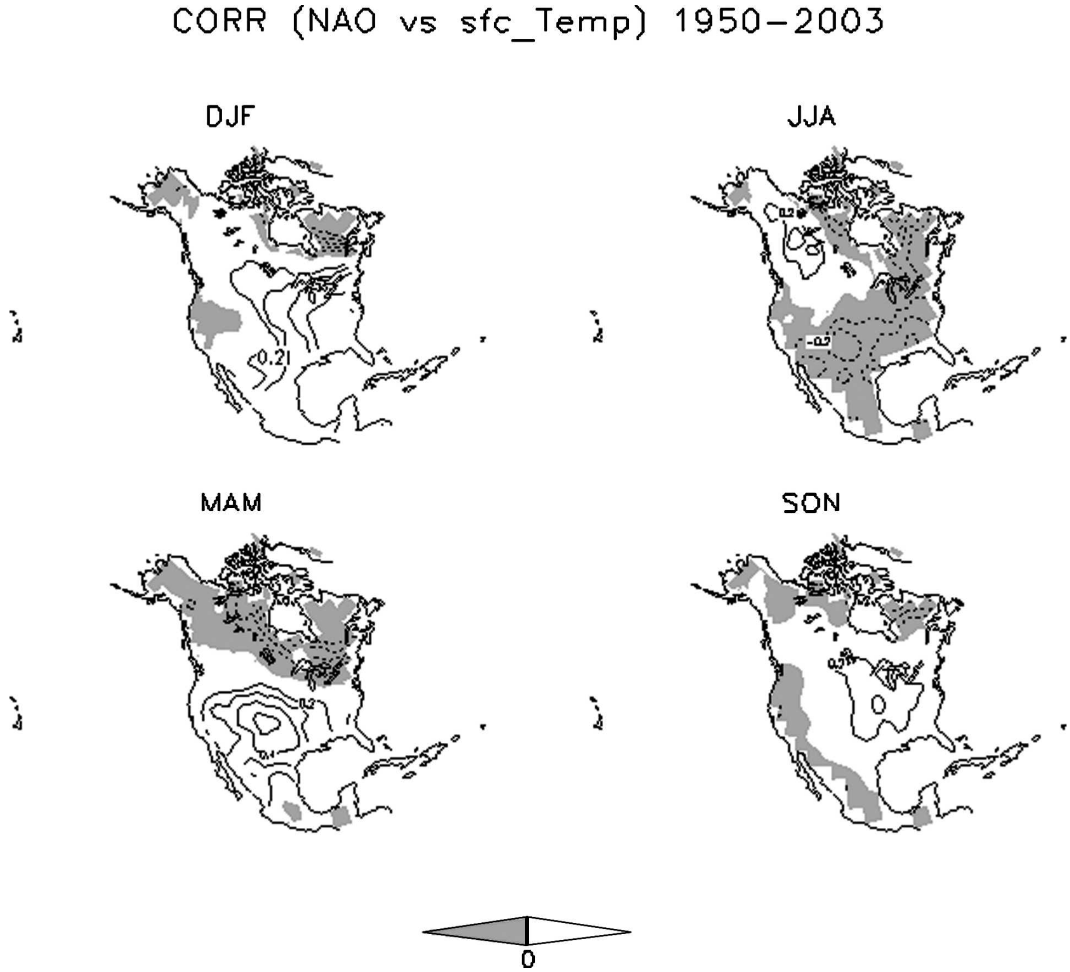

FIG. 4. Simultaneous correlation of NAO index and 2-m temperature over NA. Results based on seasonal mean data 1950–2003. The contour interval is 0.1, the starting contour is ±0.2; negative values are shaded, negative contours are dashed.

Figure 6 shows the same as Fig. 5 but for all four seasons in one display, that is, the first mode for the predictand T2m in target season DJF, March–May (MAM), JJA, and September–November (SON) when coupled to the predictor SST in antecedent ASO, November–January (NDJ), FMA, MJJ. All seasons show a large amount of trend in the time series, and an association between a warm Atlantic and a warm SW United State and NE Canada is seen in all seasons except spring. To first order the SST pattern is independent of season, and so are the time series, with a maximum in the 1950s and a minimum around 1990.

Figure 7 is the same as Fig. 6 but now NA seasonal precipitation is the predictand. It is remarkable that the first SST predictor mode for the predictands T2m (Fig. 6) and precipitation (Fig. 7) is essentially the same in all seasons. The time series and Atlantic SST patterns most related to NA T2m and precipitation are also very similar among Figs. 6 and 7. It took some coordination of choices of polarity in Figs. 6–7 to bring this out.

The quantitative bottom line is one of modest predictive ability due to Atlantic SST, the anomaly correlation (AC in %) for NA T2m being 15.7, 9.0, 20.4, and 20.6, respectively, for DJF, MAM, JJA, and SON. Although modest, CCA beats persistence in all seasons except spring (AC values are 8.2, 12.0, 7.9, and 13.1 for persistence).

The number of modes retained here is 5 (except for DJF when it is 4). This truncation is based on cross-validated skill upon the admission of a new mode. Of the (squared) covariance retained by four–five modes it takes two modes to explain 80%, but as seen from the AC values this may be no more than 5% of the predictand's original variance.

Figure 8 shows forecast skill as a function of lead and target season (all 12) for temperature (on the left) and

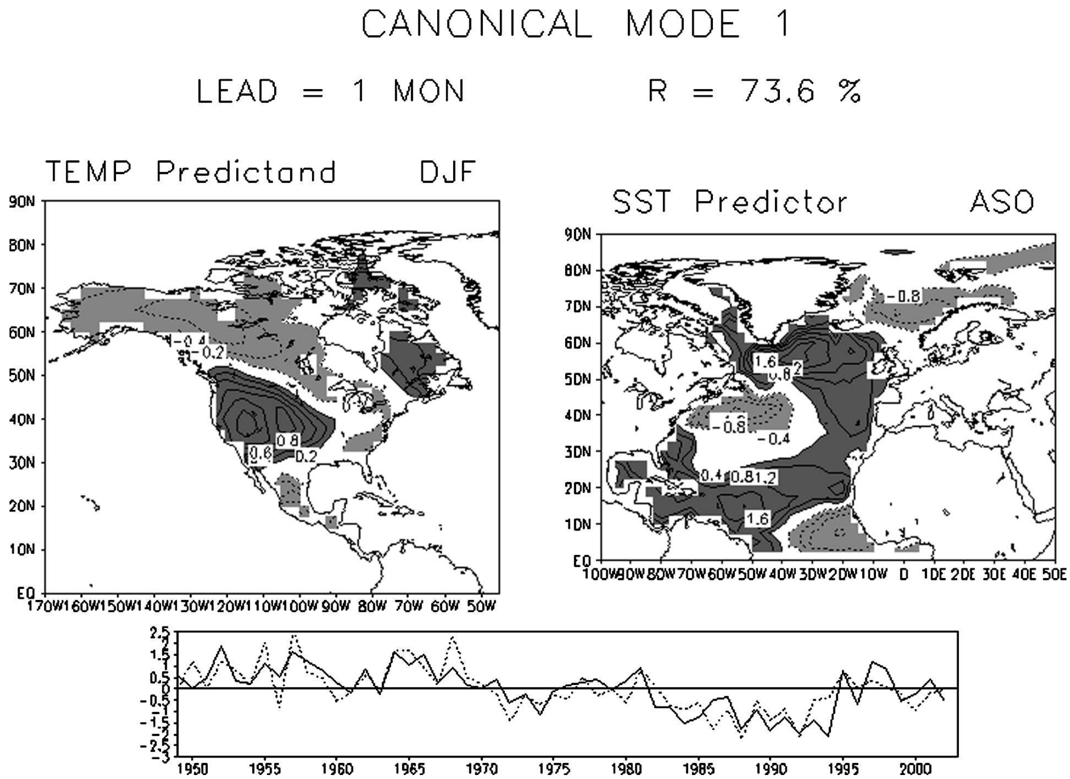

Fig. 5. CCA mode 1 for DJF prediction. Shown are the patterns for the predictor (SST in ASO), and the predictand at lead 1 month (T2m in DJF), and the associated time series for T2m (dashed) and SST (full) for 1949–2003. The *R* value shown is the correlation between the T2m and SST time series. In the left (right) map: Contour interval is (left) 0.2 with a starting contour of ±0.2 and (right) 0.2 with a starting contour of ±0.4. Negative contours are dashed, positive values are lightly shaded, and negative values are dark shaded.

precipitation (on the right). In this graph we have used four antecedent predictor seasons (as we do in operations; Barnston 1994) for some added skill. With the Pacific included (not shown) skill would be much higher in winter and early spring. But even with the Atlantic alone we have some skill, especially in summer and fall for T2m.

We redid all calculations with a 10-yr time filter applied to create high- and low-frequency data; that is, we prepared one version of CCA that used high-frequency data (which accounts for 78%–87% of the variance in seasonal mean data) and another that used low-frequency data (which accounts for the remaining 13%–22% of the variance). In both cases, however, we verified the cross-validated forecasts against unfiltered data. The high-frequency CCA has no skill at all. We thus did not find any prediction skill due to interannual variations in Atlantic SST. All skill we reported in section 5 is due to trends or interdecadal variation. To some degree this was already clear from the time series in Figs. 6 and 7.

One may of course wonder whether this CCA forecast skill over NA is truly due to the Atlantic SST specifically. An alternative explanation would be that both land and ocean areas worldwide are subject to a common low-frequency climate variation caused by unspecified forcings.

6. The Atlantic tropical cyclones and hurricanes and their prediction

In September 2003, a northwestward-bound category 2 hurricane named Isabel made landfall in northeastern North Carolina along the mid-Atlantic coast of the United States, and as the hurricane traversed inland west of Washington D.C. it devastated life and property. Hurricane Isabel was reportedly responsible for a loss of 16 lives and about $1.7 billion in property damage (NHC: 2003 Atlantic Hurricane Season Summary, data available online at http://www.nhc.noaa.gov/2003atlan_summary.shtml).

During 1970–99 a total of about 600 fatalities occurred in the contiguous United States and its coastal waters associated with tropical storms (Rappaport 2000). The property damages in 1992 due to a single hurricane alone (Andrew, category 5, the most expensive hurricane to hit the United States, prior to Katrina)

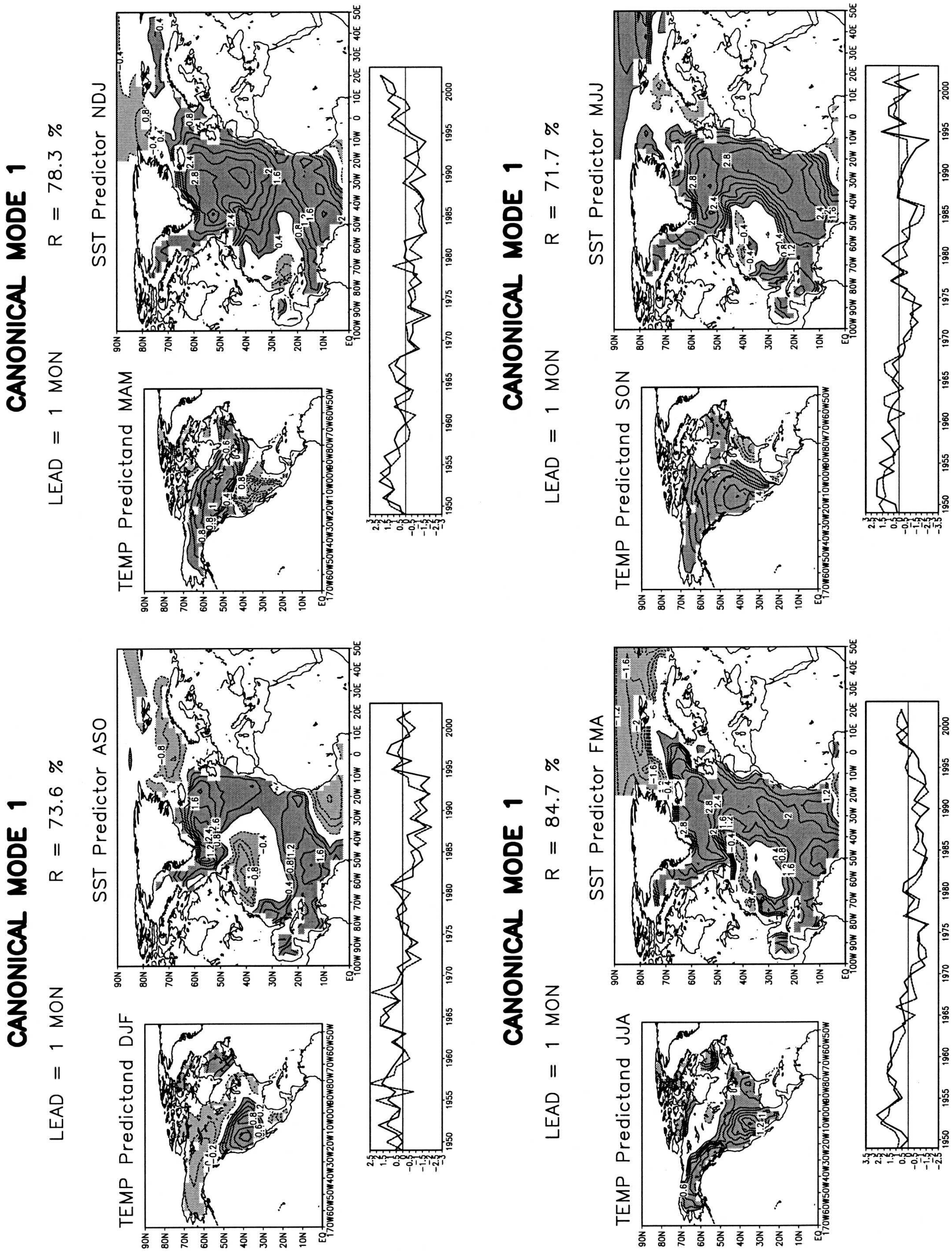

FIG. 6. Same as Fig. 5, CCA mode 1 between NA seasonal mean temperature and Atlantic SST (one season earlier), but now all four seasons with the T2m predictand in DJF, MAM, JJA, and SON. Some postprocessing was done to make the polarity of patterns and time series as similar looking as possible.

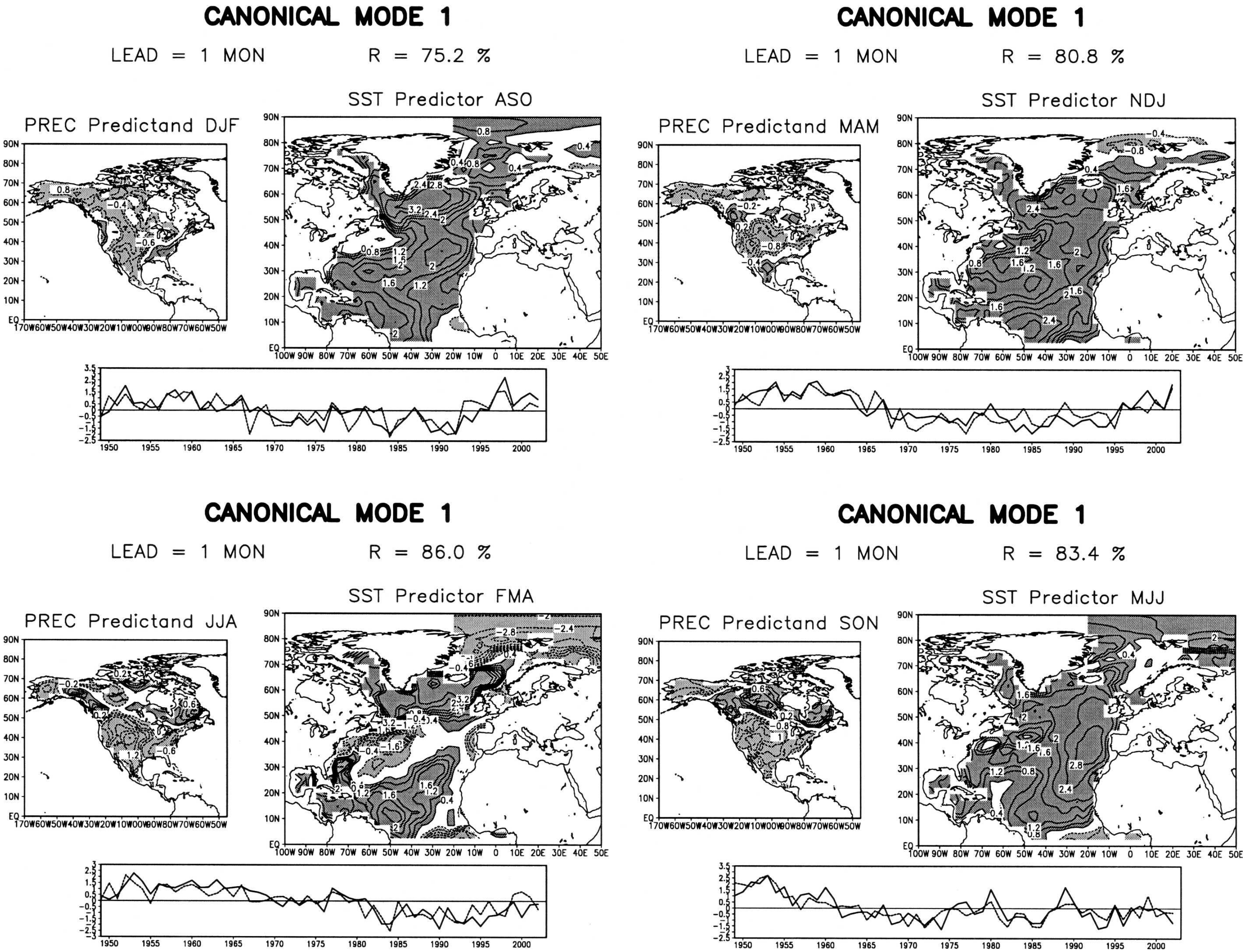

FIG. 7. Same as Fig. 6, but now for seasonal precipitation as predictand. Some postprocessing was done to make the polarity of patterns and time series among Figs. 6 and 7 as similar looking as possible.

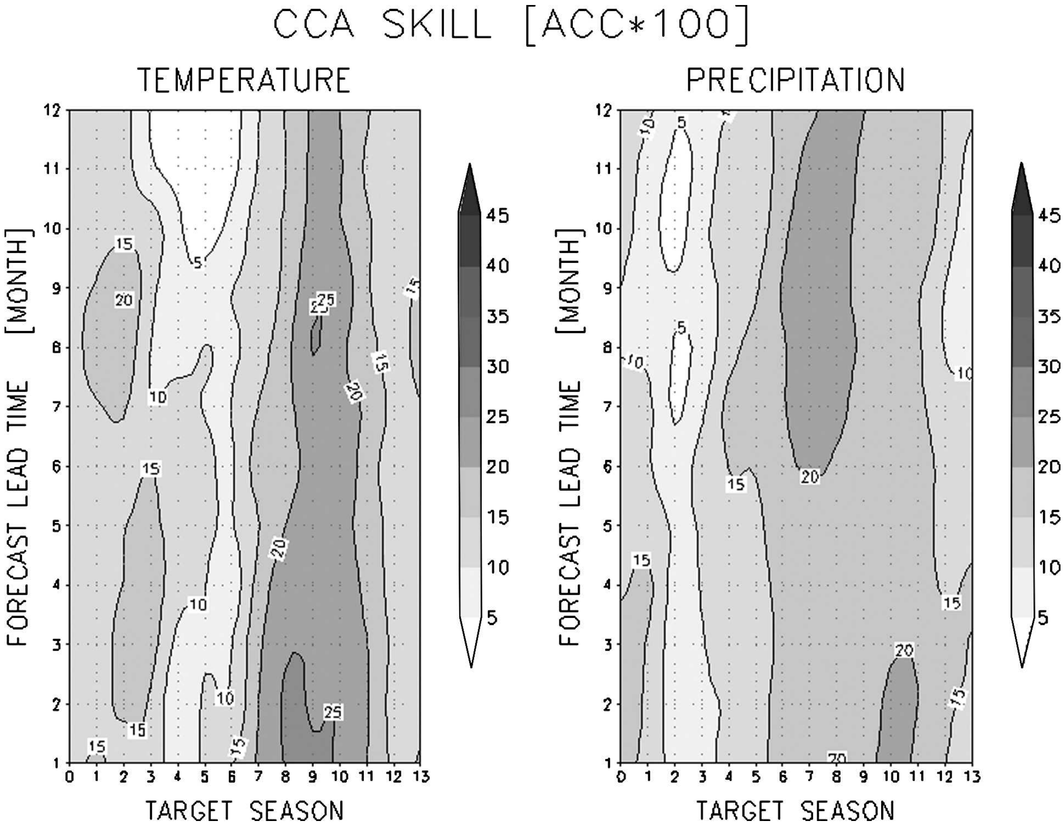

FIG. 8. Cross-validated skill of CCA (as expressed by anomaly correlation in %) of NA seasonal forecasts, as a function of lead and target season. Skill for (left) temperature and (right) precipitation. For this evaluation a string of four predictor seasons were used; e.g., T2m in DJF is predicted by SST in NDJ (previous year), FMA, MJJ, and ASO.

is about $35 billion U.S. (2000) dollars. A typical North Atlantic hurricane season, which officially runs from June through November, features about 10 tropical storms (TS), 6 hurricanes (H), and 2 major hurricanes (MH). Hence a forecast, both long lead and short range, of these tropical systems is of great value to coastal population of the United States and the Caribbean. Below we discuss the long-lead forecasts only.

Much of the North Atlantic hurricane activity is due to tropical disturbances that originate in the Main Development Region (for definition of MDR, see Fig. 9). Interannual and multidecadal variations in the Atlantic hurricane activity have been linked to ENSO (Gray 1984a; Bove et al. 1998), an AMO in SST (Goldenberg et al. 2001; Vitart and Anderson 2001) and west African monsoon variability (Hastenrath 1976; Landsea and Gray 1992). The long-lead seasonal forecasts of the Atlantic hurricane activity, pioneered by W. Gray and his colleagues since 1984 (Gray 1984a,b), plus revisions in Landsea et al. (1994), is based on regression methods. The overriding physical issue in the forecast is the modulation of the vertical wind shear in the central tropical Atlantic, by factors such as ENSO, the AMO, etc. Some secondary influence of Atlantic SST, the structure of the African easterly jet, etc. has also been noted.

NOAA, which began issuing long-lead forecasts of the North Atlantic hurricane activity in 1998, uses an "accumulated cyclone energy" (ACE) index (defined as the sum of squares of the estimated 6-hourly maxi-

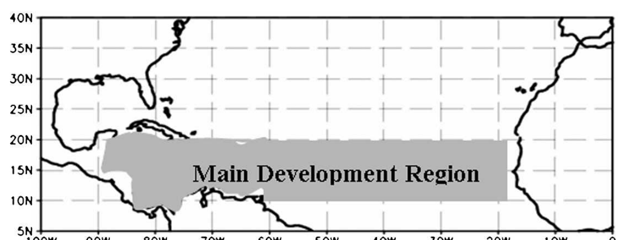

FIG. 9. The MDR for tropical cyclones/hurricanes in the tropical North Atlantic between 9° and 21.5°N. During 1949–2002 tropical systems that first formed in the MDR account for 71% of the basinwide total activity as measured by ACE index, 55% of all hurricanes, and 79% of all major hurricanes.

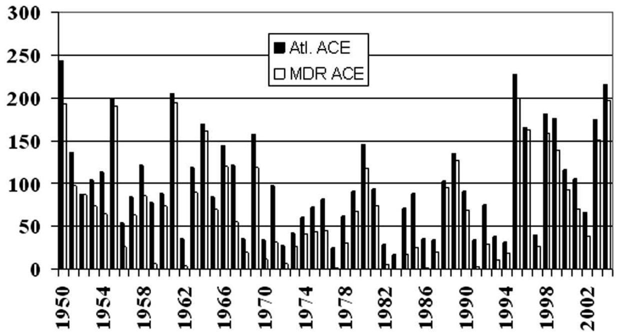

FIG. 10. Time series of the ACE index for 1950–2004 for the Atlantic basin as a whole and for the MDR.

mum sustained wind speed for all named storms while they are at least tropical storm strength) to measure the overall storm/hurricane activity (Bell et al. 2000). There is tremendous interannual and interdecadal variability in the Atlantic hurricane activity as measured by ACE (Fig. 10). Chelliah and Bell (2004) and Bell and Chelliah (2006) identified a tropical multidecadal mode (TMM) and an interannual mode (ENSO) in all seasons including the ASO period, the peak Atlantic hurricane season. The spatial and temporal characteristics of this leading interdecadal mode are robust and are independent of whether the seasonal tropical (30°N–30°S) surface temperature anomalies or 200-mb velocity potential anomalies are used as the analysis variable. As far as one can tell: the TMM subsumes the AMO.

While the characteristics of the interannual ENSO mode are well known in literature, the leading TMM is associated with an east–west seesaw in anomalous tropical convection between three key regions, the west African monsoon region, tropical South America, and the central equatorial Pacific. Hence the mode accounts for large explained variance not only in the MDR but also in other regions around the globe, thus bringing the global association with the interdecadal variability of the Atlantic hurricane activity. It is found that the coherent large-scale and regional-scale atmospheric anomalies and levels of activity associated with seasonal hurricane extremes are recovered when the tropical multidecadal mode and ENSO are in phase.

Figure 11 shows NOAA's forecast and verification of tropical North Atlantic hurricane activity from 1998 through 2004. Based on these 6 years, very high skill is suggested, much higher than anything we are used to in traditional seasonal prediction in NA. However, the Atlantic itself may not play a big role in regulating seasonal hurricane activity. The AMO appears to be closely related to the global TMM, which raises some doubt as to whether the AMO is really of Atlantic origin and whether the hurricane activity gets modulated by Atlantic trend modes or global trend modes.

7. Results with new NCEP Coupled Forecast System

Recently the new CFS (40-level global ocean, T62L64 atmosphere; one-tier system; Saha et al. 2003, 2006) was run in forecast mode on 15 different initial conditions per month for all months during 1981–2003. Each forecast run is 9 months long, so a total of over

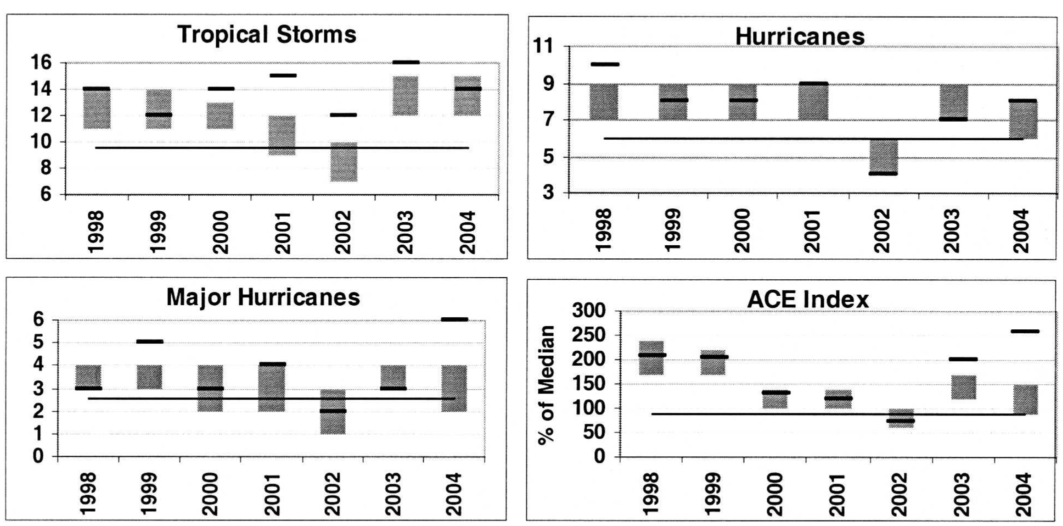

FIG. 11. Real-time NOAA forecasts of hurricane activity during 1998–2004, in terms of tropical storms, hurricanes, and major hurricanes as well as the ACE index. The forecast range of the various forecast quantities are shown as a shaded vertical bar and the actual observed values are shown as short thick horizontal lines. The 1951–2000 observed means are shown as thin horizontal lines.

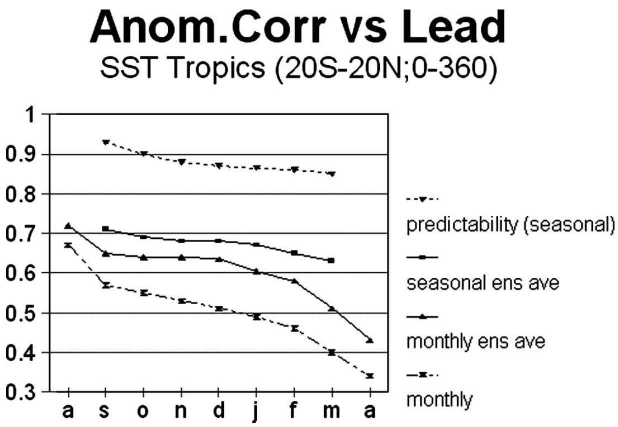

FIG. 12. Skill and predictability (both measured by anomaly correlation) of global tropical forecasts of monthly/seasonal mean SST, 1981–2003. Results from one-tier CFS (Saha et al. 2006). The forecasts originate in July, August is "zero lead" forecast, and the integration extends to April of next year. The lowercase letters along the *x* axis run from August to April. The AC of prediction improves as one goes from bottom to top: monthly mean (bottom plot) to ensemble average and seasonal mean (two plots in the middle). Predictability (one member vs the average of all other) features the highest AC (top plot).

3000 yr of coupled model integration is available for inspection. The Niño-3.4 prediction appears as good as any method we have seen, and certainly better than the previous coupled model at NCEP.

Using monthly data as basic units, we calculated forecast skill (anomaly correlation) for (a) monthly means, (b) (15 member) ensemble mean monthly means, and (c) ensemble mean seasonal means. And we added (d) "predictability" of the first kind by correlating a single member against the mean of 14 other members (under "perfect" model assumption). The correlations should normally increase when going from (a) to (d). For brevity we present results for integrations from July only. More complete results can be found in Saha et al. (2006). For global tropical SST we have substantial skill, and still higher predictability (see Fig. 12), where prediction skill and predictability are shown to decrease only very slowly from August (a) till next March (m). Locally, the highest skill/predictability is found in the Pacific, more or less in the Niño-3.4 area. To date no experiments have been done (or even defined) with CFS to identify the influence of, say, the Atlantic on NA. But one can get some impression by studying prediction skill for Atlantic SST. Figure 13 shows skill of CFS at predicting Atlantic SST in DJF at lead 1 and 6 months. Skill is restricted to several zonal bands along 55° and 15°N and mainly at short leads; that is, with present technology it is unlikely that the Atlantic contributes enormously to skill over NA beyond the shortest leads. Verification of SST forecasts in midlatitudes is difficult at this time because of substantial differences in SST analyzed in conjunction with the global ocean data assimilation system (GODAS) and more independent products like a univariate optimal interpolation of SST (OI; Reynolds et al. 2002); that is, the verifying analysis is uncertain, even in the anomalies. In Fig. 13 OI is used. Verification against GODAS shows far more favorable results; see Saha et al. (2006) for details. In terms of Z500 skill of the CFS in the North Atlantic (and North Pacific) is small and the potential not much above a 0.3–0.4 correlation in the best of seasons (January, February); see Saha et al. (2006). Consistent with experience elsewhere (Palmer et al. 2004), the seasonal NAO index can be predicted at 0.3–0.4 level at best, which is borderline significant.

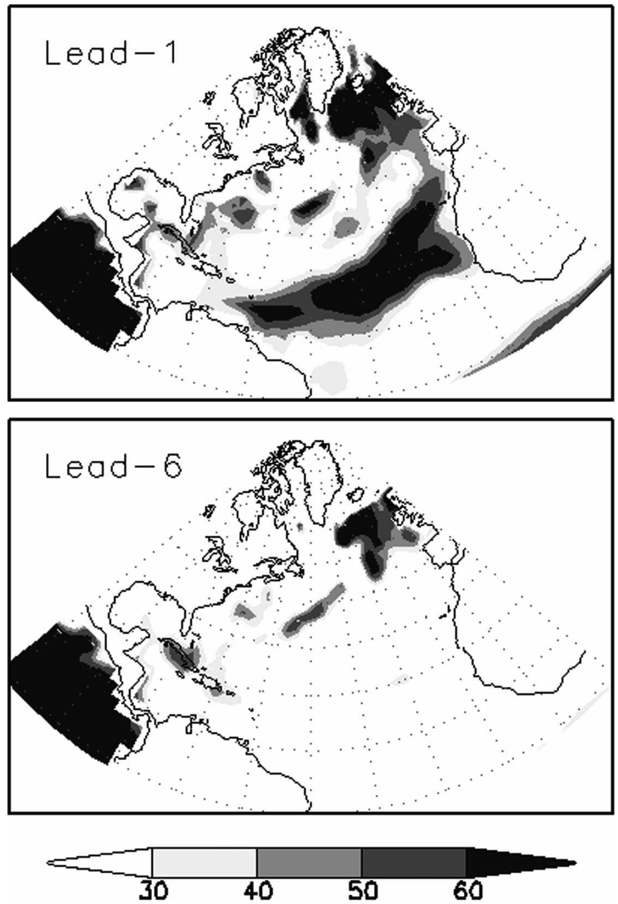

FIG. 13. Spatial distribution of AC skill (%) in forecasting seasonal mean SST in the Atlantic by CFS 1982–2004. The target season is DJF. Correlations in the darkest color are better than 0.6. In white areas the correlation is less than 0.3.

8. Conclusions and recommendations

We have considered the question of the impact of the Atlantic on North American (NA) seasonal prediction skill and predictability. Basic material is collected from the literature, a review of seasonal forecast procedures in Canada and the United States, and some fresh calculations using the NCEP–NCAR reanalysis data.

The general impression is one of low predictability (due to the Atlantic) for seasonal mean surface temperature and precipitation over NA. Predictability may be slightly better in the Caribbean and (sub)tropical America, even for precipitation. The NAO is widely seen as an agent making the Atlantic influence felt in NA, but its prediction skill is limited. We also found year-round evidence for an equatorially displaced version of the NAO (named ED_NAO) carrying a good fraction of the variance.

In general the predictability from the Pacific dominates over that from the Atlantic sector, which explains the minimal number of reported AMIP runs that explore Atlantic-only impacts over NA. Skill of a new one-tier Coupled Model System at NCEP is reviewed; we find limited skill in midlatitudes and modest predictability to look forward to in the Atlantic sector.

How one decides on the influence of the "Atlantic" on a certain target is not all that clear. In general determining the influence of a single predictor (be it the Atlantic or anything else), in a nonlinear system subject to several predictors truly is problematic. The response to predictors interacts, constructively and destructively. So an empirical study of the output of such a system may be beyond linear statistics. The "easiest" circumstance would be when one of the predictors dominates totally over all the others, a circumstance unlikely to apply to the Atlantic. Isolating the Atlantic in model experiments is equally problematic because application of ANOVA techniques assumes additive variance. Even the prediction skill due to SST of all oceans combined may be imperfectly known, unless we solve at the same time issues related to all other predictors (global land, stratosphere, atmospheric dust, chemical composition atmosphere, solar radiation . . . .).

Recent reanalyses of both oceanic and land conditions allows new research as to how SST and soil moisture are related. The NA area, more so than Europe, is often stressed by limited soil moisture, and prediction for the warm seasons appears to benefit from knowing initial soil moisture over NA. However, is there any long-lead forecast skill for land conditions, taking only antecedent oceanic conditions into account? This may be a somewhat unexplored topic although Shabbar and Skinner (2004) have recently found a strong relationship between winter Atlantic SSTs and the following summer's drought index. Van den Dool et al. (2003) report successful summer forecasts in the United States following the 1997/98 winter ENSO events, which left a strong imprint on the United States in terms of a wet (dry) lower boundary across the south (north). The interdecadal trends in soil moisture on a global scale (Fan and Van den Dool 2004) are fairly striking, but the causes are poorly known.

The topic of most interest, in terms of novelty, enthusiasm, and practical interest, is that of trends. We were somewhat surprised to find that 1) all CCA skill over NA due to Atlantic SST is of a low-frequency nature and 2) regardless whether we predict temperature or precipitation CCA mode 1 (calculated from unfiltered data) is always very similar and has the same low-frequency time series in all seasons. While trends in SST can be debated and questioned (caused by changes in observing system?), we would not expect spurious trends in SST to come out so similar looking in combination with trends in both T2m and precipitation. The latter two may be flawed observations also, but certainly not in the same way. It therefore appears there is "something" that orchestrates interdecadal up-and-down time series for the upper ocean as well as the continents. We come to this point of view in this setup with Atlantic SST as predictors. So the Atlantic is implicated. But it cannot be ruled out that it not Atlantic SST (or SST in general), that predicts the seasonal climate over land in the next season. It may be that all three variables react to some common unidentified cause of very low frequency (in which case a reverse CCA forecasting SST would show similar encouraging results, or low-frequency-filtered Pacific SST would achieve the same results over NA land). This all needs further explanation. There are certainly several signs of enthusiasm about using "trends" (low-frequency variations): (a) seasonal forecast tools include persistence of last 10-yr-averaged anomaly (relative to the most recent 30-yr climatology), (b) hurricane forecasts (high skill) are based largely on recognizing a global multidecadal mode (which is similar to an Atlantic trend mode in SST, but subsumes the Atlantic), and (c) two recent papers, one empirical and one modeling, McGabe et al. (2004) and Schubert et al. (2004), giving equal roles to (North) Pacific and Atlantic in "explaining" variations in drought frequency over NA on a 20 yr or longer time scale. Whether there is any predictability over and beyond what we harvest already via OCN remains to be seen, but we can certainly learn more by trying to understand these interdecadal variations. It will take also further research to name correctly and disentangle trends due to NAO (atmospheric westerlies; Hurrell 1995), AMO (Atlantic SST; Enfield et al. 2001), the TMM (the global tropical convection and atmospheric divergent flow; Chelliah and Bell 2004), and the thermohaline overturning in the Atlantic (Gray et al. 1997).

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