Specification of Seasonal-Mean 700 mb Heights over North America by North Pacific and North Atlantic Sea Surface Temperatures[1]

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ABSTRACT

North Pacific and North Atlantic SST (sea surface temperature) were used separately and in combination to specify seasonal-mean North American 700 mb heights. One of the goals was to quantify these relationships so that the importance of North Atlantic versus North Pacific SST could be assessed. Sea surface temperature predictors were in the form of EOF (empirical orthogonal function) amplitudes, while the predictands consisted of seasonal-mean 700 mb heights at each of 25 locations over North America. Linear regression analysis was used in the data period 1949–77 to build three kinds of models: 1) using the first five North Pacific SST EOFs, 2) using the first five North Atlantic SST EOFs and 3) using five EOFs from each field, but screening to produce the best five predictor models.

The principal findings can be summarized as:

1) Based on area-averaged skill and percent area of significant skill, North Pacific SST is a better specifier of 700 mb height than North Atlantic SST.

2) Pacific SST models have significant overall skill for all seasons except spring, with area-averaged true skill being greatest in winter ($\bar{S} = 0.247$) and least in spring ($\bar{S} = 0.061$).

3) Atlantic SST models do not attain field significance in any season, but perform best overall in winter ($\bar{S} = 0.095$).

4) A portion of the region studied for winter and summer contained grid point locations where testing indicated that Atlantic SST adds significant information to that of Pacific SST in explaining variations of 700 mb height. This amounted to 13 and 15% of the total area, respectively, which was not enough to declare field significance.

1. Introduction

One of the important steps of current long-range forecast preparation in many facilities, most particularly that of the United States National Weather Service, is the production of a forecast circulation chart for the mid-troposphere (Harnack, 1981). From this, surface air temperature and precipitation are specified with the aid of objective methods such as regression or correlation analysis. Most recently this has been studied by Klein (1983) for monthly temperature specification, Diaz and Namias (1983) for seasonal temperature and precipitation and Lanzante and Harnack (1982) for summer precipitation amount and frequency. In each of these studies the 700 mb height field for a large portion of the Northern Hemisphere was used as a predictor (or specifier) of the surface climate element.

While prediction of the circulation is of practical importance in long-range forecasting, understanding relationships between the circulation and proposed forcing mechanisms is important to further progress. Appropriately, much work has been devoted to relating the sea surface temperature (SST) field to the circulation concurrently and with lag through case studies and statistical methods. The Namias collection of papers (1975) contains numerous examples of a variety of studies which illustrate and quantify relationships between SST and the overlying atmosphere on monthly and seasonal time scales. These studies, and those of others, have served to encourage investigations whose aim is to objectively verify large-scale air–sea relationships using modern statistical methods and statistical significance tests. Relevant studies include Davis (1978) on the predictability of seasonal North Pacific SST and sea level pressure (SLP) using statistical relations between them, Barnett (1981) on the predictive skill of North American seasonal air temperature using antecedent Pacific SST and SLP, Walsh and Richman (1981) on the concurrent relationship between monthly North Pacific SST and United States surface temperature and Fritz (1982) on the concurrent relationship between winter month 700 mb height field and North Pacific SST. These

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studies all indicate that the spatial and temporal variation of North Pacific SST is related to climatic fluctuations over or upwind of North America on a monthly or longer time scale. Furthermore, they have placed the use of large-scale air–sea interaction ideas on a firmer statistical footing so as to justify their use in long-range forecast preparation.

The objective of this study is to determine the extent to which seasonal-mean 700 mb heights over North America can be specified by North Pacific and North Atlantic SST, separately and together, in order to quantify the importance of North Atlantic SST for the long-range forecast problem solution. Until recently, systematic use of North Atlantic SST in statistical climate studies has been difficult due to the lack of a machine-readable, quality-checked, gridded data set for the entire North Atlantic basin. The formation of such a data set by the Scripps Institution of Oceanography, to be described in the next section, now allows for North Atlantic SST to be used in studies in the same way that North Pacific SST has been used in earlier studies. Although basic statistics defining the temporal and spatial variability of North Atlantic SST were computed and analyzed for this study, they will not be shown here; rather, only that portion of the work that shows large-scale air–sea relationships involving North Atlantic SST[2] will be presented.

A small number of studies using North Atlantic SST in this way have been published, but these have been limited to examining atmospheric associations over and downwind of the North Atlantic. For example, the study by Namias (1964) was a case study in which North Atlantic SST for the period 1958–60 was related to anomalous 700 mb circulation downstream over Europe, while Ratcliffe and Murray (1970) produced composite monthly-mean SLP maps for the Atlantic–European sector for months following a given SST anomaly situation in the region near Newfoundland. Recently, Lanzante (1983) computed the correlations between gradients of SST anomaly and 700 mb height anomaly for the North Atlantic and North Pacific, as an extension of work by Harnack and Broccoli (1979), using monthly and three-month mean data. This indicated, not unexpectedly, that statistically significant atmosphere–ocean relationships exist for the North Atlantic, although they are generally not as strong as for the North Pacific.

While downstream atmospheric effects have been studied, upstream manifestations of North Atlantic air–sea interaction have not been given much attention, probably due to the data problems mentioned earlier. A discussion of the data sets used to accomplish the stated objective follows.

2. Data sources and procedure

The study employed three basic sets: North Atlantic SST, North Pacific SST and Northern Hemisphere 700 mb heights. Each are discussed in turn.

1) The North Atlantic SST data set, obtained from the Scripps Institution of Oceanography on magnetic tape, consisted of monthly anomaly values on a 5° by 5° latitude–longitude grid covering the period 1949–79. Data was present down to 5°N latitude and covered the rest of the basin. Quality control checks were not performed beyond what was done at Scripps. This data set is somewhat described in an article by Cayan (1982). The data set was derived by combining 1° latitude–longitude British Meteorological Office SST data with 1° latitude–longitude TDF-11 Marine Deck SST data (from NODC) using an observation number weighted average, then obtaining 5° latitude–longitude intersection values by averaging 1° data in an area around the intersection. Grid points with frequent missing values, such as several points in the extreme northwestern Atlantic, were not used. The grid network selected from the data tape for use in this study consisted of 50 grid points over the whole basin in the latitude zone 25–65°N, using a staggered 5° by 10° latitude–longitude resolution (see Fig. 1 for locations).

2) The North Pacific SST data set was also obtained from Scripps as monthly means and has been used in numerous prior investigations. The data set covers 1947 to the present. Again, 50 grid points were extracted, taken as a 5° by 10° latitude–longitude staggered grid over the region 25–55°N and 125°W–160°E.

3) Monthly mean 700 mb heights for the Northern Hemisphere were obtained from the National Meteorological Center as a 5° by 5° latitude–longitude gridded data set, from which 25 data points were extracted in the region 30–60°N, 70–130°W using a 10° by 10° resolution. This region includes the greater part of North America.

One of the basic analysis performed using the Atlantic SST data set, which has some relevance to the large-scale air–sea interaction studied here, is the seasonal correlation between the Atlantic SST and 1000–700 mb thickness. This correlation was done for the North Pacific by Namias (1973), and indicated a good association. Thickness was determined at the same grid points as used for the Atlantic SST by first computing 1000 mb heights (as done at the Climate Analysis Center using SLP and long-term monthly mean air temperature on a grid point by grid point basis), and then subtracting them from corresponding

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[2] The authors were informed by Jerome Namias and Daniel Cayan of the Scripps Institution of Oceanography (Climate Research Group) that basic analyses would be presented in a SIO Reference Series publication, in preparation. Considering that Scripps was the originator of the data set it was decided to forgo their inclusion here.

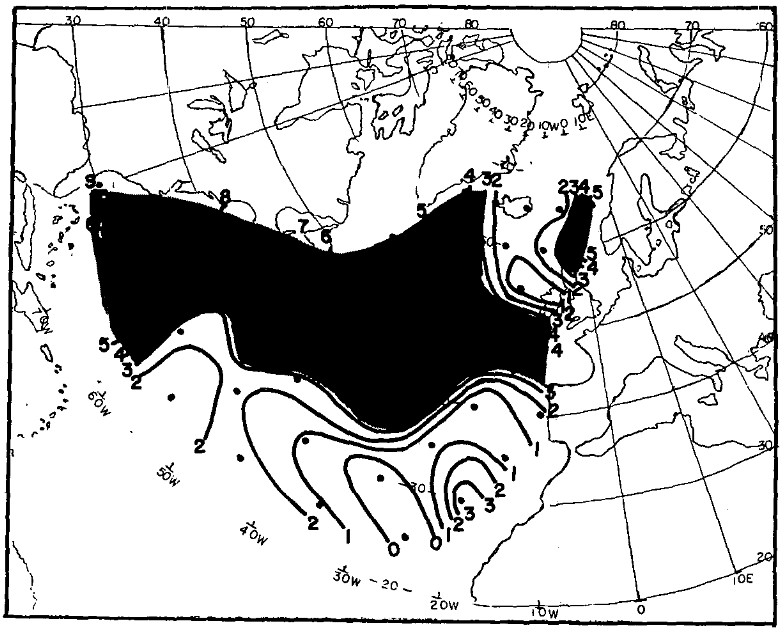

FIG. 1. Correlation between Atlantic SST anomaly and 1000–700 mb thickness for winter. Values given are times 10^{-1}. Shading denotes local statistical significance at the 5% level.

700 mb heights. Therefore, for this part of the study, 700 mb heights for the Atlantic region were also used. The contemporaneous correlations were computed for all seasons (1949–76) in order to determine the degree of thermal communication between the surface layer of ocean and the lower troposphere. Presumably there should be a good association over the North Atlantic if there is to be any real association between the Atlantic SST and upstream North American 700 mb heights.

For the specification portion of the study, seasonal-mean 700 mb heights at the 25 grid points over North America were used as the predictands in a multiple linear regression analysis. The predictors consisted of the first five empirical orthogonal function (EOF) amplitude time series from the North Atlantic SST field and the North Pacific SST field. Regression models were constructed for each of the 700 mb locations and for each season. Three kinds of regression analyses were performed: 1) using only North Pacific predictors, 2) using only North Atlantic predictors and 3) using both North Atlantic and North Pacific predictors in a screening regression procedure to build a five predictor model. Exactly five EOFs from each field were used based on Monte Carlo significance tests performed on EOF analyses in previous studies using North Pacific SSTs and based on a desire to have all regression models of the same order for comparison purposes. Regression models used a sample of 29 years (1949–77).

Explained variances for each location were computed and used to estimate and plot true skill (see Appendix), as well as statistical significance. Finally, an attempt was made to determine where and when the addition of Atlantic SST data adds significantly to Pacific SSTs in specifying North American 700 mb heights.

3. Results

a. North Atlantic SST versus 1000–700 mb thickness

Figures 1–4 show contemporaneous correlations between seasonal-mean SSTs and the 1000–700 mb thickness computed for each season at 50 grid points. Stippling denotes statistical significance at the 5% level, which was determined assuming independence between cases (a one-year interval here) and a sample size of 28.

With few exceptions the relationship is positive, and for each season large areas have a statistically significant relationship, as was true in the Namias study for the North Pacific. Overall, based on area-averaged correlation for each season, SST and thickness relate best in winter, next best in summer and worst in spring; however, the values are similar since the highest correlation is 0.38 and the lowest is 0.35. On any given map, spatial variability is large, but considerable similarity of patterns are seen from map to map. For instance, high correlation is seen from the North American coast to the central Atlantic in the 40–50°N band (roughly along the Gulf Stream) and low correlations are generally seen in lower latitudes (especially south of 35°N), particularly in

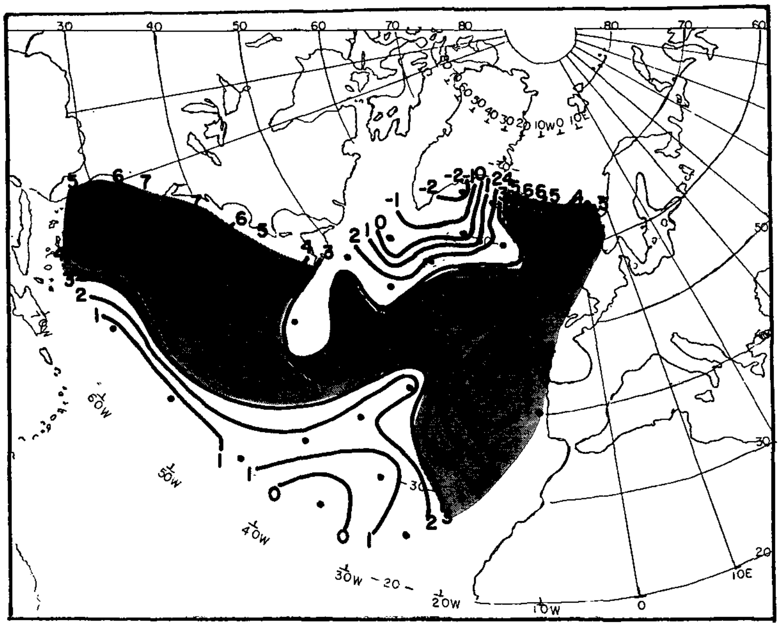

FIG. 2. As in Fig. 1 except for spring.

the southeast portion of the domain. In addition, on each map some portion of the northernmost area and extreme eastern area has low correlation, especially in fall and winter in the latter case.

Even with the exceptions noted, one would have to conclude that there is good and sufficient thermal communication between ocean and atmosphere in the North Atlantic for circulation effects outside the North Atlantic region, such as upstream over North America, to be plausable.

b. Specification of seasonal North American 700 mb heights

As noted above, three kinds of regression models were formulated for each of the 25 grid-point locations selected over North America, and for each season: a model using only North Pacific SST, a model using only North Atlantic SST and a combined model using five predictors screened from the pool of five North Pacific plus five North Atlantic SST predictors.

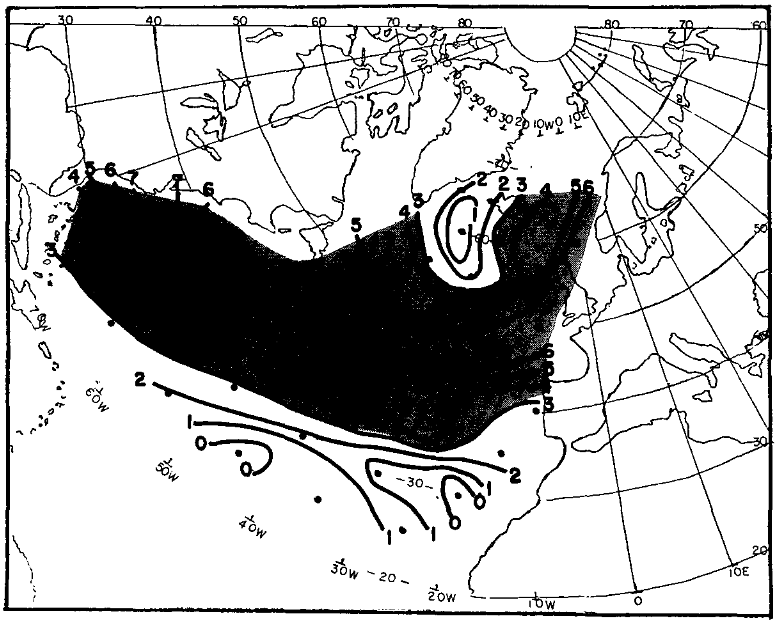

FIG. 3. As in Fig. 1 except for summer.

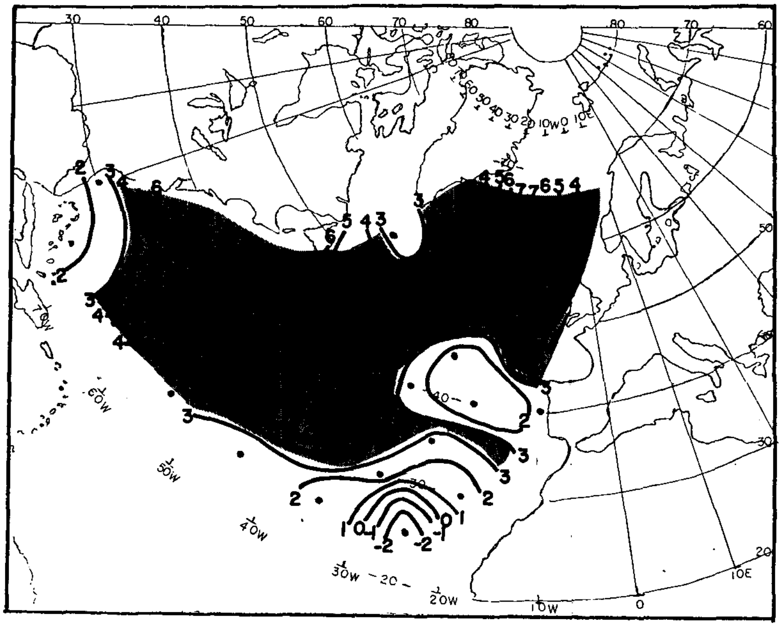

FIG. 4. As in Fig. 1 except for fall.

All predictors were in the form of EOF time series computed from the seasonal-mean SST anomaly fields, seasonally stratified. The EOF results are not shown because they are published elsewhere (Weare, 1977; Weare *et al.*, 1976) and because the purpose of EOF analysis here was data reduction for input to regression analysis.

Regression results are presented as maps of true skill for each model type and season, which is determined by subtracting an estimate of "artificial predictability" (Davis, 1976) from the hindcast skill (or model explained variance). Details may be found in the Appendix. True skill was plotted on maps for each of the seasons and for the three kinds of models (not shown here). Table 1 summarizes the overall results to help facilitate model comparisons, showing area-averaged true skill ($\bar{S}$), percent of total area where local significance was achieved and the results of field significance tests performed (see Appendix for explanation). Negative values result from overestimates of artificial skill and should not be considered different from zero. The maximum possible value for $\bar{S}$ is 1.00.

TABLE 1. Area-averaged true skill ($\bar{S}$), percent area significant at 5% level ($A_s\%$) and assessment of field significance (5% level) for regression model sets.

Season	Predictors	$\bar{S}$	$A_S\%$	Sig.
Winter	Pac. SST	0.247	64	X
	Atl. SST	0.095	17	
	Pac./Atl. SST	0.209	45	X
Spring	Pac. SST	0.061	<1	
	Atl. SST	−0.066	<1	
	Pac./Atl. SST	0.040	<1	
Summer	Pac. SST	0.121	23	X
	Atl. SST	0.068	11	
	Pac./Atl. SST	0.142	15	
Fall	Pac. SST	0.191	49	X
	Atl. SST	0.012	2	
	Pac./Atl. SST	0.178	41	X

Table 1 indicates that Pacific SST models have significant overall skill for all seasons except spring, with area-averaged true skill being greatest in winter ($\bar{S}$ = 0.247) and least in spring ($\bar{S}$ = 0.061). Atlantic SST models do not attain field significance in any season, but perform the best overall in winter ($\bar{S}$ = 0.095) when 17% of the total area has local significance achieved. These type of models also do worst in spring ($\bar{S}$ = −0.066). The combined Pacific/Atlantic SST models have an $\bar{S}$ value which is less than the best $\bar{S}$ value obtained for uncombined models in the same season, except for summer when $\bar{S}$ for the combined was 0.142 compared to the next best of 0.121 (Pacific SST). In this case, field significance was not achieved.

From an overall perspective, it appears that for the Atlantic SST specification of North American 700 mb heights either the skill is very small and/or the incremental skill obtained by using Atlantic SST with Pacific SST is unimportant. The reader should keep in mind that a corrected explained variance statistic (i.e., true skill) is used here for comparison purposes, so even if a screening regression equation has a greater explained variance (uncorrected) than a non-screening one, the latter may have a greater true skill after the effects of screening are estimated and used to correct the obtained explained variance. In addition to showing the distribution of true skill and model significance, the maps of true skill showed where Atlantic SSTs added significantly to Pacific SSTs (at the 5% level) in explaining 700 mb height variance. See the Appendix for an explanation of this determination. On both the winter and summer maps a portion (13 and 15% of the area respectively) contain grid-point locations where Atlantic SSTs add significant information while still resulting in a significant model. In winter, this occurs over the southwest United States and in summer over the extreme western part of the domain and in a swath through central to eastern Canada. This area is not large enough in these two seasons to confidently claim that the results are nonrandom.

The locations where Atlantic SSTs alone explain a significant amount of 700 mb variance varies by season. In winter this is in parts of the southeast and central regions, in summer over the north-central region and in fall over a small portion of the extreme west. These locations are generally at variance with the preconceived idea that the greatest influence of the Atlantic SST on the 700 mb height would occur near the Atlantic coast. No explanation is offered for the discrepancy; however, the area covered is relatively small and approaches field significance (5% level) only for winter.

The Pacific SST models have skill patterns which are quite similar to those obtained by Walsh and Richman (1981) when they regressed United States seasonal temperature onto concurrent amplitudes of the first five Pacific SST EOFs. The main features in this part of the study include a large area of significance (64% of the total area) in the southeastern and northwestern thirds of the domain for winter, only isolated significance for spring, significance for both the extreme west and Great Lakes region for summer and a large area of significance (49% of the total area) in the west-central and northeastern portions of the domain in fall.

The combined SST models' spatial variation of skill generally follows that of the Pacific SST model pattern, since Pacific SST is dominant in importance to Atlantic SST for specifying North American 700 mb heights. Slight shifting of the areas of significance are seen where and when the influence of Atlantic SST is important.

4. Summary and conclusions

In this study North Pacific and North Atlantic SST were used separately and in combination to specify seasonal-mean North American 700 mb heights. One of the goals was to quantify these relationships so that the importance of North Atlantic versus North Pacific SST could be assessed. The SST predictors were in the form of EOF amplitudes, while the predictands consisted of seasonal-mean 700 mb heights at each of 25 locations over North America. Linear regression analysis was used in the data period 1949–77 to build three kinds of models: 1) using the first five North Pacific SST EOFs, 2) using the first five North Atlantic SST EOFs and 3) using five EOFs from each field, but screening to produce the best five predictor model. Comparisons between model types as well as assessments of seasonal and spatial variation of skill were made by estimating "true skill," defined as the "hindcast skill" (or model explained variance) minus the "artificial skill," and then mapping or averaging the values. Local significance and field significance were determined as well as the statistical significance of adding Atlantic SST to Pacific SST for specifying 700 mb height.

The principal findings can be summarized as:

1) Based on area-averaged skill and percent area of significant skill, North Pacific SST is a better specifier of 700 mb height than North Atlantic SST.

2) Pacific SST models have significant overall skill for all seasons except spring, with area-averaged true skill being greatest in winter ($\bar{S} = 0.247$) and least in spring ($\bar{S} = 0.061$).

3) Atlantic SST models do not attain field significance in any season, but perform best overall in winter ($\bar{S} = 0.095$).

4) A portion of the region studied for winter and summer contained grid-point locations where testing indicated that Atlantic SST adds significant information to that of Pacific SST in explaining variation of 700 mb height. This amounted to 13 and 15% of the total area, respectively, which was not enough to declare field significance.

5) The locations where the Atlantic SST either adds significantly to the Pacific SST or where the Atlantic SST alone has significant skill did not tend to be along the Atlantic coast, as expected, but rather in various locations over the whole domain depending on season and model type.

In summary, the Atlantic SST does not appear to be a useful primary predictor of North American 700 mb heights on a seasonal time scale based on the overall weak relationship obtained here with no lag between the two fields, since in most locations the Pacific SST has a better relationship with the height field. Exceptions are noted, however, so at particular locations and seasons Atlantic SST information may be secondarily important to Pacific SST, though a clear case for nonrandomness cannot be made. For long-range forecasting purposes Atlantic SST may play a role locally in producing surface air temperature anomalies or precipitation anomalies even though it does not play an obvious role in affecting mid-tropospheric heights there. This has not been investigated here nor has the role of Atlantic SST on overlying and downstream circulation since our focus has been on North America. The residual (unexplained) variance implies that non-SST factors are also quite important.

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APPENDIX

Determination of Skill and Significance

The following gives explanations of the statistical techniques utilized in this paper in the assessment of skill and significance. Three sets of multiple regression equations were derived for each season at each grid point using the MAXR option of the SAS STEPWISE procedure (Helwig and Council, 1979). The dependent variable (700 mb height at each of 25 grid points) was predicted (specified) from 1) the first five Pacific SST EOFs, 2) the first five Atlantic SST EOFs and 3) the best five predictors from the pool of the first five Pacific and first five Atlantic SST EOFs. Local (grid point) skill and significance was assessed first. Next, the significance of the set (of 25 equations) for a given season was assessed (i.e., field significance).

1. Model skill

For each of the three types of models the raw explained variance (S_H) values were used to compute the true skill (S) following Davis (1978):

$$S = S_H - S_A. \tag{A1}$$

The artificial skill (S_A) was computed using Davis (1976):

$$S_A = \sum_{p=1}^{M} \tau_p/N\Delta t, \tag{A2}$$

where M is the number of predictors in the pool (five or ten in this study), τ_p the integral time scale, N the actual sample size and Δt the time interval of the model (time between successive observations). In the case of screening regression (combined Pacific and Atlantic predictors), the S_A value was computed using $M = 10$ and was multiplied by 0.90 (from Fig. 1 of Davis, 1977), since $M_s/M = 5/10$ (i.e., five taken from a pool of ten).

Each τ_p value was computed following Sciremammano (1979):

$$\tau = \sum_{i=-\infty}^{\infty} C_{xx}(i\Delta t)C_{yy}(i\Delta t)\Delta t, \tag{A3}$$

where i is the observation number and C_{xx} and C_{yy} are the autocorrelation functions of the predictors and predictands. In practice, $i = \pm L$, where L is large compared to the lag at which the autocorrelation becomes insignificant. Also, C_{xx} and C_{yy} were damped [multiplied by $1 - (i/28)$] as suggested by Livezey and Chen (1983).

2. Model significance

The significance of the Pacific- or Atlantic-only models (nonscreening) was assessed by adjusting the critical value in the F test. The sample size ($N = 28$) was replaced by the effective sample size (n) following Sciremammano (1979):

$$n = N\Delta t/\bar{\tau}, \tag{A4}$$

where

$$\bar{\tau} = \sum_{p=1}^{5} \tau_p/5. \tag{A5}$$

In the case of screening regression, a simple adjustment of the F critical value is not adequate. Instead, a Monte Carlo simulation was carried out. The predictor pool was left unchanged but the predictand (grid point 700 mb height) set was "shuffled" randomly. However, all 25 grid-point values for a given season were moved as a unit in order to preserve the spatial coherence of the set. The explained variance values from each of 200 trials were used to construct a frequency distribution. The 5% upper tail value (a one-tailed test) of the distribution was taken to be the critical value in assessing significance.

The significance testing of the addition of the Atlantic SST to the Pacific SST was also assessed using a Monte Carlo testing scheme. The pool consisted of the five actual Pacific SST EOFs plus five random numbers having the same lag one autocorrelation as the first five Atlantic SST EOFs. The best five predictors from the pool of ten were selected. Again, the 5% tail value was used in assessing significance.

3. Field significance

For each of the 12 maps (4 seasons and 3 model types) the percentage of area deemed significant was computed. In addition, the percentage of area for which the Atlantic adds significantly to the Pacific SST was determined. The significance of the field was assessed using the binomial distribution as suggested by Livezey and Chen (1983). The spatial degrees of freedom were estimated through a Monte Carlo simulation in which a random series of 28 numbers was correlated with each of the 25 grid-point values of 700 mb height. The 5% tail value of the frequency distribution of percentage of map area deemed significant in each random trial was used as before. The critical percentage of map area for field significance is 25.1% for winter (10 spatial degrees of freedom) and 22.7% for summer and fall (12 spatial degrees of freedom). Note that a spring simulation was not performed since the spring maps obviously do not have field significance.

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