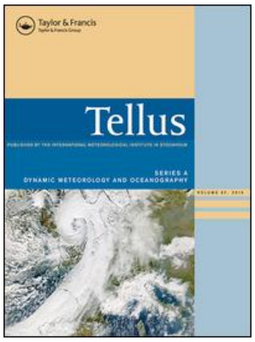

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Statistical prediction of seasonal air temperature over Eurasia

By T. P. BARNETT, *Climate Research Group, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California 92093, U.S.A.*, H.-D. HEINZ and K. HASSELMANN, *Max Planck Institute for Meteorology, University of Hamburg, Hamburg, F.R. Germany*

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ABSTRACT

Statistical models for the prediction of seasonal surface air temperature anomalies over Eurasia were constructed. The models were designed to test the relative predictive skill of Atlantic sea surface temperatures (SST), sea level pressure (SLP) and persistence in a cyclostationary setting.

Significant forecast skill was found for the spring season in central and eastern Europe. The main predictors were persistence and SLPs (the north Atlantic oscillation). SSTs had little predictive value. All results were confirmed with independent forecast experiments. The statistical results were attributed to (a) a positive feedback between given winter atmospheric circulation regimes, the snow cover they produce and the snow-induced enhancement/retardation of normal season warming and (b) the persistence of large-scale circulation patterns over the Atlantic Ocean.

1. Introduction

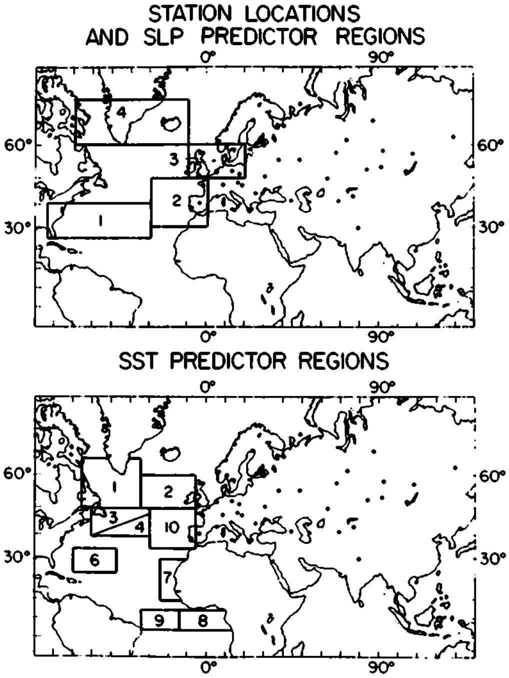
The purpose of this study was to investigate the predictability of short-term climate variations over the Eurasian continent. The work is motivated by a desire to elucidate the rôle the oceans play in the global climate system. This specific effort looked fruitful since prior studies have suggested a relation between climatic change over Europe and antecedent changes in the oceanic and atmospheric fields of the Atlantic. Also, a similar study conducted for the north American region (Barnett, 1981) gave positive results, suggesting the application of similar techniques to climate predictions over Europe. Finally, there is the practical question: can useful short-term climate forecasts be made over Eurasia using rigorously derived statistical models?

Numerous empirical studies have been carried out to investigate the relation between sea surface temperature (SST) anomalies and overlying atmospheric patterns in the north Atlantic–European region. Bjerknes (1962, 1964), and subsequently Schell (1970), van Loon and Rogers (1978); Rogers and van Loon (1979), Perry (1975), Haworth (1978), among others, have demonstrated what appears to be a link between SST variations in the north Atlantic and *contemporary* variations in the overlying atmospheric field. These authors, and also Ratcliffe and Murray (1970), Ratcliffe (1970, 1971), suggest the existence of simultaneous feedback relations between SSTs in the area south of Newfoundland and atmospheric circulations over western Europe. Many of the above studies also suggest the possibility of *forecasting* subsequent conditions in Eurasia from antecedent SST conditions. However, in many cases the statistical techniques used to draw these inferences lack sufficient rigor to be convincing.

Numerical studies by Rowntree (1976, 1979), using a general circulation model, suggest the sensitivity of climate change in Europe to SST anomalies in the tropical Atlantic. Similar relations do not seem to have been strongly demonstrated in the statistical work, although the results of Meehl and van Loon (1979) and Haworth (1978) are a possible exception. Those authors find a marginal relation between tropical Atlantic SSTs in the autumn and subsequent changes at higher latitudes.

The rôle of the atmosphere as a predictor of itself over Eurasia has not been clearly established. However, the work of Murray (1970, 1973, 1977) strongly suggests the existence of reasonable predictive skill over the British Isles. Also, van Loon and collaborators identify an out-of-phase oscillation, or "seesaw" in winter temperature between Greenland and northern Europe. The "seesaw" appears to be part of the north Atlantic oscillation identified earlier by Walker and Bliss (1932). While this feature of the atmospheric circulation has been well described, its value as a subsequent predictor of climate change over Europe does not seem to have been rigorously tested.

In subsequent sections of this paper we describe the data and statistical methods used in this study. Additional sections consider the skill of sea surface temperatures and sea level pressures (SLP) both in specifying and forecasting variations in climate over Eurasia. These climate variations are represented in this paper by interannual variability of the seasonally averaged surface air temperature at selected stations. The value of persistence as a predictor of Eurasian air temperature also was tested. A model combining the most effective predictors was derived and tested on an independent data set. In carrying out these operations, it was possible to rigorously test many of the general ideas of earlier authors. A physical synopsis of the statistical results is presented in a "discussion" section.


STATION LOCATIONS AND SLP PREDICTOR REGIONS

SST PREDICTOR REGIONS

Fig. 1. Location of surface air temperature stations (solid dots) used in this study. Also shown on the upper and lower panels, respectively, are the predictor averaging areas for sea level pressure (SLP) and sea surface temperature (SST).

2. Data

The data to be predicted, called the "predictands", are monthly values of air temperature (T_A) at selected Eurasian stations (Fig. 1). The monthly values have been averaged into seasonal time series extending from 1899 to 1978. Only series were used which seemed to have few missing data values and general long-term continuity, e.g., no sharp breaks suggesting change of station location, etc. The original data came from Roy Jenne at NCAR.

The sea surface temperature data were derived from the Marine Deck (TDF-11). The "predictors" to be used were large-area averages (Fig. 1) developed from individual ship observations. The large-averaging areas were selected: (1) from highly energetic regions defined in an empirical orthogonal function (EOF) analysis and/or (2) based on an hypothesis of one of the authors noted earlier. Averaging regions of SST variation were (Fig. 1): the northwest Atlantic, consisting of subregions 1, 3, and 4, with the division between 3 and 4 being associated with the northern wall of the Gulf Stream; the northeast Atlantic (subregions 2 and 10); the Sargasso Sea (subregion 6); and the equatorial Atlantic (subregions 7, 8 and 9). Individual 1° squares within the large areas were considered as a basic data unit. Long-term seasonal means for these units were derived and anomalies subsequently computed. The anomalies for each 1° square were then averaged over an entire large block. It turned out that there was a relatively large data volume for the north Atlantic so that continuous time series from 1899 to 1978 could be constructed with good confidence. Several examples of the SST time series are shown in Fig. 2.

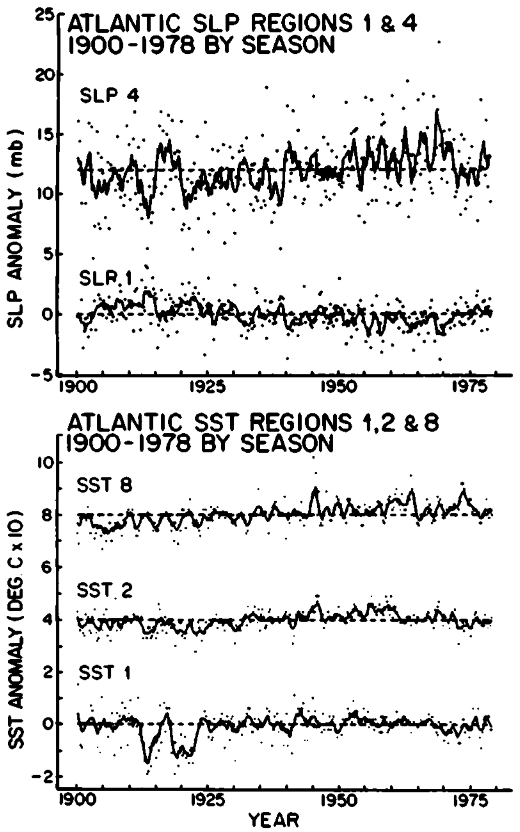


Fig. 2. Examples of selected SST and SLP predictor data. The individual dots show seasonal values while the solid line is the four season running mean through the data. A constant offset has been used to help separate the curves.

The sea level pressure data, again averaged by large areas, were also used as predictors. The SLP values came from the historical weather maps (US Weather Bureau as amended by Trenberth and Paolino (1981)), originally projected on a 5 × 5 grid from 20° N to 85° N. Care was taken to avoid problem areas in these data noted by Williams and van Loon (1976) and Trenberth and Paolino (1981). Recent SLP data came from standard NMC products. The large area averages were selected objectively from the results of an EOF analysis on the northern hemisphere sea level presure field. The regions over which sea level pressure was averaged are shown in Fig. 1. Example time series of these SLP predictors are shown in Fig. 2.

3. Methods of model construction

The regression models were constructed following the methods described in Barnett and Hasselmann (1979, BH) for systems with stationary statistics and as extended in Hasselmann and Barnett (1981, HB) to the cyclo-stationary case. The associated problems of determining model order and significance are additionally discussed by Barnett et al., 1981. The techniques used here are described briefly since the above references develop the subject in detail.

The prediction models we shall be concerned with are the class of general cyclo-stationary, multi-lagged, multi-predictor linear regression models of the form (cf. BH, HB)

$$y(t+q) = \sum_{i=0}^{m'} \sum_{l=0}^{m} D_{itl} x_i(t-l) + \eta(t), \tag{1}$$

where y denotes the predictand, x_i the predictor set, q, l are (discrete) lead and lag times, respectively, and η is the residual, which is to be minimized. Both y and x_i are detrended prior to use in the modeling process. The cyclo-stationarity is expressed by the dependence of the regression coefficient D_{itl} on time, t, and is assumed to be periodic,

$$D_{itl} = D_{i(t+p)l} = D_{i\kappa l} \tag{2}$$

where p is the period (in our case 4, for seasonal data) and $\kappa = t \pmod p$. Thus, κ represents a seasonal index, running from 0 to p-1.

The cyclo-stationary case can be reduced to the standard stationary case either by constructing separate models for each phase κ of the annual cycle (fixed phase models) or by expanding the coefficients in a Fourier-series,

$$D_{i\kappa l} = E^0_{il} + \left[E^c_{il}\cos\frac{2\pi\kappa}{p} + E^s_{il}\sin\frac{2\pi\kappa}{p}\right] + \left[E^{2c}_{il}\cos\frac{4\pi\kappa}{p} + E^{2s}_{il}\sin\frac{4\pi\kappa}{p}\right] + \dots \tag{3}$$

and then optimizing the model simultaneously over the entire annual cycle (phase averaged model).

If the Fourier expansion (3) is truncated below the Nyquist frequency, in this case 2 cpy, the phase-averaged model contains less coefficients and, therefore, generally achieves a higher statistical significance than a fixed-phase model. On the other hand, if a statistically significant fixed-phase model can be constructed, it has the advantage of providing a full resolution of the annual cycle (cf. HB).

Truncating (3) at the first harmonic and substituting it into (1), the phase-averaged model may be written in the notation of a stationary, non-lagged regression model

$$y(t+q) = \sum_{\gamma=1}^{n} a_\gamma z_\gamma(t) + \eta(t), \tag{4}$$

where $n = 3mm'$, the composite index $\gamma \equiv \{\alpha/il\}$, with $\alpha = 0, c$ or s

and

$$a_\gamma \equiv E^{\alpha}_{il}, \tag{5}$$

$$z_\gamma(t) \equiv x_i(t-l) \begin{Bmatrix} 1 \\ \cos 2\pi\kappa/p \\ \sin 2\pi\kappa/p \end{Bmatrix} \quad \text{for } \alpha = \begin{Bmatrix} 0 \\ c \\ s \end{Bmatrix}. \tag{6}$$

The best fit regression model is defined as the model which minimizes the mean square error $\langle \eta^2(t) \rangle$, averaged over the annual cycle. Prior to estimating the model coefficients it is convenient to transform the predictor set to an orthonormalized system, $z'_\gamma(t)$, defined by

$$z_\gamma(t) = \sum_{\lambda} \sigma_\gamma z'_\lambda(t) T_{\lambda\gamma}, \tag{7}$$

where σ^2_λ represents the eigenvalues and $T_{\lambda\gamma}$ the matrix of eigenvectors of the covariance matrix $\langle z_\lambda z_\gamma \rangle$. In this coordinate system

$$\langle z'_\lambda z'_\gamma \rangle = \delta_{\lambda\gamma}$$

and the regression coefficients a'_γ of the transformed model

$$y'(t+q) = \sum_{\gamma=1}^{n} a'_\gamma z'_\gamma(t) + \eta, \tag{8}$$

where $y' = y/\langle y^2 \rangle^{\frac{1}{2}}$, are given simply by

$$a'_\gamma = \langle y' z'_\gamma \rangle. \tag{9}$$

Methods of determining the appropriate model order (n in (8)) and the statistical significance of the a'_γ are given in BH and Barnett et al. (1981).

The hindcast skill of the model, defined generally by

$$S_{\mathrm{H}} = 1 - \frac{\langle (\sum_\gamma a_\gamma z_\gamma - y)^2 \rangle}{\langle y^2 \rangle} \tag{10}$$

reduces in the transformed coordinate system to

$$S_{\mathrm{H}} = \sum (a'_\gamma)^2. \tag{11}$$

We shall be concerned also with the forecast skill, S_{F}, defined as the skill, as given by (10), when the estimated model is applied to a second, independent data set.

The predictive ability of persistence will be an important aspect of this study. The appropriate models were constructed as fixed-phase models by solving explicitly for each $D_{i\kappa l}$ rather than using the phase averaged approximate (eq. 3). For the case $l = 1$, and the prediction coefficients are simply proportional to the time dependent covariance function, i.e.,

$$a_1(\kappa, \tau) \dot{\approx} \frac{1}{N} \sum_{\nu} y(\kappa, \nu) y(\kappa + \tau, \nu), \tag{12}$$

where κ is a season counter as before, ν is a year counter $(= 1, 2, \ldots, N)$ and y is the detrended time series of station air temperature arranged by (season, year). The resulting first-order model for a one-season lead hindcast is just

$$y(\kappa+1, \nu) \doteq a_1(\kappa, 1) y(\kappa, \nu). \tag{13}$$

The model skill is obtainable from (10) or (11) and the significance of the coefficient is estimated by standard means.

The fixed phase persistence model (13) is equivalent to representing the predictand as a cyclostationary, first-order Markov process. Higher-order models or models using combinations of nearby stations and lags are readily constructed by the methods noted above. In general we found these more complex models to be no more effective than the simpler version given by (13).

Interpreting model results is an important aspect of the modeling process and is described in some detail in BH and Jenkins and Watts (1968). The basic idea in this study will be to discuss the important predictor–predictand relations through the transfer functions, i.e., the prediction coefficients E^0_{il}, E^c_{il} and E^s_{il} (eq. 3). These transfer functions are equivalent to the Green functions of the differential equations which link the predictor and predictand and thereby provide information on the phase and time scales of the linkage.

4. Specification

A perspective on the predictive results to be discussed in subsequent sections was obtained by contrasting them with the skill associated with a "specification" of air temperature, i.e., $q = 0$ in eq. (1). This amounts to a zero lead forecast where one tries to estimate the predictand (seasonal air temperature) from *contemperaneous* predictors. We consider, in turn, the ability of SST and SLP to specify the Eurasian air temperature field.

4.1 *Specification from SST*

The sea surface temperature anomalies from the northwestern, northeastern and equatorial Atlantic were used to specify contemporaneous surface air temperature anomalies (T_A) over Eurasia. Both the prior season's ($m = 1$) and the prior year's SST data were used ($m = 3$, eq. 1). In the latter case this led (with cyclo stationary effects) to a total of 24 or 36 (highly correlated) predictors.

The results from the *best* of the specifications are shown in Fig. 3 and the seasonal elements of the transfer functions for Bodö and Valentia in Table 1. The clear conclusion is that simultaneous knowledge of Atlantic SST is, *on average*, of little use in objectively determining the air temperature anomaly field over Eurasia. This conclusion contrasts with the apparent results of Ratcliffe and Murray (1970). Close inspection of their work shows a marginal relation at best between a few specially selected SST conditions in the northwest Atlantic and Eurasian SLP. Problems with different data averaging periods, analysis procedures and significance tests can easily explain the remaining dichotomies.

The lone exception to low specification skill occurs in the British Isles. The transfer functions show that the air anomalies tend to have the same sign as the SST anomalies adjacent to the British Isles (northeast Atlantic), a result in agreement with that of Rodgers and van Loon (1979), Perry (1975), Schell (1970) and others. Thus local anomalous warming/cooling of the overlying air by the anomalous ocean temperatures seems to adequately explain the result. Note, however, that stations on the Iberian Peninsula, along the North Sea and in France do not follow this simple relation. Inspection of the models for these stations show they "just miss" being significant at the 90% level when the northeastern SSTs are used as predictors. Apparently the local signal is not strong enough to overcome remote forcing and noise effects.

The ability of the equatorial Atlantic to specify T_A is also limited to Britain although the entire Scandinavian area again "just misses" in the significance tests. The sense of the relation between this region and western Europe T_A is as above: warm ocean = warm T_A and vice versa. These general results are in agreement with those of

SPECIFICATION SKILL : SST

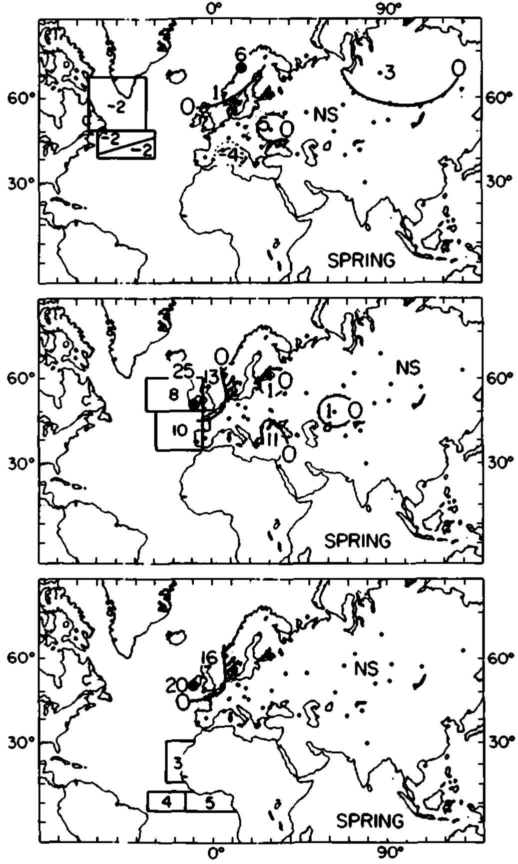


Fig. 3. The ability of SST in selected Atlantic regions to specify subsequent air temperature anomalies over Eurasia. A significant model could not be constructed for the regions denoted by "NS". Specification skill at the few significant stations shown in this illustration rarely exceeded 5%. The prediction coefficient (eq. 3), multiplied by 100, is shown in the appropriate predictor region (small numbers in the boxes) for Bodö (top) and Valentia (middle and bottom). These stations are denoted by an oversized station dot.

Table 1. *Transfer function for selected predictors/predictands and season* (×100). *See eq.* (*3*) *for definition of terms and Table 2 for cosine/sine value versus season*

Predictors	Predictand (Season)	Lead (Seasons)	E^0	E^c	E^s	D
1. SST1			0	2	0	−2
SST3	Bodö (spring)	0	0	2	0	−2
SST4	(67° N, 14° E)		0	2	0	−2
2. SST2	Valentia (spring)	0	10	2	2	8
SST10	(52° N, 10° W)		10	0	−6	10
3. SST7			3	−2	0	3
SST8	Valentia (spring)	0	5	1	−1	4
SST9	(52° N, 10° W)		5	0	−1	5
4. SLP1			9	−3	8	(1, 6, 17, 12)
SLP2	Oslo (all)	0	9	−2	8	(1, 7, 17, 11)
SLP3	(60° N, 11° E)		−9	1	−8	(−1, −8, −17, −10)
SLP4			−9	1	−8	(−1, −8, −17, −10)
						(Su, F, W, Sp)
5. SST1			1	0	−5	−4
SST3	Bodö (spring)	1	3	0	−8	−5
SST4	(67° N, 14° E)		2	1	−7	−5
6. SST2	Turgaj (winter)	1	−4	−8	1	(−12)
SST10	(50° N, 64° E)		−7	−8	3	(−15)
7. SST7			7	1	6	13
SST8	Valentia (spring)	1	13	−1	0	13
SST9	(50° N, 10° W)		14	−1	1	15
8. SLP1			4	2	8	(−4, 6, 12, 2)
SLP2	Odessa (all)	1	4	1	6	(−2, 5, 10, 3)
SLP3	(46° N, 31° E)		−12	−5	−10	(−2, −17, −22, −7)
SLP4			1	−1	−4	(3, 0, −3, 2)
						(F, W, Sp, Su)

Table 2. *Sine/cosine values by season* (*cf. eq.* (*3*))

Predictor start time	cosine	sine
summer	0	−1
fall	1	0
winter	0	1
spring	−1	0

Rowntree (1976), Haworth (1978) and Meehl and van Loon (1979).

In summary, SSTs from any region may be expected to be of rather little use in forecasting air temperatures since they can only marginally specify that variable.

4.2 *Specification from SLP*

The SLP data from the four key regions extending over the previous year gave the specification skill shown in Fig. 4 and transfer function coefficients for Oslo in Table 1 for the prior season only model. The largest skills (30–40% of the variance) occur in the winter and spring and are centered over Europe. Skills over Asia are small or not significant. The high skill area corresponds to the region associated with the "Greenland Seesaw" of van Loon and Rodgers (1978, cf. their Figs. 9 and 10) and the key SLP points discussed by Murray (1973). The summer skill is largely negative, indicating that the cool season relations are (1) determining the prediction coefficients (eq. 9) and (2) not operative during the warm season. The occurrence of negative skill also suggests the

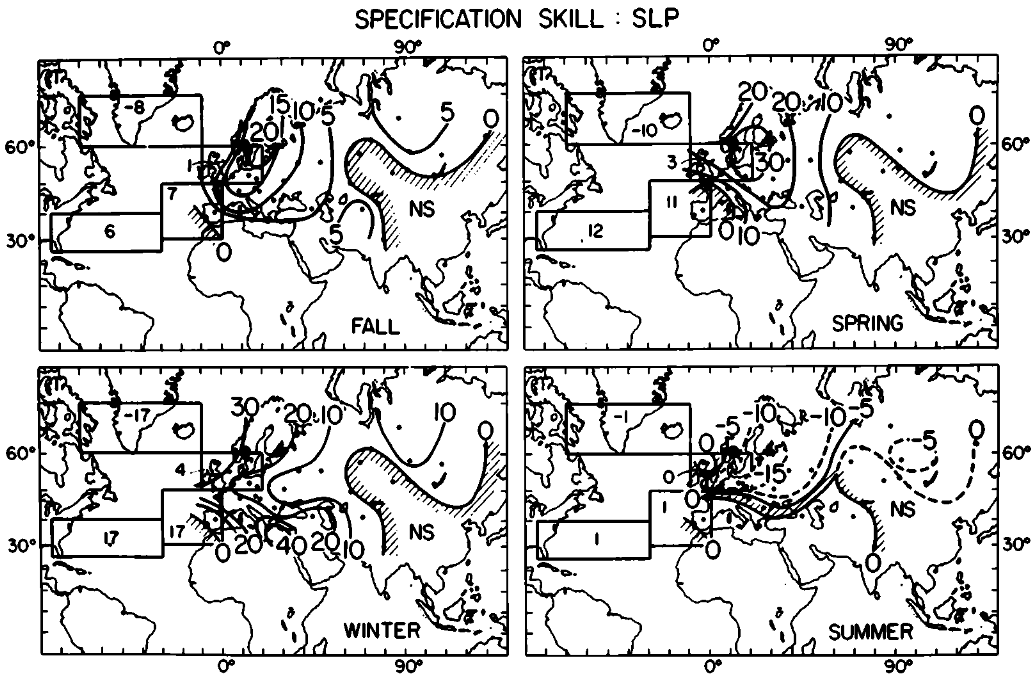


Fig. 4. The specification skill (percent of variance) using sea level pressure. The prediction coefficient (× 100) is shown for Oslo (large station dot).

assumed cyclostationary model (eq. 3) could be improved by including the second harmonic.

The transfer functions show the specification skill comes largely from Walker's "north Atlantic oscillation," i.e., the out-of-phase fluctuations of SLP in the Greenland/Iceland area and SLP in the region of the Bermuda/Azores High. The resulting modulation of the meridional pressure gradient, hence zonal flow and baroclinicity, is obviously related to concurrent weather over Europe.

5. Experiment I: persistence

The ability of individual station data to predict itself (persistence) one season in advance was tested by constructing a first-order auto-regressive model of the form (13) for the period 1902–1978. The subsequent model skill was computed according to (10) and then displayed in Fig. 5.

In general, the ability of persistence to hindcast air temperature anomalies is moderately good. The greatest skill was found for the spring season and the lowest skill for winter. The European region generally demonstrates the largest skill. The few areas of apparently high skill in Asia during the summer could be statistical artifacts, with the possible exception of northern India and northern Asia. Unfortunately the station density in these areas is insufficient to resolve these uncertainties.

Inspection of Fig. 5 and the time-dependent correlation functions themselves (not shown) demonstrate a near uniformity of persistence skill over much of Europe during the winter. This suggests the application of a single persistence measure for the entire region. An EOF analysis of the European T_A data strongly supports this idea. Consequently, the individual anomalies for all stations west of 31° E were averaged together. The resulting single time series was used to hindcast, via the persistence model of Section 3, subsequent air temperature anomalies at individual stations. The results (not shown) were as good, perhaps even marginally better, than those shown in Fig. 5. We conclude that the single, large-area average is at least as effective a hindcaster as individual station values. In many contexts, a large-area average of the type described above may be easier to use for practical prediction.

Given the relative success of the simple first-order model, it was natural to investigate the

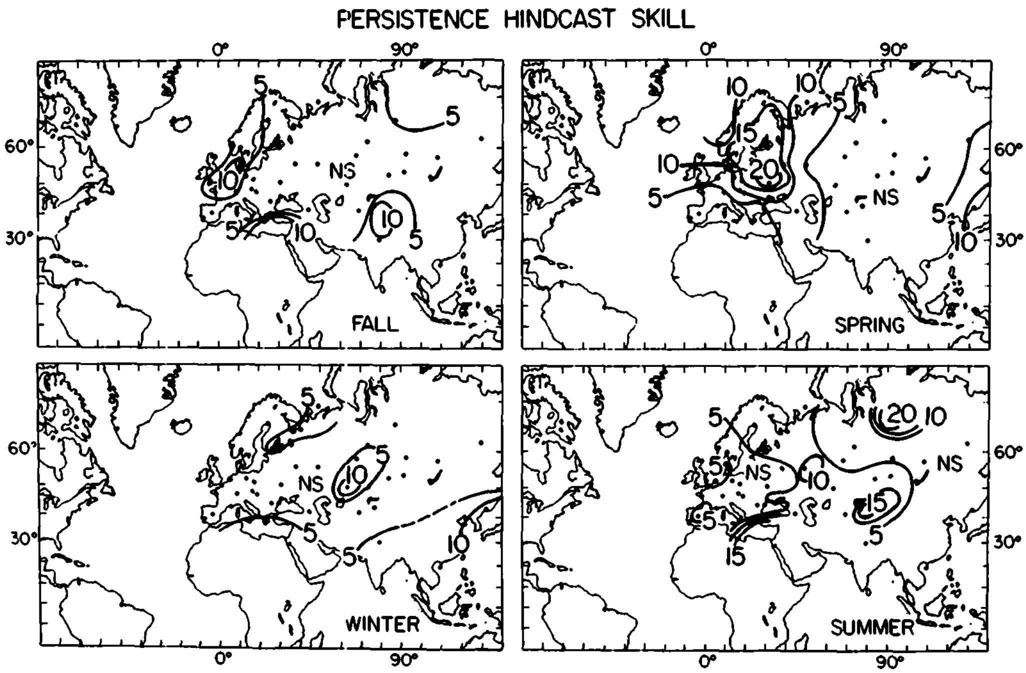


Fig. 5. One season in advance hindcast skill (as percent of the variance) using station persistence as a predictor.

possibility of obtaining even higher skill from a second order model, e.g.,

$$y(\kappa + 1, \nu) \doteq a_1(\kappa, 1)y(\kappa, \nu) + a_2(\kappa, 2)y(\kappa - 1, \nu),$$

where the fixed-phase prediction coefficients (a_l) can be found via the methods of Section 3 or Jenkins and Watts (1968). The results of such models were generally not appreciably better than those shown in Fig. 5. Thus, a simple first-order differential equation with negative feedback and random forcing captures most of the predictability of the Eurasian seasonal T_A field.

In summary, persistence seems a relatively good predictor for spring air temperature over much of Europe. It is marginally useful, regionally, in summer and fall. In the following sections, we investigate alternative prediction models using external SST and SLP fields as predictors, before combining both approaches in a single, quasi-optimal prediction model.

6. Experiment II: SST predictors

6.1. *Experimental design*

This experiment sought to answer the question: can prior knowledge of SST fluctuations in the Atlantic be used to hindcast subsequent fluctuations of air temperature over Eurasia? The experiment was divided into three sections corresponding to the three north Atlantic SST regions defined in Section 2. The location of the predictands is shown in Fig. 1. The predictors were the SST anomalies for the regions shown in Fig. 1 for the period 1902 to 1971. The predictors were defined at $m = 1$ and 4 time lags. This means (i) only the prior season's predictors were used to hindcast T_A and (ii) the prior 4 season's worth of predictor data were used to hindcast T_A. The hindcast lead (q) was set at 1 season for these experiments. Selected results of the calculations are shown in Fig. 6 and seasonally modulated transfer functions for the $m = 1$ case for Bodö, Turgaj and Valentia in Table 1. All hindcast skills are significant at the 90% level or above.

6.2. *Results*

The graphical distributions for skill for the selected *best* SST hindcast models (Fig. 6), plus results from the less successful models (not shown) lead to the following conclusions.

(1) Prior knowledge of SST anomalies in the Atlantic is of marginal use in hindcasting winter

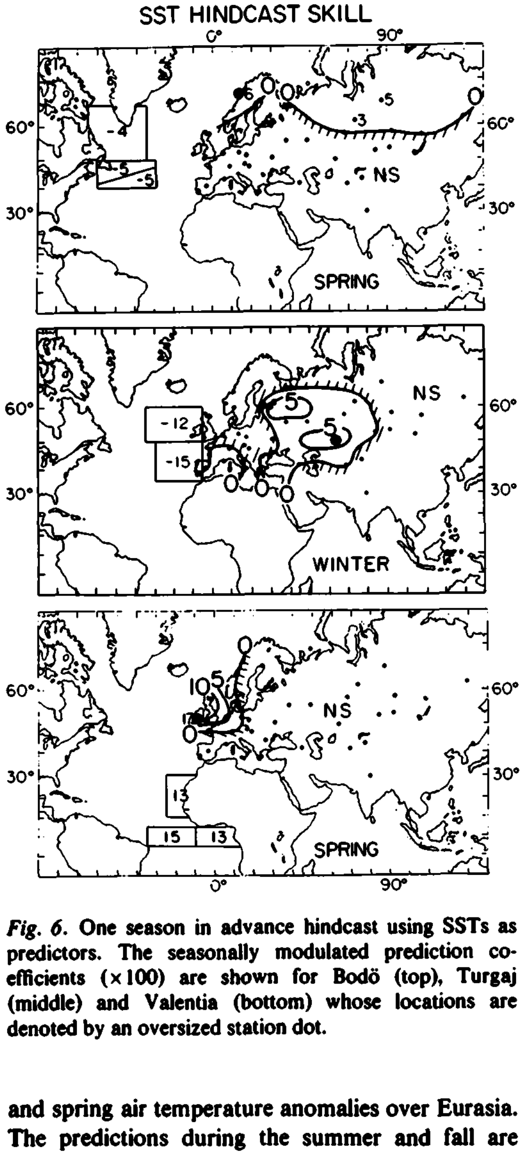


Fig. 6. One season in advance hindcast using SSTs as predictors. The seasonally modulated prediction coefficients (×100) are shown for Bodö (top), Turgaj (middle) and Valentia (bottom) whose locations are denoted by an oversized station dot.

and spring air temperature anomalies over Eurasia. The predictions during the summer and fall are either poor or nonexistent.

(2) The skill levels are uniformly low and generally worse than persistence in all seasons and areas where a significant model could be constructed. The marginal exception to this statement may be winter prediction for the region of western Asia.

(3) The SST predictor regions in the northwest Atlantic (subregions, 1, 3 and 4) were the least effective of the SST predictors, a result contrary to the suggestions of Ratcliffe and Murray (1970). The northeast Atlantic subregions (2 and 10) showed low skill over eastern Europe and western Asia. The hindcast skill from the equatorial Atlantic (subregions 7, 8 and 9) was significant only over the British Isles and along the immediate coast of western Europe. The values are again low but perhaps high enough to be useful during the spring season.

(4) Analysis of the transfer functions showed that most of the hindcast skill in the northeast Atlantic experiment was coming equally from the two SST averaging areas (cf. Fig. 6, middle). A similar analysis of the skill obtained from the equatorial Atlantic showed the same result in general agreement with the stated conclusions of Haworth (1978) and Rowntree (1976).

(5) The last full year's worth of SST information was somewhat more valuable for prediction than only the season preceding the forecast time. The transfer functions showed that the skill was generally associated with long-time scale fluctuations of ocean temperatures, the characteristic time scale of the SST fluctuations being of order 1 year. Apparently, a very low-frequency modulation of the eastern Atlantic SST and atmospheric system over Eurasia is responsible for the observed hindcast skill (cf. Bjerknes, 1964, for further discussion of this question).

(6) The relation between SST anomalies in the eastern and equatorial Atlantic and the sign of the T_A anomaly was as follows: positive SSTs in the northeast Atlantic give negative anomalies in eastern Europe and vice versa. Warm equatorial SST anomalies correlate with warm T_A anomalies and vice versa.

(7) The transfer functions also indicate that there is a strong seasonality in the predictive abilities of the SST. As noted earlier, they seem most effective during the cool seasons, a fact also found by Barnett (1981) for north America. During the warm season (summer) the hindcast skills are sometimes negative, indicating that the prediction coefficients are being determined almost exclusively by cool season relations which do not apply during the warm season.

(8) The results of Meehl and van Loon (1979) could be used to suggest the western subtropical Atlantic SST (roughly our region 6, Fig. 1) may be of use in forecasting winter T_A near Eurasia. We tested this simply computing the time-dependent correlation (eq. 12) between SST in subregion 6 and the individual Eurasian air temperature data

for all four seasons. A few of the one-lag correlations were significant, but all were low (only two of 164 exceeded 0.25) implying hindcast skills of at most 5%. We conclude the western subtropical Atlantic SST are of little value in forecasting subsequent changes in T_A near Eurasia.

In summary, SST predictors in the north Atlantic are of marginal use in forecasting Eurasian air temperatures one season in advance. The most important SST regions appear to occur in the eastern Atlantic, and in the equatorial zone. The predictive skill exists only during the cool season and is largely due to a long-period fluctuation in the SST data.

7. Experiment III: SLP predictors

7.1 *Experimental design*

This experiment sought to answer the question: can prior knowledge of SLP fluctuations over the Atlantic be used to hindcast subsequent fluctuations of air temperature over Eurasia. The predictors were the SLP anomalies for the regions shown in Fig. 1 for the period 1902 through 1971. The 4 predictors were defined at $m = 1$ and 4 time lags representing the prior season's and prior 4 season's predictor information, respectively. The forecast lead q was set at one season. Results of these calculations are shown in Fig. 7 for each season and the associated transfer functions for the $m = 1$ case in Table 1. Again all hindcast skills are significant at the 90% level or above.

7.2. *Results*

Inspection of the figures and other modeling results (not shown) lead to the following conclusions.

(1) Prior knowledge of SLP can be an effective predictor of subsequent air temperature over Eurasia. This is particularly true during the spring season when the hindcast skills are relatively large in eastern Europe. A similar result was found for the British Isles by Murray (1973). During the summer, however, the skill is small and of no practical consequence.

(2) The distribution of skill associated with the SLP predictor is more impressive than that

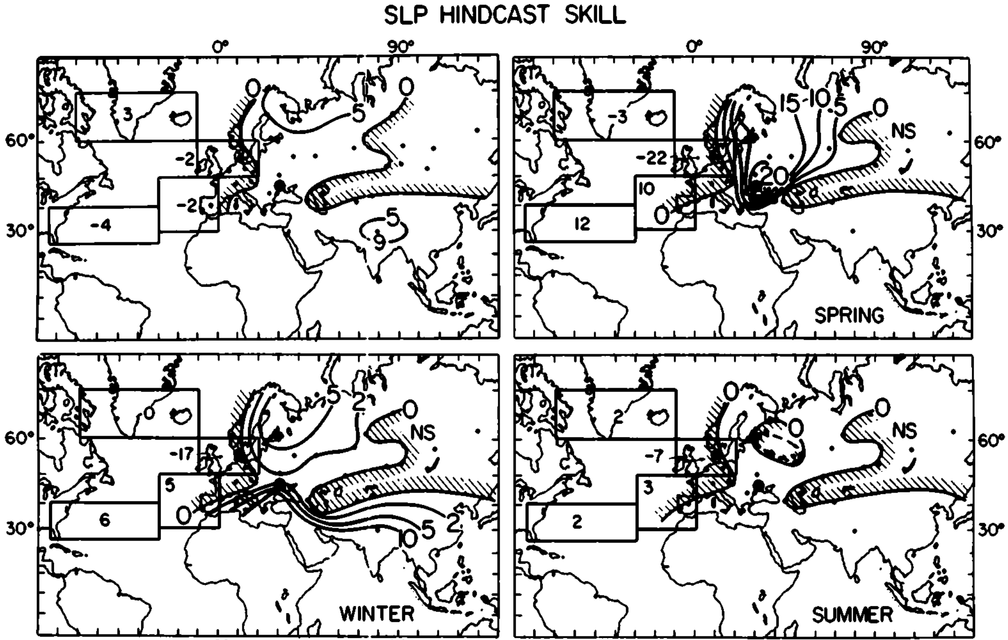


Fig. 7. One season in advance hindcast skill using SLP as a predictor. The prediction coefficient (× 100) is shown for Odessa (oversized station dot).

associated with SST. Furthermore, the SLP hindcast skill is comparable with or larger than that expected from persistence over a substantial part of the region where a significant model could be constructed. The region of maximum hindcast skill corresponds closely to the region of maximum temperature departures over Europe associated with the "Greenland seesaw" (van Loon and Rodgers, 1978).

(3) The regions of maximum predictive skill shift with season. For instance, during the spring, the highest skills are found near the Black Sea, while in winter they shift south and west. These movements correspond to a similar seasonal shift in the winter trough that overlays Europe during those seasons (Namias, 1979). In the fall, the skills, while much lower, seem to have maxima in northern Scandinavia and Europe. The associated trough is also north and east of its winter/spring position at this time.

(4) The effectiveness of the individual predictor regions is rather uniform with season. Subregion 4 and the tropical ridge strength (regions 1 and 2) have the largest prediction coefficients for the northern areas. This pattern is essentially Walker's north Atlantic oscillation (NAO). As one moves south, region 3 replaces region 4 in relative predictive importance while regions 1 and 2 retain their prominence (see Fig. 7).

(5) Inspection of the transfer function shows that virtually all of the SLP hindcast skill come from the preceding season's information. Unlike SST, information spread over the preceding year does not substantially enhance the distribution of skill.

(6) The sense of the relation between anomalies of SLP and T_A during the maximally predictable cool seasons is a follows: lower than normal pressure in subregions 3 and 4, plus higher than normal pressure in subregions 1 and 2 (tropical ridge), give warmer than normal T_A (and vice versa). This corresponds to a high index situation wherein Europe is inundated by relatively warm marine air from the Atlantic. It corresponds to the "Greenland Below" normal temperature case described by van Loon and Rogers (1978, cf. their Fig. 1).

In summary, SLP's appear effective predictors of air temperature anomalies particularly during the cool season. The main predictability comes from the north Atlantic oscillation, i.e., SLP anomalies of opposite sign at high and low latitude over the north Atlantic ocean. The "memory" of this oscillation is 1–2 seasons; shorter than the memory of the SST predictors.

8. The rôle of persistence

It could be argued that simple persistence, as discussed in Section 5, could be used to account for *all* of the predictability found in Secitons 6 and 7. This would be true if the SST, SLP and T_A all had common low-frequency variability. In such cases, it would be difficult to argue cause and effect for any single variable. On the other hand, if the SST or SLP predictors could be used to construct significant models *after* the affects of simple persistence were removed, then these variables clearly contain information on subsequent development of Eurasian temperature changes over and above the empirical information already contained in the inertia of the air temperatures alone (which could mainly reflect the influence of some other external field not included in our predictor set, such as snow cover).

The rôle of persistence relative to the other predictors was established in the following manner. First-order persistence models were constructed for each station and season (see Section 3 and 5) in the European area where persistence was an effective predictor. Individual station data were used in the persistence modeling. The seasonal time series reconstructed from these regression models were then subtracted from the original station data. The *residual* of this operation now served as the predictand that we tried to predict with the most

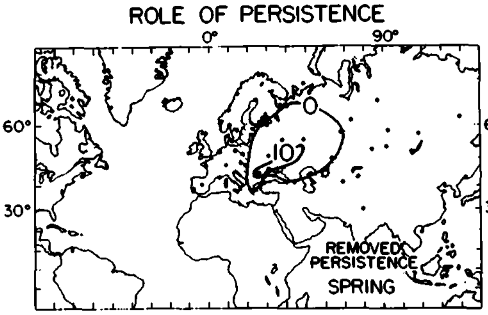


Fig. 8. The hindcast skill obtained by first removing the station persistence and then modeling the residual with SST and SLP predictors.

successful SST and SLP predictors from Sections 6 and 7 (described in Section 9). The results of these tests are illustrated in Fig. 8. This figure and the numerics associated with it led to the following conclusions.

(1) Significant predictability of the residuals from SST and SLP is indeed found at selected stations after the effects of persistence have been removed[1].

(2) The levels of external field predictability for the residuals, however, are low, amounting to approximately one half or less of the original values. This suggests that simple first-order persistence by itself could yield a reasonable, economic prediction for Eurasian air temperatures.

9. Toward an "optimal" forecast model

The purpose of this section is to select the best predictors from the preceding sections and combine them together into a single model designed to predict Eurasian air temperature one season in advance. Inspection of the results of Sections 5–7 led us to select the following predictors.

(a) Persistence associated with the prior season's temperature anomaly expressed as an average of individual station anomalies over the region north of the Mediterranean Sea and west of 31° E (cf. Section 5).

(b) A measure of SST anomaly in the northeast Atlantic obtained by averaging the time series for SST regions 2 and 10 (Fig. 1). This averaging is justified since both contribute equally and in the same sense to the hindcast skill shown in Section 6. Only the prior season's combined anomaly was used in the forecast experiment.

(c) A measure of SST anomaly in the equatorial Atlantic obtained by averaging the time series for SST regions 8 and 9. Additional comments in (b) apply here also.

(d) Sea level pressure from the preceding season for SLP regions 1 and 4 (two predictors).

The resulting semi-optimal model was derived for the 1902–1971 period and then tested on an independent data set extending from 1972–1978; a group of years that had not been used in previous analysis. This latter test is particularly important for we selected the predictors in an *a posteriori* manner, therefore largely invalidating the significance tests used in earlier modeling operations.

Two similar forecast experiments were run. In the first, the forecast was carried out as a two-step operation. The first step was to use the seasonal persistence model for each station to forecast the subsequent station temperature. A hindcast model, based on SST and SLP predictors noted above, was then used to forecast the residual time series. The persistence forecast and SST/SLP forecast of the residual were linearly combined to give an estimate of the temperature anomaly by season. In the second experiment, persistence was represented by the large area average of the preceding season's air temperature over the region of Europe west of 31° E. The results of these two forecast experiments were nearly identical although the latter was slightly better.

The results of the latter forecast experiment (the better of the two) are displayed in Fig. 9. The upper panel shows the hindcast skill associated with the

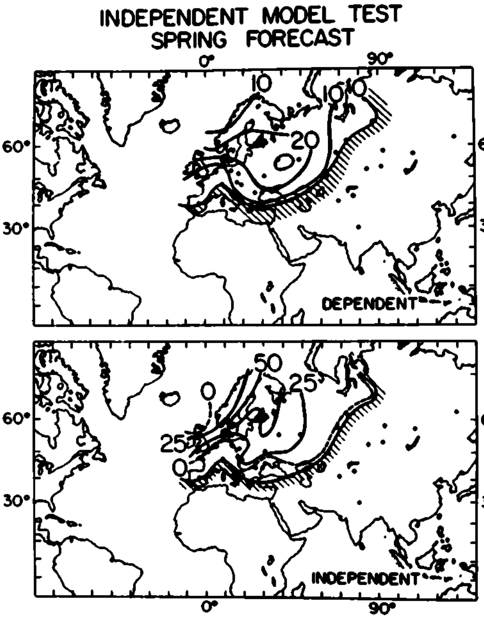


Fig. 9. Forecast experiment on independent data. The upper panel shows the hindcast skill (percent of variance) associated with the dependent model construction for the period 1902–1971. The lower panel shows the forecast skill over the 1972–1978 period. The heavy dashed line represents the "zero skill" line associated with the independent test. Note that over most of the region it follows the zero line derived from the dependent test.

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[1] This result survived attempts to initially fit higher order persistence models to the original station data.

model constructed over the dependent time period, 1902 through 1971. The regions of maximum skill are as described previously. It was noted that the effects of persistence, as represented by a large area average, gave slightly larger skills over a larger region than the individual station persistence estimates themselves. This is apparently the result of the smoothing associated with the large area average, plus the high degree of spatial correlation on seasonal time scales among European station's air temperature.

The results of the independent test with persistence represented as a large area average were impressive. 13 of the original 19 significant stations had positive forecast skill and the independent test skills are higher than in the dependent sample. This result should not be overstressed, however, since the independent sample is relatively small and therefore statistics based on it are more variable than statistics derived from the much larger dependent sample. Also, a close inspection of the time dependent properties of the key predictor patterns in the forecast model showed them to be unusually strong during the period of the early to mid 70's. Thus, it may have been anticipated that the predictive relations would yield results substantially above the long term average hindcast skill, as indeed they did. In summary we conclude that the hindcast models developed in this paper are statistically significant based on the results of both (a) rigorous statistical tests and (b) independent testing. The levels of skill, although not particularly high, should be of practical use.

10. Discussion

The physical mechanisms responsible for the hindcast skill found in this study appear somewhat different than those found in a comparable study of north American T_A by Barnett (1981). Atlantic SSTs appear of secondary importance to Eurasia T_A prediction, suggesting anomalous ocean-to-atmosphere forcing is less important than in the Pacific. Nevertheless, the SSTs in the eastern Atlantic still have a detectable influence through the enhanced ridging induced by the positive vorticity flux to the atmosphere for positive SST anomalies (e.g., Namias, 1964; Barnett, 1981), producing T_A patterns such as shown in the middle panel of Fig. 6.

The importance of SLP and persistence in forecasting T_A, plus the strong seasonality of their skill points to the rôle of the atmosphere in partially determining its own destiny over Europe. It is suggested that the snow accumulation associated with different modes of the north Atlantic oscillation act as positive feedback mechanisms that assists in maintaining the NAO. Thus a deep Icelandic low/strong tropical ridge in winter (high index situation) is associated with warmth over Europe (e.g., Namias, 1964) and diminished snow cover. Under these conditions normal seasonal warming in the subsequent spring will not be delayed by the increased albedo, higher soil moisture content and local cooling associated with the extended snow cover. The reverse situation applies when the NAO is weak. The highly autoregressive nature of the snow cover strongly supports the above interpretation (e.g., Wiesnet and Matson, 1976; Walsh et al., 1982).

A brief attempt to verify these ideas was made by inspecting the satellite derived data sets of hemispheric snow and ice cover dating from 1966 (e.g., Matson and Wiesnet, 1981). Indeed, low snow cover over Europe (warm temperatures) in winters tended to be followed by warm temperatures and low snow in the subsequent spring, although the relationship was not as pronounced as one might expect.

Also interesting is the observation that the winter–spring temperature relation seemed to depend also on the geo-orientation of the snow line over Eurasia. During cold regimes the snow line in winter was nominally east–west. During warm situations it was oriented southeast–northwest. While this finding complements the snow/no snow situation over Europe, it also offers the possibility of a more planetary scale forcing mechanism via the radiation discontinuity associated with the snow line. Thus the forcing discontinuity acts to steer the principal weather systems and hence maintains itself.

A final matter of note is the fact that the forecast skills estimated in this study are relatively low and localized in both time and space. A similar situation was found to exist over north America (Barnett, 1981). Further, the residuals from the successful prediction models and the series that could not be predicted were both essentially white noise. In a sense these are disappointing results since one would hope short-term climate change might be more predictable. Apparently it is not (at least by this method) and that is a fact worth knowing for its own sake. However, it should be remembered that only one particular method and data set have been used in this study. The limitations and weakness of the regression approach should be familiar to the reader. There is also ample reason to question the data set, particularly in the early decades of the century and in the Asian region. Before one can take the apparent low predictive skills found here as a general feature of the climate system over Eurasia it will be necessary to repeat the predictive study using a variety of techniques and predictor/predictand variables.

11. Conclusions

A statistical study of the short-term climate predictability over Eurasia has been conducted to determine the levels of skill attainable and the relative rôles of SST/SLP/persistence in estimating this forecast skill. The following results were obtained.

(1) Potentially useful forecasts, one season in advance, of air temperature anomaly (T_A) over much of Europe can be made during the spring, and to a lesser extent, the winter seasons.

(2) Persistence and SLP are the most effective predictors of T_A. The north Atlantic oscillation (Walker and Bliss, 1932) was found to be the dominant pattern most responsible for the predictive skill of the SLP field.

(3) Atlantic SSTs were of marginal use in forecasting T_A in Europe and of no use in Asia.

(4) Virtually no predictive skill was found from SST, SLP or persistence over the extensive interior regions of Asia east of the Ural mountains. The fact that the skill/no-skill division occurs at the urals may be no coincidence. A similar division was associated with the rocky mountains in north America. One can speculate that the mountain ranges cause increased flow instability in their lee, thus increasing background noise and decreasing predictability. Another possibility is that the Asian data are of exceedingly poor quality thereby rendering them ineffective in this analysis.

(5) It was speculated (partly on the basis of other data not fully investigated in this paper) that the statistical modeling results could be explained by a positive feedback between the north Atlantic oscillation and the associated snow/moisture distributions over Europe and Asia.

12. Acknowledgment

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