Long-Lived Air Temperature Anomalies in the Midlatitudes Forced by the Surface

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ABSTRACT

A study of long records of monthly mean air temperature (MMAT) for many stations in the Netherlands indicates that the atmosphere's response to surface boundary forcing is often of a very simple local nature. In the Dutch area, the atmosphere seems to respond to a sea surface temperature (SST) anomaly in the North Sea with an air temperature anomaly of the same sign. Because of the abrupt change in lower boundary forcing near the coastline, very small spatial scales are introduced in air temperature anomalies at long time scales. Over the sea MMAT anomalies have much larger time scales than over the land; a similar increase in time scale can be found in the delay of the climatologically normal temperature with respect to the solar forcing. When extended to the United States, the study showed very similar results; that is, monthly mean surface air temperature (MMAT) anomalies live longest in areas where the air temperature response is slowest to the annual cycle in incoming radiation. Apart from boundary forcing by the oceans, the Gulf of Mexico and the Great Lakes, there is some evidence of forcing by snow-cover in the Northeast.

Since surface boundary forcing by SST anomalies can be quite persistent, MMAT anomalies are more predictable over the sea and in the coastal zone than in the interior of big land masses. This explains why Madden and Shea (1978) found that the potentially predictable part of the interannual variance in MMAT is largest in predominantly coastal areas, California, in particular. A sizable fraction of the potential predictability in these areas can be effected by such simple tools as linear regression onto antecedent MMAT.

1. Introduction

It is generally believed that with increasing forecasting period, knowledge of the external driving forces of the atmosphere will become of greater importance, relative to knowledge on the initial conditions of the atmosphere. Using a general circulation model (GCM), Shukla (1981) showed that the initial conditions are important up to a month in advance. This implies that forecast skill based on a knowledge of the initial state inevitably will break down after a few weeks. However, for the largest modes of atmospheric variability the range of forecasting may be longer.

Aside from the initial state, any anomaly in external conditions will, in principle, have its influence (small or large) on the atmosphere. Since the time scale of external factors may be more than a few weeks, a limited amount of predictability may exist even after the atmosphere has forgotten details of its initial state. The slow decay rate of sea-surface temperature (SST) anomalies offers the best evidence for long-lived anomalous external factors, as documented in Namias and Born (1970).

The magnitude and spatial dimension of an SST anomaly are only two of the many aspects that determine the effect of surface boundary forcing on the atmosphere. Special conditions are required to communicate the presence of an SST anomaly into the free atmosphere. One favorable condition is deep convection as it transfers anomalous amounts of sensible heat beyond the boundary layer. Similarly, a high atmospheric moisture content is needed to release anomalously large amounts of latent heat in the free atmosphere. Both the convection and moisture conditions point to the tropics as an area where surface boundary forcing is most effective in creating a disturbance aloft. Once the upper atmosphere is perturbed, trains of waves propagate to remote areas (Hoskins and Karoly, 1981). In midlatitudes, SST anomalies can be substantial, in both magnitude and size, but the forcing of the upper atmosphere is hampered by greater static stability and the lack of water vapor in the colder air.

Does this mean that we can expect extra predictability due to surface boundary forcing only when deep anomalous convection occurs? The answer is in the negative. One of the items usually predicted is the monthly mean surface air temperature (MMAT) at 1.5 m above the surface. Especially in cases when the overlying air is stable the MMAT can, in a local sense,

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be forced strongly by the SST anomaly. Large-scale dynamics are hardly involved in determining the local relationship between the SST and MMAT anomalies. Although we have in those cases only a local response, the resulting predictability of MMAT at this spot is not necessarily smaller than in rare cases of deep convection.

It seems reasonable to expect that only the largest time and space scales have a role in long-range weather prediction. However, when surface boundary forcing is taken into account very small spatial scales enter the problem, especially near the land–sea transition. Since the forcing can be very persistent, small spatial scales will also appear in atmospheric response, even at long time scales.

The objective of this paper is to give evidence, based on observation, of increased predictability of MMAT due to local surface boundary forcing. This will be done by examining long records of MMAT in the Netherlands and in the United States. The data are discussed in Section 2. In Section 3 we give, as an example of lower boundary forcing, the composite MMAT anomalies over the Netherlands following a specified SST anomaly in the North Sea. We will consider not only the forcing of MMAT anomalies but seek for evidence of lower boundary forcing in climatological normal MMAT as well. In Section 4a we discuss the phase of the annual cycle in MMAT and the lifetime of MMAT anomalies in the context of an energy-balance equation. This simple approach indicates that at places where anomalies are long-lived the forced temperature response of the atmosphere to the annual cycle in incoming radiation is similarly slow. In spite of differences in climatological conditions in the United States and the Netherlands, observations of both areas suggest an increase of the lifetime of anomalies with increasing phase (behind the sun) of the annual cycle in MMAT (Section 4b). Finally, we will discuss the spatial distribution of so-called potential predictability of MMAT over the United States as calculated by Madden and Shea (1978). The high potential predictability in coastal areas, California in particular, is probably due to local forcing; it is shown that a sizable fraction of the interannual variability in MMAT indeed can be predicted by very simple forecast schemes.

2. Data

a. The Netherlands

The names of all stations, as well as the extent of their records, are listed in Table 1. Altogether we have a total of 30 records, varying from 30 to 130 years in length. All data are MMAT, except for station 1a which represents SST at the light-vessel *Texel* a key station. Missing data were not replaced. Fig. 1 gives the location of all stations found in the list of Table 1. The position of the *Texel* is indicated by an arrow. Also indicated is the big interior Lake Yssel. For the calculations of month-to-month correlations we used only those stations having records longer than 50 years; otherwise, the sampling error would be too large.

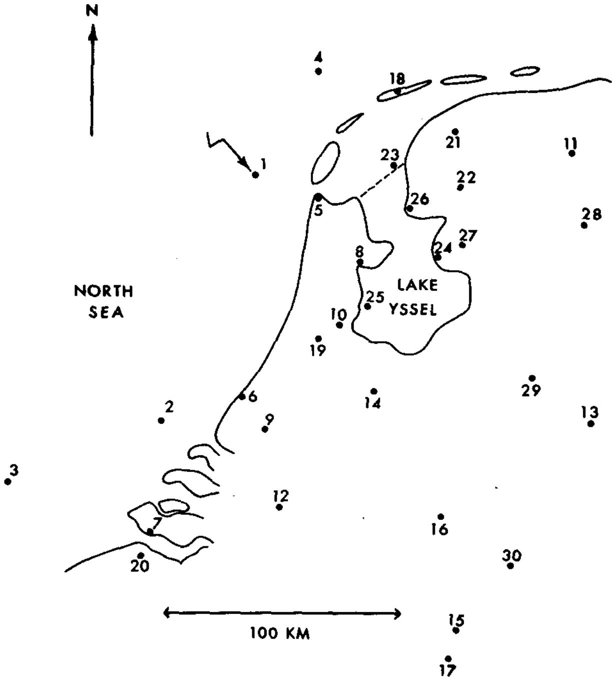

FIG. 1. Netherland stations (see Table 1). Note the location of the interior Lake Yssel (before 1932 an open water called South Sea) and the position of the key station light-vessel *Texel* (1). Note also the scale arrow.

b. The United States

The data used for the United States are those described by Walsh and Mostek (1980), covering a set of 78 years of MMAT at 61 stations scattered evenly throughout the area. The distribution of stations is such that problems related to topography, as discussed by Pielke and Mehring (1977), are only minor. It should be noted that Walsh and Mostek replaced missing data (a very small fraction) by climatological mean values. For each calendar month and each station, we calculated a second-order least-squares fit to the 78 MMAT values. Then by subtracting these from the original data, we removed, to some extent at least, the large trends known to exist for some of the stations, the cities in particular.

3. An example of surface boundary forcing

In this section we will discuss the effect of an SST anomaly in the North Sea on MMAT over the North Sea locally, and downwind over the Netherlands. Basically and SST and MMAT interact and to exclude the influence of MMAT on SST, we introduce a 15-

TABLE 1. Stations in monthly mean air temperature (MMAT) study.

	Name	Period
1a	Light-vessel *Texel* (sea)	1890–1977
1b	Light-vessel *Texel* (air)	1890–1975
2	Light-vessel *Noordhinder* (air)	1859–1979
3	Light-vessel *Goeree* (air)	1947–1979
4	Light-vessel *Terschellingerbank* (air)	1884–1975
5	Den Helder	1855–1975
6	Naaldwijk	1927–1976
7	Vlissingen	1855–1975
8	Hoorn (North Holland)	1905–1978
9	Rotterdam (filiaal)	1893–1958
10	Amsterdam (filiaal)	1855–1958
11	Eelde	1881–1975
12	Oudenbosch	1893–1978
13	Winterswijk	1894–1978
14	De Bilt	1849–1980
15	Sittard	1905–1971
16	Gemert	1905–1978
17	Beek	1855–1975
18	Hoorn (Terschelling)	1947–1979
19	Schiphol	1949–1979
20	Schoondijke	1951–1979
21	Leeuwarden	1894–1979
22	Akkrum	1920–1979
23	Kornwerderzand	1943–1979
24	Urk	1944–1979
25	Marken	1943–1979
26	Stavoren	1944–1979
27	Emmeloord	1946–1979
28	Wijster	1921–1960
29	Warnsveld	1916–1979
30	Venlo	1946–1979

FIG. 2. The geographical distribution of the average departure from normal for MMAT following very cold SST at light-vessel *Texel.* Very cold SST means a value in the lower quintile on the last day of the previous month. The unit is 0.1 C. The result is an average over all calendar months.

day lag, SST leading MMAT. As the key station representing SST in the southern North Sea, we have selected light-vessel *Texel,* 25 km off the Dutch coast. A record of SST anomalies of 90 years is available for this vessel. At the last day of a given month the SST anomaly was categorized as MB (much below), N (normal) or MA (much above), the climatological chances of occurrence being 20, 60 and 20%, respectively. We now select all years in which the SST at the last day of month i, at this vessel, fell in the class MB (MA), say SST (*Texel*, i) $\in$ MB (MA). Figures 2 and 3 show the average departure from normal in MMAT in the month following such events, say MMAT (i + 1)|SST (*Texel*, i) $\in$ MB (Fig. 2) or $\in$MA (Fig. 3). The composites shown in Figs. 2 and 3 are averages over all 12 months of the year. The number of cases involved in the composites is large, ranging from 300 for stations with long records to ~60 for stations with shorter records. From an inspection of Figs. 2 and 3, it becomes clear that an extreme SST anomaly tends to be followed, on the average, by MMAT anomalies of the same sign over the entire area. In absolute value, the MMAT anomalies are large over the North Sea (1 K) and small (~0.5 K) over land. The transition occurs in a narrow coastal zone. Over land there is little or no further decrease of the anomaly in MMAT, with increasing distance from the coast. It is suggested also that Lake Yssel acts as an area of enhanced temperature forcing, especially in the warm case. Apparently the water temperature of that lake has, in general, the same anomaly as the open water of the North Sea near

FIG. 3. As in Fig. 2, but for MMAT following very warm SST.

the light vessel. However, this suggestion is based on stations with fairly short records.

Of course we cannot rule out that the composites are contaminated by factors that go along with SST anomalies, such as anomalies in snow cover, in large-scale circulation and in soil moisture. However in spite of such problems, characteristic of all compositing, we believe that Figs. 2 and 3 show a real signal due to the nearby sea. To have a better idea of what this means in terms of predictability, we have subtracted Fig. 2 from Fig. 3 and divided the result for each station by the local standard deviation of MMAT. The result is given in Fig. 4, where this measure of the predictability of MMAT associated with knowledge of antecedent SST in the North Sea has been plotted. As can be seen, the predictability is large over the sea and small over land.

It is quite important to note that the anomalies in Figs. 2 and 3 are larger over the sea than they are over the land; in other words, the difference in predictability is not due just to a difference in standard deviation of MMAT. As a rule, when very warm or very cold weather occurs in this area, the anomalies are large over the land and small over the sea. This is understandable because very cold weather and warm weather are caused by advection throughout a deep layer of the troposphere. Due to interaction with the sea, the air over the sea responds in a lesser degree to such a forcing from above than the surface air over land. This behavior is almost diametrically opposed to what we see in Figs. 2 and 3. Indeed, these two patterns represent a modest climatic anomaly that is, at least partially, forced from below.

FIG. 4. The difference between Fig. 3 and Fig. 2 for each station divided by the standard deviation of the MMAT. A value of 10 (dimensionless) corresponds to 1 standard deviation.

The example shows that there are areas where knowledge concerning the lower boundary is of some importance for the prediction of MMAT. In this particular case, it is the SST anomaly that carries prognostic information. Obviously, it is the abrupt change in lower boundary forcing that causes the difference in lifetime of MMAT anomalies over sea and over land. Similar abrupt changes are observed in amplitude and phase of the normal annual cycle in MMAT. In Section 4, we present a simple theory that addresses this similarity.

4. Lifetime of anomalies and delay of the annual cycle

a. *Simple theory*

To a first-order approximation the annual march of temperature (T) can be described by

$$C\frac{d(T-T_0)}{dt} = A\sin\omega t - b(T-T_0), \qquad (1)$$

where C is the (effective) heat capacity; $A\sin\omega t$ represents the solar forcing at annual frequency; b is a damping coefficient; T_0 is a reference equilibrium temperature; and t is time. The solution is

$$T - T_0 = B\sin(\omega t - \Delta) + C_1\exp(-bt/C), \qquad (2)$$

where $\tan(\Delta) = \omega C/b$, and C_1 is a constant to be determined from the initial value $T\ (t = 0)$. For large enough t the response to periodic forcing will be a temperature wave lagging the forcing wave by Δ. Let us consider this as the normal annual course of the temperature. If there is an anomaly $T\ (t = 0)$, it will damp out with an e-folding time C/b.

In a system as simple as (1), the delay of the climatological annual scale, as well as the e-folding time of anomalies is governed by C/b. It was shown by van den Dool and Nap (1981) that, for the Netherlands, there is, indeed, a strong almost linear relationship between Δ and the month-to-month correlation of MMAT anomalies (ρ). This means that anomalies live longer in areas where the annual cycle is delayed relative to the forcing by the sun.

A relationship between persistence of anomalies (ρ) and delay of the annual cycle is very useful to resolve the small spatial scales in coastal zones. The ideal experiment would be to have a densely occupied array of observing stations along a line perpendicular to the coast in operation for at least 50 years. For the time being, we can use existing observations for this purpose by assuming that Δ is a measure of the proximity of water bodies. If we order all stations in the Netherlands in line with decreasing Δ, we are very close to the ideal experiment. We can study at least statistical properties of the anomalies in MMAT as a function of Δ.

We anticipate that the fairly straightforward relationship between Δ and ρ that holds for the Netherlands may be more complex for the United States because factors other than the distance to the sea may contribute to the spatial variability of ρ and Δ. In the literature, snow cover and soil moisture have been mentioned numerous times as agents for the increase of ρ, although usually on a qualitative basis. It is likely that snow cover and soil moisture have similar effects on Δ.

b. Results

The delay of the annual cycle in MMAT with respect to solar forcing is computed here by adapting a parabola to the multiyear mean temperatures of the three coldest (warmest) months. This yields a date for the extreme MMAT. The delay is defined as the difference in days from December (June) 21. Results for the Netherlands can be found in van den Dool and Nap (1981). Fig. 5 shows the delay of the annual cycle (Δ) for the United States averaged over summer and winter. The delay varies from 17 to 41 days. There is considerable evidence of coastal effects in the value of Δ for the United States. At the West Coast, the Gulf Coast and the Atlantic Coast the values decrease landwards, the gradient being largest in California. Further, we note the minimum in the Southwest desert and the generally higher values in the Northeast, especially near the Great Lakes. In the interior of the country Δ is a surprisingly constant quantity. This indicates that the sampling error in Δ must be small (only a few days).

In Fig. 6 we have plotted the yearly average of the month-to-month persistence in MMAT ($\bar{\rho}$) as a function of Δ for stations in the United States (dots) and in the Netherlands (circle); asterisks represent U.S. desert stations. To the right of $\Delta = 30$ days, the results are encouragingly similar for the very different climates of the Netherlands and the United States. However, for $\Delta < 30$ days, the linear relationship breaks down. To investigate this further, we have plotted in Fig. 7 the geographical distribution of $\bar{\rho}$. The values vary from 0.09 in the U.S. interior to 0.2–0.4 elsewhere. The main features are similar to those of Fig. 5, with the exception of the desert area where the month-to-month correlation is high in an area of low Δ. Also the relatively high values of Δ in the northern Great Plains do not fit in with very low ρ.

The subject of delay of the annual cycle has not received much attention in the meteorological literature. However, Leighly (1938) did several studies of a micro-climatological nature near the Great Lakes and in California, wherein he noted the large gradients in Δ near the water. Also Bowie (1935) studied the delay, on the basis of daily data, and found basically the same patterns over the United States as shown in Fig. 5. For a more extensive discussion of month-to-month and season-to-season persistence of U.S. temperature anomalies the reader is referred to Dickson (1967) and Namias (1978).

Except for very low values of Δ, the relationship between Δ and $\bar{\rho}$ derived from observations in the Netherlands turns out to be quite applicable throughout most of the United States. For the greater part, it ap-

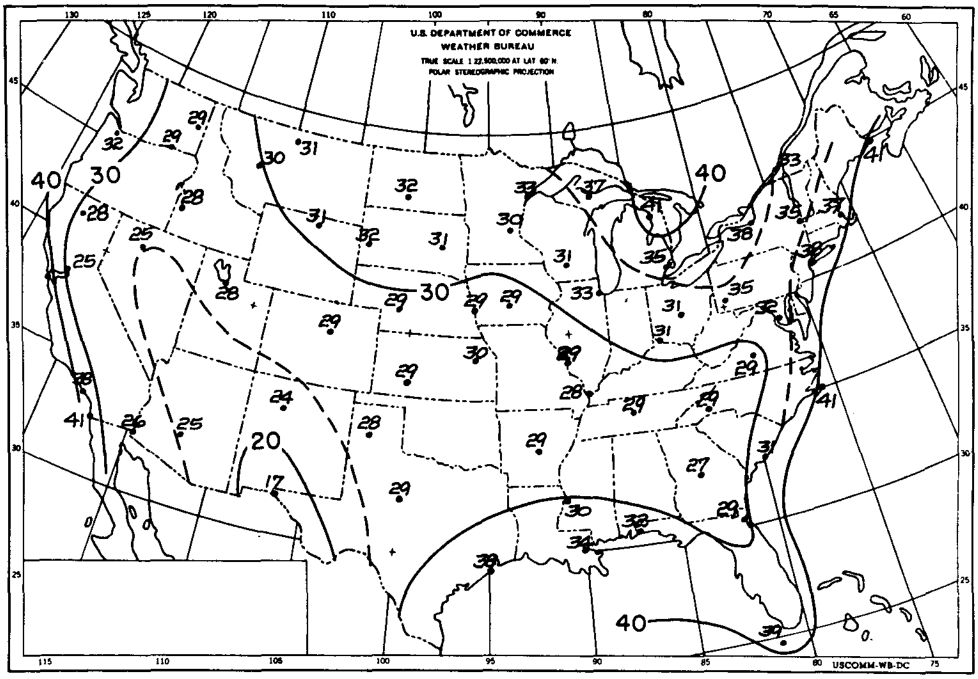

FIG. 5. The delay of the annual march in MMAT with respect to the solstices. The units are days; values displayed are averages over the delays in summer and winter.

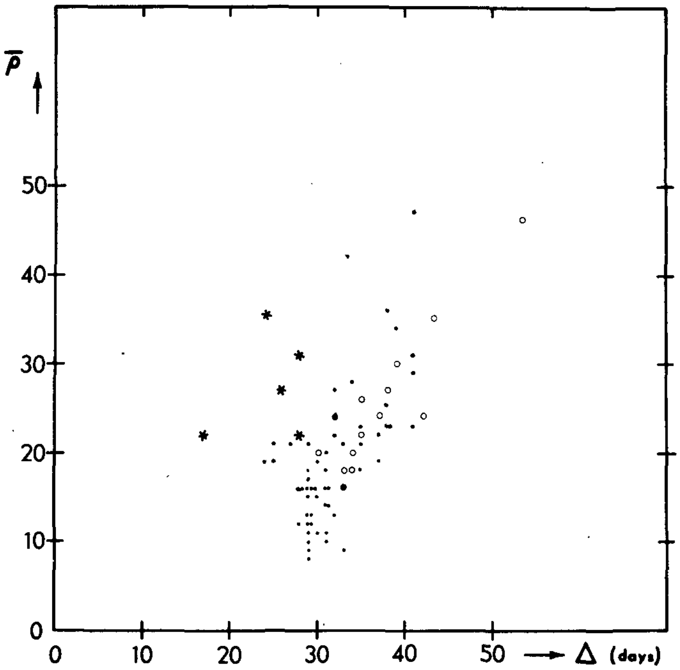

FIG. 6. Month-to-month correlation of MMAT anomalies as a function of the delay (Δ). Correlation coefficients are determined for each pair of adjacent months and then averaged to form a yearly average ($\bar{\rho}$): U.S. (dots); for the desert-stations in the U.S. (asterisks); the Netherlands (circles).

pears again to be a matter of the distance of the observational site to the lakes and oceans. The generally larger values of both $\bar{\rho}$ and Δ toward the Northeast are suggestive of a snow effect. This area, indeed, has a large interannual variability in snow cover and according to Walsh *et al.* (1982), 10–30% of the variance of MMAT can be attributed to snow cover, at least in the winter months. The high values of Δ in the Northeast are, indeed, mainly due to the long winter delay (not shown). Since $\bar{\rho}$ and Δ both increase in an area of interannual snow cover variability, the relationship between $\bar{\rho}$ and Δ still holds. The lack of correspondence of $\bar{\rho}$ and Δ in the desert can be partially explained from the atmospheric circulation in that area. The summer monsoon starting late June in that area is characterized by a sudden large increase in cloud cover. Therefore, the solar forcing suddenly drops and the temperature fails to reach its later and higher maximum as expected in the absence of a monsoon.

We interpret the U.S. results to be further evidence of the importance of local response to boundary forcing. Neither Fig. 5 nor Fig. 7 suggests much involvement of the large-scale dynamics in determining Δ and $\bar{\rho}$. The generally small month-to-month persistence of anomalies in large-scale circulation patterns (van den Dool, 1983) gives only a minor contribution to the month-to-month persistence of MMAT; probably, there is a background persistence of about 0.10 to which strong local effects are added in areas where either water or snow is nearby.

5. Lifetime of anomalies and potential predictability

In an indirect way, the topic of locally forced predictability appears in studies of potential predictability of monthly and seasonal mean air temperature (Madden and Shea, 1978; Madden, 1981). Estimates of the potentially predictable part of the interannual variance of MMAT in the United States range from 20% in the interior of the country to 50–60% in coastal areas (mainly). Fig. 7 shows that most of the excess in predictability in coastal areas can be attributed to a very simple forecast that reflects the local nature of boundary forcing. In order to make a quantitative comparison with Madden and Shea, we will review the results of Fig. 7 by calculating the skill of an explicit forecast scheme. Results of forecast schemes for the Netherlands were discussed previously in van den Dool and Nap (1981). For the United States we derived the linear regression

$$\hat{T}_{i+1} = a\hat{T}_i + c, \qquad (3)$$

where $\hat{T}_i$ and $\hat{T}_{i+1}$ are MMAT anomalies, detrended (see Section 2b), of adjacent months at a particular station. Obviously, a corresponds to the correlation coefficient previously discussed. We determined a and c empirically from data for 1900–57, stratified by month and applied the regression as a forecast for 1958–77. Fig. 8 shows the explained variance averaged over the whole year. Up to 20% of the variance of MMAT can be explained in predominantly coastal areas. The considerable skill displayed in Fig. 8 in-

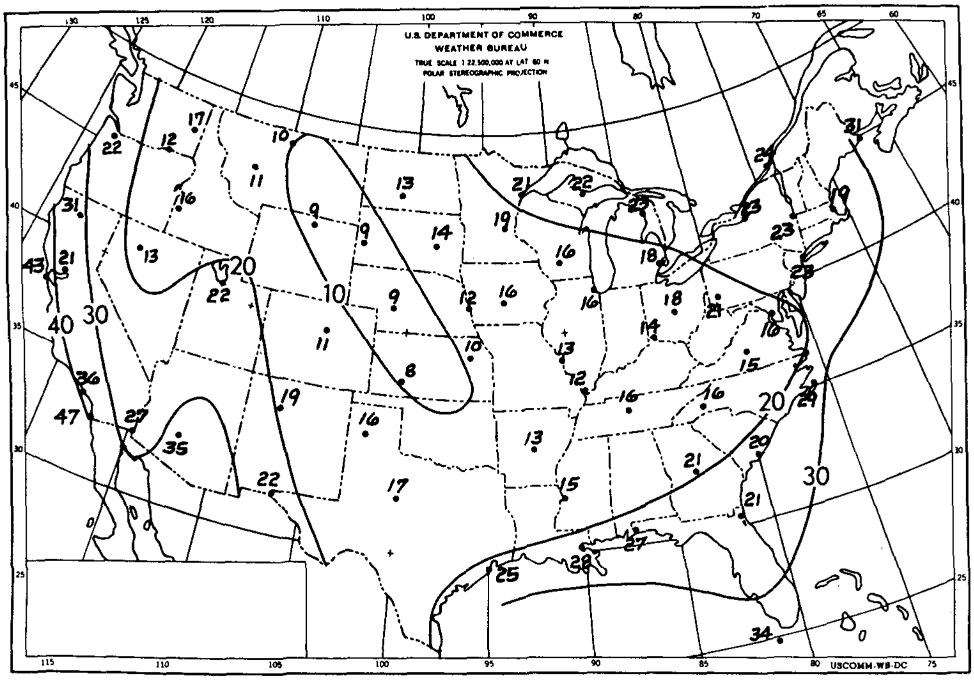

FIG. 7. Geographical distribution of the month-to-month correlation coefficient of MMAT-anomalies over the United States. Coefficients were determined for each pair of neighboring months separately and afterwards averaged to a yearly mean.

dicates that autocorrelation in MMAT anomalies reproduces itself quite well in independent data. If we subtract the variance explained by linear regression from the potentially predictable variance in MMAT (Madden and Shea, 1978) a spatially rather uniform (over the United States) 20–30% is left. This means

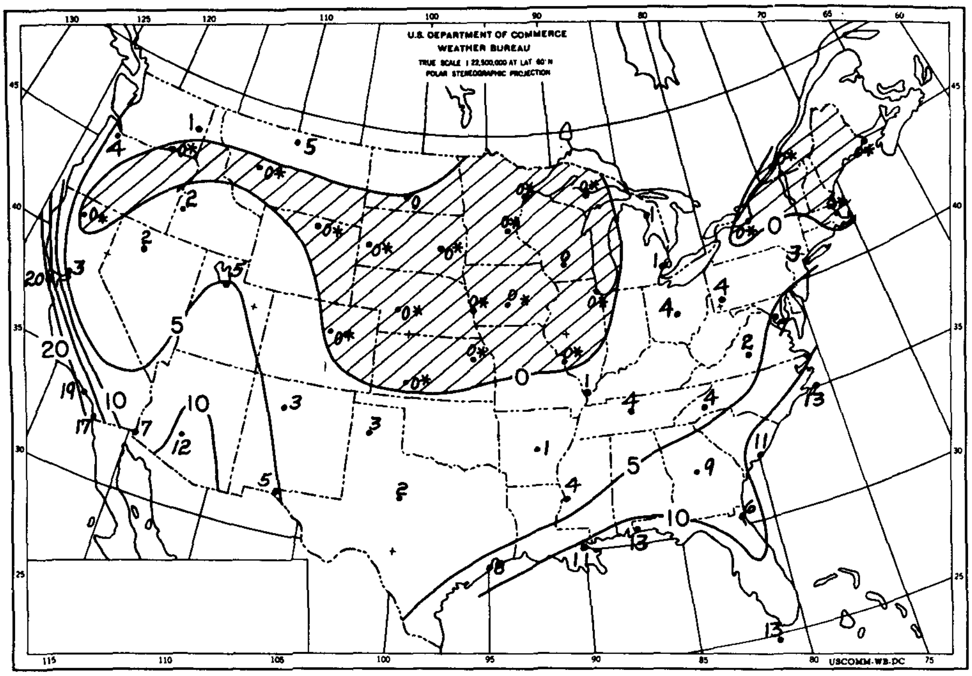

FIG. 8. Percentage variance explained of anomalies in MMAT by a linear regression onto the previous month MMAT anomaly. Regression coefficients were estimated for data from 1900–1957 and tested on 1958–1977. The procedure was separate for all pairs but the results are the yearly average. In the hatched area, the variance explained is zero, or even negative (shown by asterisks).

that models that predict the large-scale circulation first, and derive MMAT predictions from that, cannot be expected to predict more than 20–30% of the interannual variance in MMAT.

The numbers in Fig. 8 are a conservative estimate of locally forced predictability. Slight improvement over (3) can be expected from either physical or statistical models that start from knowledge concerning antecedent SST and snow cover rather than $\hat{T}_i$ alone. It would appear preferable to capitalize on the cause of persistence in $\hat{T}_i$ than to persist $\hat{T}_i$ itself.

6. Conclusions

A study of long records of near-surface MMAT for the Netherlands indicates that the response of the atmosphere to surface boundary forcing is often of a very simple local nature. In the Dutch area, the atmosphere seems to respond to an SST anomaly in the North Sea, with an air temperature anomaly of the same sign. Because of the abrupt change in lower boundary forcing, when going from sea to land, very small spatial scales are introduced in long-lived atmospheric temperature anomalies. Because SST anomalies usually are of long duration, the effect of this lower boundary forcing is that of increasing the persistence in the MMAT anomalies. As a result, month-to-month correlation of MMAT anomalies ($\bar{\rho}$) is substantially larger over the North Sea than over the land nearby. Characterizing the influence of the sea by the delay of the annual temperature cycle with respect to the solar forcing cycle (Δ), one can determine a general relationship between the distance to external memory, e.g., the sea and the time-scale of atmospheric temperature anomalies, as measured by $\bar{\rho}$. For the Netherlands, $\bar{\rho}$ increases almost linearly with Δ.

When applied to the United States the lifetime of MMAT anomalies can, indeed, be estimated fairly well from knowledge of Δ alone; i.e., month-to-month persistence is generally large in areas where the air temperature responds slowly to the annual cycle of incoming solar radiation. As in the Netherlands in the United States there are large gradients in $\bar{\rho}$ and Δ perpendicular coasts, indicating that the ocean's water is the prime agent in providing memory to the atmosphere. In the Northeast quadrant of the United States snow cover seems a likely candidate for explanation of the large values of both $\bar{\rho}$ and Δ. The only area where small Δ and large $\bar{\rho}$ are in agreement seems to be the (near) desert of Arizona, New Mexico, Nevada and Utah.

The autocorrelation of MMAT anomalies is a fairly reproducible quantity in an independent dataset. A linear regression onto antecedent MMAT derived from data for 1900–57 turns out to have a fair amount of skill when applied as a forecast for 1958–77. There are areas in the United States where 10–20% of the interannual variance can be captured by knowledge of antecedent MMAT.

The spatial distribution of the month-to-month autocorrelation of MMAT (Fig. 7) and the explained variance of forecasts based on these autocorrelations (Fig. 8) bear resemblance to the spatial distribution of potential predictability of MMAT over the United States (Madden and Shea, 1978). It seems, therefore, that the main reason why potential predictability is high in coastal areas is that the local response to surface boundary forcing by the sea contributes substantially to the interannual variance of MMAT.

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