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STRONG VARIATIONS IN THE DELAY OF THE ANNUAL CYCLE IN THE AIR TEMPERATURE NEAR THE COAST

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1. INTRODUCTION

Almost everybody knows that the oceans have a tempering effect on the climate. At the ocean borders summers and winters are known to be cool and mild, both compared to the summers and winters occurring at locations at the same latitude but at far distance from the ocean. Not only are the temperatures tempered, but there is also a delay in the annual temperature variation. Near the ocean the highest and lowest temperature occur a few weeks later than away from the seas.

In spite of this widespread qualitative knowledge it is far from easy to define the notion continentality or oceanity. Most definitions, see for example Conrad (1946) involve the annual range of temperature modified by empirical parameters that depend on latitude. In this paper we will consider the delay of the annual cycle as a measure of continentality. For the area of the Netherlands this delay turns out to be a very accurate tool to resolve the large gradients that exist in the coastal zone. In section 2 we will define the delay, results will be shown in section 3 and in section 4 we discuss a simple physical model that explains part of the observed variations in the delay.

2. CONCEPT AND DATA

Near coasts and over the sea the temperature response to the forcing by incoming radiation is known to be slower than in the middle of the continents. The phase-lag of temperature with respect to solar radiation is visualized in Fig. 1.

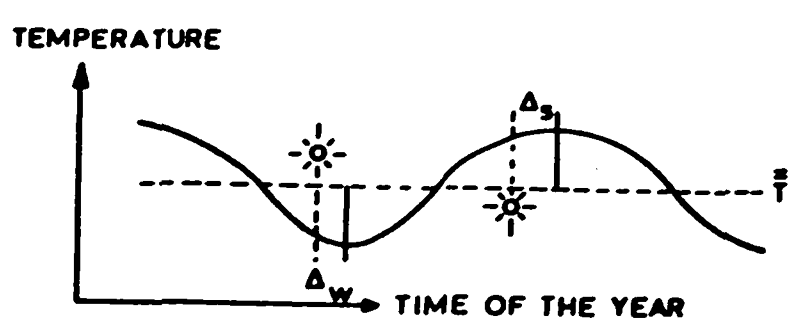

Fig. 1. The annual cycle in the temperature. The extreme temperatures are reached Δ_w and Δ_s days after the winter and summer solstices.

The delay, Δ, is expressed in days after the solstices. The dates of the extremes are computed by simply adapting a parabola to the long-term monthly mean temperature of the three coldest (warmest) calendar months. The delay is defined by:

$$\Delta \equiv \text{(date extreme temperature) - (21 dec/21 june)}.$$

It is obvious that the concept of a delay makes sense only when the extremes of the heating of the air really occur at the dates of the solstices. Cloudiness, moisture content and convergence of heat fluxes (both horizontal and vertical may shift the date of the maximum/minimum heating experienced by the air at a certain place, but we will consider none of these effects. In summer this is probably more justified than in winter because the insolation curve peaks much sharper in summer.

We selected 29 stations in the Netherlands where climatological records were readily available; the record length varies from 28 to 124 years. Three of these stations are light-vessels at some 25 km off the coast. To complete the discussion we include the 85 year record of sea-surface temperatures of one of these light-vessels (Texel). For all these data-sets Δ_w and Δ_s can be determined straightforwardly.

3. RESULTS

In Fig. 2 the delay occurring in summer has been plotted near the stations. For example 35(74j) means that Δ_s = 35 days, based on a record of 74 years.

On the basis of the station values a subjective analysis was made with a contour interval of 2 days. We were surprised to find out that it was very easy to draw isolines. None of the "observations" conflicts seriously with the very regular analysis. Apparently Δ_s is a rather stable parameter that can be determined with an accuracy of a few days.

The analysis in Fig. 2 shows several interesting features. (1) Comparing the north-south slopes of the coast-line and the isolines we conclude that Δ describes very satisfactorily the influence of the sea on the air temperature. A relatively small-scale pool of water, the Lake IJssel (former South Sea), can easily be recognised in the configuration of the isolines. (2) The delay ranges from about 55 days over the sea to about 35 days over land. However, the gradient appears to be entirely concentrated within a zone of at most

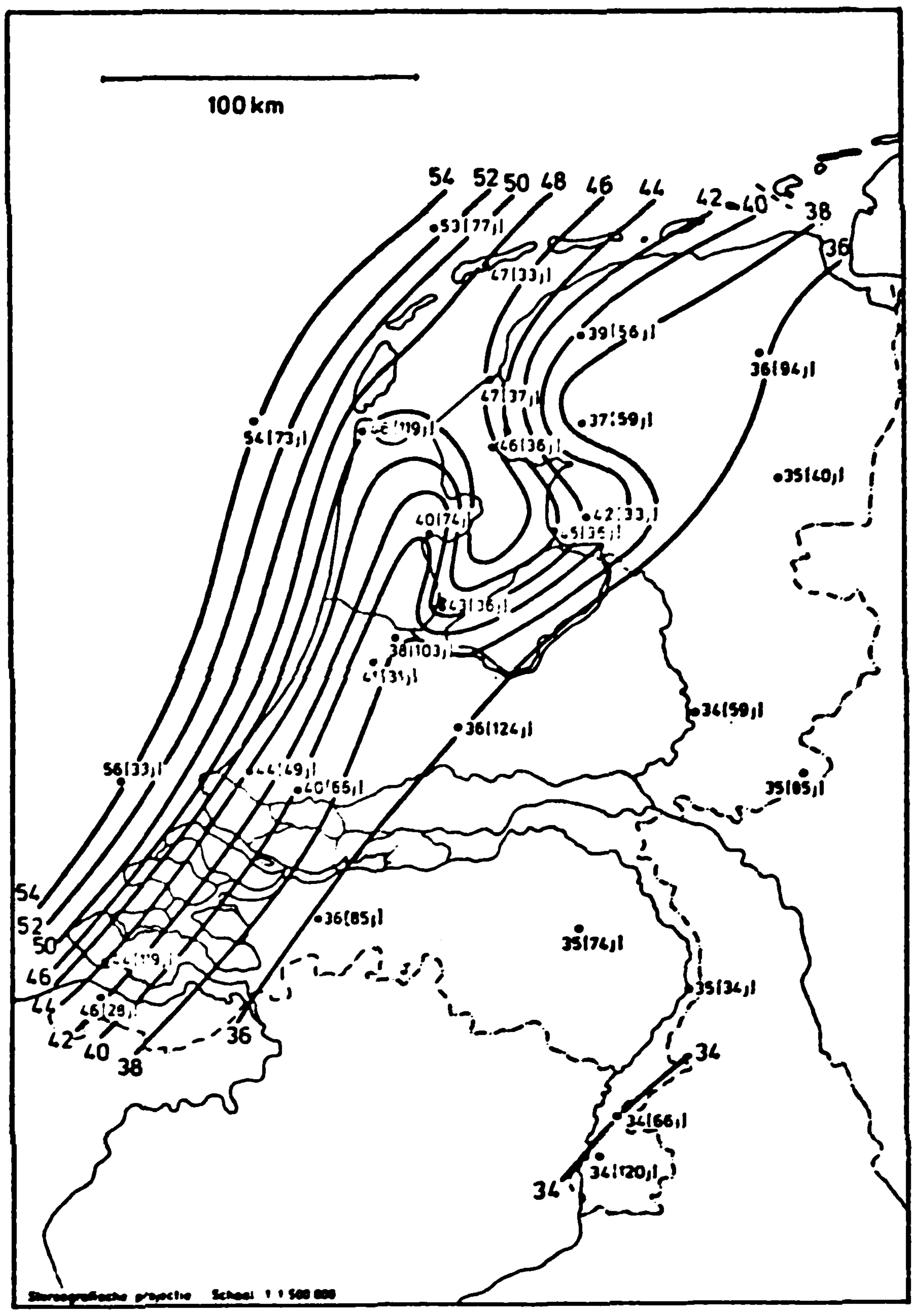

Fig. 2. Climatological values of the delay of the date of the highest temperature with respect to the date of highest insolation in the Netherlands. The units are days. Isolines are drawn every 2 days.

100 km. Outside this zone the variations in Δ are negligible, relatively speaking. We were not able to find any station around the world where Δ was substantially larger than 55 days. Even at Thorhavn, the most oceanic place according to Conrads (1946) definition, Δ amounts to only 45 days. Only the sea-surface temperature shows a larger delay namely 62 days at light-vessel Texel; this is 8 days slower than the overlying air. To find a response much faster than 30 days one has to travel to Verkoyansk, the most continental place in Conrads definition; there Δ amounts to 23 days.

The main reason to be satisfied with the results shown in Fig. 2 is that the isolines follow the coast line so closely; that confirms our intuitive notion of continentality. A similar map of the annual temperature range would be less convincing. Although the annual range increases from sea to land the picture as a whole is less clear. Especially the Lake IJssel area does not stand out in such an analysis as a maritime area.

The results for winter (not shown) are similar to Fig. 2. In summer the delay is up to 10 days larger. Assuming that the thermal inertia of the air is related to the depth of the oceanic mixed layer one would expect $\Delta_w > \Delta_s$! At light-vessel Texel the sea-surface temperature responds slower in winter than in summer: $\Delta_w = 65$ versus $\Delta_s = 62$ days, whereas for the air temperature at the same location we found $\Delta_w = 51$ and $\Delta_s = 54$ days. Maybe the effective heat capacity of the air is determined as well by the height of the atmospheric mixed layer which is large in summer and small in winter.

4. A SIMPLE PHYSICAL MODEL

On the basis of intuition it is clear that the delay of the annual temperature cycle depends on the heat capacity of the physical system. Because air and sea interact heavily the effective heat capacity of the air is larger over the sea than over land. Probably the simplest physical model that describes the dependence of the delay on the heat capacity is given by the equation

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

where C is heat capacity, T is temperature, T_o is a reference equilibrium temperature, t is time, ω is angular frequence and A and b are arbitrary constants larger than zero.(1) describes the temperature of a system that is forced by a periodic heating and Newtonian damping. If there were no Newtonian damping the phase of the cyclic variation in $(T-T_o)$ with respect to the forcing ($A \sin \omega t$) would always be $\pi/2$. The complete solution to (1) reads

$$T-T_o = \frac{A/C\omega}{(b/C\omega)^2+1}\left(\frac{b}{\omega C}\sin \omega t - \cos \omega t\right)+C_1\, e^{-\frac{bt}{C}}$$

where the term $C_1\, e^{-\frac{bt}{C}}$ can be neglected for large t. Defining the delay as

$$\Delta \equiv \text{arccotan}\ (b/\omega C)$$

one finds

$$T-T_o = \frac{A/C\omega}{\sin(\Delta) * (\text{cotan}^2(\Delta) + 1)} \sin(\omega t-\Delta) \qquad (2)$$

$$= A/b * \cos(\Delta)\ \sin(\omega t-\Delta)$$

So a sinusoidal heating leads the sinusoidal temperature wave by a delay Δ. Properties of Δ:

(a) if b is zero Δ will be $\pi/2$ irrespective of the thermal inertia.

(b) for $b \neq 0$, Δ will be less than $\pi/2$ but may reach $\pi/2$ asymtotically for large enough C (and/or ω).

Applied to the questions raised in this paper these results indicate that the delay will always be less than a season for a regular sinus-type heating. However, especially at higher latitudes the incoming solar radiation has a sharp high maximum and a flat broad minimum. When we replace $A \sin \omega t$ in (1) by a more general heating ($F(t)$, where $\int_{period} F(t)\, dt = 0$) we can easily see that the extreme will be reached when $F(t) - b(T-T_o) = 0$. In words: the next extreme will be reached before the next zero-crossing of $F(t)$. This means that one, again, would expect Δ_s to be smaller than Δ_w. In the Dutch area the opposite turns out to occur, however.

5. DISCUSSION AND CONCLUSION

In this paper we presented a climatological study of the delay of the annual variation in the surface air temperature in a coastal mid-latitude area. For this particular area of the Netherlands the delay Δ proves to be a fine quantity to indicate the transition from sea to land. We were surprised to find out that in this small fringe area almost all possible values of Δ occur. At the same time this cast doubt on the usefulness of Δ as an index of oceanity/continentality in areas that are generally considered extremely continental/oceanic. For example Δ in Thorshavn is not at all larger than Δ observed off the Dutch coast.

Our conclusion is that the delay of annual air temperature cycle discriminates very well between land and sea in the area of the Netherlands. In this region Δ seems to be a better continentality index than the annual range of temperature. However, for much more continental/oceanic climates than those occurring within the Dutch area Δ may be less meaningfull as an index.

An unresolved problem is that there are at least 2 reasons to expect $\Delta_w > \Delta_s$ whereas the opposite actually occurs. The first reason is that the oceanic mixed layer in winter is deeper than in summer; as a result the effective heat capacity of the air in winter is higher. Maybe this effect is cancelled by the fact that the atmospheric mixed layer is large in summer and small in winter. Secondly, simple theory indicates that the temperature extremes will occur at a date before the moment where the periodic heating equals its yearly averaged value. Therefore we expect $\Delta_s < \Delta_w$. Nevertheless we find $\Delta_s > \Delta_w$ at all stations in the Netherlands. One explanation could be that the flat minimum in insolation at 21 December does not represent the date at which the heating of the surface air is at its minimum. It is also quite possible that the simple model discussed in section 4 is too simple to treat the details correctly.

6. REFERENCE

V. Conrad, 1946: Usual formulas of continentality and their limits of validity. Transactions, American Geophysical Union, 27, V, 663-664.