On the cooling of the sea surface by evaporation and heat exchange

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(Manuscript received April 29, 1963)

ABSTRACT

Differences between surface and subsurface water-temperature are caused by evaporation, long-wave radiation and exchange of sensible heat. The relative importance of these three components is discussed, especially with aid of observations under neutral conditions. Evaporation as well as back radiation contributes to a cooling of the surface of 0.1 to 0.2 centigrade under neutral conditions, while under diabatic conditions greater surface temperature deviations are caused by heat exchange.

A great part of energy exchange between earth and atmosphere takes place at the oceans. The temperature of the surface layer of the sea plays a governing role in these energy exchanges. There is evidence of strong temperature gradients occurring sometimes in a boundary layer with thickness ranging from a few centimeters to fractions of millimeters. This is a problem of considerable importance. In nearly every case of interaction between air and sea, the conditions of the surface film of the sea—whatever its thickness may be—are to be taken into account.

But in fact, the "water-temperature" is customarily measured by bucket or intake thermometers somewhat underneath the surface. So we have to know the magnitude of the temperature differences between surface and subsurface temperature. In extreme cases values of 1°C have been reported. But, due to the nature of surface, it proved to be extremely difficult to get sufficiently accurate and numerous measurements in the surface layer. Various attempts have been made (BRUCH, 1940; WOODCOCK, 1947; ROLL, 1952; BALL, 1954; EWING and MCALISTER, 1960) but the number of the observations is still very small. Besides, most of the observations have been made near shore or even in shallow or extremely shallow waters. It is difficult to decide, whether the experimental conditions of these measurements may have affected the results or not. Other observations from the open sea indicate that in the neutral case the mean deviations between surface and subsurface temperatures are negligible. This may be deduced from optical measurements of temperature gradients just above the sea surface, which showed adiabatic gradients of air temperature when the temperature difference between air and sea was adiabatic (BROCKS, 1953; HASSE 1960). A presentation of 150 observations made in the Baltic Sea and in the North Sea under neutral conditions (and some additional under stable conditions) may therefore be a welcome contribution.

While discussing the observations one has to keep in mind that there are at least three major causes for strong temperature gradients near the surface: radiation, evaporation, and transfer of sensible heat. While short-wave radiation will warm both surface and subsurface layers,[1] long-wave radiation will cause a cooling of the surface depending on the temperature and humidity of the air. The exchange of sensible heat will tend to cool or warm the surface dependent on the air being cooler or warmer than the water. Evaporation in most cases will cause a cooling of the surface. In general, the effects of radiation, evaporation, and heat transfer will be indistinguishable. It therefore seems

[1] Our measurements do not permit to study the effects of short-wave radiation. It is suggested that absorption at the low frequency end of short-wave radiation may have been of importance in the case of the above-mentioned daytime optical measurements and should be thought of when dealing with intake "surface" temperatures.

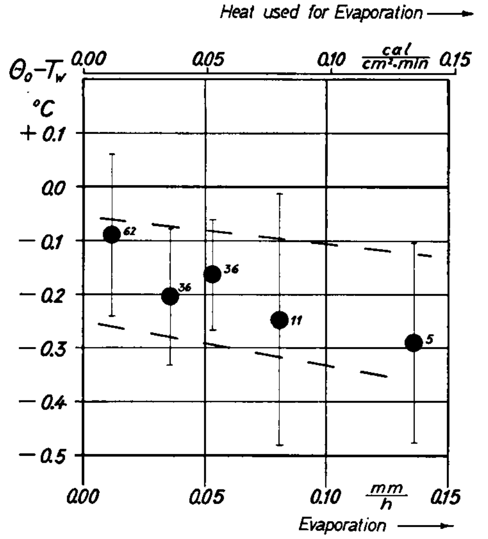

FIG. 1. Dependence of the difference between temperature at the boundary and water temperature at 0.5 m depth on evaporation. Number of observations is given by small figures, variance by vertical lines. Broken lines indicate mean values grouped according to cloudiness ("cloudy" upper, "clear skies" lower line).

to be of special interest to study the effects of two of them in a way which enables us to compare their relative magnitudes.

The results, which are to be discussed in the following, have been obtained by an indirect method. If the vertical gradient of the potential temperature (θ) vanishes in the lowest meters above the sea surface, the potential temperature in a height of say 4 m will be equal to the potential temperature of the air immediately above the surface, which may be assumed to be the same as the temperature of the thin surface layer of the water.

Measurements of the temperature profile have been made by the Geophysical Institute of Hamburg University at various times from 1958 to 1960 on a floating buoy (see BROCKS, 1959). From these observations those with vanishing potential temperature gradients have been selected. Dry and wet bulb temperatures were measured with shielded and ventilated platinum resistance thermometers at four or five heights (33 runs at two heights only) between 0.8 and 13.6 m above water. The temperature of the water (T_w) at a depth of 0.5 m was obtained with a similar platinum thermometer. The thermometers had been calibrated before and after each observation period of four or five days. The temperatures of the air at each height and of the water were recorded in turn approximately once a minute, afterwards read to 1/100°C and averaged for every quarter of an hour.

Together with other meteorological observations the short-wave radiation was recorded by means of a Robitzsch-Aktinograph (Fuess). In order to exclude radiation errors, merely profiles with short-wave radiation <0.10 cal/cm² min have been used. For each run of 15 minutes, the mean temperatures at the different heights were converted to potential temperatures by adding 0.01°C per meter of height above the surface and plotted against a logarithmic height scale. The best straight line was fitted by eye. The potential temperatures at heights of 10 and 1 m were read and every run with $|\theta_{10} - \theta_1| < 0.02$°C was taken to represent a profile with vanishing potential temperature gradient. It may then be assumed that θ_4 equals the temperature at the sea surface. As $\partial\theta/\partial z$ does not vanish completely, by aid of the logarithmic profile, a correction was applied. The temperature of the surface layer (θ_0) is then given by

$$\theta_0 = \theta_4 - (\theta_{10} - \theta_1)/(\Gamma \cdot \ln 10/1)$$

where Γ denotes the profile coefficient, taken to be equal 0.10. Thus, $\theta_0 - T_w$ indicates the difference between the surface temperature and the water temperature.

The results of the calculations are presented in Fig. 1. In order to show the cooling of the surface by evaporation, the evaporation (E) was computed from simultaneous profiles of wind speed (u) and humidity (q) by aid of the THORNTHWAITE-HOLZMANN (1939) expression (k = von Kármán's constant, ϱ = density of the air)

$$E = -k^2 \varrho (q_{10} - q_1)(u_{10} - u_1)/(\ln 10/1)^2.$$

In Fig. 1 the dots are mean values of $\theta_0 - T_w$, grouped according to evaporation. The standard deviations are indicated by vertical lines. The rather great variance is partly caused by variations in long-wave radiation. An attempt was made to show also mean values both for clear skies and cloudy, as indicated rather tentatively by the broken lines in Fig. 1 (cloudy including observations with cloudiness 6/8 to 8/8, cirrus disregarded, 76 observations; clear skies 0/8 to 1/8 low clouds and not more than 3/8 cirrus,

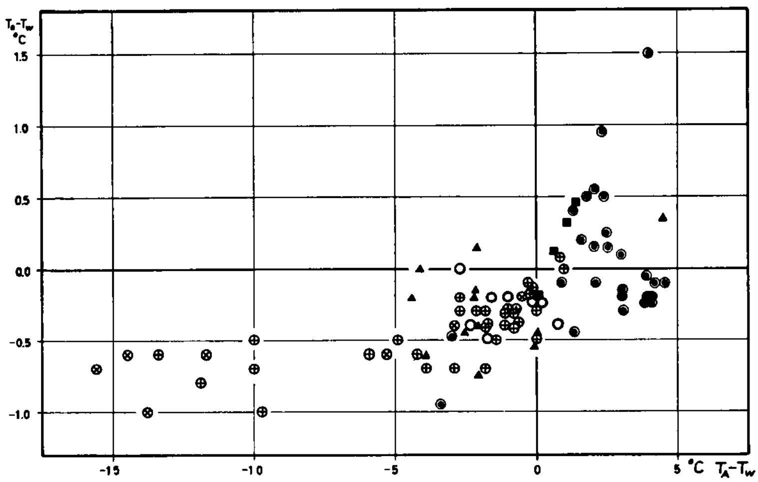

FIG. 2. Difference between surface and subsurface temperature versus temperature difference air–sea from different authors: ⊕, Woodcock; ⊗, Woodcock and Stommel; ⊙, Bruch; ○, Roll; ▲, Ball, ■, from humidity profiles.

corresponding to back radiation of roughly 0.15 cal·cm^{-2}min^{-1}, 34 observations). Due to the sensitivity of our method to small errors in the measurement of the temperature profiles numerical results should not be overemphasized.

Nevertheless when dealing with mean values one may deduce from Fig. 1 that under neutral conditions stronger differences than 0.2°C will occur only under special circumstances. In the single case anything between +0.3 and −0.7°C seems to be possible.

One may doubt the reality of these results for two reasons: (1) There may be systematic departures from the adiabatic gradient between 0 and 1 m height, even when there is an adiabatic gradient between 1 and 10 m height. (2) There may be observational mistakes in the profile measurements.

Both facts may have added something to enlarge the variance but it seems unlikely that this will have affected the mean values. For both should not depend on evaporation and back radiation in such a way as Fig. 1 demands. Note that evaporation and long-wave radiation essentially take place in the surface of the water.

These results lead to the suggestion that the reported temperature differences up to one degree are mainly due to exchange of sensible heat. To show this, in Fig. 2 the results obtained by different authors with different methods have been plotted as a function of the temperature difference between air and sea. T_0 denotes surface temperature, T_w subsurface temperature measured somewhere between 2 and 30 cm depth or with dip bucket, and T_a the temperature of the air, measured at heights ranging between 20 and 200 cm. $\Delta T = T_a - T_w$ can be taken as a measure of exchange of sensible heat between air and sea.

In addition the results of 133 humidity profiles with vanishing gradients are given. From the above-mentioned series of profile measurements those humidity profiles with $|e_{10} - e_1| \leq 0.05$ mb have been selected as representing vanishing water vapor gradients and were then treated in a similar manner as discussed with the temperature profiles. In this case for $\Delta\theta > 0.2$°C the correction was determined by

$$e_4 - e_0 = (e_{10} - e_1)\ (\theta_4 - \theta_w)/(\theta_{10} - \theta_1).$$

Assuming e_0 to be the saturation water-vapor pressure at the surface, the surface temperature T_0 is given and $T_0 - T_w$ can be calculated. The obtained mean values of $T_0 - T_w$ are plotted in Fig. 2. They represent observations with vanishing evaporation and probably small long-wave radiation, and therefore mainly show the influence of exchange of sensible heat. Due to the heterogenous sources of the published material, further attempts to show or eliminate the effects of evaporation and radiation failed to be conclusive in either sense.

In general, one may conclude that stronger differences between surface and subsurface temperatures are mainly due to exchange of sensible heat. Fig. 2 furthermore suggests that in cases of $\Delta T < 0$, even with strong $|\Delta T|$, the temperature difference $|T_0 - T_w|$ will not exceed a certain limit, while in case of $\Delta T > 0$ much greater values of $|T_0 - T_w|$ have been observed. This is easily explained by the different state of stratification of the water surface. BALL (1954) cited a theory of RAYLEIGH (1916), which shows that for $T_0 - T_w < 0$ the cold surface film may exist only when its thickness and the temperature gradient do not exceed certain limits while in the case $T_0 - T_w > 0$ the density stratification remains stable.

The author is well aware of the preliminary character of the results. But he hopes they will be of some value to those who have to make use of sea "surface" temperatures.

Acknowledgement is made to Prof. K. Brocks, Director of the Geophysical Institute of Hamburg University, for his interest in this paper.

REFERENCES

BALL, F. K., 1954, Sea surface temperatures. *Australian Journal of Physics*, **7**, pp. 649–652.

BROCKS, K., 1959, Ein neues Gerät für störungsfreie meteorologische Messungen auf dem Meer. *Archiv Met. Geophys. Biokl. A*, **11**, pp. 227–239.

BROCKS, K., 1953, Der vertikale Turbulenz-Wärmestrom in der untersten Atmosphäre. *Met. Abh. Inst. Met. Geoph.*, **2**, pp. 196–197, Berlin, 1953.

BRUCH, H., 1940, Die vertikale Verteilung von Windgeschwindigkeit und Temperatur in den untersten Metern über der Wasseroberfläche. *Veröff. Inst. Meeresk. Berlin*, Neue Folge A, **38**.

BRUNT, SIR D., 1952, *Physical and Dynamical Meteorology*. Cambridge Univ. Press, 2nd edition, 428 p.

DEACON, E. L., and WEBB, E. K., 1962, Interchange of Properties between Sea and Air. Small-Scale Interactions. *The Sea* (Editor M. H. Hill) Interscience Publishers, London, 73 p.

EWING, G. and MCALISTER, E. D., 1960, On the thermal boundary layer of the Ocean. *Science*, **131**, pp. 1374–1376, AAAS Washington.

HASSE, L., 1960, Über den Zusammenhang der Kimmtiefe mit meteorologischen Grössen. *Dt. Hydrogr. Z.*, **13** (1960), pp. 181–197.

RAYLEIGH, LORD, 1916, On convection current in a horizontal layer of fluids, when the higher temperature is on the under side. *Phil. Mag.* **32**, pp. 529–546, s. BRUNT, 1952, pp. 219 and 243.

ROLL, H. U., 1952, Temperaturmessungen nahe der Wasseroberfläche. *Dt. Hydrogr. Z.*, **5**, pp. 12–14.

WOODCOCK, A. H., 1941, Surface cooling and streaming in shallow fresh and salt waters. *J. Marine Res.*, **4**, pp. 153–161.

WOODCOCK, A. H., and STOMMEL, H., 1947, Temperatures observed near the surface of a freshwater pond at night. *J. Meteorol.*, **4**, pp. 102–103.