Papers

Heat fluxes between sea and atmosphere versus whitecap coverage

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Abstract

Heat fluxes computed from meteorological data H are compared with whitecap coverage measured during AREX–87, 91, 92 cruises. The relation between heat flux and whitecap coverage falls to a minimum within the positive heat fluxes. The same relation $H(W_c)$ was obtained earlier by numerical modelling. This study demonstrates that aerosol emission does affect air-sea heat exchange.

1. Introduction

Spray emitted from the sea surface contributes significantly to the air-sea exchange of heat and mass. This hypothesis is most readily proven by describing air-sea exchange under storm conditions. During a heavy storm, spray emission from the water surface is so intensive that the heat, latent heat and momentum it carries may exceed the turbulent fluxes. Bortkovskiy's models have confirmed this. The importance of spray droplets to the air-sea exchange of heat and water vapour has also been demonstrated by laboratory experiments (Anisimova *et al.*, 1991). When winds are weak, however, the postulated hypothesis, though still valid, does not hold so well, as will be demonstrated. Under such conditions, the droplets do not act as a heat transporting medium, but do influence the thermal structure of the air-sea interface. The droplets emitted from the water surface affect the vertical temperature profile in the air-sea mixing zone, and hence the turbulent fluxes passing through it. The mechanisms involved are illustrated by the numerical model of the thermal structure of the air-sea interface (Petelski, 1986, 1990). Experiments conducted with this model have shown that even very small latent and sensible heat fluxes carried by droplets can result in turbulent fluxes larger by one order of magnitude. However, numerical computations are very hard to prove by *in situ*-measurements, because these require the simultaneous, direct recording of turbulent fluxes and the size distribution of marine aerosol droplets at many levels over the open sea. Since such a complicated measuring system is beyond our means, we attempted to prove the hypothesis indirectly, using simplified measurements and observations. This paper attempts to show that the whitecap coverage measured under different meteorological conditions during AREX–87, 91 and 92 cruises can be used to confirm the predictions obtained by numerical modelling.

2. Numerical experiments

Numerical experiments carried out on the thermal structure model of the air-sea interface (Petelski, 1986) indicated that the air-sea heat flux is strongly dependent on the size and number of droplets contained in this mixing zone. The model computations were performed twice: once with the initial assumption that the air in the mixing zone was free from droplets, then with the same boundary conditions but assuming that droplets were present in the mixing zone. The difference ΔH between the heat fluxes calculated for the first and second cases increased exponentially with $N\bar{r}$, and with $N\bar{r} = 10$ cm, ΔH was as high as 100% H (where N – the number of droplets in unit volume, $\bar{r}$ – the mean droplet radius). The results of these numerical experiments (Petelski, 1990) are shown in Fig. 1: here, $\Delta H = H - H_1$, where H – the heat flux with droplets absent from the air-sea interface and H_1 – the heat flux at the upper boundary of the mixing zone, calculated for the same boundary conditions but including the influence of droplets on the temperature T profile. Air humidity was assumed constant in the entire interface ($f = 75\%$).

Analysis of Fig. 1 indicates that under conditions of stable stratification, droplets always reduced heat flux. The value of $\Delta H/H$ range between 2 and 3. When stratification was unstable, droplets tended to stablize small fluxes H, decreasing the heat flux at the upper border of the modelled zone. This effect was lost when $H = H_{gr}$. With larger H fluxes, the effect of high water temperature was decisive and droplets no longer acted as a cooling agent. For large values of H the ratio $\Delta H/H$ was close to 1. This led to the conclusion that when stratification was very unstable, the heat flux in a mixing zone containing droplets was nearly twice as large as in an analogous zone without droplets. A similiar increase in heat flux in the presence of droplets was observed by Anisimova *et al.* (1991) in a laboratory experiment.

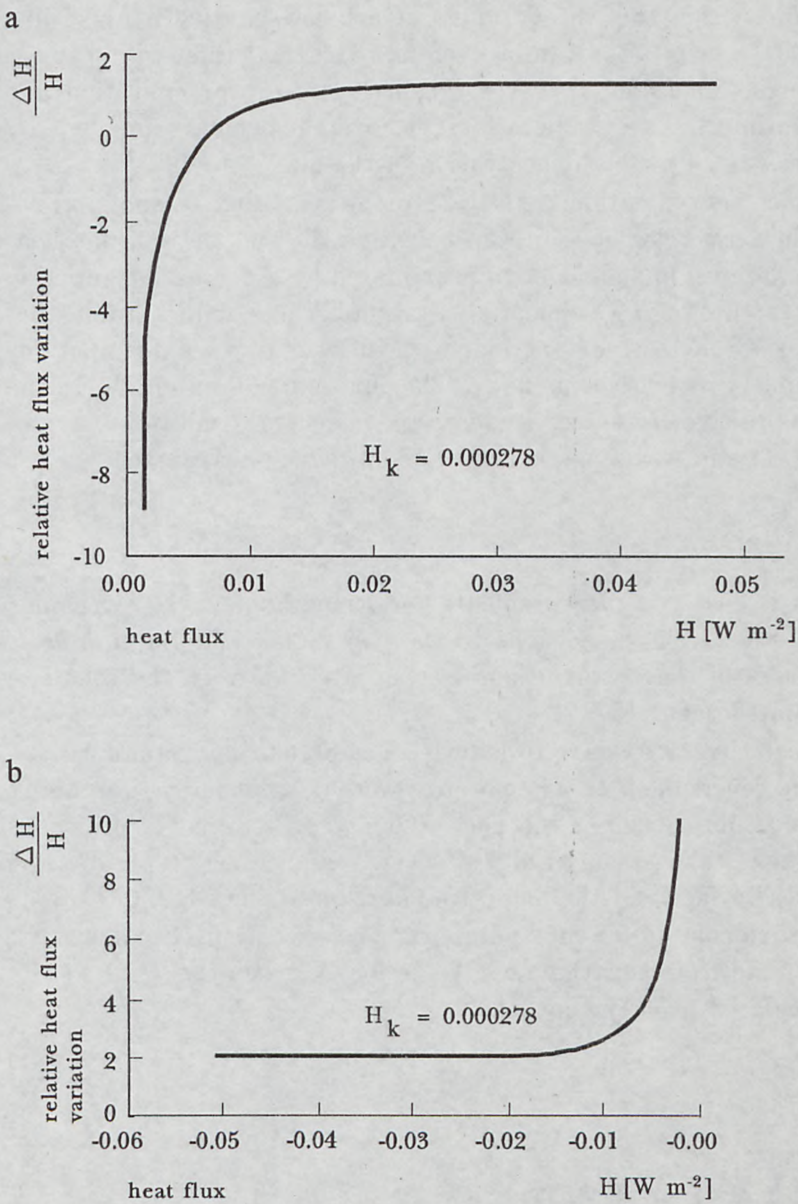

Fig. 1. Droplets medieted relative heat flux variation $\Delta H/H$ versus heat flux H at the upper boundary of the modelled zone. H_k – heat flux between air and droplets. Unstable stratification (a), stable stratification (b)

The droplet concentration at the air-sea interface is closely related to the whitecap coverage (Marks and Monahan, 1989). Needless to say, whitecaps are not the only source of droplets in the air above the sea. Droplets are also emitted as a result of precipitation hitting the sea surface or bubbles originating from within the water column (Garbalewski, 1980). According to Marks (1990), precipitation can be even more efficient than whitecaps as a source of aerosol emission. However, when there is no precipitation and water column properties are stable, whitecap coverage becomes an adequate indicator of seawater droplet concentration in the air.

Since droplet concentration is related to the heat flux, a similar relationship should exist between whitecap coverage W_c and the sensible heat flux H. This relationship should be approximated by a decreasing function for negative heat fluxes H (droplets always inhibit flux under stable conditions) and by an increasing function for positive fluxes (under unstable conditions droplets increase heat flux). The function minimum should be located within positive H values, because, under neutral conditions (as can be seen in Fig. 1) and weak instability, droplets reduce heat fluxes.

3. Measurements

This paper is based on measurements performed aboard r/v 'Oceania' during AREX–87, 91, 92 expeditions to the Norwegian and Barents Seas. The research area of these expeditions was situated between the coasts of Norway and Spitsbergen (Fig. 2).

The whitecap coverage was recorded with a camera using a standard $f =$ 50 mm lens and reversible film. The pictures were taken from *ca.* 6 m above the sea surface (from the ship's top deck). One record consisted of a series of 12 photographs taken at intervals of several minutes. The photograph included the sea surface and the line of the horizon at the edge.

W_c (%) was calculated for each photograph separately by Bortkovskiy's method (1983) and from this the mean value for every series.

H was calculated from the equation

$$H = r\, C_p\, C_H\, U\, (T - T_W), \qquad (1)$$

where

r – air density,
C_p – specific heat of air at constant pressure,
T – air temperature,
T_W – water temperature,
U – wind speed 10 m above the sea surface,
C_H – heat transport coefficient

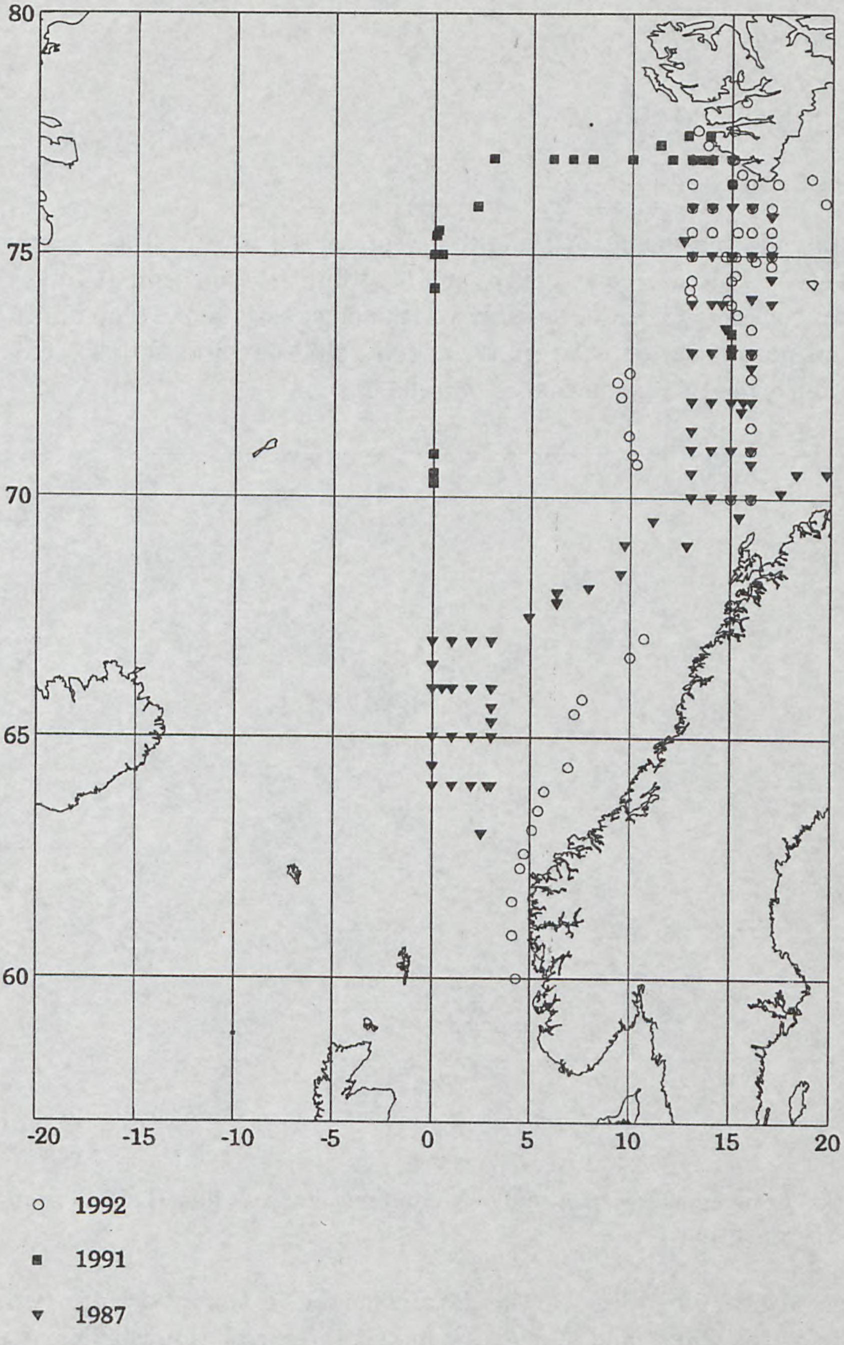

Fig. 2. Positions of stations for measuring whitecap coverage during the AREX–87, 91, 92 cruises of r/v 'Oceania'

$$C_H = \begin{cases} 0.0015 \ (T_W > T) \\ 0.001 \ (T_W < T) \end{cases}$$

(Friehe and Schmitt, 1976).

4. Results

The data collected during AREX–87 are presented in Fig. 3 as a relationship between whitecap coverage W_c and heat flux H. The ordinate gives the whitecap coverage (%), the abscissa watts per m^2 ($W\,\mathrm{m}^{-2}$). The figure indicates that no correlation between W_c and H could be found for the 1987 data set. The correlation coefficient is only 0.04.

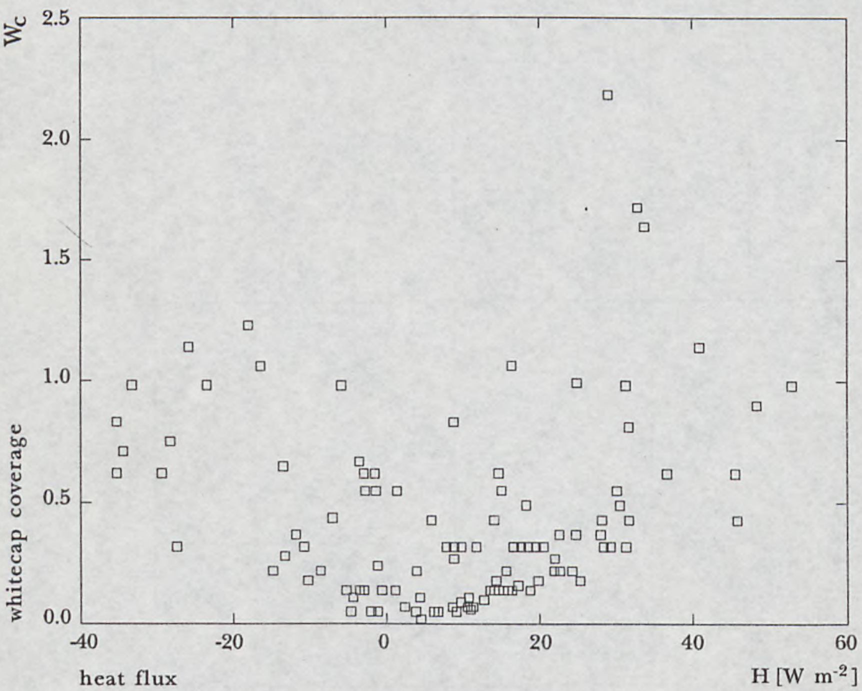

Fig. 3. Relation between whitecap coverage W_c and sensible heat flux H. Data from the AREX–87 expedition

However, after having divided the data collected in that year into two subsets – of positive fluxes and of negative fluxes, the correlation coefficients between W_c and H in these subsets are considerably higher and exceed 0.5. In accordance with earlier assumptions, negative correlations were found for negative heat fluxes and positive correlations for positive heat fluxes. Thus, the relationship $W_c\,(H)$ can be assumed to be valid. The function minimum was calculated by searching for the maximum of the module sum of correlation coefficients of the increasing and decreasing functions. The maximum of the sum was established by calculating the correlation coefficients for the various data set position. Surprisingly, the maximum correlation coefficients were obtained when the subset boundary $H = +10\,W\,\mathrm{m}^{-2}$, not when $H = 0$, as had been expected.

The $W_c(H)$ approximation curves were calculated using the least square method in both data subsets. When $H < 10$ the curve equation takes the form $y = -0.015x + 0.31$, when $H > 10$ it is $y = 0.022x - 0.06$, the curves intersect at $x = 10$.

Thus the minimum of function $W_c(H)$ is located near $H = 10\,W\,\mathrm{m}^{-2}$, which is in accordance with the result from the numerical model.

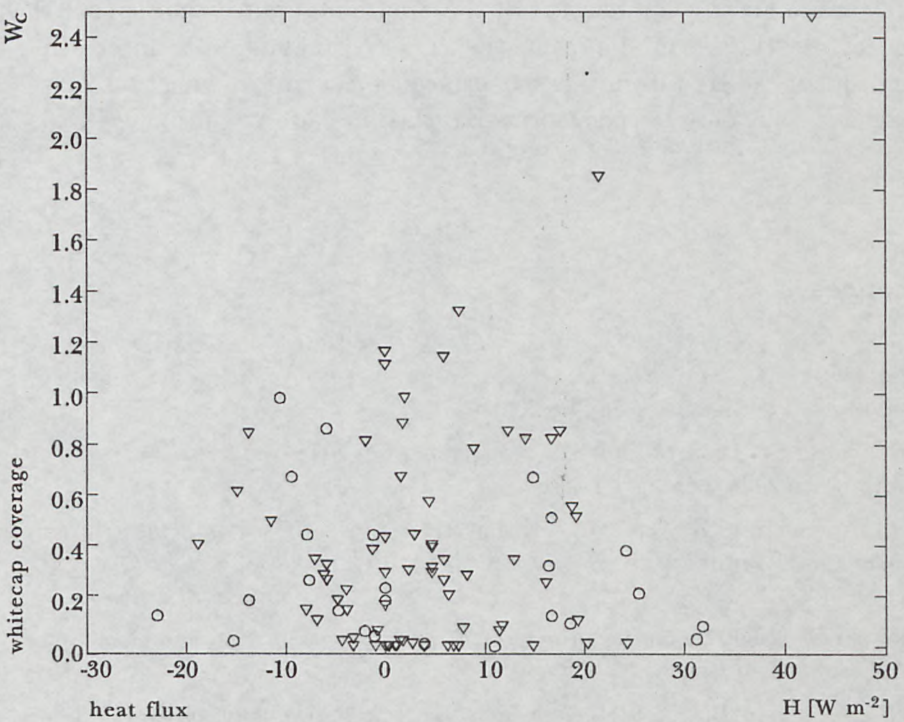

Fig. 4. Relation between whitecap coverage W_c and sensible heat flux H. Data from the AREX–91 and 92 expeditions

Fig. 4 presents the AREX–91 and 92 data. Unfortunately, no good correlations between W_c and H could be found for these data, probably because the variability range of H is much narrower than for the 1987 data. The 1991 and 1992 data were collected mostly under neutral conditions of air-sea interface stability.

Nevertheless these data do not contradict the 1987 results or the findings from the numerical experiments. As far as the W_c *vs.* H correlation is concerned, the analysis was limited to subsets containing high absolute values of H: a positive correlation was found for positive values and a negative correlation for negative ones.

5. Conclusions

The experimental data (from 1987) presented in this paper are in agreement with the results of numerical experiments. The data indicated an important fact, namely, that the minimum of the $W_c(H)$ relation is located in the region of positive heat fluxes. As the correlation between H and W_c is readily explained by the relation of these parameters to wind speed, the location of the $W_c(H)$ minimum in the $H > O$ range is quite interesting. Hence, droplets emitted from the sea surface have a certain effect on air-sea heat exchange not only during storms but also in calm conditions.

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