P2.4 THE NEUTRAL DRAG COEFFICIENT OVER POLAR SEA ICE WITH SMALL FLOES AND/OR MELT PONDS

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1. INTRODUCTION

Neutral drag coefficients observed over polar sea ice (Anderson, R.J., 1987; Andreas et al., 1984; Overland, 1985; Fairall and Markson, 1987; Guest and Davidson, 1987; Hartmann et al., 1994; Kottmeier et al., 1994; Mai et al., 1996; Garbrecht et al., 1999, 2002; Schröder et al., 2003) vary over roughly a factor of five. The variability is due to the nonhomogeneous distribution of e.g., ridge heights, distances between ridges, sea ice freeboard, ice concentration and floe sizes. The small scales in the variability of these parameters as well as the difficulties in their determination from observations or from sea ice models cause difficulties in the parametrization of the drag coefficients. Hence, attempts to relate the surface drag solely on sea ice concentration (Hanssen-Bauer and Gjessing, 1988; Mai et al., 1996; Steiner, 2001, Birnbaum and Lüpkes, 2002; Lüpkes and Birnbaum, 2005; Andreas et al., 2010) are attractive, since the latter is a parameter that can be determined most easily. We show in this contribution under which assumptions such kind of parametrizations are valid. This is done on the basis of an analytical model determining the total surface drag as a sum of skin drag and form drag calculated as the dynamic pressure caused by the flow across floe edges. For conditions being typical for the marginal sea ice zones such an approach was first formulated by Hanssen-Bauer and Gjessing (1988) (HBG88). Lüpkes and Birnbaum (2005) (LB05) investigated a further development of this parametrization and fitted then the results of their detailed model with an algebraic function giving drag coefficients as a function of the sea ice concentration A. Andreas et al. (2010) (AN10) presented a simple quadratic polynomial for the neutral drag coefficients dependent on A which they obtained as a fit to drag coefficients observed in the MIZ and summer central Arctic regions.

We show in the next section that a parametrization as simple as the algebraic LB05 and AN10 formulae can also be derived straightforward on the basis of physical principles using an equation for form drag which is more simple than that used by LB05. As in LB05 it explains the observed drag variability by the variability in the sea ice concentration, floe sizes and freeboard. Furthermore, it is shown that differences in the ice morphologies between summer sea ice with melt ponds and the marginal sea ice zone with small floes result in general in different dependences of the neutral drag coefficients on the sea ice concentration. The final formulae are as simple as the AN10-fit which contains, however, only a dependence on sea ice concentration and does not distinguish between the conditions in the MIZ and central Arctic.

2. DERIVATION OF DRAG COEFFICIENTS

The most important idea behind the analytical models of surface drag over sea ice is to account for the dynamic pressure of ice freeboard and to assume that

$$C_{dn10} = (1-A)\, C_{d,w} + A\, C_{d,i} + C_{d,f} \qquad (1)$$

where C_{dn10} is the neutral 10 m- drag coefficient, $C_{d,w}$ and $C_{d,i}$ are the skin drag coefficients over ice and over water, and $C_{d,f}$ is the form drag coefficient. In the models of HBG88 and LB05 this formula was related to ice conditions as being typical in the MIZ with freely drifting floes surrounded by open water. However, in case of large sea ice cover floes might be in contact to each other (Figure 1) so that the morphology is different from the

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free drift morphology. This is most obvious for the summer sea ice conditions in the initial stage of melting. As will be shown below form drag differs for the different types of morphology in its dependence on the sea ice concentration.

2.1 Surface drag over the marginal sea ice zone

For conditions as shown in Figure 1 (left) the sea ice concentration A is given by

$$A = N\,D_i^2/S_t\,, \tag{2}$$

where N is the number of floes which are assumed to be quadratic and have on average in the domain S_t a length D_i and freeboard h_f. Other

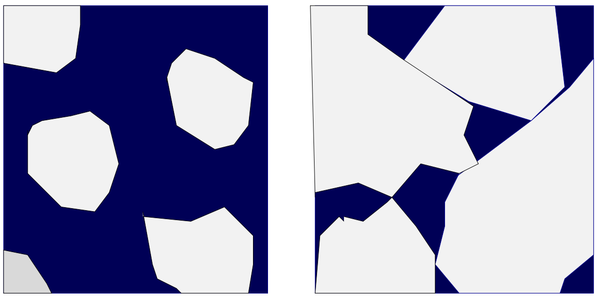

Figure 1: *Schematic of surface morphology considered as representative for the marginal sea ice zone with open water (blue) between drifting floes (left) and the summer Arctic (right) with melt ponds (blue).*

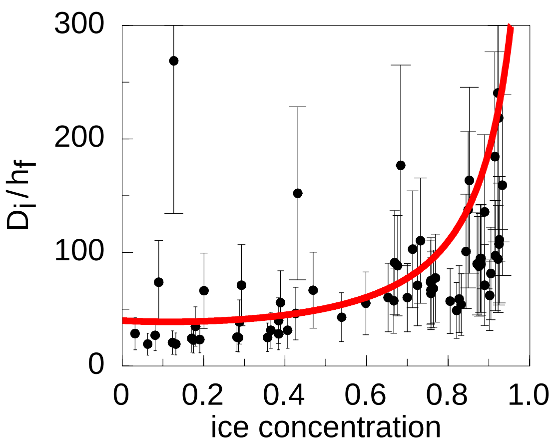

Figure 2: *Floe aspect ratio as observed during the campaign REFLEX by Kottmeier et al. (1994) (bullets) and parametrization (red).*

shapes are also possible, but then an additional factor would occur in the final equations for form drag. With (2) form drag follows as

$$\begin{aligned} F_d &= \frac{\rho}{2} c_w \underbrace{\frac{1}{N}\frac{S_c^2}{h_f D_i}\sum\left[\int_0^{D_i}\int_{z_0}^{h_f} u^2 dz dy\right]}_{P'} \frac{N h_f D_i}{S_t} \\ &= \frac{\rho}{2} c_w\, P'\, \frac{h_f}{D_i}\, A\,, \end{aligned}$$

where u is the horizontal wind speed with a logarithmic profile. $c_w = 0.3$ is the coefficient of resistance of an individual floe and $z_{0,w}$ is the surface roughness length of open water. S_c describes the sheltering of wind by upstream floes. After some further straightforward approximations we arrive at the parametriztion

$$\begin{aligned} C_{dn10} &= (1-A)\,C_{d,w} + A\,C_{d,i} \\ &+ \frac{c_w}{2}\left[\frac{\ln(h_f/z_{0,w})}{\ln(10/z_{0,w})}\right]^2 S_c^2\,\frac{h_f}{D_i}\,A\,. \end{aligned} \tag{3}$$

We found that for conditions in the MIZ as observed during aircraft campaigns over the eastern Fram Strait (as shown in Figures 2 and 3) the impact of sheltering is negligible ($S_c = 1$) so that the dependence of drag coefficients on A is there mainly a consequence of the dependence of floe number (and thus edge length per area) on the sea ice concentration. The above equation can be used in a complex air-ice-ocean model, where h_f and D_i are known from prognostic equations.

If this information is not available, a further parameterization is possible by using observed values for D_i and h_f as a function of A. Observations are shown in Figure 2 together with the fit

$$D_i = D_{min}\left(\frac{A_\star}{A_\star - A}\right)^\beta\,, \tag{4}$$

where

$$A_\star = \frac{1}{1-(D_{min}/D_{max})^{1/\beta}}\,. \tag{5}$$

$D_{min} = 8$ m and $D_{max} = 300$ m are the minimum and maximum floe lengths in the MIZ as measured in the Fram Strait by Kottmeier et al. (1994). $A_\star$ is introduced instead of the value 1 to avoid a singularity as occurring in the LB05 parameterization. With β between 1.4 and 0.3 the value of $A_\star$ varies between 1.08 and approximately 1.0. A linear fit of the freeboard to observations is given by

$$h_f = h_{min} + (h_{max} - h_{min})\, A \tag{6}$$

with $h_{min} = 0.2$ m and $h_{max} = 0.55$ m. Use of eq. (4) and (5) in (3) results finally in the parametrization

$$C_{dn10} = (1 - A)\, C_{d,w} + A\, C_{d,i} + C_f\, (A_\star - A)^\beta A$$

with (7)

$$C_f = \frac{c_w}{2} \left[\frac{\ln(h_f/z_{0,w})}{\ln(10/z_{0,w})}\right]^2 S_c^2\, \frac{h_f}{D_{min} A_\star^\beta}\,.$$

Results in Figures 3 and 4 were obtained prescribing $C_{d,i} = 1.6 \cdot 10^{-3}$ and $C_{d,w} = 1.5 \cdot 10^{-3}$, where the latter is equivalent to the assumption $z_{0,w} = 3.27{\cdot}10^{-4}$ m. The best agreement between the results of eq. (7) and aircraft observations of the drag coefficients over the Fram Strait were obtained with $\beta = 1.4$ (Figure 3), while $\beta = 0.3$ (Figure 4) seems to represent observations over the

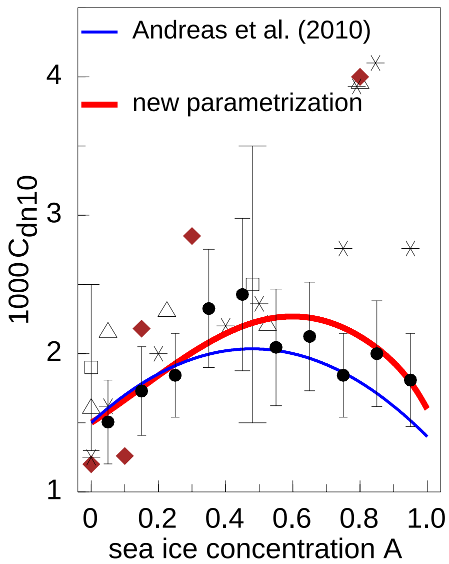

Figure 3: *Neutral drag coefficients calculated with eq. (7) (β =1.4) and according to AN10. Observations are from Hartmann et al. (1984) and Kottmeier et al. (1994) (black bullets); Andreas et al (1984) (brown), Anderson (1987) (asterisks), Guest and Davidson (1987) (triangles), Schroeder et al. (2003) (sqaures).*

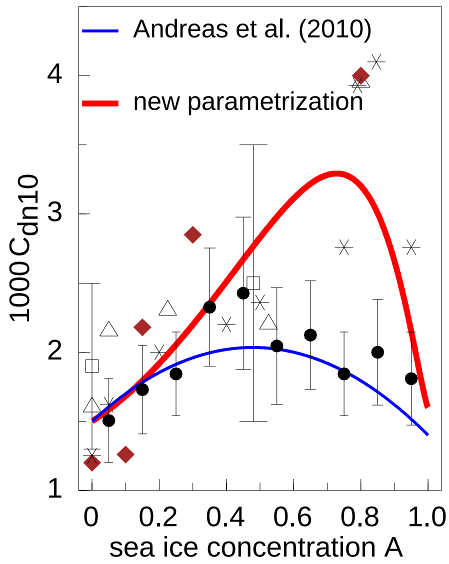

Figure 4: *As Figure 3, but results of the new parametrization were obtained with $\beta = 0.3$.*

Antarctic marginal ice zone as observed by Andreas et al. (1984). For the latter conditions also sheltering plays a role which was parameterized on the basis of results of a high resolution flow model (Lopez et al., 2005) as

$$S_c^2 = (1 - A)^{1/(10\beta)}\,. \tag{8}$$

Figures 3 and 4 show also results of the AN10 parametrization. It should first be noted that this curve represents a fit not only to the observations of the MIZ as shown in Figure 3, but also to observations in the summer central Arctic (section 2.2). It is possible to obtain the same quadratic polynomial form from eq. (7) using the following assumptions. First, $C_{d,i}$, $C_{d,w}$, $z_{0,w}$ and the freeboard h_f have to be prescribed as constant. Furthermore, $A_\star$ and β have to be set to 1 where the latter is equivalent to the assumption of a specific distribution of floe lengths. This shows that the AN10 fit represents drag coefficients for mean sea ice conditions. But specific conditions can differ drastically from these mean conditions.

3.2 Surface drag over summer sea ice with melt ponds

In analogy to the derivation of drag coefficients

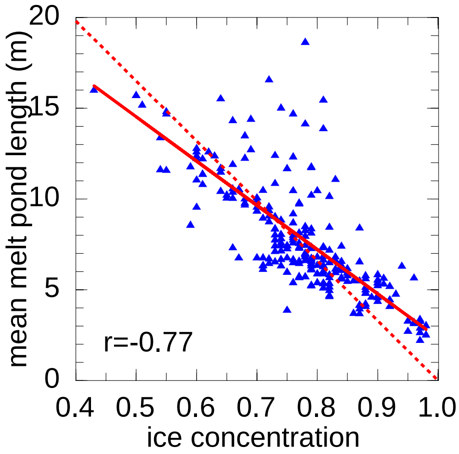

Figure 5: *Mean melt pond length derived on the basis of satellite observations analysed by Fetterer et al. (2008). Red solid line represents equation (10). For simplicity, a quadratic shape of melt ponds was assumed, other assumptions on the mean shape would result in a constant factor in the equation for form drag.*

for the MIZ we obtain for the sea ice morphology as shown in Figure 1 (right)

$$1 - A = D_w^2 \frac{N_p}{S_t} , \tag{9}$$

where D_w is now the mean length of melt ponds. Again, just a constant factor would appear, if the pond shape would differ from a square. We obtain then

$$\begin{aligned} C_{dn10} &= (1-A)\, C_{d,w} + A\, C_{d,i} \qquad (10)\\ &+ \frac{c_w}{2} \left[\frac{ln(h_p/z_{0,w})}{ln(10/z_{0,w})}\right]^2 S_c^2 \,\frac{h_p}{D_w}\,(1-A) , \end{aligned}$$

where h_p is the freeboard related to melt ponds (surface elevation between sea ice and melt pond surface). Based on satellite observations of melt ponds (Fetterer et al., 2008) we use the linear fit (Figure 5)

$$D_w = D_{min} + (D_{max} - D_{min})\,(1-A) \tag{11}$$

with $D_{min} = 2.26$ m and $D_{max} = 26.89$ m and $A > 0.5$. Assuming now that h_p depends linearly on $(1-A)$ with $h_p = h_{max}\, A$ and $h_{max} = 0.8$ m we obtain

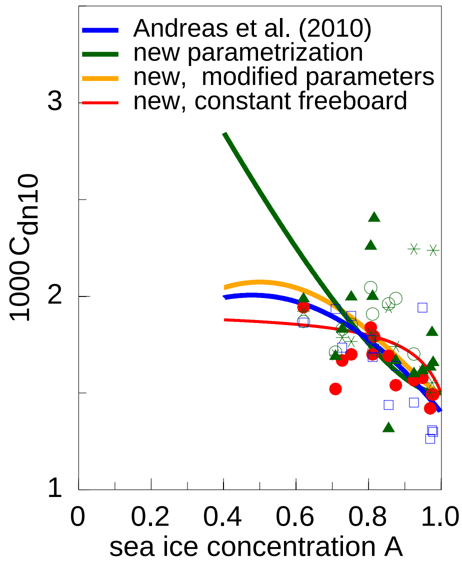

Figure 6: *Drag coefficients (symbols) observed during SHEBA at different sites as analyzed by AN10. The green sold line represents results of equation (11), while the other solid lines were obtained using equation (9) with different parametrizations of h_p and D_w as a function of A.*

$$\begin{aligned} C_{dn10} &= (1-A)\, C_{d,w} + A\, C_{d,i} + \qquad (12)\\ & \quad C_f \frac{h_{max}\,(1-A)^2}{D_{min} + (D_{max}-D_{min})\,(1-A)} \\ C_f &= \frac{c_w}{2}\left[\frac{\ln(h_{max}(1-A)/z_{0,w})}{\ln(10/z_{0,w})}\right]^2 S_c^2 \end{aligned}$$

Results of this parameterization are shown in Figure 6 (green), where we assumed the same values for $C_{d,i}$ and $C_{d,w}$ as in the previous section. The figure contains also results from observations during the SHEBA campaign as described in AN10. It should be noted that the results at the ASFG tower (red bullets) are the most reliable ones, since they were obtained from instruments installed at a tower in different heights, while the other observations were obtained from observations at 2 m only. It is obvious that the functional dependence of the drag coefficients obtained with eq. (12) differs drastically from the results in the MIZ. However, modified assumptions on the parametrization of h_p and D_w representing again very specific conditions would also result in a quadratic polynomial. Some possible curves obtained with different assumptions on h_p and D_i

are included in Figure 6.

3. CONCLUSIONS

A new parametrization of the neutral drag coefficients over the marginal sea ice zone and summer sea ice with melt ponds was derived on the basis of the skin drag/form drag concept. The principal method for the derivation of form drag on a physical basis is similar as in a previous work by Lüpkes and Birnbaum (2005), but the present one needs less assumptions on the floe characteristics and results in a formulation which is simple enough to be applied efficiently to climate models. Governing parameters besides the sea ice concentration A are the characteristic edge lengths D_i of floes and D_w of melt ponds as well as freeboard, where the sensitivity on the latter is smaller than the sensitivity on the other parameters. The most important result is that although the sea ice pattern with floes in the MIZ and melt ponds in summer sea ice looks at a first glance very similar, the different morphology results in general in different formulae for the drag coefficients with different functional dependences on the sea ice concentration. However, special conditions and special distributions of floe sizes and melt pond sizes, respectively, exist, where the dependence on the sea ice concentration is identic for the MIZ and summer sea ice with melt ponds. A simple quadratic polynomial formula given by Andreas et al. (2010) can also be derived, but only for special cases of floe and melt pond geometries and distributions and using constant surface roughness lengths over open water and sea ice.

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