The Effect of Swell on Air-Sea Exchange in the Baltic Sea

A contribution to subproject CAPMAN

Ann-Sofi Smedman[1], Anna Rutgersson[1,2] and Ulf Högström[1]

[1]*Department of Earth Sciences, Meteorology, Uppsala University, Uppsala, Sweden*
[2]*Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, Sweden*

Introduction

Swell are waves travelling faster than the wind. In the open ocean, swell is more or less omnipresent and often omnidirectional. It originates in areas with strong winds but can travel over thousands of kilometers with very little attenuation. Thus, swell observed at a given position in the open ocean at a given occasion can have any direction quite independently of the local wind direction.

Up till recently, the study of swell has received much less attention than wind waves, and its properties are hence less well known. In recent years several studies have, however, highlighted intriguing features of the effect of swell on the turbulent exchange of momentum, sensible heat and water vapor at the air-sea interface, *Smedman et al*. (1994, 1999), *Rutgersson et al*. (2001), *Drennan et al.* (1999), *Grachev and Fairall* (2000).

The Baltic Sea differs from the open ocean in an important respect, the size being small in relation to the size of typical synoptic disturbances which may give rise to swell. This means that usually there is not more than one, well-defined source of swell present at a given time in the Baltic Sea, and that the direction of swell at a certain site is likely to be more or less unidirectional.

Data from several years of measurements of concurrent atmospheric data and wave data from the site Östergarnsholm east of Gotland (see Section 2) have been used for the studies presented here. It is found that swell occurs as often as 40% of the time at this site. Very often the swell comes from a southerly direction. As winds from this sector are common, a situation with swell and wind having roughly the same direction is typical for this site. The studies presented here represent such, rather well defined conditions.

Site and measurements

Östergarnsholm is a low island with no trees, situated about 4 km east of Gotland. On the southernmost tip of the island, a 30m tower has been erected, with its base only about 1 m above mean water level. The tower is instrumented with Solent sonic anemometers at 9, 16 and 25 m above the ground and slow response, 'profile' sensors for wind and temperature at 5 levels. Wave height and direction is obtained from a Waverider buoy (run and owned by the Finnish Institute for Marine Research) anchored about 4 km to the South-south-east of the tower at a water depth of 36m. Measurements started in 1995 and have run semi-continuously since then.

The measurements on the tower represent open sea conditions with very long fetch (> 100 km) for the sector from north-east over South to south-west. As shown from the 'flux footprint' calculation in *Smedman et al*. (1999), the measurements on the tower are likely not to be influenced by limited water depth outside the island.

Effects of swell on the momentum flux

In numerical models the exchange of momentum at the surface of the sea is usually expressed in terms of the drag coefficient C_D, defined as

$$C_D = u_*^{\,2} / u_{10}^{\,2} \qquad (1),$$

where u_* is the friction velocity and u_{10} the wind speed at 10m height. *Figure 1a* shows, for *unstable conditions*, C_D plotted against the stability parameter *z/L*, where z is height above the water surface and *L* is the Monin-Obukhov length:

$$L = -\frac{u_*^{\,3} T_0}{kg\,\overline{w'\theta_v'}} \qquad (2),$$

with T_0 mean temperature of the surface layer (K), k = von Karman's constant, g = acceleration of gravity and $\overline{w'\theta_v'}$ the buoyancy flux. The filled symbols represent measurements during swell, open symbols non-swell. The full line is the corresponding standard formulation used in most models. It is seen that the momentum flux observed with swell is generally lower than expected. As shown by *Smedman et al.* (1994), *Grachev and Fairall* (2000) and others, the momentum flux during wind-following swell is sometimes even directed upwards from the ocean instead of, as usually observed, downwards.

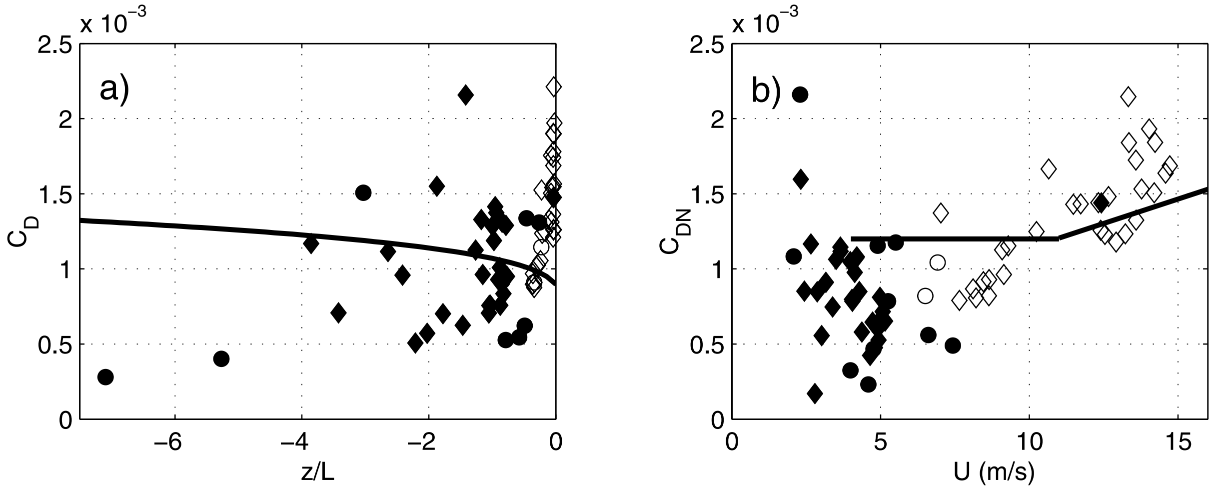

Figure 1. Drag coefficient during unstable conditions, a) C_D as a function of *z/L*; the line was calculated from standard expressions; b) neutral drag coefficient calculated with standard ϕ_m -functions, plotted as a function of 10 m wind speed; the solid line is based on *Large and P*ond (1981). From *Rutgersson et al.* (2001).

In *Figure 1b* C_D has been reduced to its value at neutrality (*z/L* = 0), denoted C_{DN}, with the aid of standard Monin-Obukhov expressions (*Högström*, 1996) and plotted against u_{10}. The full line is derived from *Large and Pond* (1981). Also in this graph it is clear that the swell data are lower than expected. This is, however, not surprising, considering that the dimensionless wind gradient expressions $\phi_m(z/L) = \frac{kz}{u_*}\frac{\partial u}{\partial z}$ observed during swell (not shown here) differ considerably from what is otherwise observed and used in reducing C_D to C_{DN}. A characteristic observed feature during swell in unstable conditions is the occurrence of a low level (< 10 m) wind maximum – a wave-driven wind which gives negative values for

ϕ_m within an appreciable part of the surface layer, *Smedman et al.*(1999). Monin-Obukhov similarity is thus not valid during these conditions.

In *stable conditions*, i.e. when $z/L > 0$, the observed ϕ_m -curves agree much better with what is otherwise observed (not shown here), but nevertheless, C_D is only half its value during non-swell conditions. *Rutgersson et al.* (2001) observe such conditions for u_{10} as high as 8 m s^{-1}.

Exchange of sensible heat and water vapor

The turbulent exchange of sensible heat, *H* is derived in numerical models with a bulk formulation similar to that for the exchange of momentum:

$$H = \rho \overline{w'\theta'} = \rho C_H u_{10}(\theta_{10} - \theta_s) \qquad (3),$$

where ρ is air density, C_H the bulk exchange co-efficient, θ_{10} potential temperature at 10 m and θ_s surface temperature.

Figure 2 presents data for C_H plotted against *z/L* for *unstable* conditions ($z/L < 0$). The measurements show that C_H is only about 10 % lower in the mean than expected from standard expressions (the thin line) during swell. Note, that swell occurs over a very wide stability range, $-7 < z/L < 0$, whereas non-swell conditions, represented by the thick line, is obtained only for $z/L > -0.5$. As noted in Section 3, the friction velocity is strongly reduced during swell conditions and, as seen from the definition of the Monin-Obukhov length, Eq. (2), this will result in a strong reduction in $-L$ and correspondingly large values of $-z/L$ even for a comparatively small heat flux.

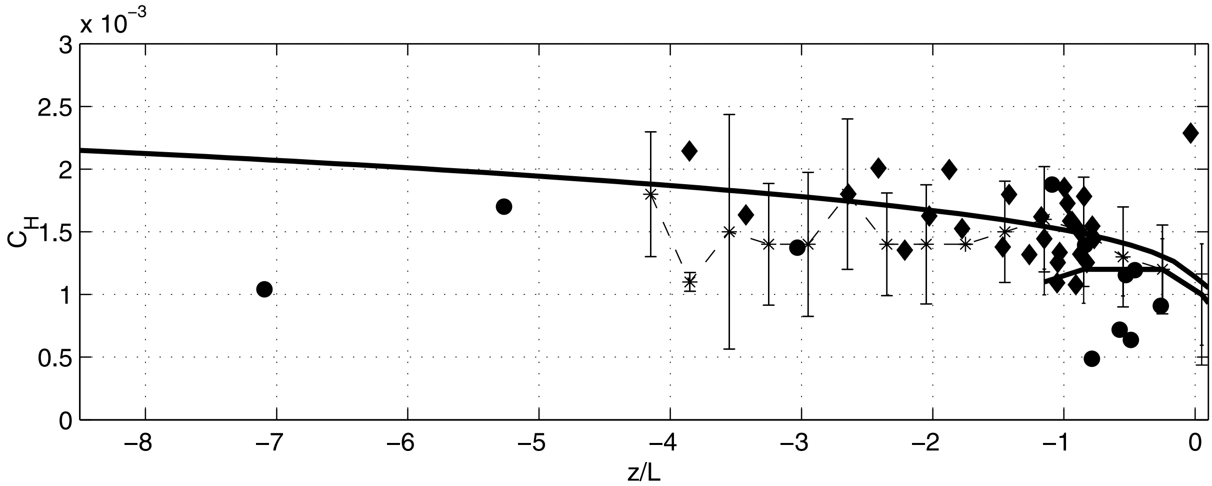

Figure 2. C_H plotted as a function of *z/L* for unstable conditions. Filled symbols represent measurements during swell conditions. The thin solid line has been derived with $C_{HN} = 1.1 \cdot 10^{-3}$ and standard ϕ_h - functions. Dashed lines connects averages over *z/L* intervals using all available swell data for 1995 – 1998 in the range $-4.5 < z/L < 0$. Thick solid line is average of all data from the same time period *without* swell. From *Rutgersson et al.* (2001).

Figure 3 shows C_H for *stable conditions* as a function *z/L*. Again the thin line has been derived from standard expressions. The observational swell data are found to be approximately constant $\approx 0.5 \cdot 10^{-3}$ over the stability-interval $0 < z/L < 1.5$, decreasing probably for higher *z/L*. Also the data for non-swell conditions, the short thick line, indicates that $C_H \approx 0.5 \cdot 10^{-3}$ for near-neutral stable conditions, rather than about $1.1 \cdot 10^{-3}$ as traditionally thought. This lower value was also found by *Davidson* (1974) during swell and by *Oost et al* (2000). Thus, there is almost a discontinuity of C_H at $z/L = 0$. This is probably caused by a feedback effect: stable stratification reduces turbulence, which reduces the waves, which reduces friction further etc. This interpretation is in agreement with the finding reported in Section 3. During stable conditions, C_D is found to be only about half of what is usually assumed in spite of the fact that ϕ_m agrees with what is found over land, indicating that the roughness length is being reduced over sea in stable air by this feedback effect.

Title:
figg.ps
Creator:
MATLAB, The Mathworks, Inc.
Preview:
This EPS picture was not saved
with a preview included in it.
Comment:
This EPS picture will print to a
PostScript printer, but not to
other types of printers.

Figure 3. C_H for stable conditions plotted against z/L. Notations as in Figure 2. From *Rutgersson et al*. (2001).

The results obtained for the flux of sensible heat appears to be equally valid for the corresponding exchange of water vapor, but the experimental data are still relatively scarce.

Conclusions

Analysis of several years worth of measurements at Östergarnsholm shows that swell occurs as often as 40% of the time in the Baltic Sea. As the source of swell is in most cases located in a well-defined geographical area of the Baltic, uni-directional swell is often found. At Östergarnsholm, the swell has often approximately the same direction as the local wind. The results given here all represent such conditions.

The exchange of momentum at the water surface is strongly influenced by swell. This results in a reduced bulk exchange coefficient, C_D. Often a wind maximum is found below 10 m (a wave-driven wind), invalidating Monin-Obukhov similarity.

The exchange of sensible heat and water vapor is also affected by swell but not as much as in the case of momentum. At slightly and moderately stable conditions, the bulk coefficient C_H is found to be virtually constant at $0.5 \cdot 10^{-3}$, also during non-swell.

Acknowledgement

This work has been performed within the framework of the EU-funded project PEP in BALTEX (contract no ENV4-CT97-0484).

References

Davidson, K.L., (1974). Observational results on the influence of stability and wind-wave coupling on momentum transfer and turbulent fluctuations over ocean waves. *Boundary-Layer Meteorol.,* **6**, 305 – 331.

Drennan, M.W., K.K. Kahma and M.A. Donelan (1999). On momentum and velocity spectra over waves. *Boundary-Layer Meteorol.,* **92**, 489 – 515.

Grachev, A.A. and C.W. Fairall (2000). Upward momentum transfer in the marine boundary layer. *J. Phys. Ocean.*, In press.

Högström, U. (1996). Review of some basic characteristics of the atmospheric surface layer. *Boundary-Layer Meteorol.,* **78**, 215 – 246.

Large, W.G. and S. Pond (1981). Open ocean momentum flux measurements in moderate to strong winds. *J. Phys. Ocean.*, **11**, 324 – 336.

Oost, W.A., M.J. Jacobs and C.van Oort (2000). Stability effects on heat and moisture fluxes at sea. *Boundary-Layer Meteorol.,* **95**, 271-302.

Rutgersson, A., A. Smedman and U. Högström (2001). The use of conventional stability parameters during swell. *J. Geophys. Res.*, Accepted.

Smedman, A., M. Tjernström and U. Högström (1994). The near-neutral marine atmospheric boundary layer with no surface shearing stress: A case study. *J. Atm. Sci.*, **51**, 3399-3411.

Smedman, A., U. Högström, H. Bergström, A. Rutgersson, K.K. Kahma and H. Pettersson (1999). A case-study of air-sea interaction during swell conditions. *J. Geophys. Res.*, **104**, 25,833-25,851.