MARINE BOUNDARY-LAYER HEIGHT ESTIMATED FROM NWP MODEL OUTPUT

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INTRODUCTION

In today's operational atmospheric dispersion models, the meteorological fields are often taken from routinely available weather forecasts. Such forecasts are based on simulations with Numerical Weather Prediction models (NWP). Typical output from a NWP model consists of coarse hourly profiles of wind, temperature and humidity on a rough horizontal grid. The height of the boundary layer does not form a part of the output from the NWP model, but has to be estimated from the available output data, usually by use of bulk Richardson numbers, that vary in their definition. As much emphasis has been devoted to estimate the connection between the critical Richardson number and the NWP output for land conditions, the Richardson methods generally are considered to make reliable predictions of the boundary-layer height over land. Based on measurements the ability from NWP model output to predict the height of the marine boundary layer is studied. It is found that the predicted boundary-layer height in general is too large which suggests that for the marine boundary layer the critical Richardson numbers are smaller than over land - we found critical Richardson numbers around 0.03 to 0.05 to perform best over the sea. Furthermore it is found that a relatively small neighbouring island can influence development of the boundary layer height.

MEASURING SITE

Radiosoundings of the marine boundary layer were carried out on Christiansø, a small island in the southern part of the Baltic Sea. The development of the marine boundary layer was inferred from the air temperature and humidity radiosonde profiles. Figure 1 shows a map of the southern part of the Baltic Sea with the position of Christiansø marked with a cross.

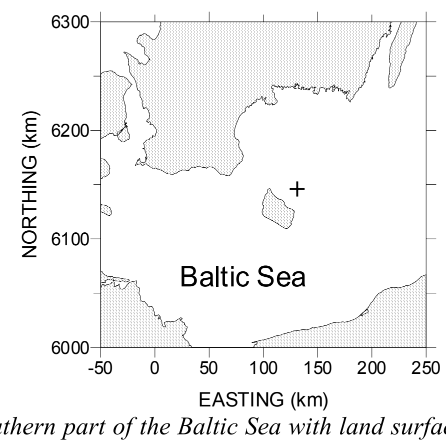

Figure 1. Map of the southern part of the Baltic Sea with land surfaces dotted. Bornholm is the island in the centre. The cross shows the location of Christiansø east of Bornholm. Co-ordinates refer to UTM34.

HIRLAM MODEL

This study is based on output from The HIgh Resolution Limited Area Model HIRLAM, which is a complete model system for operational weather forecasts maintained by national meteorological services in Northern Europe. Operationally, local versions of the HIRLAM model are used, and in this study we use HIRLAM data provided by the Swedish Meteorological and Hydrological Institute. The horizontal grid resolution is 22.5 times 22.5 km and there are 31 vertical levels. Output from the simulations with the HIRLAM model includes hourly profiles of wind (u and v components), temperature and humidity as function of the geopotential height (given at the approximate levels 30, 150, 350, 600, 950, 1300, 1750, 2200, 2650…metres). Details are given in *Rutgersson et al.* (2001). The height of the boundary layer does not form a part of the output from the HIRLAM model, but has to be estimated from the available data. In this study we apply and compare two methods to extract the boundary-layer height from the HIRLAM output data; both are based on a bulk Richardson-number approach, but they differ in the way the wind speed is taken into account. For both methods the boundary-layer height is defined as the height where the bulk Richardson number reaches a critical value, typically 0.25.

Sørensen (1998) suggests the bulk Richardson number for the layer between the surface and the height z above the surface:

$$Ri_B = \frac{gz(\theta(z) - \theta(s))}{\theta(s)(u(z)^2 + v(z)^2)} \tag{1}$$

The quantities $\theta(s)$ and $\theta(z)$ are the potential virtual temperatures at the surface (by *Sørensen* (1998) taken as the lowest model level) and height z, respectively, $u(z)$ and $v(z)$ are the horizontal wind components at height z, and g is acceleration due to gravity. *Sørensen* (1998) recommends a value of 0.25 for the critical value of the bulk Richardson number. *Vogelezang and Holtslag* (1996) suggest a Richardson-number where the wind is defined with respect to the lowest model level (here 30 m), and a term that accounts for surface friction has been added

$$Ri_B = \frac{gz(\theta(z) - \theta(s))}{\theta(s)\left[(u(z) - u(s))^2 + (v(z) - v(s))^2 + bu_*^2\right]} \tag{2}$$

where b is a parameterisation constant, recommended by *Vogelezang and Holtslag* (1996) to be taken as 100. The critical Richardson number is taken as 0.25.

Both expressions for the Richardson number are proportional to $z(\theta(z) - \theta(s))$. In the ideal case where the virtual potential temperature is constant in the boundary layer and increases at a certain rate above it, this means that for increasing z, a correspondingly smaller temperature change is needed in order to reach the prescribed Richardson-number value. This makes the determination of the boundary-layer height sensitive to even small changes between successive temperature profiles, and may partly explain the large variability that is often found in time series of the boundary-layer height determined from numerical weather-prediction models by use of Richardson-number method.

The expressions treat differently the wind-velocity influence. In equation (1) the wind speed is taken at the given height. Equation (2) applies the difference between the lowest model level and the actual height, and the surface boundary layer is accounted for through an additional friction-velocity term. This term can be large compared to the wind-profile contribution. Then the boundary-layer height is determined mainly from the temperature profile and the friction velocity. Over water owing to the small roughness length the wind speed is typically high with small friction velocity. Hence over water the Richardson number suggested by *Sørensen* (1998) would tend to predict a higher boundary layer as compared to the Richardson number suggested by *Vogelezang and Holtslag* (1996). This effect is clearly seen in the simulations of the boundary-layer height over Christiansø.

SIMULATIONS WITH THE HIRLAM MODEL

During an observation period from 24 October to 5 November a total of 24 radiosoundings were performed at Christiansø. The meteorological conditions were characterised by heat flux from the sea to the atmosphere, creating an unstable boundary layer over the sea. Gryning and Batchvarova (2002) gives details. The wind speed and direction predicted by the HIRLAM model at Christiansø during the experiment are shown in Figure 2. In the beginning of the period the wind speed is very high, followed by moderate values at the end. It should be noted that for the sector 190 to 270 the wind has passed over Bornholm some 20 km away. In the northerly sector the water fetch to Christiansø is of the order of 100 km or more.

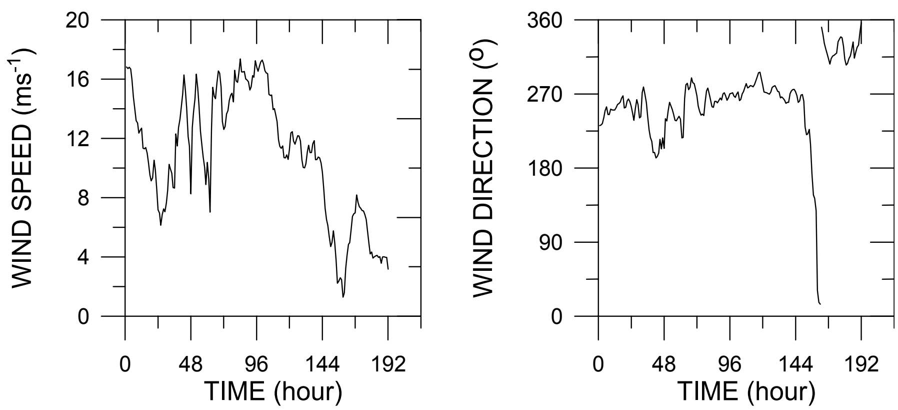

Figure 2. Wind speed and direction at Christiansø from the HIRLAM model during the period 26 October to 3 November 1998. The time is shown in hours starting on midnight 25/26 October and ending on midnight 3/4 November (hour 216).

Both the above presented Richardson-number methods to extract the boundary-layer height from the output of Numerical Weather Prediction (NWP) models were applied to the hourly output from the HIRLAM model.

The result from the analysis using the Richardson number suggested by *Sørensen* (1998) is shown on the left panel in Figure 3. It can be seen that the predicted boundary-layer height is clearly too high during the first part of the experimental campaign where the wind is southwesterly. At 160 hours when the wind turns north, such that Bornholm no longer affects the air mass over Christiansø, agreement between measurements and predicted boundary-layer heights improves considerably, but it also can be seen that the method still overpredicts the height of the marine boundary-layer.

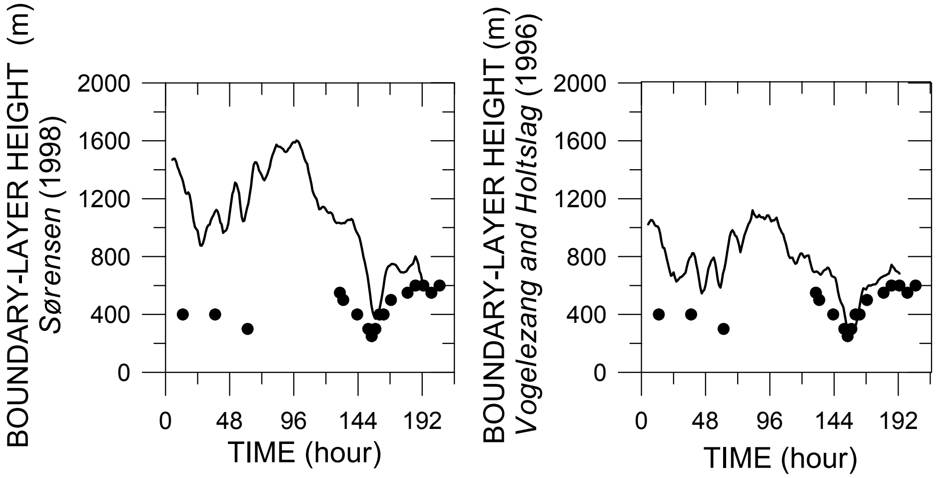

Figure 3. Boundary-layer height over Christiansø during the observation period, estimated from the HIRLAM model, full line. The results represent the HIRLAM grid point closest to Christiansø. The left panel shows the results using the Richardson number suggested by Sørensen (1998), the right panel when using the Richardson number in Vogelezang and Holtslag (1996). Bullets show measurements. Time indications as in Figure 2.

The right panel in Figure 3 shows the results when using the Richardson number suggested by *Vogelezang and Holtslag* (1996). It can be seen that the predicted boundary-layer height generally is lower than on the left panel, but still overpredicts the boundary-layer height both for the first period of the simulation where the wind passes over Bornholm before reaching Christiansø, as well as for the last part although less pronounced, when the wind is northerly and the effect of Bornholm is absent.

DISCUSSION

During the experiment the water was generally warmer than the air which is a very typical feature for the Baltic Sea during the late summer, autumn and early winter. This results in the generation of a convectively driven boundary layer over the water. The period from 26 October until midday 1 November 1998 is characterised by winds about 12 ms^{-1} from southwest to west. In this sector Christiansø is downwind of Bornholm with a water fetch of about 20 km. Following a wind direction shift on 1 November 1998 to northwest and north, the wind ceased to about 4 m s^{-1}. Then Christiansø is not downwind of Bornholm and the over water fetch from the Swedish coast is of about 100 km.

The height of the measured boundary layer is rather low during the first period indicating that the island of Bornholm controls the boundary layer over Christiansø. The boundary-layer height that was estimated from the HIRLAM data is higher than the measured one. The grid resolution in the HIRLAM model is of the same size as the distance between Christiansø and Bornholm and the size of Bornholm itself. This suggests that it is too coarse to reflect the meso-scale features that control the boundary-layer height over Christiansø when Christiansø is downwind of Bornholm.

Originally the critical Richardson-numbers for both methods are determined from measurements of the height of the boundary layer over land. In this study the boundary-layer height predicted by the Richardson number of *Sørensen* (1998) is systematically higher than for *Vogelezang and*

Holtslag (1996), and both predict boundary layers that are higher than the measured ones. This suggests, considering the low roughness of the sea surface, that there is dependence between the surface roughness and the critical Richardson-numbers and that the dependence is not the same for the two Richardson-numbers. During the last period of the experiment the wind was northerly. The air that reached Christiansø did not pass Bornholm on its way, but the water fetch to the nearest coast was about 100 km. The critical Richardson number that during this period subjectively gave the overall best fit to the measurements was found to be 0.03 for the method suggested by *Sørensen* (1998) and 0.05 for *Vogelezang and Holtslag* (1996). This is illustrated in Figure 4 where it also is evident that the *Vogelezang and Holtslag* (1996) method for this limited set of measurements give a slightly better overall fit than *Sørensen* (1998).

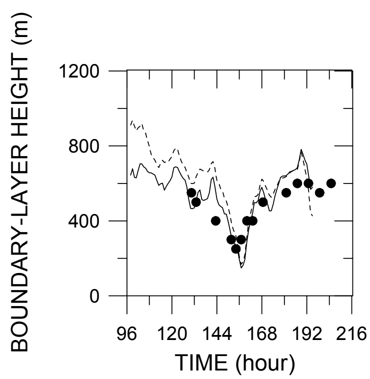

Figure 4. Height of the marine boundary layer during the last part of the observational period. The dotted line illustrates the boundary-layer height predicted by the method of Sørensen (1998) when applying a critical Richardson number of 0.03, the full line shows the predictions of the Vogelezang and Holtslag (1996) with a critical Richardson number of 0.05. Bullets show measurements. Time indications as in Figure 2.

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