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Marine boundary-layer height estimated from the HIRLAM model

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Two-weeks of measurements of the boundary-layer height over a small island (Christiansø) in the Baltic Sea is discussed. The meteorological conditions were characterised by positive heat flux over the sea. The boundary-layer heights derived from radiosonde measurements were compared to Richardson-number estimates based on output from the operational numerical weather prediction model HIRLAM (a version of SMHI with a grid resolution of 22.5 km × 22.5 km). For southwesterly winds it was found that a relatively large island (Bornholm) lying 20 km upwind of the measuring site influences the boundary-layer height. In this situation Richardson-number based methods with the HIRLAM data fail most likely because the island of Bornholm and the water fetch to the measuring site are about the size of the grid resolution of the HIRLAM model and therefore poorly resolved. For northerly winds the water fetch to the measuring site is about 100 km and the Richardson methods reproduce the height of the marine boundary layer. This suggests that the HIRLAM model adequately resolves a water fetch of 100 km with respect to predictions of the height of the marine boundary layer.

Introduction

The structure and height of the coastal boundary layer over the sea surface is important for several reasons. The water that evaporates from the sea surface into the atmosphere is dispersed vertically through the action of turbulence and becomes mixed over the whole atmospheric boundary layer. Because the top of the boundary layer to a high degree acts as a lid, it is one of the parameters controlling the water content in the air over the sea surface, and therefore has a feed back on the evaporation from the water surface. It is one of the fundamental parameters used to characterise the structure of the boundary layer. The marine boundary layer is also of importance in the field of atmospheric dispersion modelling.

Measurements

As a part of a Pilot study on Evaporation and Precipitation over the Baltic Sea (PEP-in-BALTEX) measurements were carried out on Christiansø, a small island in the southern part of the Baltic Sea (Fig. 1). For wind directions

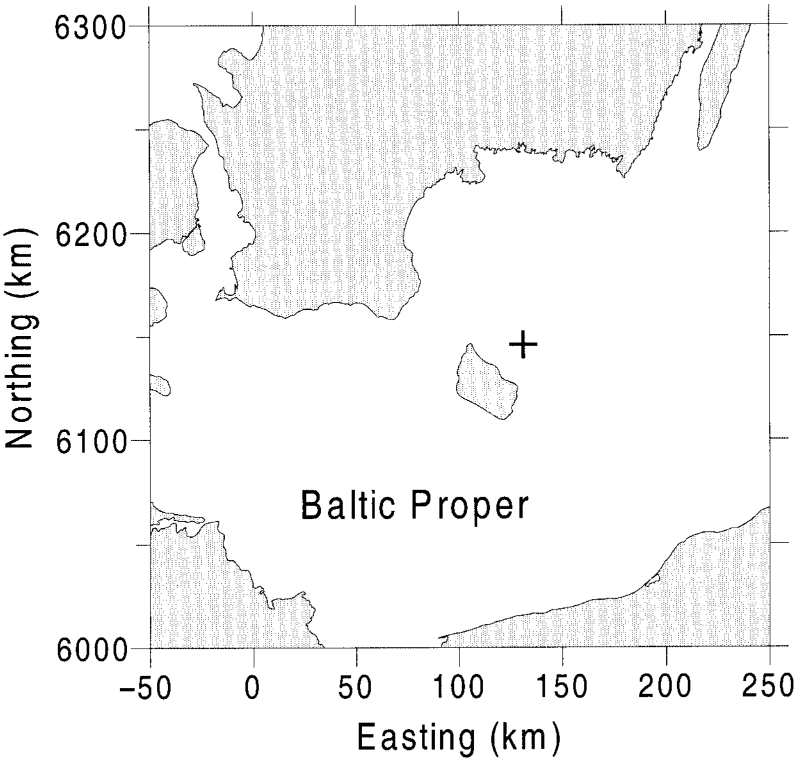

Fig. 1. Map of a southern part of the Baltic Proper with land surfaces dotted. Bornholm is the island in the center. The cross east of Bornholm shows the location of Christiansø. Coordinates refer to UTM34.

in sectors 190–270, Christiansø lies about 20 km downwind of Bornholm. In sectors 270–45, degrees the water fetch to the Swedish coast is about 100 km. During an intensive observation period from 24 October to 5 November 1998 a total of 24 radiosoundings were performed. The development of the marine boundary layer was derived from the air temperature and humidity radiosonde profiles. The meteorological conditions were characterised by a heat flux from the sea to the atmosphere, creating an unstable boundary layer over the sea. Details are given in Gryning and Batchvarova (2002).

HIRLAM model

The HIgh Resolution Limited Area Model HIRLAM is a complete model system for operational weather forecasts maintained by national meteorological services in several countries (Källén 1996). It covers northern Europe. Operationally, different local versions of the HIRLAM model are used, and in this study we use HIRLAM data provided by the Swedish Meteorological and Hydrological Institute, based on a forecast period of 6 to 11 hours. The horizontal grid resolution is 22.5 × 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 of the model and the simulations can be found 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 applied and compared two methods to extract the boundary-layer height from the HIRLAM output data; both are based on a bulk Richardson-number approach. 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) gives the bulk Richardson

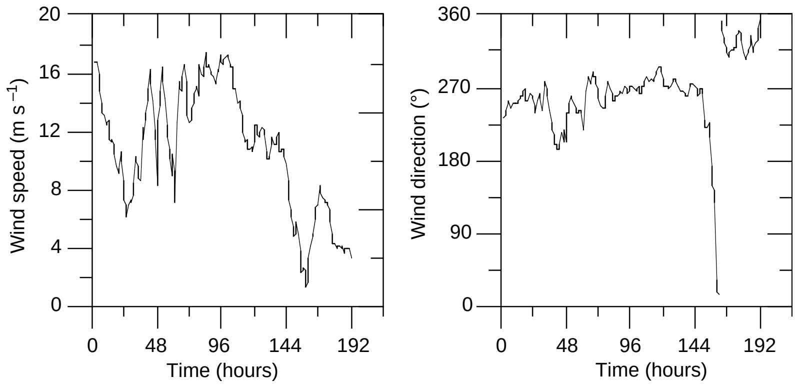

Fig. 2. Wind speed and direction at Christiansø from HIRLAM during the period 26 October to 3 November 1998. The time is shown in hours starting on midnight 25–26 October and ending on midnight 3–4 November (hour 216).

number for the layer between the surface and the height z above the surface by the following expression

$$Ri_B = \frac{gz\left[\theta(z) - \theta(s)\right]}{\theta(s)\left[u(z)^2 + v(z)^2\right]} \quad (1)$$

The quantities $\theta(s)$ and $\theta(z)$ are the potential virtual temperatures at 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 (30 m), and a term that accounts for surface friction has been added

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

where b is a parameterisation constant, recommended by Vogelezang and Holtslag (1996) to be taken as 100, and u_* the friction velocity. 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 the Richardson-number method.

The expressions treat differently the wind-velocity influence. In Eq. 1 the wind speed is taken at the given height. Eq. 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).

Simulations with the HIRLAM model

The wind speed and direction at 10 m predicted by the HIRLAM model at Christiansø during the experiment are shown in Fig. 2. In the beginning of the period the wind speed is very high, followed by moderate values at the end. Gryning and Batchvarova (2002) found that the HIRLAM

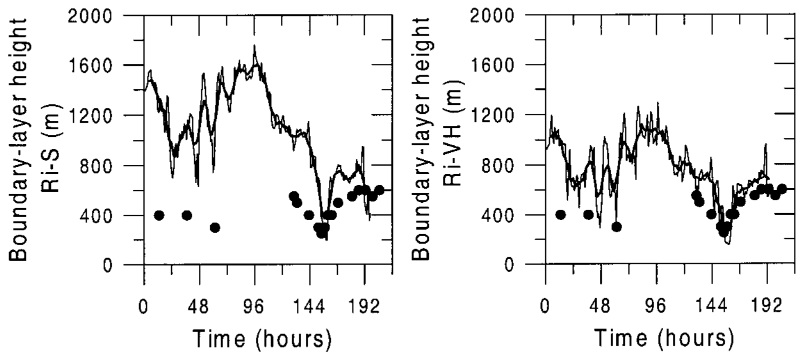

Fig. 3. Boundary-layer height over Christiansø during the observation period, estimated from the HIRLAM model (thin line). The results represent the HIRLAM grid point closest to Christiansø. The left panel shows the results using the Richardson number suggested by Sørensen (1998), the right panel when using the Richardson number in Vogelezang and Holtslag (1996). Bullets show marine boundary layer height derived from radiosonde measurements. Time indications as in Fig. 2. The thick lines illustrate a running mean over 9 points.

model overestimates the latent heat flux and predicts fairly well the sensible heat flux, friction velocity, wind speed and direction during the intensive observational period.

Two Richardson-number methods to extract the boundary-layer height from Numerical Weather Prediction (NWP) models simulations were applied to the hourly output from the HIRLAM model at a grid point 3 km west-northwest of Christiansø.

The result from the analysis using the Richardson number suggested by Sørensen (1998) is shown on the left panel in Fig. 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.

The right panel 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 substantially lower than on the left panel, but still overpredicts the boundary-layer height for the first part of the simulation where the wind passes over Bornholm before reaching Christiansø. There is fair agreement during the last part 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 m s^{-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 influences the boundary layer over Christiansø. The boundary-layer height that was estimated from the HIRLAM data is higher than the measured one, which suggests that the HIRLAM model did not resolve the meso-scale features that control the boundary-layer height over Christiansø.

During the last period of the experiment the wind was northerly. The water fetch to the nearest coast was about 100 km. For this case good agreement between measured and simulated boundary-layer heights was found for all the model simulations.

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. It is too coarse to reflect the mesoscale features that control the boundary-layer height over Christiansø when Christiansø is downwind of Bornholm. It seems to be adequate for northerly winds when Christiansø is downwind of the Swedish coast with a water fetch of 100 km or more.

Simulations with a high-resolution (2 km × 2 km) model of the boundary-layer height (Gryning and Batchvarova 1996, Batchvarova *et al*. 1999) reported by Gryning and Batchvarova (2002) reproduce the boundary-layer development over Christiansø during the whole observational period.

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) in accordance with the theoretical discussion in chapter 3. The difference is more pronounced during the higher wind-speed period. Both methods 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.

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