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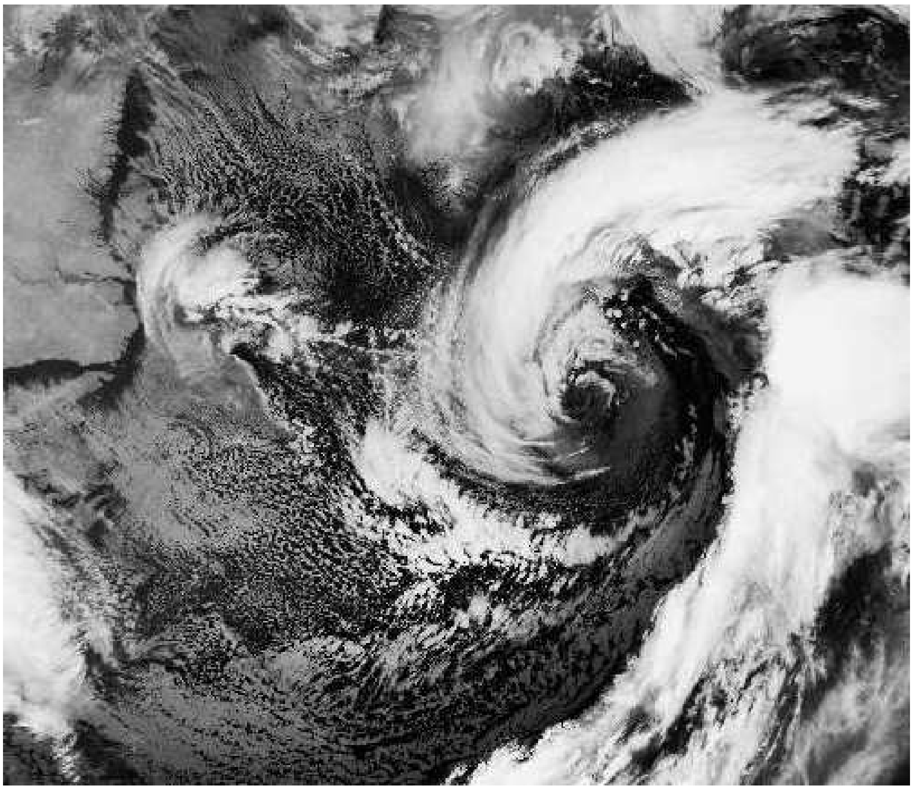
Niels Woetmann Nielsen, Claus Petersen and Bjarne Amstrup



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Authors:
Niels Woetmann Nielsen, Claus Petersen and Bjarne Amstrup

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Dansk Resume

Fordampning fra havoverfladen og overførsel af varme mellem luft og hav er vigtige processer for atmosfærens energibudget. Målinger fra Østersøen tyder på at navnlig fordampning fra havoverfladen under visse vejrforhold er større end man hidtil har regnet med. Det gælder når vinden er moderat til kraftig nær havoverfladen og temperaturfaldet fra hav til luft samtidig er lille. I rapporten beskrives hvordan dette vind- og temperaturregime er blevet implementeret i en eksperimentel version af DMI-HIRLAM og der vises verifikationsresulteter fra vejrmodel-kørsler for en vinterperiode.

Abstract

Evaporation from the sea and exchange of sensible heat between sea and air are imoportant processes for the energy budget of the atmosphere. Measurements in the Baltic indicate that the sensible heat transfer and in particular the evaporation in certain weather conditions are larger than anticipated. The enhanced surface fluxes occur in weather conditions with moderate to strong surface winds and weakly unstable stratification in the atmospheric surface layer. It is described how this regime has been implemented in DMI-HIRLAM and verification results for a winter period are shown.

Introduction

Recent measurements at the Östergarnsholm island in the Baltic have shown enhanced surface fluxes of sensible and latent heat from the sea in a weak unstably stratified surface layer with moderate to strong near-surface winds and a weak to moderate air-sea temperature difference. The present report describes how this ’unstable very close to neutral’ regime (UVCN regime) has been implemented in an experimental version of DMI-HIRLAM. Three tests have been performed. Firstly the algorithm was developed and tested in a one-dimensional version of DMI-HIRLAM. Secondly, the algorithm was implemented in DMI-HIRLAM-T15 and tested on a severe winter storm case over southern Scandinavia. Finally, a semi-operational test for an extended winter period was done on the DMI-HIRLAM-M15 domain (Yang et al., 2005). Verification against observations showed that both the operational model and the version including the UVCN regime was warmer than observed in the lower troposphere and had a warming trend with forecast lead time. The experiments were therefore repeated with modifications which had the effect of reducing the surface fluxes of heat and moisture in the unstably stratified surface layer over sea.

The UVCN regime algorithm has been developed to fit field measurements at a single location. A firm theoretical explanation for the UVCN regime is lacking at present. Therefore the implementation should be regarded as a first step in the process of representing this regime in DMI-HIRLAM. Future adjustments may be foreseen guided by a deeper theoretical understanding and more measurements and numerical experiments.

The front-page image is a combined NOAA15 channel 3,4 and 5 AVHRR image from 07.33 UTC on 11 December 2006. Cold air flowing from the North American Continent eastward over the North Atlantic has been warmed and moistened by the sea. In this process an extensive open cell cloud pattern has formed south and east of an intense surface low in the core of the spiraling clouds south of Iceland. UVCN-regime conditions (i.e. moderate to strong surface winds and weakly unstable stratification in the atmospheric surface layer) are likely to be present southeast and east of the surface low. The deep convection near the British Isles is probably influenced by rising motion in the large sale flow downstream of the upper trough above the mature surface low.

The UVCN regime

Turbulence flux measurements at the Östergarnsholm island in the Baltic have shown enhanced latent and sensible heat flux from the sea surface in the UVCN regime (Smedmann et al., 2005 and Sahlée et al., 2005). According to these measurements the UVCN regime is characterized by a Monin-Obukhov (MO) stability parameter $L < -150$ and a surface wind speed (at $10\,\mathrm{m}$ height) higher than $9\,\mathrm{m\,s^{-1}}$. No measurements have been taken at wind speeds higher than $14\,\mathrm{m\,s^{-1}}$. In Rutgersson et al. (2006) it is tentatively assumed that the exchange coefficients for sensible heat (C_h) and latent heat (C_e) at higher wind speeds in the UVCN regime have the same values as at $14\,\mathrm{m\,s^{-1}}$.

The exchange coefficients in the UVCN regime, estimated from measurements at Östergarnsholm, are (Rutgersson et al., 2006).

$$C_{h_{UVCN}} = \max\left[C_{h_{noUVCN}}, \left(\alpha_h\left(1-\frac{\Delta T}{\Delta T_h}\right)\frac{U-U_c}{U_c}\right)10^{-3}\right] \tag{1}$$

$$C_{e_{UVCN}} = \left(C_{e_{noUVCN}} + \alpha_e\left(1-\frac{\Delta T}{\Delta T_e}\right)\frac{U-U_c}{U_c}\right)10^{-3} \tag{2}$$

Here the equations are written in dimensionless form. In the referenced paper they are written in dimensional form and look quite different from (1) and (2). The reference height for U is 10 meter and $U_c = 9\,\mathrm{m\,s^{-1}}$ is a lower threshold value for the UVCN wind regime. $\Delta T = T_s - T_{10}$, where T_s is the sea surface skin temperature and T_{10} the temperature at $10\,\mathrm{m}$ height. The estimated threshold values for the temperature difference are $\Delta T_h = 7.88\,\mathrm{K}$ and $\Delta T_e = 3.73\,\mathrm{K}$ and the estimated dimensionless proportionality factors are $\alpha_h = 5.67$ and $\alpha_e = 2.79$. In the DMI-HIRLAM implementation $C_{h_{noUVCN}}$ and $C_{e_{noUVCN}}$ are the unmodified exchange coefficients obtained without taking into account the UVCN regime. In Rutgersson et al. (2006). the no-UVCN exchange coefficients refer to the algorithm derived from the Tropical Ocean Global Atmosphere (TOGA) Coupled Ocean-Atmosphere Response Experiment (COARE) (Fairall et al., 1996).

According to (1), $C_{h_{UVCN}} > 1.6\cdot 10^{-3}$ (the COARE algorithm neutral value at U=14 $\mathrm{m\,s^{-1}}$) at U=14 $\mathrm{m\,s^{-1}}$ for $\Delta T < 0.51\,\mathrm{K}$. But for $U < 10.76\,\mathrm{ms^{-1}}$, $C_{h_{UVCN}} < 1\cdot 10^{-3}$ even for $\Delta T = 0\,\mathrm{K}$, indicating that the UVCN regime for sensible heat flux is not well defined in terms of ΔT . However, according to (2), the latter is the case in the UVCN regime for moisture flux with a threshold value $\Delta T = \Delta T_e = 3.73\,\mathrm{K}$ for the temperature difference across the lowest $10\,\mathrm{m}$ of the marine atmosphere. If the COARE algorithm is applied in the no-UVCN regime (with $C_{e_{noUVCN}} = 1.09\cdot 10^{-3}$) the maximum values for $C_{h_{UVCN}}$ and $C_{e_{UVCN}}$ are $3.15\cdot 10^{-3}$ and $2.55\cdot 10^{-3}$, respectively.

In numerical models use of equations like (1) and (2) are impractical. Instead enhancement of C_h and C_e can be obtained by modifying the roughness lengths for temperature (z_{0T}) and moisture (z_{0E}). For the UVCN regime Rutgersson et al. (2006) has suggested to add

$$z_{0T_{UVCN}} = \min\left(\exp(2.19\ln\left(\frac{L^2 Re}{|L_{lim}|}\right) - 24.0), 1.5\cdot 10^{-2}\right) \tag{3}$$

$$z_{0E_{UVCN}} = \min\left(\exp(3.73\ln\left(-LRe\right) - 36.0), 6.0\cdot 10^{-3}\right) \tag{4}$$

to the original roughness lengths, i.e. to the roughness lengths valid without any UVCN regime. The UVCN roughness lengths in (3) and (4) are functions of L and the surface Reynolds number Re defined by $Re = \frac{u_* z_{0m}}{\nu}$. Here u_* is the surface friction velocity, z_{0m} the momentum roughness length and ν the molecular kinematic viscosity. In (3) L_{lim} is the upper limit for the UVCN regime in terms of L. Analysis of field measurements indicate $L_{lim} \approx -150$. Since no measurement data in the UVCN regime have been taken for wind speeds above $14\,\mathrm{m\,s^{-1}}$ the maximum values $z_{0T_{UVCN}} = 1.5\cdot 10^{-2}$, m and $z_{0E_{UVCN}} = 6.0\cdot 10^{-3}\,m$ obtained from the measurements (Rutgersson et al., 2006) are utilized as upper limits in the UVCN regime.

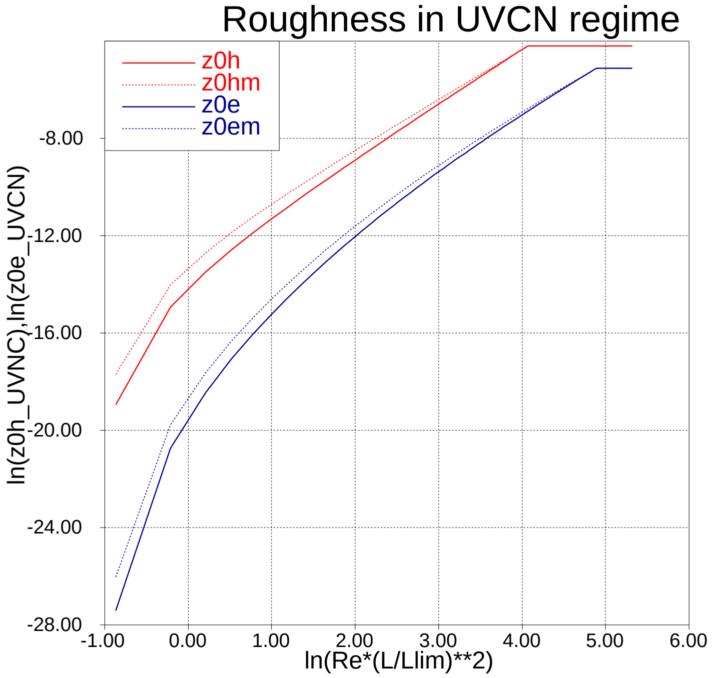

Figure 1: Logarithmic plot of additional roughness lengths for temperature $\mathrm{z_{0T_{UVCN}}}$ and moisture $\mathrm{z_{0E_{UVCN}}}$ in the UVCN regime versus the logarithm of the dimensionless number $\mathrm{Re} \cdot (\mathrm{L}/\mathrm{L_{lim}})^2$. Full curves (z0h and z0e) show results from equation (3) and (4) and dotted curves (z0hm and z0em) show results from equation (5) to (7).

Implementation of the UVCN regime in DMI-HIRLAM

In the implementation in DMI-HIRLAM (3) and (4) has been replaced by

$$
\begin{aligned}
z_{0T_{UVCN}} &= -a_T \cdot L \cdot Re^2 \left(\frac{L}{L_{lim}}\right)^3 && (5)\\
z_{0E_{UVCN}} &= \min\left(a_E \cdot Re^{3/2}\left(\frac{L}{L_{lim}}\right)^{-1/2} \cdot z_{0T_{UVCN}}, 6.0 \cdot 10^{-3}\right) && (6)\\
z_{0T_{UVCN}} &= \min\left(-a_T \cdot L \cdot Re^2 \left(\frac{L}{L_{lim}}\right)^3, 1.5 \cdot 10^{-2}\right). && (7)
\end{aligned}
$$

In (5) $a_T = \exp(-17.289)$ and in (6) $a_E = \exp(-4.284)$. The modification has been done to avoid multiple use of the exponential function. Figure 1 shows that the difference between the roughness lengths calculated by (3) and (4) and (5) to (7), respectively, is small and decreases with both increasing Re and increasing $|L|$. The small increase in roughness lengths leads to a negligible increase in the exchange coefficients for sensible heat and moisture in the UVCN regime as shown in Figure 2. The variation of L in Figure 1 and 2 has been done by keeping a fixed value of θ_* (the temperature analogue to u_*) and stepwise incrementing u_*. From (5) and (7) follows

$$
\left(\frac{L_{max}}{L_{lim}}\right)_T = \left(\frac{z_{0Tm}}{|L_{lim}| \cdot a_T}\right)^{1/4} \cdot Re^{-1/2} \approx 7.54 \cdot Re^{-1/2}. \qquad (8)
$$

In the same way (6) yields

$$\left(\frac{L_{max}}{L_{lim}}\right)_E = \left(\frac{z_{0Em}}{|L_{lim}| \cdot a_E \cdot a_T}\right)^{2/7} \cdot Re^{-1} \approx 26.32 \cdot Re^{-1}. \tag{9}$$

The limit values z_{0Tm} and z_{0Em} for the UVCN modified roughness lengths are the same as in (6) and (7), i.e. $z_{0Tm} = 1.5 \cdot 10^{-2}\, m$ and $z_{0Em} = 6.0 \cdot 10^{-3}\, m$. L_{max} is the magnitude of L at which the limit value z_{0Tm} or z_{0Em} is obtained. Equations (8) and (9) show that above a certain Re, (different for heat and moisture, the maximum values of $z_{0T_{UVCN}}$ and $z_{0E_{UVCN}}$ are obtained at $L = L_{lim}$.

In DMI-HIRLAM $z_{0T_{noUVCN}}$ and $z_{0E_{noUVCN}}$ are calculated as follows:

$$z_{0T_{noUVCN}} = \frac{z_{0m}}{\exp(\alpha_H Re^{1/4} - 2.0)} \tag{10}$$

$$z_{0E_{noUVCN}} = \frac{z_{0m}}{\exp((\alpha_H - \alpha_Q) Re^{1/4} - 2.0)}, \tag{11}$$

where $\alpha_H = 0.05 f(u) + 2.43$, $\alpha_Q = -0.50 f(u) + 0.70$ and $f(u)$ is an interpolation function, defining the transition between a smooth and rough sea. The smooth regime ($f(u) = 0$) ends at $u = 3\,\mathrm{m\,s^{-1}}$ and the rough regime ($f(u) = 1$) begins at $u = 5\,\mathrm{m\,s^{-1}}$. In DMI-HIRLAM u is the wind speed at the lowest model level.

In the surface scheme (ISBA) in HIRLAM a bulk Richardson number Ri_b is applied as stability parameter instead of $\frac{z}{L}$. The two stability parameters are related by

$$Ri_b = \frac{z}{L} \frac{\ln \frac{z}{z_{0h}} - \psi_h}{\left(\ln \frac{z}{z_{0m}} - \psi_m\right)^2}. \tag{12}$$

In the unstably stratified surface layer

$$\psi_m \approx \ln\left[\left(\frac{1+x^2}{2}\right)\left(\frac{1+x}{2}\right)^2\right] - 2\tan x^{-1} + \frac{\pi}{2} \tag{13}$$

$$\psi_h \approx 2\ln\left(\frac{1+x^2}{2}\right) \tag{14}$$

and $x = \left(1 - 15\frac{z}{L}\right)^{1/4}$.

Figure 3 compares Ri_1 calculated from (12) with Ri_2 obtained by ignoring ψ_m and ψ_h in this equation. The small difference between Ri_1 and Ri_2 justifies use of the much simpler Ri_2 in the UVCN regime.

However, it is a problem that L calculated from Ri_2 depends strongly on z_{0h}. The latter may differ from the non-UVCN regime value by several orders of magnitude. If L is calculated from Ri_2 by using the non-UVCN value of z_{0h} its numerical value becomes smaller in the UVCN regime than if the UVCN-modified (and larger) z_{0h} is used.

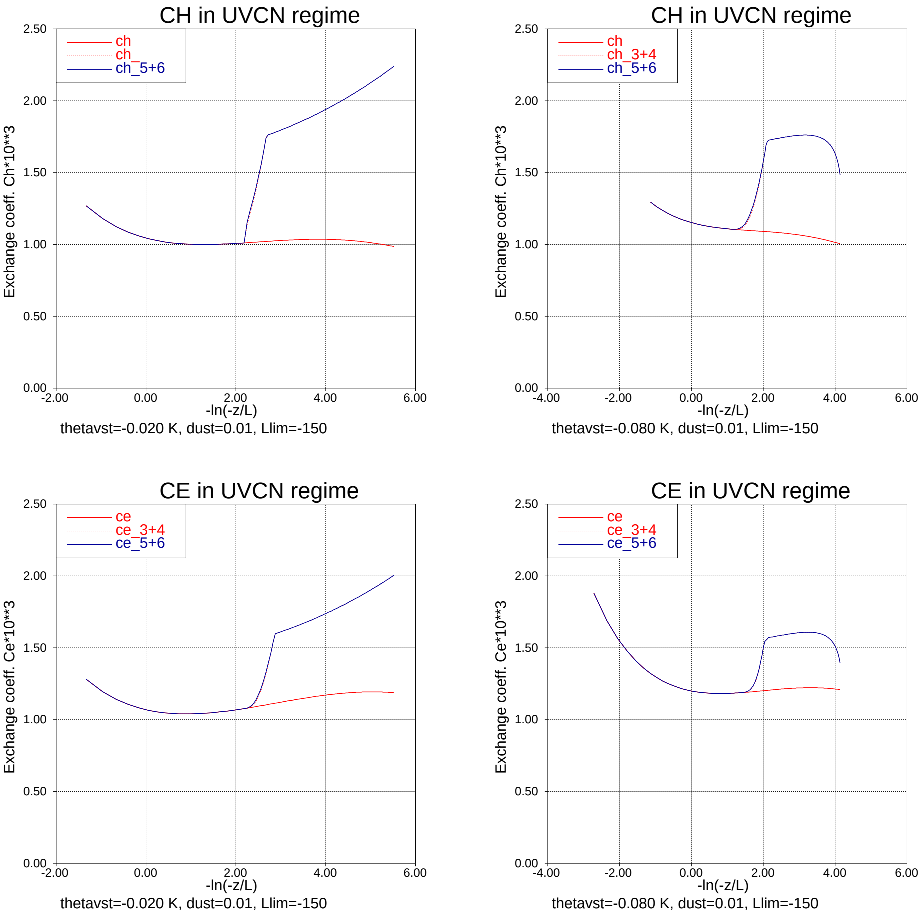

Figure 2: Plots of exchange coefficients for sensible heat (C_h) and moisture (C_e) as function of -ln($-z/L$) for the unstably stratified surface layer over sea. Full red curves show results without the UVCN regime (equations (10) and (11)) and dotted red curve and full blue curve show results with the UVCN regime included from (3) and (4) and (5) to (7), respectively. Note that the latter two curves are practically on top of each other. Left and right column is for $\theta_* = -0.02\,\mathrm{K}$ and $\theta_* = -0.08\,\mathrm{K}$, respectively. Note that the neutral limit is in the direction of increasing values on the horizontal axes.

It appears to be most appropriate to implement the UVCN regime at the place in the surface scheme where the surface exchange coefficients are calculated (i.e. in subroutine "surcof-sea"). Because of the problem mentioned above it was decided not to calculate L from Ri_2 (equation (10)), but instead calculate L from parameters passed to "surcof-sea". Since

$$L = \frac{\theta_0}{kg} {u_*}^3 \left(\frac{H_V}{\rho c_p} \right)^{-1} \tag{15}$$

this was done by using the following approximate relation for virtual heat flux H_V:

$$H_V \approx H + 0.61 \theta_0 \frac{c_p}{L_v} H_L, \tag{16}$$

where $H = \rho c_p u_* \theta_*$ and $H_L = \rho L_v u_* q_*$ is the surface sensible and latent heat flux, respectively. Note that the sign convention used here is such that flux from sea/land to air is counted negative. Parameter q_* is the specific humidity analogue to u_* and θ_*, c_p is specific heat of air at constant

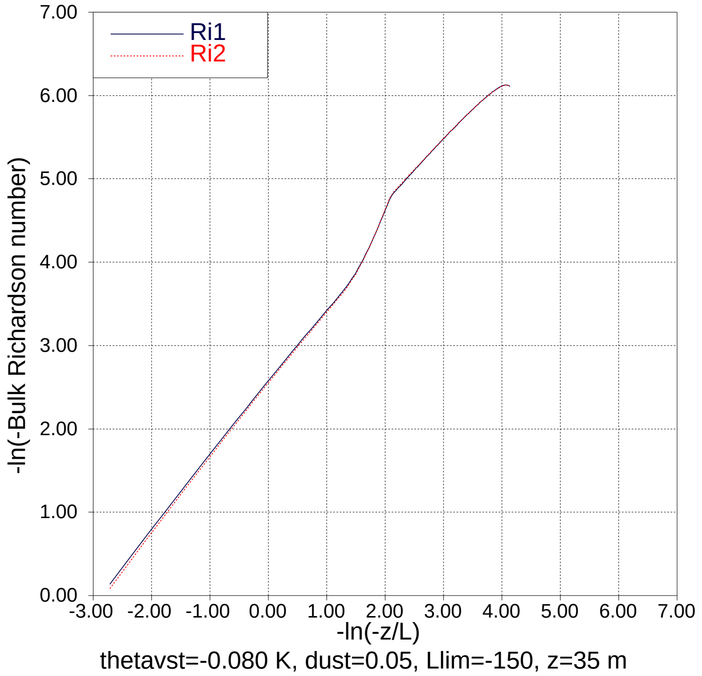

Figure 3: Logarithmic plot of the bulk Richardson number versus the Monin-Obukhov stability parameter. Ri_1 is the bulk Richardson number obtained from (12) to (14) and Ri_2 is the same number obtained by ignoring $\psi_m$and ψ_h in (12). Note that the neutral limit is in the direction of increasing values on the horizontal axis.

pressure, L_v is latent heat of vaporization and ρ and θ_0 is density and potential temperature of near-surface air, respectively.

The roughness length for momentum (z_{0m}) is not directly affected in the UVCN regime. As previously it is calculated by using Charnok's relation for a rough sea ($f(u) = 1$) and using a constant surface Reynolds number $Re_c = 0.11$ for a smooth sea ($f(u) = 0$)

$$z_{0m} = (1 - f(u))\frac{Re_c \nu}{u_*} + f(u)\beta\frac{{u_*}^2}{g}, \tag{17}$$

with $\beta = 0.014$ for open sea and $\beta = 0.032$ for coastal waters. Charnok's relation is an acceptable approximation for a well developed sea, but less accurate for a growing sea or a sea dominated by swells (Nielsen, 2003).

A gradual transition to the UVCN regime is obtained by defining $fi = fu \cdot ft \cdot fl$, where

$$fu = \left(\max\left(\min\left(\frac{U - U_c}{2}, 1\right), 0\right)\right)^{1/2} \tag{18}$$

$$ft = \max\left(\min\left(\frac{\Delta T + 3.5}{2}, 1\right), 0\right) \tag{19}$$

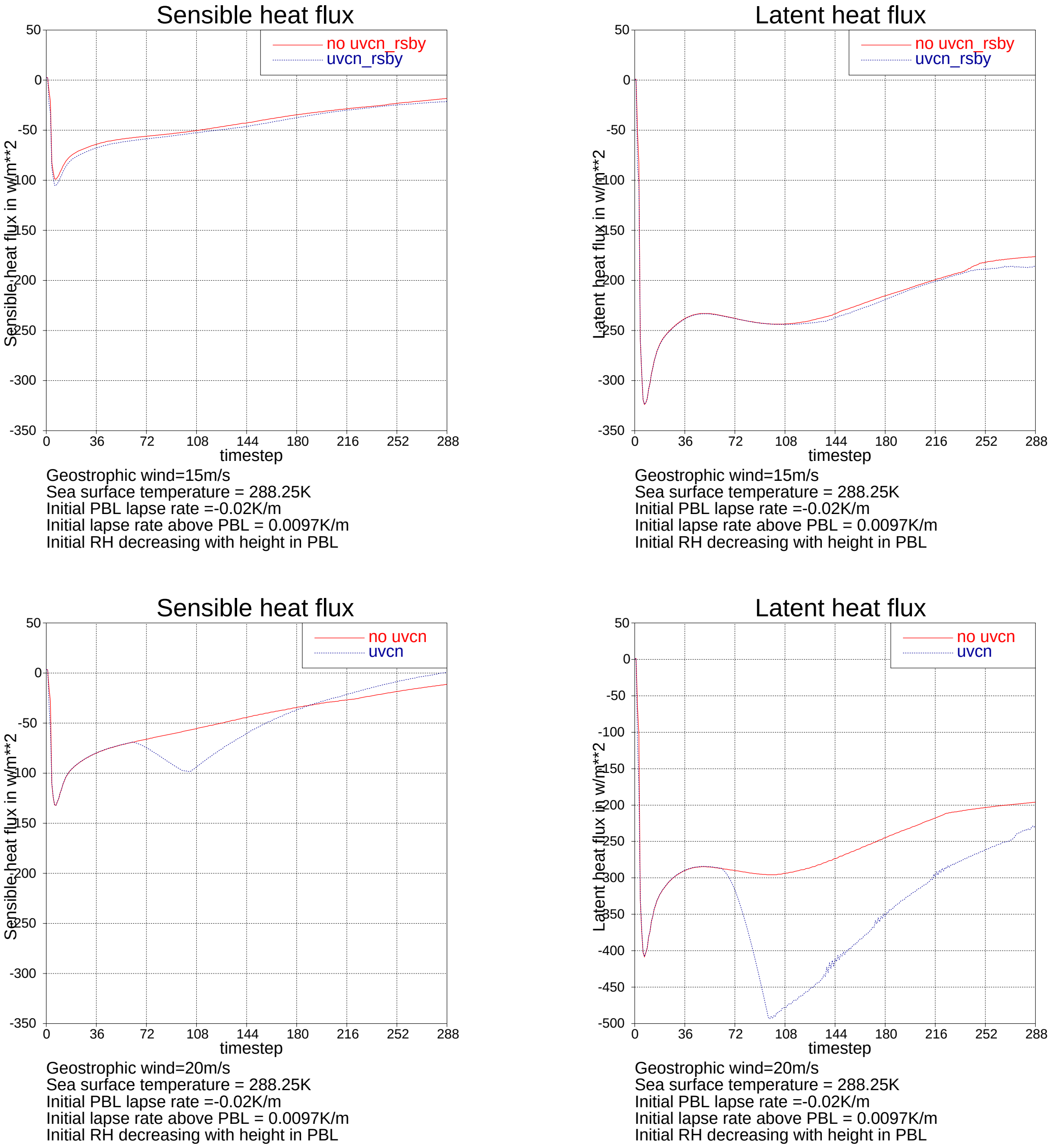

Figure 4: Sensible (left) and latent (right) heat flux at the sea surface in a developing, unstably stratified, marine boundary layer forced by a constant geostrophic wind and a constant sea surface temperature. Red and blue curves show results without and with the UVCN regime included. The geostrophic wind speed is $15\,\mathrm{m\,s^{-1}}$ and $20\,\mathrm{m\,s^{-1}}$ in the upper and lower row, respectively. See text for further details.

$$fl = \max\left(\min\left(\frac{|L|-100}{200},1\right),0\right) \tag{20}$$

and calculating the total roughness lengths from (21) and (22)

$$z_{0T} = z_{0T_{noUVCN}} + fi \cdot z_{0T_{UVCN}} \tag{21}$$

$$z_{0E} = z_{0E_{noUVCN}} + fi \cdot z_{0E_{UVCN}} \tag{22}$$

One-dimensional test

The UVCN regime implementation has been tested in a one-dimensional version of DMI-HIRLAM (1D-HIRLAM). Two hypothetically, highly non-steady cases were chosen. They differed only with respect to the magnitude of a constant in time geostrophic wind V_g, which was set to $15\mathrm{m\,s^{-1}}$ in one case and to $20\mathrm{m\,s^{-1}}$ in the other case. The test cases also had a constant in time sea surface temperature $T_{sea} = 288\,\mathrm{K}$. Furthermore, the initial state of the atmosphere was specified in such a way that the evolving marine surface layer entered the UVCN regime and/or its transition zone during the 24 hour runs. This was done by specifying a rather large initial lapse rate of $-0.02\,\mathrm{K\,m^{-1}}$ in the boundary layer (PBL) and a stable stratification of $0.0097\,\mathrm{K\,m^{-1}}$ above the PBL. The initial relative humidity decreased with height in the PBL.

The results for the surface fluxes of sensible and latent heat due to turbulence are shown in Figure 4. In the first test case (Figure 4, upper row) the PBL only entered the transition zone between the UVCN and no-UVCN regime. Therefore the surface fluxes are only numerically a little higher in the UVCN run than in the no-UVCN run. In the second run (Figure 4, lower row) the increased geostrophic wind speed drives the PBL into the UVCN regime. This leads to a much larger increase in the magnitude of the fluxes in the UVCN run. In the last part of the run the sensible heat flux becomes numerically smallest in the UVCN run due to a history of larger warming of the near-surface air by the surface sensible heat flux. The large spin-up at the beginning of the runs is due to an inertial oscillation generated by the initial imbalance occurring when model physics suddenly is switched on.

Three-dimensional test

The implementation of the UVCN regime in DMI-HIRLAM-T15 (Yang et al., 2005) was tested on a severe storm case over southern Scandinavia, occurring on 8 January 2005. Results at 18 hour forecast lead time are shown in Figure 5. The upper row of this figure shows that the predicted surface latent heat flux in the reference (no-UVCN) run is negative (i.e. from sea/land to air) south of the surface low over Scandinavia with fairly large negative values (between - 200 $\mathrm{W\,m^{-2}}$ and - 400 $\mathrm{W\,m^{-2}}$) upstream over the North Sea and the Atlantic west of the British Isles. In contrast the sensible heat flux is positive and fairly large south and downstream of the low. Upstream over the North Sea and the Atlantic west of the British Isles the sensible heat flux is generally negative, but numerically smaller than the latent heat flux, typically by a factor of 2 or more. The bottom row shows the difference in latent and sensible heat flux between the UVCN and reference run. The difference in latent heat flux is generally larger than the difference in sensible heat flux. The difference is small (between - 15 $\mathrm{W\,m^{-2}}$ and 15 $\mathrm{W\,m^{-2}}$) over most of the area. Fairly large and mostly negative (up to about - 200 $\mathrm{W\,m^{-2}}$) differences are seen over parts of the sea surrounding the British Isles. Over these parts the marine surface layer is in the transition zone to or in the UVCN regime. Regions with positive differences are seen downstream of areas with negative values.

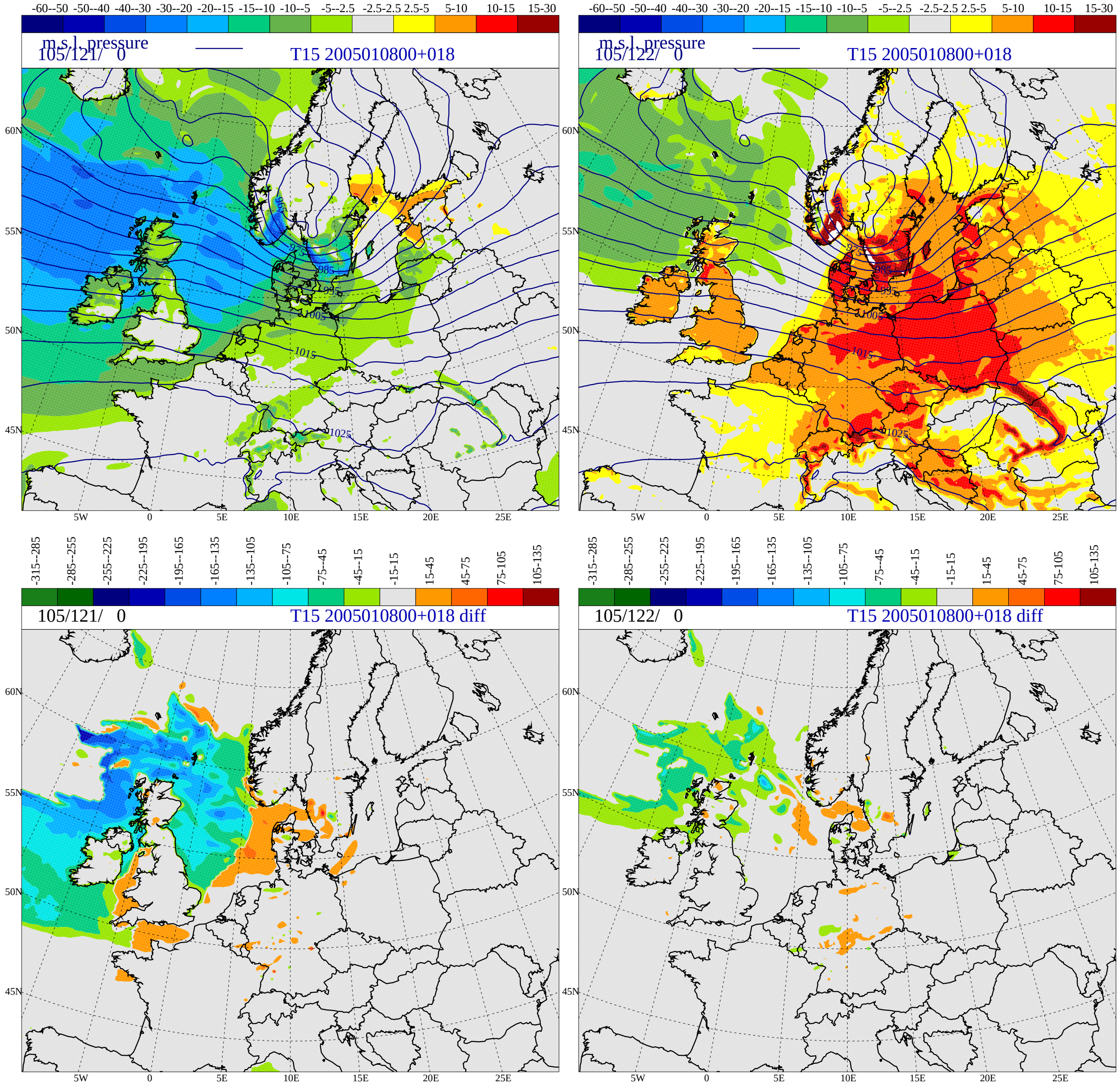

Figure 5: Upper row shows 18 hour forecasts of latent (left) and sensible (right) heat flux at the surface. The bottom row shows corresponding surface heat flux differences between the UVCN and no-UVCN runs. Note that the numbers on the color scale in the upper row must be multiplied by 10 to get the flux in W m $^{-2}$.

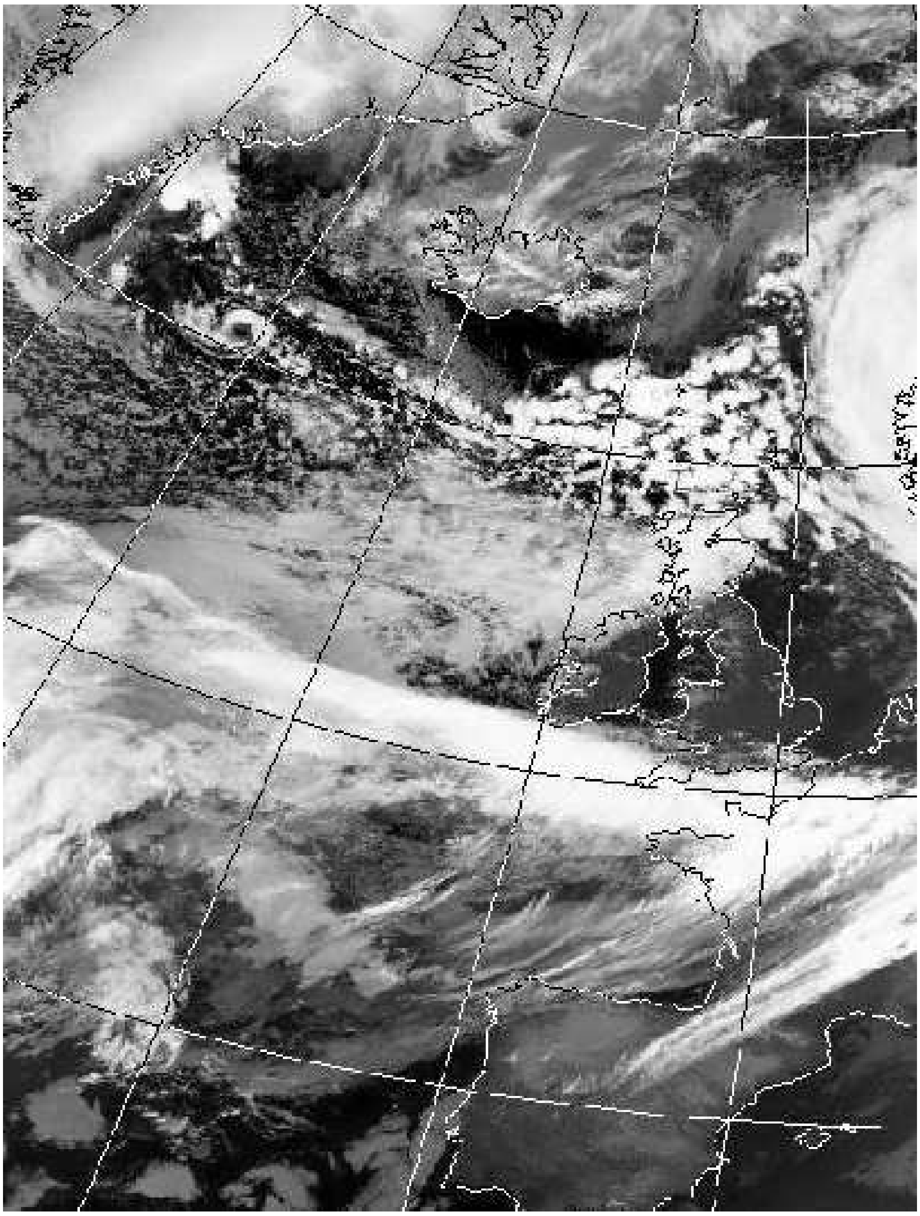

Figure 6: NOAA-12 infrared (channel 5) AVHRR satellite image from 17.04 UTC on 8 January 2005, approximately at the valid time of the forecasts shown in Figure 5. Fairly deep convection is present in regions over sea with forecasted enhanced latent heat flux (Figure 5, bottom row, left). Courtesy Dundee Satellite Receiving Station (www.sat.dundee.ac.uk).

Non-UVCN modifications to HIRLAM

Two modifications have been made to DMI-HIRLAM. They contribute to a reduction in surface fluxes of sensible and latent heat over sea. First a modification has been done in the stability function applied in DMI-HIRLAM in the unstably stratified surface layer over sea. This stability function has the form

$$f_\gamma = 1 + \frac{a_\gamma \cdot Ri}{1 + b_\gamma \cdot c_\gamma \cdot C_{\gamma N}(Ri \cdot z/d_\gamma)^{1/2}}, \tag{23}$$

where $\gamma = M, H$ and Q is the stability function for momentum, heat and moisture, respectively. The length scale d_γ is

$$d_\gamma = \left(\delta_H \cdot Pr^{-2/3} \cdot e_\gamma\right)^2 \cdot \nu/u_{FC}, \tag{24}$$

in which $\delta_H \approx 0.17$, ν is the molecular kinematic viscosity of air, $Pr = \nu/\kappa_H$ is the Prandtl number, κ_H is the molecular thermal diffusivity of air, $e_M = 7.5 \cdot Pr^{4/3}$, $e_H = e_Q = 5$, and u_{FC} is a free convection velocity scale, defined by

$$u_{FC} = \left(\frac{g}{\theta_v} \cdot \Delta\theta_v \cdot \nu\right)^{1/3}. \tag{25}$$

The first modification only affects f_H and f_Q.

In the operational DMI-HIRLAM $C_{HN} = C_{QN} = C_{MN}$, $a_H = a_Q = 15$, $b_H = b_Q = 75$ and c_H=$c_Q = 0.9855$. However, to be consistent with (24) and (25) $C_{\gamma N}$ in (23) whould read $c_\gamma = 1$ and

$$C_{\gamma N} = C_{MN}\left(1 + \ln\frac{z_{0M}}{z_{0\gamma}} / \ln\frac{z}{z_{0M}}\right)^{-1} \tag{26}$$

This consistency has been reintroduced and $c_H = c_Q$ has been given the value of 2 (instead of 0.9855). The combined effect is to decrease the surface fluxes of heat and moisture in the unstably stratified marine atmospheric boundary layer.

The second modification is in the calculation of the roughness lengths for heat (z_{0h}) and moisture (z_{0q}) over sea. In DMI-HIRLAM these are related to the momentum roughness z_{0m} by

$$\ln\frac{z_{0m}}{z_{0h}} = \alpha_h \cdot Re^{1/4} - 2 \tag{27}$$

and

$$\ln\frac{z_{0m}}{z_{0q}} = \ln\frac{z_{0m}}{z_{0h}} - \alpha_q \cdot Re^{1/4}. \tag{28}$$

Recall that $Re = \frac{z_{0m}u_*}{\nu}$ is the surface roughness Reynolds number and u_* is the surface friction velocity. In experiment M1M (see next section) the constant of proportionality in α_h has been changed from 0.05 in DMI-HIRLAM to 0.92 and correspondingly the proportionality factor in α_q has been changed from -0.5 to -0.08. These changes imply a reduction in the heat and moisture roughness for a rough sea. Both the changes in α_h and α_q and $C_h = C_q = 2$ applied in M1M have been used in the Rossby Center climate model at SMHI (Swedish Meteorological and Hydrological Institute) (Rutgersson, personal communication).

Extended winter period tests with data assimilation

Figure 7 and Figure 8 show EWGLAM station list verification results from 4 experiments. Corresponding surface parameter verification results for Danish observation sites are shown in Figure 9. The UVCN-regime enhances the latent heat flux and to a lesser degree also the sensible heat flux at the ocean surface. The impact on verification scores over Europe are seen in Figure 7 and Figure 8. The runs M1A and M1R are with and without the UVCN regime included in DMI-HIRLAM, run on the domian DMI-HIRLAM-M (Yang et al., 2005, which is a subdomain of DMI-HIRLAM-T. For the considered 1-month winter period the UVCN regime leads to an increase in the negative mean sea level pressure(mslp) bias. The rms error also increases a little due to the increase in magnitude of the mslp bias. The 2-meter temperature (T2m) and the temperature at 850 hPa (T850) are also affected. A cooling of T2m in the first hours of the forecasts is followed by a warming trend (i.e. here a less negative bias with increasing forecast lead time) which is largest in the UVCN-regime run (M1A). For the same reason the rms error is a little smaller in M1A than in the operational-like run M1R. The T850 bias is positive and has the largest warming trend in M1A, while the rms error is almost identical in the two versions. This indicates that the st.dev. error is lowest in M1A. The effect of the UVCN-regime on the other parameters shown in Figure 7 is generally marginal, although M1O has a smaller negative bias and a slightly smaller rms error of the geopotential height of the pressure surfaces, particularly 500 hPa. If the non-UVCN modifications are added to the UVCN modifications (run M1O) the verification results generally become close to those for the operational-like run (M1R), except for somewhat warmer T850 (in between the results for M1A and M1R).

In Figure 8 the verification results for M1A and M1R are compared with results from M1M, which is the operational-run like modified by the changes listed in the previous section (i.e. the non-UVCN modifications). M1M has the coldest T2m bias, the largest rms errors at 500 hPa and 250 hPa for geopotential height and at 850 hPa and 500 hPa for temperature. On the beneficial side this run has the smallest negative mslp bias and the smallest positive T850 bias.

The verification of surface parameters against observations in Denmark (Figure 9) shows similar results with a more negative mslp bias and a less negative T2m bias in the UVCN run (M1A). In addition an effect on the wind speed at 10 m height (W10m) is also seen. The UVCN run has a smaller positive wind bias than the operational-like run (Figure 9, upper row, right). If the non-UVCN modifications are added (M1O) the W10m bias becomes almost identical to that for the operational-like run M1R (Figure 9, lower row, right) and if the non-UVCN modifications are added to the operational-like model (as in M1M) the W10m bias becomes larger than in the operational-like run.

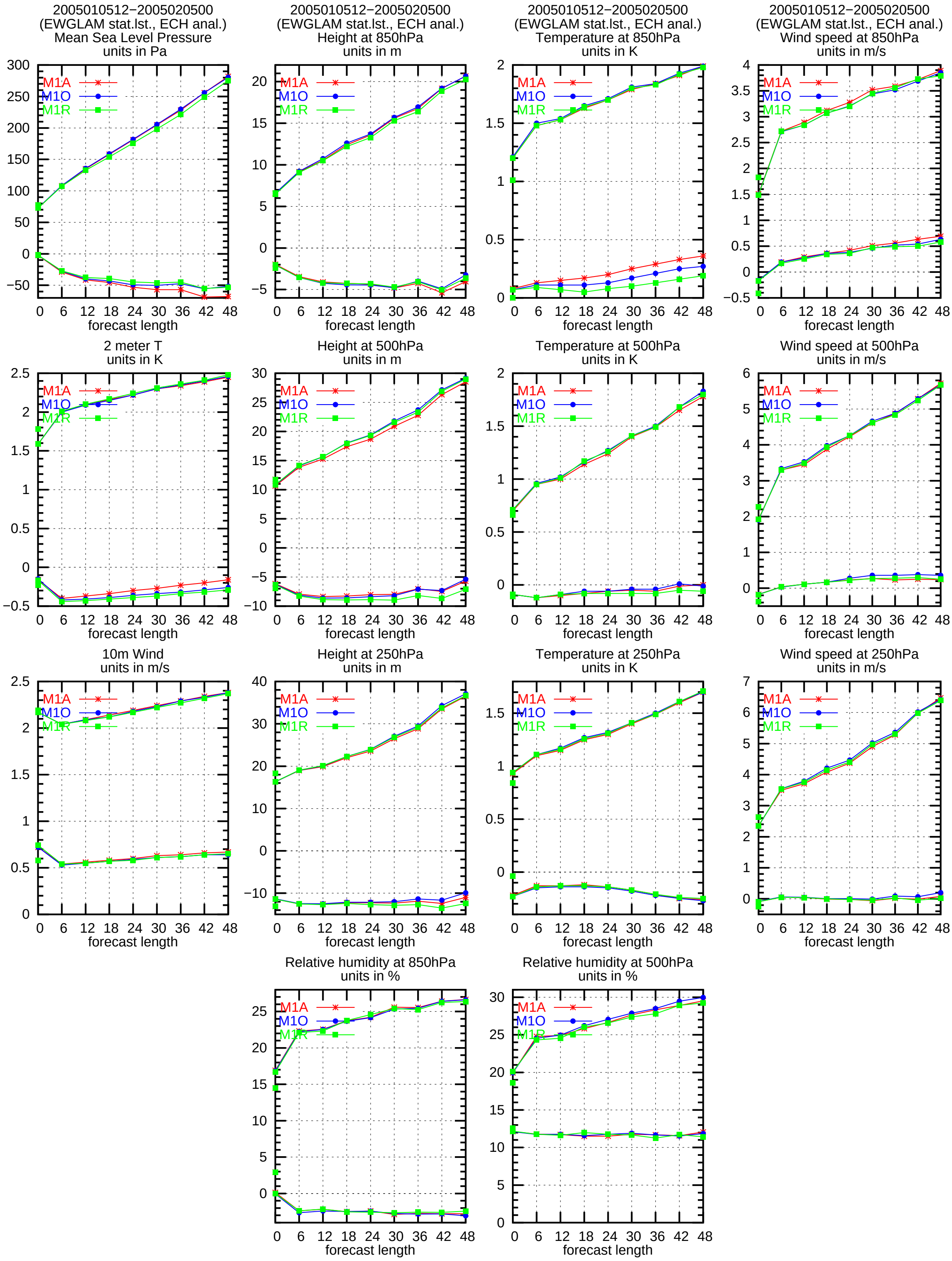

Figure 7: EWGLAM station list verification results for the period 5th January to 5th February 2005. Lower and upper curves show bias and root mean square error (rms), respectively M1R is for the operational-like DMI-HIRLAM-M, M1O is for DMI-HIRLAM-M with inclusion of the UVCN-regime and reduced surface fluxes of sensible and latent heat in the unstably stratified marine boundary layer. M1A is for DMI-HIRLAM-M with inclusion of the UVCN regime.

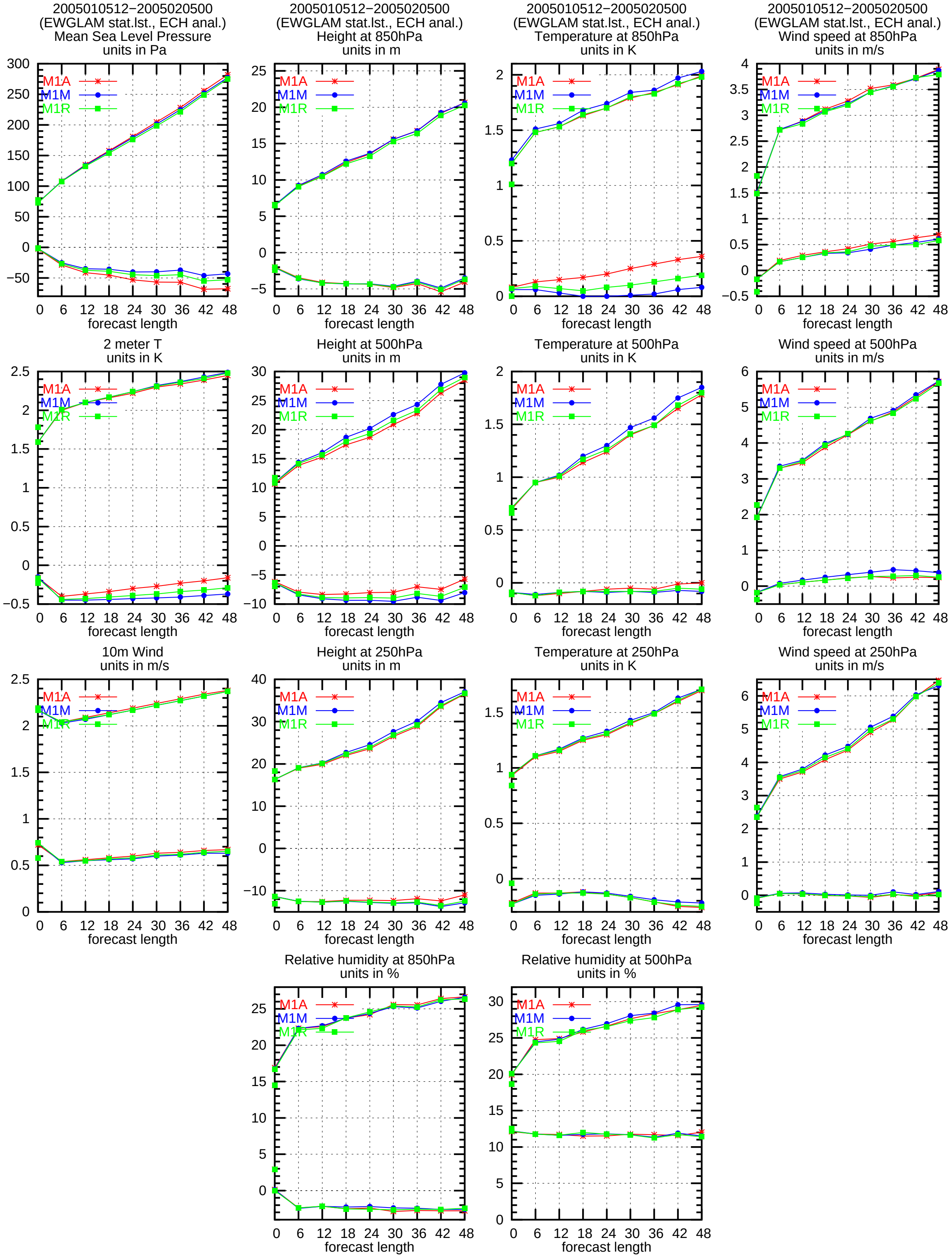

Figure 8: EWGLAM station list Verification results for the period 5th January to 5th February 2005. Lower and upper curves show bias and root mean square error (rms), respectively. M1R is for the operational-like DMI-HIRLAM-M, M1M is for DMI-HIRLAM-M with reduced surface fluxes of sensible and latent heat in the unstably stratified marine boundary layer and M1A is for DMI-HIRLAM-M with inclusion of the UVCN regime.

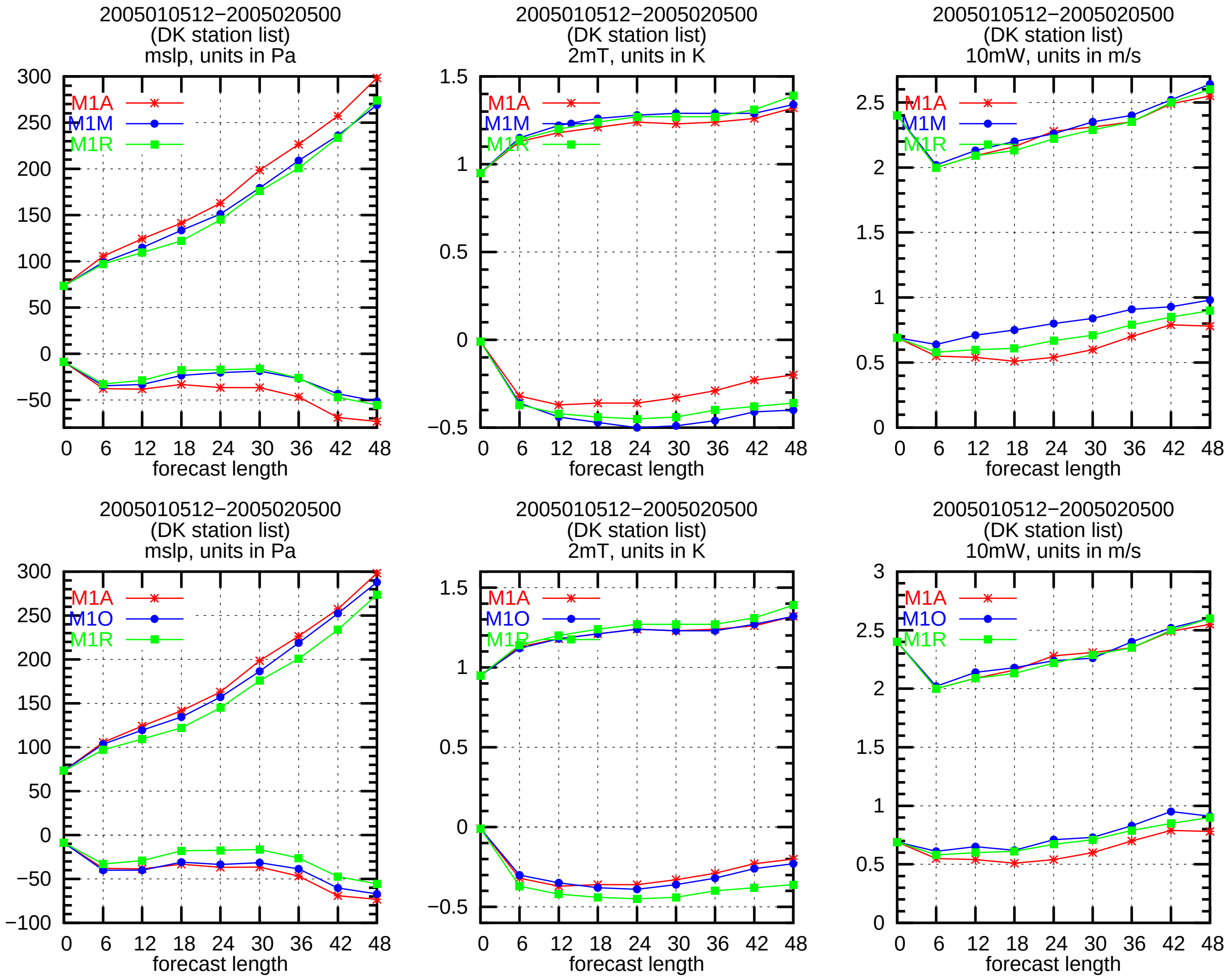

Figure 9: Denmark station list verification results for the period 5th January to 5th February 2005. Lower and upper curves show bias and root mean square error (rms), respectively. M1R is for the operational-like DMI-HIRLAM-M, M1O is for DMI-HIRLAM-M with inclusion of the UVCN-regime and reduced surface fluxes of sensible and latent heat in the unstably stratified marine boundary layer, M1A is for DMI-HIRLAM-M with inclusion of the UVCN regime and M1M is for DMI-HIRLAM-M with reduced surface fluxes of sensible and latent heat in the marine boundary layer.

Concluding remarks

It has been demonstrated that enhancement of the surface fluxes of sensible and latent heat over the ocean in an atmospheric surface layer with weakly unstable stratification and moderate to strong surface winds, the so-called UVCN-regime, in DMI-HIRLAM leads to a weak warming of the lower troposphere and a weak decrease in surface pressure over Europe. A warming of the lower troposphere connected with a decrease in surface pressure is in agreement with quasi-geostrophic reasoning. The verification results holds for a typical winter month with prevailing westerly flow over the North Atlantic upstream of Europe. During summer the occurrence of the UVCN-regime is less frequent due to weaker winds and absence of cold air masses over the continents. The impact of the UVCN-regime is therefore expected to be negligible during summer. The operational-like model runs have a weaker warming of the lower troposphere and a slightly less negative mslp bias than the UVCN runs. This might indicate that the latent and sensible heat flux over the North Atlantic in the operational-like model is larger than in reality, but smaller than in the UVCN runs. A general reduction of the surface heat fluxes over the ocean in case of unstable stratification (the non-UVCN modifications) was therefore introduced in the operational-like model as well as in the UVCN version. Both these model runs (M1M and M1O, respectively) showed a decrease in the warming of the lower troposphere and a decrease in the negative mslp bias. In the M1M runs the T850 bias was close to zero.

Although the inclusion of the UVCN-regime in DMI-HIRLAM has a positive impact on some of the verification parameters (such as geopotential height) it can not be recommended to include this regime in its present form due to the resulting warming trend in the lower troposphere. An improved formulation requires a deeper theoretical understanding and measurements at more locations. However, it could be considered to include the non-UVCN modifications operationally, but since these modifications have an effect in all seasons more tests (and possible tunings) are necessary.

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