Re-stating the PBL parameters in off-line dispersion models

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Motivation: off-line dispersion modelling

- No direct connection between dispersion and NWP models
- pro-s
  - multiple dispersion runs are cheap (no need to rerun NWP)
  - possibility for multi-NWP-input
  - easier model development (smaller code, simpler portability issues, etc)
  - no influence of simplifications in one model to another one
- contra-s
  - no possibility for feedback to NWP
  - internal NWP variables are not accessible
  - limitations on input data size force compromises on accuracy and level of details
- Necessity for special module: meteorological pre-processor

Motivation: meteorological pre-processor

- Prepares meteorological input data for dispersion model
  - extra variables, non-existing in the input files
  - checking/restating the governing equations – as they are in the dispersion model
  - enhanced resolution in time and/or space
- Varying levels of complexity
  - simple interpolation & range-checking
  - sophisticated algorithms – up to own assimilation of meteorological observations and recomputation of dynamic equations (MM5)

Motivation: boundary layer parameters

- Numerous approaches to parameterization
- Specific variables and equations vary from model to model and even from run to run
- Most of ABL parameters are not explicitly validated in NWP models and not available in the output files
- Result: practically all dispersion models include re-stating the ABL basic parameters in their meteorological pre-processor

Problem statement

- Available: profiles of basic meteorological variables: wind $\vec{u}$, temperature *T,* humidity *q*
- Find: basic ABL parameters: temperature, velocity and humidity scales *T, u*, q**, Monin-Obukhov length *L*, profile of some characteristic of turbulence, e.g. K_Z – if K-theory is used
- Verification possibility: consistency checking via comparison of sensible and latent heat fluxes H_S, H_l

Problem solution(1)

- Closure equation obtained from M-O similarity consideration (Berlyand & Genikhovich, 1971):

$$\sqrt{TKE}\,\frac{d}{dz}\left(\frac{K_z}{TKE}\right) = \kappa\, c_{\varepsilon}^{0.25}\,\Phi(\zeta)$$

- For practical applications, $\Phi = 1$; it corresponds to a differential expression combining the eddy diffusivity and TKE
- Using this closure expression together with equations governing the surface layer, one can obtain the following formula:

$$K_z = \left\{ \frac{\kappa}{2} \int_0^z \frac{\left[\left(dU/dz \right)^2 - \sigma\beta\, d\theta/dz \right]^{5/4}}{\left(dU/dz \right)^2 - 0.5\sigma\beta\, d\theta/dz}\, dz \right\}^2$$

Problem solution (2)

$$\left\{ K_z(z_K) = \left[\int_0^{z_K} \frac{\left(\left(\partial U/\partial z\right)^2 - \sigma\beta\, \partial T/\partial z \right)^{5/4}}{\left(\partial U/\partial z\right)^2 - 0.5\sigma\beta\, \partial T/\partial z} dz \right]^2 \right\}$$

$$u^* = \sqrt{K_z(z_K) \frac{\partial U}{\partial z}(z_K)}$$

$$H_s = -\frac{c_p \rho}{\Pr} K_z(z_K) \frac{\partial T}{\partial z}(z_K)$$

$$T^* = -\frac{H_s}{c_p \rho\, u^*}$$

$$L = -\frac{(u^*)^3 c_p \rho}{\kappa \beta H}$$

$$H_l = -\frac{E\rho}{\Pr} K_z(z_K) \frac{\partial q}{\partial z}(z_K)$$

Here all derivatives are NOT computed numerically
but rather taken from the analytical approximations of profiles.

Since z_k~*1m*, these profiles can be taken purely logarithmic. Non-logarithmic corrections start to play a strong role at |*z/L*|~*0.5*

Assuming the logarithmic shape, it is enough to have 2 values – at the screening and the 1st model levels – to determine the profile.

All fluctuating and not well-defined parameters are inside the integral, thus their effect is smoothed out

Problem solution (3)

Logarithmic profile assumption near the surface (*z*<<|*L*|)

$$T(z) = T_g + T^* \Pr \ln\frac{z}{z_{0T}} \quad \Rightarrow \quad \frac{\partial T}{\partial z}(z) = T^* \Pr \frac{1}{z}$$

Having temperature values at two levels, obtain:

$$T(z_2) - T(z_1) = T^* \Pr \ln\frac{z_2}{z_1} \quad \Rightarrow \quad T^* \Pr = \frac{T(z_2) - T(z_1)}{\ln\frac{z_2}{z_1}} \quad \Rightarrow \quad \frac{\partial T}{\partial z} = \frac{T(z_2) - T(z_1)}{z \ln\frac{z_2}{z_1}}$$

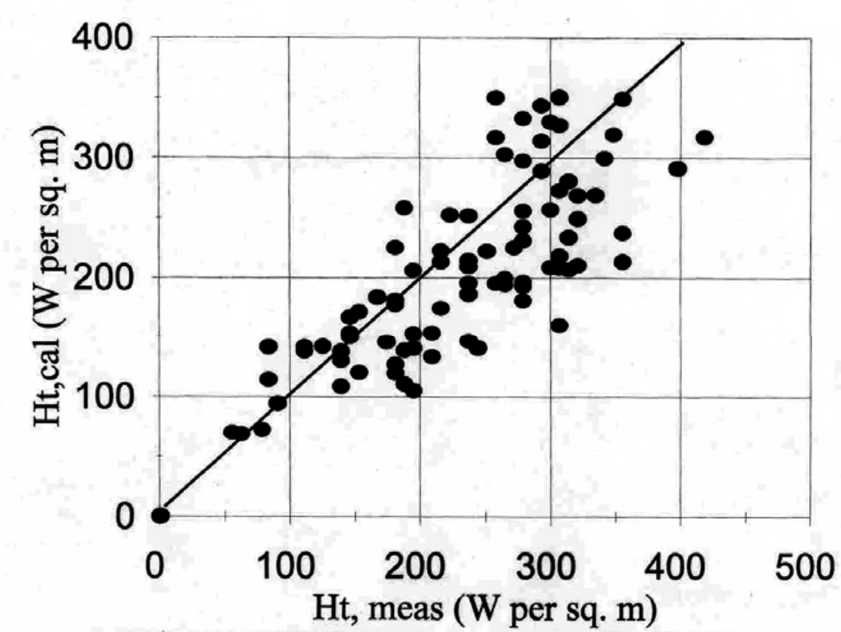
Analogously, for velocity scale:

$$\frac{\partial U}{\partial z} = \frac{U(z_2) - U(z_1)}{z \ln\frac{z_2}{z_1}}$$

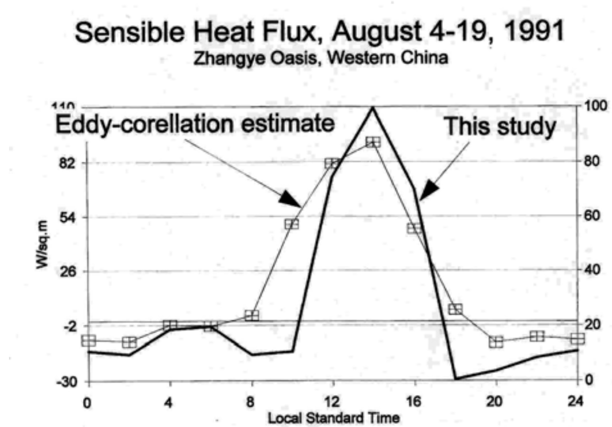
These dependencies are substituted into K_z formula, where the integral is tabulated

Method verification: measurements

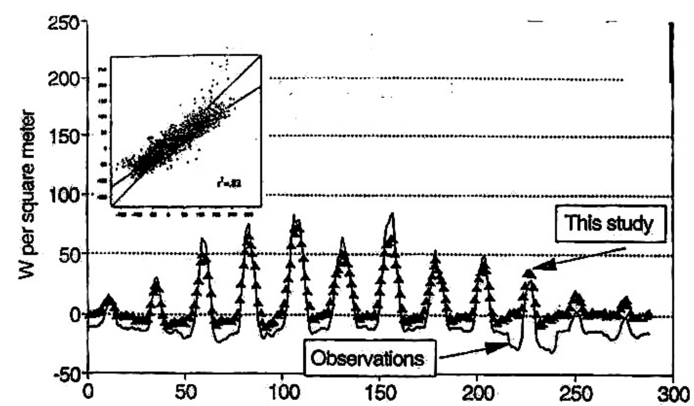
Eddy-correlation measurements, Tsimlyansk, 1976



SENSIBLE HEAT FLUX, TSIMLYANSK, 1976

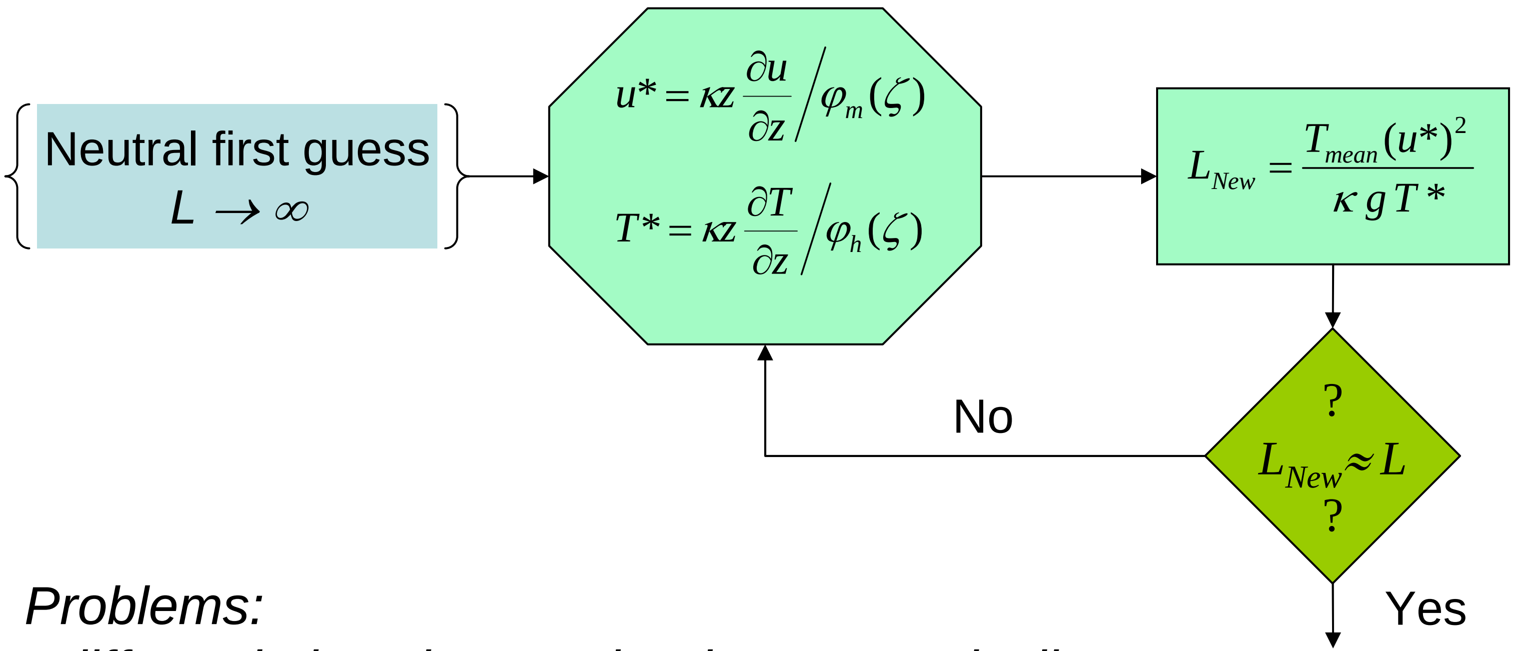


Profile measurements, Cabauw, 1987



Groisman & Genikhovich (1997), using the lower available measurement level and ground surface; the temperature jump is estimated after Zilitinkevich (1970)

Problem discussion: iterative solution

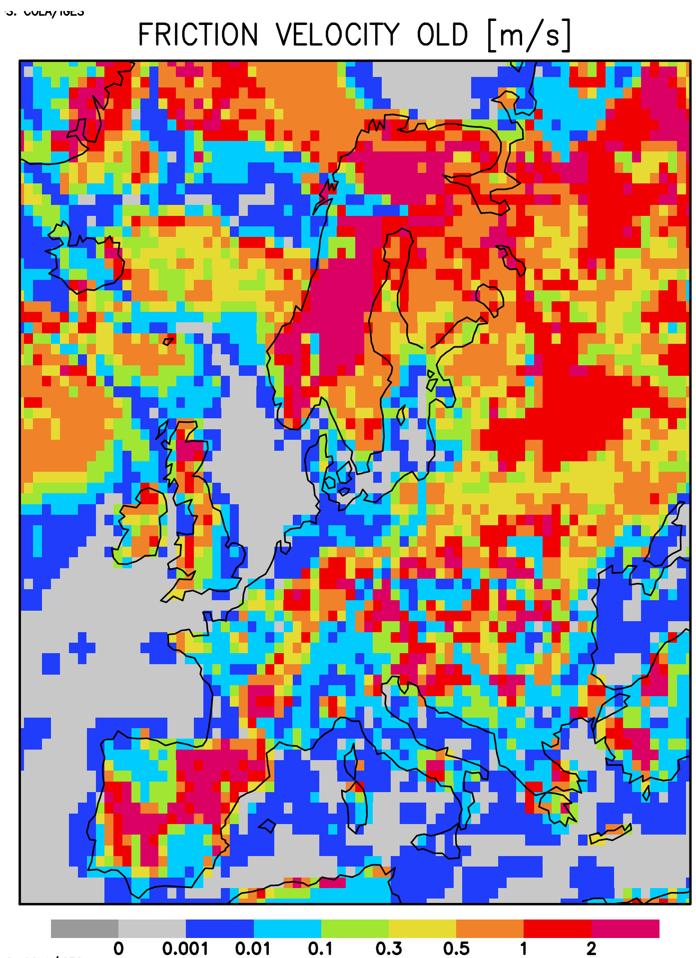


Problems:

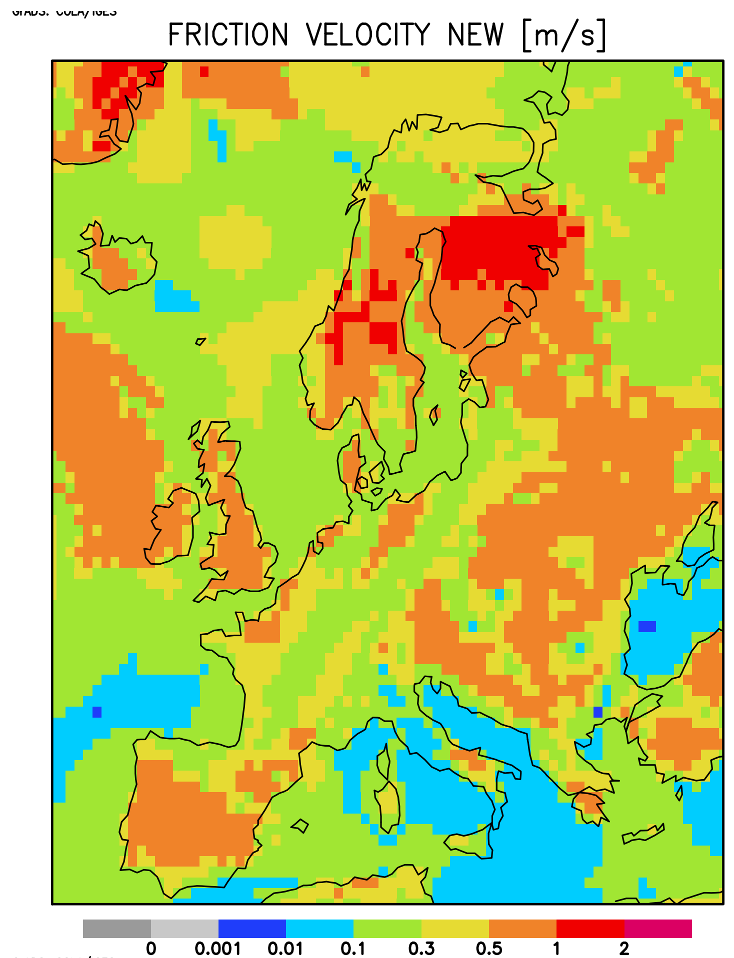
- differentiations have to be done numerically

- convergence of the iterations is not proven

Comparison of solutions



Friction velocity, iterative solution



Friction velocity, K_z-based solution

Problem discussion (2)

- A supposedly simpler way is to use NWP fluxes of momentum *(M_x, M_y)* and heat *(H_s, H_l)* to get the ABL characteristics, for example:

$$u^* = \left[\frac{1}{\rho} \sqrt{M_x^2 + M_y^2} \right]^{1/2}$$

$$T^* = \frac{-H_s}{c_p \rho u^*} \qquad q^* = \frac{-H_l}{E \rho u^*}$$

$$L = \frac{T_{sl} (u^*)^2}{\kappa g T^*}$$

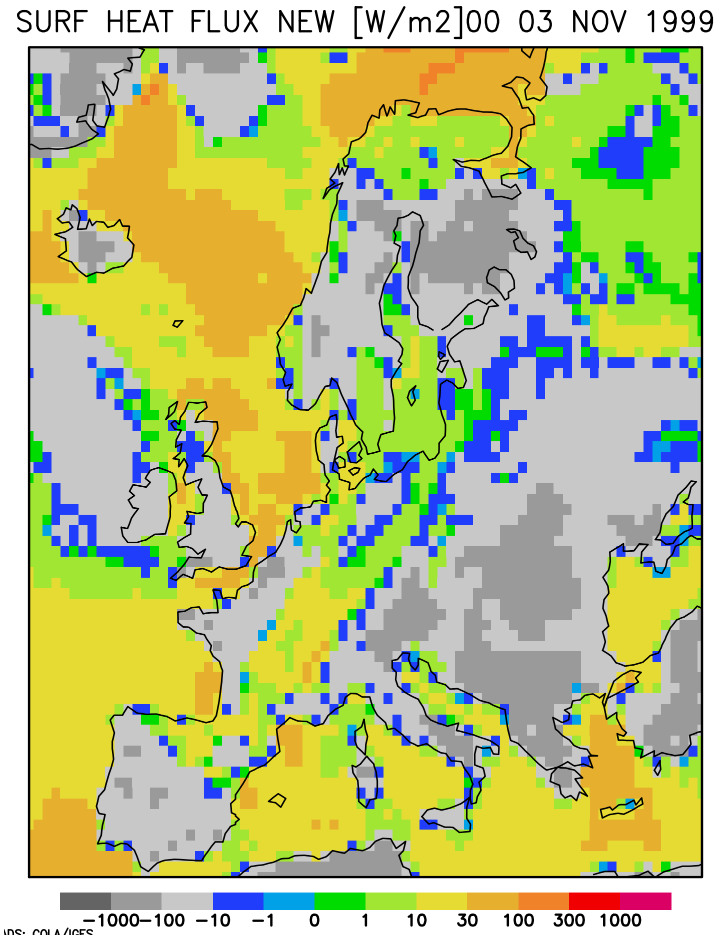
Here ρ is an air density, c_p is a constant-pressure heat content, *E* is an energy of evaporation or sublimation, depending on screen-level (usually, 2m) temperature T_{sl}, *k* is a von-Karman constant, *g* is an acceleration of gravity

A problem: the heat and momentum fluxes are not routinely verified in the NWP models and thus cannot be considered reliable

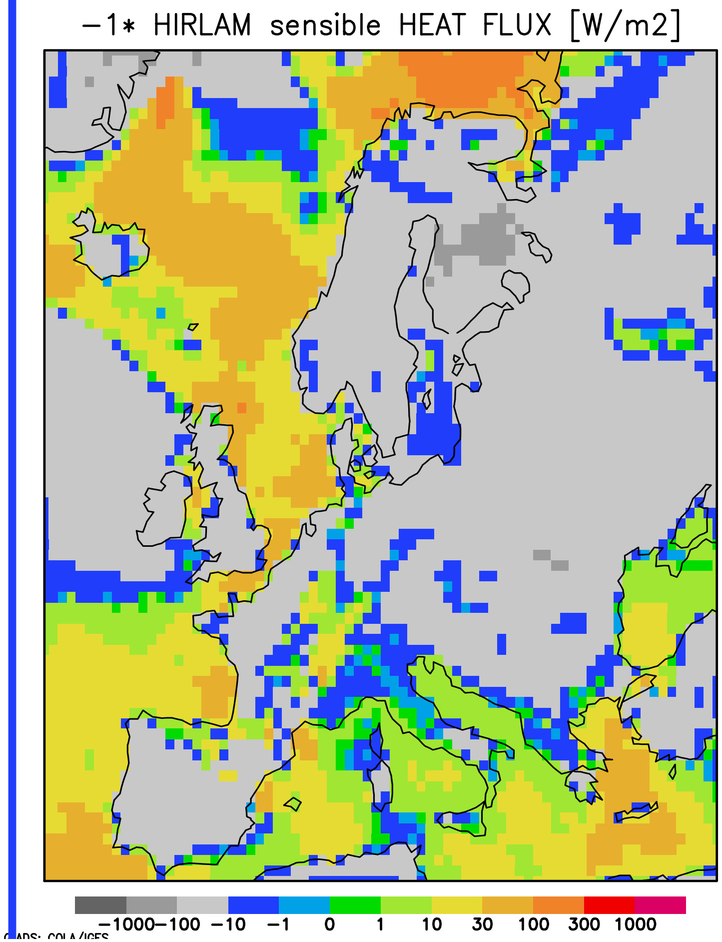
Comparison with NWP (HIRLAM, ECMWF)

- Intuitively, there must be almost 1:1 agreement
  - theoretical basis is more or less the same, variations in the formulations should not lead to excessive quantitative discrepancies
  - within HIRLAM *u,q,T* profiles and heat fluxes are computed together, thus being highly correlated
- However, certain deficiencies are inevitable
  - still, there are differences in the computational algorithms
  - HIRLAM & ECMWF provide accumulated fluxes e.g. for 3 hours, while *u,q,T* are instant, thus re-stated fluxes will be instant too

Comparison with HIRLAM



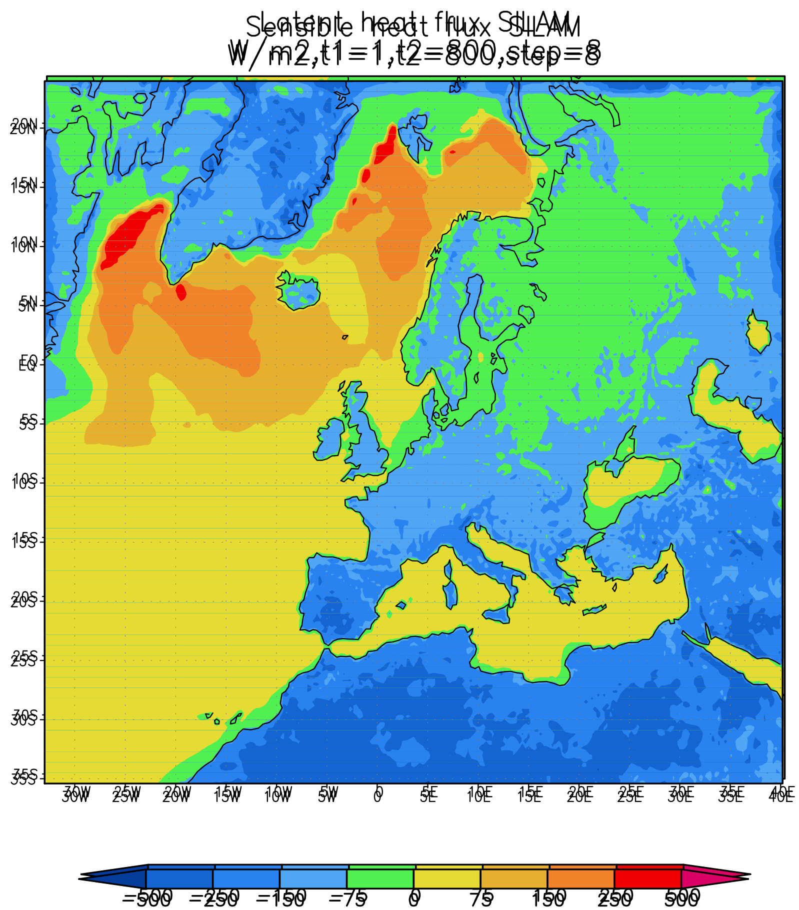
Re-stated sensible heat flux



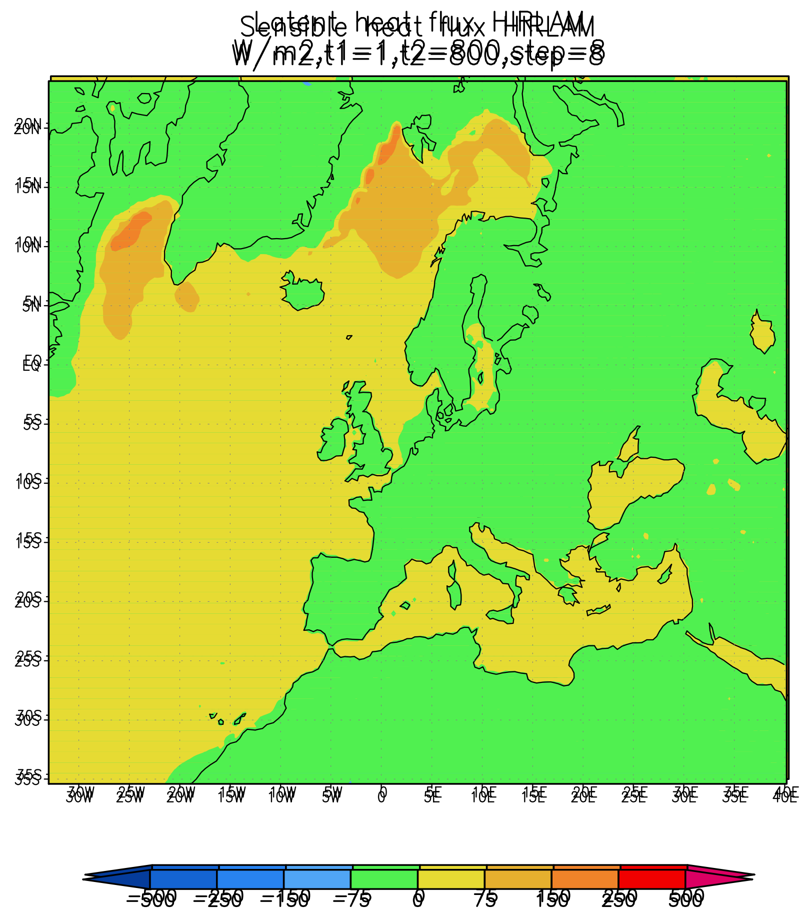
HIRLAM sensible heat flux *(-1)

Verification statistics: HIRLAM, Jan-March 2000, night

Latent heat flux re-stated
Sensible heat flux re-stated



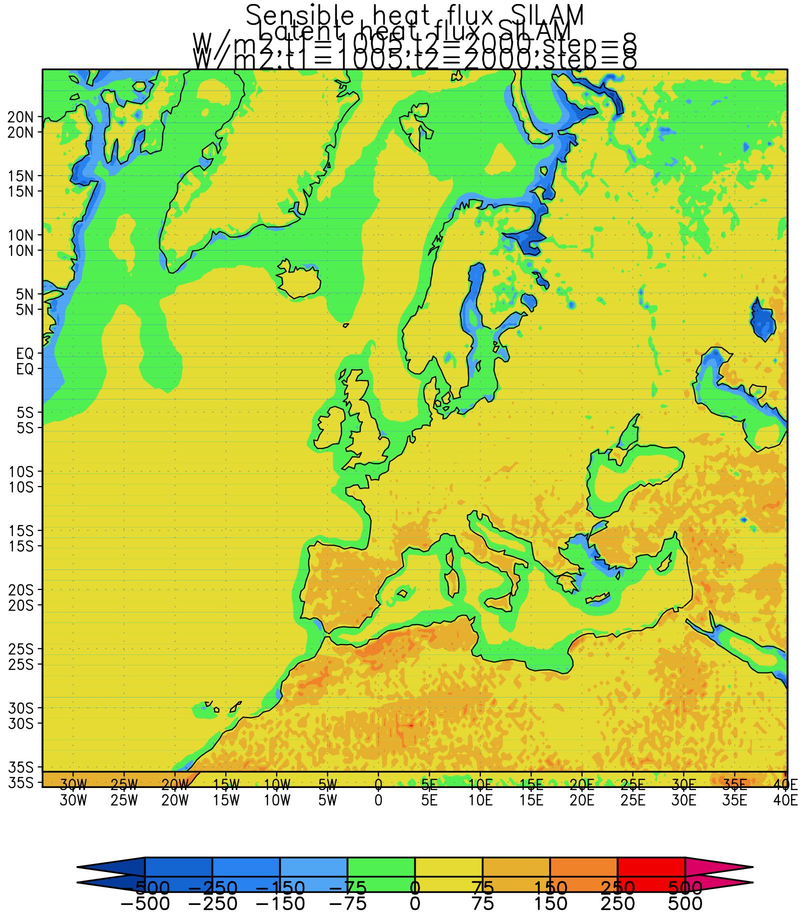
HIRLAM
HIRLAM



Verification statistics: HIRLAM, May-Sep 2000, day

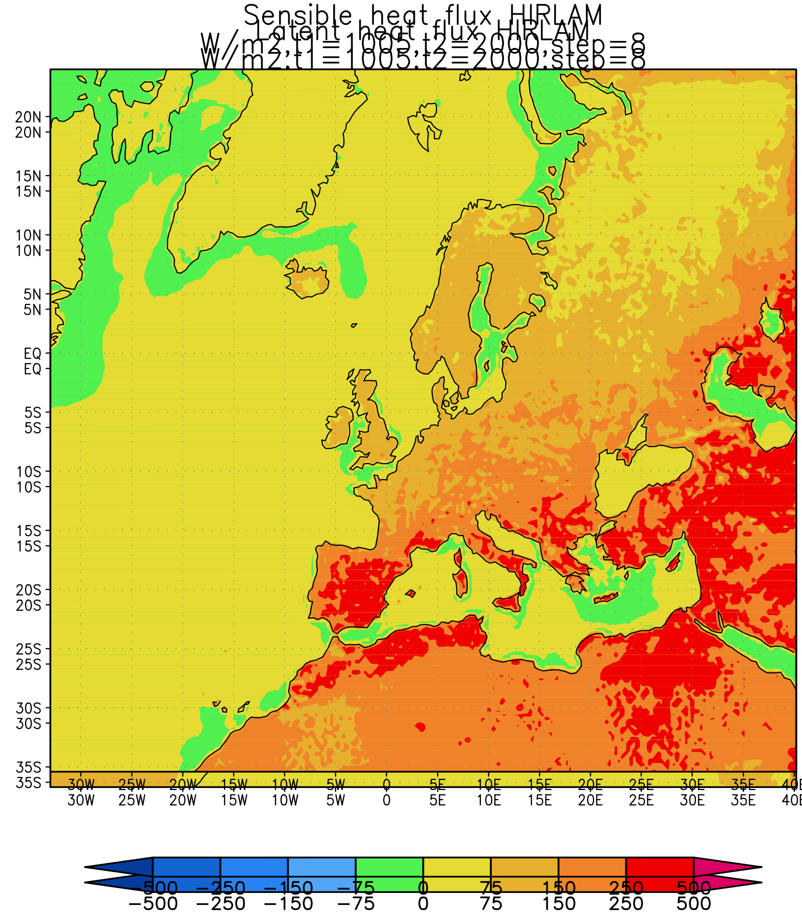
Latent heat flux re-stated

Sensible heat flux re-stated

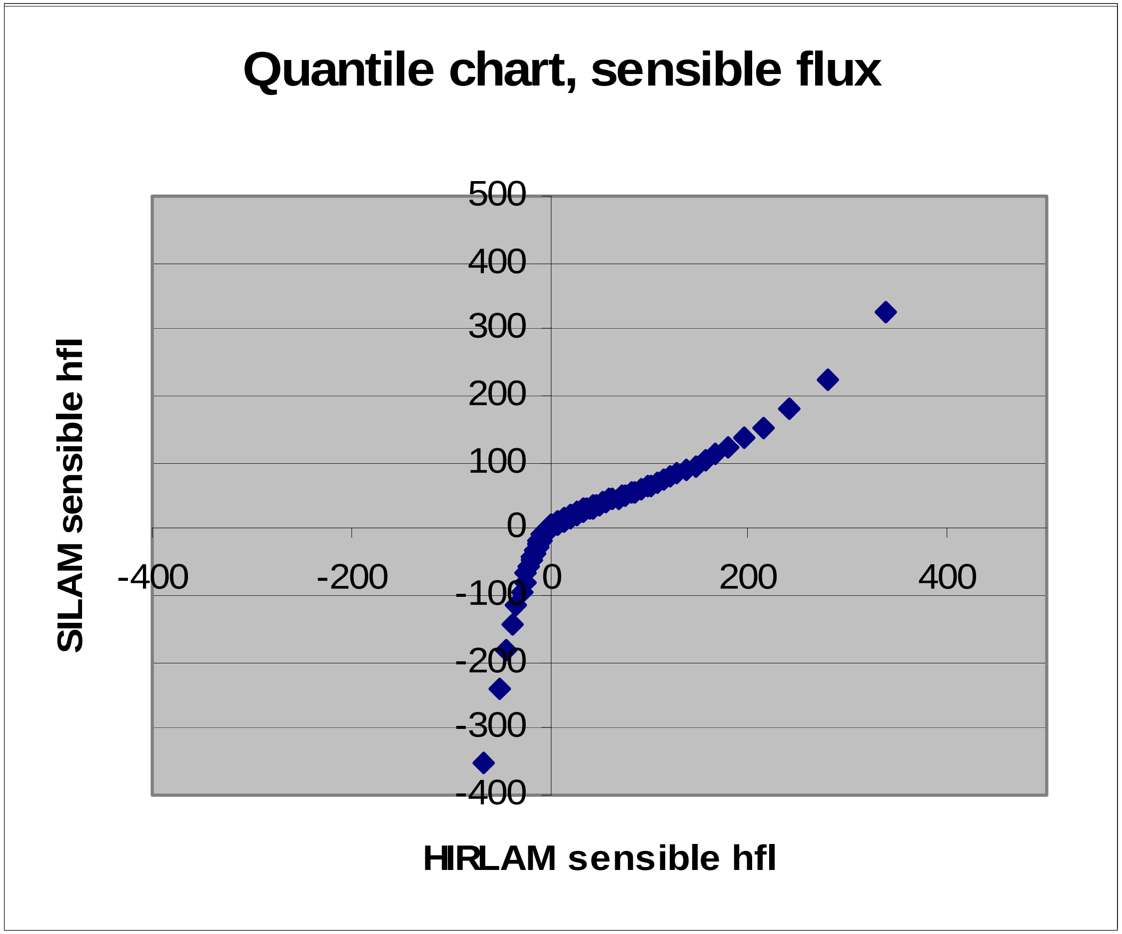


HIRLAM

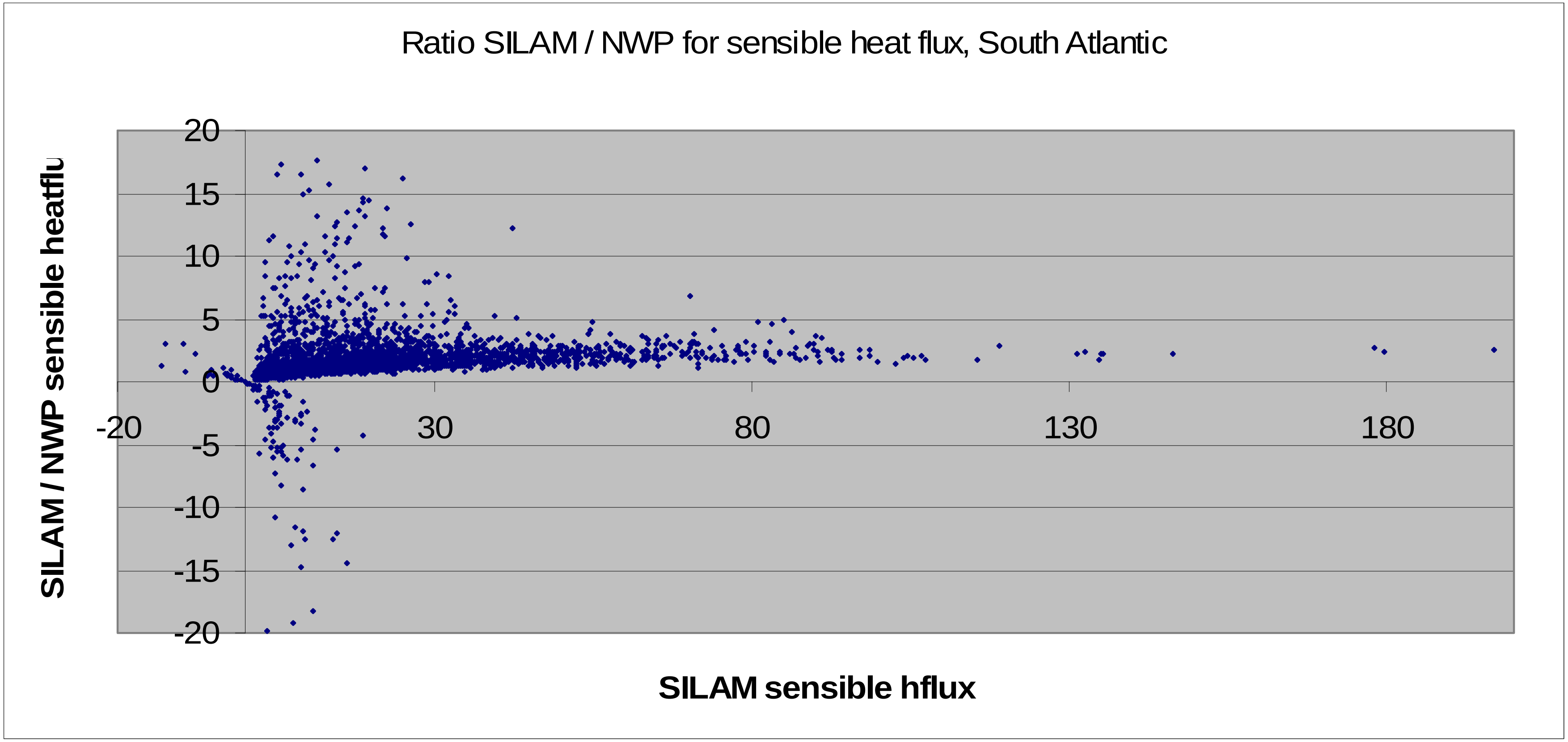
HIRLAM



Verification statistics: time correlation, quantile charts

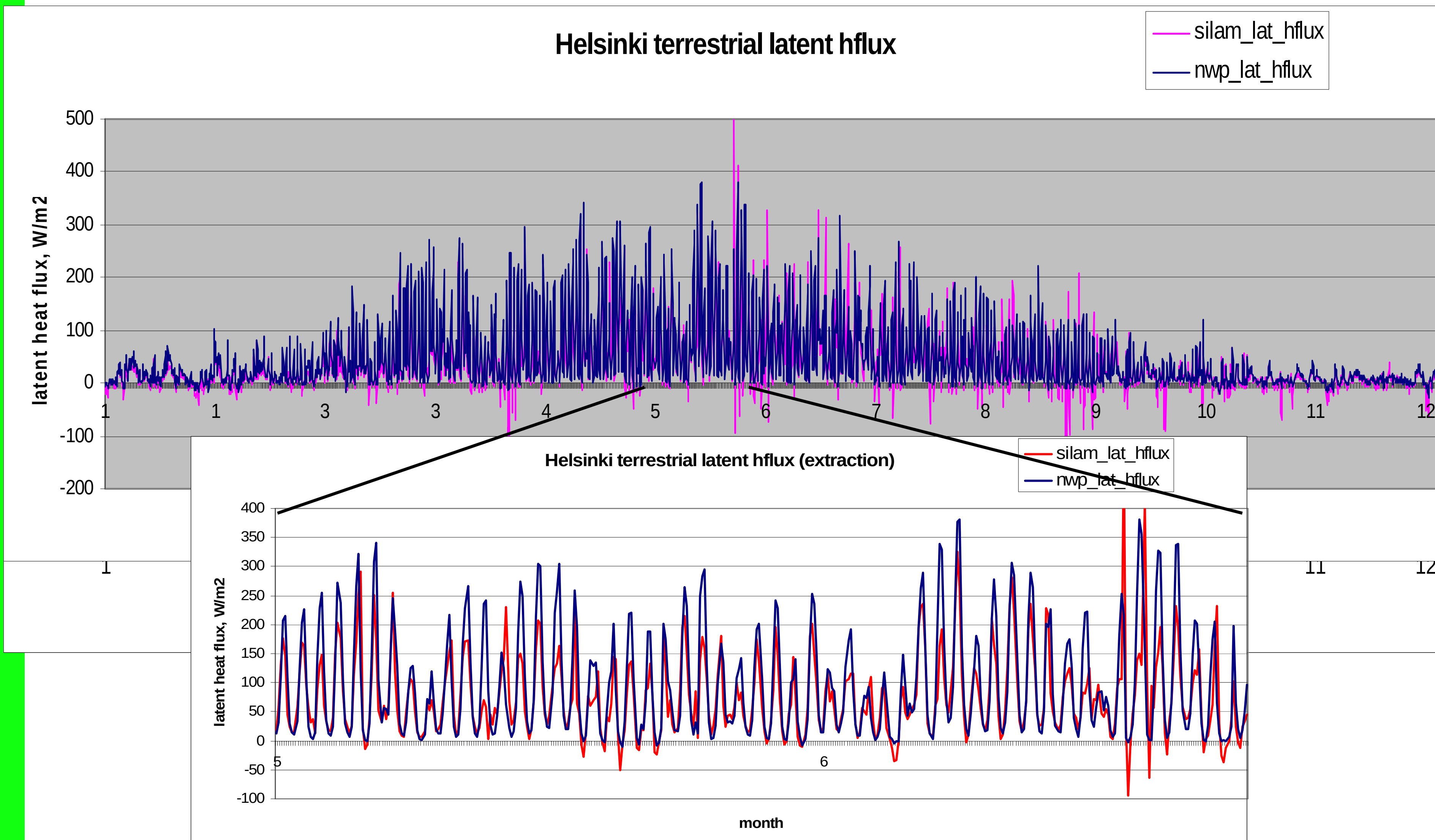


Verification statistics: stratification influence

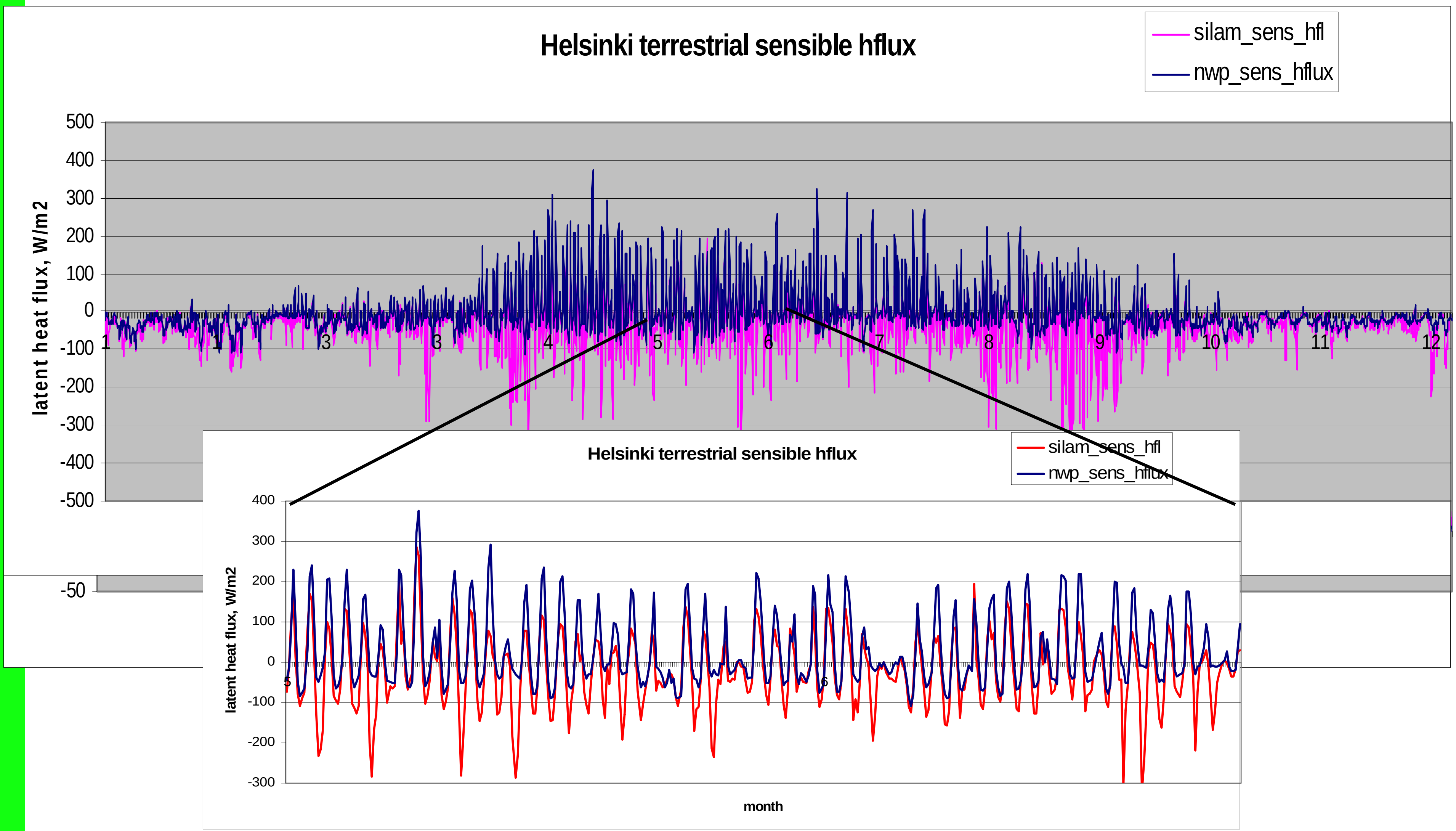


A ratio of re-stated and NWP-computed sensible heat fluxes versus re-stated one. HIRLAM 5.2.1, south Atlantic, complete year 2000

Comparison of time series (latent flux)



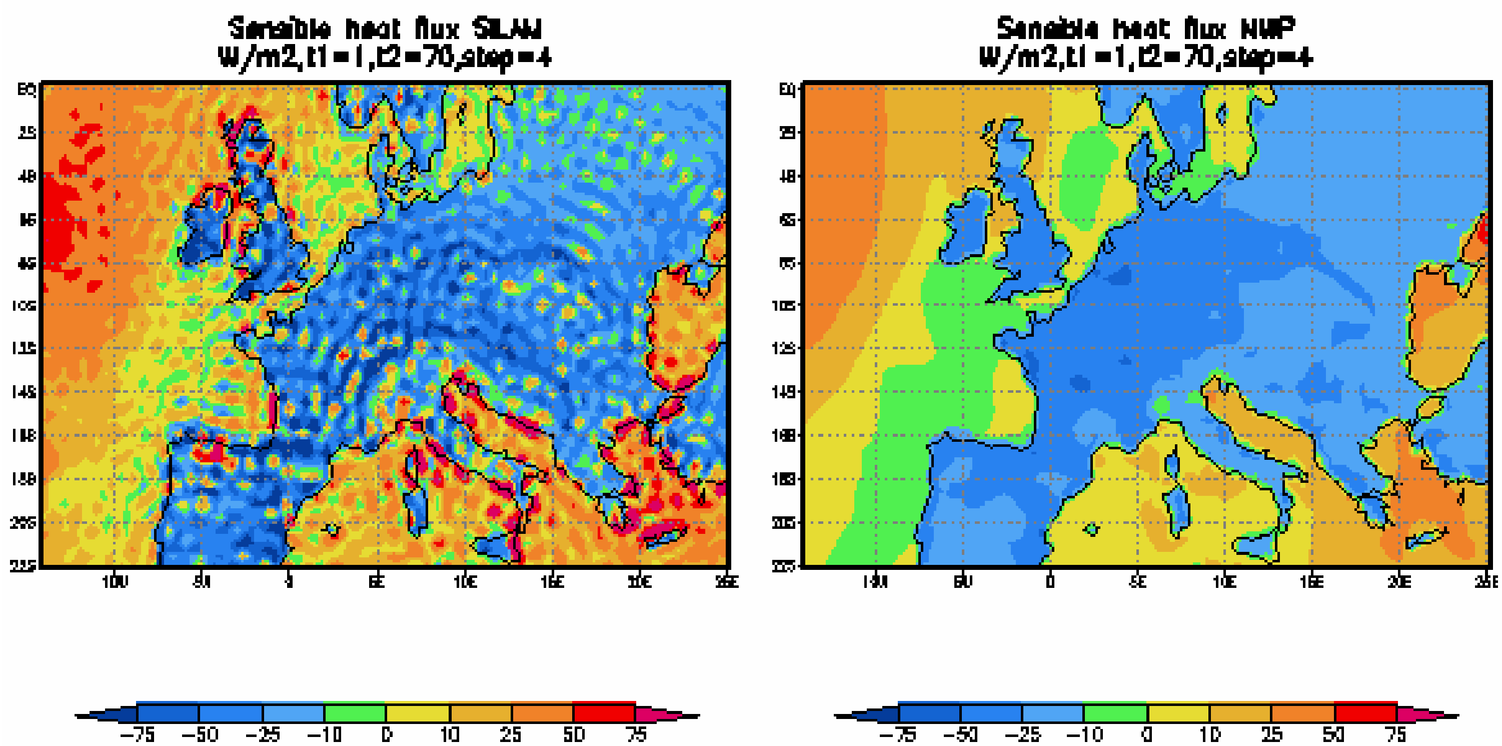
Comparison of time series (sensible flux)



Discussion of comparison

- The closest values are shown for latent heat flux; usually reasonable similarity of sensible heat fluxes over sea and in unstable cases (with a correction of *Pr*-number dependence on stratification)
- Larger deviations in stable cases
  - slightly stable case is practically OK
  - stronger stability leads to re-stated downward flux much stronger than HIRLAM one
- Fluxes should not be the same (above reasons)
- High sensitivity of the parameters “by nature”
  - small differences in approaches may magnify
  - possibility for explosion of numerical error (hardly)
  - coding error in implementation – in either model

Example on numerical accuracy



An effect of “error explosion” for ECMWF operational model data, 1-17.12.2000

Call for future studies

- Available methodology
  - universal approach for re-stating the main ABL characteristics from the basic meteorological variables
  - verification against observations showed good results
- Existing problem
  - comparison with HIRLAM heat fluxes showed significant differences, especially for sensible heat flux over terrestrial areas in stable cases. Reason is largely unknown
- Research needed
  - comparison with independent datasets
    - ECMWF model fields
    - Sodankyla mast data
    - other datasets
  - fine-tuning of the methodology (and/or HIRLAM) and/or its implementation