Diagnostics and validation

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CONTENTS:

- Examples of experiment verification
  - A parallel run with TOVS-data
  - A climate mode run

Validation against special observations

- Example: Radiation
- Example: Other possibilities

Budget studies

- Tasks of the budget studies
- Equations
  - Dynamical and physical tendencies
  - Basic equations
  - Balance of heat and moisture
  - Vertically integrated budgets
- Examples
  - Fullfilling the balance conditions
  - Fluxes over sea
  - A study of moisture budget

About the tools of meteorological analysis

- Looking around
- Analysis of case studies
- Example: IPV

Why validation and diagnostics?

Main questions

- Are there technical problems in the model runs -
  e.g. Did we forget to use the sounding data?
  e.g. Are there bugs and inconsistencies in the programs?
- Do our model results correspond reality?
- Does our model obey the laws of physics?

Tasks

- Monitoring and meteorological control of the model
- Studying and solving the known problems:
  e.g. Are the 10-metre winds of HIRLAM too weak?
- Testing the new model components

Needed

- Systematically looking around to find problems
- Experience in analysis and interpretation
- Tools to find problems and formulate hypotheses

Possibilities of validation

Operational

- Synoptic control
- Station verification

Experimental

- Sensitivity studies
- Comparison with special observations
- Synoptic case studies
- Parallel runs
- Budget studies

VERIFICATION AGAINST STATION DATA AND ANALYSES

Variables verified

- Surface parameters: $p_s, T_{2m}, RH_{2m}, \vec{v}$, precipitation, (cloudiness), against SYNOP-observations
- Upper level parameters: $\Phi, T, RH, \vec{v}$, against TEMP-observations

Common verification parameters

Mean error

$$ME = \frac{1}{N}\sum_{1}^{N}(F_n - O_n)$$

Root-mean-square error

$$RMSE = \sqrt{\frac{1}{N}\sum_{1}^{N}(F_n - O_n)^2}$$

Standard deviation

$$SD = \sqrt{RMSE^2 - ME^2}$$

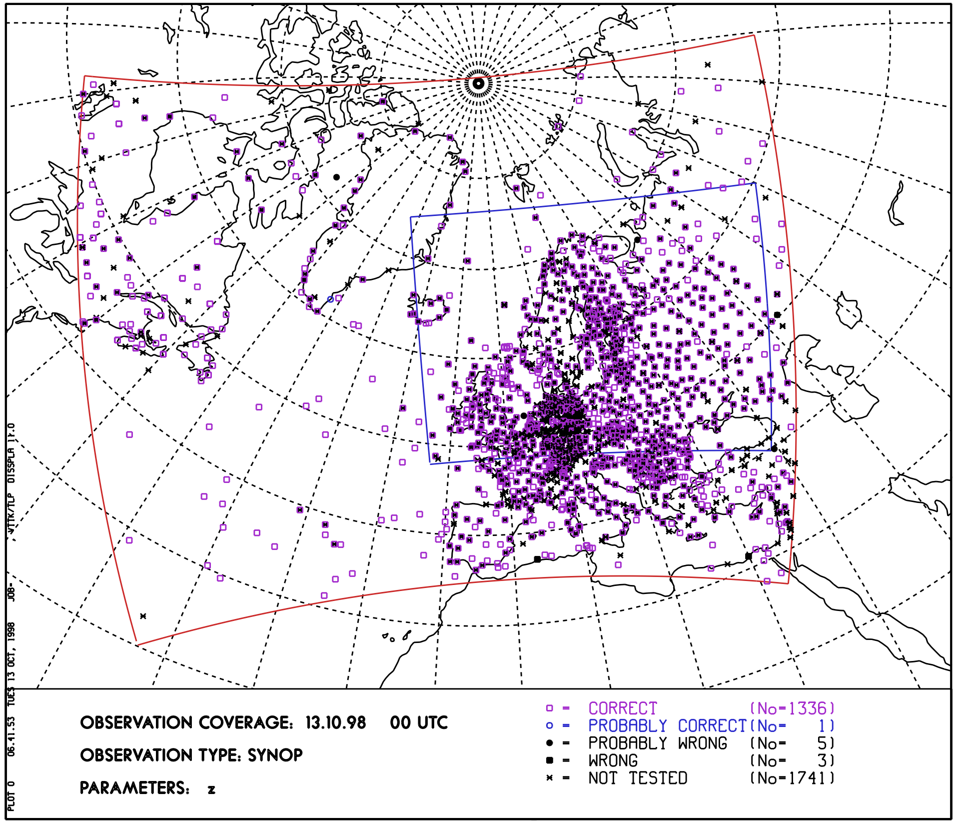


Figure 1: Synoptic stations used in FMI HIRLAM analysis at 00UTC Oct,13,1998.

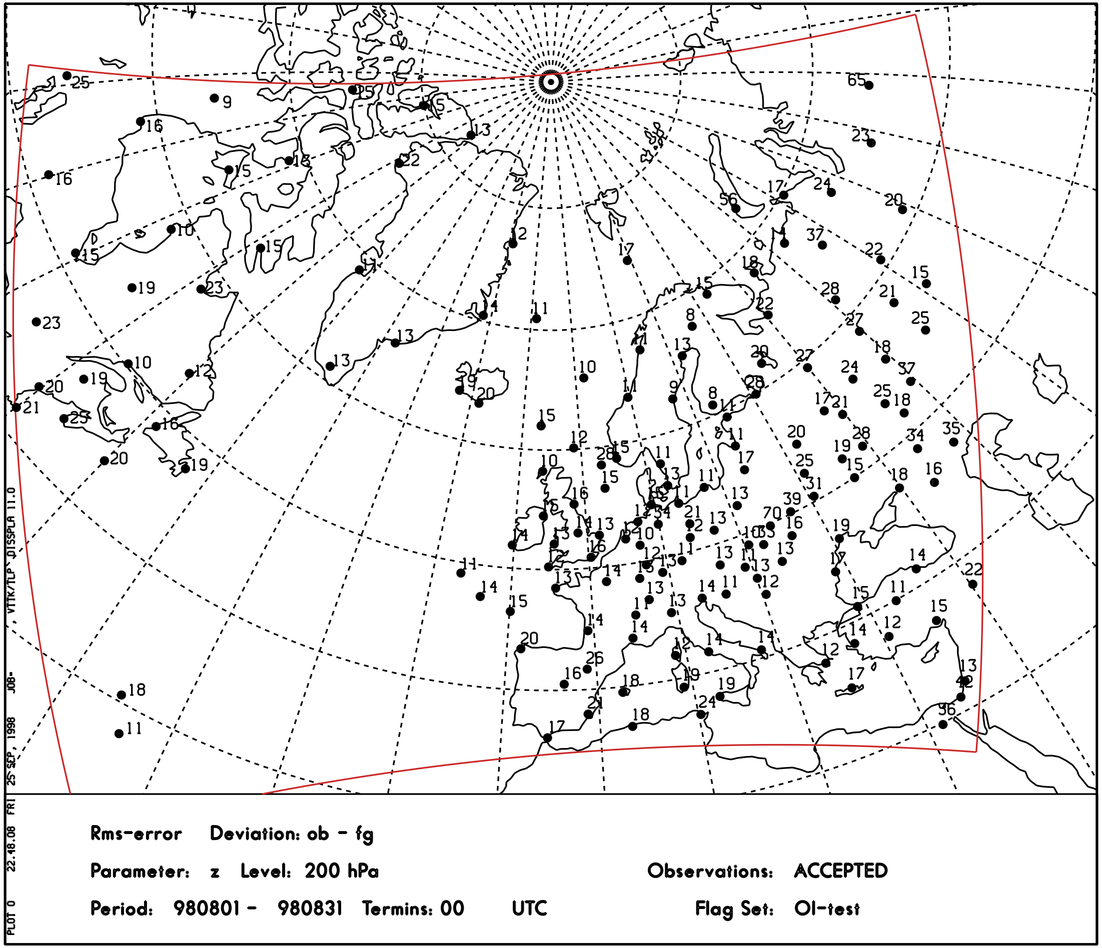


Figure 2: Observation quality control example (Aug, 1998,FMI HIRLAM)

Standard verification: p_s

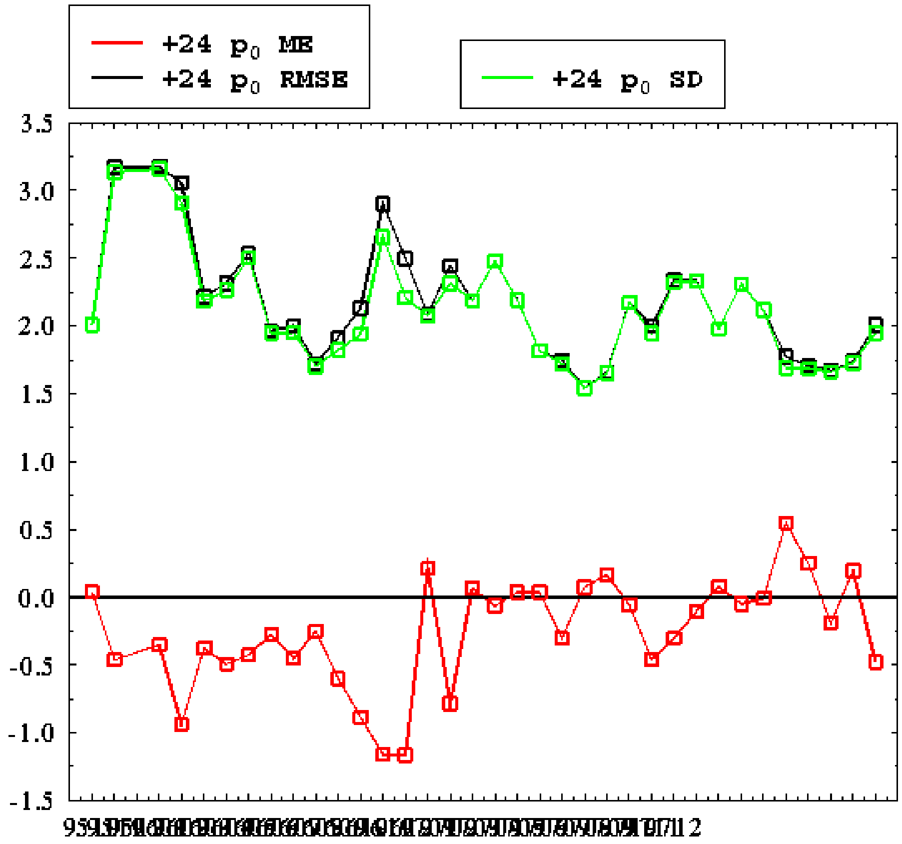


Figure 2: 36 month MSLP time series of +24h FMI HIRLAM forecasts

Standard verification: T_{2m}

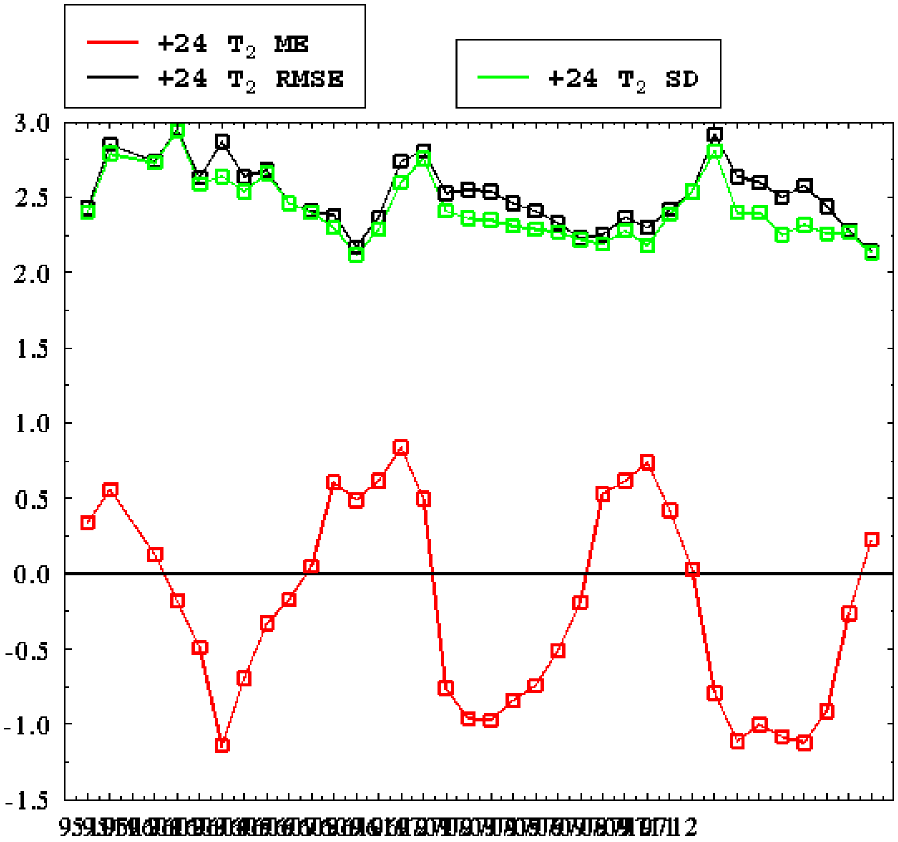
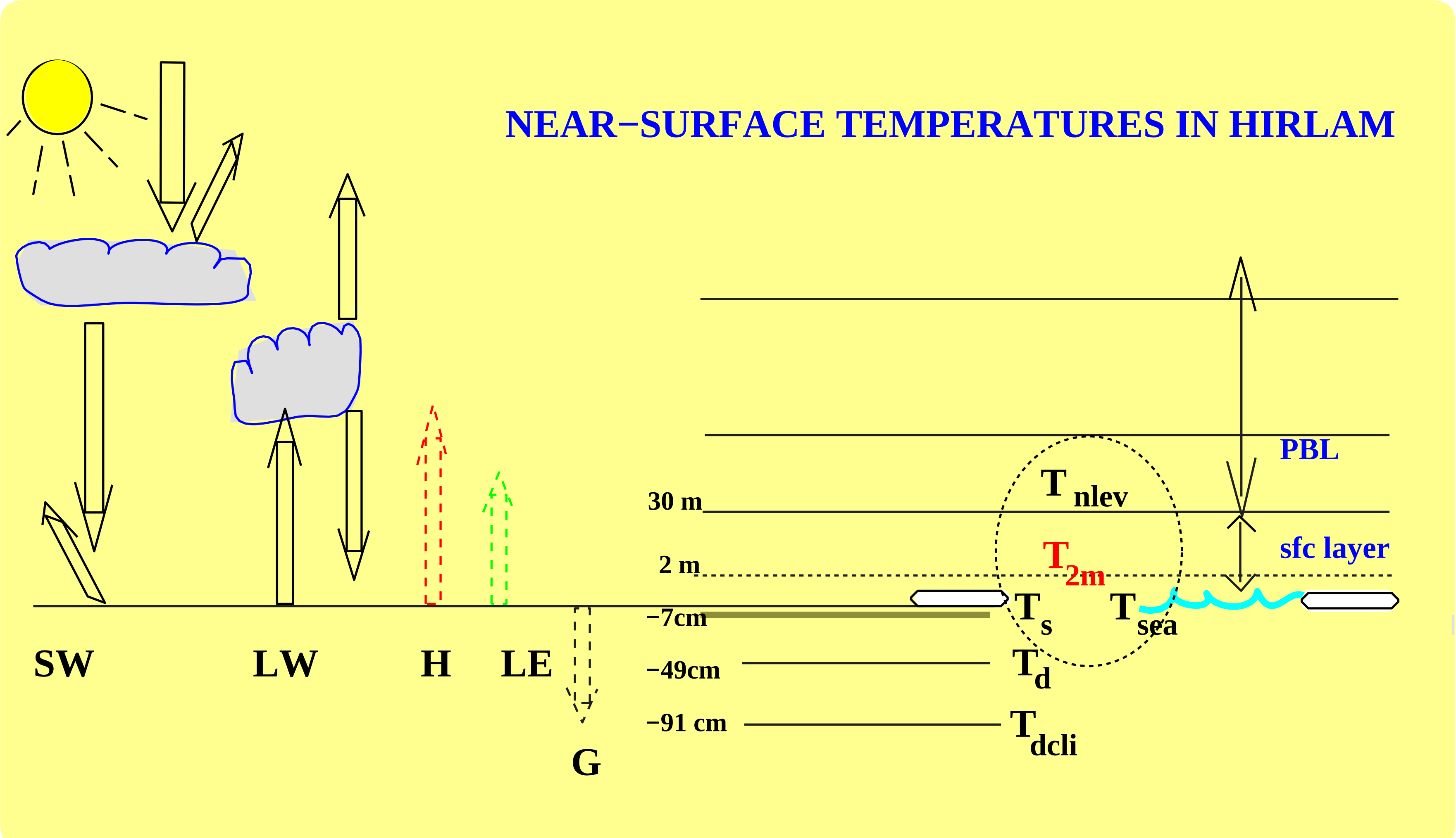


Figure 3: 36 month T_{2m} time series of +24h FMI HIRLAM forecasts

Problem:


NEAR−SURFACE TEMPERATURES IN HIRLAM
PBL
sfc layer
30 m
2 m
−7cm
−49cm
−91 cm
T nlev
T 2m
T s
T sea
T d
T dcli
SW
LW
H
LE
G

Wind verification problems

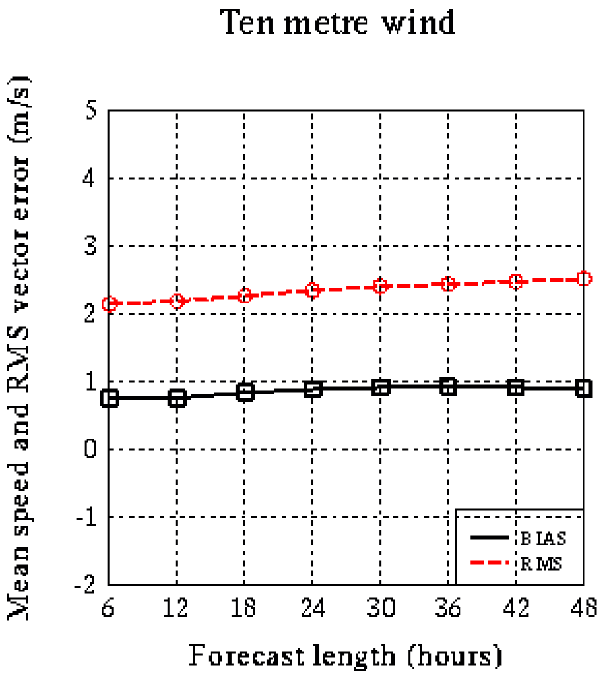


Figure 4: FMI HIRLAM wind verification, Sept 1998

1. Operational verification shows, that in the HIRLAM 10-metre winds there is slight positive bias, i.e. the winds verified over European SYNOP-stations are slightly too strong in the average.
2. Synoptic experience tells, that HIRLAM 10-metre winds over sea, in cases of strong winds, are far too weak.
3. When HIRLAM 10-metre winds with a 55 km grid resolution are given as input to wave models, too shallow waves are produced.

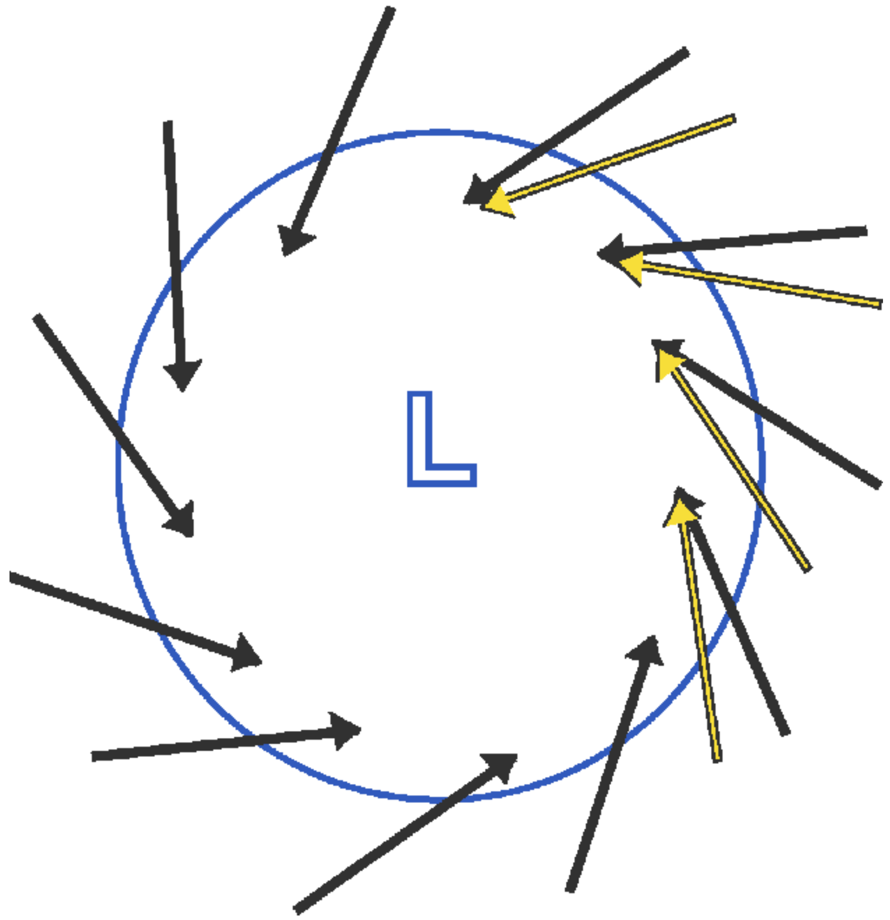
Check (2)

$\rightarrow$ How to verify 10-metre winds? $\rightarrow$ Wind measurement problems

$\rightarrow$ How to compare winds at the level of measurement? $\rightarrow$ 10-metre winds vs. lowest model layer winds . . .

Check (3)

Put HIRLAM 10-metre/lowest model layer winds with a 22 km grid resolution into the wave model


L

1. Analysis of the wind verification data obtained showed, that boundary layer wind direction is systematically overestimated in FMI operational 22km resolution HIRLAM forecasts

2. The conclusion was confirmed checking short forecasts: the forecasts were found to systematically add about 15^o wind direction to the analysed values

3. What to do:
   - Ask boundary layer people
   - Think about the consequences: Ekman pumping $\rightarrow$ filling of cyclones $\rightarrow$ Ask forecasters
   - See what could be found out from an enstrophy (vorticity) budget study

Experiment verification: p_s

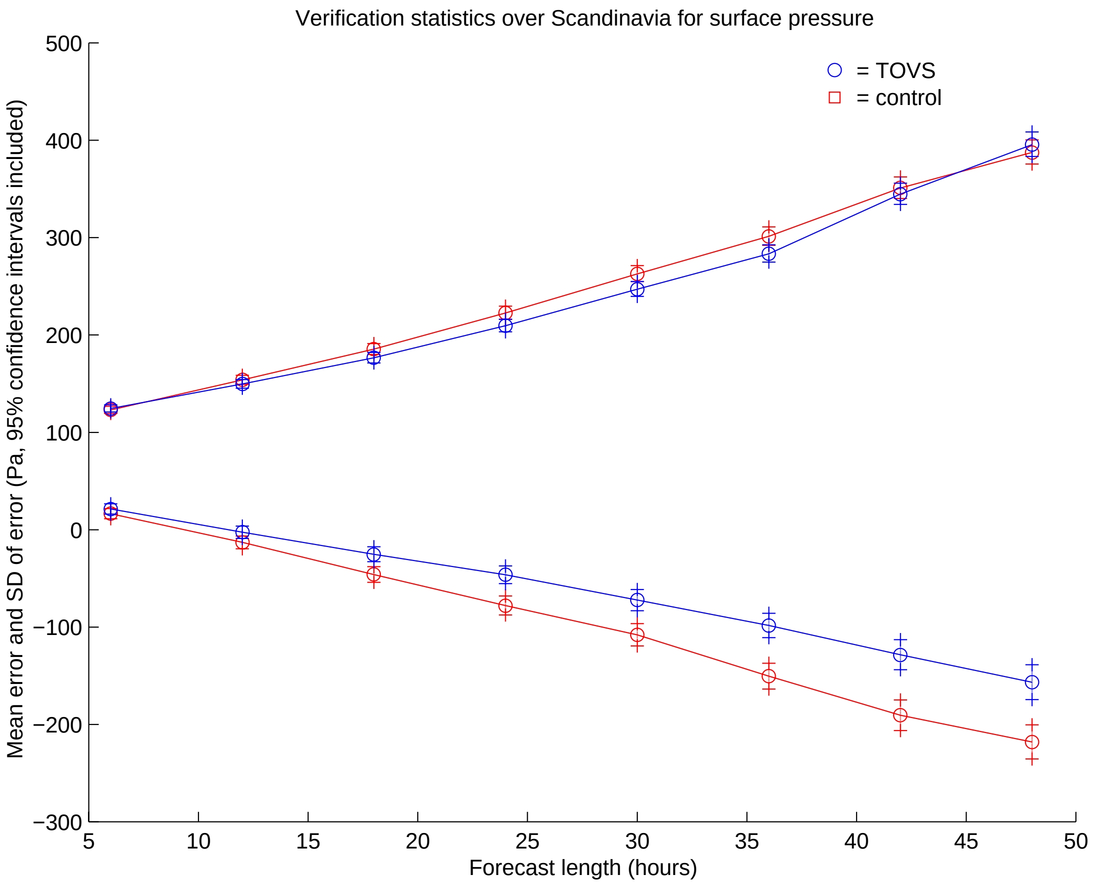


Figure 5: HIRLAM 4.1 with and without TOVS-data

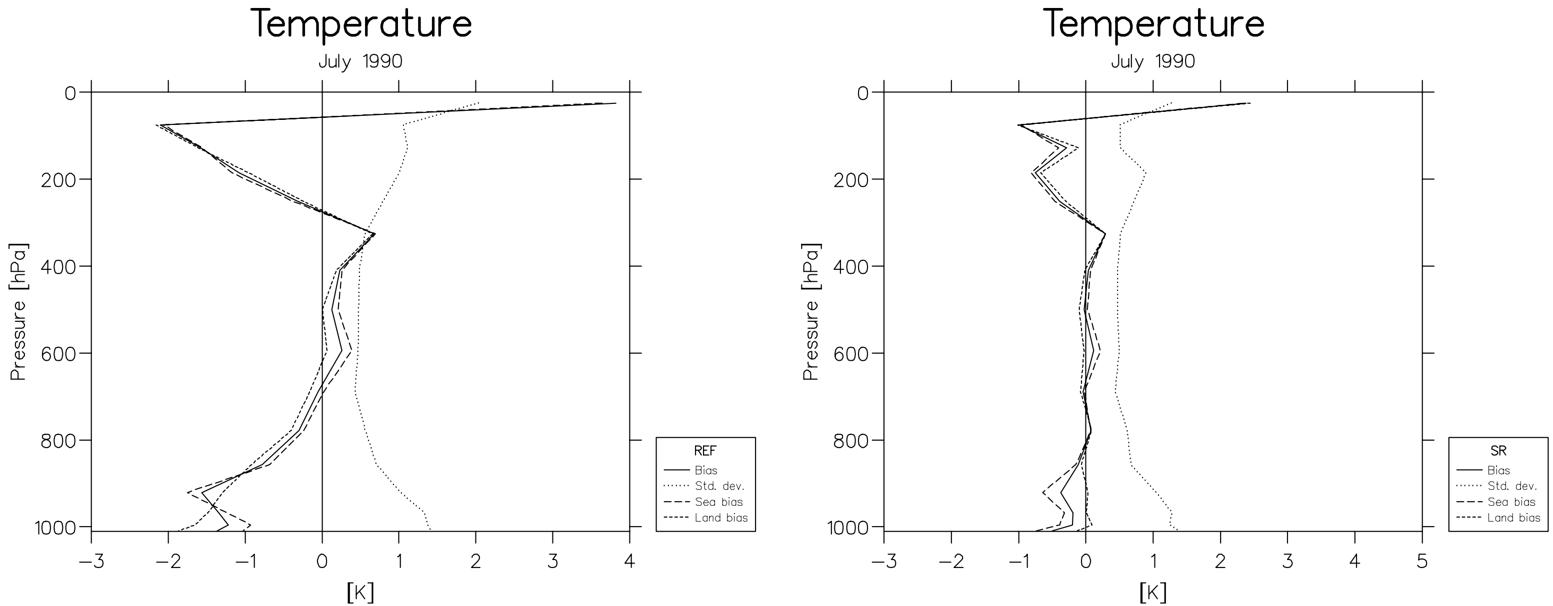


Figure 6: Old and present HIRLAM radiation scheme compared in a climate mode run

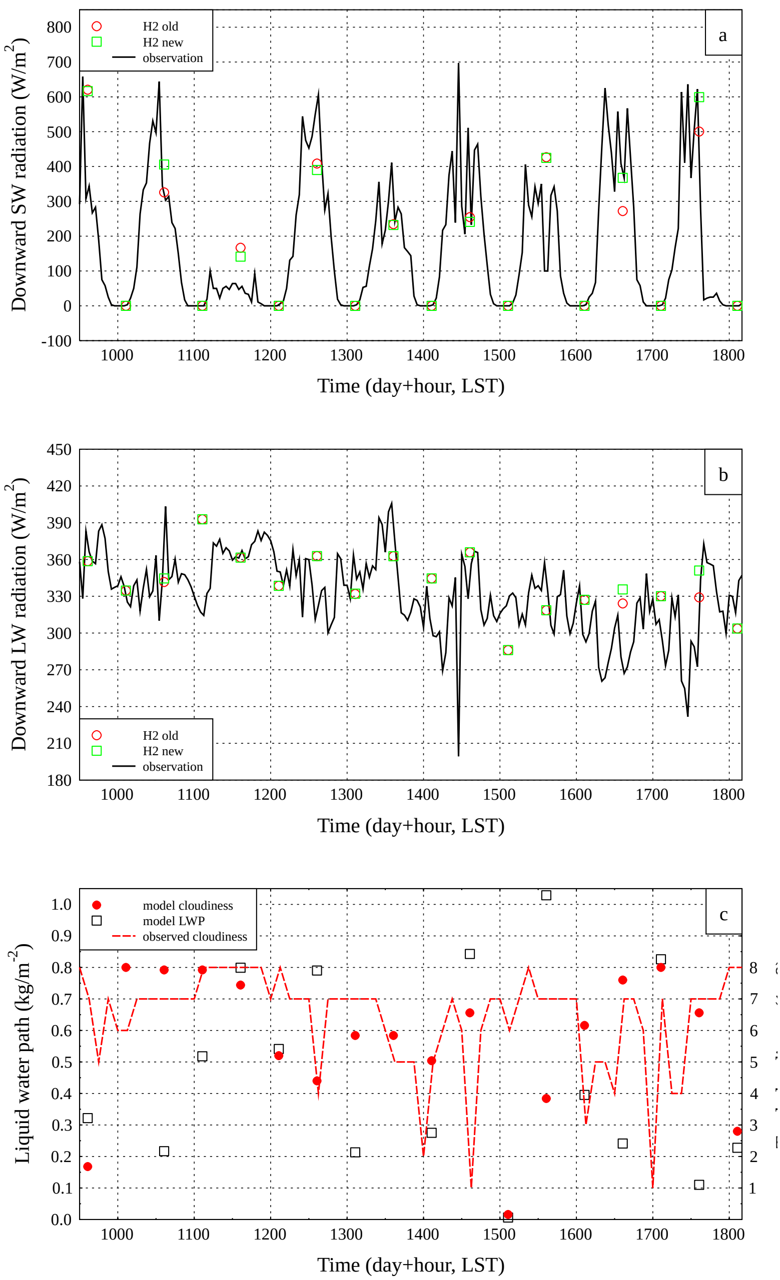


Figure 7: Downward short-wave (a) and long-wave (b) radiation fluxes at Jokioinen from 12 UTC 9 July to 12 UTC 19 July, 1989.

Verification against special observations: examples

- comparison of boundary layer parametrizations with tower data
- comparison surface parametrizations against surface flux measurements over land and sea
- comparison of model cloudiness with satellite cloudiness
- verification of radiation parametrizations against flight measurements
- comparison of model albedo with albedo derived from satellite measurements
- comparison of heat flux in snow with measurements
- ...

BUDGET STUDIES

$$\frac{\partial x}{\partial t} = \sum terms, \qquad (1)$$

where **terms** include

- advection and other dynamical interactions
- parametrized effects
- boundary relaxation
- analysis increment
- etc

$\Rightarrow$ Budget studies

Possibilities of the budget studies

- External:
  Compare individual components of balance equations to available observations: fluxes at surface (SFC) and at the top of the atmosphere (TOA)

- Internal:
  Calculate budget equations within the model, i.e. study how the physical conservation laws are fullfilled during model runs

DYNAMICAL AND PHYSICAL TENDENCIES

$$\hat{x} = \int_0^{p_s} x \frac{dp}{g} \tag{2}$$

$$\frac{\partial x}{\partial t} = (\frac{\partial x}{\partial t})_{dyn} + (\frac{\partial x}{\partial t})_{phys} \tag{3}$$

$$\int_0^{p_s} \frac{\partial x}{\partial t} \frac{dp}{g} = \frac{\partial \hat{x}}{\partial t} - x_s \frac{\partial p_s}{\partial t} = (\widehat{\frac{\partial x}{\partial t}})_{dyn} + (\widehat{\frac{\partial x}{\partial t}})_{phys} \tag{4}$$

$$\frac{\partial \hat{x}}{\partial t} = x_s \frac{\partial p_s}{\partial t} + (\widehat{\frac{\partial x}{\partial t}})_{dyn} + (\widehat{\frac{\partial x}{\partial t}})_{phys} \tag{5}$$

For a simple budget equation:

$$
\begin{aligned}
\left(\widehat{\frac{\partial x}{\partial t}}\right)_{dyn} + x_s\frac{\partial p_s}{\partial t} &= -\int_0^{p_s}\left(\nabla\cdot x\vec{v} + \frac{\partial x\omega}{\partial p}\right)\frac{dp}{g} + x_s\frac{\partial p_s}{\partial t} \\
&= -\nabla\cdot\widehat{x\vec{v}} - x_s\omega_s + x_s\vec{v}_s\cdot\nabla p_s + x_s\frac{\partial p_s}{\partial t} \\
&= -\nabla\cdot\widehat{x\vec{v}} - \frac{\mathrm{dp}}{\mathrm{dt}} + \frac{\mathrm{dp}}{\mathrm{dt}} \\
&= -\nabla\cdot\widehat{x\vec{v}}
\end{aligned} \quad (6)
$$

HIRLAM model can give us the total tendency $\frac{\partial \hat{x}}{\partial t}$ and the tendency due to physics $\widehat{\frac{\partial x}{\partial t}}_{phys}$

BASIC EQUATIONS

$$\frac{\partial u}{\partial t} = A(u) + P_x + fv + J_x \tag{7}$$

$$\frac{\partial v}{\partial t} = A(v) + P_y - fu + J_y \tag{8}$$

$$\frac{\partial T}{\partial t} = A(T) + \frac{\alpha\omega}{c_p} + \frac{1}{c_p}[Q_{rad} + Q_{cond} + Q_{turb} + Q_{diss}] \tag{9}$$

$$\frac{\partial q}{\partial t} = A(q) + W_{cond} + W_{turb} \tag{10}$$

$$\frac{\partial c}{\partial t} = A(c) + C_{cond} + C_{turb} \tag{11}$$

The red terms are related to physical parametrizations.

$$
\begin{aligned}
A(x) &= \vec{v} \cdot \nabla x \\
P_x &= \frac{1}{\rho}\frac{\partial p}{\partial x} \\
P_y &= \frac{1}{\rho}\frac{\partial p}{\partial y} \\
J_x &= \frac{\partial \tau_x}{\partial z}, \tau_x = \rho\overline{u' w'} \\
J_y &= \frac{\partial \tau_y}{\partial z}, \tau_y = \rho\overline{v' w'} \\
Q_{rad} &= -\frac{1}{\rho}\frac{\partial F_{rad}}{\partial z} \\
Q_{cond} &\approx L(e_c - c_c + e_p) \\
Q_{turb} &= -\frac{1}{\rho}\frac{\partial c_p \rho\overline{\theta' w'}}{\partial z} \\
Q_{diss} &= -\vec{v} \cdot \vec{J} \\
W_{cond} &= e_c - c_c - e_p \\
W_{turb} &= -\frac{1}{\rho}\frac{\partial \rho\overline{q' w'}}{\partial z} \\
C_{cond} &= -e_c + c_c - g_p \\
C_{turb} &= -\frac{1}{\rho}\frac{\partial \rho\overline{c' w'}}{\partial z}
\end{aligned}
$$

BALANCE EQUATIONS FOR HEAT AND MOISTURE

Integrate the red terms of the basic equations (9, 10 and 11) to get the vertically integrated physical tendencies

$$\widehat{\frac{\partial T}{\partial t}}_{phys} = \frac{1}{c_p}[\widehat{Q_{rad}} + \widehat{Q_{cond}} + \widehat{Q_{turb}} + \widehat{Q_{diss}}] \tag{12}$$

$$\widehat{\frac{\partial q}{\partial t}}_{phys} = \widehat{W_{cond}} + \widehat{W_{turb}} \tag{13}$$

$$\widehat{\frac{\partial c}{\partial t}}_{phys} = \widehat{C_{cond}} + \widehat{C_{turb}} \tag{14}$$

Combining Equations (13 and 14) we get

$$\frac{\partial \widehat{(q + c)}}{\partial t}_{phys} = \widehat{\frac{\partial r}{\partial t}}_{phys} = \widehat{R_{cond}} + \widehat{R_{turb}} \tag{15}$$

Heat sources

$$\widehat{Q_{rad}} = -(F_{rad})_{TOA} + (F_{rad})_{SFC} \tag{16}$$

$$\widehat{Q_{turb}} = H \tag{17}$$

$$\widehat{Q_{diss}} = D \tag{18}$$

$$\widehat{Q_{cond}} \approx L(P_R + \frac{\widehat{\partial c}}{\partial t}_{phys}) + L_i P_S \tag{19}$$

Sources of moisture

$$\widehat{W_{turb}} = E \tag{20}$$

$$\widehat{W_{cond}} = -P_R - P_S - \frac{\widehat{\partial c}}{\partial t}_{phys} \tag{21}$$

or for the total water content r:

$$\widehat{R_{turb}} = E \tag{22}$$

$$\widehat{R_{cond}} = -P_R - P_S \tag{23}$$

VERTICALLY INTEGRATED BUDGETS

Thus we get balance equations for the conservative variables
enthalpy $S = c_p T$

$$\widehat{\frac{\partial S}{\partial t}}_{phys} = (F_{rad})_{TOA} - (F_{rad})_{SFC} + L(P_R + \widehat{\frac{\partial c}{\partial t}}_{phys}) + L_i P_S + H + D \quad (24)$$

and total moisture r

$$\widehat{\frac{\partial r}{\partial t}}_{phys} = E - P_R - P_S \quad (25)$$

How to use the bugdet studies

- Elementary: Check the balance in the model
- External: Compare observed and calculated fluxes
- Internal: Study reasons of suspected imbalance

Examples

- Pictures of the balance
- Fluxes over sea
- A study of humidity balance

A study of humidity balance

Problem

Comparing forecasted and analysed integrated humidity tendencies of the SMHI HIRLAM reanalysis a bias was found: over large areas model tends to dry the atmosphere, $\overline{\frac{\partial \hat{q}}{\partial t_{an}} - \frac{\partial \hat{q}}{\partial t_{fc}}} > 0$.

Why: too much precipitation / too little evaporation?

- map of the bias
- vertical distributions
- method of regression analysis
- α and β

Method

The forecasted tendency of a variable τ_{forec} can be written as

$$\tau_{forec} = \tau_{dyn} + \tau_{phys} = \tau_{obs} + imb$$

Let us consider the moisture balance,

$$\tau_{phys} = \frac{\partial \hat{q}}{\partial t} = E - P$$

and assume, that the imbalance between observations and forecast is caused by physics. We can now write an estimate

$\tau^* = \tau_{dyn} + \alpha E - \beta P$ and find the optimal values of the coefficients α and β by minimizing the imbalance defined by the root-mean-square-error

$$rmse = \sum_{t=t_o}^{t_N} (\tau^* - \tau_{obs})_t^2$$

where the sum is taken over a time period and τ_{obs} is taken from analyses.

Differentiating with respect to α and β and requesting the result to be $\equiv 0$ we get a system of equations for every grid point, where $\alpha(x, y)$ and $\beta(x, y)$ can be solved.

Results

- α
- β
- corrected bias

Thus, everywhere where evaporation is significant, the method used tries to increase evaporation and leave precipitation unchanged.

References

[Trenberth(1997)] Trenberth, K.E., 1997. *Using atmospheric budgets as a constraint on surface fluxes.* **J.Climate**,10,2796-2808.

[Fortelius(1998)] Fortelius, C., 1998. *Atmospheric moisture and energy budgets for the Baltic Sea area.* In: Final report for the EU contract ENV4-CT95-0072:Numerical studies of the energy and water cycle of the Baltic region, Lennart Bengsson, coordinator. 73-84, Hamburg, August 1998.