Use of TOVS data in Nordic analyses

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Abstract

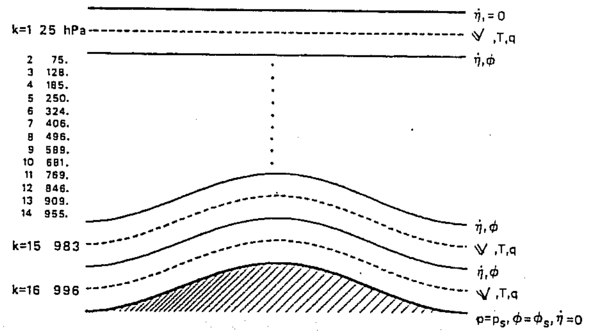
Since the autumn of 1985 the NWP work in the Nordic countries (e.g. Denmark, Finland, Iceland, Norway and Sweden) has been coordinated in the HIRLAM project. HIRLAM (High Resolution Limited Area Modelling) is a joint Nordic-Dutch development project aiming at an operational system for short-range (up to two days) high resolution analysis and forecasting. The proper use of TOVS data has been considered an essential part of the work. In this report the TOVS work carried out so far will be summarized.

1 The HIRLAM system.

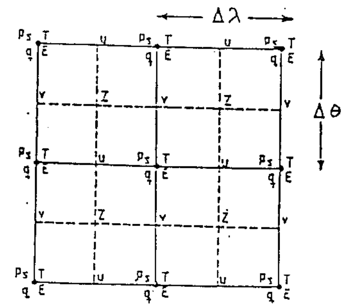
The HIRLAM development work has now been going on for three and a half years. The preset goal was a forecast model with a resolution corresponding to that of a grid-point model with a meshsize of the order 50 kilometer, and a vertical resolution of some 20 levels. The work has resulted in a prototype of an operational system, consisting of pre-processing, analysis, initialization, forecast and post-processing. The prototype, called the HIRLAM Level 1 System, is presently being implemented for operational use in Denmark and Finland. In the Netherlands, Norway and Sweden operational implementation is still waiting final decisions on computer facilities, in the meantime pre-operational testing and further development is being carried out. The first phase of the HIRLAM work is summarized in [1]. The work has been carried out primarily on the ECMWF computer systems, and observational data as well as lateral boundary data for the testing have been extracted from the ECMWF data bases.

The joint development activity is, since March 1st 1989, being continued in a second phase, referred to as HIRLAM 2. Its aim is to develop the existing system, by adding more sophistication to numerical techniques, physical parameterization and analysis methods. Furthermore, more basic research into methods for, and problems with, still higher resolutions will be investigated.

In designing the HIRLAM Level 1 system a primary objective has been a working system that could be handed over for operational implementation at the participating National Institutes at the end of the three year development period. In order to safely fulfill this goal, the Level 1 system is in many aspects rather conventional, building on already existing models and methods. The system is described in considerable detail in a documentation manual [2]. It is summarized in figure 1, and consists of the following parts.



Vertical distribution of model levels and staggering of variables for the 16 level version of the HIRLAM model. Rounded pressure values are calculated with a surface pressure of 1000 hPa.



The horizontal (transformed lat.-lon., Arakawa C) grid.

ANALYSIS

Method	3-dimensional multi-variate statistical interpolation (Limited area version of the ECMWF scheme with modified parameters)
Independent variables	λ, θ, η, , t
Dependent variables	ϕ, u, v, r (geopotential, horizontal wind, relative humidity)
Grid	Non-staggered horizontal grid, vertical levels as in the prediction model
First guess	6 hour forecast (complete prediction model)
Data assimilation frequency	6 hour (±3 hour window)

INITIALIZATION

Method	Adiabatic non-linear normal mode initialization. 4 vertical modes initialized (Modified KNMI scheme)

PREDICTION

Independent variables	λ, θ, η, t
Dependent variables	T, u, v, q, p_s (temperature, hor. wind, mixing ratio, surface pressure)
Grid	Staggered in the horizontal (Arakawa C-grid) Uniform horizontal (transformed latitude-longitude grid). Non-uniform vertical spacing of levels (see above).
Finite difference scheme	Second order accuracy.
Time-integration	Leapfrog, semi-implicit (Δt = 5 min)
Horizontal diffusion	Non-linear second order scheme with height-dependent q-diffusion.
Earth surface	Albedo, roughness, soil moisture and snow are geographically specified (climatology). Sea surface temperature and sea ice are analysed.
Orography	Smoothed US Navy mean orography.
Physical paramerization	Vertical diffusion: (i) Boundary eddy fluxes dependent on roughness length and local stability (Monin-Obukhov) (~ ECMWF, version RM3/REV3, 1/87). (ii) Shallow convection (HIRLAM scheme). (iii) Free-atmosphere turbulent fluxes based on mixing length theory (ECMWF, version RM3/REV3, 1/87, except λ_m = 30 m).
	Convection: KUO convection scheme (slightly modified ECMWF scheme).
	Stratiform condensation: Slightly modified ECMWF scheme (model saturation point at true relative humidity of 95 %).
	Radiation: HIRLAM scheme. Longwave radiation scheme (refined 'direct cooling to space' scheme) + shortwave radiation scheme (with diurnal cycle and multiple reflections between model layers). Clouds given as a function of relative humidity. (100 % cloudiness at saturation point of stratiform condensation scheme).
	Surface processes: HIRLAM scheme. 3 layers in soil. Separate fluxes from land and water part of the grid box.
Lateral boundaries	Simplified Davis relaxation scheme

Figure 1: The HIRLAM Level 1 system

1.1 Analysis

The HIRLAM Level 1 analysis system consists of a scheme for analysis of wind, mass and humidity fields, based on the present operational ECMWF analysis, [3], and a scheme for analysis of sea surface temperature and ice coverage based on a successive correction method developed by the HIRLAM group. The ECMWF analysis scheme has been modified to accomodate the limited area and higher resolution of HIRLAM as compared to the operational ECMWF system.

- The geometry has been modified to a limited area. For HIRLAM a rotated equidistant latitude-longitude spherical coordinate system is used.
- The assumed forecast first guess error is allowed to grow quicker from its assumed initial value (i.e. the analysis error) than in ECMWF operations. This leads to relatively greater weights given to the observations.
- Analysis "box size" and data search radius have been reduced to 330km and 930km respectively, due to the higher data density in the HIRLAM area compared to the globe.

The sea surface analyses are carried out with a successive correction method. The input observations may be genuine observations from ship or satellite, "pseudo-observations" extracted from manual analyses or gridpoint values form other SST analyses. A special feature of the HIRLAM system is that each and every grid box is assumed to consist of a "sea/lake" part and a "dry land" part. SST analyses must then be carried out for (almost) all gridpoints, and each gridpoint is assigned two surface temperatures, one for water and one for land.

1.2 Initialization

The initialization scheme is a non-linear normal mode scheme, utilizing the Machenhauer technique. In the standard version all gravity modes in the four gravest vertical modes are initialized, using adiabatic tendencies and two iterations. The vertical modes are determined as eigenfunctions to a linearized form of the vertically discretized model, using the ICAO atmosphere at rest as basic state for the linearization. The horizontal modes are the eigenfunctions in terms of velocity potential, stream function and geopotential of linearized shallow water equations for the equivalent depths of the vertical modes. In the linearization, the Coriolis parameter is assumed constant and equal to the value at the centre of the limited area. The forecast model itself is employed for the calculation of the adiabatic tendencies. These tendencies include contributions from the lateral boundary fields through the relaxation scheme of the forecast model.

1.3 Forecast Model

The HIRLAM Level 1 forecast model was developed from earlier limited area versions of the first ECMWF gridpoint model [4], [5]. The present model has undergone major redesigns and revisions, the most important are the following.

- The model is formulated in vertical hybrid coordinates.
- The model is prepared for a general conformal horizontal coordinate system or map-projection, through the inclusion of two map-factors. At present the model employs a rotated spherical coordinate system with equidistant latitude and longitude increments.

- The model physics is in many aspects inspired from the present operational ECMWF model, while other parts are developed entirely by the HIRLAM group.
- The model code has been written in such a way that it utilizes the potential of vector computers with large internal memories. Thus, in the dynamic part, calculations are carried out over a complete horizontal surface without the need of an I/O-scheme. This simplifies the introduction of alternative numerical techniques, such as semi-Lagrangean advection or spectral methods. The physics code is to a great extent independent of the dynamics part, employing vertical slabs consisting of a number of grid-columns.

2 HIRLAM activities with TOVS data.

For northern Europe the data void areas in the Arctic and north Atlantic is a serious problem when it comes to short range (up to two days) numerical forecasting. Hence the advent of remotely sensed, high resolution profiles of temperature and humidity, such as TOVS, has generated much optimism, and the proper use of high resolution TOVS data was given high priority in the HIRLAM planning. Data impact studies and observing system experiments on TOVS data retrieved with different methods, as well as research into the representativity and accuracy of the profiles were planned. However, during the course of the HIRLAM work so far only a few limited experiments have been carried out, due mostly to other pressing problems encountered in the HIRLAM work, but also to the fundamental problems encountered by colleagues working with TOVS data elsewhere.

2.1 A data assimilation experiment with high resolution TOVS data.

High resolution TOVS profiles are derived in many places by the use of the International TOVS Processing Package (ITPP) developed by the Cooperative Institute of Meteorological Studies (CIMSS), University of Wisconsin, Madison, Wisconsin, USA. TOVS products are calculated with a resolution of about 75 km. Version 3 of this package has been implemented at the Swedish Meteorological and Hydrological Institute (SMHI). An alternative inversion technique (THAP) developed at SMHI by Jan Svensson, [6], has been incorporated in the local version of ITPP3.

The basis of the inversion method is the radiative transfer equation. Surface data of temperature, humidity and pressure are also incorporated into the method. Basis splines (B-splines) are used to represent the temperature and humidity profiles. Physical constraints, some of them represented as linear inequality constraints, are also included. This leads to a linear least-squares problem with linear inequality and equality constraints. The behaviour of the solution, e.g. its smoothness, is influenced by the use of a "penalty term" or regularization functional which reflects the supposed behaviour of the solution. Because of the nonlinear properties of the radiative transfer equation, the process has to be iterated a few times.

The temperature profiles in ITPP are represented in 40 levels transformed to a spline representation in THAP. One problem is the low resolution near the ground, the four lowest levels are 850,920,950 and 1000 hPa. In order to resolve surface inversions an extra constraint was added to the least squares problem by comparing the temperature at the lowest model level ($\sigma = 0.992$) with an analysed or diagnosed 2-meter temperature (T_{2m}).

The THAP inversion profiles have been used in a data assimilation experiment carried out by N. Gustafsson and J. Svensson, [7], where model generated temperature-humidity profiles were used as first guess profiles for the THAP inversion, and with objectively analysed 2 meter temperatures (T_{2m} and humidities (RH_{2m}) as a "weak" constraint during the inversion. This experiment was carried out with an early version of the HIRLAM syst... referred to as the "Baseline System", [9]. It differed from the present HIRLAM Lev... system in several aspects, in particular the objective analyses were carried out with a version of the operational Swedish-Danish analysis system, [8], rather than the limited area version of the ECMWF system. The use of model generated first guess profiles lead to a modification of the penalty term, in that it required the corrections to the initial guess profile to be smooth, rather than the profiles themselves. This would allow model generated details, (e.g. inversions) to be retained.

The experiment was carried out in an area of 74 $*$ 66 gridpoints with a horizontal resolution of $0.6° * 0.6°$ and 12 vertical levels.

Some features of the experiment are listed below.

- The analysis method is three-dimensional optimum interpolation of forecast errors. The analysis is applied univariately first to mass and then to wind, followed by a variational adjustment of the increments toward geostrophic balance.
- The TOVS data enter as thicknesses between 1000hPa and the analysis levels.
- Standard deviations for the observational errors as well as their spatial correlation were given ad-hoc values, they are listed in ref. [7].
- At most 4 radiosonde geopotential values, 3 sea-level pressures and 3 TOVS thicknesses were selected to influence the geopotential analysis in one gridpoint.
- Operational SMHI analyses were used as initial first guess and as lateral boundary conditions.
- Manually analyzed SST was used as the lower boundary condition over sea.
- The satellite data were received at the Danish Meteorological Institute, Observatory for Space Research, Rude Skov, Denmark, where a read-out station is situated. Five passages from May 18th and 19th 1983 were treated.

The data assimilation was started on May 18th 1983, 00UTC. One reference assimilation, called NOTOVS, excluding the TOVS data, but in all other aspects similar to the TOVS assimilation was used for comparison. The general weather situation over Europe was characterized by a large-scale cold trough over the British Isles and a warm ridge over eastern Europe. The main feature to be captured by the analyses is a small wave on a frontal zone separating the two air-masses. On May 18 12UTC the wave is found over southern Scandinavia, see fig. 2, and in the following 24 hours it develops and moves north-north-west towards the Norwegian Sea, fig 3. Since this development took place in a region with good coverage of conventional data, already the NOTOVS run gave gave a very good forecast, fig. 4. It must be pointed out that the period was selected from availability of TOVS radiances, rather than synoptic interest.

The retrieved TOVS profiles were first compared with the corresponding profiles retrieved with climate as first guess. The RMS differences of 39 TOVS profiles to radiosondes are compared in figure 5. It can be concluded from the figure that the use of +6 hour forecast first guess profiles results in better retrievals than the use of climatology, particularly near the ground and the tropopause. The forecast model is able to provide the retrieval scheme with a better tropopause guess, and the ground inversion treatment improves the profiles in that part of the atmosphere.

A comparison of analysis increments from the two experiments reveals that the TOVS data have an impact on the analyses mainly in areas without radiosonde data. This is a direct effect of the assumptions, i.e. that TOVS data were given larger observational errors than the conventional data. TOVS impact is greater at 06UTC and 18UTC than at 00UTC and 12UTC due to the timing of radiosondes. Perhaps a more important test

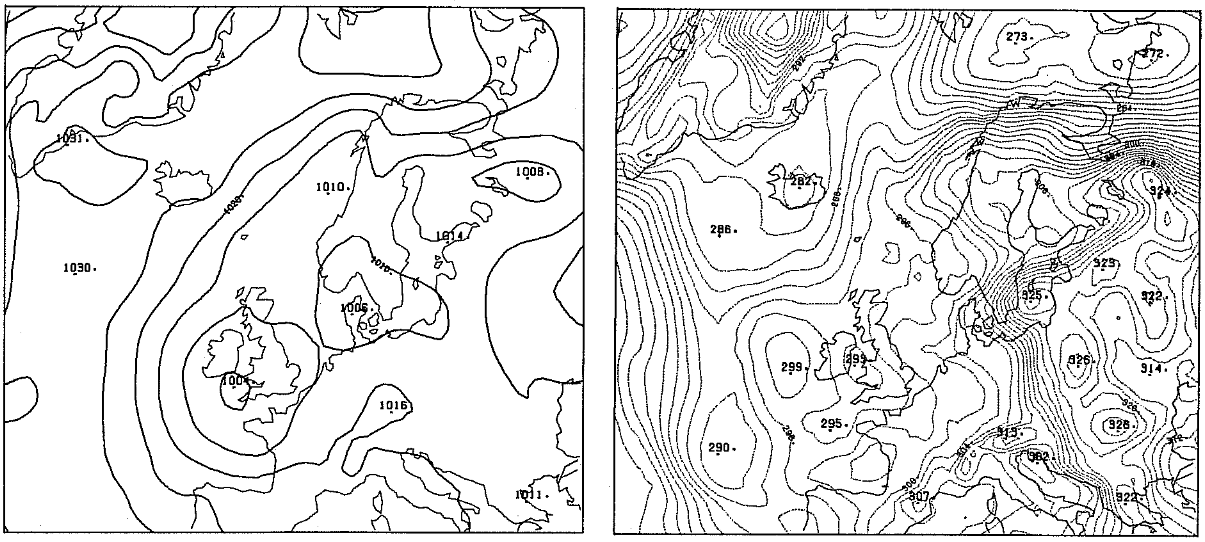


Figure 2: Analyses of $P_{m.s.l.}$ (left) and θ_{e850} (right), valid at May 18 1983 12UTC.

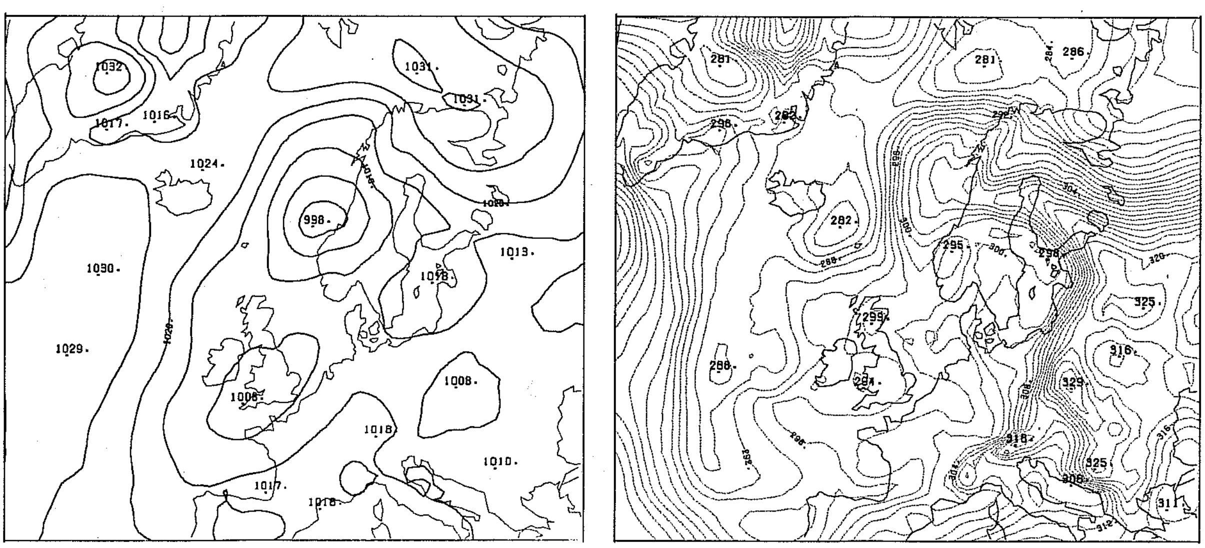


Figure 3: Analyses of $P_{m.s.l.}$ (left) and θ_{e850} (right), valid at May 19 1983 12UTC.

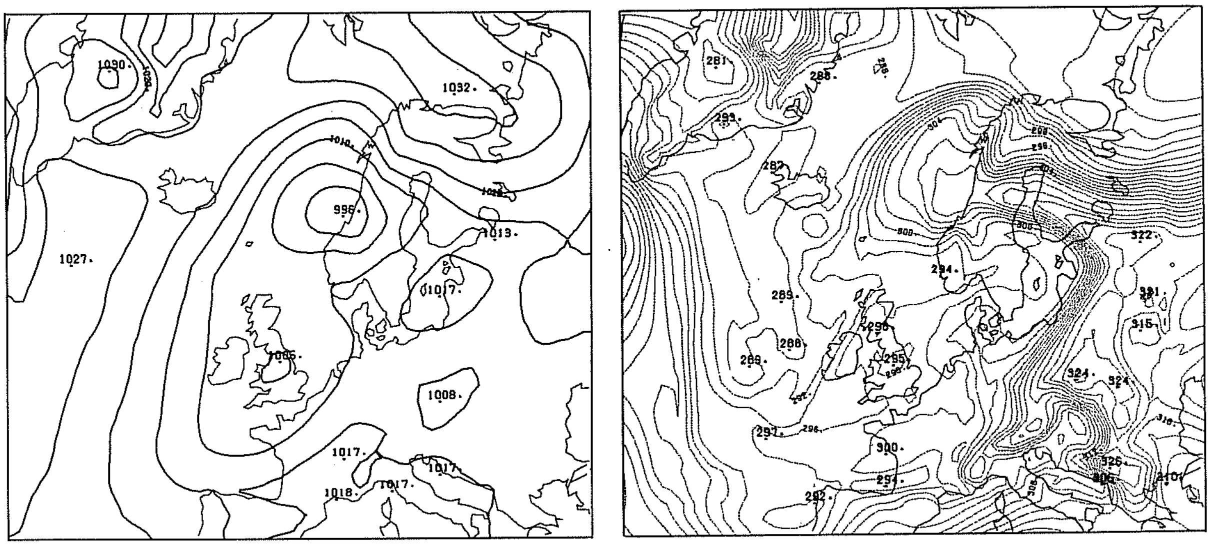


Figure 4: +24 hour NOTOVS forecasts of $P_{m.s.l.}$ (left) and θ_{e850} (right), valid at May 19 1983 12UTC.

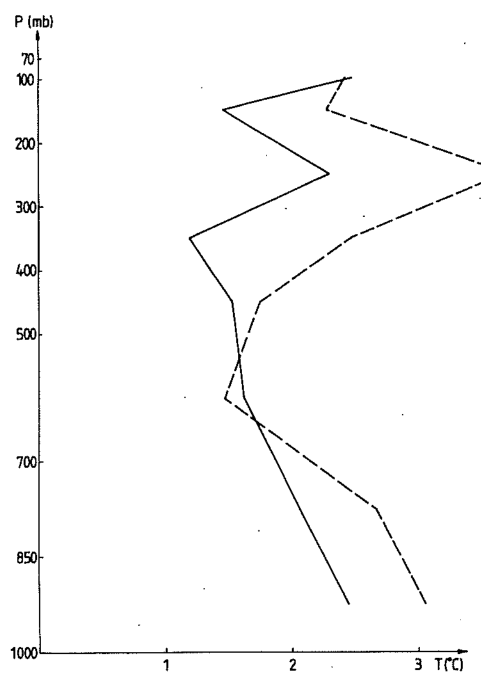


Figure 5: RMS differences in layer mean temperature between TOVS profiles and radiosonde data. Full lines are retrievals using forecast first guess, dashed are form climatological first guesses.

Verification time and forecast length	Experiment	Layer hPa	N (sample size)	Bias °K	RMS °K
May 18 1983 12:00	NOTOVS	500/850	99	0.18	0.96
forecast length +6h	TOVS			0.33	0.99
	NOTOVS	300/500	98	0.38	1.18
	TOVS			0.45	1.22
	NOTOVS	100/300	88	-0.20	0.96
	TOVS			-0.25	0.98
May 19 1983 00:00	NOTOVS	500/850	102	-0.33	1.19
forecast length +6h	TOVS			-0.36	1.10
	NOTOVS	300/500	101	-0.30	1.20
	TOVS			-0.11	1.05
	NOTOVS	100/300	93	0.23	1.13
	TOVS			0.07	1.08
May 19 1983 12:00	NOTOVS	500/850	101	0.29	0.90
forecast length +6h	TOVS			0.32	0.91
	NOTOVS	300/500	101	0.33	1.04
	TOVS			0.37	1.06
	NOTOVS	100/300	94	-0.23	0.90
	TOVS			-0.26	0.89

Table 1: Mean differences (bias) and RMS differences between radiosonde and short-range LAM forecast values of layer mean temperatures.

of the impact of the TOVS data is a comparison between the +6 hour forecasts used as first guess in the data assimilations. The obvious purpose of the data assimilation is to produce as good a first guess as possible in order to make the best use of observations from the next cycle in the intermittent assimilation. The mean and RMS differences between radiosondes and three +6-hour forecasts are shown in table 1. If only RMS differences of the order 0.1K or greater are considered to be of any significance, the TOVS forecasts are seen to be somewhat closer to the radiosondes than the NOTOVS forecasts, at least for some of the analysis times.

Forecasts from the TOVS and NOTOVS assimilations were verified against analyses from both assimilations. In figure 6 the RMS differences of the 500 hPa forecasts when verified against NOTOVS are shown, and the same forecasts are verified agains TOVS analyses in figure 7. In the case of verification against TOVS analyses, the TOVS forecasts are slightly superior throughout the forecast lengths. In the case of verification against NOTOVS the NOTOVS forecasts are better at the start, which is natural since the initial deviation obviously is zero, but soon the TOVS forecasts overtake them. Unfortunately the TOVS assimilation was not carried far enough in time to allow verification of the last forecast. Although the statistical measures indicated a small positive benefit from the TOVS data, it was impossible to demonstrate a synoptic feature that was clearly superior in the TOVS forecast.

From this study, the authors [7] concluded that the THAP method applied to data assimilation forecast first guess profiles gave clearly improved retrievals when compared with climatological first guess profiles. The retrievals were sensitive to the treatment of ground inversions. Analysis and forecast experiments indicated a small but noticeable improvement from the THAP profiles, although the synoptic situation selected was not optimal for TOVS impact demonstration.

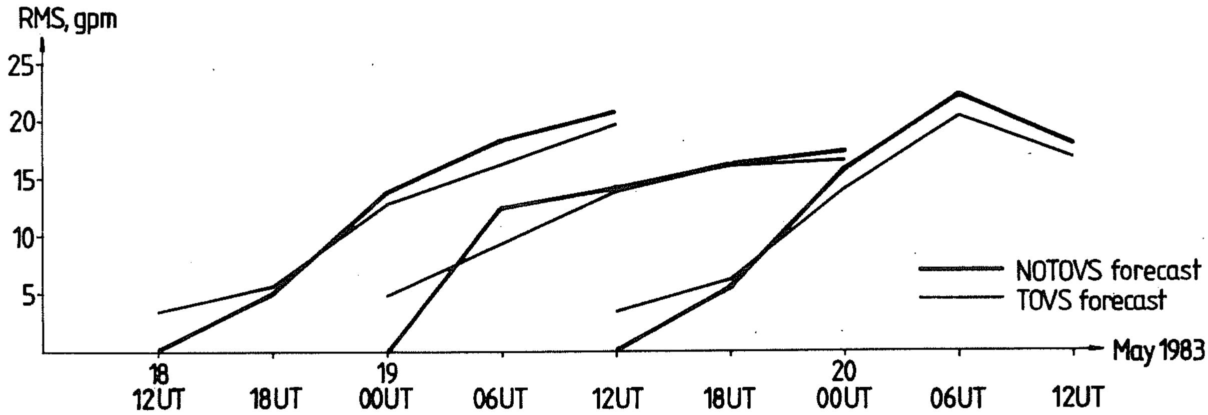


Figure 6: Verification of TOVS (thin lines) and NOTOVS (thick lines) forecasts against NOTOVS analyses. RMS values of the Φ_{500} differences over the whole domain are given.

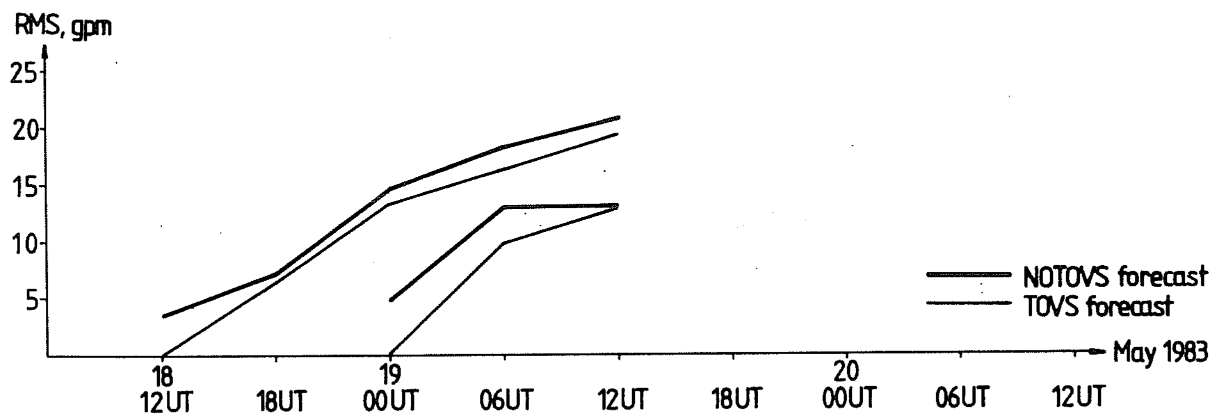


Figure 7: Verification of TOVS (thin lines) and NOTOVS (thick lines) forecasts against TOVS analyses. RMS values of the Φ_{500} differences over the whole domain are given.

2.2 HERMES data

Through a kind effort by the U.K. Meteorological Office, a set of high resolution TOVS profiles, retrieved with the HERMES system, were made available to the HIRLAM group. The data covered the period September 3 - 5 1985, a period that was extensively used in the HIRLAM "baseline experiments", [9]. Nils Gustafsson made a comparison of the HERMES data with the HIRLAM analyses. Standard GTS "SATEM" profiles had been utilized for these analyses. The comparison was made in the form of plots of observed deviations from the analyses, and some conclusions could be drawn.

- The HERMES data showed a spatially and temporally consistent deviation from the analyses.
- At the initial time of a forecast run of a rapid cyclogenesis originating over the Irish Sea, the HERMES data indicated a general weakening of the baroclinicity of the frontal zone. Profiles on the warm side were too cool while those on the cold side were too warm. The profiles in the critical region had been retrieved with the "partly cloudy" algorithm. The correct analysis of this baroclinicity turned out to be crucial for the correct forecast of the explosive cyclogenesis, see [9].
- Six hours seems to be too long a period for the intermittent data assimilation. At one instance, profiles valid around 0330UTC 5 Sept 1985 indicated a small-scale wave that was ahead of the 00UTC analysis, but behind the 06UTC analysis. Application of these profiles indiscriminantely at either of the analysis times would have resulted in incorrect analyses.

2.3 Future activities

The HIRLAM project is now being continued in a second phase, initially concentrating on further development of the existing system, but also aiming at studies of even higher resolutions. A project plan for HIRLAM 2 has been approved by the participating institutes; the plan contains the following TOVS- and general satellite related activities.

- Monitoring and tuning of TOVS radiance data: Optimal use of locally received radiances calls for monitoring and tuning of the so-called δ/γ corrections applied to the (not completely known) transmission functions used for the retrievals. A subproject for such tuning and monitoring, concentrating on high latitude data, is in progress.
- Data assimilation experiments: Planned TOVS assimilation experiments in the HIRLAM 1 phase were only carried out to some extent due to other urgent work. In HIRLAM 2 we hope to be able to carry out more experimentation with different retrievals and datasets. This work will be carried out in close cooperation with other groups in Europe engaged in similar activities.
- New analysis techniques: For optimum use of new observation sources, such as TOVS data, it is now believed that rather radical changes to the assimilation methods are required. One promising approach is that of the adjoint technique developed in France. In HIRLAM 2 it is intended to follow this development very closely, and also to carry out own experiments, initially with the existing HIRLAM spectral limited area shallow water model, [1].
- AVHRR - data: High quality cloud and precipitation data deduced from multispectral classification of AVHRR-data, see below and [10] is a potential source of information for analyses of cloud water and latent heat release. Such analyses will be used for initialization of model cloud water and as forcing in diabatic normal mode initialization.

3 Swedish TOVS activities

At SMHI the THAP retrieval scheme has been running in a semi-operational mode during the winter and spring of 1989. Retrievals have been produced during the first week of October and December 1988 and February and April 1989 respectively. The radiances are read down locally at SMHI with the "PROSAT"-system capable of reception and processing of data from both polar-orbiters and geostationary satellites (Meteosat). Presently PROSAT is used operationally primarily for reception of AVHRR data for imagery and multi-spectral classification of clouds and precipitation, for a description of this activity see Karlsson 1989, [10].

As first guesses for the TOVS retrievals, short forecasts from the operational SMHI LAM system are used. The operational SMHI LAM system is similar to the system used for the assimilation experiment described above, but with a lower resolution of 0.9° * 0.9° and 12 vertical σ-levels. In addition, the LAM analyses of T_{2m} and RH_{2m} are also used. The retrievals are not used in the data-assimilation, but as stand-alone data copresented together with other information, in the form of AVHRR imagery and LAM analysis/forecast contours. The THAP profiles of layer mean temperature and integrated water contents are expressed as numerical values, presented on a colour-screen at the sites of the radiances. Both basic parameters (e.g. $\Delta\Phi_{500-1000}$, integrated water content or O_3 content) and derived parameters (e.g. a convection index dependent on temperature and humidity) are presented. The purpose of the exercise is to see what information the TOVS data in this form can provide to the real-time forecaster ("Nowcaster"). Also, the quality and usefulness of the retrievals in relation to the synoptic patterns is being investigated.

This activity is in progress and so far the results are available in the form of colocation statistics of the retrievals with nearby radiosondes. Tables 2 and 3 presents the first preliminary results for layer mean temperatures and integrated water contents respectively. Only NOAA-10 has been used for the retrievals, hence the comparisons have been made to 06UTC and 18UTC radiosonde data.

Pressure layer hPa	Bias °K	RMS °K	St.Dev. °K	Sample size
1st week, October 1988				
100-70	-1.2	1.76	1.34	57
200-100	-0.5	2.25	2.21	144
300-200	-0.5	2.53	2.48	154
400-300	-1.7	3.08	2.60	156
500-400	-1.8	3.10	2.55	156
700-500	-1.0	2.34	2.14	156
850-700	-0.7	2.05	1.92	156
1000-850	0.0	2.14	2.14	157
1st week, December 1988				
100-70	-1.6	2.55	2.02	63
200-100	-0.2	2.29	2.49	151
300-200	0.4	3.10	3.09	163
400-300	-0.5	2.47	2.42	163
500-400	-0.5	3.21	3.17	164
700-500	-0.5	3.00	2.97	165
850-700	-0.5	2.78	2.75	165
1000-850	0.1	2.82	2.82	165
1st week, February 1989				
100-70	-0.1	2.00	2.01	63
200-100	0.6	2.43	2.37	153
300-200	1.1	3.07	2.87	161
400-300	0.0	2.70	2.71	166
500-400	-0.5	3.28	3.25	170
700-500	-0.7	2.55	2.45	170
850-700	-0.6	2.07	1.99	170
1000-850	0.0	2.28	2.29	170
1st week, April 1989				
100-70	-0.6	1.53	1.42	91
200-100	-0.1	1.80	1.81	198
300-200	0.3	2.21	2.19	212
400-300	-1.0	2.07	1.79	213
500-400	-1.2	2.35	2.03	214
700-500	-0.9	2.13	1.95	214
850-700	-0.6	2.35	2.28	214
1000-850	-0.3	2.58	2.57	214

Table 2: Mean differences (Bias), RMS and Standard Deviation between TOVS (NOAA-10) retrievals and radiosonde layer thicknesses. 06 and 18UTC. Colocation window: $\pm 3h$ and $\leq 150km$

Pressure layer hPa	Bias *mm.*	RMS *mm.*	St.Dev. *mm.*	Sample size
1st week, October 1988				
400-500	0.02	0.29	0.29	107
400-700	0.15	1.56	1.56	107
400-850	0.28	2.51	2.50	107
400-1000	0.09	3.16	3.18	107
1st week, December 1988				
400-500	0.04	0.19	0.19	105
400-700	0.07	0.88	0.88	105
400-850	0.11	1.55	1.55	105
400-1000	-0.02	2.32	2.33	105
1st week, February 1989				
400-500	0.07	0.15	0.13	111
400-700	0.20	0.68	0.65	111
400-850	0.26	1.44	1.42	111
400-1000	-0.04	2.16	2.17	111
1st week, April 1989				
400-500	0.05	0.19	0.19	142
400-700	0.19	0.98	0.97	142
400-850	0.24	1.86	1.85	142
400-1000	0.37	2.78	2.77	142

Table 3: Mean differences (Bias), RMS and Standard Deviation between TOVS (NOAA-10) retrievals and radiosonde integrated water contents in mm. 06 and 18UTC. Colocation window: $\pm 3h$ and $\leq 150km$

Acknowledgements:

The Nordic Council of Ministers is acknowledged for financial support of the HIRLAM project. The work and progress of the project would not have been possible without the expertise, objective analysis scheme, meteorological data and computer resources of ECMWF. The work reviewed here has been carried out by Nils Gustafsson and Jan Svensson, in co-operation with the rest of the HIRLAM group. Any errors or inadequacies in this paper are entirely due to the reviewer.

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