# Sunshine and Rain inside a Computer

**Numerical weather prediction (NWP) models are among the most omnipresent applications in computational science. Most of us are interested in tomorrow's or even next week's weather, be it for personal or professional reasons. Although plans based on weather forecasts may still sometimes be laid in an air of uncertainty, the modern NWP models can be heralded as one of the triumphs of modern computer architectures and computational methods.**

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The earliest attempts at weather forecasts were founded on reading the signs of nature. The physical principles behind meteorological phenomena have been understood fairly well for about a hundred years, and the meteorological observation network has been available and growing for roughly the same period. However, it's only since 1950s that the development of computers and numerical methods have made NWP models possible and increasingly reliable.

It is a historical curiosity that **L. F. Richardson** attempted a numerical solution of the equations governing the atmosphere's behaviour in 1922 by hand. Richardson's computational model failed; not only by being too slow to predict anything – even though only two grid points were considered – but also by yielding pressure changes that were wrong by an order of magnitude. Looking back, the numerical method used was unstable. At the time, the failure was attributed mainly to the absence of upper-air soundings for initial data.

NWP models are typical representatives of physical and engineering problems solved by a computer, and can be considered as a branch of computational fluid dynamics. Today's NWP models are based on standard computational methods and tools for partial differential equations.

HIRLAM (*High Resolution Limited Area Model*) is an NWP model used operationally by the Finnish Meteorological Institute (FMI). It is a short-range forecasting model that has been developed in cooperation between nine European national weather services, including the FMI. Each country has a version of HIRLAM tuned to its needs. The development of HIRLAM started in 1985, and the first version was made operational in Finland in 1990. A joint research project continues to develop the model.

## Meteorology in equations

The dynamics of the atmosphere are governed by the universal conservation laws for momentum, energy, and mass. Their mathematical formulation can be written as a system of partial differential equations that describe how atmospheric quantities, or fields, depending on three spatial co-ordinates, change with time from some given initial values. Typical fields considered in the NWP models are wind, temperature, pressure, specific humidity, and the cloud condensate content. The equations that govern the evolution of these fields are shown in Figure 1.

This system of equations is too complex to be solved analytically: computers are used to find approximate solutions by numerical methods. Before they can be solved numerically, the continuous equations must be discretized by representing the field variables by their values at a set of grid points in a three-dimensional space. The further apart the grid points are spatially, the less accurate the forecast will be. On the other hand, the finer the discretization is, the more computer time and memory the solution requires. The variables' nodal values are calculated only at fixed moments. The difference between two consequent moments is a time-step. The length of the time-step is determined by accuracy considerations in order to limit cumulative numerical errors. A NWP model steps from a state of atmospheric variables to another as shown in Figure 2.

Many important processes have too small spatial scales to be resolved by NWP models, and have to be parametrized in terms of the

$$\frac{du}{dt} + \frac{1}{\rho}\frac{\partial p}{\partial x} + fv = F_x$$

$$\frac{dv}{dt} + \frac{1}{\rho}\frac{\partial p}{\partial y} - fu = F_y$$

$$0 = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g$$

$$c_v\frac{dT}{dt} + p\frac{d\rho^{-1}}{dt} = Q$$

$$\frac{dq}{dt} = S$$

$$\frac{dCCC}{dt} = P$$

$$\frac{1}{\rho}\frac{d\rho}{dt} = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right)$$

$$p = \rho RT$$

*Figure 1. The system of hydrodynamic equations equations governing the behavior of atmosphere. The terms in green denote unresolved sources and sinks.*

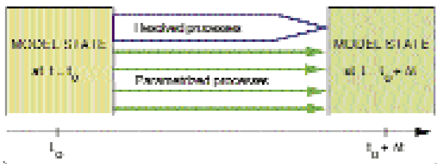



*Figure 2. The HIRLAM model steps from one state of atmospheric variables to another by solving the hydrodynamic equations without subgrid-scale sources and sinks and parametrizing the effect from the latter.*

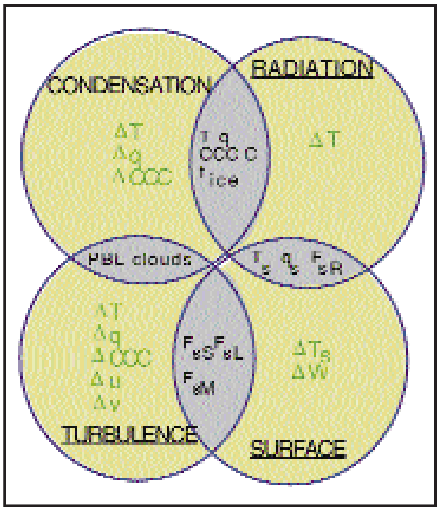



*Figure 3. Interactions between the HIRLAM model components. The green terms with Δ denote the change of a model variable within a specified parametrization scheme. The variables in the areas of intersection of parametrization schemes are influenced by both of the schemes.*

### Notation used in Figures 1-3.

| Variable / Constant / Abbreviation | Meaning |
|---|---|
| $p$ | Air pressure |
| $\rho$ | Air density |
| $u$ and $v$ | Northward and eastward wind components |
| $w$ | Vertical velocity |
| $T$ | Temperature |
| $q$ | Specific humidity |
| $CCC$ | Cloud condensate content |
| $C$ | Cloud cover |
| $f_{ice}$ | Fraction of ice in cloud |
| $T_s$ | Surface temperature |
| $q_s$ | Surface specific humidity |
| W | Soil moisture |
| $F_{sR}$ | Net radiation flux at the surface |
| $F_{sM}$ | Momentum flux at the surface |
| $F_{sS}$ | Sensible heat flux at the surface |
| $F_{sL}$ | Latent heat flux at the surface |
| $f$ | Coriolis parameter |
| $g$ | Gravity constant |
| $c_v$ | Specific heat of dry air at constant volume |
| $R$ | Gas constant for dry air |
| $PBL$ | Planetary boundary layer |

grid-scale variables. The most important parametrized phenomena include surface and soil processes, the condensation and generation of clouds and precipitation, radiative exchange and atmospheric turbulence.

In most cases, there is no universal relationship between the grid-scale variables and a particular process. The design of parametrization schemes is a difficult task calling for sound judgement. In a NWP model, typically about one half of the computing time is allocated to parametrized processes. Thus besides physical veracity, computational efficiency is important. From a practical point of view, what we usually think of as weather, e.g., surface air temperature, likelihood and amount of rain, cloudiness and near-surface wind, is strongly influenced by parametrized phenomena.

The equations describing the atmospheric flow behave chaotically: arbitrary small differences in initial conditions lead to completely different solutions in a limited time. Even if the initial state could be determined exactly, the errors introduced by discretization and parametrizations would still always limit the range of deterministic forecasting using NWP-models. A theoretical limit for deterministic weather prediction is estimated to be about two weeks. Today, the atmospheric state variables can be forecasted quite accurately one or two days ahead, while forecasts a week ahead often give the correct tendencies. Longer range forecasts are based on ensembles of deterministic forecasts starting from slightly different initial states. Even seasonal forecasts are being made with coupled atmosphere-ocean models using this technique.

## Parametrization of subgrid-scale processes

HIRLAM includes parametrizations for surface and soil processes, condensation and the generation of clouds and precipitation, radiative exchange and atmospheric turbulence. Interactions between the pa-

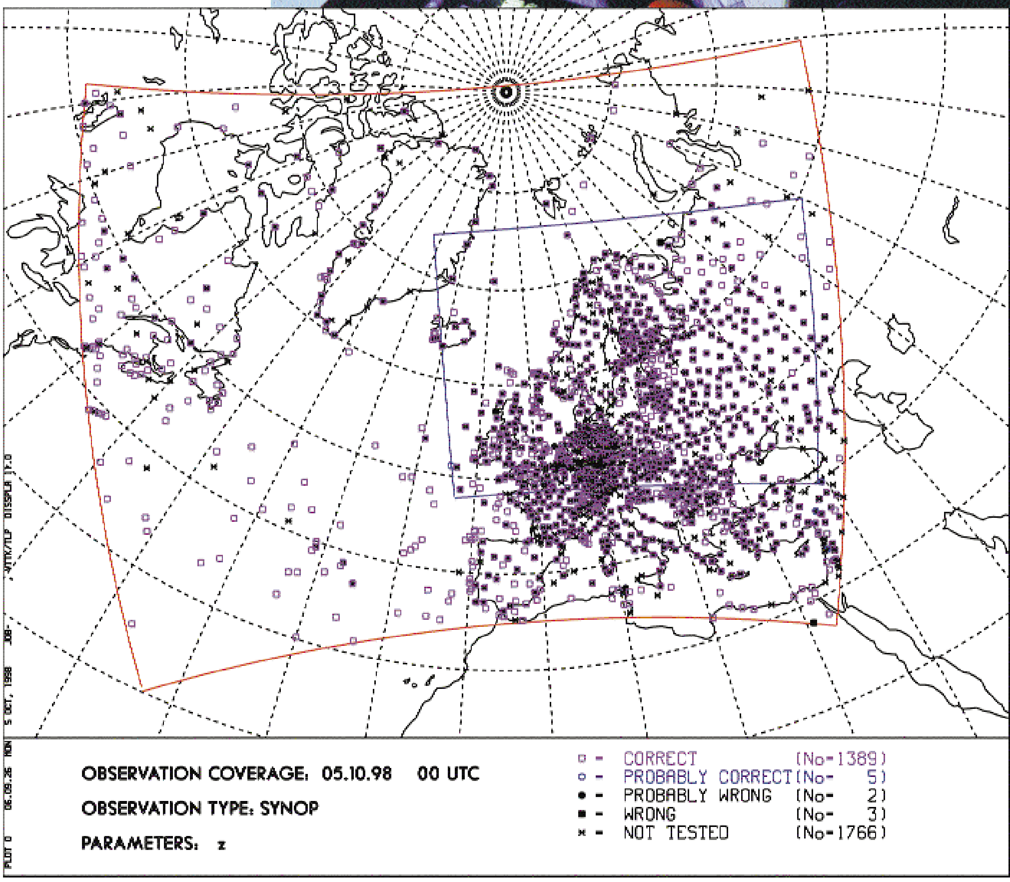



*Figure 4. Integration areas of the HIRLAM model and an example of available land surface surface observations. The outer area is for the Atlantic run and the inner for the Northern European run.*

rametrization schemes are shown in Figure 3.

The solar radiation is the ultimate driving force for atmospheric motions. The incoming radiation is absorbed and scattered by the air molecules, clouds, and earth surface. These also emit long-wave radiation back to space and towards the surface. It is impossible to calculate the radiative exchange in detail. In the Finnish HIRLAM model – developed in cooperation with the Department of Meteorology at the University of Helsinki – a parametrized two-interval scheme for long-wave and short-wave fluxes is adopted. For both intervals, cloudy and clear cases are treated separately.

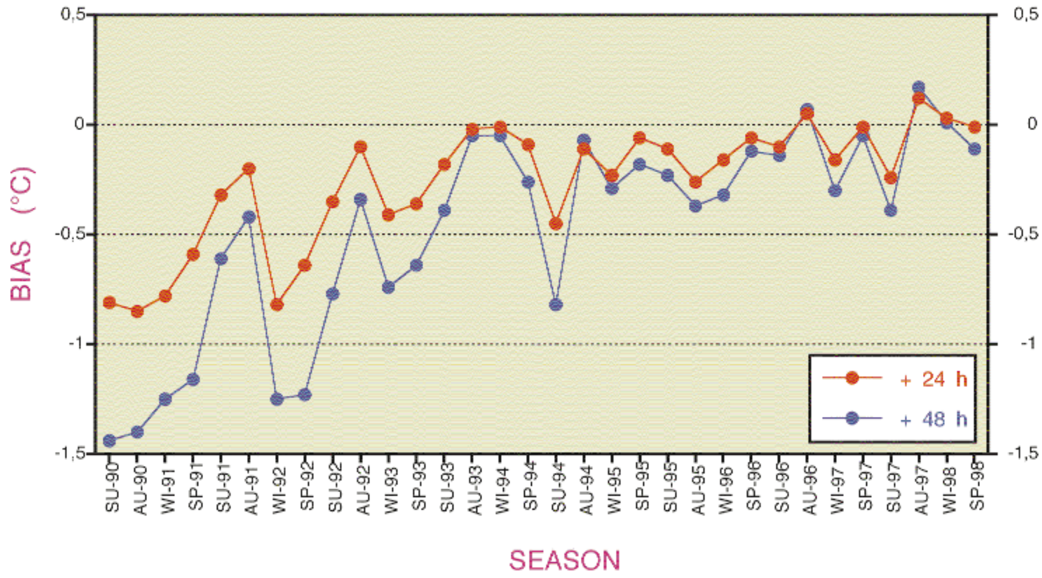
The surface parametrization describes the evolution of surface temperature, soil moisture, and snow depth with simple equations. Soil temperature at the uppermost layer is affected by net radiation flux, sensible and latent heat fluxes, and by ground heat conduction. The soil moisture varies with evaporation, precipitation, snowmelt, and the ground conduction of the soil water. The surface parametrization scheme uses observations of the sea surface temperature, the fraction of ice cover and snow depth.

In addition to the surface scheme itself, it is also important to describe the properties of the land and water surfaces as well as possible. The HIRLAM grid box is divided into land and water fractions, and the land part can further be divided into forest and open land fractions. This information has been collected from high resolution physiographic databases and is used further for determining some important surface parameters such as surface albedo and roughness length.

The planetary boundary layer (PBL) is the part of atmosphere that is directly influenced by the earth's surface and responds to surface forcings in about an hour or less. The PBL is a part of the troposphere, the atmosphere's lowest part, where the phenomena considered as weather take place and which reaches up to about 10 km. The height of the PBL may vary from about 30 m to over 3 km, depending on weather conditions, season of the year, and time of the day. In the PBL, the vertical transport of heat, momentum, and water are typically dominated by turbulence – the random and irregular small-scale flow. These fluxes are parametrized by using information of the vertical distribution of temperature, moisture and wind.

Clouds form in the atmosphere when water vapor condenses into cloud droplets. The most common causes of cloud formation are rising air currents, where the air is cooled as it expands due to decreasing pressure. Such currents may be connected with frontal systems or

*Figure 5. HIRLAM model verification: bias of the temperature at the 850 hPa pressure level (approximately 1.5 km) during 1990-1998.*




heating of the near-surface air by the sun. Condensation takes place because cold air can hold much less water vapor than warm air. Once the cloud droplets are formed, they can grow by collecting water vapor and smaller droplets. At sufficiently low temperatures, the droplets may freeze to form ice-crystals. In suitable conditions, the ice crystals grow rapidly until they fall out of the cloud. Most of the rain that falls over middle and high latitudes has actually gone through such a freezing phase. HIRLAM includes the parametrizations of cloud and precipitation microphysics, including condensation, evaporation, freezing and melting of cloud and rain droplets, as well as the dynamics of convective clouds.

## Discretization in space and time

HIRLAM (High Resolution Limited Area Model), as its name implies, covers only a fraction of the globe. The advantage of a limited area model is that for a given number of grid points – which together with the number of time-steps determines the computing time – one can afford a finer discretization. The difficulty is to account for the atmosphere's influence outside the treated area, on the weather inside it.

The Finnish HIRLAM is run operationally in two different horizontal areas and resolutions, as shown in Figure 4. The larger one, the main HIRLAM or ATL, covers Europe and Northern Atlantic and is run four times a day to produce 48-hour forecasts with the spatial resolution of approximately 44 km. The smaller integration area covering Northern Europe (EUR) is also run four times a day for a 48-hour forecast with the resolution of 22 km.

Both models have 194 x 140 grid points in the horizontal area and 31 levels in the vertical, reaching the altitude of approximately 30 km. The vertical levels are distributed so that the resolution is densest near the surface, where the levels follow the topography. The uppermost levels follow constant pressure surfaces.

Time-integration methods depend on the equation and the term considered to ensure the numerical stability and the efficiency. The time-step is three minutes in the ATL version of HIRLAM and two minutes in the EUR version.

## Initial and boundary values

The forecast model needs the initial conditions of the state of variables: temperature, wind components and humidity at all model levels, and for surface pressure and some other surface parameters, at the beginning of a simulation. This initial state, or the initial analysis, is based on the previous 6-hour forecast, which is corrected with the latest observations in the so-called analysis step. These observational data include radiosonde, satellite, surface and aircraft observations, which are received regularly at FMI from GTS (Global Telecommunication System). The observations are distributed geographically very unevenly as shown in Figure 4 for available surface observations. Moreover, the data sources are divided into quality classes to describe their reliability, and the acceptance or rejection of a given piece of observational data is decided during each analysis. Determining the initial state is done with the so-called optimum interpolation method and is a time-demanding computational task in itself.

A limited area model like HIRLAM also needs boundary conditions. The lateral boundary fields are obtained from the ECMWF (European Centre for Medium Weather Range Forecasts) global model. The boundary fields are adjusted to the HIRLAM grid by horizontal and vertical interpolation. Because the boundary data are based on a different forecast system and on an older analysis time than the present HIRLAM forecast, there is often mismatch between the boundary condition forecast and the HIRLAM forecast. This mismatch or "boundary error" is advected from the boundary zone into the inner area by the winds during the forecast. Due to strong westerly winds, typical of Scandinavia and the Northern Atlantic, the integration area's western border is placed much further than the eastern border in order to reduce the boundary error effect in our area of interest, i.e., Northern Europe.

## Computing power

The operational Finnish HIRLAM is run on 128 processors of the Cray T3E computer at CSC, taking precedence over other batch jobs. To get the most out of the CPU time available, efficient numerical and parallelization methods are chosen for solving the discretized equations. After rewriting a large part of the HIRLAM code – in co-operation with FMI, the Cray Research Ltd, SMHI (Swedish Meteorological and Hydrological Institute) and INM (Spanish Meteorological Institute) – the code scales excellently, giving a performance of 8.5 billion floating point operations per second. Recently, HIRLAM was benchmarked on Cray T3E-900, demonstrating near-linear scalability to 1024 processors. The data are communicated between processors using the Cray SHMEM library, but the program may also be run as a portable MPI version.

The data for one model state (or a forecast) takes 6 MB. These data are stored permanently on a disk with one-hour resolution and are kept on-line as long as the valid time of the forecast has not been passed. The long-term forecast data is stored on the fileserver.

## Forecasts and applications

The daily forecast published in various formats and media is largely based on the HIRLAM model results. A meteorologist, the duty forecaster, interprets, corrects, and adds new information to the numerical weather prediction by using additional observation data, knowledge of local climate, and the experience of the model's behavior in various weather situations to produce an up-to-date weather forecast. In addition to standard forecasts, FMI offers customised services for aviation, agriculture, and marine transport. The HIRLAM data is also used as an input for long- and short-term dispersion models of air pollutants, such as ozone, nitrogen and sulphur compounds, and radioactive and toxic matter.

FMI continuously monitors the quality of the HIRLAM forecasts. This verification is carried out in two streams: forecasts vs. observations and forecasts vs. analyses. The bias and RMS error are calculated monthly and are used to reveal model deficiencies and to test the model updates and improvements. Figure 5 shows an example from forecast vs. analysis verification: the seasonal temperature bias for the 850 hPa temperature (i.e., the temperature at the height of approximately 1.5 km) in HIRLAM forecasts during 1990-1998. The cold bias was considerably large in the early days of the operational HIRLAM, but has been much smaller since autumn 1994, mainly because of the introduction of the new improved radiation scheme.

## More information

Popularised and excellent treatment of atmosphere, weather, and climate is offered in [3]. Basic course books on numerical meteorology are [1,2].

The HIRLAM home page is at the FMI http://www.fmi.fi/TUT/MET/hirlam/.

The ECMWF WWW pages are found at http://www.ecmwf.int/.

There is a host of WWW sites offering meteorological services. One can get started, e.g., from Mikon sääsivu http://www.hyperaika.fi/weather/.

[1] Haltiner G.J. and Williams R.T., 1980. Numerical prediction and dynamic meteorology. John Wiley & Sons.

[2] Holton J.R, 1992. An introduction to dynamical meteorology. Third edition. Academic Press.

[3] Karttunen H., Koistinen J., Saltikoff E. and Manner O., 1998. Ilmakehä ja sää. Ursa.