ASPECTS OF WEATHER SIMULATION BY NUMERICAL PROCESS

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Weather prediction relies nowadays on the representation and numerical modelling of the atmosphere by a computer model. Since physical-mathematical equations that are exploited in order to govern the atmospheric flow are not precise, the models do not represent the real atmosphere entirely and accurately. Despite of this flaw the numerical weather prediction (NWP) provides the basis for the forecasting tools of modern meteorology. This dissertation investigates some specific problem areas of modern NWP activities.

Cloud microphysical processes and development of precipitation are examined. A physical mechanism is presented, which explains the initial step of rain droplet formation due to condensational growth and small-scale turbulent fluctuations. As such detailed simulations of microphysical processes are too slow and too expensive computationally to resolve directly in NWP models, simpler parameterization schemes are widely adopted. In this study so-called Sundqvist NWP rain parameterization scheme is studied. Special attention is given to the scheme’s sensitivity on the vertical resolution of the host model, the tuning of the coalescence parameterization constants and the scheme’s spectral compatibility by utilizing typical cloud and rain drop distributions.

Mesoscale winds and their mechanisms are studied in a sea gulf environment as the function of the prevailing flow. The inaccuracy of the predicted wind characteristics for coastal zones is serious problem for many NWP models. Eight different NWP setups with different grid spacing are examined, showing that the sea-land distribution of a model plays an essential role on the accuracy of the coastal wind forecasting. Increasing the horizontal resolution in mesoscale models below 10 km does improve the realism of the forecast but does not necessarily improve the traditional verification scores of deterministic forecast in cases of a sparse observational network and complicated heterogeneous surface like in coastal zones. Finally, two case studies are considered, aiming at the evaluation of HIRLAM (HIgh Resolution Limited Area Model) operational NWP model over the Baltic Sea as well in southern Finland in a case of a severe air pollution episode.
PREFACE

This work has been carried out at the Department of Physical Sciences, University of Helsinki and at the Finnish Meteorological Institute (FMI). Financial support by the FMI and by the Academy of Finland is gratefully appreciated.

I wish to express my deepest gratitude to my supervisor Prof. Hannu Savijärvi for his valuable advice during my academic career and professional guidance at every stage of my work. I would like to express my gratitude to Prof. Mikko Alestalo, to whom I am greatly indebted for the opportunity to be involved in research activities and for providing excellent working conditions and pleasant working atmosphere. I also want to acknowledge Prof. Markku Kulmala for fruitful discussions, criticism and encouragement. I am grateful to the FMI Meteorological Research division, especially colleagues in HIRLAM group for all the help. Special thanks to Carl Fortelius, Laura Rontu, Kalle Eerola and Simo Järvenoja for daily discussions and help whenever needed. Special thanks to Niko Sokka for the help and advice with MPI coding. I would like to thank also all the co-authors of the articles and referred papers.

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PAPERS I-VI
1. INTRODUCTION

Modern meteorology would be unthinkable without powerful computing facilities. In addition to a modern, powerful technical environment, present-day prediction of weather relies on detailed numerical weather prediction (NWP) models. NWP models such as HIRLAM (HIgh Resolution Limited Area Model, used in the Finnish Meteorological Institute and many other European Weather Services) do not represent the real atmosphere accurately, but are approximations formulated by using many mathematical equations.

The idea of numerical weather forecasting – predicting the weather by solving physical-mathematical equations – was formulated in 1904 by Vilhelm Bjerknes and developed by British mathematician Lewis Fry Richardson. Richardson introduced publicly his ideas and results in his 1922 book *Weather Prediction by Numerical Process*. It is indisputably the most famous book in meteorology but was unfortunately astonishingly ahead of its time. Richardson proposed a technique of using grid-point spacing and time-stepping finite difference calculations. And despite the fact that it took him 6 weeks to produce a 6-hour forecast that was wildly inaccurate, all modern computer weather and climate models are nowadays based upon Richardson’s idea. In his book’s Preface, he wrote: “Perhaps some day in the dim future it will be possible to advance the computations faster than the weather advances and at a cost less than the saving to mankind due to the information gained. But that is a dream.” Now the dream is fulfilled and the most powerful supercomputers in the world instead of 64000 human calculators (a vision of Richardson) are labouring with the most sophisticated NWP models.

The aim of the present study is to look at some specific problem areas of modern NWP activities and especially HIRLAM-based weather forecasts for Finland. The work itself may be divided into sections based on different assumptions. Thus, the curious reader can find here issues concerning modeling both precipitation and wind fields. Time scales extend from the careful study of the very first minutes of the cloud droplet growth up to operational NWP forecasts with typical maximum length of approximately 2 days. Spatially, a very fine resolution of turbulent medium as well as the impact of increasing both the typical vertical and horizontal resolutions in mesoscale models is touched. Emphasis, however, has been in all cases on the enhancement of our knowledge concerning the possible improvement of numerical weather prediction models.

The present thesis consists of two main sections. The first section focuses mainly on basic research and deals with the study of the development of precipitation. Thus, the early growth of individual cloud particles and the widely adopted Sundqvist (1988) rain parameterization scheme are examined. The second main section is devoted to more practical aspects of NWP like evaluation of the operational HIRLAM model and
experiments with different horizontal resolutions. Special attention is devoted to coastal winds, which are perhaps the most difficult surface winds to predict due to the complexity of the coast. The thesis thus reflects the fact that precipitation and local winds are probably the hardest weather parameters to get right in short- and medium-range weather forecasting.

This thesis is based on the following six original articles, referred to in the text by Roman numerals:


II Tisler, P. and Savijärvi, H., 2002: **On the parameterization of precipitation in warm clouds.** Atmospheric Research, 63, 163-176.


VI Tisler, P., Gregow, E., Niemelä, S. and Savijärvi, H., 2005: **Wind field prediction in coastal zone: operational mesoscale model evaluation and simulations with increased horizontal resolution.** Accepted (1st Nov 2005) to publish in the Journal of Coastal Research.

The author of this thesis bore the main responsibility for writing papers I, II and VI. All calculations and data analyses were carried out by the author in Papers I and II with the exception of working out the code with Dr. E. Zapadinsky in Paper I. Model computations (case studies) with MM5 and the nonhydrostatic version of HIRLAM were performed in Paper VI by Mr. E. Gregow and Mr. S. Niemelä. Prof. H. Savijärvi and Prof. M. Kulmala acted as supervisors and provided valuable comments on the contents and formats in Papers II, VI and Paper I, respectively. The author’s contribution to Papers III-V was less intense, related mainly to technical issues and data management concerning the observations and HIRLAM model results.
2. INITIATION OF RAIN AND PARAMETERIZATION OF PRECIPITATION FOR NWP MODELS

The study of the formation of clouds and the development of precipitation is often defined as the core of cloud microphysics and has attracted attention for many years (e.g., Mason, 1971; Rogers and Yau, 1989; Pruppacher and Klett, 1997). The formation of raindrops can be divided by mechanisms into three steps: 1) activation of droplets on cloud condensation nuclei, 2) condensation growth, and 3) coalescence growth (Beard and Ochs, 1993). In spite of the general agreement in the scientific community that rapid gravitational collision-coalescence among cloud droplets can be significant only after a few droplets (perhaps only one in $10^5$ droplets) have grown to as large as 20 $\mu$m in radius (Rogers and Yau, 1989), the source of large droplets is not well understood. An example of calculations for droplet growth by condensation and coalescence in still air is given in Fig. 1, assuming conditions appropriate to a moderate cumulus cloud (Jonas, 1996). As we can see, the growth of a droplet to radius of 20 $\mu$m by condensation at a typical in-cloud supersaturation of 0.2% takes almost 20 min while growth by coalescence from 20 $\mu$m to drizzle drop size in a cloud with a liquid water content of 1 g m$^{-3}$ would take around 1 h. The combined growth time is thus much greater than the lifetime of many small precipitating cumulus clouds.

![Fig. 1. Calculated droplet growth by condensation and coalescence in still air assuming conditions typical for small cumulus clouds (Jonas, 1996).](image)

Another longstanding puzzle regarding the triggering of the coalescence process is the broadening of the droplet spectrum in clouds. The discrepancy between observations and distributions predicted by the conventional diffusion growth equation (e.g., Brenguier and Chaumat, 2001) is still awaiting physical explanations.
Numerous models and hypotheses have been proposed over the last few decades. A viable mechanism is suggested in Paper I in order to analyze and explain the spectral broadening and the possibility of triggering the coalescence process. It consists of a phenomenological approach to condensational growth in a turbulent cloud medium and shows results of extensive Monte Carlo type computer simulations. Since some degree of turbulence and entrainment is always present within clouds, it follows and is shown that even relatively small quasi-random turbulent fluctuations in temperature and water vapor concentration may play an essential role in the broadening of the droplet size distribution, quickly producing a few big cloud droplets and thus accounting for the onset of a fast stochastic coalescence process leading to precipitation. An example of droplet size distribution as a result of 10000 random sequences (realizations) of the fluctuating parameters is shown in Fig. 2. Note that a few large drops with radii between 40 and 50 µm have appeared in only approx. 17 minutes (1000 s).

![Droplet size distribution](image)

Fig. 2. Droplet size distribution for mean size in the accumulation mode (deterministic radius 8.6 µm) after growth time of 1000 s. Temperature and water vapor fluctuations are negatively correlated (correlation coefficient -0.9) and the cloud-producing vertical velocity is assumed to be 0.3 ms⁻¹. The number of realizations is 10000. The tail of the distribution with largest droplets is shown in the magnified part of the figure.

Such detailed simulations of cloud microphysical processes, including activation of nuclei, evolution of droplet spectra (as above) and growth of precipitation droplets is much too slow and too expensive computationally to apply directly in NWP models. Therefore, cloud processes must be described in them by simpler ‘bulk’ parameterizations. In Paper II a now widely adopted fast NWP precipitation scheme, proposed by Sundqvist (1988), is examined by giving a realistic cloud liquid water profile \( m(z) \) of a typical warm low cloud as input. Precipitation in this scheme is parameterized (diagnosed) as the function of the amount of cloud water, which has been...
predicted precedingly in each grid point of the model domain. This ‘rain’ parameterization has been adopted in many operational NWP models (e.g., HIRLAM), and even in some, which do not use the original Sundqvist cloud scheme itself (e.g., the ECMWF model, Tiedtke, 1993).

The conversion of cloud water into rain i.e. the rate of release of precipitation \( G_p \) \((s^{-1})\) is parameterized in this scheme by

\[
G_p = C_0 m \left[1 - \exp\left(-\frac{m^2}{m_r^2}\right)\right],
\]

where \( m \) is the nondimensional (predicted) cloud water mixing ratio, \( C_0 \) \((s^{-1})\) is the efficiency for the production of precipitation \((1/C_0\) representing a characteristic time scale for the conversion of cloud droplets into raindrops) and \( m_r \) is the threshold value of \( m \) for the onset of coalescence. To simulate the collection of droplets by rain falling from above, an additional factor \( F_{co} \) is introduced,

\[
F_{co} = 1 + C_1 \sqrt{P},
\]

which multiplies \( C_0 \) and divides \( m_r \). Here \( C_1 \) \((\text{kgm}^{-2}\text{s}^{-1})^{-1/2}\) is an additional tunable constant and \( P \) is the local precipitation flux. Rain rate at the cloud base is obtained by integration from the top of cloud down to the cloud base.

In Paper II, the results of simulations via these equations are compared with simultaneous satellite observations of the rain rate (RR) and the cloud liquid water path (LWP). In addition, all the above-mentioned disposable constants, the vertical resolution and the scheme assumptions are varied in order to check and possibly improve and tune this parameterization scheme. Furthermore, the bulk computations are enlarged into drop spectra, by utilizing typical cloud and rain drop distribution. Finally, Paper II consists of the direct numerical integration over the droplet spectrum in order to study some auxiliary parameters such as the mean terminal velocity and effective radius of the droplets.

The results confirm that the Sundqvist parameterization of rain is acceptable, given its simplicity. It is somewhat sensitive to the vertical resolution, such that improving the vertical resolution of the host NWP or climate model may artificially reduce the obtained rain rates.

The ‘Sundqvist rain scheme’ is also fairly sensitive to its constant of collection efficiency \( C_1 \). A value of 400-500, instead of the original 100 (Sundqvist, 1988) or the 300 SI units (Sundqvist et al., 1989) appears to give a better fit with satellite microwave estimates of warm rain over the ocean, see Fig. 3.
Fig. 3. Plot of rain rate RR vs. liquid water path LWP as given by the Sundqvist scheme using different numerical values for the constant $C_1$. Curry et al. (1990) satellite data shown as reference.

The evolution of the cloud droplet spectrum, illustrated in Fig. 4 as the cloud gets thicker and starts to produce drizzle and rain, looks reasonable. Moreover, the values of the effective drop radius and the average terminal velocity of the falling drops, obtained from numerical integration over the spectrum, agree reasonably well with various observational aircraft and satellite measurements (e.g., Curry et al. 1990, Gerber, 1996), as shown in Paper II.

Fig. 4. Droplet size distribution for a warm marine model Sc cloud. Curves in sequence from left to right correspond to cloud heights of 100, 300, 600, 1000 and 1500 m respectively. The cloud droplet spectra (left) are approximated by gamma distributions; for raindrops, lognormal distribution is used (right).
3. WIND FORECASTING FOR COASTAL ZONES AND HIRLAM VALIDATION

3.1. Wind field in the coastal zone

Knowledge of wind over the sea and over coastal areas is of great importance for numerous activities. Examples include the daily operational weather forecasting, commercial ship routing, towing and maintenance work on oil rigs. In addition, many applications like wave forecasting and modeling of pollutant transport and e.g. oil spill drifting are forced by surface winds. Sudden changes in the lower boundary conditions such as roughness discontinuities and large temperature contrasts have significant effects on the development of weather and wind in the coastal zone.

During the past two decades many studies have been published discussing different aspects of wind conditions in coastal zones. Influence on the cloudiness and precipitation is discussed e.g. in Alestalo and Savijärvi (1985) and Roeloffzen et al. (1986) while the characteristic features of the sea and land-breeze circulation have been studied by e.g. Savijärvi and Alestalo (1988), Arritt (1993) and Zhong and Takle (1992, 1993). Recently, local wind observations and results by high-resolution two-dimensional model simulations concerning typical small-scale coastal mesoscale effects have been documented by Savijärvi (2004). Unfortunately, small-scale and even mesoscale phenomena are not well represented by many NWP models due to their relatively coarse horizontal resolution.

As an example, the reasons for the systematically strong coastal afternoon surface winds observed along the Gulf of Finland but missed by large-scale models are studied in Paper III. The high-resolution two-dimensional University of Helsinki mesoscale model has been used in order to simulate the typical early summer situation with either clear or overcast sky. Relatively strong afternoon surface winds blowing along the coast were indeed obtained for the north coast of the Gulf of Finland for moderate geostrophic

Fig. 5. Observed surface winds on 29 August 1997, 1200UTC and HIRLAM surface pressure +12 h forecast (hPa) from 29 August 1997 0000UTC with 7.7 km horizontal grid length.
winds from about 135 and 282 degrees. A case study for geostrophic wind from about 135° was carried out also with HIRLAM, which used a small experimental 7.7 km grid length. This case (with supergeostrophic surface easterlies observed near the Finnish coast) is presented in Fig. 5. The HIRLAM winds were close to those observed and thus confirm the above-mentioned features obtained with the 2D simulations. The reason for the strong along-coast winds was that the latitude and width of the Gulf of Finland are such that the inertial oscillation mechanism triggered by suddenly reduced vertical mixing over the sea, favours local low-level jets blowing parallel with the Finnish coast, when moderate large-scale winds blow from the south-east or from west.

However, the inaccuracy of the predicted wind characteristics (especially wind direction) remains to be a serious problem for many NWP models if low resolution has to be used. Due to the rapid technological progress and corresponding increase of computer power the general trend in the beginning of the 21st century has been towards making use of smaller and smaller grid spacing. The debate concerning the possible benefits of increasing horizontal resolution in short-range NWP models has become one of the major questions confronting the meteorological community (Mass et al., 2002). Indeed, increasing the horizontal resolution in mesoscale models below 10 km provides more realistic representation of weather with more details and fine structure but this does not necessarily improve the standard verification scores of deterministic forecasts (Colby, 2004, Mass et al., 2002, Rife et al., 2004). Paper VI has attempted to extend these studies. Two versions of the NWP model HIRLAM, used operationally at FMI, are exploited in order to verify wind forecasts in the eastern part of Gulf of Bothnia, where a high-quality set of wind observation sites (on an island and at the coast) was available. In addition, two cases of interest are studied in detail by making use of two other mesoscale models: the Penn State/NCAR Mesoscale Model (MM5) and a nonhydrostatic version of HIRLAM, both applied at three different horizontal resolutions.

Sparse observational network and representativity problems make local verification difficult as model resolution is increased. It appears, for instance, that models’ sea-land distribution has a significant impact on the objective verification scores when transitioning to finer scales (Paper VI). Even utilization of more sophisticated parameterization schemes does not necessarily compensate this impact in case of traditional means of verification. This ‘verification sensitivity to model horizontal resolution’ is illustrated in Fig. 6. There, the island station Nahkiainen is located in a HIRLAM ATX version grid square (33x33 km) covered by less than 50% of open water while in the HIRLAM ENO version we are dealing with a grid square (22x22 km), including the same island observation point, but without any land. Due to differences in the fraction of land the HIRLAM ATX clearly underestimates wind speed in Nahkiainen as compared to ENO. The nearby Raahe station is located exactly at the coastline and, consequently, the differences between fractions of land for the corresponding gridsquares are less dramatic.
Fig. 6. Distribution of the fraction of land in HIRLAM ENO and ATX versions for the Gulf of Bothnia. Locations of Nahkiainen and Raahe stations are marked with filled circles.
3.2. Case studies and validation of the HIRLAM NWP model

It is often quite difficult to judge on how reliable one or another NWP model really is. The evaluation of the forecast accuracy is traditionally based on comparing model outputs with real weather system behavior and real observations. Some case-studies and results of model and process verifications are touched already in the preceding chapters. Papers IV and V attempt to contribute to the discussion regarding a simple question - is the HIRLAM model suitable enough for the purpose for which it was developed, i.e. to adequately predict short-range weather for Finland.

The HIRLAM project has been established in order to develop and provide NWP data assimilation systems and models for analysis and short-range forecasting, which are state-of-the-art. The HIRLAM model itself (Källén, 1996; Undén et al., 2002) is nowadays used as the basis for operational short-range prediction in a number of European national meteorological services. In order to study the applicability and accuracy of HIRLAM model output as forcing for marine models, Paper IV focuses on HIRLAM performance over the Baltic Sea. Two cases are considered: a coastal sea ice region in March and the open Baltic Sea far from the coasts in October, both during 1999. The significant contribution of this study was making use of independent validation data (i.e. not assimilated into HIRLAM) – in the form of radio-soundings and surface observations from the open sea and sea ice, where no regular observations exist. In general, the HIRLAM temperature, humidity and wind profiles agreed rather well with these extra observations. Main discrepancies were related to a surface-based temperature inversion: the surface and 2 meter temperatures were often too high in HIRLAM and the minimums were delayed.

The purpose of Paper V was to evaluate the performance of the operational HIRLAM model in a synoptic situation favourable to formation of severe wintertime air pollution episodes. One specific episode in December 1995 with a very strong ground-based temperature inversion causing especially poor air quality in the Helsinki Metropolitan Area was considered. In addition to simulations with HIRLAM model version 4.6.2 (Eerola, 2000), exploited also in Paper IV, the results of the more sophisticated HIRLAM version 6.2.1 (Järvenoja, 2004) were compared with various observational measurements. Similarly to the results of Paper IV, HIRLAM had difficulties in predicting correctly the strong inversions. However, it was noticed that the performance of version 6.2.1 was substantially better compared to the older HIRLAM version, most probably because of the improved vertical resolution in the lowest 3 km and an improved surface parameterization scheme. Note that the poor quality of the predicted 2-metre temperature has been a long-lasting problem in HIRLAM (Järvenoja, 2005). These very stable situations are also the most problematic for wind predictions. Thus, despite the noticeable progress and model amendments there is still room for improvement.
4. SUMMARY

This thesis concentrated on local numerical forecasts, especially those for precipitation and coastal winds. The main results can be listed as follows:

- A physical mechanism is presented, which explains the initial step of rain droplet formation. Since some turbulence and entrainment is always present in clouds, it is claimed and shown by Monte Carlo type simulations that even relatively modest fluctuations in temperature and water vapor concentration can produce big cloud droplets (within the framework of condensational growth theory) in a short time interval. These can in turn account for the onset of a fast stochastic coalescence process leading to precipitation. This provides a new level of fine-scale treatment of turbulent medium and has great significance on understanding of the global hydrological cycle (Paper I).

- A widely used fast NWP rain parameterization scheme, suggested by Sundqvist (1988), is tested by defining a realistic liquid water profile of a warm low model cloud as input and compared with remote sensing observations. Also the scheme’s sensitivity on the vertical profiling of the LWC, the vertical resolution of the host model and the coalescence parameterization constants is examined. Results confirm that the Sundqvist parameterization, given its simplicity, is acceptable, especially after tuning its rain collection constant. Enhancing the vertical resolution of the host NWP or climate model, however, has a tendency to artificially reduce the rain rates. Extending the calculations by considering typical cloud and raindrop size spectra, extra variables such as drizzle amount, average terminal velocity of falling drops and droplet effective radii (forced by the bulk Sundqvist rain rates) are estimated by numerical integration. The results agree reasonably well with observational aircraft and satellite measurements (Paper II) and with the ideas of Paper I.

- The latitude and width of the Gulf of Finland are such that the inertial oscillation mechanism favours local low-level jets blowing parallel with the Finnish coast, when moderate large-scale winds blow from the south-east or from west. Strong surface winds blowing parallel with the coast are the result. The jets are further enhanced by sea breeze action during clear days. It is encouraging that HIRLAM with a small 7.7 km grid length can produce them, as well as the associated sea breezes (Paper III).

- Higher-resolution modeling is therefore one way, which may improve skill and accuracy of local weather forecasts. Traditional objective approach (verification at fixed measurement stations for eight different NWP setups with different grid spacings) however shows that the sea-land distribution of a model plays an essential role on the interpretation of the accuracy of coastal wind speed forecasting. Considering wind directions in the coastal zone, all experiments unfortunately displayed similar systematic discrepancies. Though decreasing the grid spacing of a mesoscale model does improve the realism of the forecast, it also brings along a growing need for improved verification procedures, especially in cases of a sparse observational network and complicated heterogeneous surface like in coastal zones (Paper VI).

- Evaluation of the HIRLAM operational NWP model (versions 4.6.2 and 6.2.1) over the Baltic Sea as well in southern Finland in a case of a severe air pollution
episode illustrated a common problem in the HIRLAM system – positive bias of 2-metre temperatures in high latitudes in winter, especially in case of ground-based inversions. Though both model versions considered (4.6.2 and 6.2.1) were able to predict the occurrence of the inversion, the actual surface temperatures and wind speeds near the surface were generally overestimated. Comparison of the older configuration of HIRLAM with a more recent model version indicated improved performance but the underestimation of the strength of the inversions requires further investigations (Papers IV and V).
REFERENCES


