High resolution weather forecasting and predictability - applications in complex terrain

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2006

Storm
WEATHER CENTER

Forsvarsbygg

Imagine a rotating sphere that is 12,800 kilometres (8000 miles) in diameter, has a bumpy surface, is surrounded by a 40-kilometer-deep mixture of different gases whose concentrations vary both spatially and over time, and is heated, along with its surrounding gases, by a nuclear reactor 150 million kilometres (93 million miles) away. Imagine also that this sphere is revolving around the nuclear reactor and that some locations are heated more during one part of the revolution and other locations are heated during another part of the revolution. And imagine that this mixture of gases continually receives inputs from the surface below, generally calmly but sometimes through violent and highly localized injections. Then, imagine that after watching the gaseous mixture, you are expected to predict its state at one location on the sphere one, two, or more days into the future. This is essentially the task encountered day by day by a weather forecaster.

On the difficulty of weather forecasting, Bob Ryan, Bulletin of the American Meteorological Society, 1982.

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Preface

This thesis is a part of the dr.scient degree submitted to the University of Bergen, Norway. The work was started in September 2000 as part of an ongoing project at the Geophysical Institute in cooporation with Forsvarsbygg. The first two and a half years of the dr.scient work I was sitting at the Geophysical Institute at the University of Bergen. For the last three and a half years I have been employed as a researcher at Storm Weather Center in Bergen. My main responsibilities there have been to set up a real-time weather forecasting system with the mesoscale atmopheric model MM5. This has involved everything from setting up linux clusters and optimimizing these for forecasting to the creation of a autonomos weather prediction system running different model configurations 15-20 times a day. Finisihing this thesis along with a full time employment has been a tough experience and much harder than expected. The path from the beginning to the end of the thesis have been a very exciting path with a lot of different challenges. I have a enormous gratitude for the support of many people during the work on this thesis for the last six years. To all of you not directly mentioned here: Thank you all!

First of all, I would like to thank my supervisors, Prof. Sigbjørn Grønås and Dr. Lars Robert Hole for their good support and help writing this thesis. I would also like to thank Dr. Anne Sandvik and Dr. Asgeir Sorteberg for a lot of help with the MM5 model and interesting discussions during all my years as a student at the Geophysical Institute. The mesouser at NCAR and the MM5 community has also been of tremendous help with model specific problems. I would also like to thank all my co-authors for a good cooperation with the papers presented in this thesis.

Without the financial contributions from Forsvarsbygg and Storm this work would not have been possible. Thank you for giving me this opportunity! My collegues at Storm are hereby thanked for their support, but mostly for the totally meaningless discussions over a cup of coffee or beer. Børge, and Knut Frode are appreciated for their social support during my years as a student and dr.scient student.

In the end I would like to give my gratitude to my brother Runar, my late mother Liv and my father Arnvid for their special support and help all these years. And finally: thank you Trude for putting up with a ”workaholic” like me - you are everything!

Bergen, October 2006

Gard

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Contents

1 Introduction

The history of weather forecasting is an exciting story starting with Vilhelm Bjerknes in 1904 [Bjerknes 1904] to modern era numerical weather prediction with advanced data assimiliation systems. The development of numerical weather prediction has closely followed the evolution of computers, and has led to forecasting systems as we know them today.

Increased computer combined with lower hardware costs have during the last decade made high resolution weather forecasts down to 1 km or feasible. A traditional approach to increase model resoluion has been to take existing models and try them out at higher resolutions. This can create problems since the parameterizations used in the models in many cases are tuned for coarser scale resolutions.

Model physics represent a major challenge for mesoscale modeling systems today [Klemp et al. 2006], and causes the largest forecast errors in limited area models along with the lateral boundary conditions used to initialize these models. Advancement on many of the model physics issues is not merely a technological or development challenge, but requires progress in fundamental understanding of a number of atmospheric processes on a wide range of scales. The predictability - the extent to which it is possible to predict the weather - is also an important question at high model resolutions.

This dr.scient thesis investigates some aspects necessary to evaluate and improve fine scale weather prediction systems. It is also imperative to test the usability of such forecast on broad spectrum of applications in order to test its usefulnes to society. The first work of this thesis explores how short wave radiation have an impact on the break up of a temperature inversion. In MM5 an many other models, radiation is traditionally calculated under the assumption that the grid box describing the surface is flat. When increasing the resolution down to scales this assumption is no longer valid, and different parameterizations needs to be used in order to reproduce accurate radiation patterns. In the second paper [Hole and Hauge 2003] the focus has changed to applications of high resolution forecasts of the break up of a temperature inversion coupled to a sound propagation model in order to create acoustical forecasts, which can be applied to i.e. military shooting activities. High resolution forecasts are also tested to evaluate if 1 km forecasts are accurate enough to be used to model in cloud icing events [Drage and Hauge 2006]. In the last paper of this thesis, paper IV [Hauge et al. 2006], the focus is on real-time forecasting of winds and temperature at very high horizontal resolution. Here, two modelling systems (MC2 and MM5) with different nesting strategy are evaluated in order to evaluate the forecast accuracy in complex coastal terrain. Predictability in of winds and temperature in complex terrain is adressed in this work.

An introductory part (this synthesis) and a collection of papers constitute my thesis presented in partial fulfillment of the requirements for the degree of Doctor Scientiarum in Meteorology at the Geophysical Institute, University of

Bergen. The work presented here are organized as follows: In Section 3.1 a brief historical of numerical weather predictions is given overview is given. This is followed by a description of predictability (Section 3.2) and the limitations for all weather prediction systems. Predictability of a weather forecast is strongly coupled to the way a model is initialized (described in Section 3.3), or how the models are nested down from a global model to a limited area model setup (see Section 3.3). Another limiting factor for models are their sub-grid scale parameterizations used in most weather model, described very briefly in Section 3.4. An overview of the results achieved in this dr.scient work is presented in Section 4 along with conclusive remarks in Section 5. The complete version of the scientific papers, I – IV, are presented thereafter.

2 List of Papers

Paper I

Hauge, G. and Hole, L.R [2003], Implementation of slope irradiance in Mesoscale model version 5 and its effect on temperature and wind fields during the break-up of a temperature inversion, *JGR*, **108(D2)**,4058, doi:10.1029/2003JD002575.

Paper II

Hole, L.R. and Hauge, G. [2003], Simulation of a morning air temperature inversion break-up in complex terrain and the influence on sound propagation on a local scale, *Appl. Acoustics*, **64**, 401–414.

Paper III

Drage, M. and Hauge, G. [2006], Atmospheric icing in a coastal mountainous terrain. Measurements and numerical simulations, a case study, *accepted for revision and resubmitted, Cold regions science and technology*

Paper IV

Hauge, G., Holstad, A. , Lie, I. and Dagestad, K.F. [2006], Predictability of very high resolution operational weather models in complex terrain, *Submitted to Weather and Forecasting.*

3 Numerical weather prediction

Numerical weather prediction has seen a tremendous evolution the last century from Wilhelm Bjerkes to modern era computer based weather forecasting. The hardware costs neccessary to run real-time forecasts have decreased enormously the last decade, and fully operational forecasting systems do not any longer require large govermental agencies and enormous recources. Today, weather prediction models can easily be downloaded along with necessary boundary data required to run the models for free on the internet. Examples of such models are the Mesoscale Model version 5, MM5, or the new Weather Research and Forecasting model, WRF.

3.1 A brief historical overview

A century ago, in 1904, the Norwegian physicist Bjerknes [1904], claimed that the weather could quantitatively be predicted by applying the complete set of hydrodynamic and thermodynamic equations to the atmosphere. His procedure contained two steps: a diagnosis to determine the initial state from observations; and a prognosis where future states were computed from the equations. Bjerknes started the theoretical approach and published the first textbooks on dynamical meteorology. Lacking both the practical means to make any quantitative predictions, he initiated instead the qualitative approach that has became known as the ”Bergen School of Meteorology” [Grønås 2005].

Inspired by Vilhelm Bjerknes, Lewis Fry Richardson, developed the first numerical weather prediction system [Richardson 1922]. His initial data were based on a series of synoptic charts published in Leipzig by Vilhelm Bjerknes. Richardson divided the area of interest into grid cells and calculated the finite differences solutions of differential equations. Richardson formed a complete set of based equations named the primitive equations of motion and tried to solve them numerically on a very small limited area for six hours. His own attempt to calculate weather for a single six-hour period took him at least six weeks and ended in failure [Lynch 1993].

After the Second World War two technological developments appeared to introduce mathematical weather forecast along the lines suggested by Bjerknes possible: the establishment of a hemispheric network of upper-air stations and the development of the first electronic computers. John von Neumann set up a group of scientists in Princeton, USA to deal with the problem of figuring out the weather with the aid of computers, efforts based on Bjerknes' thinking and Richardson's numerical experiment. The research field was called Numerical Weather Prediction (NWP). Simplified mathematical models of atmospheric motion was derived in the group based on quasi-geostrophic assumptions. The first NWP experiments were conducted in 1950 by Charney, Fjørtoft and Von Neuman [Charney et al. 1950]. Due to the limited computer capacity only the most simple model could be used; the barotropic equation of atmospheric motion. The results were surprisingly successful: the general 500 hPa flow pattern over North America was forecasted 24 hours in advance with greater skill than previous subjective methods.

From this successful start two different strategies developed: countries with limited computer resources preferred to explore the potential of the barotropic model, whereas countries like the US and Britain took a more ambitious approach by developing baroclinic models where forecasts of vertical motion were possible. It soon turned out that the nature of the problem was much more complicated than envisaged. That is why during the 50's the first operationally useful NWP forecasts were barotropic: in Sweden in 1954 [Bergthorsson 1955], in the US in 1958 [Nebeker 1985] and Japan in 1959. In 1962 could the US launch the first operational quasi-geostrophic baroclinic model [Cressman 1963], followed by the UK in 1965 [Gadd 1985]. By that time, work was already under way to introduce more realistic numerical models, based on the primitive equations.

In a primitive equation model changes in wind and mass fields are not restricted by any quasi-geostrophic constraint, but are allowed to interact freely. The physical parameterizations sub-scale processes, such as convection, which are difficult to handle in quasi- geostrophic models, could now be realistically incorporated, so that the tropical regions, essential for forecasts over Europe beyond two or three days, could be included. The first global PE model came in operation in 1966 at National Meteological Center (NMC) Washington, with a 300 km grid and six-layer vertical resolution [Shuman and Hovermale 1968]. During the 70's several other PE models were implemented, global, hemispheric or as Limited Area Models, which ran with a higher resolution over a smaller area with lateral boundary values from a larger hemispheric or global model.

During the 1970's several modelling systems were implemented, global, hemisferic or as limited area models (LAMs). LAMs ran with a higher resolution over a smaller area and took boundary conditions from a larger hemispheric or global model. During the last decades, several regional LAMs have been developed such as the MM4 and later the MM5 [Grell et al. 1994], the new WRF model [Skamarock et al. 2005], the Canadian MC2 model [Benoit et al. 1997], the HIRLAM model [Källén 1996], the RAMS model [Pielke et al. 1992] or the MesoNH nonhydrostatic model [Lafore et al. 1998] among many. The use of meso- to micro-scale non-hydrostatic models have now become the future of modern numerical weather prediction for short-term forecasting.

Numerical modelling of small-scale atmospheric features requires an accurate description of the large-scale atmosphere, explicit representation of appropriate physical mechanisms, and assimilation of relevant meteorological data. This allows analysis and forecasting of important weather phenomena such as thunderstorms, temperature inversion, precipitation and floods, fog, orographically-induced winds, or urban weather and pollution. Depending on the situation, local weather may be more or less predictable than large-scale weather, and short-range forecasts may be harder to produce than longer-range ones.

Increased computer power, combined with lower hardware costs during the last decade has made global ensemble prediction systems and high resolution deterministic forecasts feasible. The background of ensemble forecasts are the intrinsic forecast inaccuracy in all forecasting system, described in some details in Section 3.2. Ensemble predictions made by ECMWF and other institutions has improved the skill of medium range forecasts considerably.

3.2 Predictability

An crucial issue throughout in weather forecasting is *predictability*. Thompson [1957], who presented some of the earliest work on the problem of atmospheric predictability, proposed a definition as:

"The extent to which it is possible to predict [the atmosphere] with a theoretically complete knowledge of the physical laws governing it."

Thompson [1957] went to analyze the relationship between the spatial scale of disturbances and the growth of errors. Thompson's analysis, using the tools of the statistical theory of homogeneous turbulence, concluded that small amplitude disturbances with spatial scale larger than the radius of deformation (the length scale at which the geostrophic balance between the Coriolis and the horizontal pressure gradient force will become important) would grow in time. Errors with scales much smaller than the deformation radius would remain small in amplitude. Thompson's results were useful in the early days of numerical weather prediction for they instilled the hope that accurate predictions on large scales were possible. This implied that partially or completely unobserved small scale - whose errors would not grow - would not disrupt the accuracy of the synoptic and planetary scale features.

With the advent of more powerful computers in the 1960s, the field of numerical weather prediction flourished, and with this interest in the predictability problem expanded. Lorenz [1963] showed that even low-order representations of atmospheric flow could have limited predictability. Lorenz [1969] used a two dimensional flow model to quantify more precisely Thompson's analytic results. Lorenz's numerical model demonstrated a slow inverse cascade of errors from small to large scales, an effect too subtle to be capture in Thompson's early work. Using improved closure models for the evolution of the energy in wave number space, Leith and Kraichnan [1972] and later Tennekes [1978] verified Lorenz's results which has led to the accepted picture of the evolution of errors in the wave number spectral domain (see Figure 1). This picture combines the elements of Thompson's earliest work with Fjørtoft's theory of spectral kinetic energy and enstrophy transfer [Fjørtoft 1953]. In this conventional picture *errors* in small scales (high wave numbers) propagate up-scale with a constant flux of error energy in the spectral space. The main addition

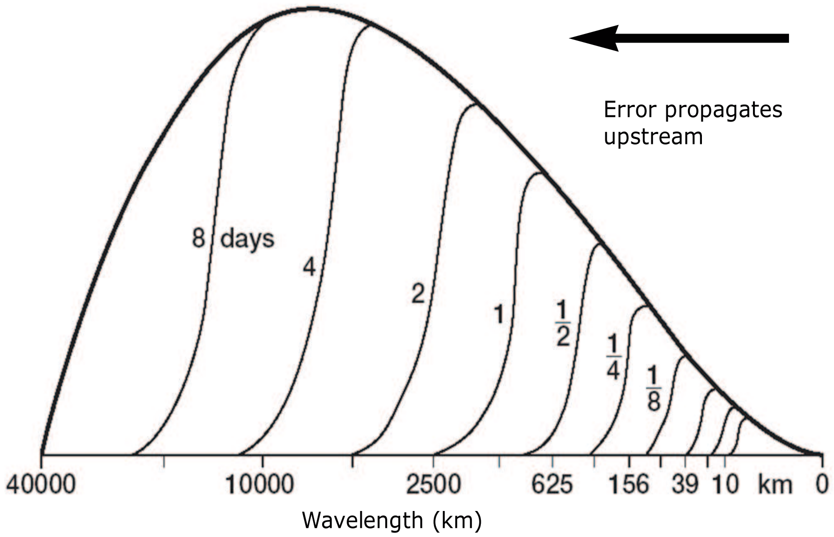

Figure 1: **Growth of errors initially contained to smallest scales, according to a theoretical model. The Figure is taken from Lorenz [1984] and shows horizontal scales on the bottom and the upper curve is the full atmospheric motion spectrum.**

to Thompson's work is that small-scale errors grow and eventually contaminate all skill remaining in larger scale. The implication for weather forecasting is that eventually even the smallest amplitude small-scale error will creep up scale and amplify in time, rendering practical and accurate weather prediction feasible for only a finite length of time. A significant outcome of these studies was that attention turned to estimates of this finite time where useful synoptic scale forecasts could be made. Daley [1981] gave an estimate of this time scale of approximately 10 days. Throughout, the conceptual model of gradual inverse cascade has remained, and with the extension to three-dimensional flow through the concept of quasigeostrophic (QG) flow developed by Charney [1971], the supposition of long-time predictability of planetary scales has remained part of the conventional wisdom of atmospheric predictability.

Previous studies by Anthes [1986], Baumhefner [1984], and others have focused on the growth of synoptic scale errors and their impact on predictability, Results from Baumhefner [1984] indicate that the typical error doubling time is about 2 days for the synoptic scale and that it may decrease with decreasing synoptic scale. Tennekes [1978] suggests that the mesoscale rapid growth of errors will occur due to the transfer of energy from smaller scales to larger scales (backscattering) by three dimensional turbulence, which will further decrease the predictability time limit. However, for mesoscale phenomena that does not fit the average spectrum of turbulence, this rate of energy transfer, and thus the forecast error, may be quite different. Warner [1978] suggests that some mesoscale phenomena may be more predictable than others. Especially those forced by strong fixed surface features such as the mesoscale terrain. This assertion has not been widely tested and many efforts in mesoscale numerical forecasting are based upon this unproven assertion.

The atmospheric kinetic energy spectra plays an important role in predictability issues. This energy spectra in the free troposphere and lower stratosphere possess a robust and remarkable universality. Results from an observational analysis of kinetic energy spectra produced in a study by Nastrom and Gage [1985] using Global Atmospheric Sampling Program (GASP) dataset is shown on Figure 2. The cascade rates are intimately connected with eddy turnover times in a turbulent fluid, and these are determined by the slope of the kinetic energy spectrum (see Figure 2).

The prevailing explanation for the large-scale k^{-3} dependence of the kinetic energy spectrum (between length scales from several thousand to several hundred kilometers) have arisen from applications of two dimensional turbulence theory (see Charney [1971] or Lilly [1969] for details). The theory predicts a downscale enstrophy cascade (and enstrophy inertial range) and no energy cascade in the k^{-3} below scales of around 5000 km [Boer and Sheperd 1983] where energy is input from the large scale due to differential meriodonal heating.

The mesoscale spectral range is not as well understood as the large scale. Three-dimensional turbulence theory, which should be appropriate for cloud resolving scales and below, predicts a $k^{-5/3}$ behaviour. This is generally what is observed and found in modelling studies. 3D turbulence cannot characterize the mesoscale since the flows are highly stratified and 2D in nature. An explanation is put forward in Lilly [1983] and states that energy at small scales (by convection or other sources) and an upscale transfer (negative cascade) of a small portion of this energy results in the $k^{-5/3}$ spectrum predicted by stratified (2D) turbulence theory.

The spectre in Figure 2 illustrates the large-scale k^{-3} dependence of the atmospheric kinetic energy spectrum, along with a transition to a $k^{-5/3}$ dependence found in the mesoscale and smaller scales. Cho et al. [1999a,b] analyzed more resent aircraft data collected above the Pacific Ocean and also found that the kinetic energy spectra follow a $k^{-5/3}$ power law at mesoscales.

While dynamics of the mesoscale portion of the kinetic energy spectrum are not well understood, the spectral characteristics in themselves have significant implications for mesoscale and cloud-scale numerical weather prediction. The $k^{-5/3}$ dependence of mesoscale (and cloud scale) suggests that the small scales are energetic and that error growth may be faster than at synoptic scales. For mesoscale and fine scale NWP models with grid sized ranging from 1 - 20

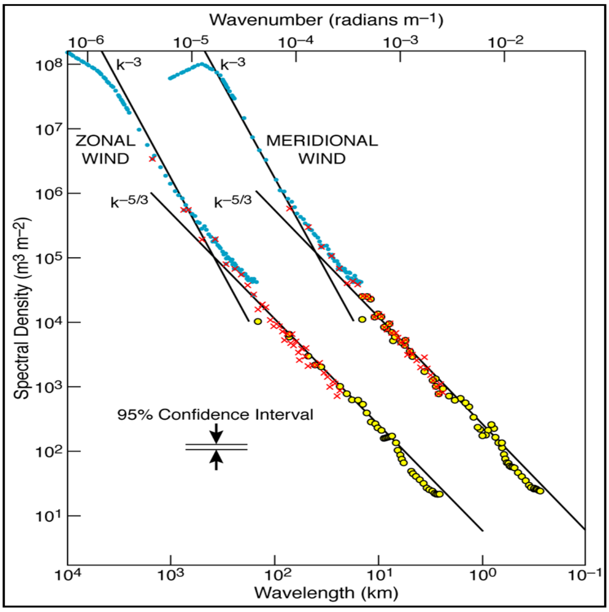

Figure 2: **The energy spectrum observed of U and V components of wind in the atmosphere. The Figure is taken from Nastrom and Gage [1985].**

km and forecast period of 1 to 3 days, many of the resolved features, such as cumulus clouds, are not predictable and errors at these scales have sufficient time to propagate upscale. Thus, the characteristics for the mesoscale kinetic energy spectrum cast doubt of the viability of small-scale NWP at traditional mesoscale time periods, especially given the additional difficulty of initializing and verifying forecasts at these small scales because of lack of meso to local-scale observations.

There are still a number of reasons to attempt high-resolution forecasts. Significant predictability may be possible for small-scale phenomena forced by the large scale or tied to fixed forcings such as terrain or surface heterogeneities. Forecasts may also benefit from improved representation of distinctive small-scale physical phenomena. NWP's using grid spacing smaller than a few kilometres will be able to explicitly resolve deep convection, foregoing the need for a deep convection parameterization. It should also be appreciated that at some time in the not too distant future we will have the computing facilities to perform ensembles of very high resolution forecasts with the goal of producing statistically meaningful probabilistic forecasts.

Even with error-free observations and a "perfect" model, forecast errors will grow with time. No matter what resolution of observations is used, there are always unmeasured scales of motion. The energy in these scales transfers both up and down scale. The upward transfer of energy from scales less than the observing resolution represents an energy source for larger-scale motions in the atmosphere that will not be present in a numerical model. Thus, the real atmosphere and the atmosphere that is represented in the numerical model are different. For this reason, the model forecast and the real atmosphere will diverge with time. This error growth is roughly equal to a doubling of error every 2-3 days.

The quantitative and reliable assessment of uncertainty of weather forecasts is very valuable, both for scientific and economic reasons. Scientifically, quantification of atmospheric predictability asks for the rate at which two initially close solutions for atmospheric dynamics and physics diverge in time. Such estimates place upper bounds on time horizons over which useful forecasts may be expected. Economically, a reliable estimate of the uncertainty for a particular forecast will led to increased credibility and utility of weather forecasts.

Approaches to understand the predictability of a model need not coincide with efforts designed to improve forecasts. Complete understanding of a modelling system is not a prerequisite for forecasting, as demonstrated by the success of operational weather prediction. Because many forecasting applications rely heavily on parameterizations of poorly understood processes, research results may lead to forecast improvement without concomitant improvement in physical understanding.

3.3 From global to local-scale weather prediction

Large-scale models of the atmosphere are global, which means they are self sufficient in terms of the horizontal propagation of atmospheric phenomena. The largest problems nowadays are the acquisition of observations in data-poor regions such as the Northern areas of Norway and the Barents Sea, the modelling of the large-scale effect of sub grid-scale physical phenomena's, and the numerical costs associated with increased resolution. High resolution models on the range up to 20 km can alleviate some of the shortcomings of global models. They are necessarily limited area models (LAMs) because of the numerical costs involved. A doubling of horizontal resolution needs normally to be met by a similar increase in vertical resolution - given the aspect ratio of the features to represent (e.g. clouds). A trade-off between the resolution, the size of the resolved domain and the length of the simulation are the normal approach.

A unavoidable aspect of limited area models (LAMs) that will continue to represent a limitation is the lateral boundary conditions (LBCs), regardless of how much sophistication we use in limiting the other error sources. A number of studies, for instance Warner et al. [1998], have demonstrated that the LBCs of the LAMs can have a significant impact on the evolution of the predicted fields through the propagation of boundary errors onto the interior of the domain. The boundary conditions are obtained from coarser mesh models, such as the ECMWF with 0.5 degrees horizontal resolution. Tribbia and Baumhefner [2004] investigated how different scales in the atmosphere interacts and implications for the error growth. This study also shows how the errors of the initial conditions can be a limiting factor of fine scaled limited area models in addition to errors in model numerics.

The obvious reason for increased model resolution is the need to represent fine orography. This gives a more accurate description land-sea contrast (coastlines) in order to represent local phenomena such as wind over complex terrain, temperature inversions and trapping of pollutants over regions enclosed by mountains, foehn effects, drainage flow and sea breezes. Predictions of low-level winds are nearly always improved whenever horizontal model resolution is increased. Forecasts of low-level humidity and temperature requires additional refinements in the description of land surface characteristics: soil moisture, albedo, ground freezing, roughness and evapotranspiration. These need to be described by sophisticated land surface schemes interactively coupled with atmospheric fluxes of heat, moisture and radiation.

At horizontal grid sizes below 5-10 kilometres, the change in the aspect ratio between the model's horizontal grid and the depth of the troposphere implies that some of the approximations used in global scale models are not longer valid: the vertical accelerations cease to be negligible and the atmosphere cannot be assumed to be in a state of hydrostatic equilibrium. Non-hydrostatic dynamical equations must be used, which explicitly represent the evolution of vertical wind, gravity waves and even acoustic waves. Deep convective clouds induce circulations at scales resolved by the model, and their internal structure needs to be resolved explicitly, which again require an explicit representation of cloud liquid water, ice and various other phases of water. The microphysical processes are also important to gain the correct transition between the different water phases. Relevant mixing processes can be complex, e.g. between a cloud and its environment, and require an explicit representation of turbulence. Turbulence modelling is on the other hand sensitive to the resolution and representation of clouds and surface characteristics. All these new features to the non-hydrostatic dynamics adds to the cost of running fine scaled models and will further increase the computational costs.

Both subjective and objective evaluations have found clear benefits in increasing the model resolution in regions where orographic flows or diurnal circulation are important. Rao et al. [1999] used two-way nesting procedure with 1.6 to 0.1 km horizontal grid spacing to show that less than 1 km was required to realistically simulate the diurnal circulation of the Cape Canaveral region of Florida using the ARPS mesoscale model. Davis et al. [1999] demonstrated that reducing the grid spacing in the MM5 forecasts from 10 to 1.1 km helped to improve the simulation of the diurnal circulations over Utah produced by the variable surface conditions and topography. Other studies, such as Mass et al. [2002] has shown that higher horizontal resolution improved the realism of the forecasts, but not necessarily the objectively scored forecast skill.

If fine scale models are properly initialised to provide realistic forecasts, they can bring enormous benefits to the population through detailed weather forecasts. This allows analysis and forecasting of critical weather events such as thunderstorms, floods, fog, orographically-induced winds, or urban weather and pollution.

Fine-scale models can be used without a fine-scale data analysis; this is called dynamical local adaption. In this setup, a limited area model is initialised using the state of a larger scale model, interpolated onto the fine-scaled grid. Running the model requires the specifications of a history of lateral boundary forcing conditions, prepared using a large-scale forecast. The lateral boundaries specify how new weather features will enter the area of interest as the limited-area forecast proceeds. The idea behind dynamical local adaptation is that it is possible to improve over the large-scale forecast by

- the prediction of higher-resolution atmospheric features when they are implied but the large-scale flow
- the representation of fine-scale local weather phenomena that are generated by high resolution surface conditions, notably orographic, coastlines and surface types

An example of this is mountain induced winds, which in some areas totally can dominate the local weather. Their simulations depends critically on a precise modelling of local topography, but can be rather insensitive to details of the large-scale atmospheric flow. Local dynamical adaption is very popular since it gives the opportunity to run fine scaled forecasts at minimal costs forced with global atmospheric models.

An obvious limitation of adaption is that short-range forecasts will lack detail, since they will be nearly identical to the forcing model fields. [Elía and Laprise 2002] showed that if fine scale phenomena's are present in the lateral boundary conditions the fine-scale forecasts will gain improved accuracy.

The quality of the model surface analysis is of crucial important to mesoscale and fine scale models. A reliable high-resolution surface analysis is critically dependent on the availability of high-quality alnd-use datasets and the way in which these data are used in the atmopsheric model. The optimal way of initializing a limited area model through data assimilation, i.e. a mix of all available sources of information including observations, previous fine-scale model runs and large-scales models. The fundamentals of data assimilations are thoroughly described in the literature [Courtier et al 1994; Evensen 1994]. Additional information gained by data assimilation is the presence of fine scaled features in the analysis of the forecast. Data assimilation for use in limited area models is however a challenging task since it requires use of observations in denser networks at higher resolution in time. In addition data assimilation is very computer demanding and would increase the computational cost dramatically.

Application of improved observation system toghether with data assimilation at fine scales are expected to be very important in operational forecasting systems in the future.

3.4 Subgrid scale processes and model parameterizations

A model is by definition an approximation of reality, and although NWP models continue to grow in complexity, they cannot take into account all factors that affect the weather. The most important components of any numerical weather prediction model are the subgrid-scale parameterization schemes, and the analysis and understanding of these schemes is a key aspect of numerical weather prediction. On the one hand these parameterization methods influence the general quality of the numerical weather forecast, as the energy transformations in the atmosphere that they describe (release of latent heat, radiation processes, microfphysical process amoung others) have a decisive influence on further developments. On the other hand, a number of forecast quantities (e.g. precipitation, degree of cloud cover, near-ground temperature development) are supplied direct from the parameterization methods or are strongly influenced by them. This aspect is significant above all in the short-range sector, while the interaction between parameterized and scaling processes influences mainly the development of the forecasts over a period of several days.

There are a manifold of different parametereizations used in NWPs today, and among them are:

- Land surface-atmosphere parameterizations
- Soil-vegetation-atmosphere parameterizations
- Water-atmosphere parameterizations
- Planetary boundary layer and turbulence parameterizations
- Convective parameterizations
- Microphysics parameterizations
- Radiation parameterizations

The strategies to describe these sub-grid scale phenomens aer many. For a list of references on parameterizations in MM5, see the papers presented in this thesis. Some details are also presented in Section 4.1 Even with prefect initial conditions, an inaccurate prediction model will lead to rapid growth of forecast error. The uncertainties and approximations in the physics are believed to be the most significant contributors to model errors today. The cloud microphysics, in particular, contain significant sources of uncertainty for explicit prediction of convective cells. Different parameterized physics are important for other features such as the evolution of the planetary boundary layer (PBL) and the diurnal cycle.

Model physics represents a major challenge for all mesoscale modelling systems today, see e.g.Klemp et al. [2006]. The largest source of errors in today's numerical weather prediction is likely to be the unavailability of high resolution data over the entire forecast domain. New observing systems, which measure the variables we need under all weather conditions, are crucial to improve NWP forecasts together with data assimilation systems to incoorporate them into the models. Advancements of model physics is not merely a technological or development challenge, but will require progress in fundamental understanding of a number of atmospheric processes on a wide range of scales. But there are still large needs for improvements in the parameterizations seen in the state of the art models today such as the MM5 and WRF. These two tasks are highly coupled since a weather forecast needs accurate observations for initialization. In addition, observations are imperative to improve the understanding and the knowledge of fine scale weather phenomena's to improve the accuracy of the model parameterizations.

Klemp et al. [2006] gives an overview of many of the key issues neccessary to improve high resolution forecasting systems in the years to come. A major issue of parameterizations suitable for ultra high model resolutions (100 m – 5 km), is that many phenomenas which no longer are sub-grid scale. Key physical processes, such as cumulus convection and boundary-layer eddies are then partially resolved in the model.

4 Summary of results

4.1 Predictions of temperature inversions and its applications

Of special interest in this dr.scient thesis have been surface air temperature inversions and the diurnal variation of them. Surface temperature inversions are weather conditions which are traditionally causing large forecast errors. In most cases, the atmospheric stability is neutral, but in Scandinavia there are many cases during winter time with strong stability in the atmosphere. Surface temperature inversions are one of the most common weather conditions favourable for high levels of air pollution (see for instance Berge et al. [2002]), but the weather forecasts are in many cases poor due to smooth model topography and deficiencies in the parameterizations used in the models.

Flow near ground is strongly influenced by interactions with the surface. The no-slip boundary condition requires that the wind velocity must vanish at the surface, causing an important vertical wind shear, which is unstable and consequently produces turbulence (shear production). Apart from the lowest few millimetres, shear-induced turbulence, together with convective turbulent eddies caused by surface heating, are effectively transferring momentum and moisture down to or away from the surface. Turbulent eddies in the planetary boundary layer (PBL) have scales of 10^{-3} - 10^{3}m. Thus, they are not explicitly resolved in numerical weather prediction models and must be parameterised.

If the static stability of the atmosphere is great enough near the surface to cause temperatures to increase with height, then that portion of the PBL is classified as a *temperature inversion* [Stull 1988]. The balance in the PBL between mechanical generation of turbulence and damping by static stability might vary considerably. This creates stable boundary layers (SBL) that range from being well mixed to be nearly non-turbulent. Sometimes the SBL turbulence is sporadic and patchy, allowing the upper portions of the boundary layer to decouple from surface forcings. Because of this complexity, the SBL is difficult to describe both theoretically and by numerical models. In today's weather prediction models, there are large deficiencies in their capability to create accurate forecasts of temperature inversions. There are several reasons for this. In MM5 and other models, the parameterizations used during stable stratification are based on Monin-Obukhov theory. For all model results presented in this thesis, the PBL-scheme of Hong and Pan [1996] is used. This scheme has a first order turbulence closure in which vertical diffusion is based on the local gradients of the wind and potential temperature in the stable case.

The temperature inversions normally starts in the afternoon after sunset and breaks up in the hours after sunrise. During this period, and especially at the break-up, the parameterisations of surface processes and turbulent exchange is important (See Avissar and Pielke [1989] or Mahfouf et al. [1987]. A rapid progress has recently taken place in model description of land surface processes and turbulence in the PBL (e.g. Chen and Dudhia [2001a, 2001b], Viterbo et al.[1999] or Oncley and Dudhia [1995]), but few of these parameterisations currently used in numerical models are thoroughly tested for real-time purposes in the area from 1 - 10 km resolution. During stable conditions with calm winds and fair weather, the quality of near surface predictions of wind and temperature depend less on the quality of boundary conditions and more on locally generated circulations. Such regimes, together with the description of temperature inversions, are controlled by many factors (see e.g. Stull [1988] or Garrat [1999]) such as turbulence, SW and longwave (LW) radiation, advection and subsidence. The energy balance at the surface might shed some light on the different processes:

$$(1-\alpha)S^{\downarrow} + L^{\downarrow} - L^{\uparrow} = H + L \cdot E_{tot} + G_0, \tag{1}$$

where α is the surface albedo, $S^{\downarrow}$ is incoming short wave radiation, L is downward($^{\downarrow}$) and upward ($^{\uparrow}$) long wave radiation, H is turbulent heat-flux, $L \cdot E_{tot}$ is turbulent latent heat-flux and G_0 is heat-flux down into the soil. Surface temperatures in numerical models are normal calculated according to the energy balance (1) and heating or cooling takes place whenever net incoming fluxes are positive or negative. The heat flux at the surface is thus naturally important in the energy budget and the corresponding surface temperatures. In order to describe the conditions in the planetary boundary layer, it is essential to parameterises the terms in Eq. 1 as accurately as possible. As mentioned above, there are large deficiencies in the parameterizations of the fluxes, and especially during stable conditions.

The left hand side of Eq. 1 describes the radiative contribution to the energy budget at the surface. This balance strongly depends on cloud cover and humidity of the atmosphere above the PBL. Cloud cover would effect the radiation at the surface, which further influences the surface temperatures and humidity. Changed surface characteristics changes the turbulent fluxes in the PBL, which again changes the surface temperatures and humidity. This is a non-linear behaviour, which makes an accurate description of the planetary boundary layer difficult. Paper I [Hauge and Hole 2003] addressed some problems and solutions to improve the break-up of a temperature inversion in complex Norwegian terrain with a new parameterization scheme for short wave radiation.

Due to the interactions and non-linear feedbacks between different errors terms within a numerical simulation, the separation of individual errors related to specific parameterisations are a difficult task. Errors may partly cancel each other, and attempts to improve the model performance may easily lead to introduction of compensating errors. This problem is in particular pronounced for complex numerical systems such as the MM5, where the interaction and feedbacks between different parts of the model system are difficult to investigate due to its complexity. But this interaction-study is necessary in order to improve weather forecasts at resolutions below 5-10 km along with better observing systems.

Applications of accurate predictions of temperature inversions are many. Noise and air-pollution can be a problem during such weather events. Military training and shooting activities normally takes place during daytime. Since inversions are common during wintertime and late autumn and early spring in Norwegian inland terrain good knowledge of the periods *without* temperature inversion is valuable for the planning of military shooting activities. This information can be used to create forecasts of the noise propagation inn an area In the work described in Paper II [Hole and Hauge 2003], the results from a very high resolution model run with MM5 were coupled to a sound propagation model. Such a coupling is somewhat challenging since it tries to combine weather predictions with time scales on hours with acoustical phenomena's with time scales on seconds. The interesting with this coupling is that acoustical models normally use predefined assumptions of the weather conditions instead of real forecasts. By the application it is possible to make real-time "sound forecasts" in areas with much noise, for instance in military shooting areas.

To understand the basic effect of wind and temperature on the sound propagation we can investigate the directional sound velocity, DSV;

$$DSV(z) = C_0\sqrt{1 + \frac{T(z)}{273.15}} - V(z)cos(\alpha(z) - \beta), \qquad (2)$$

where z is the height above ground, C_0 the speed of sound in air at 0^oC, 331.6 m/s, T is the temperature in Celsius, V(z) the wind speed as a function of height, and $\alpha(z)$ is the wind direction and β is the source to receiver bearing. Colder air gives lower sound velocity and warmer air gives a higher velocity. Simple stated, the air waves follows Snell's law for refraction which means that the sound will be refracted from a layer with higher speed of sound towards an area where the speed is lower. In temperature inversions with little vertical wind-shear, the refraction is towards the ground - which can lead to high levels of sound [Hole and Hauge 2003].

4.2 Modelling of icing events based on high resolution forecasts

Atmospheric icing has severe economical and technological consequences for human activities. It occurs frequently in sub arctic and artic climates as well as exposed locations at a certain height above sea level. Convincing evidence of its effects comes from the long list of human activities that have occasionally been disrupted, such as aircraft operations, telecommunication networks, power transmission lines, roads and railways [Poots. 2000]. Icing directly onto structures occurs as rime ice, clear ice or wet snow deposit. Reliable icing forecasts require meteorological data of standard parameters such as air temperature, relative humidity, wind speed, wind direction and turbulence, in addition to more specific parameters such as median volume droplet size and liquid water content of the air masses concerned.

One of the earlier attempts to apply a numerical boundary-layer model to predict LWC for icing calculations was made by Vassbø et al. [1998]. They used the HIRLAM (High Resolution Limited Area Model) over Finnish topography. This was however a study which used very coarse horizontal and, not least, vertical resolution. The horizontal resolution was 22 km by 5.5 km. The model had only 3 layers below 627 m, which reproduced the planetary boundary layer poorly. In the work presented in Paper III [Drage and Hauge 2006], the horizontal resolution were increased to 1 km and the vertical resolution to 38, giving 17 layers the lowest kilometre of the atmosphere. There are still a lot of work that have to be adressed before such icing forecasts can be made operational. The results presented in Drage and Hauge [2006] gives reason to be optimistic for the application of very high resolution forecasts to estimate icing events on buildings and structures.

4.3 Predictability of high resolution forecasts in complex terrain

The general question of predictability were discussed in some details in the foregoing chapters. Many of the scientific works on the topic have focused on convective events which normally are have poor predictability. These events can be seen as weather phenomena with some sort of instability in them. Systems with instiabilities, such as fronts, convective systems or turbulence will have less forecasting skill that weather phenomena foreced by complex topography and land-surface contrasts. In Paper IV [Hauge et al. 2006] of this thesis the focus were on how the complex topography influenced the local scale predictability at model resolutions down to 500 metres in two different modelling systems (MC2 and MM5).

The results from Hauge et al. [2006] show that a horizontal resolution of at least 1 km is required to realistically reproduce wind fields along the Norwegian coast, and that high resolution models are far superior to models with coarser resolution. The predictability studies show that the errors grow very slowly in a 48 hour forecast, and hence indicate that high resolution models with a resolution of approximately 1 km can indeed be useful, and better than reported in previous works in the litterature , see for instance Anthes [1986] or Baumhefner [1984].

5 Concluding remarks

The daily weather in Norway is primarily driven by large scale synoptical systems coming in from the west. Complex topography with fjords and high mountains creates circulation patterns with large variations in the weather conditions over few kilometres. Traditional weather forecasting have until the last few years focused on the synoptic to mesoscale weather phenomena's, ranging from 50 – 10 km

The futuristic trend in numerical weather prediction is high resolution forecasts on horizontal scales down to a few kilometres or even hundreds of meters. Numerical modelling of small-scale atmospheric features requires an accurate description of the large-scale atmosphere, explicit representation of appropriate physical mechanisms, and assimilation of relevant meteorological data. This allows analysis and forecasting of important weather phenomena such as thunderstorms, temperature inversion, precipitation and floods, fog, orographically-induced winds, or urban weather and pollution. Depending on the situation, local weather may be more or less predictable than large-scale weather, and short-range forecasts may be harder to produce than longer-range ones.

This dr.scient thesis have focused on very high resolution forecasts and some potentially useful applications for such forecasts. This thesis are trying to point out several ways that high resolution models can be improved in order to produce high quality forecasts.

Very high resolution is often required in order to resolve many of the weather conditions observed daily in complex terrain. Model physics of the numerical models used today are in many cases neither tuned or designed for use on scales down to a few hundred metres. Paper I of this thesis [Hauge and Hole 2003] addresses the issue of the surface parameterizations of short wave radiation in complex terrain. It is shown that the inclusion of slope irradiance can change the circulation patterns during the break up of a temperature inversion and reduce the bias of the MM5 model.

If weather models realistically can reproduce observed features at fine scales, there are a wide variety of applications. Paper II and III of this shows som interesting applications of such forecasts; noise propagation forecasts [Hole and Hauge 2003] and forecasts of icing incidents [Drage and Hauge 2006].

A limiting factor of LAMs will always be the lateral boundary conditions used to force the models. The study investigated in paper IV of this thesis Hauge et al. [2006] shows, that significant improvements of forecasts can be made at high resolutions in complex terrain. It is also seen that a model resolution of at least 1 km is necessary to realistically simulate the observed features along the complex topography along the Norwegian coast. The strong influence of topography combined with large scale forcings gives good short range predictability of winds and temperature at high model resolution despite poor quality of the initial conditions often seen in real-time forecasts.

The error growth can in some cases be smaller in complex terrain [Hauge et al. 2006] and it is reason to believe that improved quality of boundary conditions through improved assimilation systems will further increase the predictability of very high resolution forecasting systems. Improved model physics along with better initialisation and data assimilation systems seems to be the most prominent improvements that have to be made in order to create highly accurate fine scaled forecasts.

In the years to come, real-time weather prediction system at resolutions on scales from hundreds of metres to a few kilometres will become common. Ensemble prediction system will also probably evolve towards short and very short range scales, and towards extreme weather events. A variety of teqhniques has been tried out to model predictability in the short range: breeding modes, targeted singular vectors, stochastic physical parameterizations and multi model systems. The probabilistic distributions from these systems are still far from reliable, certainly for prediction of severe weather events.

The future of numerical weather predictions will for sure be very exiting, and research and development required for improvements are significant. Society will greatly benefit from such increased forecasting systems and especially in notoriously complex areas like Norwegian terrain.

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