Meteorologisches Institut
Universität Bonn

National Center for Atmospheric Reasearch
Boulder Colorado

Masterthesis

Evaluation of the COSMO- and WRF-Model by Application of the Initial Tendency Method

Florian Losch

September 30th, 2015

Mentors: Dr. Petra Friederichs and Dr. Judith Berner

Dies hier ist ein Blindtext zum Testen von Textausgaben. Wer diesen Text liest, ist selbst schuld. Der Text gibt lediglich den Grauwert der Schrift an. Ist das wirklich so? Ist es gleichgültig, ob ich schreibe: „Dies ist ein Blindtext" oder „Huardest gefburn"? Kjift – mitnichten! Ein Blindtext bietet mir wichtige Informationen. An ihm messe ich die Lesbarkeit einer Schrift, ihre Anmutung, wie harmonisch die Figuren zueinander stehen und prüfe, wie breit oder schmal sie läuft. Ein Blindtext sollte möglichst viele verschiedene Buchstaben enthalten und in der Originalsprache gesetzt sein. Er muss keinen Sinn ergeben, sollte aber lesbar sein. Fremdsprachige Texte wie „Lorem ipsum" dienen nicht dem eigentlichen Zweck, da sie eine falsche Anmutung vermitteln.

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Contents

1 Theory

1.1 Numerical Weather Prediction Model

Modern weather prediction always bases on use of output from Numerical Weather Prediction (*NWP*) models. To improve the quality of these predictions, one has to assess possible errors in the NWP-models. First the procedure of a NWP-model will be described.[1]

To initialize the numerical model, information about the current state of the atmosphere (and other modelled systems) is needed. These initial values have to be given in the „model space". Meaning, that all values describing the system are needed in the way the model would produce them on every grid point.

Due to practical reasons, there can't take place measurements of the state of the atmosphere on every grid point in the 3D-Atmosphere multiple times a day for every weather forecast. To introduce a possibility to start a NWP-model nevertheless, the process of data assimilation is used.

1.1.1 Data Assimilation

Main objective of the data assimilation process is to find a model state, for that holds, that the forecast of the NWP-model will be closest possible to the physical truth. This objective differs from the task, to find a model state closest to the current/initial, true atmospheric state.

Another problem addressed by the data assimilation process is the presence of measurement errors. Already small errors in a single measurement can imply extensive imbalances and thereby erroneous processes in the forecast. Therefore it is important to damp the influence of any single measurement in favor of correct balancing and hence a correct representation of physical processes in the model.

To realise both objectives of data assimilation, a model run is started about one hour before the forecast is to be produced. As initial condition a forecast for that point in time is used. In the timeframe between start of the model run and start of the forecast process, the data assimilation takes place. During this process all available measurements are beeing incorporated in the model. The way this is done depends on the specific data assimilation scheme choosen.

One particular assimilation scheme is the *observation-nudging*. This scheme is used in the COSMO-model. In this scheme the incorporation is realised by a change of the prognostic tendency produced by the model during forward integration. The change for any observed variable $\phi(x,t)$ by kth observation is given by([3]):

$$\frac{\partial}{\partial t}\phi(\mathbf{x},t) = F(\phi,\mathbf{x},t) + G_\phi \cdot \sum_{k_{(obs)}} W_k(\mathbf{x},t) \cdot \left[\phi_k^{obs} - \phi(x_k,t)\right] \qquad (1.1)$$

Where F is the tendency produced by model dynamics and physics, G a variable dependend constant, W_k a observation depend weight decreasing with distance from the observation in space and time and ϕ^{obs} the observed value. By this procedure the model is forced to stay close to observed values where these are available but can develop free where no information is known.

If the model physics and dynamics $F(\cdots)$ were zero, the assimilation terms would produce a exponential convergence of ϕ to ϕ^{obs}. To guarantee, that the modelled system is still conform to the physical model, the assimilation term should be small compared to the model physics and dynamics. To ensure this, W_k is being adjusted with the formula:

$$W_k = \frac{w_k + 1}{\sum_j w_j + 1} \cdot w_k \qquad (1.2)$$

Where the individual measurements weight w_k is being limited by the utilization of the sum over all influencing weights w_j

An advantage of this method is, that measurements can flexibly be added to the assimilation process whenever they are available while other methods are only able to incorporate additional information at fixed times.

For nudging based assimilation the measured „truth" has to been known in model space (see ϕ in 1.1), thus no satellite data can effectively be used in data assimilation.

TBD: Data Assimilation in WRF: ETKF, hybrid, 4D-Var, 3D-Var?

1.2 Model Error

While there is obvious description of what a model error is, namely a discrepance between the forecast and the actual physical development, there are different concepts of describing model errors.

From a perspective of model development there are three kinds of errors. First of all there are approximations and neglections consciously implemented into the numerical model. These errors are taken into account to allow computability in a certain timeframe as the

forecast always has to be computed faster than the forecasted event takes place. A second source of error are uncertainties in parameters, boundary and initial data, and measurement errors. These errors are thought to be countered by data assimilation and ensemble forecasting. The third source of errors are implementation errors. This is expressed by differences between the formal „numerical model" and the model actually implemented by the source code.

One insightful way of describing model errors follows [2]. Judd describes different types of errors by their origin, neglecting whether they're distinguishable later. He also describes the data assimilation process not as independent, but as part of the model.

1.2.1 Initialisation Error

One widely known source of error is error in the initial data. Often it is assumed, that uncertainty of the initial state will grow even in a perfect model exponentially with time. [4] however finds, that this behaviour will not always be observed.

In dissipative systems *sometimes* a initialisation error will be dissipated and the model trajectory will converge to the real one. However *statistically* the assumption of an exponential error growth due to initialisation errors still holds.

Another implication of the exponential growth is, that for a certain time after the beginning the errors due to initialisation errors will be small compared to other errors.

1.2.2 Spin Up Error

Both numerical models as the physical climate are describable by a multidimensional attractor [2]. For the physical climate this attractor implies a recurrence time of $\mathcal{O}(10^{30}\,\mathrm{yrs})$ for which the climate system would return to a similar state. The spatial dimension of this attractor is with $\mathcal{O}\left(10^5\ to\ 10^6\right)$ also too big to be imagined or visualized.

It is observed, that numerical weather models will be strongly attracted to an attractor, which might differ from the physical climate attractor. If a difference between the physical and the model attractor exist and the model is initialized in a state lying on the physical attractor, in the beginning of the simulation the model will move from the physical attractor to the intrinsic attractor of the numerical model, resulting in erroneous tendencies called *spin up*.

Spin up errors can also occur due to artificial different treatment of the first time steps of numerical modelling. This can be implemented as simplification or by error.

Spin up errors can be reduced by using appropriate data assimilation. To minimize the time model output is influenced by spin up it's important to use the same model system in data assimilation as will be used for simulation. Also model configuration (choice of

parametrizations) has to be equal. Otherwise the spin up process can need more then several days, dominating the whole forecasting time.

1.2.3 Tendency Error

A numerical forecast model might also exhibit constant error in tendencies of variables. This kind of error differs from spin up as tendency errors don't diminish with longer forecast periods letting the actual error grow larger and larger.

As this kind of error often implies a breaking of conservation laws of energy or similar these errors are either included by mistake or by neglection of processes in the atmosphere. Examples for such processes might be aerosols, 3D-radiation scattering or sound waves.

Weather forecast models with higher resolution often don't run for more than a few days therefore small tendency errors might not grow large or are indistinguishable from spin up effects.

1.3 Reforecasts

One complication in the evaluation process of numerical weather model used in production is inconsistency over time. For the production use of weather services mistakes in the model are fixed as soon as possible. However this leads incomparability of model behaviour over longer time scales.

To develop a deeper understanding of model behaviour *reforecasts* are used. Therefor the model is started from initialization states in the past and a forecast for the past is produced. This method differs from a reanalysis as here during the forecast no measurements are incorporated into the model.

By freezing on a specific model configuration and re-evaluation of free forecasts from reanalysis initial data, one can investigate the attractor of the numerical model.

There are different applications imaginable for utilizing reforecasts for model evaluation. [?] compared the model output to measurements and [?] investigated physical properties of the climate exhibited by the model in terms of humidity fluxes [?] as in terms of conservation properties [?].

The initial data used from the HeRZ-reanalyses are in this work considered as free from systematic biases. With this assumption no errors can be found, that are not constrainable by measurements during data assimilation.

1.4 Initial Tendency Method

Objective of the evaluation method used in this work is to evaluate the models without the use of additional measurements. This kind of evaluation has to verify intrinsic physical properties or the general behaviour of the model.

Under the assumption of a stationary climate one can assume, that statistically all variables have to be constant. This is expectably true for extensive or intensive variables.

The time scales for which different variables in the climate system are quasi constant can become very large.

1.5 COSMO Model

1.6 WRF Model

2 Methodology

2.1 Entropy Production

2.1.1 Entropy Temperature

$$\text{mixing ratio: } r^t = r^1 + r^2 + r^3$$

$$c^* = c_{p0} + c_2 r^t$$

$$a_{21} = R_1 T \ln \frac{p^{21}}{p^1}$$

$$a_{32} = R_1 T \ln \frac{p^{31}}{p^{21}}$$

$$\Theta_s = T \left(\frac{p^0}{p_0} \right)^{-\frac{R_0}{c^*}} \cdot \exp \left[\frac{(l_{21} + a_{21}) r^1}{c^* T} - \frac{(l_{32} + a_{32}) r^3}{c^* T} \right] \qquad (2.1)$$

2.1.2 Entropy Production

$$\frac{\mathrm{d}s}{\mathrm{d}t} = m^0 c^* \frac{\mathrm{d}\ln\Theta_s}{\mathrm{d}t} \qquad (2.2)$$

2.2 Richardson Number

$$\text{Brunt-Väisälä frequency: } N = \sqrt{\frac{g}{\Theta} \frac{\mathrm{d}\Theta}{\mathrm{d}z}}$$

$$Ri = \frac{N^2}{\left(\frac{\mathrm{d}u}{\mathrm{d}z} \right)^2} \qquad (2.3)$$

2.3 Helicity

$$H = \int_V \vec{\mathbf{v}}_{\mathbf{h}} \cdot \boldsymbol{\nabla} \times \vec{\mathbf{v}}_{\mathbf{h}} \tag{2.4}$$

2.4 COSMO

2.5 WRF

2.5.1 Physics Parametrizations

Microphysics	New Thompson et al incl. Graupel, rain number density
Longwave Radiation	RRTMG (RRTM + random cloud overlap)
Shortwave Radiation	RRTMG
Clay Surface Layer	Eta similarity (Monin Obukhov)
Surface Layer	Noah land surface model
Boundary layer	Mellor-Yamada-Janjic scheme, 1D TKE + local vert. mixing
Cumulus param	Tiedtke scheme (coarse resolution only)

3 Application

$$\frac{dx^2}{dt} = \frac{\partial x}{\partial t} = \frac{\partial x^2}{\partial t} + \left(\vec{v} \times \vec{\nabla}\right) x^2 \tag{3.1}$$

3.1 COSMO

3.2 WRF

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

4 Results

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

This is the second paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

And after the second paragraph follows the third paragraph. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

After this fourth paragraph, we start a new paragraph sequence. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there

no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Bibliography

[1]   WT Grandy Jr. "Time evolution in macroscopic systems. II. The entropy". In: *Foundations of Physics* 34.1 (2004), pp. 21–57.

[2]   Kevin Judd et al. "The geometry of model error". In: *Journal of the atmospheric sciences* 65.6 (2008), pp. 1749–1772.

[3]   C. Schraff and R. Hess. "COSMO Documentation Part III: Data Assimilation". In: *Foundations of Physics* ().

[4]   Leonard A Smith, C Ziehmann, and K Fraedrich. "Uncertainty dynamics and predictability in chaotic systems". In: *Quarterly Journal of the Royal Meteorological Society* 125.560 (1999), pp. 2855–2886.