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## Masterthesis

# EVALUATION OF THE COSMO- AND WRF-MODEL BY APPLICATION OF THE INITIAL TENDENCY METHOD

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# *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.

## *1.2 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 realize 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 being

incorporated in the model. The way this is done depends on the specific data assimilation scheme chosen.

### 1.2.1 Observation Nudging (COSMO)

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

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

Where  $F$  is the tendency produced by model dynamics and physics,  $G$  a variable dependent constant,  $W_k$  a observation depend weight decreasing with distance from the observation in space and time and  $\phi^{obs}$  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  $F(\dots)$  were zero, the assimilation terms would produce a exponential convergence of  $\phi$  to  $\phi^{obs}$ . To guarantee, that the modeled 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:

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

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  $\phi$  in (1.1)), thus no satellite data can effectively be used in data assimilation.

Also the incorporation of radar precipitation data needs special procedure called *latent heat nudging*. It would not be effective to just add the precipitation observed where the model is not producing it, as the precipitation would just fall to the ground without adjusting the model dynamics effectively. This would just be fixing the symptoms but not the cause of a lack of precipitation.

To fix the cause of a lack or excess of precipitation latent heat is added or removed from the lower bound of clouds. This will then increase or reduce vertical motion in the cloud and then cause an adjustment of the precipitation rate in the needed direction.

While the observation nudging scheme is rather pragmatically designed it shows best performance in operational weather forecasts due to its high adjustability. Also the forecasting framework is easier to set up. Operationally the model is always in „data assimilation“ mode, and as soon as no observations are available anymore the model will automatically be running as free model – the second righthand term in (1.1) will be zero.

Also this scheme allows the model during data assimilation to move to its attractor, and therefore minimizing spin up errors (see section 1.3.2).

### 1.2.2 Ensemble Kalman Filter (WRF)

Another approach of data assimilation is chosen in the WRF data assimilation program called *DART*. The Ensemble Kalman Filter is based on the original by Kalman introduced Kalman Filter.

The Kalman Filter works on linear systems. The initial conditions are not exactly known but their probability distribution is. Also measurements after a certain time and their error distribution are known. The Kalman Filter then proceeds in two steps.

- First from the initial condition a forecast is produced. Because of the linearity the propagation of the uncertainty is feasible computable. The result is called the bayesian prior.
- Second the measurements and their uncertainty, called bayesian posterior, are taken into account. Utilizing Bayes' Theorem both the prior and the posterior are combined to the assimilation.

From this assimilation output now again a forecast can be started, which then in combination with new measurements allows to *cycle* the assimilation scheme. For systems with normal distributed errors, this scheme is known to produce the optimal solution.

In numerical weather prediction however the dynamic system is very strongly not linear. This makes it infeasible to predict the propagation of uncertainty with time as the Fokker-Planck equations would have to be solved. The usage of the Ensemble Kalman Filter avoids this tedious task at the cost of losing the property of optimal solution.

The Ensemble Kalman Filter utilizes a bootstrapping method to simulate a solution of the Fokker-Planck equations. To achieve this, the initial uncertainty is represented by a sample  $\mathcal{O}(50 \text{ to } 100)$  of initial conditions whose variance is maximized along the Lyapunov vectors with biggest Lyapunov exponents.

## 1.3 Model Error

While there is obvious description of what a model error is, namely a discrepancy 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 neglects 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.

### 1.3.1 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 behavior will not always be observed.

In dissipative systems *sometimes* a initialization 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 initialization errors still holds.

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

### 1.3.2 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  $\mathcal{O}(10^{30} \text{ yrs})$  for which the climate system would return to a similar state. The spatial dimension of this attractor is with  $\mathcal{O}(10^5 \text{ to } 10^6)$  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 modeling. 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.

### 1.3.3 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 neglect 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.

## 1.4 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 behavior over longer time scales.

To develop a deeper understanding of model behavior *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.

## 1.5 Initial Tendency Method

For a Variable  $\Phi$  let  $\Phi_0^R$  be the reanalysis field from which the model is started and  $\Phi_1^R$  the next reanalysis field available after a time of  $\Delta T$ .

The forecast field for  $t$  seconds after  $\Phi_0^R$  is denoted  $\Phi^M(t)$ . The model time step numbered  $0 \leq i \leq n \in \mathbb{N}$  is  $\Delta t$  seconds. Therefore model fields are available for  $t = i\Delta t$  and called  $\Phi_i^M$ .

The Background tendency is  $\dot{\Phi}^R = (\Phi_1^R - \Phi_0^R)/\Delta T$  if  $i < \Delta T/\Delta t$ , otherwise  $\Phi_{2,3,\dots}^R$  will be used such that the time step  $i$  is in between the used reanalyses. The model tendency  $\dot{\Phi}_i$  exclusive the background tendency between the time steps  $i$  and  $i + 1$  is then calculated by:

$$\dot{\Phi}_i = \frac{\Phi_{i+1}^M - \Phi_i^M}{\Delta t} - \dot{\Phi}^R \quad (1.3)$$

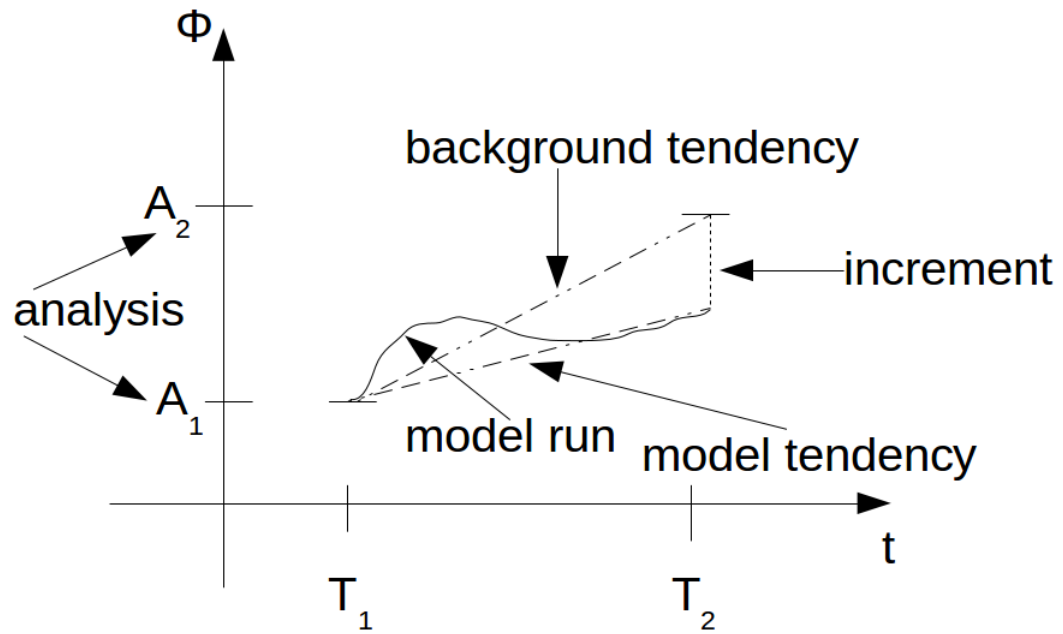
Occasionally due to practical reasons some model tendencies  $\dot{\Phi}_i$  to  $\dot{\Phi}_j$  will be examined only averaged:

$$\dot{\Phi}_{ij} = \frac{1}{j-i} \sum_{k=i}^{j-1} \dot{\Phi}_k = \frac{\Phi_j^M - \Phi_i^M}{(j-i)\Delta t} - \dot{\Phi}^R \quad \text{with: } i < j \leq n \quad (1.4)$$

For some variables the model can be configured or adapted to add different tendency terms, that are normally are integrated, directly to the model output. This then allows for another way to compute  $\dot{\Phi}_i$ :

$$\dot{\Phi}_i + \dot{\Phi}^R = \sum_k \dot{\varphi}_k^M \quad (1.5)$$

Here  $\dot{\phi}_k^M$  are the different model tendencies from the dynamics and physics of the NWP. It is important that all processes are included for this equation to hold.



## ***1.6 COSMO Model***

Strict licensing prohibits free use for commercial purposes.

Developed mainly by German weather service (DWD) together with other institutions in the COSMO consortium.

### ***1.6.1 Coordinate System***

#### ***Horizontal***

Spherical coordinates with rotated north pole.

#### ***Vertical***

...

### ***1.6.2 Sound Waves***

Fast time stepping...

## ***1.7 WRF Model***

Public domain license.

Developed mainly at NCAR, but everyone is free to participate.

### ***1.7.1 Coordinate System***

#### ***Horizontal***

Cartesian, lambert conformal projection

#### ***Vertical***

...

### ***1.7.2 Sound Waves***

Fast time stepping...

## 2 Methodology

### 2.1 Entropy Production

#### 2.1.1 Entropy Temperature

$$\begin{aligned}\text{mixing ratio: } r^t &= r^1 + r^2 + r^3 \\ c^* &= c_{p0} + c_2 r^t \\ a_{21} &= R_1 T \ln \frac{p^{21}}{p^1} \\ a_{32} &= R_1 T \ln \frac{p^{31}}{p^{21}} \\ \Theta_s &= T \left( \frac{p^0}{p_0} \right)^{-\frac{R_0}{c^*}} \exp \left[ \frac{(l_{21} + a_{21})r^1}{c^* T} - \frac{(l_{32} + a_{32})r^3}{c^* T} \right]\end{aligned}\tag{2.1}$$

#### 2.1.2 Entropy Production

$$\frac{ds}{dt} = m^0 c^* \frac{d \ln \Theta_s}{dt}\tag{2.2}$$

### 2.2 Richardson Number

$$\begin{aligned}\text{Brunt-Väisälä frequency: } N &= \sqrt{\frac{g}{\Theta} \frac{d\Theta}{dz}} \\ Ri &= \frac{N^2}{\left( \frac{du}{dz} \right)^2}\end{aligned}\tag{2.3}$$

## 2.3 Helicity

$$H = \int_V \vec{v}_h \cdot \nabla \times \vec{v}_h \quad (2.4)$$

## 2.4 COSMO

### 2.4.1 Physics Parameterizations

Gridscale Precip:

4 Graupel scheme with prognostic cloud water, cloud ice, and graupel.

Radiation: Grid- and sub-grid scale (including convective) water and ice clouds are considered; cloud cover, water content and ice content are calculated by the default diagnostic scheme.

Coarser grid, every 50 timesteps (= 15min)

no topographic correction

constant aerosol fields, surface albedo is determined by soil type

Convection:

Shallow convection based on Tiedtke scheme

every 10 timesteps (= 3min)

Convection forcing fields are averaged before calling the scheme.

No CAPE or TKE closure

Vertical turbulent diffusion:

Prognostic TKE-based scheme; includes effects from subgrid-scale condensation/evaporation.

Neumann boundary conditions for heat and moisture transport at the lower boundary

Grid- and sub-grid scale water clouds are considered

No explicit corrections of implicitly calculated turbulent heat and moisture fluxes due to effects from subgrid-scale condensation

No consideration of thermal TKE-source in enthalpy budget

horizontal turbulent diffusion included

calculate SSO-wake turbulence production for TKE

don't consider convective buoyancy production for TKE

Only vertical shear

Surface Layer fluxes:

TKE-based scheme including a laminar sub-layer



Clouds are not considered for subgridscale condensation

Soil Processes:

Lake model FLake is not used

Terra is run with 7 soil layers

2 soil water layers

no minimum stomata resistance map

BATS is used for transpiration of vegetation and bare soil

for heat conductivity an average soil moisture is used.

No subgridscale orography is used

## 2.5 WRF

### 2.5.1 Physics Parameterizations

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

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

### 3.1 COSMO

#### 3.1.1 Lowest Model Levels

During first timestep: Too cold and dry in lowest level, too hot and moist in 2nd lowest level.

All timesteps: Too hot and moist in lower 1 km. Explanation: Convective scheme too active in lower atmosphere during Spin-Up. Transport of moisture and heat from ground up. Later double counting of dynamics and convective scheme at cloud base leads to too much enthalpy there. Dissipates to lower atmospheric levels.

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### 3.2 WRF

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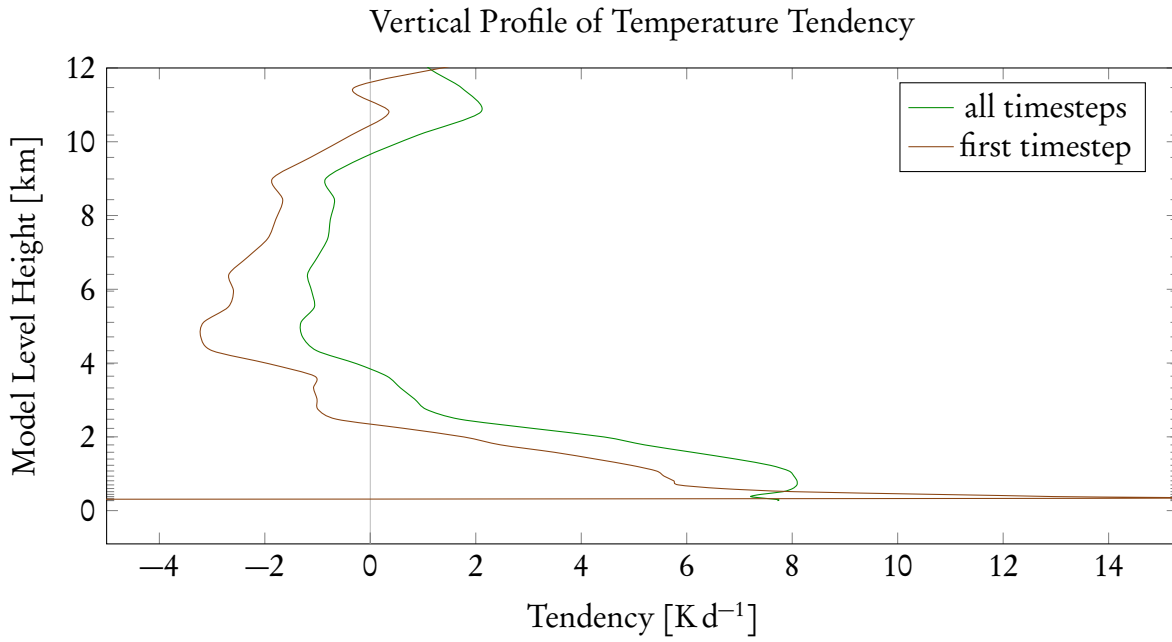


Figure 3.1: *y axis*: For the vertical profile model levels have been used. For each level the mean height is used. Full model levels are taken to be in the geometric mean height between half levels. *x axis*: Tendency of the model Temperature. Using the first timestep only (brown) and the mean for all timesteps (green). Values for the lowest and highest model levels are omitted and  $< -20 \text{ K d}^{-1}$ .

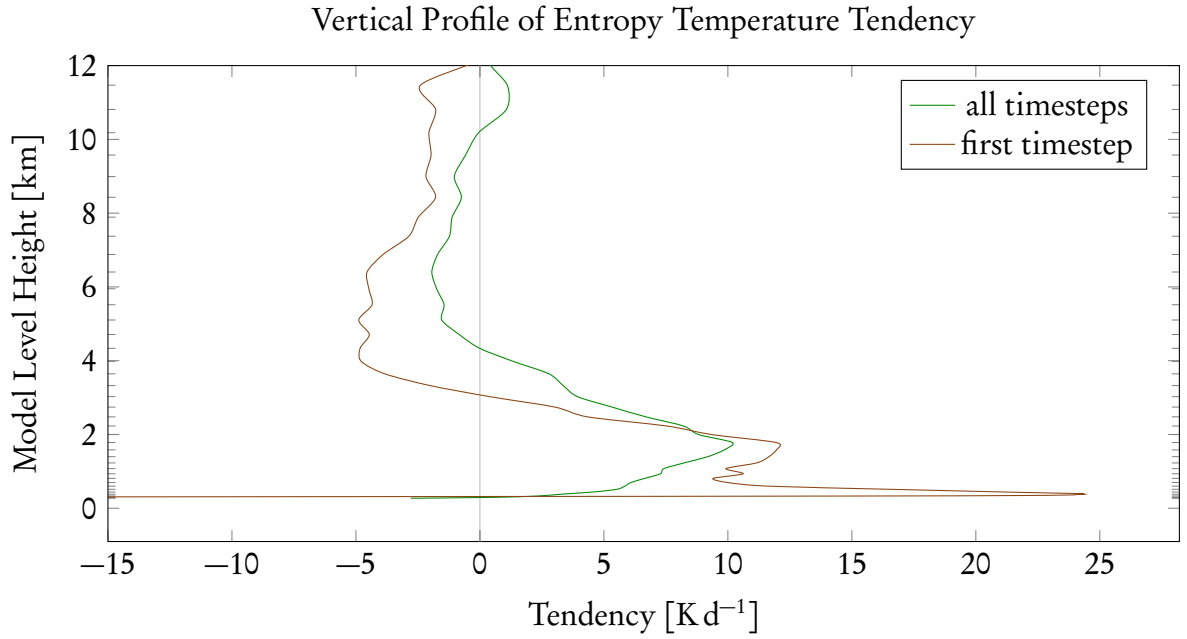


Figure 3.2: *y axis*: For the vertical profile model levels have been used. For each level the mean height is used. Full model levels are taken to be in the geometric mean height between half levels. *x axis*: Tendency of the model Entropy Temperature. Using the first timestep only (brown) and the mean for all timesteps (green). Values for the lowest and highest model levels are omitted and  $< -180 \text{ K d}^{-1}$ .

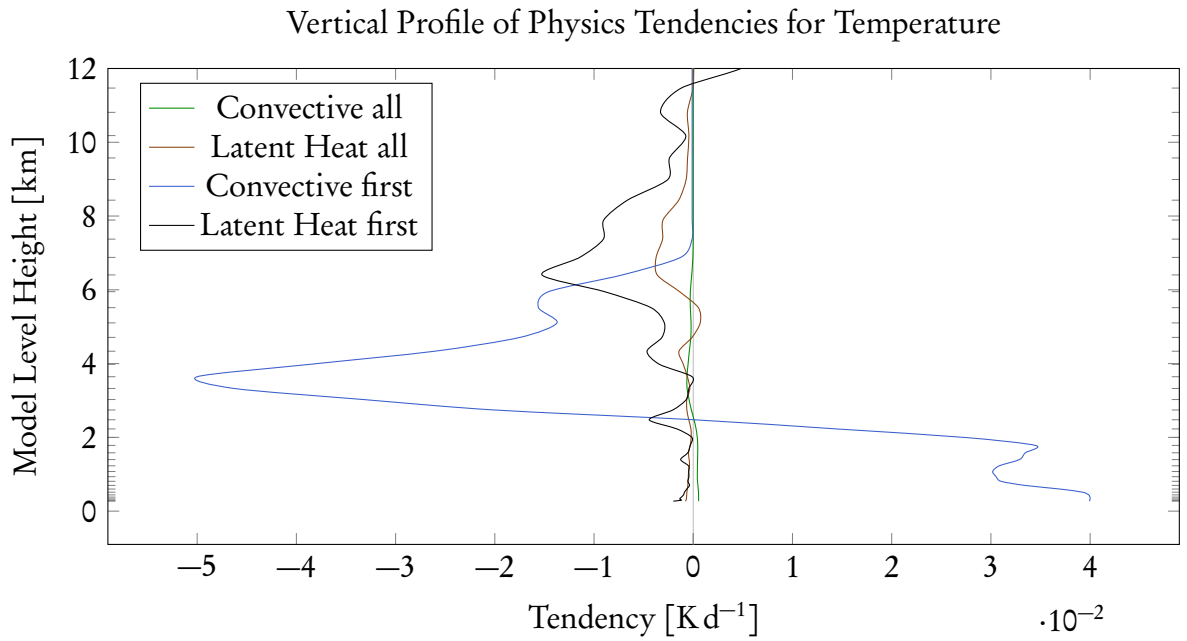


Figure 3.3: bla

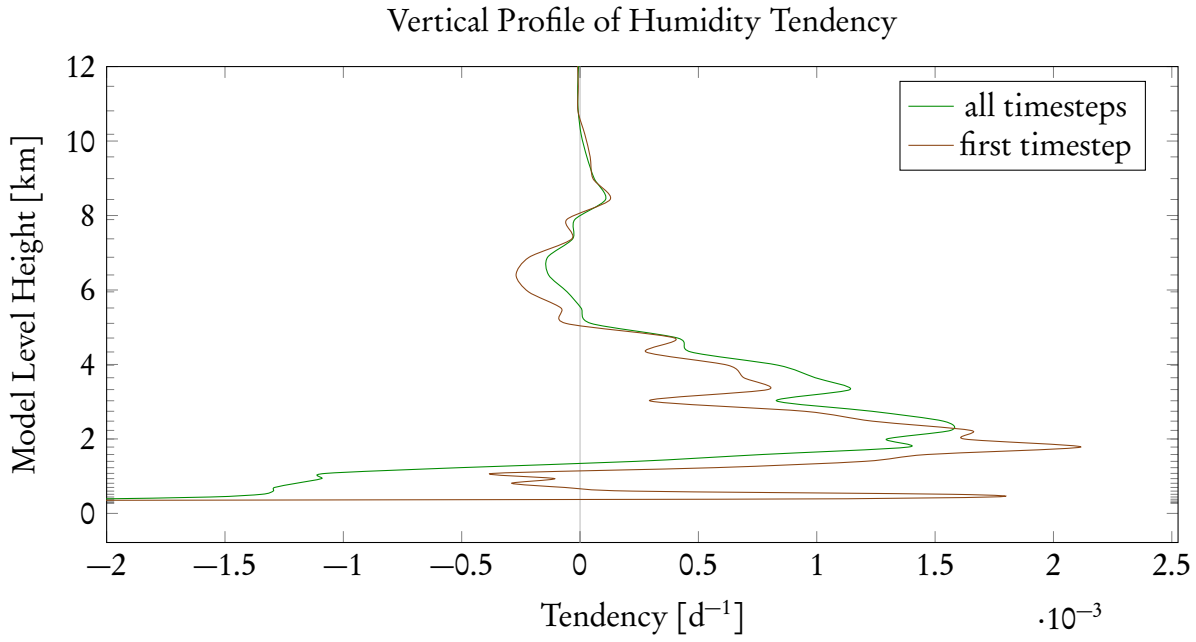


Figure 3.4: *y axis:* For the vertical profile model levels have been used. For each level the mean height is used. Full model levels are taken to be in the geometric mean height between half levels. *x axis:* Tendency of the model Humidity (mixing ratio of water vapor). Using the first timestep only (brown) and the mean for all timesteps (green). Values for the lowest model level are omitted and  $< -1.5\% \text{d}^{-1}$ . Values for the upper atmosphere (not shown) are very close to 0.

## 4 *Results*

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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.

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