Sensitivity of quantitative precipitation forecast to height dependent changes in humidity

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[1] The impact of humidity variations on QPF is studied performing a series of sensitivity experiments with the COSMO model at a horizontal mesh size of 7 km. Generally, variations of humidity in the boundary layer have the largest impact on precipitation, and the sensitivity decreases with height. An increase of humidity by 10% in the boundary layer is equivalent to an increase of 20% in the mid-troposphere. While the impact of humidity variation on stratiform precipitation persists throughout the 36-h forecast period, the impact diminishes after 24 h in the convective rainfall area. Increasing the boundary layer humidity by 30% leads to a 6 h earlier initiation of convection and a five times larger precipitation amount in the convective area, whereas it is doubled in the stratiform region. These results indicate that accurate measurements of humidity in the boundary layer are most important for QPF. **Citation:** Keil, C., A. Röpnack, G. C. Craig, and U. Schumann (2008), Sensitivity of quantitative precipitation forecast to height dependent changes in humidity, *Geophys. Res. Lett.*, *35*, L09812, doi:10.1029/2008GL033657.

1. Introduction

[2] Humidity is a key atmospheric variable influencing clouds and precipitation processes, radiation, dynamics and chemistry. However, the distribution of humidity in the vertical is poorly observed by the current observing systems [*Bengtsson et al.*, 2004; *Andersson et al.*, 2005]. In numerical weather prediction models the main backbone of humidity observation at different heights still stems from radiosondes, which are concentrated over northern hemisphere continents. Although satellite data are nowadays widely used, these data provide mainly observations of the upper troposphere during cloud free conditions, mostly over the oceans. For instance, data from the multi-spectral infrared sounders (AIRS,GOES and HIRS) are the dominant source for the ECMWF humidity analysis in the upper troposphere, at 200–300 hPa [*Andersson et al.*, 2007].

[3] Recently, airborne observations using a differential absorption lidar (DIAL) have shown the capability to measure vertical curtains of tropospheric humidity with unprecedented detail [*Flentje et al.*, 2005]. The vertical resolution of these measurements is about 100 m with a systematic error of less than 5%. In an exploratory study, *Gerard et al.* [2004] propose humidity profiling with a water vapour lidar experiment in space (WALES). However, for a particular laser mode of operation, atmospheric humidity can be observed over a limited range of heights. Given this potential new source of humidity information, how would it impact numerical weather forecasts, and which tropospheric layers are most sensitive regarding particularly quantitative precipitation forecasts (QPF)?

[4] Whereas modeling of the large-scale hydrological cycle may be rather insensitive to humidity observations [*Bengtsson and Hodges*, 2005], an accurate depiction of the humidity distribution is a necessary requirement for successful short-range (less than 24 h forecast time) weather forecasting, and in particular for convective and severe precipitation events [*Andersson et al.*, 2007]. *Crook* [1996] found that variations in boundary layer temperature and moisture can make a difference between no initiation and intense convection. Once convection is present, its intensity is more sensitive to moisture variations. Two studies have shown promising initial results from assimilation of DIAL data in weather forecasting models: *Kamineni et al.* [2003] have found a positive impact on tracks and intensities of tropical cyclones, whereas *Wulfmeyer et al.* [2006] have found a positive impact on the spatio-temporal prediction of convective initiation during the IHOP_2002 field campaign.

[5] In this study we attempt to quantify the sensitivity of precipitation in a weather forecasting model to humidity in different atmospheric layers, as might be observed by multi-wavelength DIAL instrument, to provide an indication of how such a system should be designed for maximum impact. The mesoscale model and experimental design are described in section 2. The numerical results are discussed in section 3, and concluding remarks are provided in section 4.

2. The Mesoscale Model and Experimental Design

[6] The sensitivity of quantitative precipitation forecasts to humidity variations at different heights is performed using the numerical weather prediction model COSMO of the Consortium for Small-scale Modelling [*Steppeler et al.*, 2003]. The high-resolution non-hydrostatic COSMO model is the operational short-range weather forecasting tool at various European Weather Services, including Deutscher Wetterdienst (DWD) since 1999, and its sensitivities should be typical of current mesoscale forecasting models. The model domain encompasses all of Central Europe (Figure 1), with a horizontal mesh size of 7 km. While it would also be interesting to examine the sensitivities of a higher resolution research model that does not use a cumulus parameterization, the hydrological cycle in such models has not been as extensively verified. The vertical coordinate in the model is of a generalized terrain-following type, which divides the atmosphere in 35 layers from the bottom up to 20 hPa. The

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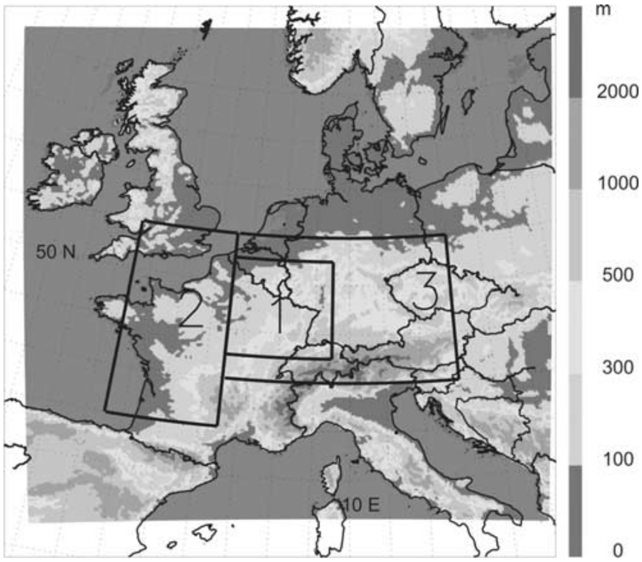

Figure 1. Domain of COSMO model with coastlines, political boundaries and topographic heights of the model's orography. The black rectangle denoted 1 (2) represents the region with predominant convective (stratiform) rainfall referred to in the text. The 11 day mean is averaged in region 3.

prognostic variables are the three wind components, temperature, pressure perturbation, specific humidity, cloud liquid water, cloud ice, snow and rain content. The model includes a grid-scale cloud and precipitation scheme as well as a parameterization of moist convection [*Tiedtke*, 1989]. The model physics include a level-2 turbulence parameterization, a delta-2-stream radiation scheme and a two-layer soil model (for more details see *Doms and Schättler* [2002]). Initial and hourly boundary conditions for the limited area COSMO model are provided by the Global Model (GME) of DWD.

[7] The experimental design is inspired by the ability of the DIAL instrument to measure vertical curtains of humidity over different height intervals depending on its mode of operation. The troposphere is split into three height intervals: the boundary layer 1000-830 hPa, the mid-troposphere 830-600 hPa, and the upper-troposphere 600-200 hPa. Moisture is added or removed in order to change the specific humidity uniformly by ±10 and ±30% at the initial time and at the lateral boundaries (on corresponding model levels for simplicity). A 30% increase of humidity corresponds to an increase of about 5 g/kg specific humidity in the boundary layer and about 2 g/kg in the mid-troposphere. If the relative humidity surpasses 100% at the initial time, the excess humidity is neglected. The magnitude of the humidity perturbations brackets the root-mean-square observation error assigned to conventional radiosonde observations of 17 % in the IFS model at ECMWF [see, e.g., *Keil and Cardinali*, 2003].

3. Results

[8] First, a case study on 25 June 2006, characterized by strong pre-frontal convection in Central Europe, is investigated. Findings of this prototype case are complemented by a sequence of daily 36-h forecasts covering the preceding 11 days in June 2006. The impact of humidity variations on QPF is studied within distinct regions (Figure 1), characterized by different precipitation types (stratiform versus convective). These are selected based on satellite and radar observations. Region 1 covers the pre-frontal, mainly convective precipitation ahead of an upper-level short-wave trough; whereas region 2 is dominated by stratiform precipitation processes on 25 June 2006.

[9] The time series of area averaged 6-h-mean precipitation of COSMO model experiments with humidity variations in the boundary layer are depicted for the two regions in Figure 2. The rainfall amount is normalized with the values of the reference experiment with unmodified humidity. In the stratiform region, a uniform impact on QPF

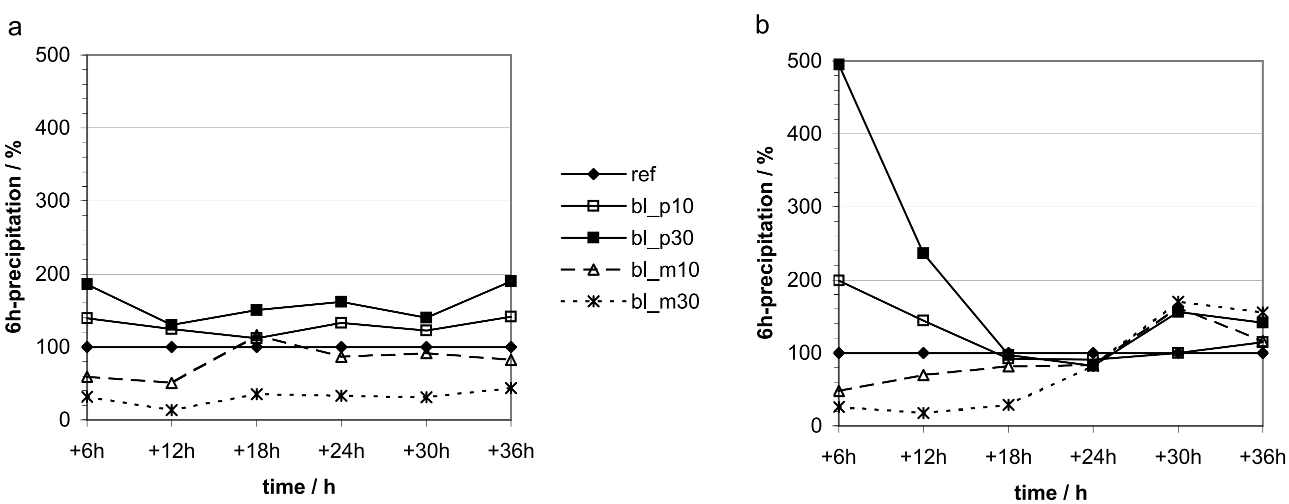

Figure 2. Time series of 6-h precipitation depending on the amount of humidity change in the boundary layer averaged across (a) the stratiform and (b) the convective subdomain given in percent of the reference experiment. The meaning of the legend is as follows: reference simulation (ref); 10 % increased specific humidity in the boundary layer (bl_p10); etc.

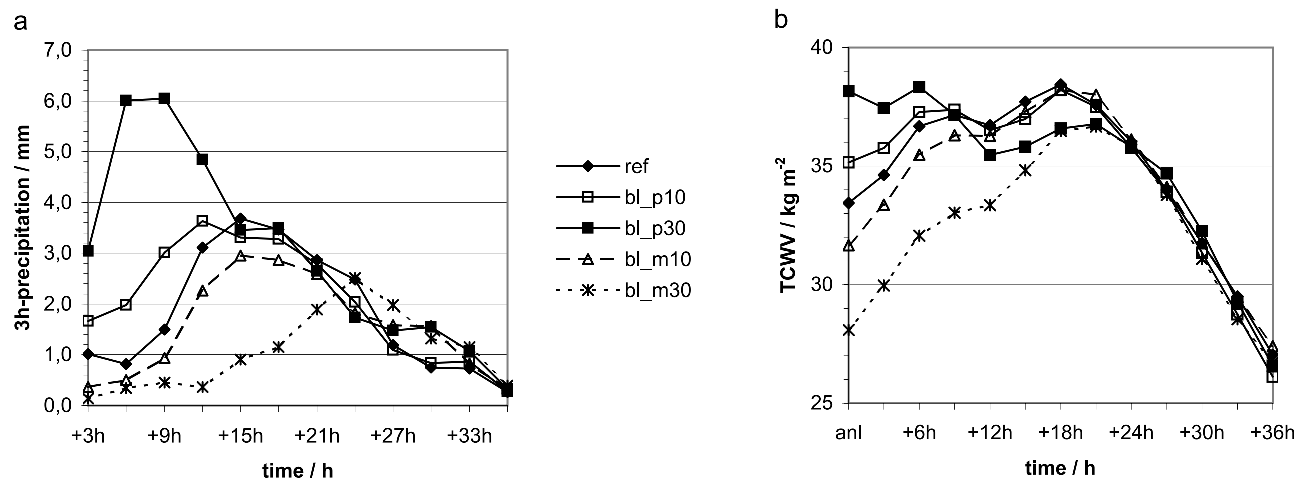

Figure 3. Time series of (a) 3-h precipitation and (b) total column water vapour depending on the amount of humidity change in the boundary layer averaged across the convective region.

prevails during the entire 36-h forecast range. The sensitivity experiment with 30% increased humidity in the boundary layer (bl_p30) produces the most rainfall, ranging between 150 and 200% of the reference experiment. Conversely, the experiment with 30% decreased humidity (bl_m30) results in 20 to 50% decreased 6-h-mean rainfall during the entire forecast period.

[10] In the convective region, the impact is qualitatively quite different (Figure 2b). Initially, experiment bl_p30 produces five times more precipitation within the first 6 h period, and from +18h onwards the rainfall amounts are comparable with the reference experiment. In contrast, experiment bl_m30 produces only 20 to 40% of the reference-experiment rainfall within the first 18 h of the forecast. Since the precipitation ceases after 30 h (see Figure 3a), the relative amounts towards the end of the forecasting period loose significance.

[11] More insight into the behaviour in the convective region can be obtained from time series of the 3-h-mean precipitation and total column water vapour (TCWV), as shown in Figure 3. In the reference experiment, the maximum precipitation intensity (3.7 mm within 3 h) at 15 UTC marks the passage of the cold front with a line of strong convection. Until 15 UTC the accumulated rainfall amounts to 10 mm. An increase of humidity causes this precipitation maximum to occur earlier; in experiment bl_p10 at 12 UTC and in experiment bl_p30 between 6 and 9 UTC. Additional humidity destabilizes the atmosphere leading to an earlier release of instability and the generation of strong precipitation. An increase of 30% (10%) in the boundary layer results in maximum precipitation rates of 6 mm (3.7 mm) within 3 h leading to an accumulated rainfall of 24 mm (14 mm) until 15 UTC. A decrease of boundary layer humidity by 10% (30%) reduces the intensities of precipitation resulting in 7 mm (2 mm) accumulated precipitation until 15 UTC. Changing the humidity by ±10 % influences the rainfall intensities while the shape of the rainfall time series with a maximum in the afternoon stays similar. In contrast, a change of ±30% leads to different diurnal evolution. An increase of this magnitude leads to an intensification of precipitation processes already in the morning, whereas a decrease suppresses the pre-frontal convection almost entirely. From 18 UTC onwards the rainfall intensities of all experiments are comparable except

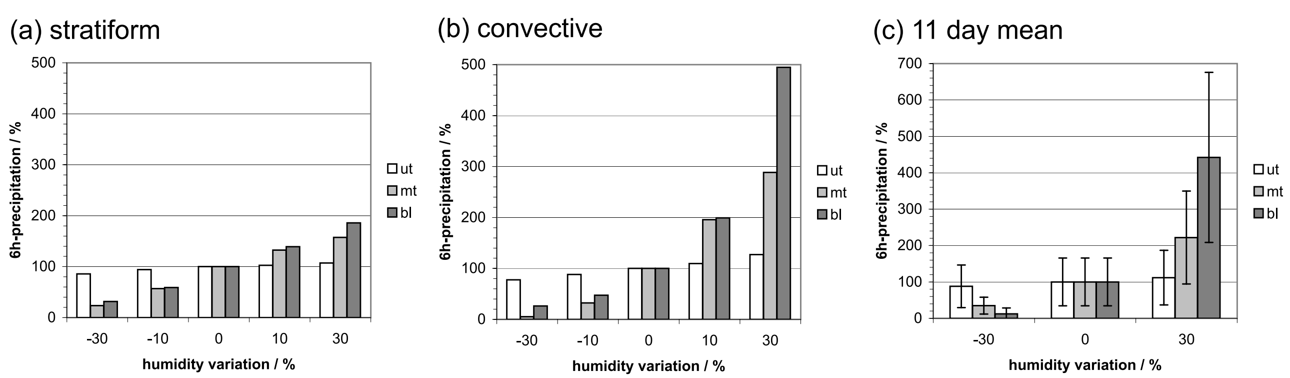

Figure 4. Accumulated 6-h mean precipitation depending on the humidity variation (w.r.t. height and amount) in the (a) stratiform and (b) convective region given in percent of the reference experiment. (c) The 11 day average of accumulated 6-h precipitation in region 3 with error bars denoting the variability within this period is shown. The meaning of the legend is as follows: boundary layer (bl); mid-troposphere (mt) and upper-troposphere (ut).

experiment bl_m30 which is still recovering from the strong decrease of boundary layer humidity. The time series of area averaged TCWV reflect the described precipitation differences. Starting with an integrated moisture variation of 10 kg/m^2 centred around the reference value of 33 kg/m^2 at initial time, TCWV of the different experiments converges towards the reference experiment as the forecast proceeds. However, TCWV of experiment bl_p30 falls below the value of the reference experiment from 9 UTC onwards for 15 h (e.g. 95% TCWV of reference experiment at 15 UTC) due to increased precipitation activity removing humidity from the atmosphere. From forecast range +24 h onwards TCWV decreases uniformly with the advection of the post-frontal drier air mass.

[12] The impact of humidity variations at different heights on QPF is summarized in Figure 4 for the precipitation from 00 UTC to 6 UTC. Two key results become evident: (i) there is a decreasing impact of humidity variations on QPF with increasing height, and (ii) the amplitude of rainfall change depends on the predominant precipitation type. The maximum impact is gained when increasing the humidity by 30% in the boundary layer under convective conditions leading to five times the reference precipitation. A similar but smaller impact is discernible for stratiform conditions (nearly twice the reference rainfall). Humidity changes of +30% in the mid-troposphere generate three times more precipitation under convective conditions, as compared to 50% more under stratiform conditions. Humidity variations in the upper-troposphere of 10% show a negligible impact (less than 10%) on QPF, and even a 30% decrease of humidity reduces the rainfall only by 5 to 25% of the reference amount.

[13] Systematic evaluation of 11 short-term forecasts (14 until 24 June 2006) support the case study results, reproducing the magnitude of the sensitivity to humidity variations and showing the same decrease in sensitivity for variations at increasing height (Figure 4c). Enhancement of boundary layer humidity by 30% leads on average to 4.5 times more precipitation in the convectively dominated region (region 3 in Figure 1). The variability of the additional 11 cases is given by error bars. For unmodified humidity conditions the precipitation varies considerably, that is there are days within this period when 70% more (less) than the average precipitation is forecast. Increasing, e.g., the boundary layer humidity by 30% leads to 4 to 7 times the reference precipitation, and the maximum (minimum) precipitation within the 11 days varies by 55% from the mean rainfall, respectively.

4. Conclusions

[14] Sensitivity experiments using a mesoscale weather forecasting system (the COSMO model) with a horizontal resolution of 7 km are performed to study the impact of relative variations of humidity at different heights on QPF. For this purpose, the troposphere is split into three different layers in which the specific humidity is changed by ±10 and ±30% of its local value in a reference simulation. This variability is of the same order of magnitude as typical humidity observation errors of radiosondes.

[15] The sensitivity of QPF to fixed relative variations in height dependent humidity decreases with increasing height. The precipitation is relatively insensitive to perturbations in the upper troposphere. Two distinct regions within the simulation are inspected, one characterized by predominant convective precipitation, and the other by predominant stratiform precipitation. In both regions variations of humidity in the boundary layer are most important for QPF. An increase of humidity by 10% in the boundary layer is equivalent to an increase of 20% in the mid-troposphere with respect to total column water vapour. In the stratiform region, the impact of humidity variation on precipitation prevails throughout the 36-h forecast period. In contrast, the impact of humidity variations diminishes after 24 h time in the convective area. Under convective conditions the extra humidity destabilizes the atmosphere, shifting the onset of strong convection 6 to 9 h earlier, and giving a disproportionately large increase in precipitation. Increasing the boundary layer humidity by 30% enhances the precipitation in the convective region by five times within the first 6 h, whereas it is twice larger in the stratiform region. Changes in mid-level humidity also produce large changes in precipitation since fewer clouds are terminated by entrainment of dry environmental air [*Derbyshire et al.*, 2004].

[16] As always in model studies a general reservation is required whether the result is particular to the limited period under investigation and the specific model being used. The results of this study are consistent with basic physical principles and would likely to be similar if a different numerical model with parameterized convection were used. Quantitative differences might very well occur however in a high-resolution model run without a deep convection scheme, which would have a fundamentally different representation of the initiation of convection by low-level variability, and a different representation of the modification of buoyancy in convective clouds by entrainment.

[17] The simulations show clearly that boundary layer humidity is of prime importance for quantitative precipitation forecasts, but that mid-tropospheric humidity also plays role. The quantitative result that the sensitivity to boundary layer perturbations is twice as large as to changes in the mid- troposphere suggests that the priority in improved measurements of humidity, such as with a DIAL instrument, should be in the lowest levels. However, it is also important to consider the error characteristics of the existing observing system, as well as the data assimilation and forecasting system where the observations will be used, since these will significantly influence the impact of any new observations.

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