Atmospheric Research 157 (2015) 91–107

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

Predictability of convective precipitation for West Africa: Does the land surface influence ensemble variability as much as the atmosphere?

Vera Maurer *, Norbert Kalthoff, Leonhard Gantner

Institut fur Meteorologie und Klimaforschung (IMK-TRO), Karlsruhe, Germany

ARTICLE INFO

Article history:
Received 19 August 2014
Received in revised form 14 January 2015
Accepted 15 January 2015
Available online 30 January 2015

Keywords:
Sahel
NWP
COSMO model
Soil moisture

ABSTRACT

In recent studies, the importance of the influence of the land surface and especially of soil-moisture heterogeneities on convective systems and convection initiation in the Sahel was established. This investigation aims at comparing the land-surface part of the influence on convection with that of the atmosphere. For this reason, realistic land-surface perturbations were generated to set up an ensemble of convection-permitting simulations that contains atmospheric as well as land-surface perturbations. The simulation of precipitation by the ensemble proved to be sufficiently realistic. By comparing precipitation forecasts of individual members, it was found that the effectiveness of soil perturbations in generating ensemble variability is as large as the effectiveness of the atmosphere. This means that the representation of the land surface, reflected by parameters such as the soil-type distribution and absolute soil moisture as well as its heterogeneities, is as important for the predictability of convective precipitation in the Sahel region as atmospheric conditions. However, soil perturbations do not determine the day on which larger convective systems occur. This rather depends on larger-scale factors such as African easterly waves, the strength of the monsoon flow as well as the location and intensity of the heat low. In each case, it is a combination of different processes determining the occurrence of convection and convective precipitation.

1. Introduction

After the drought in the Sahel region in the 1970s, Charney (1975) was one of the first to highlight the importance of land-surface atmosphere feedbacks in West Africa on a climatological scale. More recently, Koster et al. (2004) showed by a comparison of simulations with several general circulation models that the Sahel region is one of the hotspots of land–atmosphere coupling strength also on a time scale of days. The sensitivity of these simulations to the land surface was shown by soil-moisture variations. Taylor et al. (2011a) investigated the relationship between soil moisture and convection initiation with an event-based approach: From infrared satellite observations for five consecutive years, they identified about 3500 initiation points of mesoscale convective systems (MCSs) and were thus able to analyze the land-surface characteristics at these points. They detected a clear minimum of soil moisture at the initiation points for an average of all cases. The length scale of the land-surface variability is in the range of 20–75 km and on average, one out of eight MCSs is initiated above moderately strong horizontal gradients. This statistical evidence gives no hint at the involved physical processes. However, the relevant length scales are a strong indicator for the contribution of thermally-driven mesoscale circulations that can occur above land-surface gradients as described by Pielke and Segal (1986). For a case study of 10 July 2006, for which in-situ measurements were taken during the African Monsoon Multidisciplinary Analysis (AMMA) measurement campaign, convection initiation was observed to take place at the location of the maximum of the surface sensible heat flux

* Corresponding author at: Karlsruher Institut für Technologie, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen.
E-mail address: vera.maurer@kit.edu (V. Maurer)

http://dx.doi.org/10.1016/j.atmosres.2015.01.016
0169-8095/

(Lothon et al., 2011). For the same case, Couvreux et al. (2012) conducted idealized large-eddy simulations that revealed that deep convection developed only for a high Bowen ratio (ratio of sensible to latent heat flux). These studies all underline the influence of the soil moisture and more generally, the land surface, on the initiation of MCSs in the Sahel. The role of mesoscale circulations in the Sahel was also addressed by Dixon et al. (2013). They compared land-surface temperature and wind measurements retrieved on low-level (≈200 m above ground level) flights in the Sahel and detected coherencies of the two variables on length scales of 16 km to 33 km for eight out of nine cases. Vertical velocities from convergence and divergence of along-track wind components, i.e. vertical motion caused by mesoscale circulations, can be estimated to 0.25 m s^{-1}.

On the other hand, we know that the soil-moisture initialization constitutes a problem for numerical weather prediction (NWP) models. On 11 June 2006, an MCS was observed in Burkina Faso during the AMMA measurement campaign (Schwendike et al., 2010). In an investigation by Gantner and Kalthoff (2010), the MCS could only be reproduced by the Consortium for Small-scale Modeling (COSMO) model after a significant reduction of soil moisture that had originally been adopted from the operational analysis carried out by the European Centre for Medium-range Weather Forecasts (ECMWF). For the same model simulations, Adler et al. (2011) showed by an analysis of the terms of the heat and moisture budget that for high soil moisture, boundary-layer depth is lower and hence convective inhibition (CIN) higher than for low soil moisture. Moreover, they identified thermally-induced circulation patterns in the area where first cells occurred afterwards.

With both the known influence of the land surface on convection initiation and the experiences from previous simulations, we now want to investigate in a more systematic way how much the land surface influences convection in West Africa and, consequently, how much it affects precipitation forecasts. A good systematic approach is the use of ensemble simulations. For this reason, we need soil perturbations that are as realistic as possible and that reflect the given uncertainties. In the operational runs of COSMO at the German Weather service, soil moisture is not assimilated but used as a tuning parameter to correct for example too high near-surface temperatures in areas where too little precipitation has been simulated in the previous hours (Hess, 2001). By choosing soil moisture to generate different ensemble members, this effect is exploited to account for uncertainties in the near-surface variables. In Klüpfel et al. (2011), it was investigated whether soil-moisture variations could be used to create members of a forecast ensemble for West Africa and it was shown that this approach was promising. Additionally, uncertainties exist due to the representation of the land surface in the model, i.e. of the soil-type distribution and of dependent model parameters. These uncertainties should be considered as well.

At the same time, the dynamical forcing of convection in West Africa has been investigated extensively: On the one hand, MCSs can be forced by African easterly waves (AEWs, e.g. Reed et al., 1977; Payne and McGarry, 1977; Diedhiou et al., 1999; Fink and Reiner, 2003; Kiladis et al., 2006). Most of these studies found the maximum of convection in the vicinity of AEW troughs. However, not all mechanisms of interaction between convection and AEWs have been clarified (e.g. Thorncroft et al., 2008). Laing et al. (2008) identified convective episodes from cold clouds in satellite imagery that last up to 150 h. Most of them indicate a propagation speed of MCSs of 10–20 m s^{-1} and are first observed in mountainous regions. According to Laing et al. (2008), the episodes cannot all be clearly linked to AEW activity in terms of initiation locations and propagation speeds. Preferential initiation locations lying in mountainous terrain in West Africa are also described by Tetzlaff and Peters (1988), Hodges and Thorncroft (1997) or Bennartz and Schroeder (2012). Another dynamical aspect with an effect on convective activity is the strength of the monsoon flow itself. The monsoon flow and hence the convective activity are more pronounced during periods with a strong Saharan heat low (SHL; Lavaysse et al., 2010).

The question is how much the land-surface feedback influences convection and convective precipitation in West Africa in comparison to the influence of the existing dynamical forcings. The overall aim is thus the systematic investigation of the influence of the land surface on the predictability of convective precipitation compared to the one of the atmosphere, using ensemble simulations. Therefore, the ensemble has to consist of two components: Atmospheric and land-surface perturbations. In detail, three specific questions are addressed: 1) How realistic are the simulations and is the ensemble spread adequate? This question is addressed because realistic simulations are desired to underline the validity of the results. For ensemble forecasts, the spread within the ensemble should correspond to the forecast error. In the case of a convection forecast, which is usually of low predictability and high uncertainty, this means that the forecast error can become large so that the ensemble spread should also be large. 2) How large is the produced variability of precipitation as well as of other relevant variables in the ensemble? Which differences between simulations are caused by soil perturbations on the one hand and which can rather be attributed to atmospheric perturbations on the other hand? 3) Which are the most important processes that generate variability within the ensemble? We should be able to identify the processes described in the above-mentioned studies and to understand how strongly they contribute to the ensemble variability.

2. Model and ensemble setup

2.1. The COSMO model

The COSMO model is a non-hydrostatic limited-area numerical weather prediction model (Steppeler et al., 2003; Baldauf et al., 2011). The configuration for the model release 4.18 used for our investigations is close to, but not identical to the one of COSMO-DE, which is the operational version for Germany with 2.8 km horizontal resolution. Our version uses an upper boundary of 28.5 km to allow for very deep tropical convection. Apart from the vertical distribution, the number of vertical layers was not changed and is equal to 50. As in the operational version, the turbulence scheme is the level-2.5 closure after Mellor and Yamada (1982) that essentially uses a prognostic equation of turbulent kinetic energy (TKE) together with K-theory and a TKE-dependent K. For the land surface, transfer coefficients for momentum, heat, and moisture are determined using a corresponding TKE-based approach (Baldauf et al.,