RESUMES D'ARTICLES

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The behaviour of a cloud ensemble in response to external forcings

By F. GUICHARD*, J.-L. REDELSPERGER and J.-P. LAFORE
Centre National de Recherches Météorologiques, France

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SUMMARY

The behaviour of a population of tropical moderate precipitating clouds is investigated with a cloud-resolving model over a period equivalent to 2–3 days. The response of the system is analysed as a function of external forcings, comprising shortwave and longwave radiation, large-scale ascent effects and surface fluxes. Radiative and large-scale ascent processes enhance the convective activity. In all the experiments, an accumulation of humidity is observed in the upper part of the cloud layer and in the region above. In the case of weak large-scale ascent, a diurnal cycle of convection is found, having maximum activity during the night and minimum activity around noon. Depending on the anvil cloud coverage, a modulation of this cycle is found whose cause can be explained through an infrared radiative feedback. The anvil deck also has a diurnal cycle but phase shifted by six hours with reference to the convective cycle.

KEYWORDS: Cloud-resolving model Convection Radiative feedback Tropical precipitation

1. INTRODUCTION

Cloud processes have a major effect on the terrestrial climatic system. They have a dominant role in the radiative budget, directly through cloud radiative properties, and indirectly because convection is responsible for most of the vertical transport of water vapour, a very important greenhouse gas. Convection affects the large-scale circulation through the vertical redistribution of mass and momentum, sensible and latent heat.

Unfortunately, many cloud processes occur on temporal and spatial scales smaller than the grid spacing of general circulation models. Therefore, the large-scale effects of clouds have to be parametrized in these models, based on an assumption of scale separation.

Current parametrizations take into account an apparent heat source, Q1, and an apparent moisture sink, Q2, associated with cumulus convection. A large diversity of schemes exists, including some relatively simple ones (e.g. Kuo 1974) as well as schemes that rely on a much more physical basis (Arakawa and Schubert 1974). Parametrizations have been tested, validated and calibrated with the help of existing observational studies which diagnose the effects of cumulus convection on the large-scale environment (Yanai *et al.* 1973; Johnson 1984), and also, in a few cases, with the help of numerical simulations (Xu and Arakawa 1992). Cloud–radiation and cloud–surface interactions, as well as cumulus momentum transport, are still poorly represented, and there is a lack of consistency between the different cloud processes. For these reasons, the World Climate Research Programme has established a Cloud System Study (GCSS) as part of its GEWEX (Global Energy and Water Cycle Experiment), (Browning *et al.* 1993). Refer to Emanuel and Raymond (1993) for a review of the representation of cumulus convection in atmospheric models.

Climate studies are undertaken with the help of observations and general circulation models (GCMs) including complex 3-D models and also simplified 1-D vertical models (Betts and Ridgway 1989; Hu and Randall 1994; Satoh and Hayashi 1992). The last category allows one to isolate the convective component in climate and so to investigate several idealized scenarios. All these studies show that there is an important sensitivity to the treatment of convective subgrid processes (Arking 1991). Sensitivity to cloud schemes implies great uncertainties with regard to global warming induced by doubling atmospheric CO_2. An inter-comparison of 19 GCMs (Cess *et al.* 1990) showed that important differences occurred, mainly through cloud feedbacks, with a global climate sensitivity parameter, λ,

* Corresponding author: Centre National de Recherches Météorologiques, (CNRS and Météo-France), 42 avenue de Coriolis, 31057 Toulouse Cedex, France.

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Thermodynamical impact and internal structure of a tropical convective cloud system

By F. GUICHARD*, J.-P. LAFORE and J.-L. REDELSPERGER
Centre National de Recherches Météorologiques, France

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SUMMARY

A three-dimensional cloud-resolving model is used to simulate a cloud system, observed during the Tropical Ocean/Global Atmosphere Coupled Ocean–Atmosphere Response Experiment, corresponding to the development of shear parallel convective lines and characterized by the absence of large-scale ascent. The system life cycle includes different types of clouds interacting in both space and time.

The thermodynamical impact as well as statistical properties of the system are analysed using a partition of the total domain into several (6 to 12) internal areas. In-cloud temperature excess is weak as observed, whereas water vapour excess is significant and correlated with vertical velocity. However, buoyancy deviations are extremely small, indicating an equilibrium of density, involving thermodynamics and microphysics. Decomposition of budgets highlights the mechanisms of compensation occuring between the precipitating system and its environment.

Moisture convective transports are extremely intense and complex to analyse. A decomposition into vertical and horizontal parts shows that horizontal exchanges are important, in particular to explain moistening at upper levels. The effective part of vertical fluxes (after removing the compensating parts) occurs in active shallow and deep clouds, at very fine scales. These results question some basic hypotheses assumed in existing convective parametrizations.

KEYWORDS: Cloud-resolving model Convection Thermodynamical impact

1. INTRODUCTION

Cloud processes are a major element of the climatic system, involving in-cloud latent-heat release and precipitation as well as cloud–radiation interactions and convective vertical transport of water vapour. These small-scale transient features also represent a cause of great uncertainties in the understanding of climate dynamics and its response to a modification such as doubling CO_2 (Lindzen 1990; Betts 1990). In effect, cloud processes correspond to subgrid parametrized processes for large-scale models, and the latter appear very sensitive to the schemes that are used (Cess *et al.* 1990).

There are several explanations for this. Amongst them can be noted the lack of present knowledge concerning moist convection initiation (when and why does convection occur?), the way it interacts with the large-scale flow and its tendency toward organized mesoscale cloud systems. This leads to delicate problems for parametrization in terms of criteria for convection triggering, the choice of closure scheme and scale separation.

Convection schemes aim to parametrize modifications of temperature and water vapour fields due to cumulus convection. Some of them also determine the momentum transport by convection, or high-anvil generation (Tiedtke 1993). They have been tested and validated using existing observations, in particular with data from the Global Atmospheric Research Programme Atlantic Tropical Experiment (Lord 1982; Bougeault 1985; Tiedtke 1989). With observations alone, however, the different contributions of the various processes involved cannot be quantified. It is now possible to simulate explicitly an entire cloud system with cloud-resolving models (CRMs). Thus, CRMs appear now as useful tools, and complementary to observations for this problem, allowing one to further investigate cloudy processes and their parametrization.

CRMs have been extensively developed and used during the last fifteen years to study cloud systems. Several studies have been carried out with CRMs to determine the

* Corresponding author: Centre National de Recherches Météorologiques (CNRS and Météo–France), 42 avenue de Coriolis, 31057 Toulouse Cedex, France.

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Cloud-resolving simulation of convective activity during TOGA-COARE: Sensitivity to external sources of uncertainties

By F. GUICHARD*, J.-L. REDELSPERGER and J.-P. LAFORE
CNRM/GAME, Météo-France and CNRS, France

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SUMMARY

A one-week convective period of the Coupled Ocean–Atmosphere Response Experiment (10–17 December 1992), prior to a westerly wind burst, has been simulated with a cloud-resolving model. Large-scale advection derived from observations is used to force the model, in the same way as usually done in single-column models. Our aim is to evaluate this explicit simulation against observed large-scale thermodynamic and radiative fields, and to investigate the sensitivity of model results to observational uncertainties. Precipitation, apparent heat source and moisture sink are fairly well reproduced by the model as compared to those diagnosed from observations. Temperature (T) and moisture (q_v) fields are also reasonably well captured except for a moderate cold and moist bias. Simulated moist static energy is too high below 6 km and too low above, possibly because convection is slightly less active in the model than observed.

In order to investigate the sensitivity of model results to observational uncertainties, results are analysed with the moist static energy budget together with independent observational radiative datasets. This analysis suggests that the atmospheric radiative rate that is in equilibrium with the applied large-scale advection and observed surface fluxes is too weak and that its diurnal cycle is not realistic. The most likely reason for this problem is found to be related to uncertainties in the large-scale advection diagnosed from observations. This analysis also indicates that the simulated high-cloud cover is too large in the model. It is greatly improved by increasing the ice-crystal fall speed. Additional tests show a large sensitivity of the simulated moist static energy, and thus T and q_v, to the range of uncertainties previously found for large-scale advection. The vertical structure of the model bias is not significantly modified by changing the intensity of these forcings, but it is most sensitive to their vertical structures.

It is argued that it is crucial to get some insights into the range of uncertainties of external forcings (large-scale advection, surface fluxes and atmospheric radiative-heating rate) so as to assess the relevance of any evaluation of simulated temperature and moisture when a model, either resolving clouds or parametrizing them, is forced with large-scale advection deduced from observations.

KEYWORDS: Cloud-resolving models Clouds GCSS TOGA-COARE

1. INTRODUCTION

An accurate representation of the impact of convective cloud systems on their environment is a crucial issue for weather-forecast and climate models. Though many studies have been devoted to this topic, a better understanding of convective cloud systems is still required, in particular in the Tropics, in order to further improve our knowledge of large-scale dynamics and budgets at these latitudes (Hartmann *et al.* 1984; Gregory 1997). Deep convective systems are important because they affect their environment through strong latent-heat release and vertical redistribution of temperature, water vapour and momentum. They also play a significant role in the radiative budget, directly through temperature and water-vapour vertical redistributions but also via the radiative impact of convectively generated clouds, for instance the large tropical anvils (e.g. Del Genio *et al.* 1996). Furthermore, convective systems also impact the ocean through their impact on the surface heat and stress fluxes (Godfrey *et al.* 1998; Redelsperger *et al.* 2000a).

At mesoscale, cumulus cloud ensembles appear as complex nonlinear atmospheric features involving various processes—turbulence, large-scale motion, microphysics and radiation—that take place and strongly interact *at smaller scale than currently resolved by large-scale models.* Various cumulus schemes have been developed, aiming at

* Corresponding author: CNRM/GAME, 42 Av. Coriolis, 31057 Toulouse Cedex 1, France.
e-mail: francoise.guichard@meteo.fr

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A GCSS model intercomparison for a tropical squall line observed during TOGA–COARE. I: Cloud-resolving models

By J.-L. REDELSPERGER[1]* P. R. A. BROWN[2], F. GUICHARD[1], C. HOFF[1], M. KAWASIMA[3], S. LANG[4], T. MONTMERLE[5], K. NAKAMURA[6], K. SAITO[7], C. SEMAN[8], W. K. TAO[4] and L. J. DONNER[8]

[1]*Centre National de Recherche Météorologiques, France*
[2]*Joint Centre for Mesoscale Meteorology, UK*
[3]*Institute of Low Temperature Science, Japan*
[4]*Goddard Space Flight Center, USA*
[5]*Centre d'étude des Environnements Terrestre et Planétaires, France*
[6]*Ocean Research Institute, Japan*
[7]*Meteorology Research Institute, Japan*
[8]*Geophysical Fluid Dynamics Laboratory, USA*

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SUMMARY

Results from eight cloud-resolving models are compared for the first time for the case of an oceanic tropical squall line observed during the Tropical Ocean/Global Atmosphere Coupled Ocean–Atmosphere Response Experiment. There is broad agreement between all the models in describing the overall structure and propagation of the squall line and some quantitative agreement in the evolution of rainfall. There is also a more qualitative agreement between the models in describing the vertical structure of the apparent heat and moisture sources.

The three-dimensional (3D) experiments with an active ice phase and open lateral boundary conditions along the direction of the system propagation show good agreement for all parameters. The comparison of 3D simulated fields with those obtained from two different analyses of airborne Doppler radar data indicates that the 3D models are able to simulate the dynamical structure of the squall line, including the observed double-peaked updraughts. However, the second updraught peak at around 10 km in height is obtained only when the ice phase is represented. The 2D simulations with an ice-phase parametrization also exhibit this structure, although with a larger temporal variability.

In the 3D simulations, the evolution of the mean wind profile is in the sense of decreasing the shear, but the 2D simulations are unable to reproduce this behaviour.

KEYWORDS: Cloud-resolving models Clouds Doppler radar GCSS

1. INTRODUCTION

Current general-circulation models (GCMs) use sophisticated parametrizations to represent the effects of clouds and precipitation and their interactions with other physical processes occurring in the atmosphere. To evaluate and improve these parametrizations, it is important to compare them with observations and more detailed numerical models. In response to this challenge, the GEWEX† Cloud Systems Study (GCSS) has established a strategy based on the use of cloud-resolving models (CRMs), single-column models (SCMs) and observations.

The Precipitating Convective Cloud Systems Group of the GCSS has recently initiated two projects designed firstly to evaluate CRMs against observational datasets, and secondly to evaluate SCMs against numerical datasets produced by CRMs (Moncrieff *et al.* 1997). In the last decade, the numerical modelling of convective systems has shown that CRMs are an effective means of simulating many of their observed features; this is especially true for squall-line systems. Nevertheless, no detailed intercomparison of CRMs for a precipitating convective case has been successfully accomplished, in contrast with the many intercomparisons of GCMs (e.g. Gates 1992; Slingo *et al.* 1996) and boundary-layer models (e.g. Moeng *et al.* 1996; Bretherton *et al.* 1999) that

* Corresponding author: CNRM/GAME, CNRS and Météo-France, 42 Av Coriolis, 31057 Toulouse Cedex, France.

† Global Energy and Water-cycle EXperiment.

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A GCSS model intercomparison for a tropical squall line observed during TOGA–COARE. II: Intercomparison of single-column models and a cloud-resolving model

By P. BECHTOLD[1]*, J.-L. REDELSPERGER[2], I. BEAU[2], M. BLACKBURN[3], S. BRINKOP[4], J.-Y. GRANDPEIX[5], A. GRANT[6], D. GREGORY[7], F. GUICHARD[2], C. HOFF[2] and E. IOANNIDOU[3]

[1]*Observatoire Midi-Pyrénées, France*

[2]*Centre National de Recherche Météorologiques, France*

[3]*University of Reading, UK*

[4]*Deutsche Zentrum für Luft- und Raumfahrt, Germany*

[5]*Laboratoire de Météorologie Dynamique, France*

[6]*Hadley Centre for Climate Prediction and Research, UK*

[7]*European Centre for Medium-Range Weather Forecasts, UK*

SUMMARY

This paper presents single-column model (SCM) simulations of a tropical squall-line case observed during the Coupled Ocean–Atmosphere Response Experiment of the Tropical Ocean/Global Atmosphere Programme. This case-study was part of an international model intercomparison project organized by Working Group 4 'Precipitating Convective Cloud Systems' of the GEWEX (Global Energy and Water-cycle EXperiment) Cloud System Study.

Eight SCM groups using different deep-convection parametrizations participated in this project. The SCMs were forced by temperature and moisture tendencies that had been computed from a reference cloud-resolving model (CRM) simulation using open boundary conditions. The comparison of the SCM results with the reference CRM simulation provided insight into the ability of current convection and cloud schemes to represent organized convection. The CRM results enabled a detailed evaluation of the SCMs in terms of the thermodynamic structure and the convective mass flux of the system, the latter being closely related to the surface convective precipitation. It is shown that the SCMs could reproduce reasonably well the time evolution of the surface convective and stratiform precipitation, the convective mass flux, and the thermodynamic structure of the squall-line system. The thermodynamic structure simulated by the SCMs depended on how the models partitioned the precipitation between convective and stratiform. However, structural differences persisted in the thermodynamic profiles simulated by the SCMs and the CRM. These differences could be attributed to the fact that the total mass flux used to compute the SCM forcing differed from the convective mass flux. The SCMs could not adequately represent these organized mesoscale circulations and the microphysical/radiative forcing associated with the stratiform region. This issue is generally known as the 'scale-interaction' problem that can only be properly addressed in fully three-dimensional simulations.

Sensitivity simulations run by several groups showed that the time evolution of the surface convective precipitation was considerably smoothed when the convective closure was based on convective available potential energy instead of moisture convergence. Finally, additional SCM simulations without using a convection parametrization indicated that the impact of a convection parametrization in forced SCM runs was more visible in the moisture profiles than in the temperature profiles because convective transport was particularly important in the moisture budget.

KEYWORDS: Convection parametrization Mass flux Single-column models

1. INTRODUCTION

In a recent critical survey paper Raymond (1997) stated 'There have been many observational studies of moist convection and many attempts to parameterize cumulus convection. However, there have been few of the former which have succeeded in aiding the latter, even though projects like GATE† were touted as serving this function'. The author continued 'I believe that the inability to make connections between these two important areas arises primarily from the lack of a well-defined and physically consistent conceptual framework for the parameterization of convection'.

While there still exists a lot of confusion about how to tackle atmospheric convection conceptually (although the mass-flux approach provides one possible mathematical

* Corresponding author: Laboratoire d'Aérologie, UMR UPS/CNRS 5560, Observatoire Midi-Pyrénées, 14 av Belin, 31400, Toulouse, France. e-mail: becp@aero.obs-mip.fr

† GARP (Global Atmospheric Research Programme) Atlantic Tropical Experiment.

A Parameterization of Mesoscale Enhancement of Surface Fluxes for Large-Scale Models

JEAN-LUC REDELSPERGER, FRANÇOISE GUICHARD, AND SYLVAIN MONDON

CNRM/GAME, Météo-France, CNRS, Toulouse, France

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ABSTRACT

The paper investigates the enhancement of surface fluxes by atmospheric mesoscale motions. The authors show that horizontal wind variabilities induced by these motions (i.e., gustiness) need to be considered in the parameterization of surface fluxes used in general circulation models (GCMs), as they always occur at subgrid scale.

It is argued that there are two different sources of gustiness: deep convection and boundary layer free convection. The respective scales (time and length) and the convective patterns are very different for each of these sources. A general parameterization of the gustiness distinguishing these two effects is proposed.

For boundary layer free convection, the gustiness is related to the free convection velocity. To establish this relationship, both observations and numerical simulations are used. Revisiting the Coupled Ocean–Atmosphere Response Experiment data, the authors propose a new value of the proportionality coefficient that links the free convection velocity and the gustiness.

For deep convection, the dominant source of gustiness is the occurence of downdrafts and updrafts generated by convective cells. It is shown that these motions produce large enhancement of surface fluxes and should be parameterized in GCMs. Results indicate that the gustiness can be related either to the precipitation or to the updraft and downdraft mass fluxes.

1. Introduction

Ocean–atmosphere interactions are known to play a key role in the earth's climate, especially over tropical oceans. Atmospheric general circulation models (GCMs) and coupled ocean–atmosphere models suffer from uncertainties in the fluxes of heat, moisture, momentum, and radiation at the air–sea interface. The atmosphere over tropical oceans is indeed very sensitive to sea surface temperature (SST) fluctuations, and the response of the models to SST variations depends on the surface flux parameterizations (e.g., Palmer et al. 1992; Webster and Lukas 1992).

The Tropical Ocean Global Atmosphere and Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) addressed this issue. One major goal was to obtain a better understanding of the principal processes that are responsible for the coupling between the ocean and the atmosphere in order to improve the surface flux parameterizations (Webster and Lukas 1992; Godfrey et al. 1998). COARE was conducted in the vicinity of the western equatorial Pacific warm pool where the SST is higher than 28°C and the monthly mean wind speed is typically less than 3 m s^{-1}. It is also one of the most convectively active regions on the planet. Variations over the warm pool are thought to play a key role in the triggering of El Nino–Southern Oscillation (ENSO). The coupling between the ocean and the atmosphere in this region occurs on timescales ranging from intradiurnal to interannual and on space scales ranging from a fews kilometers (cloud scale) to thousands of kilometers (westerly wind bursts) (e.g., Palmer and Mansfield 1986; Geisler et al. 1985; Lukas et al. 1991; Godfrey et al. 1998). Accurate surface fluxes of heat and moisture, and stresses need to be accurately predicted by GCMs. Thus the net surface heat flux must be known to an accuracy of 10 W m^{-2} in order to predict an SST change that indicates the initiation of an ENSO event (Godfrey et al. 1991). On the basis of climatological data, it is estimated that the overall uncertainty of the heat budget over the Pacific warm pool is of the order of 80 W m^{-2} (Godfrey and Lindstrom 1989). The net heat budget is the sum of the radiative, sensible, and latent heat flux. Each of these fluxes has to be known as accurately as possible to provide a precise heat budget.

The parameterization of surface fluxes in atmospheric and oceanic GCMs is based on the bulk aerodynamic method. Current schemes, in general, use formulas

Corresponding author address: Dr. Jean-Luc Redelsperger, CNRM/GAME, 42 av. G. Coriolis, 31057 Toulouse Cedex, France.
E-mail: redels@meteo.fr

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Thermodynamic and Radiative Impact of the Correction of Sounding Humidity Bias in the Tropics

F. GUICHARD, D. PARSONS, AND E. MILLER

NCAR/ATD, Boulder, Colorado

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ABSTRACT

Accurate measurements of atmospheric water vapor are crucial to many aspects of climate research and atmospheric science. This paper discusses some of the meteorological implications of a bias discovered in the measurement of water vapor in widely deployed radiosonde systems. This problem apparently arose in the early 1990s, and a correction scheme has been recently developed that intends to remove the bias. The correction scheme also includes improvements in the humidity measurements in the upper troposphere and near the surface. It has been applied to data taken during the Tropical Ocean and Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE).

The impact of the bias on the general stability of the tropical atmosphere to deep convection, as measured by the convective available potential energy (CAPE) and the convective inhibition (CIN), is quite large. On the basis of the uncorrected dataset, one might erroneously conclude that it is difficult to trigger deep convection over the region. When the correction is taken into account, the atmosphere over the tropical western Pacific becomes typically unstable to deep convection, with convective instability similar to that measured from aircraft in the vicinity of active convective systems.

Radiative fluxes are also significantly modified. For clear sky conditions, it is found that on average, the net surface radiative flux increases by 4 W m^{-2}, and the outgoing longwave flux decreases by more than 2 W m^{-2} due to the humidity correction. Under more realistic cloudy conditions, the differences are weaker but still significant. Changes in radiative fluxes are explained at first order by the precipitable water increase.

It is likely that such a dry bias would hide any modifications of the atmospheric water vapor associated with the increase of greenhouse gases.

1. Introduction

Atmospheric water vapor plays a crucial role in our climate. For example, it is well established that water vapor is the most important greenhouse gas in the atmosphere. Thus, the distribution of water vapor in the atmosphere strongly impacts the vertical profile of the radiative cooling and the magnitude of the radiative fluxes at the surface and the top of the atmosphere (TOA). In addition, the three-dimensional distribution of water vapor and how it interacts with the dynamics and thermodynamics of the earth's atmosphere directly control the three-dimensional distribution of clouds. Hence, it is not surprising that the vertical distribution of water vapor must be measured very accurately for observational studies aimed at investigating the climate of the earth and for estimating global climate change. Recent studies have shown that current measurement strategies can result in large uncertainties in the observed radiative budget in the Tropics (Gutzler 1993) and have stressed the importance of improving the accuracy of water vapor measurements for detecting climate change (e.g., Harries 1997).

There is also a need for accurate measurement of water vapor for a variety of other problems in the atmospheric sciences, including boundary layer studies, atmospheric chemistry, hydrology, polar meteorology, and the prediction of severe weather events (Weckwerth et al. 1999). It has also been argued that advances in the quantitative prediction of convective rainfall in part hinge on our ability to improve the characterization of atmospheric water vapor (Emanuel et al. 1995; Dabberdt and Schlatter 1996). Accurate measurements of water vapor are also needed to estimate convective parameters (Crook 1996; Zipser and Johnson 1998), such as convective available potential energy (CAPE) and convective inhibition (CIN) (Colby 1983), which are useful for diagnosing global variations in convective intensity, convective structure, and the general stability of the atmosphere to convective overturning.

Partly due to the performance limitations of remote sensing techniques for water vapor (e.g., Smith and Ben-

Corresponding author address: Dr. Françoise Guichard, CNRM-GAME (CNRS & Météo-France), 42 av Coriolis, 31057, Toulouse Cedex, France.
E-mail: francoise.guichard@meteo.fr

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A mass-flux convection scheme for regional and global models

By P. BECHTOLD[1]*, E. BAZILE[2], F. GUICHARD[3], P. MASCART[1] and E. RICHARD[1]

[1] *Laboratoire d'Aérologie, France*
[2] *CNRM-GMAP, Météo France, France*
[3] *CNRM-GMME, Météo France, France*

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SUMMARY

A bulk mass-flux convection parametrization for deep and shallow convection is presented that includes an efficient and straightforward treatment of numerics, moist thermodynamics and convective downdraughts. The scheme is evaluated in a single-column model context for a tropical deep-convective period and a trade-wind cumulus case. Preliminary applications in a global numerical weather-prediction model and a mesoscale model are also discussed.

The results suggest that the present scheme provides reasonable solutions in terms of predicted rainfall, and tropical temperature and moisture structures. The application of the scheme to various scales is supported by the use of a convective available potential energy convective closure that assures a smooth interaction with the large-scale environment and efficiently suppresses conditional instability of the second kind-like spin-up processes on the grid-scale.

Finally, the theoretical and practical limits of the present approach are discussed together with possible future developments.

KEYWORDS: Convection Mass flux Numerical weather prediction

1. INTRODUCTION

It has been well recognized since the 1960s (e.g. Charney and Eliassen 1964; Manabe and Strickler 1964; Kuo 1965; Ooyama 1971; Yanai *et al.* 1973) that cumulus convection is one of the major processes that affects the dynamics and energetics of atmospheric circulation systems. Since then many cumulus parametrization schemes have been developed for numerical weather-prediction (NWP) models and general-circulation models (GCMs), to account for the subgrid-scale release of latent heat and mass transport associated with convective clouds. A non-exhaustive list of these schemes includes e.g. Arakawa and Schubert (1974), Anthes (1977), Kuo and Raymond (1980), Fritsch and Chappell (1980), Bougeault (1985), Betts and Miller (1986), Tiedtke (1989), Gregory and Rowntree (1990), Kain and Fritsch (1990), Emanuel (1991), Donner (1993), Grell (1993), Wang and Randall (1996), Sun and Haines (1996), and Hu (1997). The common point of all cumulus parametrizations is that they aim to diagnose the presence of larger-scale conditions that would support the development of convective activity and, under appropriate conditions, to introduce tendencies for temperature and moisture (and possibly momentum) that would be consistent with the effects of convective activity. In particular, most parametrizations are designed to drive the model atmosphere towards a convectively adjusted state when they activate. This adjusted state is either predefined ('adjustment' schemes), or is computed using a bulk or spectral cloud model and adjusting the atmosphere through mass exchange between the cloud and the environment (mass-flux schemes).

Two necessary characteristics of any convective parametrization are (i) a reasonable set of criteria to determine when convective adjustment should be initiated, and (ii) procedures for determining the characteristics of a final convectively adjusted state. These characteristics can be evaluated in single-column model (SCM) integrations where large-scale forcing tendencies can be specified to vary with time, and where the

* Corresponding author: Laboratoire d'Aérologie UMR UPS/CNRS 5560, Observatoire Midi-Pyrénées, 14 av. Ed. Belin, F-31400, Toulouse, France. e-mail: becp@aero.obs-mip.fr

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Aspects of the parametrization of organized convection: Contrasting cloud-resolving model and single-column model realizations

By D. GREGORY[1] and F. GUICHARD[2]*

[1]*European Centre for Medium-Range Weather Forecasts, UK*
[2]*CNRM-GAME (CNRS and Météo-France), France*

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SUMMARY

Cloud-resolving model (CRM) simulations of organized tropical convection observed in the Tropical Ocean/Global Atmosphere Coupled Ocean–Atmosphere Response Experiment are used to evaluate versions of the European Centre for Medium-Range Weather Forecasts convection and cloud schemes in single-column model simulations. Emphasis is placed upon the ability of the convection scheme to represent 'convective-scale' processes with typically mode-1 heating structures through the troposphere, together with a cloud scheme representing the 'stratiform (mesoscale) component' with upper-level heating and low-level cooling due to the evaporation of precipitation. While diagnosis of convective and stratiform precipitation is sensitive to the sampling criteria applied to the CRM, vertical structures of the mass and heat budgets are robust. Using diagnostics from the CRM simulations as a guide, revisions to the convection and cloud schemes are suggested in order to enable the parametrization to represent the two scales. The study suggests that a mass-flux convection scheme linked via detrainment to a prognostic treatment of cloud can represent organized convection, provided that the upward motion in the upper-level stratiform cloud is considered.

KEYWORDS: GCSS General-circulation models Numerical weather prediction TOGA COARE

1. INTRODUCTION

The development of representations of convective processes for large-scale models has been a subject of importance to meteorologists for the past 40 years. Early large-scale models of the atmosphere tended to view the parametrization of convection as a mechanism for maintaining stability, through crude adjustments of the thermodynamic profile to moist neutrality. Observations of convection during the 1960s and 1970s led to the development of parametrizations (such as Kuo-type schemes (Kuo 1965) and the mass-flux approach pioneered by Arakawa and Schubert (1974)) based upon the insights obtained. Over the past ten years the mass-flux approach has come to dominate the field.

Key to many of these developments has been the use of observational data both to provide insight into convective processes and also to evaluate the performance of convection schemes in single-column model (SCM) simulations (Betts and Miller 1986; Tiedtke 1989; Gregory and Rowntree 1990). The most frequently used observational experiment in this regard has been GATE†. The TOGA COARE‡ now provides a more recent complementary dataset. A limitation of such data is that they only provide a view of the bulk effects of convection. For example mass-flux theory points to the importance of the convective mass flux in determining the intensity and vertical distribution of convective heating. This cannot be obtained directly from observations, although Yanai *et al.* (1973) demonstrated a technique to obtain such information from observations through a diagnostic application of mass-flux theory. This method has since been used by a number of workers studying deep and shallow convection. However, as a parametrization is used in its derivation, care must be exercised in the use of such data to evaluate and develop convection schemes.

* Corresponding author: CNRM-GAME (CNRS and Météo-France), 42 av Coriolis, 31057 Toulouse Cedex, France.

† GARP (Global Atmospheric Research Programme) Atlantic Tropical Experiment.

‡ Tropical Ocean/Global Atmosphere Coupled Ocean–Atmosphere Response Experiment.

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Recovery Processes and Factors Limiting Cloud-Top Height following the Arrival of a Dry Intrusion Observed during TOGA COARE

J.-L. REDELSPERGER

Centre National de Recherches Météorologiques, Météo-France and CNRS, Toulouse, France

D. B. PARSONS

Atmospheric Technology Division, National Center for Atmospheric Research, Boulder, Colorado*

F. GUICHARD

Centre National de Recherches Météorologiques, Météo-France and CNRS, Toulouse, France

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ABSTRACT

This study investigates the recovery of the tropical atmosphere to moist conditions following the arrival of a dry intrusion observed during the Tropical Ocean and Global Atmosphere Program Coupled Ocean–Atmosphere Response Experiment (TOGA COARE). A cloud-resolving model was used to quantify the processes leading to the moistening of the lower and middle troposphere. The model replicates the general recovery of the tropical atmosphere. The moisture field in the lower and middle troposphere recovered in large part from clouds repeatedly penetrating into the dry air mass. The moistening of the dry air mass in the simulation was due to lateral mixing on the edges of cloudy regions rather than mixing at cloud top. While the large-scale advection of moisture played a role in controlling the general evolution of moisture field, the large-scale thermal advection and radiation tend to directly control the evolution of the temperature field. The diurnal variations in these two terms were largely responsible for temperature variations above the boundary layer. Thermal inversions aloft were often found at the base of dry layers.

The study also investigates which factors control cloud-top height for convective clouds. In both the observations and simulation, the most common mode of convection was clouds extending to ~4–6 km in height (often termed cumulus congestus clouds), although the period also exhibited a relatively wide range of cloud tops. The study found that cloud-top height often corresponded to the height of the thermal inversions. An examination of the buoyancy in the simulation suggested that entrainment of dry air decreased the parcel buoyancy making these inversions more efficient at controlling cloud top. Water loading effects in the simulation were generally secondary. Thus, there is a strong coupling between the dry air and thermal inversions as clear-air radiative processes associated with the vertical gradient of water vapor produce these inversions, while inversions and entrainment together limit the vertical extent of convection. One positive impact of dry air on convection occurred early in the simulation when clouds first penetrate the extremely dry air mass just above the boundary layer. At this time in the simulation, water vapor excesses within the rising parcels strongly contributed to the positive buoyancy of the clouds. In general, however, the impacts of dry air are to limit the vertical extent of convection and weaken the vertical updrafts.

1. Introduction

The appearance of extremely dry air over the tropical western Pacific has received a great deal of attention in recent years (e.g., Parsons et al. 1994; Numaguti et al. 1995; Yoneyama and Fujitani 1995; Mapes and Zuidema 1996; Johnson et al. 1996; Sheu and Liu 1995; DeMott and Rutledge 1998; Yoneyama and Parsons 1999; Parsons et al. 2000). These dry air events are termed dry intrusions, since the dry air originates aloft at higher latitudes and subsides into the Tropics in long filaments, several hundred kilometers in width. It is thus now quite established that this dry air is not a consequence of convection but, rather, it affects the behavior of convection and precipitation. These extreme events were apparently unknown before the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE). Recently, Yoneyama and Parsons (1999) showed that the intrusions are related to

* The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Corresponding author address: Dr. J.-L. Redelsperger, CNRS/GAME, Avenue Coriolis 42, Toulouse 31057, France.
E-mail: redels@meteo.fr

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An intercomparison of cloud-resolving models with the Atmospheric Radiation Measurement summer 1997 Intensive Observation Period data

By KUAN-MAN XU[1]*, RICHARD T. CEDERWALL[2], LEO J. DONNER[3], WOJCIECH W. GRABOWSKI[4], FRANÇOISE GUICHARD[5], DANIEL E. JOHNSON[6], MARAT KHAIROUTDINOV[7], STEVEN K. KRUEGER[8], JON C. PETCH[9], DAVID A. RANDALL[7], CHARLES J. SEMAN[3], WEI-KUO TAO[6], DONGHAI WANG[10,1], SHAO CHENG XIE[2], J. JOHN YIO[2] and MING-HUA ZHANG[11]

[1] *NASA Langley Research Center, USA*
[2] *Lawrence Livermore National Laboratory, USA*
[3] *NOAA Geophysical Fluid Dynamics Laboratory, USA*
[4] *National Center for Atmospheric Research, USA*
[5] *Centre National de Recherches Météorologiques, France*
[6] *NASA Goddard Space Flight Center, USA*
[7] *Colorado State University, USA*
[8] *University of Utah, USA*
[9] *Met Office, UK*
[10] *Hampton University, USA*
[11] *State University of New York, USA*

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SUMMARY

This paper reports an intercomparison study of midlatitude continental cumulus convection simulated by eight two-dimensional and two three-dimensional cloud-resolving models (CRMs), driven by observed large-scale advective temperature and moisture tendencies, surface turbulent fluxes, and radiative-heating profiles during three sub-periods of the summer 1997 Intensive Observation Period of the US Department of Energy's Atmospheric Radiation Measurement (ARM) program. Each sub-period includes two or three precipitation events of various intensities over a span of 4 or 5 days. The results can be summarized as follows.

CRMs can reasonably simulate midlatitude continental summer convection observed at the ARM Cloud and Radiation Testbed site in terms of the intensity of convective activity, and the temperature and specific-humidity evolution. Delayed occurrences of the initial precipitation events are a common feature for all three sub-cases among the models. Cloud mass fluxes, condensate mixing ratios and hydrometeor fractions produced by all CRMs are similar. Some of the simulated cloud properties such as cloud liquid-water path and hydrometeor fraction are rather similar to available observations. All CRMs produce large downdraught mass fluxes with magnitudes similar to those of updraughts, in contrast to CRM results for tropical convection. Some inter-model differences in cloud properties are likely to be related to those in the parametrizations of microphysical processes.

There is generally a good agreement between the CRMs and observations with CRMs being significantly better than single-column models (SCMs), suggesting that current results are suitable for use in improving parametrizations in SCMs. However, improvements can still be made in the CRM simulations; these include the proper initialization of the CRMs and a more proper method of diagnosing cloud boundaries in model outputs for comparison with satellite and radar cloud observations.

KEYWORDS: Continental cumulus convection Model intercomparison study

1. INTRODUCTION

Cloud-related processes occur on finer scales than those resolved by large-scale models. A subset of these models are the general-circulation models (GCMs) used for weather forecasts and climate studies. These models have to use parametrizations to represent these subgrid-scale cloud processes, for example, cumulus convection, cloud microphysics and cloud-cover parametrizations. Improvements to GCMs rely heavily on the development of more physically based parametrizations of cloud processes. It is the objective of the Global Energy and Water-cycle Experiment (GEWEX) Cloud System Study (GCSS) to develop new parametrizations of cloud-related processes for large-scale models (Browning 1994; Randall *et al.* 2000).

* Corresponding author: Mail Stop 420, NASA Langley Research Center, Hampton, VA 23681, USA.
e-mail: k.m.xu@larc.nasa.gov

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Evaluating Mesoscale Model Predictions of Clouds and Radiation with SGP ARM Data over a Seasonal Timescale

FRANÇOISE GUICHARD

CNRM-GAME (CNRS and Météo-France), Toulouse, France

DAVID B. PARSONS, JIMY DUDHIA, AND JAMES BRESCH

National Center for Atmospheric Research, Boulder, Colorado*

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ABSTRACT

This study evaluates the predictions of radiative and cloud-related processes of the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5). It is based on extensive comparison of three-dimensional forecast runs with local data from the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site collected at the Central Facility in Lamont, Oklahoma, over a seasonal timescale. Time series are built from simulations performed every day from 15 April to 23 June 1998 with a 10-km horizontal resolution. For the one single column centered on this site, a reasonable agreement is found between observed and simulated precipitation and surface fields time series. Indeed, the model is able to reproduce the timing and vertical extent of most major cloudy events, as revealed by radiative flux measurements, radar, and lidar data. The model encounters more difficulty with the prediction of cirrus and shallow clouds whereas deeper and long-lasting systems are much better captured. Day-to-day fluctuations of surface radiative fluxes, mostly explained by cloud cover changes, are similar in simulations and observations. Nevertheless, systematic differences have been identified. The downward longwave flux is overestimated under moist clear sky conditions. It is shown that the bias disappears with more sophisticated parameterizations such as Rapid Radiative Transfer Model (RRTM) and Community Climate Model, version 2 (CCM2) radiation schemes. The radiative impact of aerosols, not taken into account by the model, explains some of the discrepancies found under clear sky conditions. The differences, small compared to the short timescale variability, can reach up to 30 W m^{-2} on a 24-h timescale.

Overall, these results contribute to strengthen confidence in the realism of mesoscale forecast simulations. They also point out model weaknesses that may affect regional climate simulations: representation of low clouds, cirrus, and aerosols. Yet, the results suggest that these finescale simulations are appropriate for investigating parameterizations of cloud microphysics and radiative properties, as cloud timing and vertical extension are both reasonably captured.

1. Introduction

Evaluation and validation of atmospheric models coincided with and contributed to the emergence of these numerical tools; they are indeed as old as models themselves and of critical importance. With time, this task has become more and more complex. Numerical models have been continuously improved to reach a greater degree of realism, the latter being required in order to be able, via a modeling approach, to successfully address a large number of operational and research questions raised within the atmospheric sciences. The evaluation and validation similarly require more sophisticated observational approaches. In particular, the evaluation of model-simulated cloud and radiative processes requires observations, including accurate cloud data and radiation budgets, which are not provided by conventional data utilized for numerical weather prediction. Cloud processes also occur on a subgrid scale with respect to the resolution (both horizontal and vertical) of large-scale models. Cloud–radiation interactions depend on cloud height and thickness, cloud water content, but also microphysical characteristics of cloud such as the size and state of hydrometeors. Thus, large uncertainties affect the prediction of cloud processes by numerical models, including their interaction with radiation via water vapor transports and cloud cover as well as the formation of precipitation. Some aspects of numerical simulations are still difficult to evaluate from operational data alone.

* The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Corresponding author address: Dr. Francoise Guichard, CNRM-GAME, 42 av Coriolis, 31057 Toulouse Cedex France.
E-mail: francoise.guichard@meteo.fr

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La campagne IHOP 2002

Une campagne de mesure de la vapeur d'eau dans la couche limite

Cyrille Flamant[1], Françoise Guichard[2], Joël van Baelen[2], Olivier Bock[1], Fleur Couvreux[2], David Parsons[3], Tammy Weckwerth[3], Jacques Pelon[1], Philippe Drobinski[1], Karen Lhomme[1], Mikael Guenno[2] et Erik Doerflinger[4]

(1) Institut Pierre-Simon Laplace - Service d'aéronomie, CNRS
Université Pierre et Marie Curie - Boîte 102, 5 place Jussieu, 75252 Paris Cedex 05
cyrille.flamant@aero.jussieu.fr
(2) Météo-France
Centre national de recherches météorologiques (CNRM) - Toulouse
(3) National Center for Atmospheric Research - Atmospheric Technology Division
Boulder Co, ÉTATS-UNIS
(4) Laboratoire de la dynamique de la lithosphère
CNRS et université Montpellier-2 - Montpellier

Résumé

Le projet IHOP 2002 (International H2O Project) s'est déroulé du 13 mai au 25 juin 2002 au-dessus des Grandes Plaines de l'Oklahoma. Il résulte d'une initiative des communautés scientifiques américaine et européenne. L'objectif scientifique principal est d'améliorer la caractérisation spatio-temporelle de la distribution de la vapeur d'eau dans l'atmosphère afin de mieux comprendre et prédire les phénomènes convectifs. La région présente l'avantage de posséder un réseau d'instruments (expérimentaux et opérationnels) déjà en place et de se situer dans une zone fréquemment caractérisée par de forts gradients d'humidité et très active du point de vue de la convection. Cet article expose les moyens mis en œuvre et la stratégie expérimentale. Une attention particulière est portée à la contribution de la communauté française. Enfin, quelques résultats préliminaires sont présentés.

Abstract

The IHOP 2002 experiment: a field experiment on water vapor in the boundary layer

The International H2O Project (IHOP 2002) was a joint American and European field experiment that took place over the Southern Great Plains of the USA (Oklahoma) from 13 May to 25 June 2002. Its chief aim was to improve characterization of the four-dimensional distribution of water vapor and its application to improving the understanding and prediction of convection. The region has the advantage of existing experimental and operational facilities, strong variability in moisture, and active convection. In this paper, we present the means used as well as the experimental strategy. Particular attention is paid to the contribution of French scientists. Preliminary results are also presented.

Le radar S-POL effectuant des mesures à l'approche d'un front le 15 juin 2002. S-POL est un radar Doppler, à double polarisation, en bande S (mesure de l'indice de réfraction, classification des hydrométéores, taux de précipitation, vitesse radiale des écoulements en air clair). Il est ici situé près de la ville de Balko dans le sud de l'« Oklahoma panhandle ». Sa portée en air clair comme nuageux est de 120 km environ.

En dépit des avancées régulières de la capacité des modèles numériques à prévoir de plus en plus de paramètres atmosphériques, la prévision précise des précipitations pendant les saisons chaudes reste encore un défi (Uccellini et al., 1994). Un point particulièrement bloquant pour la prévision numérique des précipitations reste la détermination correcte du déclenchement de la convection (à savoir : où ? et quand ?) et de son cycle de vie. Ces limitations s'expliquent en partie par les critères employés pour activer la convection, qui sont trop éloignés des mécanismes effectivement à l'œuvre. La prévision du déclenchement de la convection dans les modèles dépend fortement de la paramétrisation des processus de couche limite atmosphérique (CLA), mais également des évaluations très précises de la variabilité spatio-temporelle (4-D) du champ de vapeur d'eau dans la CLA et au-

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Modelling the diurnal cycle of deep precipitating convection over land with cloud-resolving models and single-column models

By F. GUICHARD[1]*, J. C. PETCH[2], J.-L. REDELSPERGER[1], P. BECHTOLD[3], J.-P. CHABOUREAU[1,4], S. CHEINET[5], W. GRABOWSKI[6], H. GRENIER[1], C. G. JONES[7], M. KÖHLER[3], J.-M. PIRIOU[1], R. TAILLEUX[5] and M. TOMASINI[1]

[1]*CNRM/GAME, Toulouse, France*
[2]*Met Office, Exeter, UK*
[3]*European Centre for Medium-Range Weather Forecasts, Reading, UK*
[4]*Laboratoire d'aérologie, Paris, France*
[5]*Laboratoire de Météorologie Dynamique, Paris, France*
[6]*National Center for Atmospheric Research, Boulder, USA*
[7]*Swedish Meteorological and Hydrological Institute, Rossby Center, Norrköping, Sweden*

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SUMMARY

An idealized case-study has been designed to investigate the modelling of the diurnal cycle of deep precipitating convection over land. A simulation of this case was performed by seven single-column models (SCMs) and three cloud-resolving models (CRMs). Within this framework, a quick onset of convective rainfall is found in most SCMs, consistent with the results from general-circulation models. In contrast, CRMs do not predict rainfall before noon. A joint analysis of the results provided by both types of model indicates that convection occurs too early in most SCMs, due to crude triggering criteria and quick onsets of convective precipitation. In the CRMs, the first clouds appear before noon, but surface rainfall is delayed by a few hours to several hours. This intermediate stage, missing in all SCMs except for one, is characterized by a gradual moistening of the free troposphere and an increase of cloud-top height. Later on, convective downdraughts efficiently cool and dry the boundary layer (BL) in the CRMs. This feature is also absent in most SCMs, which tend to adjust towards more unstable states, with moister (and often more cloudy) low levels and a drier free atmosphere. This common behaviour of most SCMs with respect to deep moist convective processes occurs even though each SCM simulates a different diurnal cycle of the BL and atmospheric stability. The scatter among the SCMs results from the wide variety of representations of BL turbulence and moist convection in these models. Greater consistency is found among the CRMs, despite some differences in their representation of the daytime BL growth, which are linked to their parametrizations of BL turbulence and/or resolution.

KEYWORDS: Cloud parametrization Moisture Stability Transition regimes

1. INTRODUCTION

'Convective organization' refers to the various space and time scales of convective phenomena, and frequently to their degree of mesoscale organization. In this respect, the diurnal cycle of solar radiation represents an efficient and widespread mode of convective organization. Its magnitude is particularly large over land in summer (e.g. Wallace 1975; Duvel 1989; Dai *et al.* 1999) as a result of stronger daytime boundary-layer heating during this season. In this situation, precipitating convection typically takes place during the afternoon and/or evening. This broad picture is further modulated by regional features, such as land–sea and mountain–valley breezes (Garreaud and Wallace 1997; Yang and Slingo 2001; Liberti *et al.* 2001) and meteorological regimes (e.g. Rickenbach *et al.* 2002). Some areas are also characterized by complex diurnal cycles of rainfall as a result of the propagation of mesoscale convective systems over hundreds of kilometres, or even very large convective episodes initially triggered by daytime heating, as reported by Carbone *et al.* (2002).

In addition to its importance for weather forecasts, this temporal organization is not neutral with respect to the energy and water budgets on a local scale, but also at

* Corresponding author: CNRM/GAME (CNRS and Météo-France), 42 avenue Coriolis, 31057 Toulouse Cedex, France. e-mail: francoise.guichard@meteo.fr
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The role of stability and moisture in the diurnal cycle of convection over land

By J.-P. CHABOUREAU[1,2]*, F. GUICHARD[1], J.-L. REDELSPERGER[1] and J.-P. LAFORE[1]

[1]*CNRM/GAME, Météo-France and CNRS, France*
[2]*Laboratoire d'Aérologie, Université Paul Sabatier and CNRS, France*

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SUMMARY

The diurnal cycle of convection over land is investigated by a cloud-resolving model simulation. Three regimes of convection—dry, shallow, and deep—successively take place during daytime under the presence of substantial convective available potential energy. The convective inhibition (CIN) and the normalized saturation deficit (NSD) in the cloud-base layer are identified as the major two variables that characterize the cycle of the convective regimes. The surface heating during daytime leads to the development of a quasi-dry well-mixed convective planetary boundary layer (PBL). This yields a decrease of CIN while NSD remains steady. Shallow convection is initiated as soon as the CIN becomes lower locally than the vertical kinetic energy in the PBL. This timing also marks the minimum of CIN, both in local and in domain-mean senses. Then, detrainment of moisture from the cloud layer gradually moistens the low free troposphere, resulting in a NSD decrease. Finally, deep convection is triggered when sufficient moistening is realized, as measured by a NSD minimum. During deep convection, NSD rapidly increases and CIN increases. Once CIN has exceeded the vertical kinetic energy in the PBL, deep convection ceases.

KEYWORDS: Convective inhibition Saturation deficit

1. INTRODUCTION

The diurnal cycle of moist convection is of major importance for climate studies due to its strong radiative feedbacks, the resulting precipitation, and its control on surface temperature. The diurnal cycle of convection is stronger over land than over oceans, and strongest during summer. Over continents, convection usually occurs in the late afternoon or early evening under a dominant influence of daytime boundary-layer heating (Wallace 1975; Duvel 1989). The diurnal cycle varies regionally due to the modulations of low-level convergence by land/sea and mountain/valley breezes as well as mesoscale features (Yang and Slingo 2001; Nesbitt and Zipser 2003). Recent studies have shown deficiencies in general-circulation models (GCMs) for capturing the diurnal cycle of deep convection, both in magnitude and phase (Dai *et al.* 1999; Lin *et al.* 2000; Yang and Slingo 2001; Bechtold *et al.* 2004). Especially, deep convection in GCMs tends to be in phase with low-level temperature and atmospheric instability as measured by the convective available potential energy (CAPE), and thus it tends to occur earlier than observed. This is a well-established deficiency in global models, suggesting their fundamental shortcomings in parametrizing the surface, boundary layer, and convective processes.

However, comprehensive studies describing the diurnal cycle of deep convection at convective scale are still missing. The relationship between CAPE and convection is not so straightforward as often claimed. Both are clearly linked on a climatological scale, but the situation is much less simple at shorter scales. For instance, in the tropical western Pacific, Sherwood (1999) found that for 90% of the time there is enough CAPE for convection, which is only 20–30% likely to break out. Other factors appear to play a role, such as the convective inhibition (CIN) and the moisture field, as pointed out by Brown and Zhang (1997), Mapes (2000), Parsons *et al.* (2000) and Redelsperger *et al.*

* Corresponding author, present affiliation: Laboratoire d'Aérologie, Observatoire Midi-Pyrénées, 14 av. Belin, 31400 Toulouse, France. e-mail: chajp@aero.obs-mip.fr

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Estimations of Mass Fluxes for Cumulus Parameterizations from High-Resolution Spatial Data

Jun-Ichi Yano, Francoise Guichard, Jean-Philippe Lafore, and Jean-Luc Redelsperger

CNRM, Météo-France, and CNRS, Toulouse, France

Peter Bechtold

ECMWF, Shinfield Park, Reading, United Kingdom

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ABSTRACT

The core of the mass flux formulation, on which the majority of the current cumulus parameterizations are based, is to transport physical variables by the so-called mass flux for individual physical components, such as convective updrafts, downdrafts, and environment. These parameterizations use horizontal means over the subdomains occupied by these physical components to define the mass fluxes and transported variables. However, evaluations of the mass flux formulation against high-resolution spatial data obtained from explicit numerical models reveal that it substantially underestimates vertical transport of heat, moisture, and momentum by deep convection.

The present paper proposes an alternative approach, in which the effective values weighted toward extreme values are used both for the mass flux and the transported variable to obtain an accurate estimate of vertical transport. Statistically, the distribution of convective variables is so widely distributed within individual subdomains that the vertical transports are controlled by extreme values, rather than by simple means. Evaluation for these *effective* values are facilitated by considering four categories depending on the sign of both the vertical velocity and the transported variable, instead of the conventional convective-type classifications. A best estimate of the effective value is obtained empirically by weighting the variable by a power of one-quarter during the averaging.

A major consequence of this alternative approach is that the mass fluxes must be defined differently for the individual variables. Thus, chemical species would not be transported by the same mass flux as that for temperature or moisture. With this extra elaboration, the proposed formulation provides more robust estimation of the subgrid-scale convective transports.

1. Introduction

Currently, the majority of cumulus parameterization is constructed using a mass flux formulation (cf. Emanuel and Raymond 1993). The basic idea behind this formulation is to transport physical variables by the so-called "mass flux" for individual convective components. A major step is to separate subgrid-scale convective variability within the large-scale grid box into two subdomains, namely the "environment" and convective areas, in the simplest bulk mass flux formulation. The convective area can further be divided, for example, into the convective-scale and mesoscale. The physical variables are assumed to be distributed homogeneously within each subdomain at each vertical level, which we refer to as the segmentally constant approximation [cf. Eq. (3.2) below].

This segmentally constant approximation enables one to estimate vertical fluxes within these individual subdomains by a simple product of the mass flux and the transported variable averaged over each subdomain [cf. Eq. (3.3) below], which constitutes the core of constructing the mass flux formulation (Ooyama 1971; Arakawa and Schubert 1974; Yanai and Johnson 1993). This formulation originally developed for the thermodynamic variables has been extended for other variables such as momentum (e.g., Kershaw and Gregory 1997; Gregory et al. 1997) and chemical species (e.g., Mahowald et al. 1995, 1997; Mari et al. 2000). Hence, consistency of the vertical flux estimated from this mass flux formulation with both observations (de Laat and Duynkerke 1998) and cloud-resolving models (CRM; cf. Moncrieff et al. 1997; Redelsperger et al. 2000) is a crucial test.

With this general goal in mind, the present paper is concerned with the estimation of the mass fluxes and

Corresponding author address: Jun-Ichi Yano, Laboratoire de Météorologie Dynamique, Boite 99, Université Pierre-et-Marie Curie, 4 place Jussieu, 75252 Paris Cedex 05, France.
E-mail: yano@lmd.jussieu.fr

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Water-vapour variability within a convective boundary-layer assessed by large-eddy simulations and IHOP_2002 observations

By F. COUVREUX[1]*, F. GUICHARD[1], J.-L. REDELSPERGER[1], C. KIEMLE[3], V. MASSON[1], J.-P. LAFORE[1] and C. FLAMANT[2]

[1]*Centre National de Recherches Météorologiques–Météo-France and Centre National de Recherche Scientifique, France*

[2]*Institut Pierre Simon Laplace/Service d'Aéronomie, France*

[3]*Deutsche Zentrum für Luft- und Raumfahrt/Institut für Physik der Atmosphäre, Germany*

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SUMMARY

This study presents a comprehensive analysis of the variability of water vapour in a growing convective boundary-layer (CBL) over land, highlighting the complex links between advection, convective activity and moisture heterogeneity in the boundary layer. A Large-eddy Simulation (LES) is designed, based on observations, and validated, using an independent data-set collected during the International H_2O Project (IHOP_2002) field-experiment. Ample information about the moisture distribution in space and time, as well as other important CBL parameters are acquired by mesonet stations, balloon soundings, instruments on-board two aircraft and the DLR airborne water-vapour differential-absorption lidar. Because it can deliver two-dimensional cross-sections at high spatial resolution (140 m horizontal, 200 m vertical), the airborne lidar offers valuable insights of small-scale moisture-variability throughout the CBL. The LES is able to reproduce the development of the CBL in the morning and early afternoon, as assessed by comparisons of simulated mean profiles of key meteorological variables with sounding data. Simulated profiles of the variance of water-vapour mixing-ratio were found to be in good agreement with the lidar-derived counterparts. Finally, probability-density functions of potential temperature, vertical velocity and water-vapour mixing-ratio calculated from the LES show great consistency with those derived from aircraft *in situ* measurements in the middle of the CBL. Downdraughts entrained from above the CBL are governing the scale of moisture variability. Characteristic length-scales are found to be larger for water-vapour mixing-ratio than for temperature

The observed water-vapour variability exhibits contributions from different scales. The influence of the mesoscale (larger than LES domain size, i.e. 10 km) on the smaller-scale variability is assessed using LES and observations. The small-scale variability of water vapour is found to be important and to be driven by the dynamics of the CBL. Both lidar observations and LES evidence that dry downdraughts entrained from above the CBL are governing the scale of moisture variability. Characteristic length-scales are found to be larger for water-vapour mixing-ratio than for temperature and vertical velocity. In particular, intrusions of drier free-troposphere air from above the growing CBL impose a marked negative skewness on the water-vapour distribution within it, both as observed and in the simulation.

KEYWORDS: Heterogeneities High-resolution simulations Humidity Lidar data

1. INTRODUCTION

Water vapour is important in several major areas in the atmospheric sciences, on scales from turbulence to synoptic-scale systems, and including cloud formation and maintenance, radiation and climate. Numerous studies have underlined the importance of the moisture field for convection. Crook (1996), for example, showed that the thermodynamic structure (both temperature and moisture) of the boundary layer (BL) is crucial for the development of deep convection. Moreover, convective boundary layer (CBL) circulations are responsible for moisture variations that can still be quite large (e.g., Weckwerth *et al.* 1996). A common manifestation of such BL heterogeneities takes the form of fair weather cumuli, which arise when and where thermals bring sufficiently moist air from the lower BL to its lifting condensation level (Stull 1985, Wilde *et al.* 1985). Weckwerth (2000) showed how small-scale water-vapour variability could also affect the determination of whether or not deep convection will be initiated through its impact on atmospheric stability.

* Corresponding author: Fleur Couvreux, CNRM/GAME (CNRS and Météo-France), 42 avenue Coriolis, 31057 Toulouse Cedex, France. e-mail: fleur.couvreux@meteo.fr

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A generalization of CAPE into potential-energy convertibility

By JUN-ICHI YANO[1]*, JEAN-PIERRE CHABOUREAU[2] and FRANÇOISE GUICHARD[1]

[1]*CNRM–GAME (CNRS and Météo-France), France*

[2]*Laboratoire d'Aerologie,Observatoire Midi-Pyrenees, France*

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SUMMARY

The concept of the potential-energy convertibility (PEC) is proposed as a generalization of convective available potential energy (CAPE). It is defined as a vertical integral of buoyancy weighted by a non-dimensional normalized vertical momentum. This is a measure of convertibility of potential energy into kinetic energy in the sense that the actual conversion rate is recovered when PEC evaluated by the convective-scale local buoyancy and vertical momentum, as available from cloud-resolving model (CRM) simulations, is multiplied by the normalization factor for the vertical momentum. It reduces to CAPE, when the standard parcel-lifted buoyancy and a unit value for the normalized vertical momentum are used. It is equivalent to Arakawas–Schubert's cloud work function, when the buoyancy and the vertical momentum profile for an entraining plume are used. PEC evaluated from locally defined buoyancy and vertical momentum in CRM simulations correlates better with the convective precipitation than CAPE. The evaluation of PEC within a convective parametrization may be possible with an appropriate definition of the effective entrainment rate, for example, which is expected to improve CAPE-based convective parametrizations.

KEYWORDS: Convective parametrization Energy cycle PEC

1. INTRODUCTION

The convective available potential energy (CAPE), originally introduced by Moncrieff and Miller (1976), is a commonly used quantity as a measure of moist-convective instability (conditional instability) of the atmosphere (cf. Roff and Yano 2002; see also Emanuel 1994). However, in spite of its name, CAPE cannot be directly identified as a part of standard energy cycles in the atmospheric dynamics. In the standard description of the global atmospheric dynamics (e.g. Holton 1992, section 10.4), the energy cycle is defined by the exchange between the kinetic energy and the available potential energy, with the latter defined as a 'convertible' part of the *total* potential energy. This energy cycle is naturally derived by applying the standard procedure of the energy integral (cf. Goldstein *et al.* 2002) to the primitive-equation system, or to the non-hydrostatic anelastic system.

As far as such a formal energy cycle is concerned, the inclusion of convective heating effects does not change its formulational structure, into that CAPE does not enter. The latter is defined by a heuristic process associated with a hypothetical pseudo-adiabatic lifting of an air parcel, independent of this formal description.

In the present paper, we are going to argue that CAPE is better interpreted as a measure of *convertibility* of the potential energy into the kinetic energy, rather than as a potential energy. This point is, in fact, already stated mathematically by Eq. (132) of Arakawa and Schubert (1974), but without further physical remarks, in introducing the cloud work function, which is typically interpreted as a natural extension of CAPE to entraining plumes (cf. Mapes 1997; Brown and Zhang 1997; Yano 1999; Donner and Phillips 2003). Here, the standard CAPE is defined for a hypothetical lifting of an air parcel without mixing (i.e. undiluted).

We will develop our argument by stepwise physical considerations in the next section. This naturally leads to a further generalization of the concept of CAPE. We call

* Corresponding author: CNRM–GAME, Météo-France, 42 av Coriolis, 31057 Toulouse Cedex, France.
e-mail: yano@cnrm.meteo.fr.

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Mode decomposition as a methodology for developing convective-scale representations in global models

By JUN-ICHI YANO[1]†, JEAN-LUC REDELSPERGER[1], PETER BECHTOLD[2] and FRANÇOISE GUICHARD[1]

[1]*CNRM–GAME, Météo-France and CNRS, 31057 Toulouse Cedex, France*
[2]*ECMWF, Shinfield Park, Reading, RG2 9AX, UK*

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SUMMARY

Mode decomposition is proposed as a methodology for developing subgrid-scale physical representations in global models by a systematic reduction of an originally full system such as a cloud-resolving model (CRM). A general formulation is presented, and also discussed are mathematical requirements that make this procedure possible. Features of this general methodology are further elucidated by the two specific examples: mass fluxes and wavelets.

The traditional mass-flux formulation for convective parametrizations is derived as a special case from this general formulation. It is based on the decomposition of a horizontal domain into an approximate sum of piecewise-constant segments. Thus, a decomposition of CRM outputs on this basis is crucial for their direct verification. However, this decomposition is mathematically not well-posed nor unique due to the lack of *admissibility*. A classification into cloud types, primarily based on precipitation characteristics of the atmospheric columns, that has been used as its substitute, does not necessarily provide a good approximation for a piecewise-constant segment decomposition. This difficulty with mass-flux decomposition makes a verification of the formulational details of parametrizations based on mass fluxes by a CRM inherently difficult.

The wavelet decomposition is an alternative possibility that can more systematically decompose the convective system. Its completeness and orthogonality also allow a *prognostic* description of a CRM system in wavelet space in the same manner as is done in Fourier space. The wavelets can, furthermore, efficiently represent the various convective coherencies by a limited number of modes due to their spatial localizations. Thus, the degree of complexity of the wavelet-based *prognostic* representation of a CRM can be extensively reduced. Such an extensive reduction *may* allow its use in place of current cumulus parametrizations. This wavelet-based scheme can easily be verified from the full original system due to its direct reduction from the latter. It also fully takes into account the multi-scale nonlinear interactions, unlike the traditional mass-flux-based schemes.

KEYWORDS: Cloud-resolving model Cumulus parametrization Mass flux Wavelets

1. INTRODUCTION

The subgrid-scale physical representation (normally called the parametrization) is a major source of uncertainties in current global climate modelling. As it stands, different physical processes in subgrid scales are represented separately by different schemes, without much consideration of mutual consistency. As emphasized in a recent review by Arakawa (2004), a unified description of these subgrid-scale physical processes is obviously what is needed. Such a unified description would become possible if the originally full physical system could be systematically and extensively reduced into a simpler system. The present paper proposes mode decomposition as a general methodology for this purpose. As an example of a full physical system, we take the cloud-resolving model (CRM), keeping particularly in mind the convective-scale processes that are traditionally represented by cumulus parametrizations.

The CRM has widely been recognized as a promising tool for developing and verifying cumulus parametrizations (Browning *et al.* 1993; Moncrieff *et al.* 1997; Redelsperger *et al.* 2000) since the pioneering work by Gregory and Miller (1989). Ability of CRMs to model realistic atmospheric deep convection has been established

† Corresponding author: CNRM–GAME, Météo-France, 42 av. Coriolis, 31057 Toulouse Cedex, France.
e-mail: yano@cnrm.meteo.fr

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An Approach for Convective Parameterization with Memory: Separating Microphysics and Transport in Grid-Scale Equations

JEAN-MARCEL PIRIOU AND JEAN-LUC REDELSPERGER
CNRM-GAME, Météo-France–CNRS, Toulouse, France

JEAN-FRANÇOIS GELEYN
Czech Hydrometeorological Institute, Prague, Czech Republic, and Météo-France, Toulouse, France

JEAN-PHILIPPE LAFORE AND FRANÇOISE GUICHARD
CNRM-GAME, Météo-France–CNRS, Toulouse, France

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ABSTRACT

An approach for convective parameterization is presented here, in which grid-scale budget equations of parameterization use separate microphysics and transport terms. This separation is used both as a way to introduce into the parameterization a more explicit causal link between all involved processes and as a vehicle for an easier representation of the memory of convective cells. The equations of parameterization become closer to those of convection-resolving models [cloud-system-resolving models (CSRMs) and large-eddy simulations (LESs)], facilitating parameterization development and validation processes versus a detailed budget of these high-resolution models.

The new Microphysics and Transport Convective Scheme (MTCS) equations are presented and discussed. A first version of a convective scheme based on these equations is tested within a single-column framework. The results obtained with the new scheme are close to those of traditional ones in very moist convective cases [like the Global Atmospheric Research Programme (GARP) Atlantic Tropical Experiment (GATE) Phase III, 1974]. The simulation of more difficult drier situations [European Cloud Systems Study/Global Energy and Water Cycle Experiment (GEWEX) Cloud System Studies (EUROCS/GCSS)] is improved through more memory due to higher sensitivity of simulated convection to dry midtropospheric layers; a prognostic relation between cloudy entrainment and precipitation evaporation dramatically improves the prediction of the phase lag of the convective diurnal cycle over land with respect to surface heat forcing.

The present proposal contains both a relatively general equation set, which can deal continuously with dry, moist, and deep precipitating convection, and separate—and still crude—explicit moist microphysics. In the future, when increasing the complexity of microphysical computations, such an approach may help to unify dry, moist, and deep precipitating convection inside a single parameterization, as well as facilitate global climate model (GCM) and limited-area model (LAM) parameterizations in sharing the same formulation of explicit microphysics with CSRMs.

1. Introduction

Since the 1970s many researchers have endeavored to improve convective parameterization concepts and schemes: the characteristic scale of convective drafts is between, say, a few meters (thermals) and a few thousand meters (moist updrafts and downdrafts), so present computational power makes it impossible for GCMs to deal explicitly with such small scales. These models can only predict the mean effect of an ensemble of subgrid-scale drafts, an exercise referred to as parameterizing convection. In such GCMs, and with respect to the present trend in increasing computational power, deep convection will remain subgrid scale for decades, and much more so for shallow convection: cu-

Corresponding author address: J.-M. Piriou, CNRM, Météo-France, 42 Avenue G. Coriolis, 31057 Toulouse CEDEX 1, France.
E-mail: jean-marcel.piriou@meteo.fr

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ORIGINAL PAPER

Negative water vapour skewness and dry tongues in the convective boundary layer: observations and large-eddy simulation budget analysis

F. Couvreux · F. Guichard · V. Masson · J.-L. Redelsperger

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Abstract This study focuses on the intrusion of dry air into the convective boundary layer (CBL) originating from the top of the CBL. Aircraft in-situ measurements from the IHOP_2002 field campaign indicate a prevalence of negative skewness of the water vapour distribution within the growing daytime CBL over land. This negative skewness is interpreted according to large-eddy simulations (LES) as the result of descending dry downdrafts originating from above the mixed layer. LES are used to determine the statistical properties of these intrusions: their size and thermodynamical characteristics. A conditional sampling analysis demonstrates their significance in the retrieval of moisture variances and fluxes. The rapid CBL growth explains why greater negative skewness is observed during the growing phase: the large amounts of dry air that are quickly incorporated into the CBL prevent a full homogenisation by turbulent mixing. The boundary-layer warming in this phase also plays a role in the acquisition of negative buoyancy for these dry tongues, and thus possibly explains their kinematics in the lower CBL. Budget analysis helps to identify the processes responsible for the negative skewness. This budget study underlines the main role of turbulent transport, which distributes the skewness produced at the top or the bottom of the CBL into the interior of the CBL. The dry tongues contribute significantly to this turbulent transport.

Keywords Convective boundary layer · Dry tongues · Large-eddy simulation · Skewness · Variance · Water vapour

1 Introduction

The water vapour field exhibits strong variability across a wide range of scales from planetary, synoptic down to small-scale turbulence. This variability plays an impor-

F. Couvreux (✉) · F. Guichard · V. Masson · J.-L. Redelsperger
GAME-Météo-France CNRM/GMME
42 avenue G. Coriolis, 31057 Toulouse Cedex 1, France
e-mail: fleur.convreux@meteo.fr

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ORIGINAL PAPER

Impact of coherent eddies on airborne measurements of vertical turbulent fluxes

Marie Lothon · Fleur Couvreux · Sylvie Donier · Françoise Guichard · Pierre Lacarrère · Donald H. Lenschow · Joël Noilhan · Frédérique Saïd

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Abstract During the Hydrological-Atmospheric Pilot Experiment (HAPEX)-Sahel, which took place in Niger in the transitional period between the wet and dry seasons, two French aircraft probed the Sahelian boundary layer to measure sensible and latent heat fluxes. The measurements over the Niamey area often revealed organised structures of a few km scale that were associated with both thermals and dry intrusions. We study the impact of these coherent structures using a single day's aircraft-measured fluxes and a numerical simulation of that day with a mesoscale model. The numerical simulation at high horizontal resolution (250 m) contains structures that evolve from streaks in the early morning to cells by noon. This simulation shows distribution, variance and skewness similar to the observations. In particular, the numerical simulation shows dry intrusions that can penetrate deeply into the atmospheric boundary layer (ABL), and even reach the surface in some cases, which is in accordance with the observed highly negatively skewed water vapour fluctuations. Dry intrusions and thermals organised at a few km scale give skewed flux statistics and can introduce large errors in measured fluxes. We use the numerical simulation to: (i) evaluate the contribution of the organised structures to the total flux, and (ii) estimate the impact of the organised structures on the systematic and random errors resulting from the 1D sampling of the aircraft as opposed to the 2D numerical simulation estimate. We find a significant contribution by the organised structures to the total resolved fluxes. When rolls occur, and for a leg length of about 30 times the ABL depth, the 1D sampled flux is shown to be sometimes 20% lower than the corresponding 2D flux when the 1D sampling direction is the same as the main axis of the

M. Lothon (✉)
Centre de Recherches Atmosphériques, 8 route de Lannemezan, Campistrous 65300, France
e-mail: lotm@aero.obs-mip.fr

M. Lothon · F. Saïd
Laboratoire d'Aérologie, UMR 5560 CNRS, Université Paul Sabatier Toulouse III, Toulouse, France

F. Couvreux · S. Donier · F. Guichard · P. Lacarrère · J. Noilhan
Météo-France/CNRM, Toulouse, France

D. H. Lenschow
National Center for Atmospheric Research, Boulder, CO, USA

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Comparison of ground-based GPS precipitable water vapour to independent observations and NWP model reanalyses over Africa

O. Bock,[a]* M.-N. Bouin,[b] A. Walpersdorf,[c] J. P. Lafore,[d] S. Janicot,[e] F. Guichard[d] and A. Agusti-Panareda[f]

[a] *IPSL/SA, Université Paris VI, France*
[b] *LAREG, IGN, France*
[c] *LGIT, CNRS, France*
[d] *CNRM/GMME, Météo-France, France*
[e] *IPSL/LOCEAN, Université Paris VI, France*
[f] *ECMWF, Shinfield Park, Reading, UK*

ABSTRACT: This study aims at assessing the consistency between different precipitable water vapour (PWV) datasets over Africa (between 35 °N and 10 °S). This region is characterized by large spatial and temporal variability of humidity but also by the scarcity of its operational observing network, limiting our knowledge of the hydrological cycle. We intercompare data from observing techniques such as ground-based Global Positioning System (GPS), radiosondes, AERONET sun photometers and SSM/I, as well as reanalyses from European Centre for Medium-Range Weather Forecasts (ERA-40) and National Center for Environmental Prediction (NCEP2). The GPS data, especially, are a new source of PWV observation in this region. PWV estimates from nine ground-based GPS receivers of the international GPS network data are used as a reference dataset to which the others are compared. Good agreement is found between observational techniques, though dry biases of 12–14% are evidenced in radiosonde data at three sites. Reasonable agreement is found between the observational datasets and ERA-40 (NCEP2) reanalyses with maximum bias $\leq$9% (14%) and standard deviation $\leq$17% (20%). Since GPS data were not assimilated in the ERA-40 and NCEP2 reanalyses, they allow for a fully independent validation of the reanalyses. They highlight limitations in the reanalyses, especially at time-scales from sub-daily to periods of a few days. This work also demonstrates the high potential of GPS PWV estimates over Africa for the analysis of the hydrological cycle, at time-scales ranging between sub-diurnal to seasonal. Such observations can help studying atmospheric processes targeted by the African Monsoon Multidisciplinary Analysis project. Copyright © 2007 Royal Meteorological Society

KEY WORDS ERA-40; NCEP2; AMMA; AERONET; radiosondes

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1. Introduction

Atmospheric water vapour is a key variable of the global climate system. It plays a crucial role in the radiative equilibrium, being the dominant greenhouse gas, and in climate change processes. Atmospheric water vapour is also an important component of the global hydrologic cycle. It shows significant variability, both in space and time over a large range of scales, resulting from the action of many atmospheric processes (transport, mixing, thermodynamics and microphysics) and interactions with the surface (evaporation of the oceans and evapotranspiration over land). Most meteorological processes (convection, cloud formation, precipitation) are influenced by local as well as large-scale variability in atmospheric water vapour.

In the present study, we will be interested in precipitable water vapour (PWV), which is the total atmospheric water vapour contained in a vertical column of unit area. This variable is strongly linked to the hydrological cycle and dynamical processes in the tropics where the overall PWV is high (Amenu and Kumar, 2005; Li and Chen, 2005). Since water vapour density on average quickly decreases with altitude (with a scale height of ~2 km), PWV is closely related to lower-tropospheric humidity. Most of the PWV variability is thus correlated with variability in the lower troposphere.

A number of observational techniques allow estimation of the atmospheric PWV: either *in situ* (e.g. radiosondes) or by microwave and near-infrared or thermal infrared remote-sensing techniques (ground-based or spaceborne radiometers). Most of these techniques have limited retrieval capability (either only daytime operation or only over oceans), and thus their use for climate studies is limited or needs careful long-term data calibration

* Correspondence to: O. Bock, Institut Pierre Simon Laplace/Service d'Aéronomie, Université Paris VI, 4 Place Jussieu, 75252 Paris cedex, France. E-mail: Olivier.Bock@aero.jussieu.fr

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Multiscale analysis of precipitable water vapor over Africa from GPS data and ECMWF analyses

O. Bock,[1] F. Guichard,[2] S. Janicot,[3] J. P. Lafore,[2] M.-N. Bouin,[4] and B. Sultan[3]

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[1] This is the first climatological analysis of precipitable water vapor (PWV) from GPS data over Africa. The data reveal significant modulations and variability in PWV over a broad range of temporal scales. GPS PWV estimates are compared to ECMWF reanalysis ERA40. Both datasets show good agreement at the larger scales (seasonal cycle and inter-annual variability), driven by large scale moisture transport. At intra-seasonal (15–40 days) and synoptic (3–10 days) scales, strong PWV modulations are observed from GPS, consistently with ECMWF analysis. They are shown to be correlated with convection and the passage of equatorial waves and African Easterly waves. The high-frequency GPS observations also reveal a significant diurnal cycle in PWV, which magnitude and spectral content depends strongly on geographic location and shows a seasonal modulation. The diurnal cycle of PWV is poorly represented in ERA40 reflecting weaknesses in the water cycle of global circulation models at this timescale. **Citation:** Bock, O., F. Guichard, S. Janicot, J. P. Lafore, M.-N. Bouin, and B. Sultan (2007), Multiscale analysis of precipitable water vapor over Africa from GPS data and ECMWF analyses, *Geophys. Res. Lett.*, *34*, L09705, doi:10.1029/2006GL028039.

1. Introduction

[2] Atmospheric water vapor is a key variable of the global climate system and hydrologic cycle. It shows significant variability, both in space and time over a large range of scales, resulting from interactions between atmospheric, land and ocean processes. Precipitable water vapor (PWV) is a good indicator of the variability of water vapor in the lower troposphere and related processes. In terms of water budget, it represents the tendency of water vapor storage in the column of atmosphere, as a result of the balance between precipitation, evaporation and convergence of humidity [*Fontaine et al.*, 2003]. In the present work, we analyze PWV variability with the help of Global Positioning System (GPS) observations, from a network of ground-based receivers in Africa (Figure 1), and the 40-year (ERA40) re-analyses from European Centre for Medium-Range Weather Forecasts (ECMWF) [*Simmons and Gibson*, 2000]. The GPS dataset consists in a combined zenith tropospheric delay (ZTD) product from the International GNSS Service [*Gendt*, 2004]. ZTD estimates are converted into PWV [*Bevis et al.*, 1994] using surface pressure and 2-m temperature from ERA40 for all stations except Dakar where data from ECMWF operational analysis were used instead (this station operated only from mid 2003 on). Since the conversion is not very sensitive to the surface parameters [*Bevis et al.*, 1994] and GPS data are not assimilated into ERA40, GPS PWV allows for an independent validation of ERA40. The GPS PWV data are representative of a spatial scale of 20–50 km in the troposphere (assuming, e.g., observations down to 5° elevation and a water vapor scale height of 2–5 km). This is of similar, though slightly higher, resolution than the ERA40 dataset (the latter having a horizontal resolution of ~125 km). We refer to *Bock et al.* [2007] for further description of these datasets. In the present letter, we present climatic features at four of these African stations.

2. Seasonal Cycle and Inter-Annual Variability

[3] The seasonal cycle in PWV observed in the tropics is a result of large-scale processes. It mainly reflects the migration of the inter-tropical convergence zone (ITCZ) from one hemisphere into the other, following the movement of maximum solar heating with a lag of about 6 weeks. Figure 2 shows the PWV seasonal cycle from GPS and ERA40 at four GPS stations located in contrasted regions of Africa for which the available time series were the longest. Nevertheless, the periods of time are unequal between them (see legend of Figure 2). The agreement between GPS and ERA40 is generally good. These stations have marked but different seasonal cycles. At the northernmost station (Mas Palomas; Figure 2a), the magnitude of PWV excursion throughout the year (12 kg m^{-2}) and the average PWV (20 kg m^{-2}) are relatively small, but their ratio is quite strong (60%), reflecting a marked seasonal cycle. The inter-annual variability for each month (lower part of the plot) is quite small at this station (standard deviation about 2 kg m^{-2}). At station Dakar (Figure 2b) the seasonal cycle is very pronounced. The average value and excursion throughout the year are both about 30 kg m^{-2}, i.e., a seasonal modulation of 100% and a ratio of highest over lowest monthly value of ~3. PWV shows a slow and regular increase between March and August, while the decrease is much faster, between September and November. The highest values are observed during the monsoon season and may be due to large moisture fluxes from the south-west in the lower troposphere and from the north-east in the middle troposphere as well as vertical transport due to convection and evaporation [*Fontaine et al.*, 2003; *Sultan*

[1] Institute Pierre-Simon Laplace, Service Aeronomie du CNRS, Université Paris VI, Paris, France.
[2] Groupe de Météorologie de Moyenne Echelle, Centre National de Recherches Météorologiques, Météo-France, Toulouse, France.
[3] Institute Pierre-Simon Laplace, Laboratoire d'Océanographie et du Climat, Université Paris VI, Paris, France.
[4] Laboratoire de Recherches en Géodésie, Institut Géographique National, Marine la Vallee, France.

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Analysis of the in situ and MODIS albedo variability at multiple timescales in the Sahel

O. Samain,[1,2] L. Kergoat,[1] P. Hiernaux,[1] F. Guichard,[3] E. Mougin,[1] F. Timouk,[1] and F. Lavenu[1]

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[1] The variability of the Sahelian albedo is investigated through the combined analysis of 5 years of in situ radiation data from the African Monsoon Multidisciplinary Analysis northernmost sites and remotely sensed albedo from 7 years of Moderate Resolution Imaging Spectroradiometer data. Both data sets are found to be in good agreement in terms of correlation and bias. The drivers of albedo variability are identified by means of in situ measurements of biological and physical properties of the land surface collected over a network of 29 long-term survey sites. Short-term variability is dominated by changes in the spectral composition of incident radiation, which reflects aerosol optical depth and integrated water content, and changes in soil moisture, which have a short-lived effect (1 d). Bush fires cause a marked decrease of albedo of the order of 10 d, whereas a dry season storm event is suspected to have increased albedo through litter and soil surface abrasion. Seasonal plant growth causes the largest changes in rainy season albedo, and displays a large interannual variability: Because of the 2004 drought, albedo increases steadily from late 2003 to early 2005 at latitude 15°N. Grazing pressure is found to impact albedo mostly in the dry season. Dry season albedo is controlled by the amount of litter and standing dead phytomass hiding the bright soils. Thus rainfall anomalies have a direct effect on albedo through plant growth but also a lagged effect caused by above normal amounts of dry phytomass that can persist until the arrival of the next monsoon. EOF analysis and Hovmüller diagrams show these effects to be present on a large scale.

Citation: Samain, O., L. Kergoat, P. Hiernaux, F. Guichard, E. Mougin, F. Timouk, and F. Lavenu (2008), Analysis of the in situ and MODIS albedo variability at multiple timescales in the Sahel, *J. Geophys. Res.*, *113*, D14119, doi:10.1029/2007JD009174.

1. Introduction

[2] Surface albedo is central to surface/climate interactions in the Sahel. Many investigations have studied the possible link between changes in albedo and the severe droughts that affected West Africa during the 1970s and 1980s. The main hypothesis, introduced by *Otterman* [1974] and developed by *Charney et al.* [1975], is that a decrease in the vegetation cover caused by drought, overgrazing, extensive clearing for cropping, deforestation or land degradation triggers an increase of the albedo. This in turn tends to reinforce subsidence in the Sahel and weaken convective activity, resulting in less precipitation and thus further decline in vegetation cover. The Charney's mechanism has been extended to account for other surface properties like the release of latent heat [*Eltahir and Gong*, 1996], and questioned as the sea surface temperature was recognized to drive the West African monsoon [*Giannini et al.*, 2003]. Nevertheless, the importance of the surface feedbacks to the atmosphere has been demonstrated, the current view being that this feedback acts more as a strong amplifier of ocean driven variability than as the initial trigger of monsoon variability [*Lamb*, 1983; *Folland et al.*, 1986; *Nicholson et al.*, 1998; *Nicholson*, 2000; *Fontaine and Janicot*, 1996; *Zeng et al.*, 1999; *Giannini et al.*, 2003].

[3] Numerical climate models showed that important land cover changes can lead to climate change in West Africa [*Xue and Shukla*, 1993, 1996; *Lofgren*, 1995; *Dirmeyer and Shukla*, 1996; *Claussen*, 1997; *Xue*, 1997; *Clark et al.*, 2001; *Notaro et al.*, 2007]. However, the magnitude of albedo changes caused by a reduction of vegetation cover is thought to have been overestimated [*Nicholson*, 2000; *Taylor et al.*, 2002]. *Notaro et al.* [2007] even suggested that the land surface feedback may be negative, an hypothesis at odds with most results so far. More precise studies are required to analyze the history of albedo changes that actually occurred in the Sahel in the last decades. In particular, it is necessary to accurately assess the contribution of the albedo feedback to the recent droughts in West Africa. There is also a need for realistic scenarios of

[1]Centre d'Etudes Spatiales de la BIOSphère (CESBIO), Joint Laboratory from CNES/CNRS/IRD/UPS, Toulouse Cedex, France.
[2]Now at EUMETSAT, Darmstadt, France.
[3]Centre National de Recherches Météorologiques (CNRM/GAME), Joint Laboratory from CNRS and Météo-France, Toulouse Cedex, France.

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West African Monsoon observed with ground-based GPS receivers during African Monsoon Multidisciplinary Analysis (AMMA)

O. Bock,[1,2] M. N. Bouin,[1] E. Doerflinger,[3] P. Collard,[3] F. Masson,[4] R. Meynadier,[2] S. Nahmani,[1] M. Koité,[5] K. Gaptia Lawan Balawan,[6] F. Didé,[7] D. Ouedraogo,[8] S. Pokperlaar,[9] J.-B. Ngamini,[10] J. P. Lafore,[11] S. Janicot,[12] F. Guichard,[11,13] and M. Nuret[11]

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[1] A ground-based GPS network has been established over West Africa in the framework of African Monsoon Multidisciplinary Analysis (AMMA) in tight cooperation between French and African institutes. The experimental setup is described and preliminary highlights are given for different applications using these data. Precipitable water vapor (PWV) estimates from GPS are used for evaluating numerical weather prediction (NWP) models and radiosonde humidity data. Systematic tendency errors in model forecasts are evidenced. Correlated biases in NWP model analyses and radiosonde data are evidenced also, which emphasize the importance of radiosonde humidity data in this region. PWV and precipitation are tightly correlated at seasonal and intraseasonal timescales. Almost no precipitation occurs when PWV is smaller than 30 kg m^{-2}. This limit in PWV also coincides well with the location of the intertropical discontinuity. Five distinct phases in the monsoon season are determined from the GPS PWV, which correspond either to transition or stationary periods of the West African Monsoon system. They may serve as a basis for characterizing interannual variability. Significant oscillations in PWV are observed with 10- to 15-day and 15- to 20-day periods, which suggest a strong impact of atmospheric circulation on moisture and precipitation. The presence of a diurnal cycle oscillation in PWV with marked seasonal evolutions is found. This oscillation involves namely different phasing of moisture fluxes in different layers implying the low-level jet, the return flow, and the African Easterly Jet. The broad range of timescales observed with the GPS systems shows a high potential for investigating many atmospheric processes of the West African Monsoon.

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1. Introduction

[2] The West African Monsoon (WAM) system has been the subject of intensive and growing research efforts during the last decades. This interest was primarily motivated by the need to understand the mechanisms responsible for the severe droughts that West Africa has undergone since the 1970s and increased interannual variability in rainfall [*Le Barbé et al.*, 2002]. Rainfall abundance is indeed of crucial importance in vulnerable regions such as the Sahel. The impact of interannual rainfall variability is increasing as the population and demand for water resources are quickly growing and are accompanied in some places by increased changes in land use and water pollution. Past studies have given evidence that the WAM system results from the interplay of various processes, involving multiple scale interactions between the ocean, land surface and vegetation, and the atmosphere. The African Monsoon Multidisciplinary Analysis program (AMMA), has been setup to improve our understanding of the WAM system as well as the environmental and socioeconomic impacts [*Redelsperger et al.*, 2006]. This program relies on embedded field experi-

[1]IGN, LAREG, Marne-la-Vallée, France.
[2]Service d'Aéronomie, Université Pierre et Marie Curie, UMR7620, CNRS, Paris, France.
[3]Géosciences Montpellier, Université Montpellier II, UMR5243, CNRS, Montpellier, France.
[4]IPGS, Université Louis Pasteur, UMR7516, CNRS, Strasbourg, France.
[5]Direction Nationale de la Météorologie, Bamako, Mali.
[6]Direction de la Météorologie du Niger, Niamey, Niger.
[7]Direction Nationale de la Météorologie, Cotonou, Benin.
[8]ASECNA, Ouagadougou, Burkina-Faso.
[9]Ghana Meteorological Agency, Tamale, Ghana.
[10]ASECNA, Dakar, Senegal.
[11]CNRM, Meteo-France, Toulouse, France.
[12]LOCEAN, Université Pierre et Marie Curie, UMR7159, CNRS, Paris, France.
[13]GAME, URA1357, CNRS, Toulouse, France.

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Verification of Cloud Cover Forecast with Satellite Observation over West Africa

NATHALIE SÖHNE AND JEAN-PIERRE CHABOUREAU

Laboratoire d'Aérologie, Université de Toulouse, and CNRS, Toulouse, France

FRANÇOISE GUICHARD

GAME/CNRM, CNRS, and Météo-France, Toulouse, France

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ABSTRACT

The 3-hourly brightness temperatures (BTs) at 10.8 μm from the Meteosat Second Generation (MSG) satellite were used to document the cloud system variability over West Africa in the summer of 2006 and to evaluate the quality of the Méso-NH model forecasts of cloud cover in the African Monsoon Multidisciplinary Analysis (AMMA) framework. Cloud systems were observed over the Guinean and Sahelian bands with more frequent occurrence and patchier structures in the afternoon. Some intraseasonal variations of the number of cloud systems were found, partly related to the intermittency of the African easterly wave (AEW) activity. Compared to the MSG observations, the Méso-NH model reproduces the overall variation of the BT at 10.8 μm well at $D + 1$ forecast. The model captures the BT diurnal cycle under conditions of clear-sky and high-cloud cover, but misses the lowest BT values associated with deep convection. Forecasted cloud systems are more numerous and smaller, hence patchier, than those observed. These results suggest some deficiencies in the model's convection and cloud parameterization schemes. The use of meteorological scores further documents the skill of the model to predict cloud systems. Beyond some systematic differences between simulations and observations, analysis also suggests that the model high-cloud forecast is improved under specific synoptic forcing conditions related to AEW activity. This indicates that room exists for improving the skills of weather forecasting over West Africa.

1. Introduction

Clouds and precipitation are sensible weather elements that are crucial to forecast in the tropics. Despite the importance of rain for human activities, skill in forecasting tropical rainfall events on a day-to-day basis has not been explored extensively, with the exception of tropical cyclones. This can be explained by the limited value of numerical weather prediction for forecasting weather involving convection because of the paucity of appropriate mesoscale observational data and the limitations of both current initialization procedures and physical parameterization (Smith et al. 2001). Thus, there has been more focus on the ability of the general circulation models (GCMs) to represent the broad characteristics of the tropical atmosphere. For example, a well-established deficiency in GCMs is the failure to capture the diurnal cycle of deep convection over land, both in magnitude and phase (e.g., Guichard et al. 2004). In particular, deep convection in GCMs tends to be in phase with low-level temperature and atmospheric instability. This results in a predicted onset of convective rainfall earlier than observed. Last, the mesoscale organization of convection poorly simulated by GCMs is also a strong issue, particularly for impact studies such as on the hydrologic cycle (Lebel et al. 2000). These features suggest fundamental shortcomings in the parameterization of the surface, radiative, boundary layer, cloud, and convective processes.

In the Sahel, a semiarid zonal band around 10°–18°N extending coherently across Africa, most of the precipitation arises from mesoscale convective systems (MCSs) during the Northern Hemisphere summer (e.g., Mathon et al. 2002). The correct prediction of MCSs is therefore of importance for human needs and has been identified as an objective of the African Monsoon Multidisciplinary Analysis (AMMA) research program

Corresponding author address: Dr. Jean-Pierre Chaboureau, Laboratoire d'Aérologie, Observatoire Midi-Pyrénées, 14 av. Belin, F-31400 Toulouse, France.
E-mail: jean-pierre.chaboureau@aero.obs-mip.fr

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Correction of Humidity Bias for Vaisala RS80-A Sondes during the AMMA 2006 Observing Period

MATHIEU NURET,* JEAN-PHILIPPE LAFORE,* OLIVIER BOCK,+ FRANÇOISE GUICHARD,* ANNA AGUSTI-PANAREDA,+ JEAN-BLAISE N'GAMINI,@ AND JEAN-LUC REDELSPERGER*

*CNRM-GAME, Météo-France, and CNRS, Toulouse, France
+LAREG/IGN, Marne La Vallée, France
#ECMWF, Reading, Berkshire, United Kingdom
@ASECNA, Dakar, Senegal

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ABSTRACT

During the African Monsoon Multidisciplinary Analyses (AMMA) program, which included a special observing period that took place over West Africa in 2006, a major effort was devoted to monitor the atmosphere and its water cycle. The radiosonde network was upgraded and enhanced, and GPS receivers deployed. Among all sondes released in the atmosphere, a significant number were Vaisala RS80-A sondes, which revealed a significant dry bias relative to Vaisala RS92 (a maximum of 14% in the lower atmosphere, reaching 20% in the upper levels). This paper makes use of a simple but robust statistical approach to correct the bias. Comparisons against independent GPS data show that the bias is almost removed at night, whereas for daytime conditions, a weak dry bias (5%) still remains. The correction enhances CAPE by a factor of about 4 and, thus, becomes much more in line with expected values over the region.

1. Introduction

Dry biases encountered from Vaisala RS80 measurements made during the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) over the "warm pool" of the tropical western Pacific Ocean have been a major issue. They have a dramatic impact on operational numerical weather prediction (NWP) and on all research activities related to the water cycle. It took several years to produce an RS80 humidity "corrected" dataset useable by researchers (Wang et al. 2002), and the RS80 dry bias is still an issue in operational NWP.

The international African Monsoon Multidisciplinary Analyses (AMMA) program (Redelsperger et al. 2006) aims to improve our understanding of the West African monsoon and its variability, from daily to intraseasonal time scales. Since 2004, AMMA scientists have been working with operational agencies in Africa to reactivate silent radiosonde stations, to renovate unreliable stations, and to install new stations in West Africa (Parker et al. 2008), where 21 stations are now active. During the period June–September 2006, some 7000 soundings were made, representing the greatest density of radiosondes ever launched in the region—greater even than during the Global Atmospheric Research Programme (GARP) Atlantic Tropical Experiment (GATE) in 1974. To complete the experimental design, around 500 additional soundings were launched from three research vessels in the Gulf of Guinea and the east Atlantic, from aircraft and from driftsondes. Simultaneous to this upgrading, six AMMA ground-based global positioning system (GPS) stations were operating during the Special Observing Period (SOP), allowing two north–south transects (Bock et al. 2008).

The monitoring of the AMMA radiosonde network by NWP centers [the European Centre for Medium-Range Weather Forecasts (ECMWF) and Météo-France] and first comparisons of Integrated Water Vapor (IWV) derived from independent GPS data revealed (Bock et al. 2007) that many humidity radiosonde measurements were negatively biased (dry bias). This may be explained by the fact that a large number of the sondes released during the AMMA 2006 SOP were

Corresponding author address: Mathieu Nuret, Météo-France and CNRS, CNRM/GMME/MOANA, 42 Avenue G. Coriolis, F-31057 Toulouse, France.
E-mail: mathieu.nuret@meteo.fr

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Radiosonde humidity bias correction over the West African region for the special AMMA reanalysis at ECMWF

Anna Agustí-Panareda,[a]* Drasko Vasiljevic,[a] Anton Beljaars,[a] Olivier Bock,[b] Françoise Guichard,[c] Mathieu Nuret,[c] Antonio Garcia Mendez,[a] Erik Andersson,[a] Peter Bechtold,[a] Andreas Fink,[d] Hans Hersbach,[a] Jean-Philippe Lafore,[c] Jean-Blaise Ngamini,[e] Douglas J. Parker,[f] Jean-Luc Redelsperger[c] and Adrian M. Tompkins[g]

[a]*ECMWF, Reading, UK*
[b]*LAREG/IGN, Marne La Vallée, France*
[c]*Météo-France/CNRM-GAME, Toulouse, France*
[d]*University of Cologne, Germany*
[e]*ASECNA, Dakar, Senegal*
[f]*University of Leeds, UK*
[g]*ICTP, Trieste, Italy*

ABSTRACT: During the African Monsoon Multidisciplinary Analysis (AMMA) field experiment in 2006 there was a large increase in the number of radiosonde data over West Africa. This has the potential of improving the numerical weather prediction (NWP) analysis/forecast and the water budget studies over that region. However, it is well known that the humidity from radiosondes can have some errors depending on sonde type, relative humidity (RH), temperature and the age of the sensor and can give rise to dry biases that are typically between 5% and 30% for RH. Three main sonde types were used in the AMMA field experiment: Vaisala RS80A, Vaisala RS92 and MODEM. In this article, a new empirical method is presented by using the operational European Centre for Medium-Range Weather Forecasts (ECMWF) short-range forecast as an intermediary dataset for computing biases. The validation of the correction method using global positioning system (GPS) total columnar water vapour (TCWV) confirms that the method is able to correct for a large part of the dry biases associated with the different sonde types. Results from analysis experiments show how the correction of humidity is particularly important in the West African region due to its impact on the development of convection in NWP models. The proposed radiosonde humidity bias correction has been applied to the special AMMA reanalysis experiment performed at ECMWF for the 2006 West African wet monsoon season. This is expected to benefit a wide number of AMMA-related studies that make use of the reanalysis, in particular those focusing on the water cycle. Copyright © 2009 Royal Meteorological Society

KEY WORDS AMMA; radiosonde bias; humidity observations; data assimilation; reanalysis

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1. Introduction

During the African Monsoon Multidisciplinary Analysis (AMMA) field experiment in 2006 there was a large increase in the number of radio soundings over West Africa (Redelsperger *et al.*, 2006), the majority of which were assimilated in numerical weather prediction (NWP) analyses (Parker *et al.*, 2008). Almost half of the radiosondes used were Vaisala RS80A, which are known to have a substantial dry bias in both the lower and upper troposphere (Wang *et al.*, 2002). Johnson and Ciesielski (2000) and Ciesielski *et al.* (2003) showed that rainfall biases in NWP forecasts initialized with reanalyses focusing on the Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA–COARE) region can be partly explained by the biases in radiosonde humidity measurements due to changes in convective available potential energy (CAPE) and convective inhibition (CIN) (Guichard *et al.*, 2000). Garand *et al.* (1992), Lorenc *et al.* (1996) and Sharpe and Macpherson (2001) have also shown the impact of radiosonde humidity biases on NWP models, in particular the effect of dry bias on cloud cover and precipitation.

Many of these radio soundings in the AMMA network are located in the region of the humidity gradient over the Sahel (Figure 1), where mesoscale convective systems (MCSs) develop during the wet monsoon season, accounting for most of the precipitation over the region (Mathon *et al.*, 2002). Nuret *et al.* (2008) investigated the dry bias at Niamey, which had been using Vaisala RS80A and RS92 radiosondes, and proposed a correction for RS80A with respect to RS92. They found a dry bias in relative humidity (RH) of up to 14% at low

*Correspondence to: Anna Agustí-Panareda, ECMWF, Shinfield Park, Reading, Berkshire, RG2 9AX, UK. Email: Anna.Agusti-Panareda@ecmwf.int

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SPECIAL
IHOP Boundary Layer Processes
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Nature of the Mesoscale Boundary Layer Height and Water Vapor Variability Observed 14 June 2002 during the IHOP_2002 Campaign

F. COUVREUX AND F. GUICHARD

GAME-Meteo-France/CNRS-CNRM/GMME, Toulouse, France

P. H. AUSTIN

Atmospheric Science Programme, Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, British Columbia, Canada

F. CHEN

National Center for Atmospheric Research, Boulder, Colorado

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ABSTRACT

Mesoscale water vapor heterogeneities in the boundary layer are studied within the context of the International H_2O Project (IHOP_2002). A significant portion of the water vapor variability in the IHOP_2002 occurs at the mesoscale, with the spatial pattern and the magnitude of the variability changing from day to day. On 14 June 2002, an atypical mesoscale gradient is observed, which is the reverse of the climatological gradient over this area. The factors causing this water vapor variability are investigated using complementary platforms (e.g., aircraft, satellite, and in situ) and models. The impact of surface flux heterogeneities and atmospheric variability are evaluated separately using a 1D boundary layer model, which uses surface fluxes from the High-Resolution Land Data Assimilation System (HRLDAS) and early-morning atmospheric temperature and moisture profiles from a mesoscale model. This methodology, based on the use of robust modeling components, allows the authors to tackle the question of the nature of the observed mesoscale variability. The impact of horizontal advection is inferred from a careful analysis of available observations. By isolating the individual contributions to mesoscale water vapor variability, it is shown that the observed moisture variability cannot be explained by a single process, but rather involves a combination of different factors: the boundary layer height, which is strongly controlled by the surface buoyancy flux, the surface latent heat flux, the early-morning heterogeneity of the atmosphere, horizontal advection, and the radiative impact of clouds.

1. Introduction

Water vapor variability was the main focus of the International H_2O Project (IHOP_2002), which took place in May–June 2002 over the southern Great Plains of the United States (Weckwerth et al. 2004). This field project gathered together most of the techniques for measuring water vapor. We address water vapor variability at the mesoscale (scales larger than thermals, ranging from tens to a few hundreds of kilometers). Comparatively few investigations have considered this scale of variability, mainly because of the lack of observations. Milford et al. (1979), using observations from an instrumented glider, first underscored the variability of water vapor at the mesoscale, which they found to be larger than the variability of either potential temperature or vertical velocity. Mahrt (1991), analyzing aircraft in situ measurements at 300 m above ground level, found that the mesoscale variability of water vapor exceeded the submesoscale variability.

Mesoscale water vapor variability has been stressed as an important condition for convection. Crook (1996), Wulfmeyer et al. (2006), and Stirling and Petch (2004) have shown that the initiation of convection is strongly tied to the accurate estimate of water vapor within the boundary layer (BL). In the latter study, the authors demonstrated that the existence of moisture fluctuations accelerates the initiation of deep convection by 1–3 h, and that convective initiation was most sensitive

Corresponding author address: F. Couvreux, GAME-Meteo-France/CNRS-CNRM/GMME, 42 av. G. Coriolis, 31057, Toulouse CEDEX 1, France.
E-mail: fleur.couvreux@meteo.fr

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Surface thermodynamics and radiative budget in the Sahelian Gourma: Seasonal and diurnal cycles

Françoise Guichard [a,*], Laurent Kergoat [b], Eric Mougin [b], Frank Timouk [b], Frédéric Baup [b], Pierre Hiernaux [b], François Lavenu [b]

[a] CRNM/GAME, URA 1357 (CNRS and Météo-France), 42 Avenue Coriolis, 31057 Toulouse Cedex, France
[b] CESBIO, UMR 5126 (CNES/CNRS/IRD/UPS), 18 Avenue Edouard Belin, bpi 2801, 31401 Toulouse Cedex 9, France

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SUMMARY

Our understanding of the role of surface–atmosphere interactions in the West African monsoon has been particularly limited by the scarcity of measurements. The present study provides a quantitative analysis of the very pronounced seasonal and diurnal cycles of surface thermodynamics and radiative fluxes in the Central Sahel. It makes use of data collected from 2002 to 2007 in the Malian Gourma, close to Agoufou, at 1.5°W–15.3°N and sounding data collected during the AMMA field campaign.

The seasonal cycle is characterized by a broad maximum of temperature in May, following the first minimum of the solar zenith angle (SZA) by a few weeks, when Agoufou lies within the West African Heat Low, and a late summer maximum of equivalent potential temperature (θe) within the core of the monsoon season, around the second yearly maximum of SZA.

Distinct temperature and moisture seasonal and diurnal dynamics lead to a sharpening of the early (late) monsoon increase (decrease), more steadiness of θe and larger changes of relative humidity in between. Rainfall starts after the establishment of the monsoon flow, once temperature already started to decrease slowly, typically during June. Specific humidity increases progressively from May until August, while the monsoon flow weakens during the same period.

Surface net radiation (R^{net}) increases from around 10-day mean values of 20 W m^{-2} in Winter to 120–160 W m^{-2} in late Summer, The increase is sharper during the monsoon than before, and the decrease fast. The seasonal cycle of R^{net} arises from distinct shortwave and longwave fluctuations that are both strongly shaped by modifications of surface properties related to rainfall events and vegetation phenology (with a decrease of both surface longwave emission and albedo). During the monsoon, clouds and aerosols reduce the incoming solar radiation by 20–25% (about 70 W m^{-2}). They also significantly enhance the day-to-day variability of R^{net}. Nevertheless, the surface incoming longwave radiative flux (LW^{in}) is observed to decrease from June to September. As higher cloud covers and larger precipitable water amounts are typically expected to enhance LW^{in}, this feature points to the significance of changes in atmospheric temperature and aerosols during the monsoon season.

The strong dynamics associated with the transition from a drier hot Spring to a brief cooler moist tropical Summer climate involves large transformations of the diurnal cycle, even within the monsoon season, which significantly affect both thermodynamical, dynamical and radiative fields (and low-level dynamics). In particular, for all moist Summer months except August, specific humidity decreases in such a way during daytime that it prevents an afternoon increase of θe.

In agreement with some previous studies, strong links are found between moisture and LW^{net} all year long and a positive correlation is identified between R^{net} and θe during the monsoon.

The observational results presented in this study further provide valuable ground truth for assessing models over an area displaying a rich variety of surface–atmosphere regimes.

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Introduction

Energy and water fluxes at the land-atmosphere interface are recognized as important actors of the West African monsoon (WAM). They play a crucial role in the mechanisms that have been put forward to explain several WAM specific features (Nicholson,

* Corresponding author. Tel.: +33 5 61 07 96 72.
E-mail address: francoise.guichard@meteo.fr (F. Guichard).

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Rainfall regime across the Sahel band in the Gourma region, Mali

Frédéric Frappart [a,*], Pierre Hiernaux [a], Françoise Guichard [b], Eric Mougin [a], Laurent Kergoat [a], Marc Arjounin [c], François Lavenu [a,1], Mohamed Koité [d], Jean-Emmanuel Paturel [e], Thierry Lebel [c]

[a] Centre d'Etudes Spatiales de la BIOsphère (CESBIO), UMR 5126 (CNES/CNRS/IRD/UPS), 18 Avenue Edouard Belin, bpi 2801, 31401 Toulouse Cedex 9, France
[b] CNRM-GAME, URA 1357 (CNRS, Météo-France), 42 Avenue Gaspard Coriolis, 31057 Toulouse Cedex 1, France
[c] Laboratoire d'Etude des Transferts en Hydrologie et Environnement (LTHE), UMR 5564 (CNRS, UJF, IRD, INPG), BP 53, 38 041 Grenoble Cedex 9, France
[d] Direction Nationale de la Météorologie, Bamako, Mali
[e] Université Montpellier 2, HydroSciences Montpellier, Case MSE, Place Eugène Bataillon, 34095 Montpellier Cedex 5, France

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SUMMARY

The Sahel is characterized by low and highly variable rainfall, which strongly affects the hydrology and the climate of the region and creates severe constraints for agriculture and water management. This study provides the first characterization of the rainfall regime for the Gourma region located in Mali, Central Sahel (14.5–17.5°N and 2–1°S). The rainfall regime is described using two datasets: the daily long term raingauge records covering the period 1950–2007, and the high frequency raingauge records collected under the African Monsoon Multidisciplinary Analysis (AMMA) project between 2005 and 2008. The first rainfall dataset was used to analyse the interannual variability and the spatial distribution of the precipitation. The second dataset is used to analyse the diurnal cycle of precipitation and the nature of the rainfall. This study is complementary to previous analyses conducted in Sahelian areas located further south, where the influence of the continental Sahara heat low is expected to be less pronounced in summer.

Rainfall regimes in the Gourma region present a succession of wet (1950–1969) and dry decades (1970–2007). The decrease of summer cumulative rainfall is explained by a reduction in the number of the rainy days in southern Gourma, and a decrease in both the number of rainy days and the daily rainfall in northern and central Gourma. This meridional difference may be related to the relative distances of the zones from the intertropical discontinuity, which is closer to the northern stations. The length of the rainy season has varied since the 1950s with two episodes of shorter rainy seasons: during the drought of the 1980s and also since 2000. However, this second episode is characterized by an increase in the daily rainfall, which suggests an intensification of rainfall events in the more recent years.

High-frequency data reveal that a large fraction of the rainfall is produced by intense rain events mostly occurring in late evenings and early mornings during the core of the rainy season (July–September). Conversely, rainfall amounts are less around noon, and this mid-day damping is more pronounced in northern Gourma. All these characteristics have strong implications for agriculture and water resources management.

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Introduction

The arid and semi-arid regions of Africa are characterized by low and unreliable rainfall, which strongly affects water resources and food security (Nicholson, 1989). The largest of these regions, the Sahel, runs 3800 km from the Atlantic Ocean in the west to the Red Sea in the east, in a belt that varies from several 100–1000 km in width, covering an area of 3,053,200 km^2. This semi-arid area is bordered to the north by the Sahara Desert and to the south by Sudanian savannas. The Sahelian climate is characterized by a unimodal rainfall regime controlled by the west African Monsoon – WAM (Nicholson, 1981; Todorov, 1985; Morel, 1992; Hiernaux and Le Houérou, 2006). During the 20th century, the Sahel experienced a multidecennial drought that started at the end of 1960s, with two sequences of extremely dry years, in 1972–1974 and 1983–1985 (Hulme, 1992; Le Barbé and Lebel, 1997; D'Amato and Lebel, 1998; L'Hôte et al., 2002; Lebel et al., 2003). This is, indeed, the strongest measured climatic event of rainfall variability at these time and space scales (Hulme, 2001). The substantial changes in the climate conditions obliged Sahelian farmers and pastoralist communities to adapt to the decrease in water resources (Mortimore and Adams, 2001; Tarhule and Lamb, 2003; Pedersen and Benjaminsen, 2008).

* Corresponding author. Tel.: +33 5 61 55 85 19.
E-mail address: frederic.frappart@cesbio.cnes.fr (F. Frappart).
[1] Deceased author.

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The AMMA-CATCH Gourma observatory site in Mali: Relating climatic variations to changes in vegetation, surface hydrology, fluxes and natural resources

E. Mougin [a,*], P. Hiernaux [a], L. Kergoat [a], M. Grippa [a], P. de Rosnay [a], F. Timouk [a], V. Le Dantec [a], V. Demarez [a], F. Lavenu [a,1], M. Arjounin [b], T. Lebel [b], N. Soumaguel [c], E. Ceschia [a], B. Mougenot [a], F. Baup [a], F. Frappart [a], P.L. Frison [d], J. Gardelle [a], C. Gruhier [a], L. Jarlan [a], S. Mangiarotti [h,i,j,k], B. Sanou [a], Y. Tracol [e], F. Guichard [f], V. Trichon [g], L. Diarra [l], A. Soumaré [l], M. Koité [m], F. Dembélé [n], C. Lloyd [o], N.P. Hanan [p], C. Damesin [q], C. Delon [r], D. Serça [r], C. Galy-Lacaux [r], J. Seghieri [s], S. Becerra [h,i,j,k], H. Dia [h,i,j,k], F. Gangneron [h,i,j,k], P. Mazzega [h,i,j,k]

[a] *Centre d'Etudes Spatiales de la Biosphère, UMR 5126 (CNRS/CNES/IRD/UPS), 18 Avenue Edouard Belin, 31401 Toulouse Cedex 4, France*
[b] *Laboratoire de Tranferts en Hydrologie et Environnement, UMR 5564 (CNRS/UJF/IRD/INPG) BP 53, 38041 Grenoble Cedex 9, France*
[c] *Centre IRD, Quartier Hippodrome, BP 2528, Bamako, Mali*
[d] *Laboratoire des Géomatériaux, Université Marne-la-Vallée, France*
[e] *Centro de Estudios Avanzados en Zonas Aridas, Casilla 599, colina El Pino s/n La Serena, Chile*
[f] *CNRM-GAME (CNRS/Meteo-France), Toulouse, France*
[g] *Laboratoire d'Ecologie Fonctionnelle, ECOLAB, UMR 5245 (CNRS/UPS/INPT), Université Paul Sabatier, 118 Route de Narbonne, 31062 Toulouse Cedex 9, France*
[h] *Laboratoire des Mécanismes et Transferts en Géologie, UMR 5563 (CNRS/IRD/UPS), 14 Avenue Edouard Belin, 31400 Toulouse Cedex 4, France*
[i] *Université de Toulouse, UPS (OMP), LMTG, 14 Av Edouard Belin, F-31400 Toulouse, France*
[j] *CNRS, LMTG, F-31400 Toulouse, France*
[k] *IRD, LMTG, F-31400 Toulouse, France*
[l] *Institut d'Economie Rurale, BP 258 – rue Mohamed V, Bamako, Mali*
[m] *Direction Nationale de la Météorologie, Bamako, Mali*
[n] *Institut Polytechnique Rural, Katibougou, Mali*
[o] *Centre of Ecology and Hydrology, Crowmarsh Gifford, Wallingford OX10 8BB, UK*
[p] *Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523, USA*
[q] *Ecologie Systématique et Evolution, UMR 8079 (CNRS/U. Paris-Sud), Université Paris-Sud, 91405 Orsay, France*
[r] *Laboratoire d'Aérologie, UMR 5560 (CNRS/UPS), 14 Avenue Edouard Belin, 31400 Toulouse, France*
[s] *Hydro Sciences Montpellier (HSM), UMR N° 5569 (CNRS/IRD/UM1/UM2) Université Montpellier 2, Case MSE Place Eugène Bataillon, 34095 Montpellier, France*

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SUMMARY

The Gourma site in Mali is one of the three instrumented meso-scale sites deployed in West-Africa as part of the African Monsoon Multi-disciplinary Analysis (AMMA) project. Located both in the Sahelian zone *sensu stricto*, and in the Saharo–Sahelian transition zone, the Gourma meso-scale window is the northernmost site of the AMMA-CATCH observatory reached by the West African Monsoon.

The experimental strategy includes deployment of a variety of instruments, from local to meso-scale, dedicated to monitoring and documentation of the major variables characterizing the climate forcing, and the spatio-temporal variability of surface processes and state variables such as vegetation mass, leaf area index (LAI), soil moisture and surface fluxes. This paper describes the Gourma site, its associated instrumental network and the research activities that have been carried out since 1984. In the AMMA project, emphasis is put on the relations between climate, vegetation and surface fluxes. However, the Gourma site is also important for development and validation of satellite products, mainly due to the existence of large and relatively homogeneous surfaces. The social dimension of the water resource uses and governance is also briefly analyzed, relying on field enquiry and interviews.

The climate of the Gourma region is semi-arid, daytime air temperatures are always high and annual rainfall amounts exhibit strong inter-annual and seasonal variations. Measurements sites organized along a north–south transect reveal sharp gradients in surface albedo, net radiation, vegetation production, and distribution of plant functional types. However, at any point along the gradient, surface energy budget, soil moisture and vegetation growth contrast between two main types of soil surfaces and hydrologic systems. On the one hand, sandy soils with high water infiltration rates and limited run-off support almost continuous herbaceous vegetation with scattered woody plants. On the other hand, water infiltra-

* Corresponding author. Tel.: +33 5 61 55 66 69; fax: +33 5 61 55 85 00.
E-mail address: eric.mougin@cesbio.cnes.fr (E. Mougin).
[1] Deceased on 2007, February 10.

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THE AMMA LAND SURFACE MODEL INTERCOMPARISON PROJECT (ALMIP)

BY AARON BOONE, PATRICIA DE ROSNAY, GIANPAOLO BALSAMO, ANTON BELJAARS, FRANCK CHOPIN, BERTRAND DECHARME, CHRISTINE DELIRE, AGNES DUCHARNE, SIMON GASCOIN, MANUELA GRIPPA, FRANÇOISE GUICHARD, YEUGENIY GUSEV, PHIL HARRIS, LIONEL JARLAN, LAURENT KERGOAT, ERIC MOUGIN, OLGA NASONOVA, ANETTE NORGAARD, TRISTAN ORGEVAL, CATHERINE OTTLÉ, ISABELLE POCCARD-LECLERCQ, JAN POLCHER, INGE SANDHOLT, STEPHANE SAUX-PICART, CHRISTOPHER TAYLOR, AND YONGKANG XUE

A multimodel comparison of the performance of land surface parameterization schemes increases understanding of the land–atmosphere feedback mechanisms over West Africa.

The West African monsoon (WAM) circulation modulates the seasonal northward displacement of the intertropical convergence zone (ITCZ). It is the main source of precipitation over a large part of West Africa. However, predominantly relatively wet years during the 1950s and 1960s were followed by a much drier period during the 1970s and 1990s. This extreme rainfall variability corresponds to one of the strongest interdecadal signals on the planet over the last half-century. There is an urgent need to better understand and predict the WAM, because social stability in this region depends to a large degree on water resources. The economies are primarily agrarian, and there are issues related to food security and health. In addition, there is increasing pressure on the already limited water resources in this region, owing to one of the most rapidly increasing populations on the planet.

Numerous researchers over the last three decades have investigated the nature of the extreme rainfall variability (e.g., Nicholson 1980; Le Barbé et al. 2002). It has been shown that a significant part of the interannual variability can be linked to sea surface (sfc) temperature anomalies (e.g., Folland et al. 1986; Fontaine and Janicot 1996), but there is also evidence that land surface conditions over West Africa make a significant contribution to this variability (e.g., Nicholson 2000; Philippon et al. 2005).

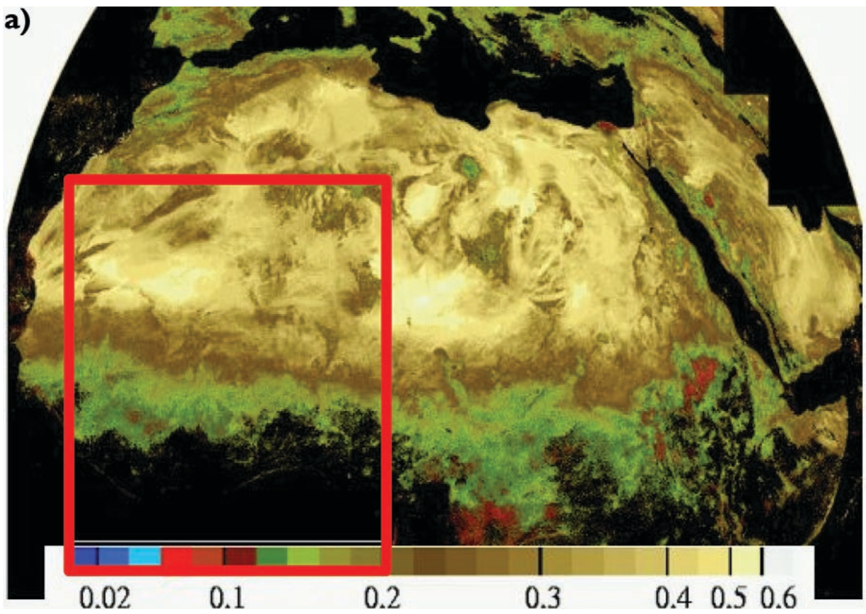
Importance of the land–atmosphere interactions on the WAM. The monsoon flow is driven by land–sea thermal contrast. The atmosphere–land surface interactions are modulated by the magnitude of the associated north–south gradient of heat and moisture in the lower atmosphere (Eltahir and Gong 1996). The links between land surface processes and the WAM have been demonstrated in numerous numerical studies using global climate models (GCMs) and regional-scale atmospheric climate models (RCMs) over the last several decades. Charney (1975) were one of the first set of researchers to use a coupled land surface–atmosphere model to demonstrate a proposed positive feedback mechanism between decreasing vegetation cover and the increase in drought conditions across the Sahel region of western Africa. Numerous modeling studies since have examined the influence of the land surface on the WAM in terms of surface albedo (e.g., Sud and Fennessy 1982; Laval and Picon 1986), the vegetation spatial distribution (e.g.,

AMMA-MODEL INTERCOMPARISON PROJECT

BY FRÉDÉRIC HOURDIN, IONELA MUSAT, FRANÇOISE GUICHARD, PAOLO MICHELE RUTI, FLORENCE FAVOT, MARIE-ANGÈLE FILIBERTI,* MAÏ PHAM, JEAN-YVES GRANDPEIX, JAN POLCHER, PASCAL MARQUET, AARON BOONE, JEAN-PHILIPPE LAFORE, JEAN-LUC REDELSPERGER, ALESSANDRO DELL'AQUILA, TERESA LOSADA DOVAL, ABDOUL KHADRE TRAORE, AND HUBERT GALLÉE

A meridional cross-section analysis provides the framework to assess regional and global model skill at simulating seasonal and intraseasonal variations of the West African monsoon, and thus mechanisms for the region's rainfall.

THE AMMA-MIP BACKGROUND. The African monsoon is characterized by a well-defined meridional structure of surface albedo and vegetation (Fig. 1a), with relatively weaker longitudinal variations. This structure is tightly connected to that of the mean rainfall (Fig. 1b), with maximum rainfall occurring in the Sudanian region (10°–13°N) during the northern summer. In addition, there is a sharp transition over the Sahel (13°–18°N), which is a particularly sensitive region that experienced a significant drought in the late 1970s and 1980s (Hulme 1992).



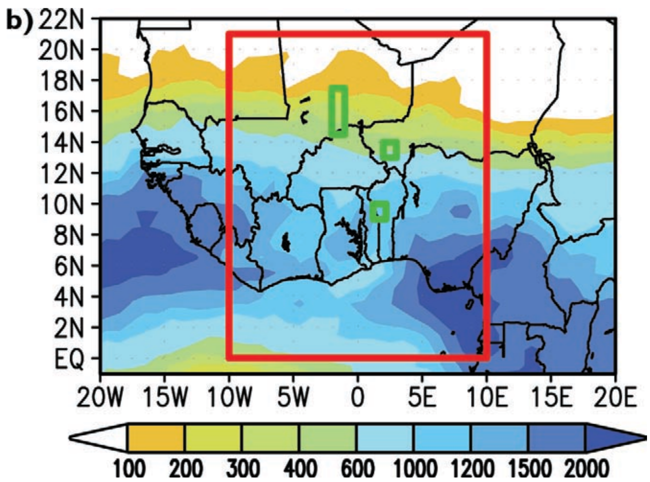


FIG. 1. (a) A satellite-based image of West African surface albedo [source: European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT); www.eumetsat.int/HOME/Main/Access_to_Data/Meteosat_Meteorological_Products/Product_List/SP_1125489019643, Pinty et al. (2005)] and (b) GPCP accumulated rainfall for the year 2000 (mm). The red rectangle corresponds to the zone retained for the AMMA-CROSS section, and the green rectangles corresponds to the mesoscale AMMA sites.

SPECIAL COLLECTION
West African Weather Prediction and Predictability

An Intercomparison of Simulated Rainfall and Evapotranspiration Associated with a Mesoscale Convective System over West Africa

FRANÇOISE GUICHARD,[a] NICOLE ASENCIO,[a] CHRISTOPHE PEUGEOT,[b] OLIVIER BOCK,[c] JEAN-LUC REDELSPERGER,[a] XUEFENG CUI,[d] MATTHEW GARVERT,[e] BENJAMIN LAMPTEY,[f] EMILIANO ORLANDI,[g] JULIA SANDER,[h] FEDERICO FIERLI,[i] MIGUEL ANGEL GAERTNER,[e] SARAH C. JONES,[h] JEAN-PHILIPPE LAFORE,[a] ANDREW MORSE,[d] MATHIEU NURET,[a] AARON BOONE,[a] GIANPAOLO BALSAMO,[j] PATRICIA DE ROSNAY,[j] BERTRAND DECHARME,[a] PHILIP P. HARRIS,[k] AND J.-C. BERGÈS[l]

[a] CNRM, CNRS, and Météo-France, Toulouse, France
[b] Hydrosciences, IRD, Montpellier, France
[c] LAREG/IGN, Marne-la-Vallée, France, and Service d'Aéronomie, CNRS and Université Paris, Paris, France
[d] University of Liverpool, Liverpool, United Kingdom
[e] Universidad de Castilla-La Mancha, Toledo, Spain
[f] National Center for Atmospheric Research, Boulder, Colorado
[g] University of Ferrara, Department of Physics, Ferrara, Italy, and Institute of Atmospheric Science and Climate, CNR, Bologna, Italy
[h] Institut für Meteorologie und Klimaforschung, Karlsruher Institut für Technologie, Karlsruhe, Germany
[i] Institute of Atmospheric Science and Climate, CNR, Bologna, Italy
[j] ECMWF, Reading, United Kingdom
[k] CEH, Wallingford, United Kingdom
[l] PRODIG, Université Paris 1, Paris, France

(Manuscript received 16 December 2008, in final form 7 September 2009)

ABSTRACT

An evaluation of precipitation and evapotranspiration simulated by mesoscale models is carried out within the African Monsoon Multidisciplinary Analysis (AMMA) program. Six models performed simulations of a mesoscale convective system (MCS) observed to cross part of West Africa in August 2005.

Initial and boundary conditions are found to significantly control the locations of rainfall at synoptic scales as simulated with either mesoscale or global models. When initialized and forced at their boundaries by the same analysis, all models forecast a westward-moving rainfall structure, as observed by satellite products. However, rainfall is also forecast at other locations where none was observed, and the nighttime northward propagation of rainfall is not well reproduced. There is a wide spread in the rainfall rates across simulations, but also among satellite products.

The range of simulated meridional fluctuations of evapotranspiration (E) appears reasonable, but E displays an overly strong zonal symmetry. Offline land surface modeling and surface energy budget considerations show that errors in the simulated E are not simply related to errors in the surface evaporative fraction, and involve the significant impact of cloud cover on the incoming surface shortwave flux.

The use of higher horizontal resolution (a few km) enhances the variability of precipitation, evapotranspiration, and precipitable water (PW) at the mesoscale. It also leads to a weakening of the daytime precipitation, less evapotranspiration, and smaller PW amounts. The simulated MCS propagates farther northward and somewhat faster within an overall drier atmosphere. These changes are associated with a strengthening of the links between PW and precipitation.

1. Introduction

At the present time, large-scale model simulations of rainfall over West Africa suffer from major weaknesses, in both numerical weather prediction (NWP) systems

Corresponding author address: Françoise Guichard, CNRM, CNRS/ Météo-France, 42 Ave. Coriolis, 31057 Toulouse CEDEX, France.
E-mail: francoise.guichard@meteo.fr

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Synoptic variability of the monsoon flux over West Africa prior to the onset

F. Couvreux,[a]* F. Guichard,[a] O. Bock,[b] B. Campistron,[c] J.-P. Lafore[a] and J.-L. Redelsperger[a]
[a]*CNRM-GAME, Météo-France and CNRS, Toulouse, France*
[b]*LATMOS, IPSL, Paris, France*
[c]*Laboratoire d'Aérologie, OMP, Toulouse, France*

ABSTRACT: This study investigates the synoptic variability of the monsoon flux during the establishment of the West African monsoon using observations and ECMWF analyses. It highlights variability at a 3–5-day time scale, characterized by successive northward excursions of the monsoon flux. Their characteristics and climatology prior to the monsoon onset are presented. These penetrations follow a maximum of intensity of the heat-low (extension and minimum of pressure) and are concomitant with an acceleration of the low-level meridional wind. Some penetrations are stationary whereas others propagate westward simultaneously with African easterly waves. Both types are investigated in more detail by case-studies. This enables us to distinguish the boundary-layer mechanisms involved in such penetrations. A similar conceptual model holds for both. It is argued that the heat-low dynamics is a major driver of these synoptic penetrations, pointing to the predominantly continental nature of this phenomenon. In turn, the heat-low can be partitioned by the penetrations. Horizontal advection is the main process that eventually accounts for these surges; nevertheless, turbulent mixing also plays a significant role by vertically redistributing moisture, and in more subtle ways by its contribution to the shaping of the low-level synoptic environment within which the surges take place. Copyright © 2009 Royal Meteorological Society

KEY WORDS West African monsoon; heat-low; moisture surge; pre-onset period

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1. Introduction

The West African monsoon (WAM) provides most of the rainfall over the Sahel. The establishment of the monsoon flux over West Africa has been explored by a few studies; in the following the monsoon flux is denoted as $\phi_q = \rho.v.q$, with ρ the air density, v the meridional wind and q the water vapour mixing ratio. Sultan and Janicot (2003) have identified a 'pre-onset' stage corresponding to the arrival of the intertropical discontinuity (ITD) at 15°N with a climatological date around 14 May (with a standard deviation of 9 days) and an 'onset' stage corresponding to an abrupt latitudinal shift of the intertropical convergence zone (ITCZ) from 5°N to 10°N with a climatological date around 24 June (with a standard deviation of 8 days). Several hypotheses have been proposed to account for the abruptness of the onset of the WAM, emphasizing the role of the ocean (Eltahir and Gong, 1996), or the role of the atmosphere dynamics or both; Sultan and Janicot (2003) propose that the intensification of the heat-low increases the cyclonic circulation leading to a larger influx of moisture from the ocean. They also indicate a possible role of orography that could enhance the low-level circulation by favouring a leeward trough. Ramel *et al.* (2006) also emphasize the role of the heat-low but through thermal forcing linked to surface albedo instead of a more dynamical forcing. Hagos and Cook (2007) show, using regional climate budget analysis, the important role of the boundary-layer circulation and supply of moisture in preconditioning the atmosphere. All these studies have focused on relatively large time-scales (>10 days) and spatial scales (>2°) and have systematically removed the higher-frequency signals from the different fields in their analyses. In this study, we investigate the higher-frequency fluctuations of the water vapour as revealed by observations and operational analyses during the period preceding the 'onset', corresponding to the phase of establishment of the monsoon flux.

The WAM is a complex system presenting many interacting processes (see fig. 1 of Redelsperger *et al.* (2002) and Peyrillé *et al.* (2007)). One of the elements of the WAM that has not been highlighted much in the literature is the monsoon flux. In particular, it plays a central role in the water vapour budget over the area. In West Africa, the water vapour variability eventually results from strongly interacting phenomena such as moist convection, wave activity, dry intrusions and monsoon flux. Here, we focus on the variability in the low levels of the atmosphere and at synoptic time-scale and therefore investigate the variability of water vapour due to the monsoon flux.

Only a few studies have focused on the variability of the water vapour and of the monsoon flux over

*Correspondence to: F. Couvreux, CNRM-GAME, Météo-France and CNRS, 42 avenue G. Coriolis, 31057 Toulouse, France.
E-mail: fleur.couvreux@meteo.fr

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Editorial
Introduction to the AMMA Special Issue on 'Advances in understanding atmospheric processes over West Africa through the AMMA field campaign'

J.-P. Lafore,[a]* C. Flamant,[b] V. Giraud,[c] F. Guichard,[a] P. Knippertz,[d] J.-F. Mahfouf,[a] P. Mascart[e] and E.R. Williams[f]

[a] *CNRM-GAME, Météo-France and CNRS, Toulouse, France*
[b] *LATMOS, CNRS and Université Pierre et Marie Curie, Paris, France*
[c] *LaMP, Clermont Ferrand, France*
[d] *University of Leeds, UK*
[e] *Laboratoire d'Aérologie, CNRS et Université de Toulouse, France*
[f] *Parsons Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*

1. Introduction

African Monsoon Multidisciplinary Analysis (AMMA) is an international project to improve our knowledge and understanding of the West African monsoon (WAM), as well as the environmental and socio-economic impacts of its variability (Redelsperger *et al.*, 2006). A specificity of AMMA is its multi-scale and multi-component approach to understanding and forecasting the WAM variability and its response to the current climate change. A key motivation of AMMA is that basic processes involved in the WAM system are insufficiently documented and understood. In order to achieve this goal, AMMA relies on the largest and most expensive field programme ever attempted in Africa as detailed in the first paper of this Special Issue by Lebel *et al.* (2010). The heavily instrumented Special Observation Periods (SOPs) occurred in 2006. Subsequent years have been dedicated to processing and scientific exploitation of this unique dataset documenting all components of the WAM system (atmosphere, surface, ocean, chemistry and aerosols) from the regional to the local scales. This focus on process studies constitutes an important step paving the way towards analyses of the couplings between the different WAM components, integrating all new knowledge on processes to understand the whole WAM system. Ultimately an improved modelling of the WAM variability will be achieved by using better parametrizations that include our new knowledge of processes.

Three years after the SOP, this Special Issue (SI) gathers a selection of 29 papers on the first results from the AMMA observing period for atmospheric processes. It aims at demonstrating the enormous progress we have made in the documentation and understanding of the atmospheric processes involved in the WAM system including some studies addressing the coupling of the atmosphere with the surface and the ocean. Nevertheless it is not possible to cover the wealth of studies performed in such a huge multidisciplinary project in one single SI. Hence, we refer the interested reader to the half dozen AMMA SIs that have already been published or are to be published, focussing on atmospheric chemistry ('AMMA tropospheric chemistry and aerosols' in *Atmospheric Chemistry and Physics*), hydrology ('Surface processes and water cycle in West Africa, studied from the AMMA-observing system' in the *Journal of Hydrology*), agriculture and adaptation ('Climate variability and rural adaptation in the Sahel' in *Cahiers Agricultures*), forecasting ('West African weather prediction and predictability' in *Weather and Forecasting*), climate ('West African climate' *in Climate Dynamics)* and the NASA AMMA campaign ('TCSP NAMMA' in the *Journal of Atmospheric Sciences*).

To guide the readers of this SI, this short introduction paper first presents a conceptual WAM model and highlights its key features (section 2). It then summarizes some major results of this issue (section 3).

2. Basic WAM conceptual model and its key features

Figure 1 provides a schematic three-dimensional view of the WAM system, highlighting some of its key features. First it is important to recall that the WAM is a coupled atmosphere–ocean–land system characterized by summer rainfall over the continent and winter drought. Indeed the thermal contrast between the hot African continent in summer and the cooler surrounding oceans (Atlantic and Mediterranean Sea) and their evolution are the primary driving mechanisms for WAM seasonal migration over the continent. In particular in spring, the cooling in the Gulf of Guinea by the establishment of

*Correspondence to: J.-P. Lafore, CNRM-GAME, Météo-France and CNRS, 42 avenue G. Coriolis, 31057 Toulouse, France.
E-mail: jean-philippe.lafore@meteo.fr

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The large-scale water cycle of the West African monsoon

O. Bock,[1,2]* F. Guichard,[3] R. Meynadier,[2] S. Gervois,[2] A. Agustí-Panareda,[4] A. Beljaars,[4] A. Boone,[3] M. Nuret,[3] J.-L. Redelsperger[3] and P. Roucou[5]

[1] *LAREG, IGN, Marne-la-Vallée, France*
[2] *LATMOS, CNRS, Université de Paris 6, Paris, France*
[3] *GAME-CNRM, CNRS, Météo-France, Toulouse, France*
[4] *ECMWF, Reading, UK*
[5] *CRC, CNRS, Université Dijon, Dijon, France*

**Correspondence to:*
O. Bock, Laboratoire de Recherche en Geodesie, Institut Geographique National, ENSG – Cite Descartes, 6-8 Avenue Blaise Pascal, Champs sur Marne, F77455 Marne-la-Vallée cedex 2, France.
E-mail: Olivier.Bock@ign.fr

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Abstract

The vertically integrated water budget of West Africa is investigated with a hybrid dataset based on observational and modelling products elaborated by the African Monsoon Multidisciplinary Analyses (AMMA) and with several numerical weather prediction (NWP) products including the European Centre for Medium-Range Weather Forecasts (ECMWF) AMMA reanalysis. Seasonal and intraseasonal variations are quantified over the period 2002–2007. Links between the budget terms are analyzed regionally, from the Guinean coast to the Sahel zone. Water budgets from the NWP systems are intercompared and evaluated against the hybrid dataset. Large deficiencies are evidenced in all the NWP products. Hypotheses are proposed about their origins and several improvements are foreseen. Copyright © 2010 Royal Meteorological Society

Keywords: AMMA; water budget; GPS; numerical weather prediction; West African monsoon; water cycle

1. Introduction

The large-scale water cycle of West Africa results from the interplay of various coupled ocean–atmosphere–land surface processes. The identification of the mechanisms involved and the scales at which they operate is a major objective of the African Monsoon Multidisciplinary Analyses (AMMA) (Redelsperger *et al.*, 2006). Before the AMMA, only a few studies focused specifically on the West African monsoon (WAM) water cycle. These studies satisfactorily revealed several key elements determining the seasonal cycle of precipitation and the water cycle of West Africa, such as the role of moisture transported by the southwesterly low-level monsoon flow and the mid-level African easterly jet (Cadet and Nnoli, 1987; Nicholson *et al.*, 1997; Fontaine *et al.*, 2003). Synoptic variability was also evidenced in the moisture fluxes at space- and timescales corresponding to African easterly waves (Cadet and Nnoli, 1987). However, only a few studies focused specifically on regional-scale water budgets (Brubaker *et al.*, 1993; Gong and Eltahir, 1996). Moreover, very contrasting results were found about the mechanisms involved at the seasonal and multi-annual timescales. A major reason for this lack of consensus is the variety and composite nature of data sources used. Among the different budget terms used in these studies, evapotranspiration appears as the most uncertain (Meynadier *et al.*, 2010a). Furthermore, a few other key timescales were almost not addressed so far (e.g. the diurnal cycle and intraseasonal variability).

Numerical weather prediction (NWP) products have been often used for computing the atmospheric part of the water budget at global and regional scales and quantifying variability at intraseasonal to interannual timescales (Trenberth and Guillemot, 1995; Roads *et al.*, 2002; Fontaine *et al.*, 2003). However, NWP products rely heavily on physical parameterizations, especially in the Tropics, and on observational data. In recent years, new precipitation products and improved NWP model reanalyses have become available. However, overall, an unprecedented experimental and modelling effort was realized during the AMMA. This was centred on 2006 with the Special Observing Period (SOP), but many observing networks operated in enhanced mode from 2005 to 2007 and beyond.

This paper gives an overview of the large-scale continental water cycle studies conducted in the AMMA. It covers mainly the intraseasonal to interannual timescales of the atmospheric water budget using two different approaches. A hybrid dataset was developed by Meynadier *et al.* (2010a), which benefited from the AMMA Land surface Model Intercomparison Project (ALMIP) (Boone *et al.*, 2009). This approach provides an advanced, comprehensive atmospheric water budget, including evapotranspiration, rainfall, atmospheric moisture flux convergence, together with other surface fluxes, such as runoff, soil moisture tendency and net radiation. In the second approach, several NWP model reanalyses have been used and intercompared with respect to the water budget. Given that the radiosondes in Africa had large humidity biases (Bock *et al.*, 2007,

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Atmospheric Science Letters

in press

Meso-scale water cycle within the West African Monsoon

C. Peugeot[1] (*), F. Guichard[2], O. Bock[3], D. Bouniol[2], M. Chong[4], A. Boone[2], B. Cappelaere[1], M. Gosset[5], L. Besson[6], Y. Lemaître[6], L. Séguis[1], A. Zannou[7], S. Galle[5], J.-L. Redelsperger[2].

(1) HSM, France;
(2) CNRM-GAME, Toulouse, France
(3) LAREG/IGN, Marne-la-Vallée, France
(4) LA, Université de Toulouse and CNRS, Toulouse, France
(5) LTHE, Grenoble, France
(6) LATMOS, Paris, France
(7) Direction Générale de l'Eau, Cotonou, Benin

(*) corresponding author: Dr. Christophe Peugeot, HydroSciences Montpellier, Université Montpellier II, CC-MSE, place Eugène Bataillon, 34905 Montpellier cedex, France

Email: christophe.peugeot@ird.fr

Abstract

We review the main studies on meso-scale water cycle from the African Monsoon Multidisciplinary Analysis •AMMA project. The estimations of precipitation and evapotranspiration, which are the coupling terms between the atmosphere and the surface water cycles, are addressed. Advances in the evaluation of the various components of atmospheric and surface water budgets are reported, and the yearly surface budgets for the Benin and Niger AMMA meso-scales sites are given as examples. The major outcomes and limitations of atmosphere-surface model coupling exercises are also reported. The paper concludes with suggestions on the research directions on which the community should make future efforts.
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Keywords: meso-scale; water cycle; water budget; atmosphere; land surface

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in revision

New Perspectives on Land-Atmosphere Feedbacks from the African Monsoon Multidisciplinary Analysis (AMMA)

Christopher M. Taylor[1], Douglas J. Parker[2], Norbert Kalthoff[3], Miguel Angel Gaertner[4], Nathalie Philippon[5], Sophie Bastin[6], Phil P. Harris[1], Aaron Boone[7], Françoise Guichard[7], Anna Agusti-Panareda[8], Marina Baldi[9], Paolina Cerlini[10], Luc Descroix[11], Herve Douville[7], Cyrille Flamant[6], Jean-Yves Grandpeix[12], Jan Polcher[12],

(1) Centre for Ecology and Hydrology, Wallingford, Oxfordshire, OX10 8BB, U.K.
(2) School of Earth and Environment, University of Leeds, U.K.
(3) Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany
(4) UCLM, Toledo, Spain
(5) University of Bourgogne, Dijon, France.
(6) CNRS/INSU, LATMOS/IPSL, UPMC, Paris, France
(7) CNRM, (CNRS and Météo-France), Toulouse, France
(8) European Centre for Medium-Range Weather Forecasts, Reading, UK
(9) Institute of Biometeorology, Ibimet-CNR, Via Taurini 19 - 00185 Rome, Italy
(10) CRC/UniPg, 1 Piazza Università, Perugia, Italy
(11) IRD, Niamey
(12) LMD/IPSL, CNRS, Paris, France

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Corresponding Author: Christopher Taylor, Centre for Ecology and Hydrology, Wallingford, Oxfordshire, OX10 8BB, U.K. email: cmt@ceh.ac.uk, tel: +44 1491 692354, fax: +44 1491 692424.

Short title: Land-Atmosphere Feedbacks in AMMA

Abstract

Research into land-atmosphere coupling within AMMA has highlighted the atmospheric impact of soil moisture on space scales of 5 km upwards and time scales of several days. Observational and modelling studies have shown how antecedent rainfall patterns affect new storms in the Sahel. The land feedback operates through various mechanisms, including a direct link to afternoon storm initiation from surface-induced mesoscale circulations, and indirectly via large-scale moisture transport in the nocturnal monsoon. The results suggest potential for significant improvements in weather forecasting through assimilation of satellite data. Intriguing questions remain about the importance of vegetation memory on seasonal-interannual scales.

Keywords

Soil moisture   Convection   Planetary Boundary Layer

Atmospheric Science Letters

in revision

Contrasted land surface processes along a West African rainfall gradient

Séguis, L.[1] (*), Boulain, N.(1), Cappelaere, B.(1),Favreau, G.(1), Galle, S.(2), Hiernaux, P.(3), Mougin, É.(3), Peugeot, C.(1), Ramier, D.(1), Seghieri, J.(1), B., Cohard, J.M.(2), Demarez V.(4), Demarty, J.(1), Descroix, L.(2), Descloitres, M.(2), Grippa M.(3), Guichard F.(5), Guyot, A.(2), S., Kamagaté, B.(6), Kergoat L.(3), Lebel, T.(2), Le Dantec V.(4), Le Lay, M.(7), Massuel, S., Timouk, F.(4), Trichon ,V.(8)

(1) HSM, IRD, France
(2) LTHE, Grenoble, France
(3) LMTG, Toulouse, France
(4) CESBIO, Toulouse, France
(5) CNRM-GAME, Toulouse, France
(6) Sciences et Gestion de l Environnement, Abidjan, Côte d Ivoire
(7) EDF-DTG, Grenoble, France
(8) ECOLAB, Toulouse, France

(*) corresponding author: Dr. Luc Séguis, HydroSciences Montpellier, Université Montpellier II, CC-MSE, place Eugène Bataillon, 34905 Montpellier cedex, France
Email: luc.seguis@ird.fr

Abstract

Distributed along a rainfall gradient from Sudanian to Sahelian climate, land surface observations on the sites of the Amma-Catch observatory were enhanced during the Amma experiment. During the rainy season, latent heat flux supplants the sensible heat flux. In Sahel, Hortonian runoff in relation with the spatial infiltration capacity distribution is the motor of the lateral water redistribution which governs the water budget. In the Sudanian site, surface water resource depends on recharge of seasonal shallow groundwaters. These hydrological functioning schemes provide explanations for the historical and contrasted evolution of water resources between Sahelian and Sudanian areas.

Keywords

Energy fluxes, Hortonian runoff, shallow groundwater, Sahel, Sudanian climate, water resources

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in revision

Progress in understanding of weather systems in West Africa

J.-P. Lafore[a*], C. Flamant[b], F. Guichard[a], D. J. Parker[c], D. Bouniol[a], A. Fink[d], V. Giraud[e†], M. Gosset[f], N. Hall[g], H. Höller[h], S. C. Jones[i], A. Protat[j], R. Roca[k], F. Roux[l], F. Saïd[l], C. Thorncroft[m]

[a]*CNRM-GAME, Météo-France and CNRS, Toulouse, France*
[b]*LATMOS, CNRS and Université Pierre et Marie Curie, Paris, France*
[c]*University of Leeds, UK*
[d]*Koeln University, Germany*
[e]*LaMP, Université Blaise Pascal and CNRS, Clermont-Ferrand, France*
[f]*LTHE, IRD, France*
[g]*LEGOS, CNRS, CNES, IRD and Université de Toulouse, France*
[h]*DLR, Germany*
[i]*Karlsruhe Institute of Technology, Karlsruhe, Germany*
[j]*BMRC, Melbourne, Australia*
[k]*LMD, CNRS, Ecole Normale Supérieure, Ecole Polytechnique and Université Pierre et Marie Curie, Paris, France*
[l]*LA, Université de Toulouse and CNRS, Toulouse, France*
[m]*State University of New York at Albany, New York, USA*
[†] Deceased 2009

Abstract

The major advances achieved during AMMA in our physical understanding of the West African Monsoon (WAM) system are reviewed. Recent research provides an advanced understanding of key WAM features. The Saharan Heat Low, the interactions of the monsoon flow with the surface and the reversed flow above all play a more important role than previously assumed. In addition to enhancing our understanding of the WAM meridional structure, recent studies also emphasize the significance of Central and East Africa. They also suggest strong interactions between the WAM and midlatitudes.

Keywords

African monsoon, Heat Low, African Easterly Jet, Convection, dry intrusions, tropical-extratropical interactions

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in press

Modeling the West African climate system: systematic errors and future steps.

PM Ruti[1], J E Williams[2], F Hourdin[3], F Guichard[4], A Boone[5], P Van Velthoven[2], F Favot[4], I Musat[3], M Rumukkainen[6], M Domínguez[7], M Á Gaertner[7], JP Lafore[5], T Losada[8], MB Rodriguez de Fonseca[8], J Polcher[3], F Giorgi[9], Y Xue[10], I Bouarar[3], K.Law[3], B. Josse[4], B. Barret[4], X. Yang[11], C Mari[3], AK Traore[12]*

1. *ENEA, Roma, Italy*
2. *KNMI, Netherlands*
3. *LMD, France.*
4. *CNRS-MF, Toulouse, France*
5. *CNRM-MF, Toulouse, France*
6. *SMHI, Rossby Center*
7. *Universidad de Castilla-La Mancha (UCLM), Toledo, Spain.*
8. *Universidad Complutense de Madrid*
9. *ICTP, Italy*
10. *UCLA, US.*
11. *Centre for Atmospheric Science and Dept. of Chemistry, University of Cambridge*
12. *LPAOSF, UCAD, Dakar, Senegal*

**Corresponding author address : Dr Paolo M Ruti, ENEA, Climate section, SP91, Via Anguillarese 301, 00060 Roma, Italy. E-mail: paolo.ruti@enea.it*

Abstract

We review the AMMA model inter-comparison activities for West Africa. The Model Intercomparison Project is an evaluation exercise of how global and regional atmospheric models represent seasonal and intra-seasonal variations of the climate and rainfall over the Sahel. The Land surface Model Inter-comparison Project in turn focuses on modelling critical land surface processes over West Africa and on their link with the atmosphere. The CHEmistry Model Intercomparison Project is a comparison of the tropospheric composition as simulated by a number of Chemical Transport Models and Chemistry-Climate Models. We highlight the main model limitations and provide recommendations for future development.

Keywords

Model audit uncertainties, Systematic errors, African Monsoon

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Coupling between the Atlantic Cold Tongue and the African monsoon in boreal Spring and Summer

Guy Caniaux, Hervé Giordani, Jean-Luc Redelsperger, Françoise Guichard

CNRM/GAME (Météo-France/CNRS, URA 1357), Toulouse, France

Erica Key

LDEO, Columbia University, U.S.A.

Malick Wade

CNRM/GAME (Météo-France/CNRS, URA 1357), Toulouse, France
LPAOSF, Dakar, Senegal

Abstract

The formation of the Atlantic Cold Tongue (ACT) is the dominant seasonal sea surface temperature signal in the eastern equatorial Atlantic (EEA). A comprehensive analysis of variability in its spatial extent, temperature and onset is presented. The physical mechanisms which initiate ACT onset, as well as the feedbacks from the ACT to the maritime boundary layer, and how the ACT influences the onset of the West African Monsoon (WAM), are also discussed.

In this paper, we argue that in the EEA, the air-sea coupling between the ACT and the WAM occurs in two phases: from March to mid-June, the ACT results from the intensification of the southeastern trades associated with the St. Helena Anticyclone. Steering of surface winds by the basin shape of the Gulf of Guinea (GG) imparts optimal wind stress for generating the maximum upwelling south of the equator. During the second phase (mid-June to August), wind speeds north of the equator increase as a result of significant surface heat flux gradients produced by the differential cooling between the ACT and the tropical waters circulating in the GG. It is anticipated that the atmospheric divergence induced at low-levels north of the equator reduces convection over the GG and that increased northward winds shift convection over land. Correlations between the ACT and the WAM onset dates over the last 27 years, measure as much as 0.8. This suggests that the ACT plays a key role in the WAM onset.

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West African Monsoon water cycle: 1. A hybrid water budget data set

R. Meynadier,[1] O. Bock,[1,2] F. Guichard,[3] A. Boone,[3] P. Roucou,[4] and J.-L. Redelsperger[3]

Received 22 January 2010; revised 22 April 2010; accepted 26 April 2010; published 1 October 2010.

[1] This study investigates the West African Monsoon water cycle with the help of a new hybrid water budget data set developed within the framework of the African Monsoon Multidisciplinary Analyses. Surface water and energy fluxes are estimated from an ensemble of land surface model simulations forced with elaborate precipitation and radiation products derived from satellite observations, while precipitable water tendencies are estimated from numerical weather prediction analyses. Vertically integrated atmospheric moisture flux convergence is estimated as a residual. This approach provides an advanced, comprehensive atmospheric water budget, including evapotranspiration, rainfall, and atmospheric moisture flux convergence, together with other surface fluxes such as runoff and net radiation. The annual mean and the seasonal cycle of the atmospheric water budget are presented and the couplings between budget terms are discussed for three climatologically distinct latitudinal bands between 6°N and 20°N. West Africa is shown to be alternatively a net source and sink region of atmospheric moisture, depending on the season (a source during the dry season and a sink during the wet season). Several limiting and controlling factors of the regional water cycle are highlighted, suggesting strong sensitivity to atmospheric dynamics and surface radiation. Some insight is also given into the underlying smaller-scale processes. The relationship between evapotranspiration and precipitation is shown to be very different between the Sahel and the regions more to the south and partly controlled by net surface radiation. Strong correlations are found between precipitation and moisture flux convergence over the whole region from daily to interannual time scales. Causality is also established between monthly mean anomalies. Hence, precipitation anomalies are preceded by moisture flux convergence anomalies and followed by moisture flux divergence and evapotranspiration anomalies. The results are discussed in comparison to other studies.

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1. Introduction

[2] The water cycle is a major component of the global climate system [*Peixoto and Oort*, 1983]. Understanding the water cycle of the West African Monsoon (WAM) system and its variability in the context of climate change is a major objective of African Monsoon Multidisciplinary Analyses (AMMA [*Redelsperger et al.*, 2006]). Rainfall is indeed of crucial importance in vulnerable regions such as the Sahel which experienced severe droughts since the 1970s and increased interannual variability in observed rainfall [*Nicholson*, 1981; *Le Barbé et al.*, 2002]. Seasonal rainfall over the Sahel is mostly contributed by mesoscale convective systems (MCSs). In terms of water budget, about 90% of seasonal rainfall is produced by a few (~12%) large organized MCSs [*Lebel et al.*, 1997; *Mathon et al.*, 2002]. Numerous synoptic meteorological factors modulate the occurrence and variability of such organized MCSs [*Barnes and Sieckman*, 1984; *Laing and Fritsch*, 1993; *Diedhiou et al.*, 1999; *Redelsperger et al.*, 2002; *Diongue et al.*, 2002; *Fink and Reiner*, 2003]. At intraseasonal scale, convective activity is modulated by large-scale dynamics and global-scale disturbances [*Sultan et al.*, 2003; *Matthews*, 2004; *Mounier et al.*, 2008], and at interannual scale to multidecadal time scales, links have been established between rainfall variability and upper air circulation [*Kidson*, 1977; *Lamb*, 1983; *Fontaine et al.*, 1995; *Long et al.*, 2000; *Grist and Nicholson*, 2001]. In addition, the significance of land-atmosphere interactions [*Charney*, 1975; *Taylor and Lebel*, 1998; *Zeng et al.*, 1999; *Douville et al.*, 2001; *Koster et al.*, 2004; *Taylor*, 2008], and ocean-atmosphere interactions has been identified across a range of space and time scales [*Rowell et al.*, 1995; *Janicot et al.*, 1998; *Vizy and Cook*, 2001; *Giannini et al.*, 2003].

[1]LATMOS, Université Pierre et Marie Curie, CNRS, Paris, France.
[2]Also at LAREG, IGN, Marne-la-Vallee, France.
[3]GAME-CNRM, CNRS, Météo-France, Toulouse, France.
[4]CRC, Université de Bourgogne, CNRS, Dijon, France.

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West African Monsoon water cycle: 2. Assessment of numerical weather prediction water budgets

R. Meynadier,[1] O. Bock,[1,2] S. Gervois,[1] F. Guichard,[3] J.-L. Redelsperger,[3] A. Agustí-Panareda,[4] and A. Beljaars[4]

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[1] Water budgets from European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA)-Interim and National Centers for Environmental Prediction (NCEP) Reanalysis I and II are intercompared and compared to GPS precipitable water and to the 6 year hybrid budget data set described in part 1 of this study. Deficiencies are evidenced in the reanalyses which are most pronounced over the Sahel. Results from operational models (ECMWF Integrated Forecast System, NCEP Global Forecast System, and ARPEGE-Tropiques) and the special ECMWF African Monsoon Multidisciplinary Analyses reanalysis confirm and help understanding these findings. A bias (~1–2 mm d^{-1}) in precipitation and evapotranspiration leads to an unrealistic view of West Africa as a moisture source during the summer. North of the rainband (13°N–16°N), moisture flux convergence (MFC) shows a minimum in the NCEP models and divergence in the ECMWF models not consistent with the hybrid data set. This feature, added to presence of a deep layer of northerly dry air advected at midlevels (800–400 hPa), is thought to block the development of deep convection in the models and the northward propagation of the monsoonal rainband. The northerly flow is part of a shallow meridional circulation that is driven by the Saharan heat low. This circulation appears too strong in some of the models, a possible consequence of the too-approximate representation of physical processes and land surface properties over the Sahel. In most of the models, evapotranspiration shows poor connection with precipitation. This is linked with large analysis increments in precipitable water, soil moisture, and MFC. Despite the large biases affecting the water budget components in the models, temporal variations (seasonal and interannual) might nevertheless be recovered with reasonable accuracy.

Citation: Meynadier, R., O. Bock, S. Gervois, F. Guichard, J.-L. Redelsperger, A. Agustí-Panareda, and A. Beljaars (2010), West African Monsoon water cycle: 2. Assessment of numerical weather prediction water budgets, *J. Geophys. Res.*, *115*, D19107, doi:10.1029/2010JD013919.

1. Introduction

[2] Numerical weather prediction (NWP) models are often used for computing the atmospheric part of the water budget at global and regional scales [*Higgins et al.*, 1996; *Trenberth and Guillemot*, 1998; *Roads et al.*, 2002] but few studies consider specifically West Africa. Several past studies have pointed to significant deficiencies in the hydrological cycle represented in NWP model analyses and reanalyses [*Kanamitsu and Saha*, 1996; *Trenberth and Guillemot*, 1995, 1998; *Andersson et al.*, 2005; *Drusch and Viterbo*, 2007]. The deficiencies in NWP products can be due to a combination of deficiencies in physical parameterizations, in the assimilation schemes, and lack of or biases in observations. Radiosonde observations are a fundamental component of the upper air observing system since they are used as a reference to adjust biases in all the other observing systems [*Simmons et al.*, 2006]. Unfortunately, the Tropics are generally poorly covered with observational networks. Especially, the density of radiosonde stations in Africa is very sparse [*Parker et al.*, 2008]. Moreover, biases in these observations have been diagnosed [*Bock et al.*, 2007, 2008] and their impact on NWP products has been evidenced [*Bock and Nuret*, 2009; *Agustí-Panareda et al.*, 2009], It is thus not surprising that poor consensus emerged from the past water cycle studies over West Africa which used either NWP products or directly radiosonde data [*Lamb*, 1983; *Cadet and Nnoli*, 1987; *Brubaker et al.*, 1993; *Fontaine et al.*, 2003; *Bielli and Roca*, 2009].

[3] During the African Monsoon Multidisciplinary Analyses (AMMA) Special Observing Period (SOP) in summer 2006, many extra (conventional and research) observations were collected over West Africa [*Lebel et al.*, 2009]. A large number of this data was assimilated with operational NWP

[1]LATMOS, Université Pierre et Marie Curie, CNRS, Paris, France.
[2]Also at LAREG, IGN, Marne-la-Vallee, France.
[3]GAME–CNRM, CNRS, Météo-France, Toulouse, France.
[4]ECMWF, Reading, UK.

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The ECMWF re-analysis for the AMMA observational campaign

Anna Agustí-Panareda,[a]* Anton Beljaars,[a] Maike Ahlgrimm,[a] Gianpaolo Balsamo,[a] Olivier Bock,[b] Richard Forbes,[a] Anna Ghelli,[a] Françoise Guichard,[c] Martin Köhler,[a] Remi Meynadier,[b] and Jean-Jacques Morcrette[a]

[a] *ECMWF, Reading, UK*

[b] *LATMOS, CNRS–Univ. Paris VI, Paris, France*

[c] *CNRM, CNRS and Météo-France, Toulouse, France*

*Correspondence to: A. Agustí-Panareda, ECMWF, Shinfield Park, Reading, Berkshire, RG2 9AX, UK. E-mail: Anna.Agusti-Panareda@ecmwf.int

During the 2006 African Monsoon Multidisciplinary Analysis (AMMA) field experiment, an unprecedented number of soundings were performed in West Africa. However, due to technical problems many of these soundings did not reach the Global Telecommunication System and therefore they could not be included in the operational numerical weather prediction (NWP) analyses. This issue, together with the realization that there was a significant bias in the radiosonde humidity, led to the conclusion that a re-analysis effort was necessary. This re-analysis was performed at the European Centre for Medium-Range Weather Forecasts (ECMWF) spanning the wet monsoon season of 2006 from May–September. The key features of the ECMWF AMMA re-analysis are presented, including the use of a newer model version with improved physics, all the AMMA radiosonde data available from the AMMA database and a new radiosonde humidity bias-correction scheme. Data-impact experiments show that there is a benefit from these observations, but also highlight large model physics biases over the Sahel that cause a short-lived impact of the observations on the model forecast. The AMMA re-analysis is compared with independent observations to investigate the biases in the different parts of the physics. In the framework of the AMMA project, a hybrid dataset was developed to provide a best estimate of the different terms of the water cycle. This hybrid dataset is used to evaluate the improvement achieved from the use of extra AMMA observations and of a radiosonde humidity bias-correction scheme in the water cycle of the West African monsoon. Finally, future model developments that offer promising improvements in the water cycle are discussed. **Copyright © 2010 Royal Meteorological Society**

Key Words: West African monsoon; water cycle; energy budget; radiosonde

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1. Introduction

Defining the state of the atmosphere as an initial condition for forecasts is an important aspect of numerical weather prediction (NWP). NWP systems use a forecast model to propagate the state of the atmosphere in time and continuously feed in observations to obtain so-called analyses. A well-designed analysis system obtains an

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Observations of the Nocturnal Boundary Layer Associated with the West African Monsoon

CAROLINE L. BAIN*

Department of Earth System Science, University of California, Irvine, Irvine, California

DOUGLAS J. PARKER

School of Earth and Environment, University of Leeds, Leeds, United Kingdom

CHRISTOPHER M. TAYLOR

Centre for Ecology and Hydrology, Wallingford, United Kingdom

LAURENT KERGOAT

CESBIO, Toulouse, France

FRANÇOISE GUICHARD

CNRM-GAME (CNRS and Météo-France), Toulouse, France

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ABSTRACT

A set of nighttime tethered balloon and kite measurements from the central Sahel (15.2°N, 1.3°W) in August 2005 were acquired and analyzed. A composite of all the nights' data was produced using boundary layer height to normalize measured altitudes. The observations showed some typical characteristics of nocturnal boundary layer development, notably a strong inversion after sunset and the formation of a low-level nocturnal jet later in the night. On most nights, the sampled jet did not change direction significantly during the night.

The boundary layer thermodynamic structure displayed some variations from one night to the next. This was investigated using two contrasting case studies from the period. In one of these case studies (18 August 2005), the low-level wind direction changed significantly during the night. This change was captured well by two large-scale models, suggesting that the large-scale dynamics had a significant impact on boundary layer winds on this night. For both case studies, the models tended to underestimate near-surface wind speeds during the night, which is a feature that may lead to an underestimation of moisture flux northward by models.

1. Introduction

The West African monsoon is caused by the northward shift in the intertropical front during Northern Hemisphere summer months. The shift is a result of increased heating over the Sahara generating a heat low, simultaneous with cooling of the sea surface temperatures over the Gulf of Guinea, creating a pressure gradient between the cooler Atlantic coast of West Africa and the north (Sultan and Janicot 2003). The seasonal time scale of the monsoon is important for annual rainfall amounts, and the daily weather is influenced by the diurnal cycle of convection, which is reliant on monsoon and African Easterly Wave (AEW) processes for moisture supply.

Observation and model studies have documented the large-scale dynamics of the West African monsoon, the formation of the African easterly jet, and AEWs (e.g., Burpee 1972; Thorncroft and Hoskins 1994; Berry and Thorncroft 2005). Despite these efforts there are continuing issues associated with the modeling of the monsoon and the relationship between the monsoon and

* Current affiliation: Met Office, Exeter, Devon, United Kingdom.

Corresponding author address: Caroline Bain, Department of Earth System Science, University of California, Irvine, Irvine, CA 92697.
E-mail: caroline.bain@metoffice.gov.uk

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Understanding the daily cycle of evapotranspiration: a method to quantify the influence of forcings and feedbacks

Chiel C. van Heerwaarden * and Jordi Vilà-Guerau de Arellano
Meteorology and Air Quality Section, Wageningen University, The Netherlands

Amanda Gounou, Françoise Guichard and Fleur Couvreux
CNRM-GAME, Météo-France and CNRS, Toulouse, France

ABSTRACT

A method to analyze the daily cycle of evapotranspiration over land is presented. It quantifies the influence of external forcings, such as radiation and advection, and of internal feedbacks induced by boundary-layer, surface-layer and land surface processes on evapotranspiration. It consists of a budget equation for evapotranspiration that is derived by combining a time derivative of the Penman-Monteith equation with a mixed-layer model for the convective boundary-layer.
Measurements and model results of days in two contrasting locations are analyzed using the method: mid-latitudes (Cabauw, The Netherlands) and semi-arid (Niamey, Niger). The analysis shows that the time evolution of evapotranspiration is a complex interplay of forcings and feedbacks. Although evapotranspiration is initiated by radiation, it is significantly regulated by the atmospheric boundary-layer and the land surface throughout the day. Boundary-layer feedbacks enhance in both cases the evapotranspiration up to 20 W m^{-2} h^{-1}. However, in the case of Niamey this is offset by the land surface feedbacks, since the soil drying reaches -30 W m^{-2} h^{-1}. Remarkably, surface-layer feedbacks are of negligible importance in a fully coupled system.
Analysis of the boundary-layer feedbacks hints the existence of two regimes in this feedback depending on atmospheric temperature, with a gradual transition region in between the two. In the low-temperature regime specific humidity variations induced by evapotranspiration and dry-air entrainment have a strong impact on the evapotranspiration. In the high-temperature regime the impact of humidity variations is less pronounced and the effects of boundary-layer feedbacks are mostly determined by temperature variations.

1. Introduction

The exchange of water between the land surface and the atmosphere is an essential component of the hydrologic cycle. Previous studies have shown that this exchange, evapotranspiration, is closely coupled to the atmosphere (e.g. Jacobs and De Bruin 1992; Betts et al. 1996; Koster et al. 2004). To be able to make credible predictions about the water balance of the earth in future climates, it is therefore fundamental to understand the driving mechanisms behind evapotranspiration and the link between the land surface and the atmospheric boundary-layer (ABL).

Evapotranspiration and land-atmosphere interactions have been the subject of many studies. These studies cover a large spectrum of spatial and temporal scales and range from conceptual studies to realistic 3D modeling. Relevant examples of large-scale studies using complex models are Betts et al. (1996), who discussed the memory of soil moisture and its impact on precipitation over a longer period, or Koster et al. (2004) who used an ensemble of GCMs to investigate the response of precipitation to soil moisture change by locating the regions with the strongest land-atmosphere coupling.

Then there are studies discussing land-atmosphere coupling on a local scale. Studies as De Bruin (1983) and McNaughton and Spriggs (1986) were the first to study the land surface, ABL and free atmosphere as a coupled system. Their finding that the ABL dynamics have an important influence on the surface evaporation formed the basis for more advanced studies. These are, for instance, Brubaker and Entekhabi (1995, 1996) and Margulis and Entekhabi (2001), who made mathematical frameworks to quantify feedbacks in the coupled land-atmosphere system. Furthermore, Ek and Holtslag (2004) quantified the link between soil moisture, surface evapotranspiration and boundary-layer clouds. Recent studies discussing evapotranspiration from an atmospheric perspective are Santanello et al. (2007), who analyzed the existence of evaporation regimes as a function of soil moisture and atmospheric stability and Raupach (2000); van Heerwaarden

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Life cycle of a mesoscale circular gust front observed by a C-band Doppler radar in West Africa

Marie Lothon *(1),
Bernard Campistron (1), Michel Chong (1),
Fleur Couvreux (2), Françoise Guichard (2), Catherine Rio (2),
and Earle Williams (3)

(1) LABORATOIRE D'AEROLOGIE, UNIVERSITE DE TOULOUSE, CNRS, TOULOUSE, FRANCE
(2) METEO-FRANCE, CNRM/GAME/GMME/MOANA, CNRS, TOULOUSE, FRANCE
(3) DEPT. OF CIVIL & ENVIRONMENTAL ENGINEERING, MASSACHUSETTS INSTITUTE OF TECHNOLOGY, CAMBRIDGE, MA, USA

* Corresponding author address: Marie Lothon, Laboratoire d'Aérologie, Centre de Recherches Atmosphériques, 8 route de Lannemezan, 65300 Campistrous, France. E-mail: marie.lothon@aero.obs-mip.fr

ABSTRACT

On 10 July 2006, during the Special Observation Period (SOP) of the African Monsoon Multidisciplinary Analysis (AMMA) campaign, a small convective system initiated over Niamey and propagated westward in the vicinity of several instruments activated in the area, including the Massachusetts Institute Technology (MIT) C-Band Doppler radar and the Atmospheric Radiation Measurement (ARM) mobile Facility. The system started after a typical convective development of the planetary boundary layer (PBL). It grew and propagated within the scope of the radar range, so that its entire life cycle is documented, from the precluding shallow convection to its traveling gust front. The analysis of the observations during the transitions from organized dry convection to shallow convection and from shallow convection to deep convection lends support to the significant role played by surface temperature heterogeneities and boundary_layer processes in the initiation of deep convection in semi-arid conditions. The analysis of the system later in the day, its growth and propagation, and its associated density current allows us to estimate the wake available potential energy and demonstrate its capability to trigger deep convection itself. Given the quality and density of observations related to this case, and its typical and quasi-textbook characteristics, we consider this a prime case for the study of deep convection initiation and evolution, and for testing their parameterizations in single column models.