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Discussions

Should we use a simple or complex model for moisture recycling and atmospheric moisture tracking?

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Abstract

This paper compares three state-of-the-art atmospheric moisture tracking models. Such models are typically used to study the water component of coupled land and atmosphere models, in particular quantifying moisture recycling and the source-sink relations between evaporation and precipitation. However, there are several atmospheric moisture tracking methods being used in the literature, and depending on the level of aggregation, the assumptions made and the level of detail, the performance of these methods may differ substantially. In this paper, we compare three methods. The RCM-tag method uses highly accurate 3-D water tracking (including phase transitions) directly within a regional climate model (online), while the other two methods (WAM and 3D-T) use a posteriori (offline) water vapour tracking. The original version of WAM makes use of the well-mixed assumption, while 3D-T is a multi-layer model. The a posteriori models are faster and more flexible, but less accurate than online moisture tracking with RCM-tag. In order to evaluate the accuracy of the a posteriori models, we tagged evaporated water from Lake Volta in West Africa and traced it to where it precipitates. It is found that the strong wind shear in West Africa is the main cause of errors in the a posteriori models. The number of vertical layers and the initial release height of tagged water in the model are found to have the most significant influences on the results. With this knowledge small improvements were made to the a posteriori models. It appeared that expanding WAM to a 2 layer model, or a lower release height in 3D-T, led to significantly better results. Finally, we introduced a simple metric to assess wind shear globally and give recommendations about when to use which model. The “best” method, however, very much depends on the spatial extent of the research question as well as the available computational power.

1 Introduction

Studying where the rain comes from is of growing interest in the scientific community. In the beginning of the second half of the twentieth century several pioneer researchers were addressing this question (e.g. Benton, 1949; McDonald, 1962; Budyko, 1974; Molion, 1975). Many studies thereafter used simple bulk methods or conceptualizations of the hydrological cycle in order to estimate the amount of precipitation that recycled within a certain region (e.g. Lettau et al., 1979; Brubaker et al., 1993; Eltahir and Bras, 1996; Schär et al., 1999; Trenberth, 1999). The results obtained were however only a rough estimate over a large region and subject to several assumptions (Burde and Zangvil, 2001a,b; Fitzmaurice, 2007). Other studies have focused on finding the recycling along a streamline (Savenije, 1995a,b; Lintner et al., 2013; Schaefli et al., 2012), which added to the conceptual understanding of moisture feedback, but has not yet proven to provide reliable estimates in real-world cases. A completely different approach using stable isotopes of water: δ^{2}H, δ^{18}O and especially the corresponding d-excess value have been shown to be a good indicator for moisture recycling (e.g. Salati et al., 1979; Njitchoua et al., 1999; Henderson-Sellers et al., 2002; Pang et al., 2004; Tian et al., 2007; Froehlich et al., 2008; Liu et al., 2008). However, good temporal and spatially consistent data is generally not available, and additional meteorological observations are needed to pinpoint the origin of the water more accurately.

There also exist many studies that numerically track moisture (we used the term moisture in this paper for all possible phases of water) in the atmosphere. The first study, to our knowledge, that can be characterized as an atmospheric moisture tracking study is that of Koster et al. (1986), who used a water vapour tracing scheme in a coarse resolution GCM to estimate the origin of precipitation in several regions. In contrast to most bulk methods, atmospheric moisture tracking can determine the statistical distribution of moisture origin rather than merely the recycling rate over a large temporal and spatial scale.

Almost all recent studies addressing the origin of precipitation or fate of evaporation, use some sort of atmospheric moisture tracking model. Moisture tracking can be done either parallel to a climate or weather model run (e.g. Bosilovich and Schubert, 2002; Bosilovich and Chern, 2006; Sodemann et al., 2009; Goessling and Reick, 2012; Knoche and Kunstmann, 2013) or a posteriori with reanalysis data (e.g. Yoshimura et al., 2004; Dominguez et al., 2006; Dirmeyer and Brubaker, 2007; Bisselink and Dolman, 2008; van der Ent et al., 2010; Tuinenburg et al., 2012), operational analysis data (e.g. Stohl and James, 2005; Nieto et al., 2006; Sodemann et al., 2008; Gimeno et al., 2010; Spracklen et al., 2012) or output of a climate model run (e.g. Gangoiti et al., 2011; Goessling and Reick, 2011). Besides using different types of input, these models use significantly different moisture tracking methods (see Gimeno et al., 2012; van der Ent, 2012).

To date, consistent comparison studies of the state-of-the-art moisture tracking models are rare and the consequences of the different assumptions made are largely unknown. Noteworthy is, however, the study of Goessling and Reick (2012), which compared continental precipitation recycling ratios and moisture origins obtained by either using 2-D or 3-D water vapour tracers within the ECHAM6 general circulation model (GCM). They concluded that in general the 2-D approximation is less appropriate in the tropics where it leads to substantial errors. This paper is to a certain extent similar to the approach of Goessling and Reick, but here we focus on the more widely applied a posteriori models. Our aim is to: (1) identify the different characteristics of atmospheric moisture tracking models, (2) quantify the differences in a particular case study, (3) try to explain these differences, (4) improve on existing models, and (5) translate our findings into recommendations for future atmospheric moisture tracking studies.

Although atmospheric moisture tracking as a research field is partly driven by pure curiosity, already in early days researchers have considered the results important for land and water management (e.g. Molion, 1975; Lettau et al., 1979; Savenije, 1995a,b) and also more recent studies generally underline the management implications of their results (e.g. Kunstmann and Jung, 2007; Dominguez and Kumar, 2008; Hossain et al., 2009; Jódar et al., 2010; Goessling and Reick, 2011; Bagley et al., 2012; Keys et al., 2012; Tuinenburg et al., 2012; van der Ent et al., 2012; Wei et al., 2012). In order to use the results of moisture tracking studies for land and water management practices it is important to better understand the effect that the use of different models may have on the outcome.

2 Model characteristics

The basic equation for all atmospheric moisture tracking models is based on the mass balance of a water mass $S(t, x, y, z)$, of which a certain part is tagged S_g:

$$\frac{\partial S_g}{\partial t} = \frac{\partial \left(S_g u\right)}{\partial x} + \frac{\partial \left(S_g v\right)}{\partial y} + \frac{\partial \left(S_g w\right)}{\partial z} + E_g - P_g + \alpha_g, \tag{1}$$

where g stands for the source area from which water gets tagged, u, v and w the wind components in x, y and z direction (Note: they can change sign), E is evaporation, P is precipitation and α is a residual. Most models only consider water vapour, i.e. $S = S_{\text{vapour}}$, and neglect the liquid and ice water content in an atmospheric column. Moreover, several models only consider horizontal transport, i.e. $\frac{\partial (S_g w)}{\partial z} = 0$. The vertical resolution in the tracing models ranges from only one layer to several tens of layers. For forward tracking of evaporation, it holds that $E_g = E$ if the considered water mass S is above the source region g and $E_g = 0$ if not. The manner in which evaporation is added to a tracing model depends on the mixing assumptions. It ranges from a moisture weighted injection over all model layers, to a release merely in the lowest model layers.

For precipitation and the (three) transport terms, it is generally assumed that their tagged fraction is proportional to the tagged moisture fraction at that location:

$$\frac{P_g}{P} = \frac{\frac{\partial(S_g\,u)}{\partial x}}{\frac{\partial(S\,u)}{\partial x}} = \frac{\frac{\partial(S_g\,v)}{\partial y}}{\frac{\partial(S\,v)}{\partial y}} = \frac{\frac{\partial(S_g\,w)}{\partial z}}{\frac{\partial(S\,w)}{\partial z}} = \frac{\frac{\partial S_g}{\partial t}}{\frac{\partial S}{\partial t}}. \qquad (2)$$

However, this assumption becomes weaker with less model layers, and if there is no information available on the layers from which precipitation falls. Often it is assumed that the precipitation is "well-mixed", i.e. moisture weighted from all model layers. The residual α in Eq. (1) can be caused by inconsistencies in the input: e.g. due to data-assimilation in reanalysis data, resolution upscaling, or model errors, e.g. due to interpolation, neglect of liquid water and ice, or the well-mixed assumptions. In order to close the (tagged) water balance, some Eulerian models (implicitly) assign a tagged value to the residual by e.g. considering the residual as a part of the precipitation (e.g. Goessling and Reick, 2011), or by assuming that $\frac{\partial S_g}{\partial t} / \frac{\partial S}{\partial t} = \frac{\alpha_g}{\alpha}$ (e.g. Yoshimura et al., 2004).

Lagrangian models generally do not consider the non-closure of the water balance, but theoretically it is possible to build it in. Also, models differ in the numerical scheme they use to solve Eq. (1). Finally, it should be noted that most models can also perform the tracing backward in time, making precipitation the source term and evaporation the sink term, with the exception of tracing models that run in parallel with a climate model, which do not allow for backtracking.

Besides uncertainties in the input data, which are independent from the tracking model used, we think that the main sources of error in a posteriori forward tracking models are: (1) insufficient number of vertical layers, (2) the moisture weighted well-mixed assumption when distributing evaporated moisture parcels over the vertical, (3) the moisture weighted well mixed assumption when parcels precipitate out of the atmosphere, and (4) the neglect of liquid water and ice. Note that a backtracking case would reverse simplifications 2 and 3.

In this study, we will look into the four error sources listed above by considering three different atmospheric moisture tracking models with three degrees of complexity (Table 1). The most complex model is RCM-tag (Knoche and Kunstmann, 2013). Where most other methods only consider transport of water vapour, RCM-tag considers all atmospheric processes, i.e. transport, horizontal diffusion as well as phase transitions. It should be noted that no subgrid scale cumulus parameterization is applied, of which Knoche and Kunstmann (2013) argue: “We assume that, with regard to moisture tagging modeling, an adequately consistent treatment by a cumulus parameterization scheme is hardly possible. Therefore, we do not apply any subgrid scale cumulus parameterization. Instead, we use model resolutions fine enough to capture the most important convection systems by grid-scale resolved model processes, and thus we calculate the relevant moisture transitions by the explicit scheme.” The tracing by RCM-tag as such can be considered “virtual reality”. Accuracy is the main advantage of this method, but on the other hand it is slow in computation and back-tracking is not possible.

The two other models are a posteriori water vapour tracing models, which means that they make use of input provided by climate models, reanalysis, gridded observed products or a combination thereof and consider water vapour only. The simplest model used is the Water Accounting Model (WAM) (van der Ent et al., 2010; van der Ent and Savenije, 2011; Keys et al., 2012), which reduces the tracing to a 2-D (x, y) problem, by computing the vertically integrated moisture fluxes. WAM excels in computation speed, but is expected to be less accurate in highly detailed studies. The next model considered is 3D-Trajectories (3D-T) (Tuinenburg et al., 2012), which is a modification of the quasi-isentropic back-trajectory (QIBT) method of Dirmeyer and Brubaker (1999, 2007), but additionally takes into account vertical wind speed. 3D-T tracks water parcels in a Lagrangian manner, which makes the time step choice less important than in WAM. Computation speed of 3D-T generally lies between WAM and RCM-tag, but is dependent on tagging source area (a larger area requires more tracer parcels) rather than the model domain only in WAM and RCM-tag.

Most atmospheric moisture tracking models used in the literature (e.g. Bosilovich and Schubert, 2002; Yoshimura et al., 2004; Dominguez et al., 2006; Dirmeyer and Brubaker, 2007; Gangoiti et al., 2011; Goessling and Reick, 2011) are essentially variations on the three models described in Table 1 (see Gimeno et al., 2012, for a review). Thus, also the complexity and the corresponding (dis)advantages in Tables 1 and 3 will lie somewhere between the models highlighted in these tables.

Furthermore, there are two other widely used and advanced Lagrangian models that are being used for atmospheric water tracking: FLEXPART (Stohl et al., 2005) and HYSPLIT (Draxler and Hess, 1998), which are distinctively different from the three models here, since FLEXPART and HYSPLIT only consider the net interaction with the surface ($P-E$), meaning that they cannot diagnose precipitation and evaporation separately. Nonetheless, these methods have been successfully applied in several recent studies (e.g. Nieto et al., 2006; Sodemann et al., 2008; Gimeno et al., 2010; Durkee et al., 2012), and for HYSPLIT there is even a web-based tool for moisture trajectory calculations (Draxler and Rolph, 2013).

3 Case study Lake Volta (West Africa)

3.1 Description

Our case study consist of the same case as studied by Knoche and Kunstmann (2013). This area is modelled with the Regional Climate Model MM5 (Grell et al., 1995) for two months: July and August 1998. The model domain (Fig. 1) is relatively flat, and the only noteworthy orographic features are the Togo Mountains (peaks of 300–1000 m), which are situated just East of the tagging source region (red rectangle in Fig. 1). Furthermore, Fig. 1 shows the wind vectors near the surface (i.e. at the lowest model level, Fig. 1a), and the wind vectors at the model level which corresponds approximately to 500 hPa or 5 km above sea level (Fig. 1b), for the period of August 1998. The wind near the surface brings in air from the ocean, while at 500 hPa the wind field is nearly geostrophic in westward direction. This system is thus to a high degree a sheared system, of which we found the interface generally to lie at approximately 800 hPa or 2 km a.s.l. (above sea level) (not shown).

Furthermore, Fig. 2 shows the evaporation and precipitation in the same month. The evaporation (Fig. 2a) is clearly highest at the places that receive most rain (Fig. 2b). Also, the actual Lake Volta grid cells (within the white rectangle) can easily be identified by their high evaporation rates. As can be seen in Fig. 2b, the coastal area experiences a small dry season and the precipitation maxima are found between 10° N and 15° N where the ITCZ is located (Pidwirny, 2006). Most of this precipitation is convective and believed to have a strong coupling with the soil-moisture (e.g. Koster et al., 2004; van den Hurk and van Meijgaard, 2009; Taylor et al., 2010), which is also evident from short length scales of local recycling (van der Ent and Savenije, 2011).

With three different models (Table 1), the evaporation from a small area (4×10^4 km^2) including Lake Volta in Ghana (red square, Fig. 1) is tagged, and subsequently traced until it leaves the model domain or precipitates. The grid cell size used is 18 km × 18 km (at the equator), with 33 vertical model layers. The RCM-tag run is performed directly in parallel with MM5. The time step used is 50 s. The two other models use hourly MM5 output data as their input data. In both WAM and 3D-T these data are downscaled to 6 min. The residuals (see Eq. 1) were found to be very small with WAM (not shown), and were not given a tagging component. The results focus on August 1998 only, but with the initial conditions (i.e. tagged water) given by the July run.

3.2 Results

This section discusses the results of atmospheric moisture tracking with 3 different models. As RCM-tag includes all the processes that are also present in the normal MM5 scheme, we assume that the results from the RCM-tag are virtual reality. First, we discuss these results and then we compare the results of the a posteriori moisture tracking methods WAM and 3D-T with the results of RCM-tag. A summary of the results is presented in Table 2.

3.2.1 RCM-tag

In Fig. 3 and Movie 1 (Supplement) we can see what happens with the evaporated water from Lake Volta in August 1998. The general pattern is that moisture is first transported to the north-east until it reaches to higher levels of the atmosphere, after which it is picked up by the African Easterly Jet (Cook, 1999). But as the Movie clearly shows this process is variable in time, which seems to be caused by variability in the surface winds. For example, on 19 August it is observed that all tagged water is transported in westerly direction.

Figure 3 shows that evaporation from Lake Volta is most likely to end up as precipitation just northward of the source region. In Movie 1 (Supplement) we saw that the tagged atmospheric moisture also reached south of Lake Volta, but that it did not rain out (see Fig. 2b). Only a few spots in the domain receive more than 5 mm month^{-1} of rain originating from Lake Volta. Compared to the total amount of rainfall (Fig. 2b) the tagged rain accounts only for a few percent. Nonetheless we can say that evaporation from Lake Volta is significantly impacting the regional system as over one-third of the evaporation recycles within the domain and about 2 % recycles over Lake Volta (see also Table 2).

3.2.2 Water accounting model

Figure 4 and Movie 2 (Supplement) show that according to WAM the evaporated water from Lake Volta appears to be primarily transported to the west. The amount of evaporated water from Lake Volta recycling within the domain happens to be almost the same as in RCM-tag (Table 2), but the patterns clearly show that WAM is not a good method to perform such a detailed analysis. We attribute the wrong pattern primarily to the fact that WAM uses a single vertical layer, and thus works with a vertically integrated moisture flux, which cannot reproduce the sheared wind system existent in this region (Fig. 1). In Sect. 3.3.1 we present an update to WAM (WAM-2layers), which is much better capable of representing the West African wind system.

3.2.3 3D-trajectories

Figure 5 shows that the 3D-T method leads to a downwind tagged precipitation pattern somewhat similar to that of the RCM-tag. However, the recycling fraction is a factor three lower than the RCM-tag simulation (see Table 2). From Movie 3 (Supplement) it can clearly be observed that, similar to the WAM run, the 3D-T method partially transports the moisture in the wrong direction. Moreover, in Movie 3 (Supplement) tagged water appears to disappear too quickly from the domain in comparison to RCM-tag (Movie 1, Supplement). This can be attributed to large differences in wind direction and speed between lower and higher atmospheric layers, making the results very sensitive to the height at which moisture parcels are released. The spatial and temporal resolution of this case study is apparently too high for the moisture weighted release in the vertical to be applicable.

Although the parcels released by the 3D-T method are transported vertically with the vertical wind speed, a significant fraction of the parcels is released in the westward flowing (higher) layers, and are transported into areas with low precipitation and subsequently out of the domain. The parcels that are released in the lower fraction of the atmosphere follow the same pattern as the RCM-tag run and produce the same downwind precipitation pattern, however only about a third of the parcels are released in the eastward flowing layer (approximately below 2 km). In Sects. 3.3.2 and 3.3.3 we present updates to 3D-T (3D-T-E_lowmixing), which release the evaporated water parcels only in the lowest levels of the atmosphere, which at this high spatial and temporal resolution study offers a better representation of the true dynamics.

3.3 Simple improvements to the a posteriori moisture tracking methods

3.3.1 WAM with 2 layers in the vertical

It was observed in Sect 3.2.2. that the WAM model provides good recycling quantities (Table 2), but not for the right reasons as too much of the moisture transport is westward (Fig. 4 and Movie 2, Supplement). A simple improvement that yielded much better results is splitting the atmosphere into two layers (WAM-2layers). Prior investigation into the vertical distribution of wind velocities showed that the shear-layer is approximately at the sigma-level (model level relative to surface pressure) which corresponds roughly to 800 hPa (2 km). Horizontal moisture fluxes in the bottom layer were computed between the surface and that sigma-level, while the horizontal moisture fluxes in the top layer were computed between that sigma-level and the top of the atmosphere. Moreover, we used the vertical velocity given at the sigma-level of around 800 hPa to calculate the moisture transport between the bottom and top layer. At an input time step of 1 h, this is an acceptable assumption.

Figure 6 and Movie 4 (Supplement) show the results for the WAM-2layers run. It can be observed that this run compares very well with RCM-tag (Fig. 3 and Movie 1, Supplement). The tagged moisture flowing around the domain, the precipitation pattern, as well as the magnitude of recycling within the domain are nearly identical. A relatively large error is, however, made for the regional recycling ratio within the Lake Volta area: 2.8 % for WAM-2layers vs. 1.9 % with RCM-tag. Yet, over the full model domain this issue is apparently not significant (see also Table 2)

3.3.2 3D-T without the well-mixed assumption for evaporation

One of the most important assumptions of the original 3D-T method is “well mixed” assumption for the height at which tracer parcels are released in the atmosphere. The validity of this assumption is related to the vertical mixing that takes place within a single time step. With a large time step this assumption could be valid, but we saw in Sect. 3.2.3 that it did not yield good results in the domain of the current study, especially since the region also has large wind shear. To quantify the effects of this assumption, the 3D-T method was modified (3D-T-E_lowmixing-P_well-mixing in Table 2) and parcels were released from just (50 m) above the land surface.

Figure 7 and Movie 5 (Supplement) show the results of this modified run. The patterns have not changed much compared to the original 3D-T run. However, the amount of precipitation in the domain has increased significantly coming much closer to the value of RCM-Tag. The pattern in Fig. 7 resembles the RCM-tag output quite well. The difference with the precipitation patterns from the RCM-tag and the WAM-models is the peak intensity, which is higher in the 3D-T runs. In the RCM-tag and WAM-models, the moisture is transported on an Eulerian grid, which causes some diffusion of the moisture, the parcel trajectories in the 3D-T do not cause this diffusion, so the precipitation shows higher peaks and is less smooth spatially, which can also be seen in the movies.

3.3.3 3D-T without the well-mixed assumption for evaporation and precipitation

Apart from the assumption of the height at which the evaporation is released into the atmosphere discussed in Sect. 3.3.2, the 3D-T method (as well as WAM and WAM-2layers) assumes that all moisture in the vertical column contributes equally to precipitation. To test the sensitivity of this assumption to the precipitation patterns, the precipitation allocation in 3D-T was adapted by using the information about the cloud layers in the RCM-tag run, i.e. the cloud water content in each of the 33 model levels. In this adaptation, the precipitation as assumed to originate only from the cloud levels. During the trajectory of the moisture parcels, the amount of precipitation from the parcel during a timestep is proportional to the ratio of the cloudfraction from the RCM-tag run at the height of the parcel and the mean cloudfraction over all levels in the column. If no clouds are present at the height of the parcel, the parcel will not contribute to the precipitation.

Figure 8 and Movie 6 (Supplement) show the results of this adaptation, together with the release of the parcels from near the land surface. The patterns are similar to that of Fig. 7 and Movie 5 (Supplement), however, the intensities are a bit higher and the recycling rates are very close to the RCM-tag run (see also Table 2). Movie 6 (Supplement) clearly shows differences with Movie 1 (Supplement) of RCM-tag, which are caused by Lagrangian vs. Eulerian modelling, but from Fig. 8 and Table 2 it can be observed that the results of this run (3D-T-E_lowmixing-P_fromclouds) are closest to the virtual reality.

3.4 Case study conclusions

From the climatology present in the West African study area (Fig. 1), especially the wind shear present in the vertical, it was known that the a posteriori water vapour tracing models (WAM and 3D-T) would face difficulties representing the results of the RCM-tag method (Fig. 3). WAM performed particularly bad in getting the direction of the moisture flux right (Fig. 4), but the addition of a second layer yielded results that were quite close to RCM-tag (Fig. 6). The 3D-Trajectory model performed well in reproducing the patterns of RCM-tag (Fig. 5), but failed mainly in getting to recycling ratios right (Table 2). Releasing the parcel near the surface instead of distributed over the vertical significantly improved the results (Fig. 7). Accounting for the presence of clouds instead of using the well-mixed assumption for precipitation improved the results even further (Fig. 8).

What can be said about the effects of the major simplifications and possible sources of error in WAM and 3D-T, which we identified beforehand? These can be summarized as: (1) an insufficient number of vertical layers (only one in the original WAM), (2) the moisture weighted well-mixed assumption when distributing evaporated moisture parcels over the vertical, (3) the moisture weighted well mixed assumption when parcels precipitate out of the atmosphere, and (4) the neglect of liquid water and ice. In summary, we can say that in this case study assumptions 1 and 2 were found to be the most crucial, and assumptions 3 and 4 of minor importance, in obtaining accurate results with the atmospheric moisture tracking models used. A more detailed discussion of these four points is found in the remaining part of this section.

3.4.1 Insufficient number of vertical layers

It was found that for this particular case study, the insufficient number of vertical layers was one of the most crucial sources of error in the atmospheric tracing results. The atmospheric moisture tracking model RCM-tag used 33 model-levels. With only one vertical layer WAM was not able to reproduce the pattern of RCM-tag (Fig. 4 and

Movie 2, Supplement). However, it was not per se necessary to use all 33 layers as is also done in 3D-T, but splitting the atmosphere in just two well-chosen layers (WAM-2layers) yielded results that were very similar to RCM-tag (see Fig. 6 and Movie 4, Supplement).

3.4.2 Vertical mixing assumption for evaporated parcels

The tagged evaporated moisture parcels released at a random starting height in 3D-T, weighed by the atmospheric moisture profile, let to an underestimating of recycling (Sect. 3.2.3). Note that the original WAM run also released its evaporated water over the entire atmospheric profile (as there is only one layer), but the effect of this was not clear as the moisture direction led to larger errors. The new runs: WAM-2layers, 3D-T-E_lowmixing-P_well-mixing and 3D-T-E_lowmixing-P_fromclouds, release their tagged moisture near the surface which led to significantly better results (Figs. 6–8). Thus, for this high spatial and temporal resolution it appears that is best to release evaporated parcels near the surface.

To illustrate this, the left side of Fig. 9 shows the mean height of parcels released from the source region (Fig. 1) for the different mixing approaches in 3D-T. The mean height of the parcels in the original 3D-T run is higher than in the run with releases from the surface (indicated with "lowmixing") during the first 70 h of the simulation; a *t* test of the differences between the runs dropped below the 95 % level after 68 h of simulation. Note that the number of parcels within the domain (on which Fig. 9 is based) decreases in time. As the wind speeds are higher in higher atmospheric layers, the number of parcels present in the original run will be reduced faster than in the "lowmixing" run, explaining the fact the black line is higher than the red line after 85 h.

3.4.3 Vertical mixing assumption for precipitation

Both atmospheric water vapour tracing methods WAM and 3D-T invoke the so called "well-mixed" assumption for precipitation. This means that the amount of moisture that precipitates out of the parcel during a time step is proportional to the total column moisture. Consequently, parcels at all height are equally likely to precipitate. From the right side of Fig. 9 it can be seen that this is in reality not the case as cloud water has a different vertical distribution than water vapour. In the run 3D-T-E_lowmixing-P_fromclouds (Sect. 3.3.3) we assumed that precipitation can only come from levels where clouds are present. This yielded a small improvement in the magnitude of moisture recycled within the domain (Table 2), but this improvement was much smaller compared to changing the release height of 3D-T (Sect. 3.2.3). Moreover, it was necessary to use additional information about cloud water content from MM5.

3.4.4 Neglect of liquid water and ice

For this case study we can conclude that tracing the water vapour only, and neglecting the presence of liquid water, ice and the corresponding phase transitions in the tracing scheme did not influence the results significantly. The improved a posteriori moisture tracking methods WAM-2layers and 3D-T-E_lowmixing were both able to reproduce the results of RCM-tag to a satisfying degree of similarity, while taking into account water vapour only.

4 Where is a complex model important?

In the case study we have seen that the wind shear in the West African domain is responsible for the largest errors in the a posteriori tracing models. In single layer WAM this lead to errors in the transport paths predicted by the model, because it used the vertically integrated moisture flux, leading to a net moisture transport in westward direction. This problem was mostly solved in the WAM-2layer runs. The model 3D-T was affected by the fact that some of the released parcels in the upper atmosphere where going in a different direction than if they had been released closer to the surface. This problem was also solved in the 3D-T-E_lowmixing runs.

It should be noted that we could only make these observations because we had the results from the RCM-tag run available, which generally will not be available beforehand. Therefore, it is desirable to say something about the necessity of running WAM with 2 layers or applying another atmospheric moisture tracking model like 3D-T or RCM-tag. In general we can reason that the larger the tagging source area, the less wind shear is a problem, because tagged water from different parts of the source area will compensate for each other. Nonetheless, to identify in which parts of the world wind shear is a problem for atmospheric moisture tracking, we propose to compute the horizontal moisture flux shear factors:

$$F_{z,\mathrm{shear}} = \frac{\left|\sum\limits_{p=0}^{p=p_\mathrm{s}} q\,u\right|}{\sum\limits_{p=0}^{p=p_\mathrm{s}} |q\,u|} \tag{3}$$

and

$$F_{m,\mathrm{shear}} = \frac{\left|\sum\limits_{p=0}^{p=p_\mathrm{s}} q\,v\right|}{\sum\limits_{p=0}^{p=p_\mathrm{s}} |q\,v|}, \tag{4}$$

where q is specific humidity, p is pressure and p_s is surface pressure and u and v are zonal and meridional wind speed, which have a positive value in respectively eastward and northward direction respectively, and a negative sign in the opposite direction. For example, in the extreme case of a completely sheared system, where wind in the lower atmosphere is in eastward direction and wind in the upper atmosphere is in westward direction while the product of q and u is equal for both parts, $F_{z,\mathrm{shear}}$ has a value of 0. On the other hand, if the wind in all layers of the atmosphere is in the same direction, then the system is without shear and $F_{z,\mathrm{shear}}$ has a value of 1. For clarity, a value of 0.5 means that 75 % of the total horizontal moisture flux goes in one direction and 25 % in opposite direction. These factors can directly be computed from standard climate model output or reanalysis data. A similar metric was proposed by Goessling and Reick (2012).

Figure 10 shows the moisture flux shear factors for the West African case study. It can be observed that shearing is most problematic in the coastal zone, and somewhat less in the north of the domain, but cannot be neglected for the moisture tagging from the small Lake Volta area. This confirms the winds shear pattern which was also observable in Fig. 1, and was found to be the main reason of errors in the a posteriori moisture tracking models.

We also applied Eqs. (3) and (4) globally with a 10 yr record of the ERA-Interim reanalysis (60 model levels) (Dee et al., 2011). These results are shown in Fig. 11. It can be observed that the area where one would expect the largest problems for accurate moisture tracking is in fact West Africa. In general the most problems are expected in Africa and to a lesser extent in South America and Australia. The temperate zones of Eurasia and North America have high horizontal moisture flux shear factors, meaning that the moisture is mostly going in one direction over the whole vertical.

5 Concluding remarks and recommendations

In this paper we compared three state-of-the-art atmospheric moisture tracking models that track evaporation until it precipitates (Table 1). For tracing results we assumed that the RCM-tag method was able to simulate the “virtual reality”. The two other, less complex, methods (WAM and 3D-T) use a posteriori (offline) water vapour tracking. It was found that the original a posteriori models had difficulties reproducing the results of RCM-tag for a case study in West Africa (Sect. 3.2). Improved versions of the a posteriori models relaxed some of the original assumptions and obtained significantly better results (Sects. 3.3 and 3.4). We concluded that the number of layers in the vertical and the mixing assumption after evaporation had the largest influence on the results (Sect. 3.4), especially due to the strong wind shear in West Africa (Figs. 1 and 10).

How the results of previous studies would be (e.g. Dominguez et al., 2006; Dirmeyer and Brubaker, 2007; Bisselink and Dolman, 2008; van der Ent et al., 2010; Goessling and Reick, 2011; Bagley et al., 2012; Keys et al., 2012; Tuinenburg et al., 2012; Wei et al., 2012) when they had used "improved" moisture tracking models is very much case-dependent. Detailed analysis is beyond the scope of this study, but Goessling and Reick (2012), for example, showed that there are significant differences (mainly in the tropics) in continental precipitation recycling ratios between 2-D and 3-D tracking. However, the global pattern as also shown by the 2-D tracing study of van der Ent et al. (2010) and 3-D tracing study of Bosilovich et al. (2002) remains very similar. For the study of Tuinenburg et al. (2012) we can conclude that their estimates of recycled moisture within the Ganges basin were on the conservative side. Releasing the parcels in the lowest layer was found to increase the Ganges basin recycling by only 5 % (Tuinenburg, 2013). This result is in line with Fig. 11, where wind shear is not as significant in India as in West Africa.

In the WAM-2layers 3D-T (all runs) methods the vertical moisture transport was forced by the instantaneous vertical wind speeds at the time resolution of the forcing data. In reality, as well as in the atmospheric models used to generate the forcing data, the vertical mixing of moisture is driven by turbulence, which acts on timescales of minutes. In this case though, we could simply use the vertical velocities, as the resolution of the forcing model MM5 was high enough not to apply a subgrid scale convective scheme. However, when either of the a posteriori moisture tracking methods would be applied to other cases where the forcing data has a coarser resolution (e.g. 6-hourly, 1° × 1∘ grid) another solution must be found to deal with the vertical transport. In the case of WAM-2layers we think that the vertical transport could be parameterized or obtained from the water balance. In the case of 3D-T it may be wise to apply an initial mixing somewhere in between the original well-mixed assumption and the lowmixing assumption. Unfortunately, this modeller's choice can only be tested when one has forcing model information such as in this study.

The well-mixed assumption of precipitation was relaxed in the 3D-T-E_lowmixing-P_fromclouds run (see Sects. 3.3.3 and 4.3.4). However, we could only do this as we had cloud water content information from MM5. In many other cases this would not always be available and one would have to assume a certain degree of mixing. In practice we think that a well-mixed situation for precipitation can be assumed and we also showed that it does not influence the results much. Another issue that we did not address is the mixing due to re-evaporation and condensation during a precipitation event. This issue is discussed in detail by Goessling and Reick (2012) who applied 3-D water vapour tracers in ECHAM6 on a 1.875° × 1.875° grid, but they also leave this a modeller's choice. It can, however, be observed that their lower and upper boundaries for this type of mixing yield very similar results.

As a side note, we also showed the differences between the Eulerian approach taken by RCM-tag and WAM and the Lagrangian approach taken by 3D-T. The precipitation patterns generated by RCM-tag and WAM are smoother than those generated by 3D-T due to the numerical mixing on the Eulerian grid that does not occur in the Lagrangian method. Given the current experiment, it is not possible to determine whether the Eulerian or Lagrangian approach is more suitable. However, it clearly shows that a Lagrangian method should release a sufficient amount of tracer parcels to produce reliable results, which unfortunately comes at the cost of computation time. The Eulerian methods, on the other hand, must not use too small time steps in order to avoid too much numerical dispersion, but is also not recommended as this obviously increases computation time (see also Table 1).

Based on our investigations we can provide recommendations on when and where to use which model (Table 3). We recommend the use of a posteriori models over RCM-tag for historical or near real time studies as a posteriori models are more flexible in their input data (They can e.g. draw on existing climate model, reanalyses or observational data sets). For future scenarios, new climate model runs may be necessary

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anyway and RCM-tag would be suitable, offline methods can of course handle this as well. Regarding the most suitable method for a certain spatial scale it is logical that a very accurate method as RCM-tag is recommended for local studies, whereas this would be computationally costly on larger scales. WAM is not recommended for the local scale studies, especially in the tropics, where the wind shear factor is low, meaning a highly sheared system (Eqs. 3 and 4 and Fig. 11). However, this model is very fast and flexible for the larger scales, especially in its updated form (WAM-2layers). When applied on local scale in areas with prominent wind shear (Fig. 11), 3D-T is not very suitable either. However, this method works well on large scale, or on local scale in areas that do not suffer that much from wind shear. The "E_lowmixing" versions of 3D-T are generally recommended above the well-mixed assumptions for released parcels on smaller spatial scales, but when interested in large spatial (and temporal) scales this is not likely to have a big effect (see also Fig. 9). In conclusion, we hope that the findings of this paper will be beneficial to future atmospheric moisture tracking and moisture recycling studies, giving them a better handle on the suitability of the several methods around.

Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci-discuss.net/10/6723/2013/ hessd-10-6723-2013-supplement.zip.

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Table 1. Characteristics of the tracing methods. q is specific humidity, u is zonal wind speed, v is meridional wind speed, w is vertical wind speed, P is precipitation and E is evaporation. In case the input data is given on pressure levels instead of model levels then surface pressure is required as well for WAM and 3D-T. For more information on the methods: RCM-tag (Knoche and Kunstmann, 2013), WAM (van der Ent et al., 2010; van der Ent and Savenije, 2011; Keys et al., 2012), and 3D-T (Tuinenburg et al., 2012).

Method	Input data needed	Traced water	Flux treatment	Model coordinate system	Numerical considerations	Computation speed	Speed dependency	Back-tracking possible
RCM-tag	Boundary conditions for the climate model	All	Transport as well as phase transitions at full model resolution	Eulerian tracking	Leap-frog scheme: Courant criterion, numerical dispersion	–	Linear proportional to the (t, x, y, z) – model domain	No
WAM	$q, u, v(t, x, y, z)^*$ $E, P(t, x, y)$	Water vapour only	Vertically integrated fluxes. "Well-mixed" assumption for E and P^{***}	Eulerian tracking on model coordinates	Explicit scheme: Courant criterion, numerical dispersion	++	Linear proportional to the (t, x, y) – model domain	Yes
3D-T	$q, u, v(t, x, y, z)^{**}$ $E, P(t, x, y)$	Water vapour only	"Well-mixed" assumption for E and P^{***}	Lagrangian tracking on Eulerian coordinates	Explicit scheme, but no numerical issues due to the Lagrangian system****	0	Linear proportional to the number of tracers released and thus the size (t, x, y) – source area	Yes

[*] In principle the vertically integrated moisture flux and the total column water vapour are sufficient, but these are usually not directly available. [**] Vertical wind speed is preferably given in Pa s^{-1} rather than m s^{-1}. In the case study in this paper the input data of vertical wind speed was given in m s^{-1} and the approximation: 1 hPa = 10 m was used. [***] The well-mixed assumption (of the vertical atmosphere) implies that precipitation is assumed to be removed weighted with the total moisture from each model layer. In case of WAM the actual horizontal tracing is performed with only one vertical layer and is thus also "well-mixed". [****] Accuracy of the solution does, however, depend on the tracer density and chosen time step.

Table 2. The amount of evaporation from the Lake Volta region (Fig. 1), which recycles as precipitation within the domain and locally computed with different water tracing models. These results are for August 1998.

Tracking model	Evaporation of Volta origin that precipitates within the domain, i.e. domain recycling	Evaporation of Volta origin that precipitates in the Volta region, i.e. local recycling	Pattern resembling that of RCM-tag's virtual reality
Original models			
RCM-tag	35 %	1.9 %	Exact
WAM	39 %	2.0 %	Bad
3D-T	12 %	1.9 %	Reasonable
Modified models			
WAM-2layers	34 %	2.8 %	Good
3D-T-E_lowmixing-P_wellmixing	29 %	1.8 %	Good
3D-T-E_lowmixing-P_fromclouds	34 %	2.0 %	Good

Table 3. Recommended applicability of methods considering both accuracy and computation speed. The choice for a method also dependents on location of the region (see Fig. 11), size of the tracer source area and available computational power (see Table 1).

Method	Historical or present day studies	Scenario studies	Detailed local scale (up to 1000 km)	Regional scale (up to 5000 km)	Global scale
RCM-tag	0	++	++	+	−
WAM	++	+	−	0	+
3D-T	++	+	0	+	+
WAM-2layers	++	+	+	+	++
3D-T-E_lowmixing-P_wellmixing	++	+	+	++	+
3D-T-E_lowmixing-P_fromclouds	++	+	++	+	+

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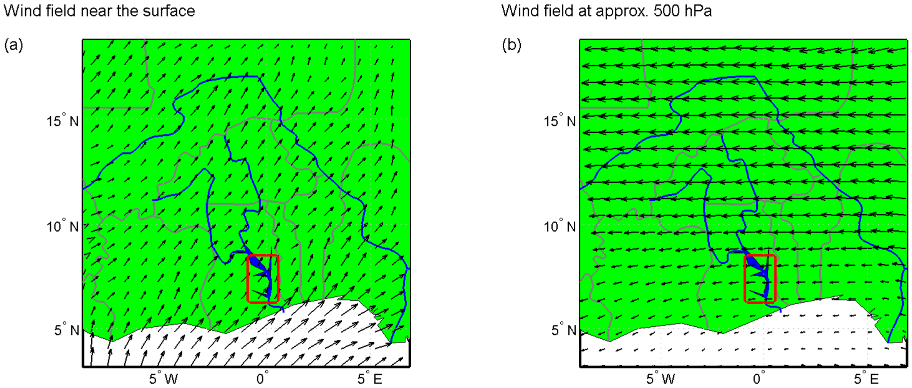

Fig. 1. Wind field at different heights (arrows) averaged over August 1998 according to the MM5 model run. **(a)** The wind field near the surface, and **(b)** the wind field at a model layer which corresponds to approximately 500 hPa or 5 km. Rivers and Lake Volta are shown in blue, country borders in grey and the tagging source area lies within the red rectangle. Note that in the text the tagging source area is sometimes referred to as Lake Volta, but actually covers some of its surroundings as well.

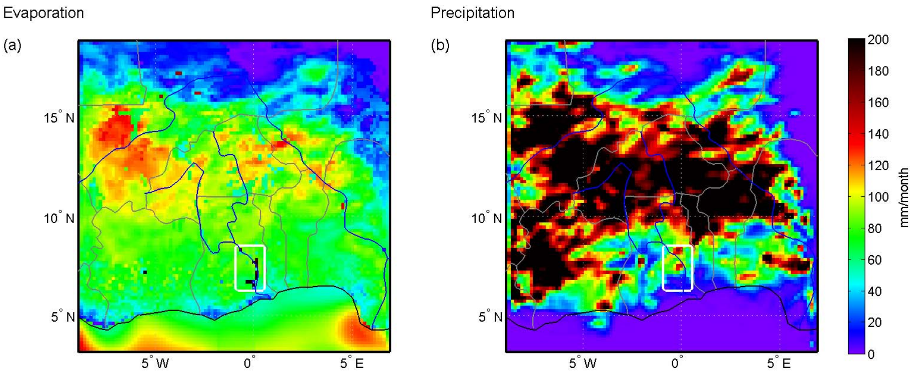

Fig. 2. Vertical fluxes in August 1998 according to the MM5 model run. **(a)** Evaporation, and **(b)** precipitation. The areal average evaporation of the Lake Volta tagging region is 85 mm month^{-1} compared to 67 mm month^{-1} over the whole domain. The areal average precipitation of the Lake Volta tagging region is 62 mm month^{-1} compared to 87 mm month^{-1} over the whole domain.

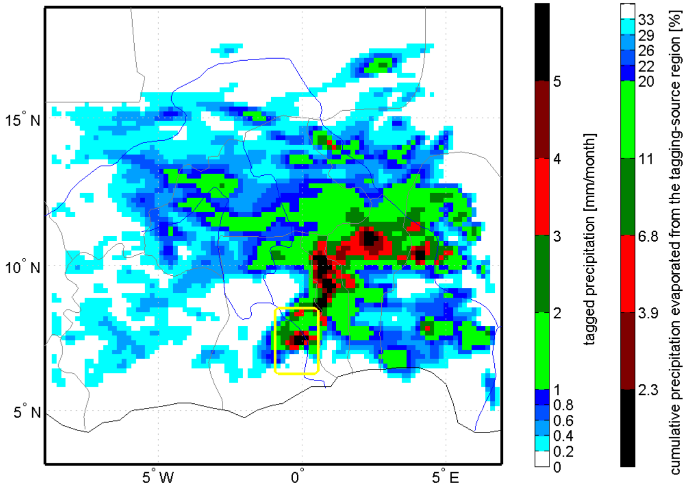

Fig. 3. Precipitation of Volta origin in August 1998 as computed by RCM-tag. The yellow rectangle indicates the Lake Volta tagging-source region. The left colour bar indicates the absolute amount of precipitation that originated from Lake Volta. The right colour bar indicates for which percentage the precipitation in the coloured areas accounts for the evaporation from the tagging-source region. For example, the light green regions receive 1 to 2 mm month^{-1} of precipitation that originated from Lake Volta, and in total the tagged precipitation in the light green areas sums up to 20 – 11 = 9 % of Lake Volta's evaporation.

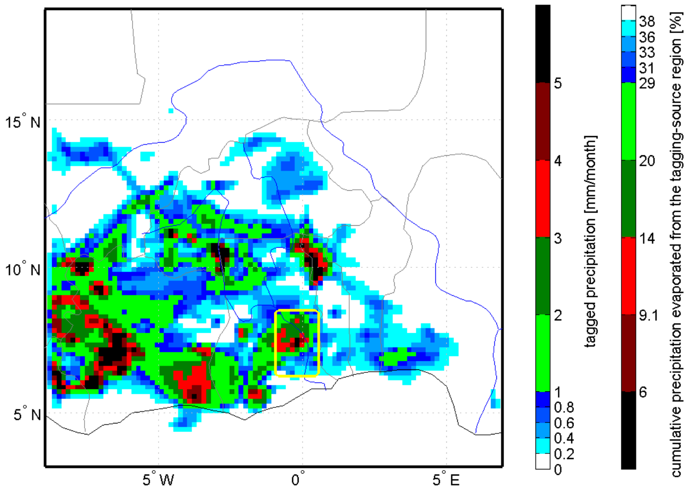

Fig. 4. Precipitation of Volta origin in August 1998 as computed by WAM. See Fig. 3 for an explanation of the colours.

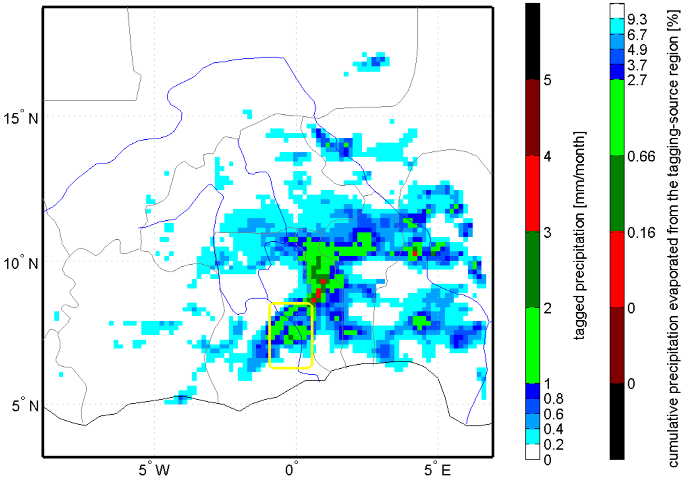

Fig. 5. Precipitation of Volta origin in August 1998 as computed by 3D-T. See Fig. 3 for an explanation of the colours.

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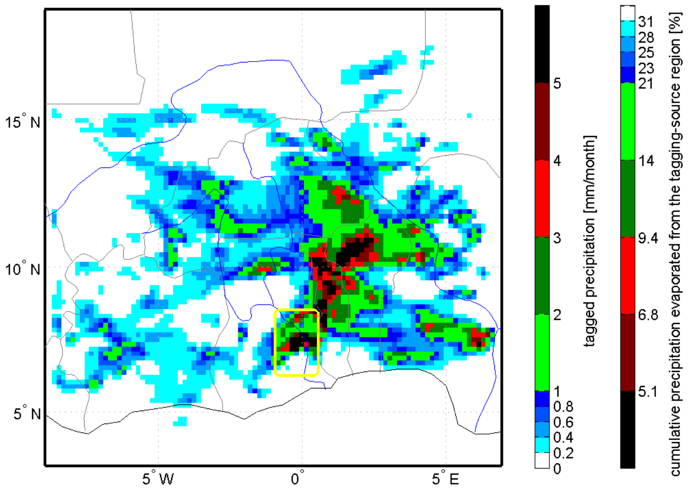

Fig. 6. Precipitation of Volta origin in August 1998 as computed by WAM-2layers. See Fig. 3 for an explanation of the colours.

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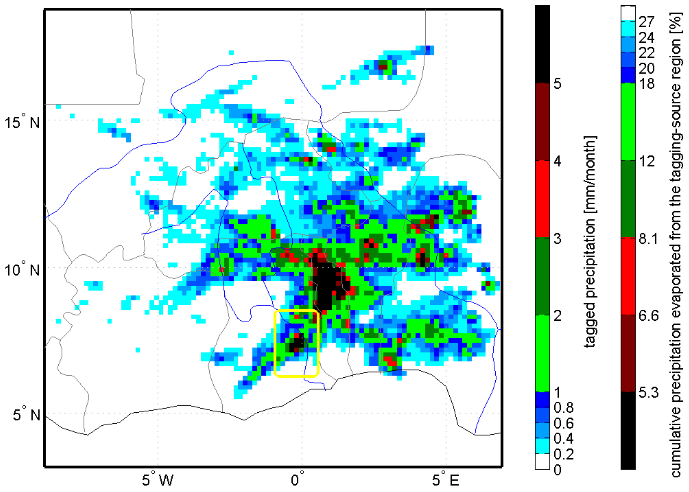

Fig. 7. Precipitation of Volta origin in August 1998 as computed by 3D-T-E_lowmixing. See Fig. 3 for an explanation of the colours.

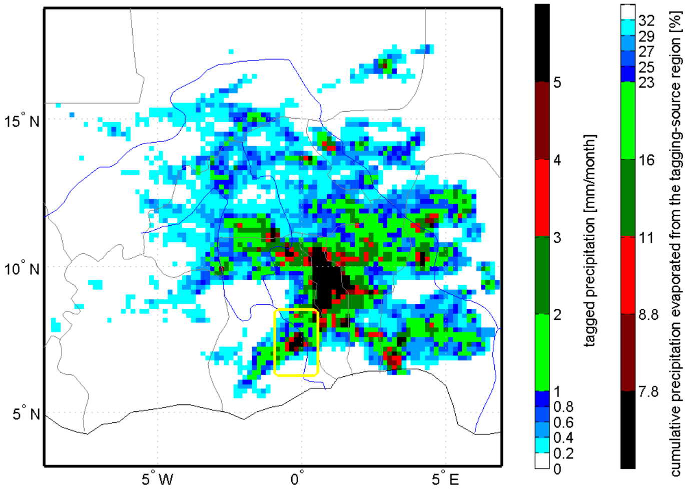

Fig. 8. Precipitation of Volta origin in August 1998 as computed by 3D-T-E_lowmixing-P_fromclouds. See Fig. 3 for an explanation of the colours.

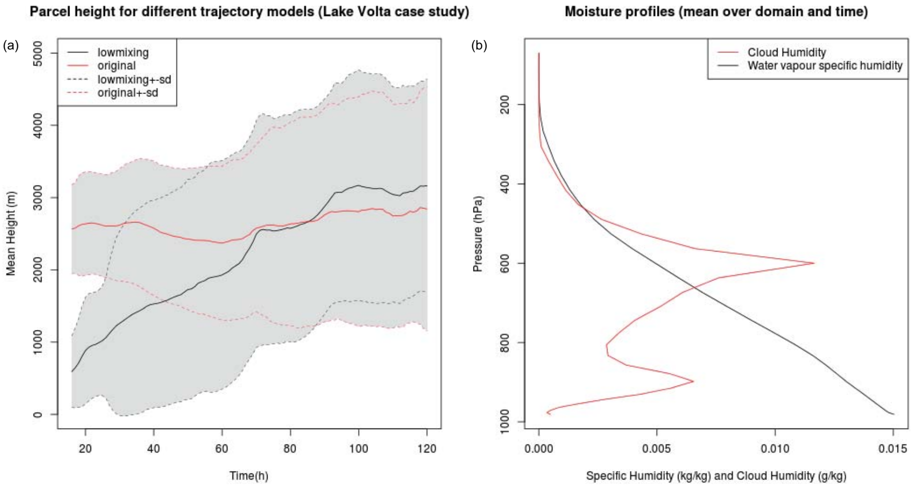

Fig. 9. (a) Mean height of parcels in 3D-T for two mixing assumptions for evaporation entering the atmosphere. The red line shows the original assumption in which evaporated moisture is released randomly along the vertical moisture profile (Fig. 5 and Movie 3, Supplement). The black line shows the assumption where moisture is released at 50 m above the land surface. Dotted lines and grey shading shows the range of one standard deviation from the mean height. Both lines are based on a sample size of 1000 parcels. **(b)** Vertical moisture profile (averaged over the domain for August 1998). The red line shows the cloud humidity and the black line the specific humidity.

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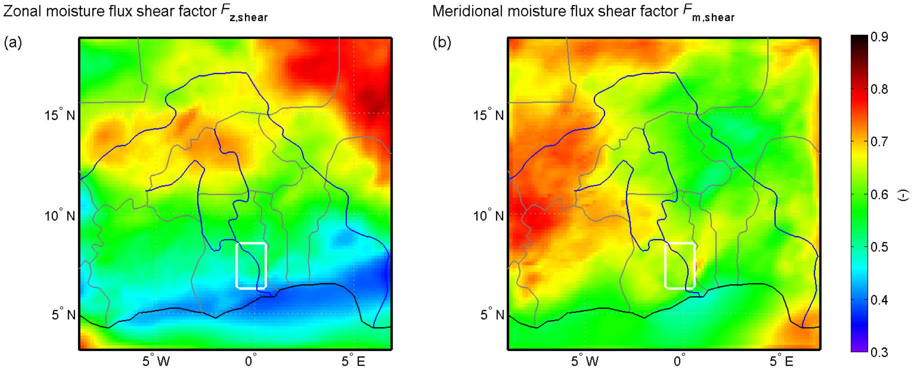

Fig. 10. Horizontal moisture flux shear factors as defined by Eqs. (3) and (4) averaged over August 1998 according to the MM5 model run. **(a)** Zonal moisture flux shear factor, and **(b)** meridional moisture flux shear factor. The lower the value the more sheared the moisture flux.

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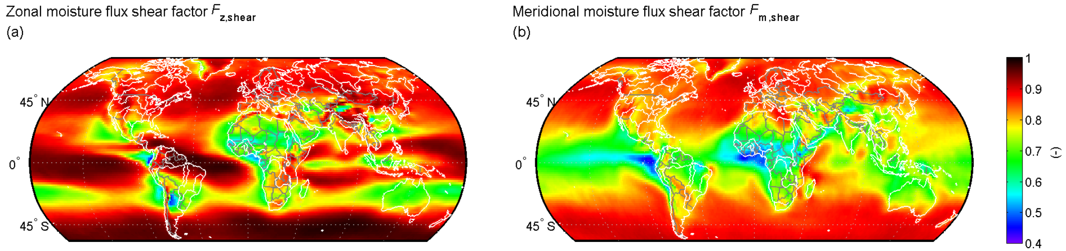

Fig. 11. Horizontal moisture flux shear factors as defined by Eqs. (3) and (4) averaged over 1999–2008 according to ERA-Interim reanalysis. **(a)** Zonal moisture flux shear factor, and **(b)** meridional moisture flux shear factor. The lower the value the more sheared the moisture flux.