<u>Reply to Anonymous Referee #1: Marsham et al., The contrasting roles of water and dust in controlling daily variations in radiative heating of the summertime Saharan Heat Low</u>

The authors provide a comprehensive empirical observational study of relationships between water vapor, dust aerosol and radiation over the important Sahara Heat Low region. Recent research suggests that this area is of importance in determining feed-backs on climate and the regional water cycle (e.g. Evan et al. 2015 doi:10.1175/JCLI-D-14-00039.1; Dong and Sutton, 2015, doi: 10.1038/nclimate2664). The analysis, though quite simple, is very well composed and useful in assessing the key drivers of radiative energy balance in the region and use of new observations make the evaluation quite novel. I have a number of mostly minor points outlined below that I consider the authors should address before the paper is ready for publication.

We would like to thank the reviewer for their thorough and valuable review.

We now cite Dong & Sutton in the introduction,

"variations in the SHL modify the WAM on time scales from days to decades [Thorncroft and Blackburn 1999; Peyrillé and Lafore 2007; Biasutti et al., 2009, Lavaysse et al, 2009, 2010; Chauvin et al., 2010, Xue et al., 2010, Martin and Thorncroft 2014, Martin et al., 2014, Dong and Sutton, 2015]. " and

"Evan et al. (2015) suggest that the increasing temperatures within the SHL over the past 30 years, key to the recovery of the Sahel from drought, are driven by longwave impacts of increasing water vapour, in the "Saharan Water Temperature" feedback and Dong and Sutton 92015) propose a greenhouse-gas driven increase with a feedback through water vapour"

We address the reviewer's other points in turn.

GENERAL POINTS

1) Since this is an empirical study it cannot demonstrate cause and effect. Figures 2-4 show relationships between variables (not "trends" or cause/effect). Further detailed radiative transfer calculations and additional modeling is required to do so. Presuming this is beyond the scope of the study, there are a number of places where this should be stressed and the text modified accordingly (see specific points).

We no longer use the word "trend", as although it can refer to any linear relationship in physics, it is often used for changes in time in climate science.

Radiative transfer modelling is out-of-scope as the reviewer suggests, and it is challenging to account for the uncertain cloud fields using this approach. We have clarified the limitations of our method by noting its limitations in the abstract,

"Although the empirical analysis of observational data cannot completely disentangle the roles of water vapour, clouds and dust, the analysis demonstrates that TCWV provides a far stronger control on TOA net radiation, and so the net heating of the earth-atmosphere system, than AOD does. In contrast, variations in dust provide a much stronger control on surface heating, but the decreased surface heating associated with dust is largely compensated by increased atmospheric heating, and so dust control on net TOA radiation is weak.”,

at the end of the introduction,

“In this paper we use observations of surface radiative fluxes from Fennec and retrievals of TOA fluxes from satellite data to investigate how dust and water together control the day-to-day variations in energy balance over the Fennec supersite-1 in the summertime SHL region, and how this is represented in ERA-Interim (ERA-I) reanalysis. Results in Section 3 show that TCWV and AOD are correlated and we cannot completely isolate the effects of either TCWV or dust. However, TCWV and AOD have sufficiently independent variations, and sufficiently distinct impacts at solar and infrared wavelengths, which conform with physical principles, that the results give unique insights into their contrasting roles in the central Sahara.”,

at the start of the results,

“In order to determine how the changing amounts of water and dust over BBM affect the changing radiative heating at the surface, TOA and within the atmosphere we analyse relationships …” and “There are correlations between dust and water (discussed below) which mean that effects of either cannot be completely isolated from the other, but nevertheless the approach allows identification of how variations in these variables affect radiative heating.”,

in the discussion,

“Although modelling is needed to fully understand the observed effects of water vapour on the radiation”

and this is already discussed at the start of the conclusions,

“Although there are limits to the extent to which our empirical approach can disentangle the roles of dust, cloud and water vapour, largely due to correlations between these factors, the results provide new insight into their roles in controlling the radiative balance of the unique environment of the central Sahara (schematic in Figure 5).”

We also made other have changes to the text that clarify our approach and what we infer. In the results,

“At the surface there is a strong and significant decrease in net radiation with increasing AOD (Figure 3b) with a regression coefficient of -13.1 W m^{-2} per AOD”.(new with-bold-font page 9 line 26)

“Decreases in surface heating associated with dust are largely compensated by direct radiative heating of the atmosphere”(new with-bold-font page 11 line 2)

And in the conclusions,

"However, variations in water vapour (and associated variables such as temperature and cloud) and not variations in dust dominates day-to-day variability of TOA net radiation"

"At the surface, dust (and associated water vapour and cloud) decreases net surface radiation in reality by around 13 W m^{-2} per AOD."

"If effects from TCWV were simply due to correlated changes in AOD, or visa versa, these contrasting roles of TCWV and AOD at the TOA and surface would not be so distinct."

Please also see responses to specific points below.

2) How representative is 2011 and 2012 of the regional climatology. Some further analysis or links to previous work would help in answering this.

For a 2 degree box centred on BBM for June 2011 and june2012 the standardised AOD anomalies from MISR, Deep blue (Terra and Aqua) and OMI are all within one standard-deviation of the long term mean. Water vapour mixing ratios at 850 and 925 hPa from analyses are also within one standard-deviation of the long-term mean, so conditions at BBM in both 2011 and 2012 are not 'anomalous'

This is now noted in the first paragraph of the results,

"Similarly, for both June 2011 and 2012 analysed water vapour at 850 and 925 hPa and AODs from MISR, Deep blue (Terra and Aqua) and OMI are all within one standard deviation of their mean values (not shown) and there is no indication that the weather regimes affecting BBM in these periods were anomalous."

3) It would be beneficial to consider or at least mention the CERES radiation data. The SYN product can provide daily averaged fluxes based upon satellite overpasses and geostationary diurnal cycle "shape". There are also estimates of surface and atmospheric fluxes that require the combination of reanalysis and additional satellite data with CERES measurements.

Given the large errors in reanalyses in the region (e.g. Marsham et al. 2011; Garcia-Carreras et al., 2013; Roberts et al., 2015) and the challenges of capturing Saharan cloud (Roehrig et al., 2013; Stein et al., 2015, both now cited in final lines of the paper) we think that for the aims of this paper it is preferable to use observed surface fluxes rather than estimates based on combinations of satellite data and analyses. We do not believe that uncertainty in TOA fluxes is the major limitation of this study (it is rather the empirical observation-based approach as noted by the reviewer) so we do not think that CERES TOA fluxes will significantly improve the paper.

4) There is some good evaluation of ERA Interim (e.g. p.19459-60). It would be useful to also consider work that has included model simulations in which the effects of dust are included (e.g. Allan et al. 2011, doi: 10.1002/qj.717).

We now put our results in the context of Allan et al., (2011) in the discussion,

"or the 20 to 40 W m^{-2} model bias that Allan et al. (2011) show can be removed by the inclusion of dust" (new with-bold-fontpage 11 line 29)

5) Given the strong influence of cloud on radiative fluxes and the co-variation between cloud, AOD and TCWV implied in the present work a more detailed analysis of these co-variations and influences of cloud would be beneficial.

The paper is an observationally-based evaluation of the roles of water and dust in the surface and TOA energy balance in the summertime Sahara, comparing unique new observations and ERA-I. Determining the role of clouds is challenging and there is a limit as to how far examining co-variations in the data will take us in this regard, especially as there is a shortage of relevant data for clouds (and as noted detecting small clouds over the bright desert is challenging). Radiative transfer modelling would be needed to further disentangle effects and as noted by the reviewer this is out of scope of this study. Rather, we see the role of this study is to demonstrate the contrasting roles of dust and water vapour, and motivate further study as the reviewer suggests, and as noted in the final lines of the paper.

6) In places the meaning of net fluxes or heating/cooling are potentially ambiguous (e.g. p.19458). It should be stated clearly if net fluxes are defined as downward and whether increased net downward fluxes correspond to an increased heating (SW) or reduced cooling (LW).

This has been clarified,

" Figure 3e (gradient -1.1) shows that at the surface in ERA-I, unlike in observations, decreased net shortwave is always compensated by increased net longwave (i.e. reduced longwave cooling)." (new with-bold-font page 10 line 3)

We now state in the first results paragraph that,

"Net fluxes are defined as downward, with increased net downward flux corresponding to increased shortwave heating or reduced longwave cooling."

SPECIFIC CHANGES

p.19448, L6 - please provide information on the site location (abstract and also in the Introduction)

We now state,

"observations from Fennec supersite-1 in the central Sahara during June 2011 and June 2012" in the abstract and

"observations of surface radiative fluxes from Fennec supersite-1 in the central Sahara" in the introduction.

The latitude and longitude of the site are in the methods, which we believe any reader who wants a precise location will look for it, and here we also now describe the location,

“We use data from Fennec supersite-1 in the central Sahara, located at Bordj-Badji Mokhtar (BBM) at 21.4N 0.9E (in the very south of Algeria, close to the triple point of Algeria, Mali and Niger), close to the SHL’s climatological centre…”

p.194448, L11 (abstract) - it is not necessarily TCWV which is driving these changes as it may be clouds associated with the TCWV variability.

Clouds are likely associated with TCWV as you say, but so is dust, but results show it is the TCWV that controls TOA net radiation far more than the dust AOD. It is difficult to explain the full detail succinctly in the abstract, but we have clarified by stating

“Although the empirical analysis of observational data cannot completely disentangle the roles of water vapour, clouds and dust, the analysis demonstrates that TCWV provides a far stronger control on TOA net radiation, and so the net heating of the earth-atmosphere system, than AOD does”

p.19460, line 3-6 (Section 3.3) - it is not correct to say that increased LW heating is expected with increased water vapor and clouds as this depends very much upon the altitude (low clouds or moisture will increase longwave radiative cooling to the surface)

Thank you for pointing this out – this statement has been removed.

Table 1 - please check units. Does AOD:TOA Net mean dAOD/dNet (Wm-2)-1?

No, gradients are from graphs in subsequent figures so are dRadiation/dAOD so units are correct

p.19450 - do inadequacies in model simulation of dust mean that responses of the hydrological cycle are questionable (e.g. Dong and Sutton, 2015, doi: 10.1038/nclimate2664)?

I do not think we can answer that question in this paper, but as in the final paragraph of the conclusions or work highlights the importance of models capturing water, clouds and moist convection in this region (as well as dust). We now cite Dong and Sutton (2015) in our introduction.

p.19451 - MPEF is a simple IR-based cloud product which may miss low cloud so some further justification or explanation is required to justify its use.

Clouds over the Sahara form at the top of the Saharan convective boundary layer at around 5-km (Cuesta et al., 2009) and confirmed by observations from Fennec aircraft, so we do not think there is a problem with low clouds. This also is the only flag that is available at the spatial/temporal scale of the GERB HR product that gives some measure of cloud presence throughout the diurnal cycle.

SECT 3.1 - "Figure 2a shows that water vapour warms the atmosphere, with a trend in TOA net radiation with TCWV of +2.2Wkg-1." This is not strictly incorrect. Figure 2a shows that net downward radiation at the top of the atmosphere increases with TCWV.

It is not a "trend" but a relationship and cause and effect is not demonstrated for which radiative transfer calculations or other modeling would be required.

Although “trend” can be used for any linear fit in physical science, we understand that in climate science it is often used for changes with time, so we now avoid using the word “trend” throughout the paper. To clarify this sentence we now state,

“Figure 2a shows that TOA net downward radiation increases with TCWV, with a regression coefficient of +2.2 W kg^{-1}.”,

which is consistent with the new sentence at the start of our methods that states, “Net fluxes are defined as downward, with increased net downward flux corresponding to increased shortwave heating or reduced longwave cooling.”

p.19453, L24 - remove 1st ","

Done

p.19455, L4 - remove "presumably"

Done

p.19455, L12: relationship not a trend (also p.19457, L8; p.19459, L21; p.19460, L16)

Corrected.

“The increase in net TOA radiation with AOD occurs because the increase in TOA longwave (+10.5 W m^{-2} per AOD) dominates the decrease TOA net shortwave (-5.2 W m^{-2} per AOD; Figures 2e and 2h).”

“However, in ERA-I the underestimation of the magnitude of the regression coefficient of TOA net longwave with TCWV”

“There are significant increases in net shortwave and net longwave radiative heating of the atmosphere with increasing TCWV (Figures 4d and 4g, Table 1).”

“ERA has a significant positive increase in shortwave atmospheric heating with TCWV (Figure 4i, 0.91 W kg^{-1}) from absorption by water”

p.19455, L17 - "shortwave cooling" is misleading as it is reduced shortwave heating

Corrected to “Therefore the observed reduced shortwave heating associated”

p.19457, L13 (Sect 3.2) - again a relationship (not a trend) is shown and so a "control" on net radiation by AOD changes has not been demonstrated

Updated to “At the surface there is a strong and significant decrease in net radiation with increasing AOD (Figure 3b) with a regression coefficient of -13.1 W m^{-2} per AOD”

p.19458, line 14-19 - I was slightly unsure about where the PCA analysis fits in and was confused about this discussion which seems to suggest AOD and TCWV both increase together in mode 1 but are anti-correlated in mode 2. What physically do these modes represent?

PCA modes do not have to represent anything physically, but explain most of the variance. The PCA has, however, been removed to aid clarity.

p.19458, L25 - does "greater net surface longwave" mean that net downward surface longwave becomes less negative?

Yes. The convention we follow is now described at the start of the results,

"Net fluxes are defined as downward, with increased net downward flux corresponding to increased shortwave heating or reduced longwave cooling." and this sentence is clarified to, "This occurs since in ERA-I greater water vapour leads to greater net surface longwave (i.e. reduced longwave cooling, Fig. 3f),"

p.19459 - the influence of dust aerosol on atmospheric net radiative cooling is also discussed by Slingo et al. (2006) doi:10.1029/2006GL027869 and Slingo et al. (2009), doi:10.1029/2008JD010497.

Added, "This is consistent with the results of Slingo et al. (2006) and Slingo et al., (2009) for dust over the Sahel."

p.19460, L3 - "The increase in net longwave heating with TCWV is expected due to the warming from both water vapour and clouds." This is not precise since the longwave changes depend very much on the altitude of water vapor (e.g. Previdi 2010 doi:10.1088/1748-9326/5/2/025211) and cloud. Increased low level cloud or water vapor will increase atmospheric radiative cooling to the surface but influence the TOA only marginally.

As noted above, this has been removed.

p.19460, L5-6 - please check this sentence and also reference Fig. 1i on L9

We have corrected the reference to Section 3.3.1 and now reference figure 4i as suggested.

p.19461, L3: "errors"; L5-7 the altitude of water vapor is important (changes in mid and upper tropospheric humidity are rather important for TOA clear-sky longwave)

Corrected to "Small errors in TCWV, in the altitude of the water vapour, or in associated cloud, could cause errors in clear-sky longwave radiation…"

p.19462, L6-10 - this is an interesting discussion but it should be caveatted by the need for radiative transfer calculations or additional modeling to confirm cause and effect.

Added,

“Although modelling is needed to fully understand the observed effects of water vapour on the radiation, the observations show that monsoon surges at BBM are expected to have significant effects on radiative heating rates. In June 2011 BBM experienced ….”

p.19462, L21 - please define ITD

“Inter Tropical Discontinuity” added.

p.19463, L6-7 - I suggest "due to longwave radiative cooling that is partially offset by shortwave radiative heating"

We have kept the original text, as the longwave cooling is more than offset by the shortwave warming at TOA and the surface to give net heating.

p.19463, L14 - TCWV may be associated with daily fluctuations in TOA radiation but could this be through co-variability in temperature and cloud

Amended to,

“However, variations in water vapour (and associated variables such as temperature and cloud) and not variations in dust dominates day-to-day variability of TOA net radiation”

p.19463, L27 - is there a reference for the ERA-I underestimation in cloud (also next page L23)?

We have added a reference where cloud bias is discussed, “These comparisons with data both support the hypothesis that ERA-I underestimates cloud cover (consistent with Dolinar et al (2015) Figure 4).”

p.19464, L4 - although the effect of TCWV is weak overall there is a strong physically robust influence on surface net longwave which could be stressed here

Added, “Although increasing TCWV reduces the surface longwave cooling, the effect of TCWV on the net surface radiation is weak, variable and a subtle balance between the competing effects of water vapour, clouds and dust (-0.2 W kg^{-1}).”

p.19465, L3 "it is important that"

Added

p.19463-5 - can the energy advection be implied from these results?

The TOA net heating suggests a balancing advective cooling, but there can be significant heat gain/loss in the system on these time-scales, and we prefer not to discuss here as we cannot say where the advection is occurring.

Figure 1 is a bit small

This has been made larger, with many figure moved to supplementary material, at the suggestion of another reviewer.

Figure 5 is a nice idea - I think it could have more impact to simply show a moist dusty and dry clear profile in a 2-panel figure

We would prefer to keep the four panels, as we wish to separate the effects of TCWV and AOD (as much as we can from our approach) and although dust and TCWV are correlated, no all moist atmopsheres are dusty, or all dusty atmospheres moist.

Figure 4 - "convergence" in the y-axis title is potentially misleading and should be changed to radiative convergence/divergence or heating/cooling

If “convergence/divergence” (or “heating/cooling”) is used the reader does not know the sign convention. A convergence of radiative flux gives a heating, so as it is it is clear that the negative values are divergence. The axes are defined in the first line of the relevant section (Section 3.3), “The TOA and surface fluxes are differenced to give the radiative flux convergence within the atmosphere, *i.e*. the direct radiative heating of the atmosphere (Figure 4).”

Reply to Anonymous Referee #2: Marsham et al., The contrasting roles of water and dust in controlling daily variations in radiative heating of the summertime Saharan Heat Low

Marsham et al. detail a very interesting study on the roles of water vapor, aerosols and clouds on the radiative forcing at the top of the atmosphere and at the surface over the Sahara. For their purpose they have used the unique and comprehensive dataset acquired during the 2011 IOP of Fennec in the Saharan Heat Low (SHL) region (so-called BBM supersite) and ERA-I reanalyses from ECMWF. The importance of water vapor in the Saharan region is a hot topic and this study is an important contribution to the subject. Water vapor variability over the Sahara has an influence on the West African Monsoon system across la wide spectrum of scales, from synoptic to decadal. Overall, the paper is well written and well structured. The paper refers to all the relevant literature on the topic, to date. I only have small changes and clarification to suggest at this stage. The paper is acceptable almost as it is.

We would like to thank the reviewer for their valuable review. We address the reviewer's points in turn.

Minor comments

Introduction p 19450, end 1st paragraph: you only are mentioning global operational models. How about mesoscale operational numerical weather prediction models?

This is now clarified,

"Operational models use either prognostic dust or dust climatologies, but struggle to capture variations in summertime dust, partly as cold-pool outflows from convection (haboobs) provide a key uplift mechanism that is missing in operational models that use parametrised moist convection [Marsham et al, 2011; Heinold et al., 2013; Marsham et al., 2013a]."

Method p 19451: line 8: define GERB

Added, "GERB (Geostationary Earth Radiation Budget experiment) measurements"

p 19452: lines 4-5: the count of days is not good, should be 11 days. p 19452: line 5: the count of days is not good, should be 4 days.

Corrected

p 19452, sunphotometer: Is there a reason why you do not consider integrated water vapor retrievals from the sunphotometer in BBM?

The radiosondes give a more consistent measurement frequency and only level 1.5 AERONET data were available for 2012, with level 2 for 2011, so we believe the radiosondes are a more reliable measure of chnages in diurnal-mean water vapour, which is the key requirement for our study.

p 19452: line 18: How do you come up with this number, 3 W m-2?

As stated, "This means that the surface-based Kipp and Zonen can miss up to 3.5 W m^{-2} net shortwave atmospheric heating as would be seen by GERB and up to 3.8 W m^{-2} of the net longwave as would be seen by GERB (Banks et al., 2014).", but these are maximum errors and the diurnal-mean error in atmospheric radiative heating would be lower. To be more explicit we have changed to "up to 4 W m^{-2}"

Results p 19453: line 11: How do you define your appreciation of "good surface data"?

Now clarified,

"Relationships are shown using days where surface data are available (referred to as "Good surface data"),"

p 19453: lines 25:-27: I fully agree. Does this mean that the LLJ associated with the harmattan is the mechanism controlling the relationship between AOD and TCWV? Is this how you explain the low correlation of 0.29?

No. The dry Harmattan LLJ does give dry dusty air, but the main mecahnisms is haboobs and monsoon surges, which both give moist dusty air. There is therefore a positive correlation between TCWV and AOD. This is now clarified,

"The mechanisms underlying this correlation are understood: Marsham et al. (2013a) shows how moist monsoon surges from the south are associated with dust at BBM. This is because the moist surges are associated with both dusty haboobs and moist nocturnal low-level jets (LLJs) that together dominate the dust uplift at BBM in June 2011 [Marsham et al., 2013a; Allen et al., 2013]. The association between dust and water vapour is consistent with Figure 16 in Marsham et al. (2013a), which shows a statistical link between AOD and cloud cover at BBM. Intense dust uplift does sometimes occur in dry air, however, mainly in the dry Harmattan LLJs [Marsham et al., 2013a; Allen et al., 2013]."

Discussion p 19462: line 5: Up to?

Corrected

Conclusion p 19464: line 17: How important is it to have an accurate dust aerosol representation in such models? Would a prognostic dust model improve the correlations in ERA-I?

The paper shows that although dust is important for surface net radiation, TCWV is more important for TOA net radiation. As stated in the conclusions, "The results show that it is important that models used for predictions can accurately capture the processes controlling the water vapour distribution over the Sahara, as well as the dust." A prognostic dust model might improve ERA, but given the dominance of haboobs at BBM and the problems that models have with these we would prefer not speculate.

<u>Reply to review of “The contrasting roles of water and dust in controlling daily variations in radiative heating of the summertime Saharan Heat Low“ by Marsham et al. by Amato Evan</u>

This manuscript uses observations from the Fennec campaign during two summers to investigate the relative roles of total column water vapour (TCWV) and dust in controlling radiative fluxes over the SHL. While I think the data set is an interesting one, I find the paper to be unpublishable in its current form. Most importantly, I think the analysis has one important error that may be leading the authors to make somewhat erroneous conclusions. Furthermore, I find the organization of the paper to be burdensome, with an excess of plots and even improper (or at least odd) use of terminology. Along those lines, the main aim of the paper is not consistent throughout; it seems to vacillate between being a heat budget analysis, an analysis of the influence of dust and TCWV on observations of radiative fluxes, and a comparison between observations and ERAI, but none is truly carried out fully. I recommend major revisions.

We believe that the reviewer has misunderstood our aims. We apologise that our approach was not clear and have now clearly described our aims and methodology in the paper, as described below, to avoid such misunderstandings.

We do not attempt to isolate effects of either TCWV or AOD. The paper is an observationally-based evaluation of the roles of water and dust in the surface and TOA energy balance in the summertime Sahara, comparing unique new observations and ERA-I. We do not aim to determine the sensitivity of fluxes to TCWV alone, or AOD alone, rather to evaluate their contrasting roles in determining day-to-day variability. Although we cannot isolate the effects of TCWV and AOD, the results still provide unique insights. The roles of TCWV and AOD are sufficiently distinct that they can be distinguished despite the correlations between them: the correlation between TCWV and TOA net flux is much stronger than for AOD and TOA net flux, but the reverse is true at the surface. This would not be the case if effects of TWCWV were simply due to associated AOD, or visa versa. We do not attempt a heat-budget analysis, but there is discussion of the implications of our results for the heat budget in the discussion section, clearly separated from the results (as note din the paper “The results give some insight into the Saharan BL energy budget”). Although we cannot analyse all causes of errors in ERA-I, the observational data provide an important and unique check on the analyses in this important region, showing how well they capture the observed relationships, which has important implications.

To avoid such misunderstandings of our aims and conclusions, we now clarify these at the end of the introduction,

“Results in Section 3 show that TCWV and AOD are correlated and we cannot completely isolate the effects of either TCWV or dust. However, TCWV and AOD have sufficiently independent variations, and sufficiently distinct impacts at solar and infrared wavelengths, which conform with physical principles, that the results give unique insights into their contrasting roles in the central Sahara.”,

in the abstract,

“Although the empirical analysis of observational data cannot completely disentangle the roles of water vapour, clouds and dust, the analysis demonstrates that TCWV provides a far stronger control on TOA net radiation, and so the net heating of the earth-atmosphere system, than AOD does. In contrast, variations in dust provide a much stronger control on surface heating, but the decreased surface heating associated with dust is largely compensated by increased atmospheric heating, and so dust control on net TOA radiation is weak”,

and in the conclusions,

“If effects from TCWV were simply due to correlated changes in AOD, or visa versa, these contrasting roles of TCWV and AOD at the TOA and surface would not be so distinct.”

We have made further changes to clarify our aims, our methodology and its limitations as noted under major comment 2 below.

We have reduced the number of plots and no longer use the word “trend” as although we do not think its use was improper, it can clearly mislead some readers.

Major comments

1. In Figure 1a the authors show that TCWV and AOD are correlated. In fact, I think the correlation between the two variables will be much higher if they remove the data points containing the “interpolated” flux measurements; these interpolated data points are largely outliers in the scatter plot.

We wish to use as much data as we can to capture of much of the variability of the natural system we are observing as possible. TCWV and AOD are measured from radiosondes and the Cimel sun-photometer, and so are measured independently of surface flux data and therefore unaffected by any interpolation of the surface flux data. Omitting TCWVs and AODs from days when surface-flux data required interpolation would be misleading and is therefore not justified. Furthermore, the paper notes how the behaviour of the interpolated surface fluxes relationship with TCWV and AODs are physically consistent with the other un-interpolated data.

In the subsequent analysis (Figs 2–5) the authors attempt to quantify the effects of TCWV and AOD on LW & SW radiative fluxes via linear regression. However, since TCWV and AOD are correlated, the linear regressions do not isolate the effect of, for example, TCWV on SW fluxes at the TOA. Rather, they give us the sensitivity of TOA SW fluxes to TCWV + the component of dust (AOD) that is correlated with TCWV. This error is basically carried throughout the entire paper, and may be one of the main reasons why the sensitivity of fluxes to TCWV is much smaller in the ERAI data than in the observations.

If the authors want to determine the sensitivity of fluxes to TCWV alone, or AOD alone, then they must modify their statistical approach, or perhaps use a radiative transfer model (*e.g.*, STREAMER in Evan et al. 2015, J. Clim.).

As noted above the reviewer has misunderstood our aims, we do not aim to isolate the effects of TCWV or AOD, and we have clarified these in the paper (see above). Although we cannot determine the sensitivity of fluxes to TCWV or AOD alone the results reveal their contrasting roles and the conclusions are novel and well supported. Radiative transfer modelling would be needed to fully disentangle effects (and for clouds this is complex and there is a shortage of data) and this is out of scope as noted by other reviewers. This observationally-based study will provide motivation for future model studies to test the hypotheses raised.

To avoid such misunderstandings of our aims and conclusions, in addition to the changes noted above in reply to the reviewer's first comments, we now also clarify these at the start of the results,

"In order to determine how the changing amounts of water and dust over BBM affect the changing radiative heating at the surface, TOA and within the atmosphere we analyse relationships …" and "There are correlations between dust and water (discussed below) which mean that effects of either cannot be completely isolated from the other, but nevertheless the approach allows identification of how variations in these variables affect radiative heating.",

in the discussion,

"Although modelling is needed to fully understand the observed effects of water vapour on the radiation"

and this is already discussed at the start of the conclusions,

"Although there are limits to the extent to which our empirical approach can disentangle the roles of dust, cloud and water vapour, largely due to correlations between these factors, the results provide new insight into their roles in controlling the radiative balance of the unique environment of the central Sahara (schematic in Figure 5)."

We also made other have changes to the text that clarify our approach and what we infer. In the results,

"At the surface there is a strong and significant decrease in net radiation with increasing AOD (Figure 3b) with a regression coefficient of -13.1 W m^{-2} per AOD".(new with-bold-font page 8 line 26)

"Decreases in surface heating associated with dust are largely compensated by direct radiative heating of the atmosphere" (new with-bold-font page 11 line 2)

And in the conclusions,

“However, variations in water vapour (and associated variables such as temperature and cloud) and not variations in dust dominates day-to-day variability of TOA net radiation”

“At the surface, dust (and associated water vapour and cloud) decreases net surface radiation in reality by around 13 W m^{-2} per AOD.”

As the reviewer rightly points out associations between TCWV and AOD may explain why the sensitivity of fluxes to TCWV is much smaller in ERA-I than in the observations, but this is noted in the paper, “The differences in the effects of TCWV in ERA-I and in observations are likely because of both errors in clouds in ERA-I and its lack of variability in dust” (We also note that there are numerous other places in the original paper where the importance of correlations between TCWV And ANOD are noted, e.g. “Impacts of TCWV on surface net heating are therefore a subtle balance of water vapour, clouds and associated dust”, “The underestimate of the longwave effect of TCWV at TOA in ERA-I is consistent with this suspected underestimation of cloud cover in ERA-I and also the lack of dust associated with TCWV”, “ the decrease in net shortwave with increased water vapour (-0.98 W kg^{-1}, Figure 2g), due to water vapour and associated clouds and dust.”, “much of the shortwave effects of TCWV are indirect, occurring via associated clouds and dust.”, “some of the observed trends with AOD are due to associated water vapour and cloud”, “*i.e*. dust, together with the water vapour and cloud associated with the dust, warms the surface in the longwave”, “ERA is of course lacking the variability in dust that correlates with TCWV”).

2.The purpose of the PCA is not clear (this is not explicitly indicated in the manuscript), and it’s difficult to determine exactly how the PCA was applied (also not explicit in the manuscript). If the PCA is important, why not dedicate a figure showing the PC time series and a table indicating the PC loadings for the various time series (it would be nicer for the reader to have these #s in a table rather than having to search through the paragraph to find relevant sign changes). Also, was the interpolated data included in the PCA? If so, are the PCA results changed if the interpolated data is not included?

The PCA results are revisited on page 19458, where it is stated that the results from the linear regressions are consistent with the PCA analysis. But here the authors are only reiterating that in the scatterplots the net surface flux is negatively correlated with dust and weakly correlated with TCWV, and that at TOA, TCWV is positively correlated with TCWV and weakly correlated with dust? Why do we need a PCA if we are only summarizing a subset of the scatterplots? I just don't see any scientific understanding added by the PCA, as it stands.

The authors found PCA a useful way to summarise the key modes of variability and their importance. They have however been removed as they are not essential to our conclusions and this simplifies the manuscript as the reviewer suggests.

3.Some of the text in the results sections is a bit confusing. For example, the authors write (P 19455, L 27), "*Daily variations in SW are anti---correlated with variations in LW such that as daily net TOA SW decreases, the net LW increases.*" The authors are simply stating that LW cooling balances SW heating. But is this surprising? Did the authors not expect this to be the case? It just feels like stating the obvious for no clear reason.

Shortwave heating does not have to balance longwave cooling on the time-scale of one day and the observations show that although, as expected, it does to a great extent, it does not completely. This is important and explored in the next sentences (discussed below).

On the next line, "*...decreased SW tends to lead to an increase in net heating due to the corresponding greater increase in LW*". I have spent some time trying to wrap my head around this statement, and I just can't make sense of what the authors are arguing here. As the downwelling solar insolation gets smaller, the radiative imbalance gets larger, and the upward LW radiation at the TOA gets smaller. Are the authors arguing that the net heating of the atmosphere is only a function of SW down? Surely other processes (thermodynamic and dynamic) are limiting the net heating? Are the authors assuming that net heating and net radiative heating of the atmosphere is the same thing?

We are sorry that our wording was not clear and we believe our argument has been misunderstood. We are not arguing as proposed above; the words "lead to" have probably caused this misunderstanding.

A multitude of factors affect daily-mean TOA net SW and LW over the BBM site in summer: the temperature and humidity profile, the dust profile, the cloud profile, and how these vary through the day. These factors are, as the reviewer notes, correlated and the net result of these competing effects is not obvious and has not previously been measured in the remote central Sahara; it might, for example, be hypothesised that days with extensive cloud cover and so reduced TOA net SW would have reduced TOA net, but we show that in our dataset the reverse is true, as on days with reduced TOA net SW there is a more-than-compensating increase in net TOA LW. Interestingly ERA captures this relationship at TOA but not at the surface.

To clarify this we now state,

“The observed gradient is -1.4, *i.e.* days with net shortwave reduced by combinations of dust and cloud are associated with increased longwave heating (i.e. reduced longwave cooling) from the water vapour, dust and cloud that more than compensates for the decreased shortwave heating, resulting in greater net heating on these days.” (new with-bold-font page 7 line 19)

Afterwards the authors write, “*As such, TOA daily variability at BBM is influenced more by variability in the LW than the SW.*” I don’t understand the justification for this statement. LW cooling is a response to SW heating. The two are coupled, and I don’t see how one can so cleanly disentangle them via the analysis presented here.

Again we believe the reviewer has misunderstood our reasoning. The two are coupled, but, on the time-scale of a day, for example: a large increase in water vapour will, without clouds, have a greater effect on net longwave than net shortwave, warming the system; brightening the land-surface would reduce net shortwave and not affect the surface emissivity, cooling the system. We have rephrased to avoid confusion we now state,

“Figure 1b shows how there is greater variance in daily longwave cooling than shortwave warming and therefore, although they are coupled, variations in longwave cooling make the larger contribution to variations in TOA net radiation.”

1. The authors discuss the role clouds play in discrepancies in the regression coefficients between obs and ERAI (P 19456), “*The underestimate of the longwave effect of TCWV at TOA in ERA---I is consistent with this suspected underestimation of cloud cover in ERA---I...*” I’m not entirely clear what the “longwave effect” is referring to. Is this the sensitivity of OLR to solar insolation? If so, then I find this argument troubling precisely because the authors had previously stated that the time series of observed and ERAI cloud were highly correlated. I would think that the regression coefficient would not be sensitive to the cloudiness mean state; the offset would be sensitive to the mean state, but not the slope of the best---fit line. Furthermore, the last line in this paragraph, about the “magnitude of the trends” in OLR, etc... seems to have very little to do with the discussion of the clouds (and dust).

This has clearly been misunderstood, so we have now clarified,

“The underestimate of the regression coefficient of TOA net longwave with TCWV in ERA-I compared with observations(1.8 compared with 3.2 W kg^{-1}) is consistent with this suspected underestimation of cloud cover in ERA-I and also the lack of dust associated with TCWV reducing outgoing longwave (Haywood et al., 2005).”. This means that the last line,

“However, in ERA-I the underestimation of the magnitude of the regression coefficient of TOA net longwave with TCWV (1.8 compared with 3.2 W kg^{-1}) and shortwave with TCWV (-0.48 compared with -0.98 Wm^{-2}) compensate to some extent give a trend in TOA net radiation with TCWV of 1.3 W kg-1 in ERA-I, close to the 2.2 W kg-1 observed.”

is in a logical place and directly follows on from the preceding statements.

Lastly, there are way too many plots in this paper. Between figures 2–4 there are 29 scatterplots!!! Does the reader really need to go through 29 scatter plots when the only real message coming from them is that surface flux variability is strongly dependent on dust concentrations, and TOA flux variability is strongly dependent on TCWV variability (and that these two features are weaker in ERAI). I think I could show that in... 2 scatter plots. This multitude of plots is particularly unnecessary given the very nice summary schematic in Figure 5. Reducing the number of plots will help to clarify the message and make the paper more readable. If you want to showcase the Fennec observations, just put the excess plots online somewhere or in a supplement.

Since TCWV and AOD are correlated it is important to examine the changes in both shortwave and longwave fluxes with each, as well as in net fluxes, in order to reach robust conclusions, and we therefore included all plots in the submitted paper. The correlations and regression coefficients from all plots are, however in Table 1, and although other reviewers did not comment on this, we have moved many of the plots to 'Supplementary Material'.

Minor Comments

1. **With regards to the effect of TCWV on surface radiative fluxes, it would be nice to compare your numbers with those presented for Tamanrasset in Evan et al. (2015, J. Clim.).**

   This has been added,

   "The observed increase in surface net longwave with TCWV of 2.0 W kg^{-1} is within the range of 1.0 to 3.0 W kg^{-1} obtained by Evan et al. (2015) for Tamanrasset from observations, analyses and radiative transfer modelling. In summer at Tamanrasset TCWV might be expected to correlate with AOD as it does at BBM, and dust and clouds associated with TCWV in reality, but missing or under-estimated in analyses and radiative transfer modelling, may account for the greater sensitivity of surface net longwave to TCWV in observations compared with radiative transfer modelling and analyses, noted by Evan et al. (2015). The BBM value of 2.0 W kg^{-1} is slightly lower than the diurnal-mean observational value of 3.0 Wkg^{-1} for Tamanrasset obtained by Evan et al. (2015), which may reflect the greater prevalence of clouds at the high-altitude Tamanrasset site, where mountains trigger moist convection (Birch et al., 2012). The BBM results also suggest that although the increases in net surface longwave with TCWV shown by Evan et al. (2015) could largely be compensated by coincident decreases in net surface shortwave (as at BBM), this is not expected at TOA, supporting Evan et al. (2015)'s proposed role of water vapour in warming the SHL."

   Thank you for suggesting this, it helps put our results in a wider context.

2. **The word "trend" is improperly used throughout the manuscript. A "trend" implies some linear change in a time series (at the very least this is common usage in our field), but here the word "trend" is confusingly used to describe a "regression coefficient". More appropriate terms would be *regression coefficient*, *sensitivity*, or *slope of the linear regression*.**

A trend does not have to imply a change with time in physical science and is widely used for any linear relationship. In climate science it is often used for changes with time, so we have now avoided using “trend” in this context and use “regression coefficient” .

3. **The text in the scatterplots is too small to read (and it’s nearly impossible to differentiate the asterisks from the crosses). Also, it would be appropriate to include mention of statistical significance of those regression lines. This will allow the authors to objectively evaluate which fluxes have a dependency on dust or TCWV.**

The symbols have been changed and some plots made larger, so that all plots are clear. As noted in caption to Table 1 and stated in the first paragraph of the results, “bold values are significant at 90 % level”.

The contrasting roles of water and dust in controlling daily variations in radiative heating of the summertime Saharan Heat Low

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Abstract

The summertime Sahara Heat Low (SHL) is a key component of the West African Monsoon (WAM) system. Considerable uncertainty remains over the relative roles of water vapour and dust aerosols in controlling the radiation budget over the Sahara and therefore our ability to explain variability and trends in the SHL, and in turn, the WAM. Here, new observations from Fennec **supersite-1 in the central Sahara** during June 2011 and June 2012, together with satellite retrievals from GERB, are used to quantify how total column water vapour (TCWV) and dust aerosols (from aerosol optical depth, AOD) control day-to-day variations in energy balance in both observations and ECWMF reanalyses (ERA-I). The data show that the earth-atmosphere system is radiatively heated in June 2011 and 2012. **Although the empirical analysis of observational data cannot completely disentangle the roles of water vapour, clouds and dust, the analysis demonstrates that TCWV provides a far stronger control on TOA net radiation, and so the net heating of the earth-atmosphere system, than AOD does.** In contrast, **variations in** dust provide **a much stronger** control on surface heating, but the decreased surface heating **associated with** dust is largely compensated by increased

atmospheric heating, and so dust control on net TOA radiation is weak. Dust and TCWV are both important for direct atmospheric heating. ERA-I**, which assimilated radiosondes from the Fennec campaign,** captures the control of TOA net flux by TCWV, with a positive correlation (r=0**.**6) between observed and modelled TOA net radiation, despite the use of a monthly dust climatology in ERA-I that cannot capture the daily variations in dustiness. Variations in surface net radiation, and so the vertical profile of radiative heating, are not captured in ERA-I, since it does not capture variations in dust. Results show that ventilation of the SHL by cool moist air leads to a radiative warming, stabilising the SHL with respect to such perturbations. It is known that models struggle to capture the advective moistening of the SHL, especially that associated with mesoscale convective systems. Our results show that the typical model errors in Saharan water vapour will lead to substantial errors in the modelled TOA energy balance (tens of W m^{-2}), which will lead to errors in both the SHL and the WAM.

1 Introduction

The Sahara lies under the descending branch of the Hadley circulation and during summer the intense solar heating combined with the arid environment leads to large sensible surface heat fluxes and the formation the Saharan Heat Low (SHL). This increases the pressure gradient from the Gulf of Guinea to the Sahara, driving the West African Monsoon (WAM), and variations in the SHL modify the WAM on time scales from days to decades [Thorncroft and Blackburn 1999; Peyrillé and Lafore 2007; Biasutti et al., 2009, Lavaysse et al, 2009, 2010; Chauvin et al., 2010, Xue et al., 2010, Martin and Thorncroft 2014, Martin et al., 2014, **Dong and Sutton, 2015**]. There is a shortage of routine observations in the SHL and substantial disagreements exist even between analyses [Marsham et al., 2011; Roberts et al., 2014]. The Fennec project aimed to better quantify processes governing the Saharan atmosphere [Washington et al., 2012; Ryder et al., 2015] and deployed an observational supersite-1 close to the climatological centre of the SHL [Marsham et al., 2013a].

The radiative budget of the Sahara is significantly modulated by variations in clouds, dust and water vapour. Charney (1975) shows how the high albedo and dry atmosphere can lead to a top-of-atmosphere (TOA) net radiative cooling in July, with heating via subsidence, proposing a positive feedback where dry soils with little vegetation generate high albedo, favouring atmospheric descent and low rainfall. The dry atmosphere means that water vapour provides a key control in the longwave with vapour at all levels affecting top-of-atmosphere (TOA) outgoing longwave (Allan et al., 1999; Brindley and Harries, 1998). Evan et al. (2015) suggest that the increasing temperatures within the SHL over the past 30 years, key to the recovery of the Sahel from drought, are driven by longwave impacts of increasing water vapour, in the "Saharan Water Temperature" feedback **and Dong and Sutton (2015) propose a greenhouse-gas driven increase with a feedback through water vapour.** Shallow clouds on top of the deep dry boundary layer [Cuesta et al., 2009] occur around 20% of the time over the Sahara, with mid-level clouds reducing net surface shortwave and increasing net surface longwave in the Sahel [Stein et al., 2011; Bouniol et al., 2011]. Dust absorbs and emits longwave radiation (Haywood et al., 2005) and scatters and absorbs shortwave [Ryder et al., 2013; Banks et al., 2014]. At the TOA, and over the bright Sahara, dust induces a warming as its longwave effects dominate its shortwave effects (Balkanski et al., 2007; Yang et al., 2009). Operational models use either prognostic dust or dust climatologies, but struggle to capture variations in summertime dust, partly as cold-pool outflows from convection (haboobs) provide a key uplift mechanism that is missing in **operational** models **that use parametrised moist convection** [Marsham et al, 2011; Heinold et al., 2013; Marsham et al., 2013a].

At low levels the Sahara is cooled by advection from neighbouring moister and cooler regions, including the WAM to the south. Representing the monsoon is a challenge to models, partly because of the representation of convection, in particular its diurnal timing and cold pools; the diurnal timing of Sahelian moist convection affects the pressure gradient driving the monsoon, modulating the flux of water vapour from the Sahel to the Sahara and hence rainfall over the Sahel (Marsham et al., 2013b; Birch et al., 2014). Furthermore cold pools form a significant component of the monsoon (Marsham et al., 2013b) and also ventilate the Sahara from the Atlas in the north [Emmel et al., 2010]; most temperature and humidity biases in the Met Office global model at the Fennec supersite-1 during June 2011 were caused by missing cold pool advection [Garcia-Carreras et al., 2013]. Similarly ventilation of the Sahara by the Atlantic Inflow involves mesoscale flows that are a challenge for global models [Grams et al., 2010; Todd et al., 2013]. Since clouds, water vapour and dust are all important to the Sahara's radiative energy balance, such model errors in convection, clouds, haboobs and advection of water vapour will all affect modelled radiative energy balances and hence climate.

There is a clear need to establish the controls on the radiation budget over the Sahara and evaluate models. In this paper we use observations of surface radiative fluxes from Fennec **supersite-1 in the central Sahara** and retrievals of TOA fluxes from satellite data to investigate how dust and water **together** control the day-to-day variations in energy balance over the Fennec supersite-1 in the summertime SHL region, and how this is represented in ERA-Interim (ERA-I) reanalysis. **Results in Section 3 show that TCWV and AOD are correlated and we cannot completely isolate the effects of either TCWV or dust. However, TCWV and AOD have sufficiently independent variations, and sufficiently distinct impacts at solar and infrared wavelengths, which conform with physical principles, that the results give unique insights into their contrasting roles in the central Sahara.** Section 2 describes methods, section 3 presents results, section 4 contains discussion and conclusions are in section 5.

2 Method

We use data from Fennec supersite-1 in the central Sahara, located at Bordj-Badji Mokhtar (BBM) at 21.4N 0.9E **(in the very south of Algeria, close to the triple point of Algeria, Mali and Niger)**, close to the SHL's climatological centre and the dust maximum [Marsham et al., 2013a], together with corresponding values from ERA-Interim [Dee et al., 2011], and satellite TOA fluxes (Harries et al., 2005; Dewitte et al., 2008). These satellite TOA fluxes are produced using a narrow to broad band conversion of SEVIRI (Spinning Enhanced Visible and Infrared Imager) radiance measurements. These are scaled by co-located GERB **(Geostationary Earth Radiation Budget experiment)** measurements and converted into broadband fluxes measurements at a horizontal resolution of 3×3 SEVIRI pixels (0.32-4 microns in the shortwave, and 4-100 microns in the longwave). This enhancement gives a spatial resolution of 9km at nadir, compared with the 45km of the native GERB. These observed fluxes are from clear and cloudy skies, but we also use the European Organisation for the Exploitation of Meteorological Satellites' MPEF (Meteorological Product Extraction Facility) cloud mask as a simple measure of cloud cover. **ERA-Interim uses aerosol climatologies so cannot capture day-to-day variations in dust. Radiosonde data from the Fennec supersite were assimilated into ERA-I, which will have improved its representation of the thermodynamic profile (see Garcia-Carreras et al., 2015 for impacts of assimilation of Fennec radiosondes on the Met Office global forecast model).**

Fennec data are from intensive observation periods (IOPs) in June 2011 and 2012, when a Cimel sun photometer provided Aerosol Optical Depths (AODs) at 675 nm, a Kipp & Zonen radiometer mounted at 2 m provided measurements of broad-band radiative fluxes and 3 to 6-hourly radiosonde observations were available (Marsham et al., 2013a). The sun-photometer is part of the AERONET program (Holben et al., 1998) and cloud-screened AOD retrievals are only available during the day. Level-2 AOD data are not available for 2012 since not all data meet level-2 requirements. However, the 0.675 nm AODs are still reliable. We therefore use level-2 data for 2011 and level-1.5 for 2012, noting that using only 2011 data does not affect our conclusions. We use the radiosondes to compute column water vapour from the surface to 300 hPa (a height consistently reached by the radiosondes), which we refer to simply as "total column water vapour (TCWV)". During June 2011 BBM was regularly cooled by nocturnal monsoon flows and embedded cold pools giving substantial variability in TCWV [Marsham et al., 2013a], and qualitatively similar weather events were observed during June 2012.

In order to study the day-to-day variations in the energy budget, we average all data to their daily means. Complete surface flux data were only available for **11** days in June 2011 (9, 10, 18-20, 23-27, 30 June) and 25 days in June 2012 (all except **4**, 16-18, 30 June). Some dates had short data gaps (around two hours on two days, but otherwise an hour or less) and these gaps were interpolated across in order to include 7, 17, 21, 22 June 2011 and 16-17 June 2012. This gave an improved range of AODs, albeit with increased uncertainties in surface fluxes. Fluxes from these days with some interpolation are marked by **squares** in Figures 1 to 4, and the effects of interpolation are discussed in Section 3, where it is seen that results from these days are physically consistent with other data from days without interpolation. The surface flux data from Kipp and Zonen radiometers have slightly different spectral ranges to the satellite-borne GERB: Kipp and Zonen are 0.3 to 2.8 µm in the shortwave and 4.5 to 42 µm in the longwave, whilst GERB is 0.32 to 4 µm and 4 to 100 µm. This means that the surface-based Kipp and Zonen can miss up to 3.5 W m^{-2} net shortwave atmospheric heating as would be seen by GERB and up to 3.8 W m^{-2} of the net longwave as would be seen by GERB (Banks et al., 2014). This introduces errors of up to **4** W m^{-2} in our inferred direct atmospheric radiative heating rates, but does not affect our analysis and conclusions, which is focused on the controls on the variability of these rates, rather than their absolute values.

Sun-photometer AODs were available from 8 June 2011 (with no observations on 13 June) and 1 to 28 June 2012 (with no observations on 17-19 June). Radiosondes were available from 8 June 2011 and 1 to 26 June 2012. The number of observations contributing to the daily mean is variable for AODs, since observations are only made when it is cloud free, but all days except one had at least eight AOD observations and the daily-mean AOD range of 0.2 to 2.7 is similar to that of the observation range in AODs (0.2 to 3.9) and the diurnal cycle in AOD is weak (Marsham et al., 2013a; Banks et al., 2014). Overall this gave 36 days with surface data, observed AOD and observed TCWV and 44 days with TCWV and AOD.

3 Results

In order to determine **how the changing amounts of water and dust over BBM affect the changing radiative heating at the surface, TOA and within the atmosphere** we analyse relationships between the daily means of key variables, using both observed quantities and the equivalent from ERA-I at the location of BBM. ERA-I uses a climatological AOD field and so cannot capture the observed daily variability in AOD. This, in effect, represents a quasi-control experiment for dust variability. **Net fluxes are defined as downward, with increased net downward flux corresponding to increased shortwave heating or reduced longwave cooling.** All correlations and **slopes of linear** regression **lines** discussed are listed in Table 1 (correlations in bold are significant at the 90% level). Relationships are shown using days where surface data are available (**referred to as** “Good surface data”), and for all available data (“All data”) where surface flux data are not required. The **regressions** are very similar whichever dataset is used and values in the text are for “Good surface data”, unless otherwise noted. The effect of subsampling is small for ERA-I, showing that general lessons can be drawn from the observational data, despite the limited time-span of the dataset. **Similarly, for both June 2011 and 2012 analysed water vapour at 850 and 925 hPa and AODs from MISR, Deep blue (Terra and Aqua) and OMI are all within one standard deviation of their mean values (not shown) and there is no indication that the weather regimes affecting BBM in these periods were anomalous.**

There are correlations between dust and water (discussed below) which mean that effects of either cannot be completely isolated from the other, but nevertheless the approach allows identification of how variations in these variables affect radiative heating. Figure 1 shows that there is a significant tendency for more dust with more TCWV, although there are a few dry dusty days (correlation = 0.29). The use of surface flux data with some interpolation (shown by **squares**) allows study of more days with high AODs. The mechanisms underlying this correlation are understood: Marsham et al. (2013a) shows how moist monsoon surges from the south are associated with dust at BBM. This is because the moist surges are associated with both dusty haboobs and moist nocturnal low-level jets (LLJs) that together dominate the dust uplift at BBM in June 2011 [Marsham et al., 2013a; Allen et al., 2013]. The association between dust and water vapour is consistent with Figure 16 in Marsham et al. (2013a), which shows a statistical link between AOD and cloud cover at BBM. Intense dust uplift does **sometimes** occur in dry air, however, **mainly** in the dry Harmattan LLJs [Marsham et al., 2013a; Allen et al., 2013].

3.1 Control of TOA net radiation by water (TCWV) and aerosols (AOD)

Daily mean net TOA radiation is always positive (i.e. downwards) and has a mean value of 26 W m^{-2}, i.e. there is warming of the earth-atmosphere system throughout the period (Figure 2a). Net heating varies between around 0 and 70 W m^{-2}, or approximately 0 to 1.2 K day^{-1} if the heating were distributed over the 5-km deep boundary layer.

There is a significant correlation of 0.74 between TCWV and TOA net radiation. **Figure 2a shows that TOA net downward radiation increases with TCWV (and associated dust and cloud), with a regression coefficient of +2.2 W kg^{-1}.** This is a result of a 3.2 W kg^{-1} increase in TOA net longwave with TCWV in observations (Figure **S1a**), from water vapour, clouds (and associated dust) reducing TOA outgoing longwave. This longwave TCWV effect dominates the decrease in net shortwave with increased water vapour (-0.98 W kg^{-1}, Figure **S1d**), due to water vapour and associated clouds and dust. The correlations are strongest between TCWV and TOA net or longwave radiation (both 0.74 and 0.68), rather than TOA shortwave (-0.36), since the water vapour directly affects the longwave, while the much of the shortwave effects of TCWV are indirect, occurring via associated clouds and dust.

The correlation between AOD and TOA net radiation (Figure 2b) is much weaker than between TCWV and TOA net radiation (0.26 compared with 0.74). Figure 2b shows that TOA net radiation increases with AOD (5.3 Wm^{-2} per AOD, comparable with Balkanski et al., 2007), but this relationship is complex and its magnitude decreases to 3.5 Wm^{-2} if all available data are used (with a correlation of 0.17). The increase in net TOA radiation with AOD occurs because the **increase** in TOA longwave (+10.5 W m^{-2} per AOD) dominates the **decrease in** TOA net shortwave (-5.2 W m^{-2} per AOD; Figures **S1b and S1e**). The observed net effect of dust at TOA and the dominance of the longwave for this effect are both consistent with previous studies (Balkanski et al. 2007; Yang et al., 2009). Banks et al. (2014) show that in clear-sky the diurnal mean effect of dust at BBM is warming in the shortwave. Therefore the observed **reduced** shortwave **heat**ing associated with dust reported in Figure 2 is likely a result of cross correlation of AOD and cloud. This cloud, as well as the water vapour and dust, reduces outgoing longwave, leading to a warming. The effects of AOD and TCWV variations on radiation normalised by the standard deviation (σ) in either AOD or TCWV (Table 1, values in square brackets) show that the variance in TCWV has a much larger effect on TOA net radiation (10.4 Wm^{-2} per σ) than the variance in AOD (3.6 W m^{-2} per σ, or 2.3 W m^{-2} if "All data" are used), *i.e.* most day-to-day variations in net TOA radiation are mostly controlled by TCWV, not AOD.

Figure **2d** shows daily net shortwave heating is always greater than net longwave cooling (the Earth-atmosphere system is warming in June). Daily variations in shortwave are anti-correlated with variations in longwave such that as daily net TOA shortwave decreases, the net longwave increases (correlation of -0.80). In Figure 2d, if the gradient is less than -1, reducing the net shortwave will increase the net flux. The observed gradient is -1.4***, i.e.* days with net shortwave reduced by combinations of dust and cloud are associated with increased longwave heating (i.e. reduced longwave cooling) from the water vapour, dust and cloud that more than compensates for the decreased shortwave heating, resulting in greater net heating on these days. . Figure 2d shows how there is greater variance in daily longwave cooling than shortwave warming and therefore, although they are coupled, variations in longwave cooling make the larger contribution to variations in TOA net radiation.**

3.1.1 TCWV and aerosol effects at TOA in ERA-I

The ERA-I **regression coefficients for** TOA net radiation with TCWV of 1.3 W kg^{-1} (1.4 W kg^{-1} for all data) is similar to that observed (2.2 Wkg^{-1}, 2.1 W kg^{-1} for all data, Figures 2c and 2a). ERA-I captures the **sign of correlations of** both TOA net longwave and shortwave with TCWV, although it underestimates **the magnitude of the regression coefficients for** both (1.8 W kg^{-1} in longwave for ERA-I, compared with the 3.2 W kg^{-1} observed, and -0.48 W kg^{-1} in shortwave for ERA-I compared with the -0.98 W kg^{-1} observed; Figures **S1c** and **S1f**). As observed, reduced net shortwave increases TOA net flux in ERA-I (Figure **2e**, gradient of -1.4).

Even though it does not account for the daily variations in dust, ERA-I captures much of the day-to-day variations in TOA net variation (correlations with observations are 0.62 and 0.73 for "All data" and "Good surface data", not shown). Table 1 shows **that** the **regression coefficients for** ERA-I fluxes with observed AODs are of the correct sign: this suggests that some of the observed trends with AOD are due to associated water vapour and cloud (captured at least to some extent by ERA-I), rather than dust. This is consistent with the lower correlations between observed AOD and observed TOA net flux (0.26) than between observed TCWV and observed TOA net flux (0.74), discussed in the previous section.

The differences in the effects of TCWV in ERA-I and in observations are likely because of both errors in clouds in ERA-I and its lack of variability in dust. Detailed validation of model clouds over the bright dusty Sahara is challenging and beyond the scope of this paper. Here, we note that ERA captures day-to-day variations of mean cloud fraction (correlation with MPEF cloud mask of 0.56), but mean cloud fraction in ERA-I is 0.22, much less than the MPEF value of 0.53, although this value is likely biased high by dust. Surface albedo in ERA-I is very close to observed, but TOA upward shortwave in ERA-I is about 15 Wm^{-2} less than in observations (although daily maxima in these values are similar, not shown). These comparisons with data both support the hypothesis that ERA-I underestimates cloud cover **(consistent with Dolinar et al. (2015) Figure 4).** The underestimate of **the regression coefficient of TOA net** longwave **with TCWV in** ERA-I **compared with observations (1.8 compared with 3.2 W kg^{-1})** is consistent with this suspected underestimation of cloud cover in ERA-I and also the lack of dust associated with TCWV reducing outgoing longwave (Haywood et al., 2005). However, in ERA-I the underestimation of the magnitude of the **regression coefficient of** TOA net longwave with TCWV (1.8 compared with 3.2 W kg^{-1}) and shortwave with TCWV (-0.48 compared with -0.98 Wm^{-2}) compensate to some extent give a trend in TOA net radiation with TCWV of 1.3 W kg-1 in ERA-I, close to the 2.2 W kg-1 observed.

3.2 Control of surface net radiation by TCWV and AOD

At the surface **there is a strong and significant decrease** in net radiation **with increasing AOD** (Figure 3b) with a **regression coefficient** of -13.1 W m^{-2} per AOD. This is a result of compensating longwave and shortwave effects, with the shortwave effect being largest: **Table 1 (and** Figure **S2e**) shows -31.9 W m^{-2} surface net shortwave per AOD, with dust reducing solar heating at the surface (largely compensated by heating the atmosphere above, comparing with -5.2 W m^{-2} TOA net shortwave per AOD, Section 3.3**). Table 1** (Figure **S2b**) shows +20.7 W m^{-2} surface net longwave per AOD, *i.e.* dust, together with the water vapour and cloud associated with the dust, warms the surface in the longwave, but unlike at TOA this does not compensate fully for the shortwave effects. The effects of AOD on net, shortwave and longwave fluxes are consistent between the days with some interpolated values (asterisks) and other days (pluses).

TCWV decreases surface net radiation by 0.20 W kg^{-1} **(Figure 3a).** This is a balance of +2.0 W kg^{-1} from the longwave and -1.8 W kg^{-1} from the shortwave i.e. is a small difference between two large numbers **(Figures S2a and S2d).** Impacts of TCWV on surface net heating are therefore a subtle balance of water vapour, clouds and associated dust. If variations in surface net radiation with AOD and TCWV are normalised by the standard deviation in AOD or TCWV, variability in AOD is seen to dominate the variations in surface net radiation (square brackets in Table 1). For the impacts of TCWV, the days with some interpolated values at first appear to be inconsistent with other days (Figures **3a, S1a, S1d**), but this is due to the high AODs for these days, the effects of which are consistent with other data (Figures 3b, **S2be, S2e**).At the surface, although the observed shortwave and longwave variations are anti-correlated (coefficient = -0.88), they cancel to a much lesser extent than at TOA. Figure 3d shows how decreased shortwave leads to increased net longwave, but this does not tend to compensate fully (gradient of -0.61), so decreased shortwaves gives decreased net surface radiation. As such, daily variability in surface net radiation at BBM is influenced more by variability in the shortwave than the longwave. Again data from days with some interpolation of surface fluxes (**squares**) are consistent with other days (pluses).

The observed increase in surface net longwave with TCWV of 2.0 W kg^{-1} is within the range of 1.0 to 3.0 W kg^{-1} obtained by Evan et al. (2015) for Tamanrasset from observations, analyses and radiative transfer modelling. In summer at Tamanrasset TCWV might be expected to correlate with AOD as it does at BBM, and dust and clouds associated with TCWV in reality, but missing or under-estimated in analyses and radiative transfer modelling, may account for the greater sensitivity of surface net longwave to TCWV in observations compared with radiative transfer modelling and analyses, noted by Evan et al. (2015). The BBM value of 2.0 W kg^{-1} is slightly lower than the diurnal-mean observational value of 3.0 Wkg^{-1} for Tamanrasset obtained by Evan et al. (2015), which may reflect the greater prevalence of clouds at the high-altitude Tamanrasset site, where mountains trigger moist convection (Birch et al., 2012). The BBM results also suggest that although the increases in net surface longwave with TCWV shown by Evan et al. (2015) could largely be compensated by coincident decreases in net surface shortwave (as at BBM), this is not expected at TOA, supporting Evan et al. (2015)'s proposed role of water vapour in warming the SHL.

3.2.1 Effects of TCWV and AOD at the surface in ERA-I

Figure 3c shows that, in contrast with observations (Figure 3a), ERA-I always produces an *increase* in net surface radiation with increasing TCWV (+0.76 W kg^{-1}, compared with -0.20

W kg^{-1}). Figure **3e (gradient -1.1)** shows that at the surface in ERA-I, unlike in observations, decreased net shortwave is always compensated by increased net longwave **(i.e. reduced longwave cooling**). This occurs since in ERA-I greater water vapour **leads to** greater net surface longwave **(i.e. reduced longwave cooling**, Figure **S2c**), without the associated dust to reduce the net surface shortwave (Figure **S2f**): the net surface radiation in ERA-I depends largely on surface longwave, whereas in observations it depends largely on the shortwave. As a result, ERA-I, which uses a monthly dust climatology, fails to capture day-to-day variations in surface net radiation, producing no correlation (0.02) with observations.

Although it does not affect the **regression coefficients** of surface fluxes with TCWV and AOD discussed above, we note here that ERA-I surface net longwave is on average 55 W m^{-2} less than observed, and this is almost all from more upward longwave than observed (not shown). Due to the non-linear nature of thermal emission, the 13% error in upward longwave can be caused by only a 3% error in skin temperature (or from an error in emissivity). Maximum values of daily ERA-I surface net shortwave are similar to observed, but minima are higher, likely from missing dust and cloud. These two errors lead to surface net radiation being around 34 W m^{-2} lower in ERA-I than observed.

3.3 Radiative heating of the atmosphere

The TOA and surface fluxes are differenced to give the radiative flux convergence within the atmosphere, *i.e*. the direct radiative heating of the atmosphere (Figure 4). As expected the atmosphere is cooling in the longwave and is heated in the shortwave. There are statistically significant positive correlations between both TCWV or AOD (which are themselves correlated, Figure 1) and net radiative heating of the atmosphere (Figures 4a and 4b). **This is consistent with the results of Slingo et al. (2006) and Slingo et al., (2009) for dust over the Sahel.** For AOD there is a strong correlation (0.93) with shortwave atmospheric heating (Figure **S3e**, 26.7 W m^{-2} per AOD, comparable with Balkanski et al., 2007) that dominates the trend of net longwave heating with AOD (Figure **S3c**, -10.2 W m^{-2}). There are significant **increases** in net shortwave and net longwave radiative heating of the atmosphere with increasing TCWV (Figures **S3a** and **S3d, Table 1**). The longwave **effect** (Fig. **S3a**) is much less clear than it is at TOA or at the surface, since the **effects** at TOA and the surface (Figures **S1a** and **S2a**) are similar (3.2 and 2.0 Wm^{-2}) and largely cancel.

When trends with TCWV and AOD are normalised by the standard deviations in TCWV and AOD to allow comparison (results in square brackets in Table 1), effects of AOD dominate those from TCWV, but this is much more pronounced in the shortwave. The results therefore show significant shortwave heating of the atmosphere by dust (consistent with Banks et al., 2014), consistent with the large effect of AOD on surface net and surface net shortwave fluxes, with much smaller effects at TOA. Decreases in surface heating **associated with** dust are largely compensated by direct radiative heating of the atmosphere. The shortwave heating from TCWV (correlation coefficient of only 0.19) is similar to that in ERA (**below and Fig. S3f**) showing that is not just from associated dust, but from shortwave absorption by water (although points with unusually high shortwave heating are explained by AODs, Figures **S3d** and **S3e**). Figure **4d** shows how increasing longwave cooling of the atmosphere is more than compensated for by the corresponding increased shortwave heating (gradient = -0.39); atmospheric heating is largely controlled by effects of dust on the shortwave, whereas longwave atmospheric heating is much less variable.

3.3.1 Atmospheric heating in ERA-I

ERA gives weaker longwave atmospheric cooling than observed and therefore less net atmospheric cooling (Figures 4c and **S3c**). Lacking the observed variability in dust, ERA has little variability in atmospheric shortwave heating, with almost no correlation of shortwave heating with observed AODs (Table 1). ERA has a significant **increase** in shortwave atmospheric heating with TCWV (Figure **S3f**, 0.91 W kg^{-1}) from absorption by water (similar to that observed, Figure S3d, 0.78 W kg^{-1}). While observations have a significant, but weak, positive correlation between TCWV and longwave atmospheric heating (Figure **S3a**, 0.34), ERA has a weak insignificant negative correlation (Figure **S3c**, -0.20). **Effects** are weak in both cases, since TOA and surface longwave fluxes both respond similarly to TCWV and ERA is of course lacking the variability in dust that correlates with TCWV and this may contribute to the difference. Despite the weak variation in shortwave atmospheric heating in ERA compared with observations, variations in shortwave dominate the variations in net atmospheric heating, giving increased net heating with increased TCWV (Figure 4c). This is however much weaker than observed (Figure 4a), since ERA has much less variability in net heating due to its use of a dust climatology.

4 Discussion

Since variability in water dominates day-to-day variability in net TOA heating it is crucial for models to capture the water content of the SHL. Small errors in TCWV, **in the altitude of the water vapour, or in associated cloud,** could cause errors in clear-sky longwave radiation comparable with the 50 W m^{-2} from dust seen in Haywood et al. (2005), **or the 20 to 40 W m^{-2} model bias that Allan et al. (2011) show can be removed by the inclusion of dust.** This paper shows that 50 W m^{-2} TOA net longwave corresponds to around 16 kg m^{-2} water (based on the 3.2 W kg^{-1} dependence of TOA net longwave on TCWV, Table 1), roughly equivalent to 3 g kg^{-1} over the 5-km deep boundary layer. Roberts et al. (2014) show that route-mean-square differences in *analyses* of WVMR at 20N in the Sahara are around 1.5 g kg^{-1}, and show a case where differences between different analyses are around 4 g kg^{-1}. Garcia-Carreras et al. (2013) show a global model mean bias of around 1 g kg^{-1} at Fennec supersite-1 in June 2011 in the model first guess (3-to-6 hour forecast), despite assimilation of the Fennec radiosoundings. Models struggle to capture monsoon flow that cools and moistens the SHL, in particular from cold pools [Marsham et al., 2013b; Garcia-Carreras et al., 2013]. This study shows that errors in fluxes of water vapour will lead to a compensating error of insufficient radiative heating from the absence of the moister air. Model errors in dust will affect the vertical distribution of heating and so also affect vertical mixing and dynamics.

The results give some insight into the Saharan BL energy budget during June over BBM. We show TOA net radiative heating of around 26 W m^{-2}. There was an observed mean night-time cooling of around 4 K over an approximately 1 km depth every night [Marsham et al., 2013a], corresponding to around 50 W m^{-2} cooling (not all of this cooling is advective, some is radiative). To compensate for this cooling an additional warming of around 20 W m^{-2} is required. Daily entrainment of free-tropospheric air will raise the BL top, which is lowered by subsidence to give, in the long-term, a constant BL top. We can estimate the heating rate of the BL either from entrainment or subsidence. The 24-hour entrainment flux is perhaps 10 W m^{-2} (20% of the 100 W m^{-2} surface flux for 12 hours). The 24-hour subsidence of a lid of 5 K/100m with 0.1 m s^{-1} is 5 W m^{-2}. These simple estimates therefore leave a mis-match of around 10 W m^{-2}, but show that all terms (net daytime radiative warming, net night-time radiative and advective cooling, entrainment of warm subsiding air) are all of a similar order of magnitude and significant.

Although modelling is needed to fully understand the observed effects of water vapour on the radiation, the observations show that monsoon surges **at BBM are expected to have significant effects on radiative heating rates. I**n June 2011 BBM experienced sudden moistenings of up to around 5 g kg^{-1} (Fig. 5, Marsham et al., 2013a). If we assume that a value of 2.5 g kg^{-1} is more representative of the change over the 5 km deep Saharan BL (Fig. 3 in

Marsham et al. (2013a) shows such monsoon surges tend to directly affect the lower of half of the 5-km layer) this gives a TOA net radiative heating of around 28 W m^{-2} (based a TCWV of 12.5 kg m^{-2} and a dependence of net radiation on TCWV of 2.2 W kg^{-1}, Table 1). If this heating is distributed over the 5 km deep Saharan BL it will result in a warming of around 0.5 K day^{-1}. It will therefore take days for the additional radiative warming to compensate for the cooling of a few degrees experienced in such events. This "radiative rewarming time scale" may be one contributing factor (together with time-scales such as those for advection & mixing time scales and synoptic features such as African Easterly waves) to the variability of the 3-to-30-day variability of the SHL observed by Lavaysse et al (2010).

The observed net radiative heating of the SHL region observed at BBM during June appears to contrast with Charney (1975), which shows heating from subsidence and TOA cooling from radiation for the Sahara in July. However, the Fennec supersite-1 is at the northern limit of the **Inter Tropical Discontinuity** and regularly receives cold moist air from the south [Marsham et al., 2013a]. Charney (1975) Figure 1 shows net TOA heating at the location of the Fennec supersite in July, with TOA net cooling only north of around 22N (interestingly the TOA heating extends northeastwards over the Hoggar mountains, a region that favours northward extent of moist monsoon air [Cuesta et al., 2010]). It is likely that further north away from the moistening from the monsoon the warmer drier atmosphere will give greater longwave cooling and a net radiative cooling, as shown by Charney (1975). This will be further investigated.

5 Conclusions

We have used unique observations of surface energy balance, TCWV and AOD from the central Sahara in June, together with retrievals from GERB, to investigate controls on the day-to-day variations in radiative heating in the SHL region. TOA fluxes show that on average the earth-atmosphere system is warming (26 W m^{-2}), the surface is warming (98 W m^{-2}) and the atmosphere is cooling (74 W m^{-2}), with the longwave cooling and the shortwave warming in each case. Although there are limits to the extent to which our empirical approach can disentangle the roles of dust, cloud and water vapour, largely due to correlations between these factors, the results provide new insight into their roles in controlling the radiative balance of the unique environment of the central Sahara (schematic in Figure 5).

Water vapour and dust are observed to correlate in the central Sahara, likely due to the uplift of dust in monsoon surges and haboobs (Bou Karam et al., 2008; Marsham et al., 2008;

Marsham et al., 2013a). However**, variations in** water vapour **(and associated variables such as temperature and cloud)** and not **variations in** dust dominates day-to-day variability of TOA net radiation, and hence total heating of the earth-atmosphere system. ERA-I captures the observed variation in TOA net radiation (correlation with observations of around 0.65), despite a monthly dust climatology in ERA-I, which cannot capture day-to-day variations in dustiness. Variations in AOD dominate day-to-day variations in surface net radiation, which unsurprisingly are not captured in ERA-I. **If effects from TCWV were simply due to correlated changes in AOD, or visa versa, these contrasting roles of TCWV and AOD at the TOA and surface would not be so distinct.**

At TOA, on average, decreased shortwave heating gives greater net heating due to associated increases in longwave heating. ERA-I captures this and the overall impact of TCWV on TOA net radiation, with a mean increase in TOA net radiation with TCWV of 1.3 W kg^{-1} compared with 2.2 W kg^{-1} in observations. There are, however, compensating errors in the effects of TOA net shortwave and longwave with TCWV in ERA-I. ERA-I under-estimates the effects of TCWV on both TOA longwave and shortwave: it misses corresponding variations in dust and although it captures much of the effects of water vapour, it likely underestimates cloud (and significant uncertainties in analysed water vapour persist at BBM, even when radiosondes are assimilated, Garcia-Carreras et al., 2013).

At the surface, dust **(and associated water vapour and cloud)** decreases net surface radiation in reality by around 13 W m^{-2} per AOD. **Although increasing TCWV reduces the surface longwave cooling, t**he effect of TCWV **on the net surface radiation** is weak, variable and a subtle balance between the competing effects of water vapour, clouds and dust (-0.2 W kg^{-1}). Unlike at the TOA, at the surface decreases in shortwave are on average not compensated by increases in longwave, leading to decreased net radiation with decreased shortwave. In contrast to the observations, ERA-I gives greater net surface radiation with decreased surface shortwave: it is missing the effects of varying dust and can only capture the effects of water and cloud, likely underestimating cloud. This gives no correlation between ERA-I surface net radiation and that observed and a mean heating of 98 W m^{-2} compared with the observed value of 64 W m^{-2}, due to an overestimation of surface downward shortwave in ERA-I. Differences between TOA and surface fluxes are used to infer atmospheric radiative heating. Effects from TCWV on these are significant, but they are more strongly controlled by AODs, since dust has a much greater effect on surface net radiation than TOA net radiation, while effects of TCWV on TOA and surface heating are more similar.

The results show that, when the SHL is cooled by cold moist air from its margins, the overall effect is to increase net TOA radiative heating, rewarming the SHL, a feedback which stabilises the system, by rewarming the cool air. This occurs in both reality and ERA-I. This ventilation by cold air is, however, normally accompanied by clouds and dust, which together reduce surface net radiation, which is not captured by ERA-I, as ERA-I is missing the variations in dust (and likely under-predicts cloudiness). As a result, even if ERA-I gives the correct TOA net radiation in response to water vapour, it fails to distribute this heating correctly in the vertical, with too much surface heating and insufficient boundary-layer heating. This will destabilise the boundary-layer profile compared with reality, affecting subsequent modelled dry and moist convection and therefore modelled transport of heat, momentum, water vapour and dust.

Improved modelling of the energy budget of the SHL region is needed in models to improve predictions of the WAM across time scales (e.g. Evan et al., 2015). The results show that it is important that models used for predictions can accurately capture the processes controlling the water vapour distribution over the Sahara, as well as the dust. This capability is currently questionable for both water [Marsham et al. 2013b; Birch et al. 2014; Garcia-Carreras et al. 2013; Roberts et al., 2014], **clouds (Roehrig et al. 2013; Stein et al., 2015)** and dust [Evan et al., 2014], with many dust errors coming from moist convection [Marsham et al., 2011; Heinold et al 2013]. The results presented here therefore strongly motivate the need to improve the representation of advection of water vapour, clouds and convection in models.

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	Observations		ERA-I	
	Good surface data	All data	Good surface data	All data
TCWV : AOD (kg m^{-2})	0.04 (**0.29**)	0.04 (**0.30**)	0.02 (0.16)	0.02 (0.14)
AOD : TOA Net (W m^{-2})	5.3 [3.6] (**0.26**)	3.5 [2.3] (0.17)	1.7 (0.12)	0.33 (0.02)
AOD : TOA Net LW (W m^{-2})	10.5 [7.2] (**0.33**)	8.5 [5.5] (**0.26**)	2.4 (0.12)	1.0 (0.05)
AOD : TOA Net SW (W m^{-2})	-5.2 [-3.6] (**-0.28**)	-5.0 [-3.3] (**-0.26**)	-0.72 (-0.07)	-0.70 (-0.06)
TCWV : TOA Net (W kg^{-1})	2.2 [10.4] (**0.74**)	2.1 [9.2] (**0.68**)	1.3 (**0.66**)	1.4 (**0.66**)
TCWV : TOA Net LW (Wm^{-2} $kg^{-1}m^2$)	3.2 [15.0] (**0.68**)	3.0 [13.3] (**0.63**)	1.8 (**0.61**)	2.0 (**0.65**)
TCWV : TOA Net SW (W kg^{-1})	-0.98 [-4.6] (**-0.36**)	-0.9 [-4.1] (**-0.33**)	-0.48 (**-0.30**)	-0.49 (**-0.30)**
TOA Net SW : TOA Net LW	-1.38 (**-0.80**)	-1.35 (**-0.79**)	-1.44 (**-0.78**)	-1.39 (**-0.72**)
AOD : Surface Net (W m^{-2})	-13.1 [-9.0] (**-0.70**)	NA	3.4 (**0.34**)	3.2 (**0.31**)
AOD : Surface Net SW (W m^{-2})	-31.9 [-21.8] (**-0.87**)	NA	-1.6 (-0.12)	-1.7 (-0.12)
AOD : Surface Net LW (W m^{-2})	20.7 [14.2] (**0.81**)	NA	5.0 (**0.28**)	4.9 (**0.27**)
TCWV : Surface Net (W kg^{-1})	-0.20 [-0.96] (-0.07)	NA	0.76 (**0.53**)	0.85 (**0.57**)
TCWV : Surface Net LW (W kg^{-1})	2.0 [9.3] (**0.54**)	NA	2.2 (**0.84**)	2.2 (**0.85**)
TCWV : Surface Net SW (W kg^{-1})	-1.8 [-8.2] (**-0.33**)	NA	-1.4 (**-0.69)**	-1.4 **(-0.68**)
Surface Net SW : Surface Net LW	-0.61 (**-0.88**)	NA	-1.1 (**-0.83)**	-1.1 **(-0.82**)
AOD : Atmospheric Net (W m^{-2})	18.5 [12.1] (**0.62**)	NA	-1.75 (-0.13)	-2.9 (0.21)
AOD : Atmospheric Net LW(W m^{-2})	-10.2 [-6.7] (**-0.41**)	NA	-2.65 (-0.18)	-3.9 (**-0.26**)
AOD: Atmospheric Net SW (W m^{-2})	26.7 [17.5] (**0.93**)	NA	0.91 (0.13)	1.0 (0.15)
TCWV : Atmospheric Net (W kg^{-1})	2.4 [10.7] (**0.56**)	NA	0.51 (**0.26**)	0.54 (**0.27**)
TCWV : Atmospheric Net LW (W kg^{-1})	1.2 [5.4] (**0.34**)	NA	-0.41 (-0.20)	-0.36 (-0.17)
TCWV : Atmospheric Net SW (W kg^{-1})	0.78 [3.4] (**0.19**)	NA	0.91 (**0.93**)	0.90 (**0.91**)
Atmos Net SW : Atmos Net LW	-0.39 (**-0.45**)	NA	-0.73 (**-0.35**)	-0.79 (**-0.36**)

Table 1. Gradients of best-fit straight lines **(i.e. regression coefficients)** for listed relationships, values in [ ] are normalised by standard deviation of TCWV or AOD. Values in ( ) are correlation coefficients (bold values are significant at 90% level). For ERA-I observed

AODs are used. Standard deviation in TCWV in ERA-I = 4.7 kg m^{-2} (4.5 for “All data”). For observations 4.7 kg m^{-2} (4.4 for “All data”). Standard deviation in AOD for observations is 0.68 (0.65 in “All data”).

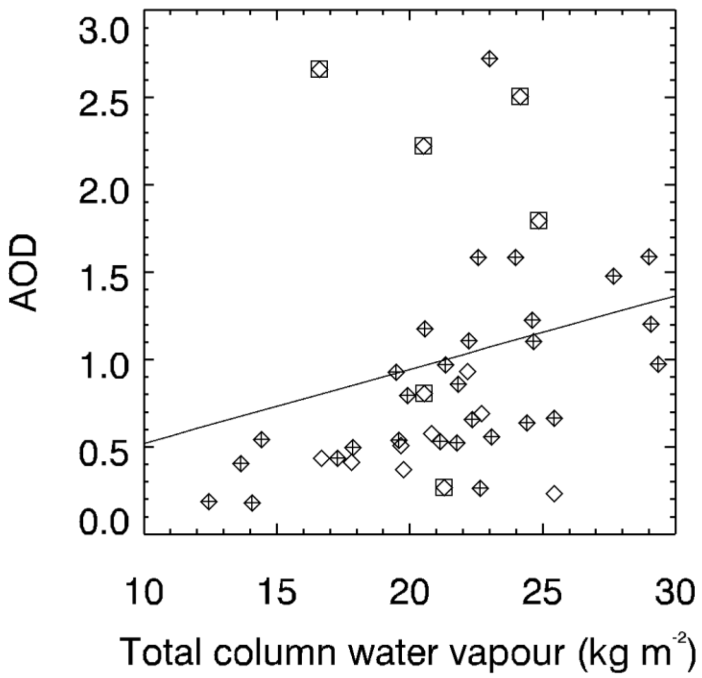

Figure 1. Daily means TCWV and AOD, pluses show days with complete surface data, squares days with some interpolation (see Section 2). Diamonds show all data points (including days with no surface-flux data).

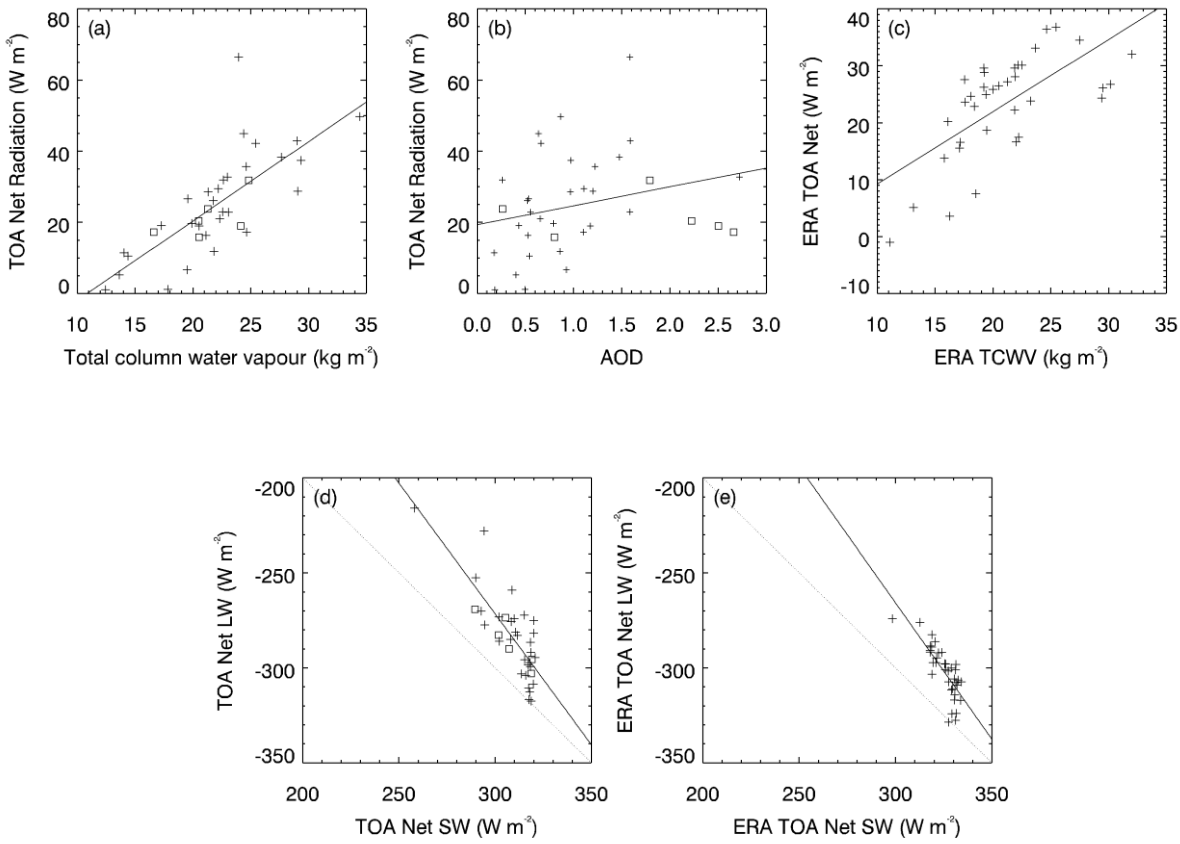

Figure 2. TOA fluxes, with symbols as in Figure 1, showing daily-means for days with surface data. Dotted lines in (d) and (e) have a gradient of -1.

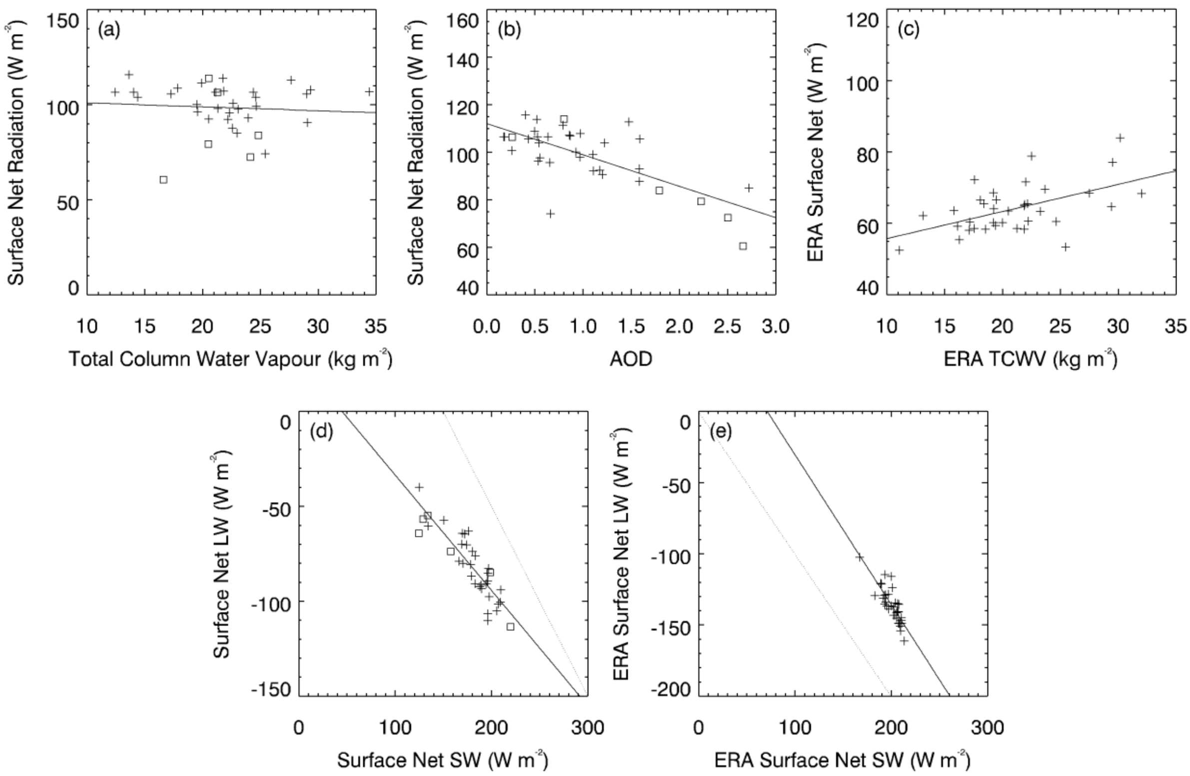

Figure 3. As Figure 2, but for surface fluxes.

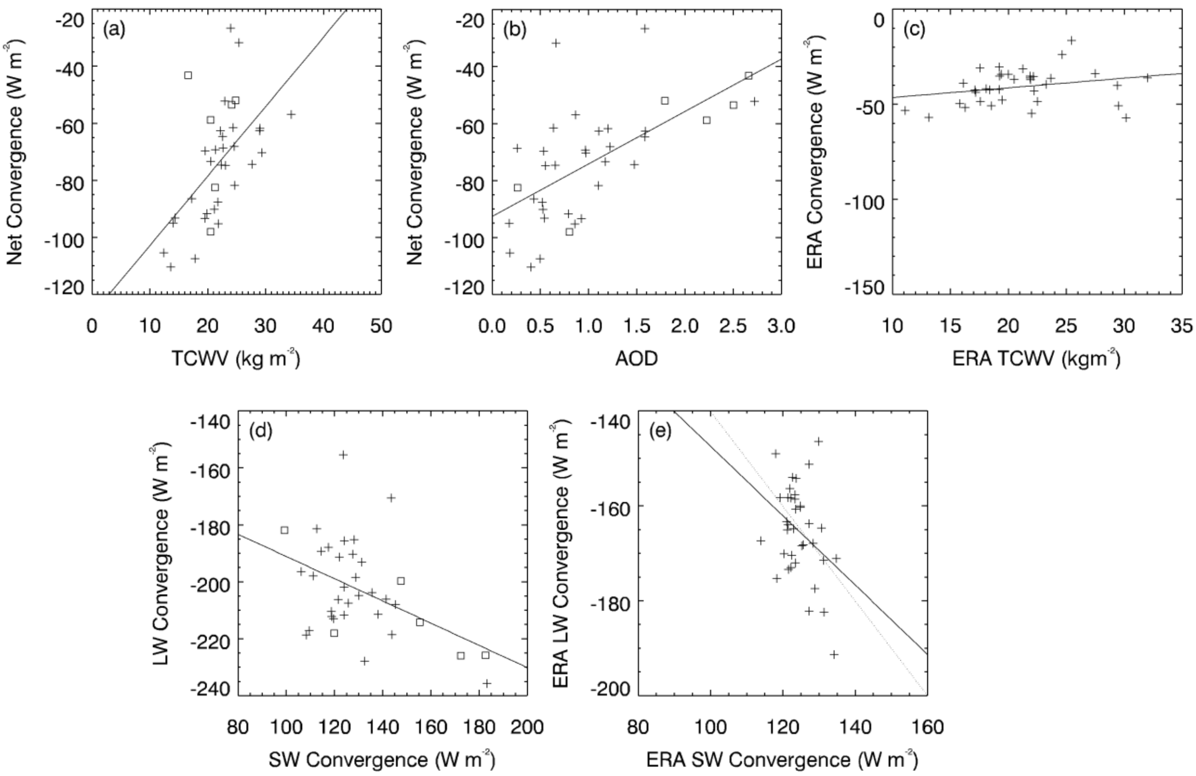

Figure 4. As Figure 2, but for inferred atmospheric heating (TOA flux minus surface flux).

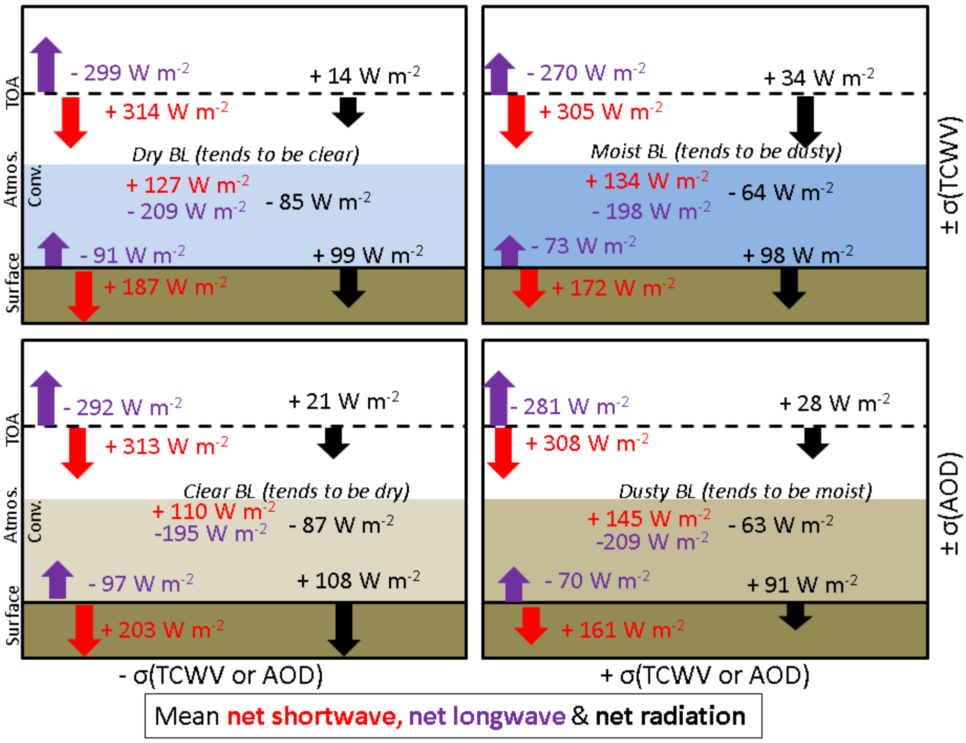

Figure 5. Schematic showing net radiation and implied tropospheric radiative heating, in situations where either TCWV (top row) or AOD (bottom row) is perturbed by plus or minus one standard deviation away from their mean state (right and left columns respectively). Moist atmospheres tend to be dusty and visa-versa. Red numbers show net shortwave, purple show net longwave and black show net radiation. TOA and surface heating are shown by plus signs with downward arrows. Values are shown at surface, TOA and for inferred atmospheric radiative heating (“Atmos. Conv.”). Variance in TCWV has the dominant effect on net TOA radiation, while variance in AOD has the dominant effect on net surface radiation. Both TCWV and AOD are important for atmospheric heating rates.