

## ***Interactive comment on “High-resolution satellite-based cloud-coupled estimates of total downwelling surface radiation for hydrologic modelling applications” by B. A. Forman and S. A. Margulis***

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### Comment 1

"This is generally a very well-written paper on a topic of significant importance and interest for HESS readership. My major criticism is that the current write-up does not provide a strong motivation for the analysis. A large number of land surface radiation estimation schemes already exist. . . what is the motivation for creating another one?"

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The last paragraph of the introduction tries to establish the need for relatively simpler schemes with less reliance on radiative transfer modeling and/or atmospheric profile measurements for data assimilation applications. . . but I don't think they quite make their case."

### Response

The reviewer makes an excellent point and one that we hoped our manuscript would relay with sufficient clarity, but perhaps did not come across well enough in our description. We agree with the reviewer that a myriad of downwelling radiation products are currently available, each with their own set of inputs and model parameterizations, and as a result, their own set of error characteristics. In a follow-on paper, we are developing an ensemble-based data assimilation scheme that uses a variety of existing radiation products to condition our model estimates and hence incorporate information content from these readily available products. Such a framework merges the different products in a way that extracts the most information while accounting for differences in their error structure. This approach not only adds value to our model but also adds value to the existing products.

To implement such a framework, an ensemble prior estimate is required, and we argue that a relatively simple bulk (low-dimensional) model makes for an easier ensemble implementation. Part of this approach requires the use of an ensemble in order to derive a covariance structure between the modeled estimate and the satellite-derived measurement. The prior (unconditioned) ensemble must be sufficiently large in order to avoid the incorporation of spurious correlations into the covariance matrix. The generation of a sufficiently large ensemble is where the advantage of a relatively simple and computationally efficient scheme (i.e., no radiative transfer model required) becomes apparent. Furthermore, the approach we have taken allows us to carefully consider the incorporation of errors and uncertainty into a prior ensemble (i.e., accounting for cross correlations, spatial correlations, and coefficients of variation) which is a significant advance over more simplistic methods (e.g., assumptions of mutually independent,

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spatially uniform errors; simple addition of Gaussian noise). This work is clearly beyond the scope of the current manuscript and is the basis for work in a follow-on paper. We do, however, highlight the potential benefit and application of this relatively simple, bulk model formulation at the end of the Introduction where we state "Such a computationally efficient, data-driven bulk model lends itself to use in an ensemble-based data assimilation scheme (e.g. Lee and Margulis, 2007b) where other products, generated at different scales and/or derived from more complex models, can be merged with prior estimates produced by the relatively simple model. In this respect, our model design is not intended to replace more sophisticated models, but rather is expected to ultimately add value to existing products via use of data assimilation schemes." Since the issue of ensemble-based data assimilation application is not the primary topic of this manuscript, we think a further elaboration is better suited to the Conclusions section. As such, we chose to leave the text as-is in the Introduction section and instead modified text in the Conclusions section of the revised manuscript as requested in response to Comment #3.

#### Comment 2

"All other things being equal, simpler approaches should be given preferences, but given the long-list of satellite (Section 2) and model-based inputs (the Appendix) is this approach really significantly less complex than the derivation of existing products? Is there some fundamental issue with the availability of atmospheric profile measurements that makes them prohibitively difficult to acquire and/or process? Or, alternatively some fundamental difference which makes this approach easier to implement. I would guess the answer stems from the difference between a "bulk" method and a "radiative transfer" one based on an entire atmospheric profile. . .but more text clarifying this would greatly help."

#### Response

Response to this comment follows from the previous comment aimed at discussing the

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motivation for the development of this model. It is true that there are a significant number of satellite-based inputs required in the model. However, all of the products used in this model formulation are produced in near real-time and are readily available. When viewed from the vantage point of an ensemble-based formulation, the use of a large number of satellite-derived land surface and atmospheric states is one of the strengths of our approach. Each state measurement has its own error characteristics that can be derived via comparison against independent observations. This capability allows for a more transparent error formulation for use in the ensemble-based scheme rather than assuming a more simple a priori error structure. By developing this data-driven model, we have the advantage of carefully considering the associated errors such that this information may be carefully and transparently propagated into an ensemble that implicitly contains the known error structure.

This is an important point made by the reviewer and one that we have attempted to point out more explicitly in the revised manuscript. The following statement is added at the end of the first paragraph in Section 2 of the revised manuscript:

"All of the products used in this model formulation are readily available and produced in near real-time. Our model approach strikes a compromise between relying minimally on modelled quantities (e.g. does not require high temporal resolution atmospheric profiles necessary for use in radiative transfer schemes), makes the most of available products that are closely related to observable quantities (e.g. utilises measureable cloud states), and maintains physical consistency while keeping the model formulation relatively simple."

#### Comment 3

"Make of the motivation appears to stem from the potential application of this type of approach to enable ensemble-based data assimilation approaches. Presumably, the author's are advocating that their model be implemented on-line by data assimilation practitioners to create background model ensemble (whose covariance structure rep-

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resents the covariance impact on model state predictions of radiative forcing errors). For a land model assimilation problem, this type of implementation seems improbable, since the land model will not predict (or require an ancillary description of) the types of cloud and atmospheric variables needed to run the author's model. Instead, it is far easier for land data assimilation practitioners to continue the common practice of taking an existing product (e.g. the NLDAS LW and SW fields), assuming a given error model for it, and randomly perturbing these fields according to this assumed model. Why would the implementation of this model in a land data assimilation context confer any advantage over this much simpler approach? If the author are thinking of a different data assimilation problem (e.g. assimilation into a boundary layer model?) they should make this clear. Regardless - given that it is invoked as the primary motivation for this particular approach (in both the abstract and the introduction) – the author need to provide more detail concerning the expected benefits of implementing their approach in a data assimilation context."

#### Response

In this paper, the goal is not to prove the ability to apply the model in real-time (or for data assimilation in general), but simply to illustrate a relatively simple model, that is forced by existing satellite products, and produces accurate results when compared to ground-based observations (and in some cases [i.e. the SRB product], more accurate than more complex models). The assimilation application is the topic of a follow-on paper and is only alluded to here as one motivation for such a model to be developed. Whether it can be applied in on-line or off-line mode is not the topic of the manuscript. That said, while the model proposed here may more easily be applied in a reanalysis-type framework, all of the satellite-derived inputs required in our model are produced in near real-time. Due to the computational efficiency of our model, an ensemble of radiative forcing fields could, in principle, be generated shortly after the satellite-derived inputs are available. The NLDAS and SRB products, too, are produced in near real-time. From a computational standpoint, the generation of an ensemble of

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radiative forcing fields via our model (complete with conditioning) or via perturbation of NLDAS/SRB fields are both feasible.

In terms of the application in land data assimilation applications, one significant advantage to our approach is best prefaced by the reviewer's comment that it is far easier for land data assimilation practitioners to take an existing product and perturb it based on some assumed error structure. For example, practitioners often apply additive normal or multiplicative lognormal noise to model input fields. Such an approach typically assumes spatially uniform (or correlated) errors across the domain. This is the standard practice, but one that we believe can be overly simplified (i.e., a poor a priori assumption about input errors). This type of an error formulation does not account for heterogeneity in the error structure. For example, cloudy-sky areas typically have larger errors due to the increased variability (and uncertainty) introduced by clouds whereas clear-sky regions generally have lower errors. Spatial correlations in these errors also exist due to correlations associated with cloud structure or regional climatology. Application of spatially uniform errors does not account for this. Furthermore, errors in estimated radiative fluxes within cloudy regions can vary considerably based on the specific cloud characteristics. Again, the typical perturbation approach does not account for this. Since a proper posterior estimate via data assimilation relies on accurate error statistics in the prior, this can lead to inaccurate posterior estimates. The approach we take in our follow-on paper considers these different sources of error by accounting for cross correlations between errors and their spatial correlations. Our model framework allows us to more easily and naturally consider these error sources and subsequently make a more careful accounting of uncertainty implicit in the resulting ensemble of radiation flux estimates.

Per the reviewer's recommendation we have added text to the revised manuscript in the Conclusions section in an attempt to more explicitly discuss the anticipated gains from our proposed data assimilation approach:

"...The simple (and computationally efficient) form of this model is by design, and is in-

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tended for use in an ensemble-based data assimilation framework. Such an approach, which is presented in a follow-on study, is an advance over more traditional methods of generating an ensemble where a nominal estimate is typically perturbed using additive normal or multiplicative lognormal noise. The traditional approach generally assumes spatially uniform (or perfectly correlated) errors across the domain. This type of error formulation does not account for heterogeneity in the error structure, most notably associated with clear- versus cloudy-sky regions, nor does it account for correlated errors associated with regional climatologies. The approach we take in our follow-on paper considers these different sources of error by accounting for cross correlations between errors as well as their spatial correlations. Shortcomings of the model parameterisations and errors present in the satellite-based inputs can be addressed through this framework via inclusion of parameter and input error and assimilation of estimates of downwelling fluxes derived from more sophisticated retrieval algorithms (e.g. Lee and Margulis, 2007b). This approach could not only improve the modelled estimates via a reduction of modelled uncertainty, but also add value to the existing product used in the assimilation scheme. . . .”

Comment 4

"The single-day illustration in Figure 1 makes the diurnal interpolation scheme look like just a bias correction approach whereby – when, based on my understanding, it is more powerful than that. Could the author's show multiple consecutive in which true temperature exhibits periods both above and below the climatological expectation. The illustration of a single day in Figure 1 does not quite capture the functionality of the approach."

Response

Figure 1 has been augmented per the reviewer's suggestion in the revised manuscript. The updated version of this figure incorporates examples from 5 October 2003 and 10 October 2003 showing interpolated results both below and above the climatologi-

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cal expectation, respectively. In addition, both examples serve to demonstrate more than just a simple bias adjustment of the satellite-based temperature measurement, including the ability of the interpolation procedure to adjust the amplitude of the diurnal signal."

Comment 5

"The manuscript makes reference to both NLDAS LW and SW products but does not describe their origin. One or two more sentences of detail would help on page 3056. Page 3060 also makes reference to "NLDAS longwave and shortwave" products. . . where does the NLDAS shortwave product come from and what is its relationship with SRB?"

Response

We chose not to describe the NLDAS products in detail in the original manuscript, but rather cited their reference publications. As for NLDAS shortwave versus SRB products, the two are essentially the same. As mentioned in the original manuscript on p. 3059, line 20 (and reiterated on p. 3060, line 7), the SRB product is included in NLDAS as the shortwave product. Per the reviewer's recommendation we have added some additional text for clarity:

"Comparison against the satellite-based Shortwave Radiation Budget (SRB) product (Pinker et al., 2003) as well as the model-based downwelling longwave radiation product from the North American Land Data Assimilation System (NLDAS) (Cosgrove et al., 2003) is also performed for reference. The SRB product is based on geostationary measurements and is essentially the NLDAS shortwave product. While satellite-based estimates of shortwave radiation (i.e., SRB) are available, no satellite-based estimates of downwelling longwave radiation in North America on an hourly timescale are readily available for comparison. Rather, the NLDAS longwave product (herein referred to as NLDAS-LW), which is largely based on Eta Data Assimilation System (EDAS) model output, is used for comparison. . . ."

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Comment 6a

"Comparison between SW and LW products from the author's algorithm and existing products represents some of the most important parts of this analysis. There are a couple of spots where these comparisons could be improved.

a. Table 2. The LW appears to do worse than the NLDAS-LW product with regards to RMSE and correlation validation metrics. However, the manuscript does not discuss this point. What accounts for the relatively low correlation value and why should this not be taken as evidence the proposed scheme performs relatively worse than existing schemes for LW?"

Response

The relatively low correlation between the longwave model and measurements is largely due to limitations in the diurnal interpolation algorithm in the presence of cloud coverage. This limitation is discussed in considerable detail in the preceding paragraph as well as in lines 5-27, p. 3065 in the original manuscript. A more explicit connection between the diurnal interpolation algorithm in the presence of clouds and the relatively low correlation with ground-based observations is made in Section 5.4 of the revised manuscript:

"...The longwave module performance, for example, suffers due to the presence of clouds and is due to two main factors: 1) clouds introduce significant variability in the downwelling longwave flux, which adds complexity to the modelling efforts, and 2) the cloud coverage prevents the MODIS sensor from measuring the near-surface states, which limits the amount of information available for the longwave module to utilise in the diurnal interpolation algorithm. The use of AIRS measurements helps overcome some of the limitations associated with this second issue. However, the limited swath width of AIRS relative to MODIS coupled with the fact that AIRS has a maximum of two SGP overpasses per day, compared to a maximum of four SGP overpasses per day for MODIS, severely limits the amount of measurement information available for use in

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the longwave module. The shortwave module performance is also degraded during the presence of clouds. However, despite the increase in values in the error statistics, the shortwave module continues to perform well relative to other satellite-based models (e.g. Meetschen et al., 2004; Pinker et al., 2003) because it depends mostly on the cloud data and does not depend on the data sources required by the longwave module.

Analysis of model performance over the entire 14-month simulation period is shown in Table 2 where spatially-aggregated, hourly-averaged model results are compared against all available SIRS measurements. NLDAS-LW and SRB comparisons are also included for reference. The model compares favorably with the SIRS measurements at an hourly timescale during all-sky conditions. MD values are -2 and -7 W m<sup>-2</sup> with RMSD values equal to 21 and 29 W m<sup>-2</sup> for the longwave and shortwave module, respectively. The modelled shortwave RMSD via comparison to SIRS measurements is less than 73% of that found in the SRB product. It is worthwhile mentioning that the computed RMSD statistics for SRB are significantly lower than those shown in Pinker et al. (2003) and Lee and Margulis (2007a). Obvious errors in SRB (e.g. zeros/gaps near local solar noon) were excluded prior to computing statistics, as these gaps were often associated with missing GOES inputs. The VISST product (and hence the shortwave module) often experienced these same gaps. In addition, missing values in the SRB product that occurred when the solar zenith angle was near 90 degrees (i.e., near the horizon) were also excluded from the statistical investigation because of a cloud detection limitation in SRB. Finally, computed Pearson correlations coefficients shown in Table 2 provide insight to the temporal correlations between the modeled estimates and the ground-based observations. The shortwave module is almost perfectly correlated with the observations. The longwave module, on the other hand, has a relatively low correlation as compared to the NLDAS-LW estimates. This relatively low correlation is largely due to problems associated with the diurnal interpolation algorithm in the presence of cloud cover as discussed above."

Comment 6b

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"b. Section 6. First paragraph. Where in the results section are the "more physically realistic" results for the LW product during "cloud-sky conditions" presented? Is this a reference to the single day results shown in Figure 3? If so, this does not seem like adequate support for such a strong statement (i.e. how do we know this particular day is typical?)."

Response

We believe the reviewer's comment stems from our use of the phrase "physically consistent" and their interpretation of that to mean "physically realistic" (e.g., in a mean squared error sense). In the first paragraph of Section 6 of the original manuscript we discuss "more physically consistent" results (p. 3066, line 22) without use of the word "realistic". Our discussion of physical consistency stems from the model formulation where cloud conditions are represented in both the shortwave and longwave models. As mentioned on p. 3060, line 5 in the original manuscript we state the following: "The model results shown in Fig. 3c and d are coupled (physically consistent) since they use the same cloud estimates as inputs. The SRB and NLDAS-LW products (which comprise the total downwelling radiative flux provided in NLDAS) are created independently from one another and therefore could contain physical inconsistencies. For example, the longwave results may suggest cloud presence and subsequent amplification whereas the shortwave estimate may suggest clear-sky conditions and hence no attenuation. Our formulation used in this study eliminates the possibility of these physical inconsistencies by accounting for cloud conditions in both the longwave and shortwave models. Figure 3 was shown as an example of this more physically consistent approach. Figure 4 also demonstrates this physical consistency by careful accounting of a dynamic and evolving cloud system. In addition, Figure 6c demonstrates this physical consistency at the point-scale. The overall approach allows us to address a significant physical inconsistency by carefully accounting for clouds, which are first-order modulators on downwelling radiative fluxes.

Additional evidence of improved physical consistency is found via computation of tem-

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poral correlations between observed SW and LW fluxes and subsequent comparison between modeled SW and LW estimates (not included in original manuscript). It is expected that during cloudy-sky conditions, SW and LW fluxes will generally be negatively correlated due to attenuation of SW fluxes and amplification of LW fluxes by clouds. The correlation of daily-averaged SW and LW fluxes on cloudy days was analyzed for the ground-truth (SIRS), our model, and NLDAS/SRB fluxes. As expected, the SIRS stations showed a negative correlation. The analysis showed that our coupled model approach agrees closely with temporal correlations computed using SIRS observations, while the NLDAS/SRB fluxes do not. A brief discussion of these results has been added to Section 5.4 of the revised manuscript:

"When total downwelling radiation (downwelling LW plus downwelling SW) is investigated, advantages to the implicitly coupled approach in our model are readily apparent. In comparing the modeled downwelling radiation to the combined NLDAS-LW/SRB product, the hourly mean difference is the same between the two estimates (can be seen in Table 2) and hourly RMSD is slightly less, but similar in magnitude (results not shown). The similar overall errors in downwelling radiation result from compensating effects in LW and SW fluxes (i.e. smaller errors in SW with larger errors in LW). However, we argue our model results are more physically consistent in cloudy conditions due to the consistent cloud inputs used. Correlations between daytime-averaged LW and SW fluxes were computed for cloudy days for the SIRS data, our model, and the combined NLDAS-LW/SRB fluxes. During cloudy-sky conditions over the 14-month simulation period the Pearson correlation coefficient between the SW and LW SIRS observations is -0.10. The negative correlation in the presence of clouds is expected and results from the attenuation of SW fluxes with simultaneous amplification of LW fluxes. When the same analysis is done on our model results, the correlation was found to be -0.07, which closely agrees with the SIRS value. However, the correlation between fluxes in cloudy conditions for the combined NLDAS-LW/SRB product was found to be 0.37. The better agreement between the model correlation and the SIRS correlation (in both magnitude and sign) is additional evidence as to the improved physical consistency

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resulting from our model formulation.”

With that said, the implicit coupling in our framework is no guarantee that our model will have better agreement with independent, ground-based observations. “Realism” in a MD/RMSD sense may not necessarily follow from the physical consistency inherent in our model. Other sources of error (e.g. erroneous near-surface air temperature estimates in the presence of significant cloud cover) may yield less “realistic” estimates relative to ground-based observations despite the physically consistent formulation. This is clearly the case in the longwave flux estimates as demonstrated in Table 2.

We appreciate the reviewer’s comment regarding physical realism and have taken this opportunity to update our manuscript accordingly. In the original manuscript where we discuss physical realism, our use of the word “realistic” was intended as an alternative (or synonym) for consistent. It was not meant to suggest our more physically consistent approach inherently yields better agreement with ground-based observations. Again, it is clearly shown in Table 2 that this is not the case. In order to remove any confusion associated with our word choice, all instances of the use of the word “realistic” in the context of model results (i.e., the two instances that occur on p. 3058, line 26 and p. 3059, line 1 in the original manuscript) have been changed to “consistent” in hopes of making a more clear distinction. In addition, the Conclusions section has been altered in an effort to make this connection more clear in which we now state in the revised manuscript:

“When compared against an advanced downwelling longwave product (Cosgrove et al., 2003), the longwave module produces more physically consistent results (in concert with shortwave fluxes) during cloudy-sky conditions (albeit with higher RMSD), produces comparable amounts of uncertainty during all-sky conditions, and yields estimates at finer scales in space and time. The longwave and shortwave modules produce implicitly coupled (and hence more physically consistent) results via explicit accounting of cloud conditions in both flux fields. . . . It is hypothesized that the improved physical consistency could add benefit when the model is applied in a data assimilation

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scheme.”

Comment 6c

"c. Figure 9 is a really nice figure, but could be improved if comparable results were plotted for the NLDAS and SRB products for comparison. If the LW product is more physically realistic for cloudy conditions (relative to the NLDAS LW product) than presumably the line in Figure 9 would be steeper for the NLDAS LW product. Adding NDLAS LW and SRB results to this figure would provide the necessary support for some of the stronger statements in the conclusions."

Response

Again, we think this comment stems from the issue discussed above. We did not intend to claim that the LW results were more accurate during cloudy conditions, simply that they were more consistent. We believe the changes made in the revised manuscript described above address this point as well. The primary point of Figure 9 was to illustrate that the LW and SW fluxes produced by the model have higher uncertainty in cloudy conditions. Adding the NLDAS data to the figure would only detract from this point. With regards to statements regarding “more physically realistic” results in the Conclusions section changes have been made where appropriate (please see response to previous comment shown above).

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 6, 3041, 2009.

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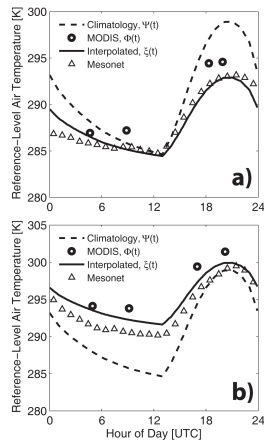


Figure 1. Example diurnal interpolations of MODIS reference-level air temperature on a) 5 October 2003 and b) 10 October 2003 using monthly climatology estimates for use in the longwave module for a location near the middle of the study domain shown in Figure 2. The available MODIS observations (circles) and hourly-averaged, ground-based Oklahoma Mesonet observations (triangles) are included for reference.

Fig. 1.