Dear Min-Hui Lo,

This is the response to the referee comments (RCs) on the manuscript “A Hydrological Cycle Model for the Globally Resolved Energy Balance Model (GREB) v1.0” submitted to GMD by Stassen et al. 2018 (gmd-2018-131). We like to thank the editor and the two anonymous referees for the time and effort spent on reviewing this manuscript and for the many helpful comments they provided. We think the referee comments have helped to substantially improve this manuscript. Please find a point-by-point response to all referee comments. All page and line numbers refer to the original manuscript and might not match up with the revised manuscript. We hope this settles all of the referee concerns and we would be happy to submit the revised manuscript.

Kind regards,
Christian Stassen

Referee 1

Comments

1. Can the authors elaborate the difference between the GREB model and CMIP5 CGCMs? As atmospheric and oceanic circulations are not simulated in the GREB model, it is probable that the GREB simulations give rise to results lacking of dynamical contribution. Does this lacking component play some roles in affecting the performance in the new model?

Response: CMIP models are earth system models containing several sub-models (i.e. atmosphere, ocean, vegetation, etc.). The atmospheric model would solve the dynamical equations of the atmosphere (i.e. Navier-Stokes). Those lead to internal variability (i.e. weather). GREB is an energy balance model. It does not contain weather or has any internal variability. Thus, reaching equilibrium (i.e. constant temperature) quickly and then remaining at equilibrium if not disturbed by external forcing.
Atmospheric circulation is not dynamically responding but prescribed as an external boundary condition. The sensitivity experiments ENSO & Climate Change in GREB take into account a change in circulation. This is done by adding an anomaly of horizontal winds and omega (and surface temperature) on top of the GREB climatological field. The anomaly is obtained from a composite of El Ninos (or La Ninas) for the ENSO case and the ensemble mean of the CMIP5 RCP8.5 response for the climate change case.
Oceanic circulations are not considered in GREB. The effect of ocean currents on the atmosphere would be reflected through a change in sea surface temperature (SST) which, is part of the GREB models external forcing. Thus, the GREB model would respond to a change in ocean currents through the change of SST.
We changed page 3 line 16-18 to: 'Thus, the GREB model is conceptually very different from the CGCM simulations in CMIP5, as atmospheric and the oceanic circulations are not simulated but prescribed as an external boundary condition in the model. The effect of ocean circulation on the atmosphere is represented only through the sea surface temperature.'

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2. Due to the fact that CMIP5 CGCMs have biases in simulating circulations (e.g., Yang et al., 2018, Journal of Climate), the differences, at least for circulations, between the GREB model and CMIP5 models could be traced to the differences between prescribed wind fields in ERA-Interim reanalysis product and simulated wind fields. In other words, different background wind states may be part of the reason generating the discrepancy. What if comparing results using the CMIP5 simulated mean fields to force the old/new GREB model? Do authors have insights toward this point?

Response: We performed a set of experiments where the GREB model is forced with boundary conditions (i.e. horizontal winds and omega) from CMIP5 models. We compared the GREB precipitation anomaly (GREB-ERAInterim forced *minus* GREB-CMIP forced) to the CMIP precipitation anomaly (CMIP *minus* ERAInterim). This showed a high pattern correlation (~0.8). For the majority of the CMIP models we looked at, most of the correlation was caused by forcing

GREB with omega. However, this needs more research and will be done in future work before we can confidently address this.
We added the following to page 12 line 11: 'A very recent study by (Yang et al., 2018) links circulation biases in CMIP models to biases in precipitation and moisture. Forcing GREB with the circulation of CMIP models could shed more light how discrepancies in circulation between CMIP models effect the hydrological cycle in the GREB model.'

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3. If no daily weather systems are simulated, does that mean the temporal integration is performed in the time step of one month or more in the GREB model? I am confused because the model time step is 12hrs as mentioned in Page 3 Line 14. In addition, having no weather system simulated does not mean no internal variability generated in the model. I suggest authors rephrasing this pragraph or providing further explanation.

Response: There are two different time steps in the GREB model:

- The physics and the tendency equations (i.e. tendencies for the hydrological cycle or surface temperature) are integrated on a 12 hours time step.
- Circulation (Advection and Diffusion) is integrated using a sub-stepping of 0.5 hours or 24 sub-steps. This is necessary for the model to be numerically stable.

We rephrased Page 3 Line 13-16 to: "The tendency equations of the model (i.e. tendency equation of specific humidity) are solved with a time step of 12 hours. For circulation, a shorter time step of 0.5 hours is used. This is necessary for the model to remain numerically stable. The daily cycle of incoming solar radiation is not resolved instead the 24hrs mean incoming solar radiation is used."

If the GREB model has no external forcings it will reach equilibrium quickly, depending on the magnitude of the forcing. After reaching equilibrium the model is stable and the tendencies of the model go towards zero. This means the GREB model is not oscillating around an equilibrium point.
We rephrased Page 3 Line 19-21 to: "Additionally, the GREB model has no internal variability. This means the model will converge to its equilibrium point and the tendency equations converge to zero."

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4. Page 1 Line 8: Does "the hydrological cycle" refer to the hydrological model? Similar mixture appears throughout the abstract.

Response: Yes. The terms 'hydrological cycle' and hydrological model' are used interchangeably. We changed this in page 1 line 8 and through the manuscript to be more precise.

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5. Page 1 Line 9: The authors should clarify the meaning of "zero order". Does the "order" means numerical convergence rate in time or space?

Response: With zero order we mean that is was a first guess or a rudimentary approach. The term is clarified in a bit more detail on page line 12: 'The hydrological cycle in the GREB model was

only needed as a zero order estimate to model the latent heat in the energy balance and the atmospheric water vapour levels.' We changed the word on page 1 Line 9 to 'rudimentary' to not cause confusion with order of numerical convergence or order of accuracy.

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6. Page 2 Line 6: Authors may consider mentioning the computational efficiency of idealized model here.

Response: We changed Page 2 Line 6-7 to: 'Because of their simplicity, they help to develop hypotheses about the processes involved and they can be run fast. The GREB numerical code computes one model year in a few seconds and on a standard personal computer. It therefore is a relatively fast tool, which allows conducting sensitivity studies to external forcing within minutes to hours (Dommenget & Floter, 2011)'

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7. Page 2 Line 23: I suggest re-organizing the paragraphs that describe the GREB model. For example, the modl layer configuration and resolution in Page 3 Line 10 can be introduced before the description of the NCEP climatological fields used in the original GREB model. This may make introduction of the GREB model framework smoother.

Response: We moved the paragraph describing the GREB model to the beginning of chapter 2

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8. Page 2 Lines 25-26: Any specific reason generating topography from an atmospheric model? Why not using ETOPO dataset?

Response: We adopted the approach form the original GREB model.

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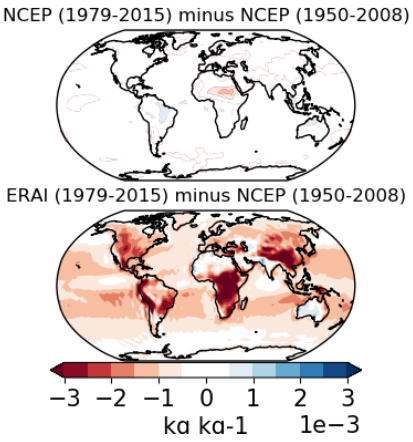
9. Page 2 Line 29: I suggest providing brief explanation for the reason of changing dataset here and directing further details to section 3.4. Also, the NCEP reanalysis datasets are used during 1950-2008, whereas the ERA-Interim reanalysis data during 1979-2015. Therefore, long-term mean climatology values may be different. What is the results using the NCEP data during 1979-2015?



Response: The difference between the mean climatologies between NCEP 1950-2008 vs. NCEP 1979-2015 is small compared to difference between NCEP and ERA-Interim (see plot above).
We added the following to page 2 Line 28: 'ERA-Interim reanalysis has a higher accuracy than NCEP and a better agreement with observations (Liu et al., 2017)' and page 8 line 28: 'The effect of changing the mean climatology from the years 1950-2008 to 1979-2015 is small compared to the differences between NCEP and ERA-Interim.'

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10. Page 4 Line 3: How important is the diffusion term compared to advection? Could we ignore diffusion effect in large-scale circulation dynamics and/or thermodynamics?

Response: The diffusion term is about 1/5 of the magnitude of the advection term (annually and

Figure 1: Annual mean advection (left) and diffusion (right) for the GREB model in kg/m2/s.

globally averaged, see Figure 1 below). Therefore, we did not ignore diffusion. We added: 'The diffusion term is one fifth of the magnitude of the advection term in global average but it is more important in some locations and therefore not ignored in the GREB model (not shown).'

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11. Page 10 Line 6: ENSO events include both El Niño and La Niña. Is the analysis for La Niña shown in the manuscript? Figure 10 only shows analysis for El Niño composite, but not La Niña. How does response to La Niña look like?

Response: The improvement in the response of the GREB model to La Niña is similar to the improvement in GREB simulated El Niño. It is however, not shown in the manuscript.
We added to Page 10 Line 6: 'La Nina events are qualitatively the same, but with opposite signs (not shown).'

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12. Page 10 Line 9: Figure 10g shows the improvement in precipitation anomalies. It could be informative also discussing extratropical precipitation response because ENSO-mid-latitude linkages were also well documented. In Figure 10g, no precipitation increases in the Southern U.S. region. Does that indicate ENSO teleconnection is still not resolved well in the new model?

Response: We focused here on a first order approximation of the response and do not want to discuss all details. The figure is in mm/day and therefore is focussed on the tropics where the absolute response in precipitation is strong. The extratropical response in GREB roughly matches

observations but is weaker than observations. We added the following to page 10 line 11:'… precipitation response is somewhat weaker than observed, especially in the extra tropics.'

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13. Page 1 Line 15: It is better to mention the full name of "CMIP" in the abstract.

Response: Changed Page 1 Line 15 to: 'The new hydrological cycle is evaluated against the Coupled Model Inter-comparison Project phase 5 (CMIP5) model simulations, …'

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14. Page 1 Line 16: El Nino -> El Niño (and through the manuscript)

Response: Changed El Nino to El Niño throughout the manuscript. Changed La Nina to La Niña throughout the manuscript.

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15. Page 1 Line 17: Add the full name of "CGCM".

Response: Added Coupled General Circulation Models (CGCMs) to Page 1 Line 17.

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16. Page 1 Line 25: What is "CGCMs" stands for? If it refers to "General Circulation Models" at the end of Line 24, it should be abbreviated as GCMs.

Response: Changed in manuscript.

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17. Page 1 Line 26: "(AR4)" only appears once here, there's no need to provide abbreviation.

Response: Removed AR4

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18. Page 3 Line 5: Figure 2c and 3c -> Figures 2c and 3c. I found this kind of error appears through the manuscript (e.g., Page 4 Line 4 and Page 5 Line 23). Please check carefully and revise them consistently.

Response: Changed to Figures 2c and 3c on page 3 line 5 and through the manuscript.

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19. Page 3 Line 7: rcp85 -> RCP8.5 (to be consistent to that in the caption of Figure 11, Page 27).

Response: Changed in manuscript.

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20. Page 4 Line 10: RHS: (dqair/dt)obs minus simulated terms?

Response: That is correct! Changed the order in the manuscript

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21. Page 7 Line 7: remove the parenthesis.

Response: Removed parenthesis

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22. Page 9 Line 7: remove the parenthesis.

Response: Removed parenthesis and added ‘and’ between citations.

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23. Page 17: what are the color shadings and streamlines in Figure 1d?

Response: Added ‘…850 hPa wind direction (streamline) and strength (shading)’ to the caption.

Referee 2

Comments

1. I believe, however, that the authors need to explain better how this model can be used. While I realize that this is a technical paper describing the model, I think there needs to be some justification as to why we need this model in the first place.

Response: We plan to apply the model for studying biases in CMIP models. This could be done by replacing boundary conditions through CMIP boundary conditions. We revised the manuscript to better highlight the use of the GREB model. For example we added the following to page 12 line 11 (also to address RC1.2): 'A very recent study by Yang et al., 2018 links circulation biases in CMIP models to biases in precipitation and moisture. Forcing GREB with the circulation of CMIP models could shed more light how discrepancies in circulation between CMIP models effect the hydrological cycle in the GREB model.'

2. It is nice that the new version of GREB is more successful in reproducing certain aspects of the hydrological cycle. On the other hand, given that the new version has more fitting parameters, is this really surprising? Using more parameters gives you a better fit but also carries the risk of overfitting. In particular, the model might be too constrained by present day climate to be useful for climate change projection because basic features of the present climate, such as the width of the Hadley circulation or the position of the ITCZ, may change.

Response: We addressed the problem of overfitting by different approaches: first we tested the development of the model in step-wise building up the complexity (see section 3). Secondly, we did a number of response experiments that test the model's skill beyond the information used to fit the parameters. For this we did three tests: Seasonal cycle, El Nino and climate change. In all three the new model showed skills in simulating changes in the hydrological cycle that would not have been achieved by overfitting the model.
We added some additional information in the introduction of Section 4 to better highlight this problem.

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3. Another way the model could be used is for understanding the climate change response of more complex models. For this purpose, it would seem that GREB's mixture of basic principles (e.g. energy balance), ad-hoc parameterization (e.g. standard deviation of omega), and fitting to observations (e.g. mean omega) does not lend itself to interpretation any more than model output itself.

Response: We agree that the mixture of basic principles and ad-hoc parameterisations helps understanding the climate change response of more complex models (i.e. their biases). The boundary conditions of GREB could for example be replaced with climatologies of CMIP models (i.e. replacing horizontal winds from ERA-Interim with horizontal winds from one CMIP model). By replacing only one or all boundary conditions would help to gain insight where changes in RCP-scenarios come from or where biases in the hydrological cycle originate from. This is indeed what we think could be a useful application of this GREB model.

We added the following to page 12 line 11 (also to address RC1.2 & RC2.0): 'A very recent study by (Yang et al., 2018) links circulation biases in CMIP models to biases in precipitation and moisture. Forcing GREB with the circulation of CMIP models could shed more light how discrepancies in circulation between CMIP models effect the hydrological cycle in the GREB model.'

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3. section 3.3 What causes f to be 2.5 rather than 1.0? Could there be an error in the calculation? Is this mismatch horizontally uniform?

Response: There are several sources of uncertainties:

- The value of the scaling height we use in GREB is larger than literature values
- The fact that GREB is a single layer model
- The coarse resolution of the GREB horizontal grid
- A mismatch of the omega climatology
- Calculating circulation as residual

f is a constant fitting parameter it has no dimensions (see table 2 page 15). It could be fitted to different regions (i.e. tropics only or extra-tropics only) to get estimate if it is horizontally uniform.
We added to page 8 line 14: '… vertical velocities may not perfectly match because of the coarse resolution, GREB uses a scaling height of water vapour that is larger than literature values and calculating circulation as residual could contain other uncertainties.

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4. p. 1, ll. 25-26: I think the authors mean AR5 here (whose models are quite dated by now). Also, "the best possible" is certainly debatable. Perhaps it suffices to say that they are very complex models.

Response: Changed line 25-26 to: 'CGCMs evaluated by the Intergovernmental Panel on Climate Change (IPCC) for the fifth assessment report (AR5), are among the most complex simulations of the climate system.'

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5. Equation (12): Please explain all the variables directly after introducing the equation. In particular, what is u_star? It seems that it should be near-surface wind speed, but then, on p.7 ll. 2-3 it says that wind speed is lower over land for a given u_star, suggesting that it is something else.

Response: U_star is the absolute wind climatology explained in Table 2. We introduced Table 2 before any equation is mentioned in section 2.

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6. p. 8, l. 26: Is the good match with observations for Ireland very meaningful if what you are really interested in is the global quality of the data?

Response: Deleted: 'and Mooney et al. (2011) found a higher correlation of surface temperature in ERA-Interim to observations then NCEP in Ireland'

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7. The English could use a little editing (e.g. number agreement). Some examples: p. 2, l. 19: "parameterisations . . . is described" -> "are described" p. 3, l. 16: "wind and cloud cover field are" -> "fields" p. 3, l. 23: "a autoregressive" -> "an autoregressive" p. 5, l. 13: "precipitation and its seasonal cycle is shown" -> "are shown" p. 5, l. 3: "It, however, has. . ." -> "It has, however, . . ." p. 6, l. 3: "range of uncertainty CMIP5 modelled" -> "of CMIP5"

Response: Thank you for pointing this out. We carefully read over the manuscript and changed all errors pointed out above plus those we additionally found throughout the manuscript.