Daniel Feldman
Lawrence Berkeley National Lab
1 Cyclotron Road
MS 74R-316C
Berkeley, CA 94720

April 2, 2015

Dear Editor:

I am submitting the revised manuscript entitled "Pan-Spectral Observing System Simulation Experiments of Shortwave Reflectance and Longwave Radiance for Climate Model Evaluation." I hope that it is acceptable for publication in the Geoscientific Model Development. I would contend that this work represents a significant step forward for describing how to model how the spectrum of the Earth, both in the shortwave and the longwave, changes in response to climate forcings, and now provides a path towards inline observational simulation for the upcoming Coupled Model Intercomparison Project – Phase 6.

I would like to thank the four reviewers for their detailed comments. All of their comments are well-taken and I have sincerely responded to all of the points that they raised, with the included reviewer response that contains the comments in italics and my response in regular type-face. The response to some of these points entailed a significant amount of human and computational resources, and was the principal cause for the lengthy time in submitting this revision. Additionally, I would like to note that I have added John L. Paige as a co-author to this publication due to his significant contribution to this work.

If you have any questions regarding this manuscript, please don't hesitate to contact me.

Thank you,

Daniel Feldman

Dan Feldman
drfeldman@lbl.gov
510-495-2171

Reviewer Response:

Reviewer 1:

Comment:
*The study presents radiative transfer calculations at high spectral resolution from the CCSM3 model for the A2 scenario, from the near-UV to the far-infrared. These calculations are used to discuss how climate change modifies the Earth's TOA spectrum. The authors also apply this methodology to other models, and discuss the utility of this approach for model evaluation. I find the paper interesting and well written. However, I don't think it presents a significant amount of new science with respect to previous work on this topic, and therefore I don't think it should be accepted for publication. I am sorry I cannot be more positive.*

Response:
We are pleased that the reviewer finds the paper interesting and well-written. With regards to the statement concerning the amount of new science in the paper, we respectfully submit that this paper presents several novel findings in relationship to previously published work including:

1. The paper formally presents the pan-spectral OSSE, which has not been covered in other manuscripts. The Feldman et al, 2011 presentation of the SW OSSE discussed the formulation of the SW OSSE in detail and the Feldman et al 2013 paper only briefly discussed the LW calculations, but the pan-spectral capability was not central to that latter paper.
2. The paper presents a discussion of radiometric validation of the OSSE for the infrared calculations and how such validation is straightforward for clear-sky conditions but challenging for all-sky conditions due to whether the radiative transfer is formulated with layers or levels. We added the following language to the revised manuscript to note the importance of radiometric validation which reads "This represents a contribution to the growing literature around instrument emulation since attainment of this consistency requires particular attention to, and extensive validation of, the issues of consistent treatment of cloud overlap / geometry, cloud condensate, the spectral optical properties of cloud condensate, and the cloud thermodynamic state. The reason why this consistency is critically important is that departures of the hyperspectral simulated signal against observations (e.g., SCIAMACHY and AIRS) can then be used directly to check the cloud physics in the model, and in turn we can examine whether broadband cloud feedbacks to climate change have a particularly large AND UNIQUE spectral signature that would be particularly useful for early-detection efforts."
3. The paper broaches the complementarity of the SW and LW signals in describing the processes that may change the top-of-atmosphere spectrum of the planet. The numerous signals in the SW and LW spectra provide a potentially large number of constraints for model performance beyond OLR and albedo.
4. The paper discusses prospect for, and provides initial results of, OSSE calculations based on the fields from the Climate Model Output Rewriter (CMOR) for two models spanning the range of climate model sensitivities in the CMIP5 archive. This

presents a path towards developing hyperspectral diagnostics for models based on their climate sensitivities and ultimately confronting those models with decadal-length satellite records. Such confrontation will be critical to reduce the range of model results for prescribed forcings in a defensible fashion in CMIP6.

5. The paper also discusses how the computational expense of simulators can be minimized through random sampling of grid cells, which could broaden the utilisation of inline simulators for CMIP6.

Reviewer 2:

*Comment:*
*1) On the use of monthly profiles*
*The simulations presented are based on monthly profiles. So is the validation, which is done by comparing to the radiation fluxes re-computed using GCM radiation codes and monthly profiles. It is understandable that long-term, multi-model, global, panspectral simulation at daily or hourly frequency is not affordable. However, it is important to recognize that the radiation fields that are associated and consistent with other aspects (e.g., surface temperature, precipitation, etc) of the GCM simulation are those averaged from instantaneous results, while those simulated from the monthly profiles may have a bias. On the other hand, the simulator package should not be limited to the use of monthly profiles. So I suggest the authors test the simulator with instantaneous profiles of some GCM for relatively short periods and validate the simulation by comparing to the original radiation field (e.g., OLR and reflected solar radiation flux) directly output by the GCM. Such comparison will offer valuable (and necessary) assessment on the consistency between the offline-simulation by the simulator and the online simulation of the GCM, concerning both the climatology and trend. And it is worth discussing whether the use of monthly profiles may obscure the climate change signal. Note a longwave assessment was done by Huang and Ramaswamy (2009, J. Clim.), but not the shortwave.*

Response:
We very much appreciate the reviewer's suggestion and have modified CCSM in order to output the fields necessary for OSSE calculations on 3-hourly time-intervals for a single month and compared that to OSSE calculations based on the monthly- averaged fields. The results reveal that the OSSE calculations based on monthly-averages tend to overestimate the effect of clouds and therefore shortwave reflectances are biased high. This finding has been added to the revised manuscript in the results section.

Comment:
*2) Simulation configuration*
*On page 3652, many details are described about the configuration of the radiative transfer simulation. However, it is not clear whether these aspects are kept consistent in the spectral simulator as compared to those in the GCM. And is the simulator flexible to adapt to different configurations of different GCMs, e.g., with regard to cloud optical property parameterization (grey body is used here) and overlap treatment (not mentioned).*

Response:
The simulation configuration is generally flexible, allowing for different, and even arbitrary, cloud-overlap approximations based on a subroutine that performs sub-column generation and uses multiple calls to MODTRAN based on the results of this generator to create a grid-box averaged spectrum. With respect to cloud optics, it is straightforward to implement different cloud optics and the gray approximation can easily be relaxed, though the exercise in model excavation necessary to determine the cloud optics parameterizations for each model may be non-trivial.

Comment:
*Page 3657, line 20. "model-reported" means GCM direct output? Given monthly pro- files are used, the bias reported here looks surprisingly small.*
*Given the nature of the journal, it may be worth presenting some benchmarking computation times under different configurations of the simulator, e.g., how many seconds on average for simulating a LW and SW spectrum respectively from each atmospheric profile, how does it vary with number of vertical level, cloud overlapping schemes, expected saving of time using different RT codes (MODTRAN, PCRTM, GCM code), etc.*

We have added the following language to the revised manuscript: "For reference purposes, we find that, using MODTRAN, for a 26-level atmosphere, each all-sky shortwave spectrum calculation, which includes 16 sub-column calls for the cloud overlap approximation, requires 184 CPU-seconds while each longwave spectrum calculation, which also includes 16 sub-column calls, requires 17.6 CPU-seconds on the NASA HEC resources. The computational expense scales with the number of levels and sub-column calls. More optimized radiative transfer codes such as Principal Component Radiative Transfer Model (PCRTM) [Liu et al. 2006] can achieve a speed-up of at least an order of magnitude in the shortwave and two orders of magnitude in the longwave."

*3) Advantage of pan-spectrum*
*Page 3658 Line 12. Huang et al. (2010, JGR) specifically noted that longwave-only fingerprinting is subject to the degeneracy of the signals of low clouds and surface temperature. We can expect this to be greatly improved by combining shortwave signals with the longwave.*

Response:
The reference to Huang et al (2010, JGR) was added to the revised manuscript and an indication of the ability of the combined shortwave and longwave spectra to resolve degeneracies regarding low-clouds and surface temperature.

Comment:
*Figure 4 (f). A great benefit (but sometimes not fully appreciated) of using spectrally resolved radiance data in climate simulation validation and climate change detection is that it is not subject to spectral compensation. Huang and Ramaswamy (2009) showed how LW spectral measurements can disclose detailed climate change signals that would otherwise hide in the broadband flux. The result here appears to show such spectral compensation may occur in the SW as well. It is worth emphasizing this obvious advantage of spectral climate monitoring here.*

Response:
Language has been added to the revised manuscript to emphasize this point with a reference to Huang and Ramaswamy (2009, JC).

Reviewer 3:

Comment:

***General Comments***

*The manuscript entitled "Pan---Spectral Observing System Simulation Experiments of shortwave Reflectance and Longwave Radiance for Climate Model Evaluation" demonstrates the value of studying the solar shortwave and emitted longwave spectral variability to diagnose climate model performance. This is an excellent presentation of new techniques that can be applied to evaluating climate models and is a valuable addition to the literature. Once the comments I have provided have been address, I believe this manuscript will be a wonderful resource particularly to the modeling community detailing the large amount of information contained in the shortwave and longwave spectral variability of Earth measured from space. I recommend this manuscript for publication, once the comments below have been addressed.*

*Many of my comments speak to reaching the climate modeling community. There is a lot of discussion of solar reflectance and infrared radiance spectra and how their spectral features illustrate the changes seen in climate models and the differences between models. This is a strength of the manuscript; however, remember that climate modelers may not be accustomed to gleaning information from spectra, such as what is shown in this manuscript. Keeping this in mind, generally describing various areas of the spectrum may not be sufficient for helping the readership follow your descriptions. I suggest making a point to include the numerical wavelength range describing where in the spectrum you are referring and making your description and physical explanations of what is shown in the spectra as specific as possible.*

Response:

We wish to thank the reviewer for such a consideration of our manuscript. We have seriously addressed the specific comments listed below, and added some additional information (in the Computational Expense section) regarding how modelers specifically can consider this manuscript for inline simulation. However, the utilization within the modeling community of OSSE techniques such as those described here will only take place if papers can convince them of the value of spectral measurements as model constraints. We hope that this paper can serve modelers as a reference for the rich information content that hyperspectral measurements can contain regarding climate-relevant processes.

Comment:

***Specific Comments Abstract***

1. *Sentence 1 is hard to follow. Can you simplify this? My suggestion is eliminate the word "evolution". Also, that the feedbacks and forcings are on the climate system is implied: "Top---of--- atmosphere spectrally---resolved shortwave reflectances and longwave radiances describe the response of Earth's surface and atmosphere to feedback processes and human---induced forcings."*

Response:

The suggested change has been made to the revised manuscript.

Comment:

2. *Line 5. (Also Introduction, Page 3649, Line 15): "long---duration" – Can you be more specific about how long? Compared to today's missions, how much longer? Decades? A few years? It will help to contrast weather---specific and climate---specific studies and measurement needs.*

Response:
The revised manuscript now reads "decadal length" instead of "long duration".

Comment:

3. *Lines 5---6: "we have projected 21st century changes described by [CCSM3]" – "Described" sounds qualitative here, and the changes represented in the CCSM3 model are certainly quantitative. Suggestions to replace "described": prescribed/illustrated/demonstrated/represented/...*

Response:
We have changed "described by" to "from" in the revised manuscript.

Comment:

4. *Lines 8---9: Make the units of the spectral range and the spectral resolutions the same. "300 nm to 2500 nm and longwave radiance spectra from 2000 to 200 cm^---1 (5 to 50 μm) at 8 nm and 1 cm^---1, respectively."*

Response:
The suggested change has been made to the revised manuscript.

Comment:

5. *Line 16: "the spectrum" is too vague. Suggestion: "how climate change alters/impacts Earth's solar and infrared spectral variability."*

Response:
The revised manuscript now reads "The goal of this effort is to understand both how climate change alters reflected solar and emitted infrared spectra of the Earth and determine whether spectral measurements enhance our detection and attribution of climate change."

Comment:

***Introduction***

1. *Line 24: Albedo is not measured directly from space (at least, not in LEO). It would be more accurate to say that albedo is calculated or estimated from measurements of radiance.*

Response:

The word “measurements” has been replaced with “observationally-based estimates” in the revised manuscript.

Comment:

2. *Page 3649, Lines 5---8: Although your statement about the lack of a formal demonstration of spectral fingerprinting in the shortwave is accurate, you may also want to cite Jin et al 2011. In that study Jin et al 2011 calculated and showed shortwave spectral fingerprints.*
   *Citation: Jin, Z., B. A. Wielicki, C. Loukachine, T. P. Charlock, D. Young, and S. Noël (2011), Spectral kernel approach to study radiative response of climate variables and interannual variability of reflected solar spectrum, J. Geophys. Res., 116, D10113, doi:10.1029/2010JD015228.*

Response:

The revised manuscript has been changed and now reads: “Recent work by Roberts et al. [2011] suggest that shortwave spectra also contain independent information about processes that contribute to albedo. Although the separability of processes that contribute to albedo from these spectra has not been addressed formally, Jin et al [2011] showed the utility of shortwave spectral fingerprints which may be extended to consider spectral separability.”

Comment:

3. *Page 3649, Lines 11---12: “OSSEs have well---established techniques” – Is it more accurate to say that “OSSEs are well---established techniques/tools”? Either way, seems there is a typo here.*

Response:

The suggested change has been made to the revised manuscript.

Comment:

4. *Page 3649, Line 14: If this doesn’t change the meaning of your statement, insert “weather” between short---term and forecasting, providing a clearer distinction between shorter weather/process---based studies and the longer---term climate studies you are focusing on in this manuscript.*

Response:

The suggested change has been made to the revised manuscript.

Comment:

5. *Page 3649, Line 16: Again “description” sounds qualitative, and the results provided by climate models are quantitative.*

Response:

The revised manuscript now reads "The decadal length of climate studies and the necessarily long measurement records that are needed to confront how models predict climate change motivate the development of climate model OSSEs."

Comment:

6. *Page 3649, Lines 19---20: "allows for an estimation of the value of certain types of remote sensing measurements" – I would suggest a stronger statement here, something like "contributes to the determination of the value of certain types..."*

Response:

The suggested change has been made to the revised manuscript.

Comment:

7. *Page 3650, Lines 14 – 15: Having read these three studies, it's obvious to me that each of these studies contributed to demonstrating why shortwave spectra are valuable for OSSES, rather than merely discussing this point. I would strengthen the statement. In doing so, I do not believe this to be an overstatement of that work.*

Response:

We are grateful for the reviewer's consideration of the scientific value of our previous works and have changed the language of this paragraph in the revised manuscript to read "Feldman et al. [2011a; 2011b; 2013] developed climate OSSEs with shortwave spectra. These works showed utility of shortwave spectra for detecting climate change, and found that shortwave measurements are more sensitive to low clouds and changes in frozen surface extent than are longwave spectral measurements."

Comment:

8. *Page 3651, Lines 9---10: Include the wavelength range here. "near---UV (0.3 μm) to the far---infrared (50 μm)"*

Response:

The suggested change has been made to the revised manuscript.

Comment:

*Methodology*

1. *Page 3651, Line 21: "Produce spectral measurements" – The OSSE does not produce spectral measurements; it simulates or emulates them.*

Response:

The suggested change has been made to the revised manuscript.

Comment:

2. *Page 3651, Lines 25---27: Align the units again. Also, if inverse cm is in parentheses for the wavelength range, have the spectral resolution be in parentheses as well. It helps your reader to not confuse the units.*

Response:
The suggested change has been made to the revised manuscript.

Comment:

3. *Page 3652, Line 2: After spectral flux, include "spectral irradiance" in parentheses. They are synonymous, and this will help to reach a larger audience.*

Response:
The suggested change has been made to the revised manuscript.

Comment:

4. *Page 3652, Line 17: I understand why you would cite Feldman et al 2011 here, but I would also suggest other classic texts as a fundamental example (e.g. Hansen and Travis, 1974)*

Response:
The suggested change has been made to the revised manuscript, and the citation for the optics from CCSM3 is also included.

Comment:

5. *Page 3653, Lines 10---14: You mention time---saving radiative transfer methods at the end of the manuscript, but I think it warrants a mention here as well. If you have worked with these time--- saving methods and have any idea about how much it reduces this ratio, I recommend including that estimation.*

Response
The suggested change has been made to the revised manuscript.

Comment:
*Results*

1. *Page 3654, Line 10: you mention the longwave fields, but I think you mention them to make the point that they have not been validated as the shortwave fields have been. Say that explicitly at the end of this sentence.*

Response:
The revised manuscript has been changed to emphasize the combined simulation and validation and now reads "While the shortwave OSSE calculations from MODTRAN have already been extensively validated against CCSM3 all-sky and clear-sky albedo [Feldman et al., 2011a], the longwave fields are a new and critical feature to the OSSE, representing the

first time that the hyperspectral climate change signal has been simulated and validated across the entire shortwave and longwave energy budget of the climate system."

Comment:

2. *Page 3654, Line 17: Your description of what is shown in this figure doesn't match what you show in the figure. In the text you need to say that we're looking at a distribution of differences between the OSSE and CCSM3 radiation code OLR and albedo. "show a comparison" doesn't do that sufficiently. – However, Figure 1 is a great display of the differences between the two data sets.*

Response:

The suggested change has been made to the revised manuscript.

Comment:

3. *Page 3654 (Figure 1): What can you say about what the OLR All Sky bias and the other differences mean for the subsequent analysis completed in this study? Do we need to consider those differences as we examine the OSSE results?*

Response:

The following has been added to the revised manuscript: "The implication here is that details of vertical formulation of the radiative transfer are critical for competent instrument simulation, especially in the LW."

Comment:

4. *Page 3655, Line 3: "with good agreement at low solar zenith angles" – From the way this is stated, it sounds like this point is demonstrated in Figures 1c and 1d, which it is not, so please restate.*

Response:

The phrase has been eliminated from the revised manuscript, as it would lead to confusion and information about the competency of the OSSE radiative transfer at high solar zenith angles, due to the plane-parallel approximation, has already been discussed in Feldman et al, 2011, JGR.

Comment:

5. *Page 3655, Line 7: I don't think a common name for the visible (0.3---0.7 μm) is a "window." The 8---12 μm range in the mid---infrared is indeed commonly referred to as the atmospheric window (i.e. the part of the atmosphere transparent to emitted terrestrial infrared radiation), but not the visible. Please just refer to that region as the "visible" and not as a window. This occurs in other places in the manuscript as well. Please change them all, including the labels in Figure 1. Additionally, the first time you mention the atmospheric window (8---12 μm), you should include a brief definition for your audience.*

Response:
The phrasing has been changed to “including two high-transmittance features” in the revised manuscript.

Comment:

6. *Page 3655, Line 8---9: Here you are talking about differences being of opposite sign. Please indicate to the reader that you are now talking about Figure 2b (I assume that you are). Simply placing it in parentheses after that statement would help.*

Response:
The suggested change has been made to the revised manuscript.

Comment:

7. *Page 3655, Line 9: Suggested changes for clarity “Additionally, the spectra indicate the role of water vapour absorption in reducing reflectance in the near---infrared overtone water bands...” In my opinion, your inclusion of overtone throughout the manuscript is not value---added and may just be confusing to the reader. If you would like to include it, it would help to include absorption before the word “bands every time you use it. “...producing rich spectral structure...” is not value---added, please delete.*

Response:
The suggested change has been made throughout the revised manuscript.

Comment:

8. *Page 3655, Line 23: You refer to the water vapor absorption bands in the near infrared as the overtone bands several times. It may help to label those bands as the overtone absorption bands in Figure 1, if you decide to keep this description in the manuscript. Doesn’t the spectral structure of the wings of the NIR water absorption bands only specifically point to the shortwave forcing due to water vapor absorption, not necessarily other greenhouse gases? The way this is stated in the text, is not clear.*

Response:
The phrasing has been changed in the revised manuscript to “indicates the potential for shortwave forcing of greenhouse gases”.

Comment:

9. *Page 3655, Line 25---27: Instead of decreasing/increasing trends, this should be positive/negative trends.*

Response:
The revised manuscript has been changed and now reads “Meanwhile, longwave radiances show a negative trend around 6.3 μm due to greater atmospheric water vapour, positive trends between 8 and 12 μm from higher surface skin temperatures, and negative trends between 14 and 16 μm from increased absorption in the wings of the mid-infrared $CO_2$

bands. The prescribed increases in $CH_4$ and $N_2O$ produce prominent negative trends around 7 μm, while increases in surface and tropospheric temperature are aliased into positive trends in the $H_2O$ mid- and far-IR bands."

Comment:

10. *Page 3656, Line 3---7: You mention this in the Figure 3 caption, but it will clarify your explanation in the text to also say that you're discussing the differences between decadal averages.*

Response:

The suggested change has been made throughout the revised manuscript.

Comment:

11. *Page 3656, Line 11---12: Even though you say "reflectance" instead of "radiance," indicating that you are referring to the shortwave, it will be clearer if you explicitly say "shortwave reflectance." Also, change window band to "visible."*

Response:

The suggested change has been made throughout the revised manuscript.

Comment:

12. *Page 3656, Line 11: "Differences" – change to "Decadal differences"*

Response:

The suggested change has been made throughout the revised manuscript.

Comment:

13. *Page 3656, Line 13: Consider adding "absorption" before "bands"*

Response:

The suggested change has been made throughout the revised manuscript.

Comment:

14. *Page 3656, Line 12---16: "striping feature" isn't sufficient to explain what the reader is looking at. Do you mean the vertical stripes in the water bands? Or horizontal stripes? Be more specific. It's a good visual description, but say something about how those stripes indicate a decrease in water vapor absorption between the two decades. Also, you say "movement of low---level stratus clouds" – but to where? To a higher level in the troposphere or to another zonal band? Additionally, do you know where the ITCZ moves based on what we see?*

Response:

The phrasing has been changed in the revised manuscript and now reads "but vertical striping features covering in the water-vapour overtone absorption bands are also present and are indicative of the decrease in low-level stratus clouds".

Comment:

15. *Page 3656, Line 20: Does "Changes" refer to an increase or decrease in cloud cover, and can you say why this change leads to the changes in spectral features that you indicate?*

Response:

The revised manuscript has been changed and now reads "Increased cloud cover at high northern latitudes over this period lead to decreases in the radiance across the longwave spectrum."

Comment:

16. *Page 3656, Line 24: I thought these were decadal averages, not annual.*

Response:

The revised manuscript has been corrected to note that the figures show decadal, and not annual, averages.

Comment:

17. *From what I read, you did not talk about the CRE sub---figures at all (Fig 3c and 3f). Include them in your existing discussion, add a discussion about them, or eliminate them. It looks like there are some good points you can make about them. You cannot, however, assume that your reader will understand how they help you make your case about the value of the shortwave and longwave all sky and clear sky OSSE output.*

Response:

The following has been added to the revised manuscript: "The CRE changes in Figure (3c) and (3f) reveal the significant changes in low-clouds at high latitudes that impact shortwave reflectance and, to a lesser extent, longwave radiance in both panels. Movement of the ITCZ by the 2090s produces a broadband increase in shortwave reflectance but a broadband decrease in longwave radiance as shown in Figure (3f). Such features are much less apparent in the Figure (3c)."

Comment:

18. *Page 3657, Line 6---7: "Difference trends" then "trend differences" makes this description unclear. Do you mean that you calculated the trends in each model's albedo and OLR and then took the differences or calculated the differences first and then calculated the trends from those differences? Your description could lead the reader either way...don't give them the room to guess.*

Response:
We meant “trend differences” and have modified the revised manuscript accordingly.

Comment:

19. *Page 3657, Line 9: This may be answered when you address the previous comment: I don’t know if by “sign of trends is reversed” really means that or if you mean that the differences in the trends changes sign.*

Response:
We meant the “differences in the trends changes sign” and have adjusted the revised manuscript accordingly.

Comment:

20. *Page 3657, Line 14---15: From the way the first sentence of this paragraph reads, it sounds like you only use shortwave reflectance for climate sensitivity (which is fine if that is true, but I don’t think it has to be). Also, the shortwave response is “larger” than what?*

Response:
The revised manuscript has been changed and now reads “For climate sensitivity, however, the difference in the processes that affect shortwave radiation of these models is larger than the longwave. “

Comment:

21. *Page 3657, Line 18: Insert “longwave” between “hyperspectral” and “simulations” for clarity.*

Response:
The suggested change has been made throughout the revised manuscript.

Comment:

22. *Page 3657, Line 19---23: These validations were done for both models and you found the same result? Also, was the bias found for both OLR and albedo for both clear---sky and all---sky? Just asking for clarification because it isn’t clearly stated. Make sure this is clear for your reader.*

Response:
The revised manuscript has been changed to read “For the shortwave simulations, the hyperspectral simulations exhibit an average bias of 0.1% and an RMS difference of 1.5% and 2.2% for clear-sky and all-sky, respectively, for both models subject to the above-mentioned issues with temporal averaging.”

Comment:

23. *Throughout the discussions of Figures 3 and 4, guide the reader to the specific subfigures better by including Figure 3x or 4x in parentheses, when you can.*

Response:
The suggested change has been made throughout the revised manuscript.

Comment:

24. *Page 3658, Line 5---7: This is a great summary of the purpose of the analysis presented in this study. Well stated. The last sentence of the section is an excellent wrap up of the bigger picture as well.*

Response:
We thank the reviewer for this commendation.

Comment:
*Discussion*

1. *Page 3658, Line 27: "Earth's spectrum" – again, too vague. Specify that you are referring to solar and infrared spectral variability.*

Response:
The revised manuscript now reads "The ultimate goal of this research is to understand both how climate change alters the evolution of the Earth's top-of-atmosphere shortwave reflectance and longwave radiance spectra and determine whether spectral measurements enhance our detection and attribution of climate change."

Comment:

2. *Page 3660, Line 29: "the pan---spectral instrumentation" – this makes it sound like there is one instrument being designed to measure across the shortwave and infrared, whereas, at least in the case of CLARREO, the plan is to have two instruments located on the same satellite that cover each spectral range .*

Response:
It is my understanding that GEO-CAPE will actually be a single, pan-spectral instrument, while CLARREO will have separate instruments. Consequently, I changed the phrasing in the revised manuscript from "instrumentation" to "measurements".

Comment:

*Figures*

1. *Figure 1: Please edit the description to better explain the sub---figures. This isn't a scatterplot; it's a histogram of the differences between the two radiation code calculations. Did you select 2099 for any particular reason? If not and it's just an*

*example, that's fine. If so, that would be good to state. The labels on the figures to point out spectral features are helpful, but try to make them bigger, if possible.*

Response:
The suggested change regarding the description has been made. January 2099 was taken as an example month and the caption for Figure 1 in the revised manuscript indicates this.

Comment:

2. *Figure 2: Although it's mentioned in the text, also specify that the trends in Figure 2b are between 2000 and 2050. Also, did you deseasonalize the reflectance and radiance before calculating these trends? Were the decadal averages used? Or the annual or monthly averages? Although the units are per decade, it is unclear how these trends were calculated. Please specify. (Also for Figure 43 and f).*

Response:
The caption in the revised manuscript has been changed following the reviewer's suggestion. Monthly, non-deseasonalized data were used to calculate the trends

Comment:
***Technical Corrections***

1. *Page 3652, Line 22: There needs to be a semi---colon after the word OSSE. Also should "are" be "of"?*

Response:
The suggested change has been made throughout the revised manuscript.

Comment:

2. *Page 3656, Line 12: Delete "covering" – your point is made well without it.*

Response:
The suggested change has been made throughout the revised manuscript.

Comment:

3. *Page 3658, Line 4: Typo – Did you mean "from models"? You could also say "from a model--- based hyperspectral simulator."*

Response:
The suggested change has been made throughout the revised manuscript.

Reviewer 4:

*This manuscript presents a set of "observing system simulation experiments" (OSSEs) for hyper spectral observations in the longwave and shortwave (as would be obtained e.g. from CLARREO). Detailed simulations of high-resolution spectra are made from atmospheric states sampled during climate-change runs with the NCAR CCSM 3 and from monthly averages with two other climate models (MIROC5 and HadGAM2-ES) chosen because they have low and high climate sensitivity respectively. The spectral features of changes in atmospheric composition and state are identified in the differences between spectra at the beginning, middle, and end of the 21st century and the differences between high- and low-sensitivity models are contrasted.*

Comment:
*The main concerns with the manuscript are a lack of focus and what appears to significant repetition of previously-reported results.*

*The authors would benefit from making their goals for the manuscript more explicit. Much of what's published in GMD deals with technical advances but this manuscript doesn't fit the bill: the combination of radiative transfer modeling with MODTRAN and the simulation of changing climate with CCSM has been previously reported and is, in any event, straightforward if computationally ambitious. The introduction suggests that the goal is to demonstrate the value of hyper-spectral observations, perhaps as a way to contain the climate sensitivity of the real world, but the manuscript doesn't follow this argument very far. Without a sense of what the authors hope to achieve it's hard to provide feedback to help them get there.*

Response:
Briefly, we seek to build a bridge between previous OSSE work and a comprehensive analysis of multi-model archives in order to understand if spectral signatures provide unique ways to differentiate models according to their climate sensitivity and ultimately how if existing hyperspectral measurements can provide that constraint. This would then help the modeling community to understand the value of spectrally-resolved measurements, and how they can be used for future model intercomparison and assessment activities (e.g., CMIP6). The goal of this paper is to present a comprehensive framework for both shortwave and longwave hyperspectral simulation to confront climate models against an entire spectral dimension that is rich in information content with respect to climate change processes.

With respect to the appropriateness of this paper for this journal, we respectfully submit that the enabling of model comparisons between both longwave and shortwave datasets is straightforward in principle, but the implementation, validation, and managing of the extreme computational expense are highly non- trivial exercises. Furthermore, there is not currently a clear pathway towards inline hyperspectral simulator calculations due to computational infeasibility, even though there is a wealth of hyperspectral data (e.g., AIRS, IASI, CrIS, SCIAMACHY) with which potentially to confront models. Nevertheless, it is necessary to do so if the existing and future information in hyperspectral datasets is to be brought to bear to constrain climate models. We discuss a simple strategy of random-sampling that can greatly reduce the computational expense of future instrument simulation to make such an exercise more tractable for inline implementation.

Comment:
*Of larger concern is the fact that the CCSM/MODTRAN calculations appear to be have been described by the authors in previous papers (the Feldman papers from 2011 and 2013). The calculations made for MIROC5 and HadGAM2-ES appear to be novel (though one would like stronger assurances that using monthly-mean fields in place of instantaneous snapshots does not introduce important artifacts). The manuscript makes a number of interesting points regarding the ability of spectrally-resolved observations to distinguish among process in ways that broadband observations can not, but the authors and others have made these points before.*

*Though the work described here may well be a useful contribution it would be difficult to recommend publication of the manuscript in its present form. The authors should clarify the goals of the manuscript for themselves and for readers and focus revisions to support those goals, presenting previously-reported results briefly and stressing the new contributions.*

Response:
As noted with the response to Referee 1, this paper formally presents the pan-spectral OSSE, which has not been covered in other manuscripts. The Feldman et al, 2011 presentation of the SW OSSE discussed the formulation of the SW OSSE in detail and the Feldman et al 2013 paper only briefly discussed the LW calculations, but the pan-spectral capability was not central to that latter paper.

As we noted in a response to Referee 2, the issue that the reviewer raises of simulations based on monthly mean values is extremely well-taken, because the integration of the equation of radiative transfer is generally non-linear. There are several challenges here, however: (1) the fields necessary in the CMIP5 archive to perform competent radiative transfer are archived at monthly resolution and (2) Currently, the OSSE radiometric validation performed with CCSM3 was based on offline calculations to the CAM radiation code and to MODTRAN. Validation against online radiation calculations has not been performed. In order to address the reviewer's comment, we have performed a limited set of calculations and found that the use of monthly means tend to bias the longwave radiance calculations low and the shortwave reflectance calculations high relative to averages of calculations at higher temporal frequencies. Language discussing this effect has been added to the revised manuscript in the Results seciont.

Another completely novel feature of this paper is a discussion of radiometric validation of the OSSE for the infrared calculations and how such validation is straightforward for clear-sky conditions but challenging for all-sky conditions due to whether the radiative transfer is formulated with layers or levels. We added the following language to the revised manuscript to note the importance of radiometric validation which reads "This represents a contribution to the growing literature around instrument emulation since attainment of this consistency requires particular attention to, and extensive validation of, the issues of consistent treatment of cloud overlap / geometry, cloud condensate, the spectral optical properties of cloud condensate, and the cloud thermodynamic state. The reason why this consistency is critically important is that departures of the hyperspectral simulated signal against observations (e.g., SCIAMACHY and AIRS) can then be used directly to check the cloud physics in the model, and in turn we can examine whether broadband cloud feedbacks to climate change have a particularly large AND UNIQUE spectral signature that would be particularly useful for early-detection efforts."

The paper broaches the complementarity of the SW and LW signals in describing the processes that may change the top-of-atmosphere spectrum of the planet. The numerous signals in the SW and LW spectra provide a potentially large number of constraints for model performance beyond OLR and albedo.

The paper discusses prospect for, and provides initial results of, OSSE calculations based on the fields from the Climate Model Output Rewriter (CMOR) for two models spanning the range of climate model sensitivities in the CMIP5 archive. This presents a path towards developing hyperspectral diagnostics for models based on their climate sensitivities and ultimately confronting those models with decadal-length satellite records. Such confrontation will be critical to reduce the range of model results for prescribed forcings in a defensible fashion in CMIP6.

The paper also discusses how the computational expense of simulators can be minimized through random sampling of grid cells, which could broaden the utilisation of inline simulators for CMIP6.

Comment:
*As a minor point, the decision to continue to use CCSM 3.0, a model that's now two generations old, is perplexing and deserves some elaboration.*

Response:
The use of CCSM3 was for demonstration purposes. This model of course is considerably less complex than CESM1 (CAM5), but the utilization of CMOR-ized variables to compare reported results MIROC5 and HADGEM2-ES also enables the comparison to CESM1.

# Pan-Spectral Observing System Simulation Experiments of Shortwave Reflectance and Longwave Radiance for Climate Model Evaluation

Daniel R. Feldman[1, †] William D. Collins[1,2], John L. Paige[1]

[1] Lawrence Berkeley National Laboratory, Earth Sciences Division

[2] University of California-Berkeley, Department of Earth and Planetary Science

[†] Corresponding Author:

drfeldman@lbl.gov

1 Cyclotron Road - MS 74R-316C

Berkeley, CA 94720, USA

Revised Submission for *Geoscientific Model Development*

Daniel Feldman 3/30/15 11:42 AM
**Deleted:** and

Daniel Feldman 3/30/15 11:42 AM
**Formatted:** Superscript

Daniel Feldman 11/21/14 1:31 PM
**Deleted:** 84R0171

## Abstract

Top-of-atmosphere spectrally-resolved shortwave reflectances and longwave radiances describe the response of the Earth's surface and atmosphere to feedback processes and human-induced forcings. In order to evaluate proposed long-duration spectral measurements, we have projected 21st Century changes from the Community Climate System Model (CCSM3.0) conducted for the Intergovernmental Panel on Climate Change (IPCC) A2 Emissions Scenario onto shortwave reflectance spectra from 300 to 2500 nm and longwave radiance spectra from 2000 to 200 cm$^{-1}$ at 8 nm and 1 cm$^{-1}$ resolution, respectively. The radiative transfer calculations have been rigorously validated against published standards and produce complementary signals describing the climate system forcings and feedbacks. Additional demonstration experiments were performed with the MIROC5 and HadGEM2-ES models for the Representative Concentration Pathway 8.5 (RCP8.5) scenario. The calculations contain readily distinguishable signatures of low clouds, snow/ice, aerosols, temperature gradients, and water vapour distributions. The goal of this effort is to understand both how climate change alters reflected solar and emitted infrared spectra of the Earth and determine whether spectral measurements enhance our detection and attribution of climate change. This effort also presents a path forward to understand the characteristics of hyperspectral observational records needed to confront models and inline instrument simulation. Such simulation will enable a diverse set of comparisons between model results from coupled model intercomparisons and existing and proposed satellite instrument measurement systems.

Daniel Feldman 3/31/15 9:04 AM
**Deleted:** evolution of the Earth's surface and atmosphere response to feedbacks in and human-induced forcings on the climate system.

Daniel Feldman 3/30/15 9:52 PM
**Deleted:** described by

Daniel Feldman 3/31/15 9:09 AM
**Deleted:** 0.

Daniel Feldman 3/31/15 9:09 AM
**Deleted:** .

Daniel Feldman 3/31/15 9:09 AM
**Deleted:** μ

Daniel Feldman 3/31/15 9:09 AM
**Deleted:** 5

Daniel Feldman 3/31/15 9:10 AM
**Deleted:** 5

Daniel Feldman 3/31/15 9:10 AM
**Formatted:** Superscript

Daniel Feldman 3/31/15 9:10 AM
**Deleted:** μm

Daniel Feldman 3/30/15 11:04 PM
**Deleted:** the spectrum

Daniel Feldman 1/20/15 11:46 PM
**Deleted:** for hyperspectral measurement-model intercomparison

Daniel Feldman 1/20/15 11:47 PM
**Deleted:** by enabling a

## 1. Introduction

The spectrally-integrated upwelling top-of-atmosphere radiant energy field comprises the Earth system's total energy balance, and comprehensive comparisons of modelled Outgoing Longwave Radiation (OLR) and albedo with observationally-based estimates of these quantities have led to important constraints on climate models [e.g., Morcrette, 1991; Kiehl et al., 1994]. The spectrally resolved energy field spans an additional dimension that contains information regarding the processes that govern that balance. Moreover, it has been demonstrated that infrared spectra contain important information that can be used to test climate models [e.g., Goody et al., 1998], primarily because the spectral signatures of individual forcings and feedbacks can be readily separated, detected, and quantified. Recent work by Roberts et al. [2011] suggest that shortwave spectra also contain independent information about processes that contribute to albedo. Although the separability of processes that contribute to albedo from these spectra has not been addressed formally, Jin et al [2011] showed the utility of shortwave spectral fingerprints which may be extended to consider spectral separability.

Daniel Feldman 3/31/15 9:11 AM
**Deleted:** measurements

Daniel Feldman 3/31/15 10:26 AM
**Deleted:** ,

This has motivated the implementation of Observing System Simulation Experiments (OSSEs) based on climate models as a means for exploring the utility of well-posed comparisons between models and measurements. OSSEs are well-established techniques for evaluating the scientific and operational value of new instruments proposed for meteorological applications [Arnold and Dey, 1986]. The role of OSSEs for climate science is less mature than that of the application to short-term weather forecasting for which they were originally developed. The decadal length of climate studies and the necessarily long measurement records that are needed to confront how models predict climate change motivate the development of climate model OSSEs. The forward evaluation of remote sensing signal sensitivity to uncertain model parametrisations and/or global climate sensitivity contributes to the determination of the value of certain types of remote sensing measurements where the underlying climate signal from the

Daniel Feldman 3/31/15 9:14 AM
**Deleted:** have

Daniel Feldman 3/31/15 9:06 AM
**Deleted:** long duration

Daniel Feldman 1/20/15 11:50 PM
**Deleted:** in their description of

Daniel Feldman 3/31/15 9:19 AM
**Deleted:** allows for an estimation of the value of certain types

model is known. To that end, it has been recently noted by the Intergovernmental Panel on Climate Change (IPCC) that instrument simulators are valuable in that they can obviate inconsistencies between models and measurements [Flato et al., 2013].

Several investigations have explored direct comparisons between measurements from a variety of existing satellite-based instruments and simulations of those measurements based on various climate model integrations.  For example, community-wide efforts have led to the establishment of the Cloud Feedback Model Intercomparison Project Observational Simulator Package (COSP) [Bodas-Salcedo et al., 2011], enabling inline instrument simulations for existing missions including the International Satellite Cloud Climatology Project (ISCCP), the MODerate Resolution Imaging Spectroradiometer (MODIS), CloudSat, and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO).  Results from COSP based on models run in historical mode are then compared to existing measurement records to identify model biases (e.g., Kay et al. [2012]; Pincus et al. [2012]).

Additionally, there have been efforts to explore how hyperspectral measurements can be utilised for facile measurement-model intercomparison. Huang et al. [2007; 2010a] and Leroy et al. [2008] examined longwave measurements and radio occultation simulations in detail and have compared the spectral signatures of variations in lapse rate, water vapour, and cloud radiative effects (CREs).  The discrepancies in measured and modelled spectra suggest that the agreement in measured and modelled OLR is a result of compensating errors between temperature, water vapour, and cloud structure in the models.

Feldman et al. [2011a; 2011b; 2013] developed climate OSSEs with shortwave spectra.  These works showed utility of shortwave spectra for detecting climate change, and found that

Daniel Feldman 3/31/15 9:30 AM
**Deleted:** have discussed

Daniel Feldman 3/31/15 9:30 AM
**Deleted:** how

Daniel Feldman 3/31/15 9:31 AM
**Deleted:** may be considered for OSSEs

Daniel Feldman 3/31/15 9:31 AM
**Deleted:** examined the

Daniel Feldman 3/31/15 9:31 AM
**Deleted:** have

shortwave measurements are more sensitive to low clouds and changes in frozen surface extent than are longwave spectral measurements.

Despite the potential utility of using visible, near-infrared, and infrared measurements, the simultaneous utilisation of shortwave reflectance and longwave radiance spectra to address climate change questions has not been explored in detail to date, despite the numerous studies based on coincident observations of broadband OLR and albedo [e.g., [Kiehl and Trenberth, 1997; Hansen et al., 2005; Wielicki et al., 2006; Loeb et al., 2009]. The combination of shortwave and longwave hyperspectral measurements could potentially be quite useful in addressing fundamental and unanswered questions related to shortwave cloud and ice feedbacks while simultaneously describing the temperature and water vapour structure of the atmosphere. The ultimate goal of this research area is to develop rigorous observational tests for climate models with a particular focus on using measurements to constrain climate model sensitivity.

Existing hyperspectral infrared measurement systems including the Atmospheric Infrared Sounder (AIRS) [Aumann et al., 2003] and the Infrared Atmospheric Sounding Interferometer (IASI) [Siméoni et al., 1997] can be considered as strong observational constraints. Moreover, hyperspectral shortwave measurements are available from the SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY (SCIAMACHY) [Bovensmann et al., 1999], and these extensive data records could be useful for measurement-model intercomparison.

This paper presents a versatile tool for simulating spectrally resolved measurements from the near-UV (300 μm) to the far-infrared (50 μm) and discusses how these measurements can be used to generalise existing OSSE efforts. It demonstrates the rigorous radiometric validation needed to establish comprehensive science traceability studies for planned instruments such

Daniel Feldman 3/9/15 10:09 PM
**Deleted:** The simulations are also designed for

those recommended by the National Research Council's Decadal Survey including CLimate Absolute Radiance and Refractivity Observatory (CLARREO) [Wielicki et al., 2013] and GEOstationary Coastal and Air Pollution Events (GEO-CAPE) [Space Studies Board, 2007]. Additionally, the pan-spectral OSSE may be utilised to develop climate model observational tests for evaluating results reported to the Coupled Model Intercomparison Project – Phase 5 (CMIP5) [Taylor et al., 2012] and Phase 6 (CMIP6) [Meehl et al., 2014].

## 2. Methodology

Following Feldman et al. [2011a], we present OSSE calculations of shortwave spectral reflectance and longwave spectral radiance that simulates spectral measurements based on the climate projections conducted with Community Climate System Model, Version 3.0 (CCSM3) integrations [Collins et al., 2006a; Meehl et al., 2006]. The spectral calculations are performed with the MODerate Resolution TRANsmission (MODTRAN$^{TM}$) radiative transfer code [Berk et al., 2005]. The shortwave and longwave spectra are calculated from 0.3 to 2.5 μm (33333 to 4000 cm$^{-1}$) at a 15 cm$^{-1}$ native resolution, and from 5 to 50 μm (2000 to 200 cm$^{-1}$) at a 1 cm$^{-1}$ native resolution, respectively. The calculations produce top-of-atmosphere (TOA) radiance spectra and upwelling and downwelling direct and diffuse spectral flux (irradiance) fields at each vertical level of CCSM3.

Daniel Feldman 3/30/15 8:53 PM
**Deleted:** produce

Daniel Feldman 3/30/15 8:58 PM
**Deleted:** (8 nm convolved instrument function)

The fields produced in CCSM3 integrations include vertical profiles of atmospheric thermodynamic properties, trace gases, and condensed species on a 26 level hybrid-sigma grid extending from the surface to a constant pressure level of 2 hPa. CCSM3 has been run at a variety of different horizontal resolutions for the spectral-Eulerian atmospheric dynamical core. The results described here have been computed and archived at T85 resolution representing a triangular truncation of the dynamics at 85 wavenumbers and corresponding to a 1.4° equilateral grid on the equator. The OSSE, as described by Feldman et al. [2011a], utilises monthly-mean values for profiles of temperature, water vapour ($H_2O$), carbon dioxide ($CO_2$), ozone ($O_3$), methane ($CH_4$), nitrous oxide ($N_2O$), trichlorofluoromethane (CFC-11), and dichlorodifluoromethane (CFC-12). Profiles of both liquid and ice cloud area, condensed water content, and effective radius are utilised. The treatment of cloud optics for the spectral simulations in the OSSE is identical to that used by the CCSM3. In the shortwave, the optical properties of liquid and ice clouds vary with wavelength [Hansen and Travis, 1974; Slingo, 1989]. In the longwave, liquid and ice clouds are treated as grey bodies where liquid clouds are assigned a constant emissivity and ice clouds are assigned an emissivity that varies with the effective radii diagnosed for the constituent ice crystals. The infrared absorption and scattering by aerosols are not included in the longwave OSSE; although the direct radiative effects of dust, sulfate, carbonaceous, and sea-salt aerosols are incorporated in the shortwave OSSE.

Daniel Feldman 3/30/15 9:01 PM
**Deleted:** Feldman et al., 2011a]

Daniel Feldman 3/31/15 6:12 PM
**Deleted:** ,

Daniel Feldman 3/31/15 6:12 PM
**Deleted:** are

The treatment of the optical surface properties utilises the MODIS Bi-directional Reflectance Distribution Function [Schaaf et al., 2002] and has been critical for the realism of the shortwave OSSE [Feldman et al., 2011b] under present-day conditions. The formulation of the land-surface optical reflection reproduces the snow-free and snow-covered bidirectional reflectance properties from MODIS, and it also includes the effects of retreating snow cover on projections of the Earth's future reflectance field. The longwave portion of the OSSE treats ocean surfaces with unitary emissivity, while land surface emissivity is based on an annually-cyclic monthly-mean climatology derived from spatial and temporal binning of the MODIS Land Surface Emissivity product [Wan and Zhao-Liang, 1997]. By design, the effects of changes in sea-ice extent and snow cover are included in the OSSE calculations while the effects of future land-use and land-cover change and of changing soil moisture on near-infrared surface albedos are not.

This OSSE software framework requires multiple calls to the MODTRAN radiative transfer code and the OSSE is quite computationally expensive despite the optimised load-balancing and intrinsic parallelism of the calculations. Even though it is has been run on a massively parallel NASA High-End Computing (HEC) facility, the ratio of OSSE computational time to the computational time to integrate the fully-coupled CCSM3 for the 21st Century is approximately 50:1. There are several potential methods to reduce this computational expense, which will be discussed in Section 4.

In support of the IPCC Fifth Assessment Report, modelling centres have undertaken significant efforts to produce a large set of model integrations for CMIP5. A similar infrastructure to the CCSM3 offline hyperspectral calculations was adopted for two climate models. These models were MIROC5 [Watanabe et al., 2010] and HadGEM2-ES [Jones et al., 2011], which lie on the low and high end of the model range of CMIP5 equilibrium climate sensitivities at 2.72 and 4.59 °K/2x$CO_2$, respectively [Andrews et al., 2012]. Simulations were implemented for the first three decades of the Representative Concentration Pathway 8.5 (RCP8.5) scenario [Van Vuuren et al., 2011]. The fields necessary to perform reflectance and radiance calculations in the OSSE have, unfortunately, only been archived at monthly-mean temporal resolution for this scenario. Due to the nonlinearity of radiative transfer, it is challenging to validate offline OSSE calculations with the reported values of albedo and OLR from these models, the latter of which are based on averages of radiation calculations performed with time-steps of a few minutes.

## 3. Results

In order to meet the requirement for high-accuracy calculations to support both mission design and climate model evaluation, there has been extensive validation performed on both the longwave and shortwave OSSE calculations based on CCSM3. As a result, the radiation calculations performed by MODTRAN are fully consistent with those produced by the CCSM3 radiation code, which itself is extensively evaluated against line-by-line models [Collins et al., 2006b; Oreopoulos et al., 2010]. While the shortwave OSSE calculations from MODTRAN have already been extensively validated against CCSM3 all-sky and clear-sky albedo [Feldman et al., 2011a], the longwave fields are a new and critical feature to the OSSE, representing the first time that the hyperspectral climate change signal has been simulated and validated across the entire shortwave and longwave energy budget of the climate system.

Daniel Feldman 3/9/15 10:12 PM
**Deleted:** .

Longwave validation of the two codes was performed using a comparison of TOA OLR. Differences between the two radiative transfer schemes are less than 1% for both clear- and all-sky conditions and arise from several factors. These factors include the contrasting treatments of clouds as vertically extended non-isothermal layers in MODTRAN versus infinitely-thin isothermal objects in CCSM3 together with the contrasting solutions to the radiative equations using 8 discrete-ordinate streams in MODTRAN versus two streams in CCSM3. Figure (1a-b) shows a distribution of the differences between the OLR produced by the OSSE through offline calls to the CCSM3 longwave radiation code and the OLR produced from the MODTRAN instrument emulator. Figure (1b) indicates the clear-sky calculations agree to better than 2 W/m$^2$. Meanwhile, the level of agreement between the all-sky OLR from CCSM3 and MODTRAN is degraded relative to the clear-sky case, as shown in Figure (1a), with a mean offset of 1 W/m$^2$ and a root-mean-square (RMS) value of 3.1 W/m$^2$. A closer investigation revealed that the differences in the numbers of streams in the radiative solution and level-layer formulation differences accounted for the all-sky discrepancies. This is consistent with the performance of the shortwave reflectance component of the OSSE, though the all-sky agreement between MODTRAN and the Community Atmosphere Model (CAM) component of CCSM3 exhibit less spread because the level-layer formulation discrepancy affects OLR more than albedo. The implication here is that details of vertical formulation of the radiative transfer are critical for competent instrument simulation, especially in the LW. The agreement between MODTRAN and CAM for shortwave fluxes is shown in Figure (1c) and (1d) with a mean offset of around 3 W/m$^2$ in all-sky conditions and 1 W/m$^2$ for clear-sky conditions.

Daniel Feldman 3/31/15 11:23 AM
**Deleted:** comparison

Daniel Feldman 3/31/15 11:53 AM
**Deleted:** , with good agreement at low solar zenith angles

Globally-averaged longwave radiance and shortwave reflectance spectra are shown in Figure (2a) for both clear-sky and all-sky conditions at the beginning of the integration. This figure demonstrates many of the complementary features, due to a number of climate-relevant processes, in these two spectral ranges, including two high-transmittance features in the visible and the mid-infrared which are affected by the presence of clouds, but, as shown in Figure (2b), clear-sky and all-sky differences are of opposite sign between the visible and infrared. Additionally, the spectra indicate a role of water vapour in reducing reflectance in the near-infrared overtone absorption bands between 0.8 and 2.0 μm and producing rich spectral structure and decreased infrared radiance between 5 and 8.3 μm and 17 and 50 μm. Prominent greenhouse-gas absorption features are also indicated for $CO_2$, $O_3$, $CH_4$, and $N_2O$.

Daniel Feldman 3/31/15 12:23 PM
**Deleted:** the

Daniel Feldman 3/31/15 12:16 PM
**Deleted:** window

Figure (2b) shows the corresponding globally-averaged trends in shortwave reflectances and longwave radiances during the first 50 years of the A2 scenario simulation. Several prominent features can be seen. First, the shortwave reflectances generally increase with the increased aerosol loading projected for the first half of the 21st Century under both clear- and all-sky conditions, and this effect is evident at shorter wavelengths. While much of the spatial and seasonal heterogeneity in shortwave reflectance trends that was identified in Feldman et al. [2011a] is averaged out in the globally and annually averaged trends, the contrast between clear-sky and all-sky reflectance trends gives an indication of the additional increase in reflectance from clouds. Also, the complex spectral structure in the wings of the near-infrared $H_2O$ overtone absorption bands indicates the potential for shortwave forcing of greenhouse gases, a topic that deserves greater scrutiny [Collins et al., 2006b].

Meanwhile, longwave radiances show a negative trend around 6.3 μm due to greater atmospheric water vapour, positive trends between 8 and 12 μm from higher surface skin

Daniel Feldman 3/31/15 12:48 PM
**Deleted:** decreasing

Daniel Feldman 3/31/15 12:49 PM
**Deleted:** increasing

temperatures, and negative trends between 14 and 16 μm from increased absorption in the wings of the mid-infrared $CO_2$ bands. The prescribed increases in $CH_4$ and $N_2O$ produce prominent negative trends around 7 μm, while increases in surface and tropospheric temperature are aliased into positive trends in the $H_2O$ mid- and far-IR bands.

Daniel Feldman 3/31/15 12:49 PM
**Deleted:** decreasing

Daniel Feldman 3/31/15 12:49 PM
**Deleted:** signals

Figure (3a-c) shows differences in zonally- and decadally-averaged shortwave reflectance and longwave radiance spectra for clear-sky and all-sky conditions and cloud radiative effect (CRE) between the decade from 2050-2059 and the first decade of the 21st Century, while Figure (3d-f) show the differences between 2090-2099 and the first decade of the 21st Century. Increases in anthropogenic aerosol loading between the decades of the 2000s and the 2050s result in increased clear-sky reflectance at low latitudes and visible and near-infrared wavelengths during that time period. Concurrent changes in the frozen surface coverage decrease reflectance at higher latitudes in the window band but not in the near-infrared. Decadal differences in all-sky shortwave reflectance share some similarities to decadal differences in the clear-sky shortwave reflectance, but vertical striping features in the water-vapour overtone absorption bands are also present and are indicative of the decrease in low-level stratus clouds. Additionally, movement of the InterTropical Convergence Zone (ITCZ) produces a dipole in reflectance near the equator with diminished striping features across the overtone absorption bands.

Daniel Feldman 3/31/15 6:13 PM
**Deleted:** covering

Daniel Feldman 3/31/15 1:20 PM
**Deleted:** movement

The changes in both all-sky and clear-sky longwave radiance exhibit the spectral features highlighted in Figure (2b). The only other prominent feature is the polar amplification of surface temperature warming that produces meridional gradients in the window band. Increased cloud cover at high northern latitudes over this period lead to decreases in the radiance across the longwave spectrum. Additionally, the stratospheric cooling and increased $CO_2$ are prominent around 15 μm while increasing $CH_4$ and $N_2O$ produce significant signals around 7 μm.

Daniel Feldman 3/31/15 1:22 PM
**Deleted:** Changes

Daniel Feldman 3/31/15 1:22 PM
**Deleted:** in

Daniel Feldman 3/31/15 1:24 PM
**Deleted:** except between 14 and 16 μm around the ITCZ

Differences in zonally- and decadally-averaged shortwave reflectance and longwave radiance between the start and end of the 21st Century under the A2 emissions scenario are shown in Figure (3d-f). These spectra show decreased frozen surface extent at high latitudes in visible reflectances and increased water vapour loading leading to lower reflectances in the water vapour overtone bands and at 6.3 μm and in the far-infrared $H_2O$ rotational band. All-sky pan-spectral simulations reveal the shifts in storm-tracks with striping features in the $H_2O$ near-infrared overtone bands at mid-latitudes, and they reveal a stronger dipole near the ITCZ near the equator across the shortwave and longwave.

Daniel Feldman 3/31/15 1:25 PM
**Deleted:** annually

The CRE changes in Figure (3c) and (3f) reveal that significant changes in low-clouds at high latitudes that impact shortwave reflectance and, to a lesser extent, longwave radiance in both panels. Movement of the ITCZ by the 2090s produces a broadband increase in shortwave reflectance but a broadband decrease in longwave radiance as shown in Figure (3f). Such features are much less apparent in the Figure (3c).

OSSEs can also be used for inter-model comparisons. To demonstrate this, we considered the contributions of the MIROC5 and HadGEM2-ES models to the CMIP5 archive. Trend differences in albedo and OLR are shown in Figure (4a-d). In all-sky OLR, as shown in Figure (4b), trend differences indicate model disagreement in deep convective response in the Tropical Western Pacific, with HadGEM2-ES showing increased deep convection as compared to MIROC5, though the difference in the trends changes sign over South America. The clear-sky OLR trend differences, as shown in Figure (4d) are small, but spatially expansive and are due in large part to the water vapour response both in convective and subsidence regions. The MIROC5 model exhibits a water vapour loading response that impacts OLR more than the HadGEM2-ES model.

Daniel Feldman 3/31/15 2:46 PM
**Deleted:** Difference

Daniel Feldman 3/31/15 2:46 PM
**Deleted:** trends

Daniel Feldman 3/31/15 2:47 PM
**Deleted:** of trends is reversed

For climate sensitivity, however, the difference in the processes that affect shortwave radiation of these models is larger than the longwave. Differences in the models' description of sea-ice loss and cloud response at high latitudes and particularly in subsidence regions, have been shown to contribute most significantly to the discrepancy in their equilibrium sensitivities [Andrews et al., 2012]. Hyperspectral longwave simulations based on these models have been validated with a bias of 3 $W/m^2$ and an RMS difference of 0.5 and 3 $W/m^2$ for clear-sky and all-sky longwave, respectively, with respect to the model-reported TOA fluxes. For the shortwave simulations, the hyperspectral simulations exhibit an average bias of 0.1% and an RMS difference of 1.5% and 2.2% for clear-sky and all-sky, respectively, for both models subject to the above-mentioned issues with temporal averaging. Nevertheless, Figures (4e) and (4f) indicate that there are numerous differences in the models' response in hyperspectral simulations in subsets of the OSSE spectra from the Arctic and the Tropical Western Pacific. Both the visible and infrared window spectral regions readily differentiate the two climate model runs, and spectral trends of the model differ significantly. Also, in the TWP, the sign of the change in the shortwave visible differs from that of the near-infrared water vapour overtone regions, potentially improving signal detectability, and indicating the potential for spectra to identify processes that contribute to different trends in OLR and albedo. The corollary of this is that long-term spectral trends from measurements can be confronted with the results of a hyperspectral simulator from models to exclude one or more model descriptions of the response to known forcings. It is worth noting that Huang and Ramaswamy [2009] showed that longwave spectral radiance measurements can disclose detailed climate change signals that would have otherwise been hidden in the model-reported broadband fluxes due to compensating effects. The results here also suggest that such compensation may be occurring in the shortwave as well.

Daniel Feldman 3/31/15 7:36 PM
**Deleted:** response

One important caveat to these results, though, is, as mentioned above, the use of monthly-mean profiles for simulation. Previous work by Huang and Ramaswamy [2009] found that calculations based on monthly-mean profiles rather than instantaneous ones could introduce negative brightness temperature biases between 3 and 4 °K. To test the effect in the shortwave, we modified CCSM such that it reported the fields necessary for the OSSE at 3-hour intervals for a single month, and then compared the results from the OSSE based on a monthly-mean profile.  We find that the use of monthly mean profiles leads to a positive shortwave reflectance bias RMSE of 0.05, due to the effect from clouds, but, as was found previously by Roberts et al, [2011], does not appear to impact variability significantly.  However, this shortwave is larger than the climate change signal, and modelling centres therefore need to archive the fields necessary for instantaneous radiative transfer calculation to avoid precluding offline diagnoses.

Hyperspectral instrument simulators such as the one presented here enable researchers to explore the spectral dimension of climate change to understand how various processes contribute to changes in albedo and OLR.   The large number of data points generated by this pan-spectral OSSE provide numerous opportunities for measurement-model intercomparison, and the contrasting performance of the OSSE in the visible and infrared windows and near-infrared water vapour overtone bands and mid-infrared vibration-rotation bands provide an indication for the potential benefit for the construction of combined shortwave and longwave spectral fingerprints (e.g., [Leroy and Anderson, 2010], [Huang et al. 2010b]) of climate change, without the degeneracy of signals from low-clouds and surface temperature.

## 4. Computational Expense

The computational expense of the OSSE described here is extreme, even for advanced supercomputers, and requires a careful consideration of system queuing priorities to balance throughput with resource request size. Furthermore, even the expense of the COSP simulators, which is considerably less than the OSSE described herein, is prohibitive.

For reference purposes, we find that, using MODTRAN, for a 26-level atmosphere, each all-sky shortwave spectrum calculation, which includes 16 sub-column calls for the cloud overlap approximation, requires 184 CPU-seconds while each longwave spectrum calculation, which also includes 16 sub-column calls, requires 17.6 CPU-seconds on the NASA HEC resources. The computational expense scales with the number of levels and sub-column calls. More optimized radiative transfer codes such as Principal Component Radiative Transfer Model (PCRTM) [Liu et al. 2006] can achieve a speed-up of at least an order of magnitude in the shortwave and two orders of magnitude in the longwave.

In preparation for the large number of simulations that will likely be submitted to the CMIP6 archive, there is, a pressing need to consider how observational simulators can have reduced computational expense. We therefore consider how future OSSEs may perform spatial sampling to achieve tolerable radiometric accuracy with fewer radiative transfer calls. Figure (5a-d) show that global and regional averages can be obtained by randomly sampling grid boxes and then performing radiative transfer calculations. This will produce a level of radiometric error that is less 2% for global average and 1% for Tropical Western Pacific regional average, which is consistent with the CLARREO mission specification [Wielicki et al. 2013] with two orders of magnitude fewer calculations. These results imply that inline satellite simulation, may be tractable for CMIP5 and CMIP6 models where climatological averages are desired.

## 5. Discussion

Daniel Feldman 3/9/15 10:25 PM
**Deleted:** 4

This paper has introduced a software framework that is capable of simulating the shortwave and longwave TOA spectral signatures of the climate change diagnosed from projections from global climate and Earth system models. This represents a contribution to the growing literature around instrument emulation since attainment of this consistency requires particular attention to, and extensive validation of, the issues of consistent treatment of cloud overlap / geometry, cloud condensate, the spectral optical properties of cloud condensate, and the cloud thermodynamic state.

The reason why this consistency is critically important is that departures of the hyperspectral simulated signal against observations (e.g., SCIAMACHY and AIRS) can then be used directly to check the cloud physics in the model, and in turn we can examine whether broadband cloud feedbacks to climate change have a particularly large AND UNIQUE spectral signature that would be particularly useful for early-detection efforts.

The pan-spectral simulations span from the near-UV to the far-infrared and indicate a rich level of information content. Long-term measurements of changes in these quantities will capture many of the climate change processes and the relationships between these processes that are sources of uncertainty in climate models. They also indicate that the shortwave measurements are much more spatially heterogeneous than the longwave measurements, so analysis of globally-averaged changes in shortwave spectra is less suited towards diagnosing the processes that contribute to spectral changes than detailed examination of spatially resolved differences.

The ultimate goal of this research is to understand both how climate change alters the evolution of the Earth's top-of-atmosphere shortwave reflectance and longwave radiance spectra and determine whether spectral measurements enhance our detection and attribution of climate

Daniel Feldman 3/31/15 8:27 PM
**Deleted:** spectrum

change. The pan-spectral OSSE described here will enable formal comparisons between models and a broad suite of planned and existing instrumentation, and will help establish observational metrics for differentiating between climate models according to specific processes. This may also enhance the current efforts to utilise the highly-regularised climate model reporting framework of the CMIP5 to simulate specific instrumentation through the Observational Simulator Package (COSP) [Bodas-Salcedo et al., 2011]. As of this writing, the COSP framework (version 1.3.1) currently has an ISCCP, MODIS, CloudSat, and CALIPSO instrument emulators. It can be linked with the Radiative Transfer for Television Infrared Observation Satellite Operational Vertical Sounder (RTTOV) [Saunders et al., 1999], which is a hyperspectral mid-infrared simulator, but that package has only been developed for clear-sky applications. Regardless, is a critical need to develop the methodology to utilise the spectral dimension to gauge model performance. Recent works by Roberts et al. [2011; 2013] provide a path forward for how this can be undertaken quantitatively using principal components, and these tools may be helpful for the modelling community for narrowing the range in reported shortwave feedback.

A primary challenge to the utilisation of instrument simulators for model and measurement-model intercomparison is their large computational expense. For pan-spectral simulators, the expense is even more significant, with over 70% arising from the shortwave simulation. However, it should be noted that we found a contrast between the visible and near-infrared response to climate change, with the former largely controlled by spectrally-flat features and the latter controlled by the interaction between clouds, aerosols, water vapour, and greenhouse gases. Spectral resolution is required to capture those interactions in the near-infrared. Moreover, Roberts et al. [2011] showed that the principal component spectrum from SCIAMACHY measurements changed significantly between 25 and 100 nm Full-Width Half Max (FWHM) resolution, suggesting that information about shortwave processes requires dozens of channels, but not thousands. The computational expense can be lowered with ultra-fast radiative transfer methods (e.g., Liu et al. [2006]). Alternatively, regional calculations may be considered for addressing those regions that contribute most significantly to climate sensitivity divergence [Armour et al., 2013]. We also demonstrate that global and regional averages can be obtained with acceptable levels of radiometric error via simulations based on random grid-box sampling. This approach does have the potential to encompass a large number of existing and proposed measurement concepts. It is much more of a challenge to use narrow-band simulators to explore the value of new mission concepts.

Daniel Feldman 3/16/15 12:11 PM
**Deleted:** Finally, while the computational expense of the calculations presented here is extreme, t

For competent simulation, it is critical that model intercomparison projects, such as those of CMIP5, archive the fields necessary to perform offline diagnostic radiative transfer across the electromagnetic spectrum. This includes the three-dimensional thermodynamic, gaseous, and condensate structure of the atmosphere, and land emission and reflectance at time-scales sub-daily time-scales. The Cloud Feedback Model Intercomparison Project [Bony et al., 2011] archived these fields for snapshots of several experiments associated with CMIP5, but the level of participation by the modelling centres was less than for the CMIP5 Tier 1 experiments including RCP8.5.

Spectra can be a very important tool for measurement model intercomparison, but OSSE development needs to be expanded to consider existing hyperspectral data records, which contain numerous indicators of processes that control the Earth’s energy balance. As of the writing of this paper, the data record from AIRS is over 11 years’ long, the IASI record is over 7 years’ long, and the SCIAMACHY record is over 10 years’ long. These decadal length records provide an opportunity to test present day climate model performance in multiple ways that cannot be easily be adjusted with problematic tuning [Mauritsen et al., 2012] and can therefore be strict constraints for model development and testing. However, the challenges that have faced other long-term satellite data record analyses [Norris, 2007; Clement et al., 2009; Spencer and Christy, 1992; Fu and Johanson, 2004; Seidel et al., 2011] must be considered. While orbit and calibration are considerably less problematic for newer instrumentation, the climate quality of the instantaneous retrievals must be established. This pan-spectral simulation capability may also be applicable to recent efforts by CLARREO and GEO-CAPE to develop the pan-spectral measurements in order to answer questions related to the processes that contribute to TOA atmospheric energetics and also the evolution of tropospheric chemistry.

Daniel Feldman 3/31/15 7:40 PM
**Deleted:** instrumentation

The community should consider how the advent of pan-spectral measurements may have the potential to detect climate change and to distinguish which climate models produce more realistic projections, sooner than is possible with conventional broadband instruments [Feldman et al., 2013]. Spectral Empirical Orthogonal Functions may accelerate this ability to distinguish models even further by exploiting spectral redundancy to minimise noise and discern spectral multi-pole features less readily detected with broadband instruments. Pan-spectral techniques can then be used to detect low-cloud feedbacks sooner and with greater accuracy than broadband or spectral infrared techniques alone. Optimal detection techniques [e.g., Newchurch et al., 2003; Leroy and Anderson, 2010] are critical to establishing how the hyperspectral dimension can be utilised to detect climate change and assess models.

## Acknowledgements

Funding for this research was supported by NASA grants NNX10AK27G, and NNX11AE65G and NASA High-End Computing grants SMD-08-0999, SMD-09-1397, and SMD-10-1799.  This work was also supported by Contractor Supporting Research (CSR) funding from Berkeley Lab, provided by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. The following individuals also contributed: David Young, Bruce Wielicki, and Rosemary Baize of the NASA Langley Research Center, Tsengdar Lee of the NASA Science Mission Directorate, Lex Berk of Spectral Sciences, Inc., and four anonymous reviewers.

Daniel Feldman 3/31/15 10:01 PM
**Deleted:** and

## References

Andrews, T., Gregory, J. M., Webb, M. J., & Taylor, K. E. (2012). Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere‐ocean climate models. *Geophysical Research Letters*, *39*(9).

Armour, K. C., Bitz, C. M., & Roe, G. H. (2013). Time-Varying Climate Sensitivity from Regional Feedbacks. *Journal of Climate*, *26*(13).

Arnold, C. P., Jr.  and C. H. Dey (1986), Observing-systems simulation experiments: Past, present, and future, *Bulletin of the American Meteorological Society,* 67, 687-695.

Aumann, H. H., Chahine, M. T., Gautier, C., Goldberg, M. D., Kalnay, E., McMillin, L. M., Revercomb, H., Rosenkranz, P., Smith, W., Staelin, D., Strow, L., Susskind, J. (2003). AIRS/AMSU/HSB on the Aqua mission: Design, science objectives, data products, and processing systems.  *IEEE Transactions on Geoscience and Remote Sensing, 41*(2), 253-264.

Berk, A., Anderson, G. P., Acharya, P. K., Bernstein, L. S., Muratov, L., Lee, J., ... & Lewis, P. E. (2005, June). MODTRAN 5: a reformulated atmospheric band model with auxiliary species and practical multiple scattering options: update. In *Defense and Security* (pp. 662-667). International Society for Optics and Photonics.

Bodas-Salcedo, A., et al. (2011), COSP: Satellite simulation software for model assessment. *Bulletin of the American Meteorological Society*, 92, 1023–1043.

Bony, S., Webb, M., Bretherton, C., Klein, S. A., Siebesma, P., Tselioudis, G., & Zhang, M. (2011). CFMIP: Towards a better evaluation and understanding of clouds and cloud feedbacks in CMIP5 models. *Clivar Exchanges*, *56*(2), 20-22.

Bovensmann, H., Burrows, J. P., Buchwitz, M., Frerick, J., Noël, S., Rozanov, V. V., Chance, K. V., Goede, A. P. H. (1999). SCIAMACHY: Mission objectives and measurement modes. *Journal of the Atmospheric Sciences*, *56*(2), 127-150.

Clement, A. C., Burgman, R., & Norris, J. R. (2009). Observational and model evidence for positive low-level cloud feedback. *Science*, *325*(5939), 460-464.

Collins, W.D. et al. (2006a), The Community Climate System Model: CCSM3. *Journal of Climate*, 19, 2122 – 2143.

Collins, W. D., Ramaswamy, V., Schwarzkopf, M. D., Sun, Y., Portmann, R. W., Fu, Q., Cassanova, S.E.B., Dufresne, J.-L. , Fillmore, D.W., Forster, P.M.D., Galin, V.Y., Gohar, L.K., Ingram, W.J., Kratz, D.P., Lefebvre, M.-P., Li, J., Marquet, P., Oinas, V., Tsushima, Y., Uchiyama, T., Zhong, W. Y. (2006b). Radiative forcing by well‐mixed greenhouse gases: Estimates from climate models in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). *Journal of Geophysical Research: Atmospheres (1984–2012)*, *111*(D14).

Feldman, D. R., et al. (2011a), CLARREO shortwave observing system simulation experiments of the twenty-first century: Simulator design and implementation, *Journal of Geophysical Research-Atmospheres,* 116, D10107, doi:10.1029/2010JD015350.

Feldman, D. R., et al. (2011b), Simulation studies for the detection of changes in broadband albedo and shortwave nadir reflectance spectra under a climate change scenario, *Journal of Geophysical Research-Atmospheres*, 116, D24103, doi:10.1029/2011JD016407.

Feldman, D.R., D.M. Coleman, W.D. Collins, (2013), On the Usage of Spectral and Broadband Satellite Instrument Measurements to Differentiate Climate Models with Different Low-Cloud Feedback Strengths. *Journal of Climate*, doi: 10.1175/JCLI-D-12-00378.1.

Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, P. Cox, F. Driouech, S. Emori, V. Eyring, C. Forest, P. Gleckler, E. Guilyardi, C. Jakob, V. Kattsov, C. Reason and M. Rummukainen, 2013: Evaluation of Climate Models. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Fu, Q., & Johanson, C. M. (2004). Stratospheric influences on MSU-derived tropospheric temperature trends: A direct error analysis. *Journal of Climate*,*17*(24).

Goody, R., J. Anderson, G. North, (1998), Testing climate models: An approach. *Bulletin of the American Meteorological Society*, 79, 2541-2549.

Hansen, J.E., L.D. Travis. (1974), Light scattering in planetary atmospheres. *Space Science Reviews*, 16(4), 527-610.

Hansen, J., L. Nazarenko, R. Ruedy, M. Sato, J. Willis, A. Del Genio, D. Kock, A. Lacis, K. Lo, S. Menon, T. Novakov, J. Perlwitz, G. Russell, G. Schmidt, N. Tausnev, (2005), Earth's energy imbalance: Confirmation and implications, *Science*, 208, 1431-1435.

Huang, Y., V. Ramaswamy, X. Huang, Q. Fu, C. Bardeen, (2007), A strict test in climate modeling with spectrally resolved radiances: GCM simulation versus AIRS observations, *Geophysical Research Letters*, 34, L24707, doi:10.1029/2007GL031409.

Huang, Y. and V. Ramaswamy (2009), Evolution and trend of the outgoing longwave radiation spectrum. *Journal of Climate*, 22, 4637-4651.

Huang, Y., S.S. Leroy, J.G. Anderson (2010a), Determining Longwave Forcing and Feedback Using Infrared Spectra and GNSS Radio Occultation, *Journal of Climate*, 23, 6027-6035.

Huang, Y., S. Leroy, J. Gero, J. Dykema, and J. Anderson (2010b), Separation of long- wave climate feedbacks from spectral observations. *Journal of Geophysical Research-Atmospheres*, 115, D07104, doi:10.1029/2009JD012766.

Jin, Z., B.A. Wielicki, C. Loukachine, T. P. Charlock, D. Young, and S. Noël, (2011), Spectral kernel approach to study radiative response of climate variables and interannual variability of reflected solar spectrum, *Journal of Geophysical Research-Atmospheres*, 116, D10113.

Jones, C. D., et al. (2011). The HadGEM2-ES implementation of CMIP5 centennial simulations. *Geoscientific Model Development*, *4*(3), 543-570.

Kay, J. E., Hillman, B. R., Klein, S. A., Zhang, Y., Medeiros, B., Pincus, R., Gettelman, A., Eaton, B., Boyle, J., Marchand, R. Ackerman, T. P. (2012). Exposing Global Cloud Biases in the Community Atmosphere Model (CAM) Using Satellite Observations and Their Corresponding Instrument Simulators. *Journal of Climate*, *25*(15).

Kiehl, J. T., J.J. Hack, B.P. Briegleb (1994), The simulated Earth radiation budget of the National Center for Atmospheric Research community climate model CCM2 and comparisons with the Earth Radiation Budget Experiment (ERBE), *Journal of Geophysical Research*, *99*(D10), 20,815–20,827, doi:10.1029/94JD00941.

Kiehl, J.T., and K.E. Trenberth (1997), Earth's annual global mean energy budget, *Bulletin of the American Meteorological Society*, 78,197-208.

Leroy, S., J. Anderson, J. Dykema, R. Goody, (2008), Testing climate models using thermal infrared spectra, *Journal of Climate*, 21, 1863-1875.

Liu, X., Smith, W. L., Zhou, D. K., & Larar, A. (2006). Principal component-based radiative transfer model for hyperspectral sensors: theoretical concept. *Applied Optics*, *45*(1), 201-209.

Loeb, N.G., et al. (2009), Toward Optimal Closure of the Earth's Top-of-Atmosphere Radiation Budget, *Journal of Climate*, 22, 748-766.

T.Mauritsen, B. Stevens, E. Roeckner, T. Crueger, M. Esch, M. Giorgetta, H. Haak, J. Jungclaus, D. Klocke, D. Matei, U. Mikolajewicz, D. Notz, R. Pincus, H. Schmidt, L. Tomassini, (2012), Tuning the climate of a global model, *Journal of Advances in Modeling Earth Systems*, 4, M00A01, doi:10.1029/2012MS000154.

Meehl, G.A., et al. (2006), Climate Change Projections for the Twenty-First Century and Climate Change Commitment in the CCSM3. *Journal of Climate*, 19, 2597-2616.

Meehl, G. A., R. Moss, K. E. Taylor, V. Eyring, R. J. Stouffer, S. Bony, and B. Stevens, (2014), Climate Model Intercomparison: Preparing for the Next Phase, *Eos, Trans. AGU*, 95(9), 77.

Morcrette, J.-J. (1991), Radiation and Cloud Radiative Properties in the European Centre for Medium Range Weather Forecasts Forecasting System, *Journal of Geophysical Research*, *96*(D5), 9121–9132, doi:10.1029/89JD01597.

Nakicenovic, N. et al. (2000), *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, U.K., 599 pp.

Norris, J. R. (2007). Observed Interdecadal Changes in Cloudiness: Real or Spurious?. In *Climate Variability and Extremes during the Past 100 Years* (pp. 169-178). Springer Netherlands.

Oreopoulos, L., & Mlawer, E. (2010). MODELING: The Continual Intercomparison of Radiation Codes (CIRC) Assessing Anew the Quality of GCM Radiation Algorithms. *Bulletin of the American Meteorological Society*, *91*(3), 305-310.

Pincus, R., Platnick, S., Ackerman, S. A., Hemler, R. S., & Patrick Hofmann, R. J. (2012). Reconciling Simulated and Observed Views of Clouds: MODIS, ISCCP, and the Limits of Instrument Simulators. *Journal of Climate*, *25*(13).

Roberts, Y. L., Pilewskie, P., & Kindel, B. C. (2011). Evaluating the observed variability in hyperspectral Earth‐reflected solar radiance. *Journal of Geophysical Research: Atmospheres*, 116(D24).

Roberts, Y., Pilewskie, P., B.C. Kindel, Feldman, D.R., W.D. Collins, (2013), Quantitative Comparison of the Variability in Observed and Simulated Shortwave Reflectance, *Aerosol Chemistry and Physics*, acp-2012-681.

Saunders, R., Matricardi, M., & Brunel, P. (1999). An improved fast radiative transfer model for assimilation of satellite radiance observations. *Quarterly Journal of the Royal Meteorological Society*, *125*(556), 1407-1425.

Schaaf, C.B., F. Gao, A.H. Strahler, W. Lucht, X. Li, T. Tsang, N.C. Strugnell, X. Zhang, Y. Jin, J.-P. Muller, P. Lewis, M. Barnesly, P. Hobson, M. Disney, G. Roberts, M. Dunderdale, C. Doll, R.P. d'Entremont, B. Hu, S. Liang, J.L. Privette, D. Roy (2002), First operational BRDF, albedo nadir reflectance products from MODIS, *Remote Sensing of Environment*, 83(1-2): 135-148.

Seidel, D. J., Gillett, N. P., Lanzante, J. R., Shine, K. P., & Thorne, P. W. (2011). Stratospheric temperature trends: Our evolving understanding. *Wiley Interdisciplinary Reviews: Climate Change*, *2*(4), 592-616.

Siméoni, D., Singer, C., & Chalon, G. (1997). Infrared atmospheric sounding interferometer. *Acta Astronautica,* 40(2), 113-118.

Slingo, A. (1989). A GCM parameterization for the shortwave radiative properties of clouds, *Journal of the Atmospheric Sciences*, 46, 1419-1427.

Space Studies Board (2007), *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. National Academies Press (Washington DC), 456 pp.

Spencer, R. W., & Christy, J. R. (1992). Precision and radiosonde validation of satellite gridpoint temperature anomalies. Part II: A tropospheric retrieval and trends during 1979-90. *Journal of Climate*, *5*(8), 858-866.

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, *93*(4), 485-498.

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G., Kram, T., Krey, V., Lamarque, J.-F., Masui, To., Meinshausen, M., Nakicenovic, N., Smith, S., Rose, S. K. (2011). The representative concentration pathways: an overview. *Climatic*

*Change*, *109*(1-2), 5-31.

Wan, Z., and L. Zhao-Liang (1997), A physics-based algorithm for retrieving land-surface emissivity and temperature from EOS/MODIS data, *IEEE Transactions on Geoscience and Remote Sensing*, 35(4): 980-996.

Watanabe, M., et al. (2010). Improved climate simulation by MIROC5: mean states, variability, and climate sensitivity. *Journal of Climate*, *23*(23), 6312-6335.

Wielicki, B.A., et al. (2006), CERES radiation budget accuracy overview. Preprints, *12th Conf. Atmospheric Radiation*, Madison, WI, Amer. Meteor. Soc., 9.1.

Wielicki, B. A., Young, D. F., Mlynczak, M. G., Thome, K. J., Leroy, S., Corliss, J., Anderson, J.G., Ao, C., Bantges, R., Best, F., Bowman, K., Brindley, H., Butler, J.J., Collins, W., Dykema, J.A., Doelling, D.R., Feldman, D.R., Fox. N., Huang, X., Holz, R. (2013). Achieving Climate Change Absolute Accuracy in Orbit. *Bulletin of the American Meteorological Society*, *94*(10).

## Figure Captions

Figure 1: (a) Histogram of all grid points for the difference in all-sky OLR calculated by the CCSM radiative transfer code and by MODTRAN for the 32,768 grid boxes from an example month January 2099 for the A2 simulation. Also included are the Pearson correlation coefficient ($r^2$) and the mean ($\mu$) and standard deviation ($\sigma$) of the differences between the two codes. (b) Same as (a) but for clear-sky OLR. (c) Same as (a) but for all-sky shortwave flux. (d) Same as (b) but for clear-sky shortwave flux.

Figure 2: (a) Pan-spectral composite of the globally-averaged all- and clear-sky shortwave reflectance and longwave radiance from January 2000 for the A2 simulation. (b) Same as (a) but showing the least-squares trends in shortwave reflectance (in reflectance units per decade) and longwave radiance (in W/m$^2$/sr/μm/decade) between 2000 and 2050. Shading indicates 95% confidence interval of uncertainty in trends.

Figure 3: (a) Differences in zonally- and decadally-averaged pan-spectral clear-sky composite for 2050-2059 and 2000-2009 for the A2 simulation. (b) Same as (a) but plotting differences in all-sky conditions between the 2050s and the 2000s. (c) Differences in cloud radiative effect (CRE) between the 2050s and 2000s. (d) Same as (a) but plotting differences between the 2090s and the 2000s. (e) Same as (d) but plotting all-sky conditions. (f) Same as (c) but plotting differences between the 2090s and 2000s.

Figure 4: (a) Difference in all-sky shortwave TOA flux trends between HadGEM2-ES and MIROC5 running the RCP8.5 scenario over the period 2005-2035. (b) Same as (a) but for longwave TOA flux trends. (c) Same as (a) but for clear-sky shortwave TOA flux trends. (d) Same as (a) but for clear-sky longwave TOA flux trends. (e) Pan-Spectral all-sky trends shortwave reflectance and longwave radiance for the MIROC5 and HadGEM2-ES models

Daniel Feldman 3/31/15 8:33 PM
**Deleted:** Scatterplot

Daniel Feldman 3/31/15 8:33 PM
**Deleted:** 00

derived for the Arctic (70-90N; 0-100E) and (f) for the Tropical Western Pacific (10S-10N; 100-150E).

Figure 5: (a) RMSE vs. number of randomly-sampled grid cells for January 2000 global average. (b) Same as (a) but for a Tropical Western Pacific region (10S-10N; 100-150E). (c) Same as (a) but for decadal average 2000-2009. (d) Same as (b) but for the decadal average 2000-2009.