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Climate Sensitivity Analysis with Globally Resolved Energy Balance Model

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Abstract

Knowing about climate sensitivity is paramount to knowing the future of our planet's climate. The earth is a highly non-linear and complex system that is subject to natural and anthropogenic (energy) forcings, which make it an extremely difficult system to model. However, it is of greatest importance that we understand our climate system and especially the effect we have on one another. One way of learning about a complex system is to analyse its derivatives, in our case, climate sensitivity.

This project uses the approximated GREB model to simulate the climate response to a warming scenario with different components of the model switched on and off. The aim is to confirm the roles of ice-albedo feedback, hydrological cycle, water vapour feedback, atmospheric circulation and deep ocean circulation in climate simulations.

Method

The model

The Globally Resolved Energy Balance (GREB) model is a relatively simple climate model developed by Dommenget and Floeter in 2011 to approximate Global Circulation Models (GCMs). Where the latter are run on super-computers for days to weeks and months, the GREB model can run on any ordinary PC computer and simulate 100000 years in 24 hours of CPU time. It is capable of exhibiting the main characteristics of global warming and provides an accessible tool for conceptual understanding of climate change (Dommenget & Floeter, 2011).

The GREB model has eight main processes: Solar radiation, thermal radiation, hydrological cycle, sensible heat transport, advection, diffusion (of water vapour and heat), formation of sea ice and deep ocean circulation. The latter 6 processes are internal – meaning they are not considered boundary conditions in the model. This project focuses on the effect of these processes on climate sensitivity.

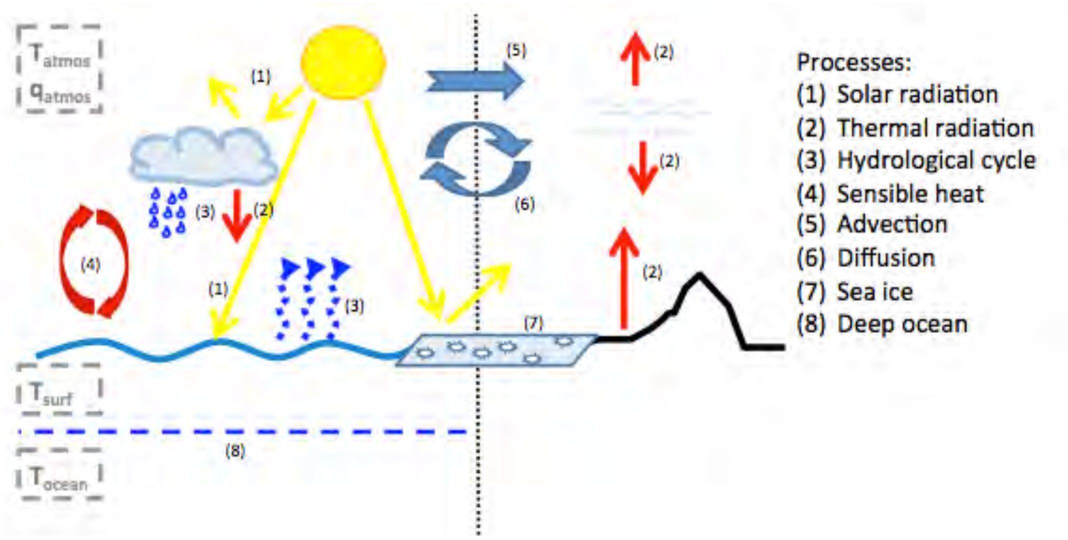


Figure 1: The GREB model (Dommenget D, 2012)

The project consisted of 6 main simulations each conducting a different experiment (5 – 10). The experiments 5 – 10 examined the effects of key climate feedbacks and processes by systematically switching these processes on with successive experiments.

Table 1: Experiment model description

log_exp	Experiment
5	Solar + Thermal Radiation, non-constant cloud cover and water vapour content of atmosphere.
6	Above + Ice-albedo feedback
7	Above + Local hydrological cycle for latent heat, water vapour
8	Above + Diffusion of heat and water
9	Above + Advection of heat and water vapour Complete model without deep ocean
10	As 9 + Deep Ocean circulation

The experiment

Each experiment is run for 30 years and under the same boundary conditions. A local temperature forcing is programmed in to warm a central grid point 1

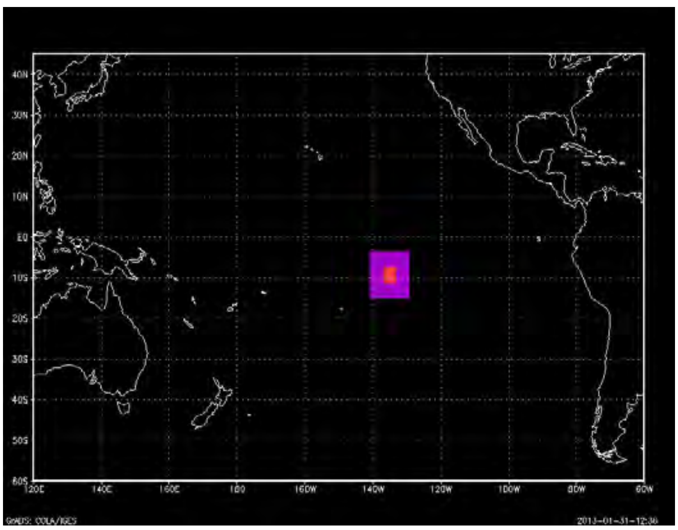


Figure 2 Example of gridpoint warming

degree constantly and the surrounding 8 grid points a third of a degree.

Figure 2 shows a snapshot of a simulation that is about halfway through a single experiment. The warming point is in the mid latitude pacific and the model will be calculating the global response from that warming over 30 years. Once the model has calculated the change in temperature for each of the grid points from that particular warming in the mid pacific, the point will then move one to the right and the model will simulate for 30 years again. When every grid point has been forced and the global response calculated for each, the experiment is complete and the data stored in binary files.

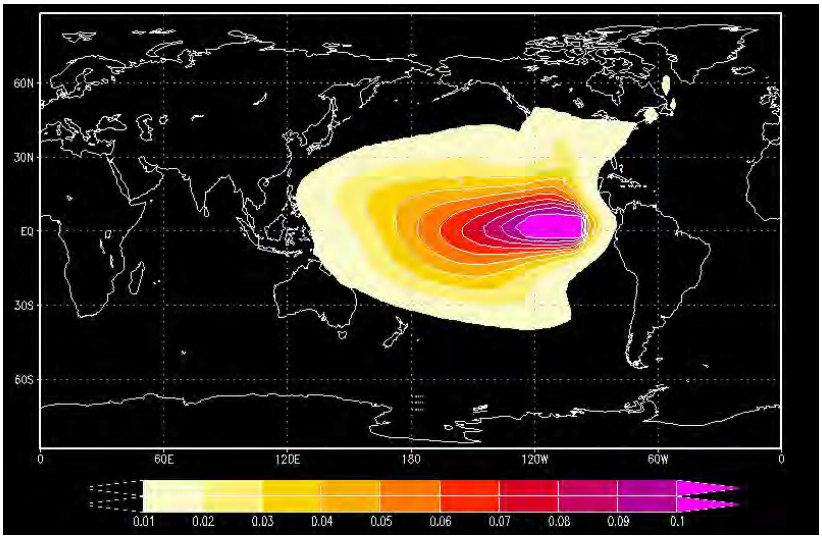


Figure 3 Single warming response

Results

The following graphs are the output of Grid Analysis and Display System (GRaDS), a specialist tool for analysing earth science data. The post processing procedure involved averaging each response cycle spatially over the whole globe, so that each grid point has been assigned a globally averaged temperature response value. This is what gives the graphs below. The response values are graphed as a coloured contour over the globe. The higher the value, the higher the average impact a warming has on the rest of the globe at that particular grid point. For example, Figure 3 shows the globally averaged response signal for experiment 5 – the most simple model simulation. The particular darker grid point in southern Chile (circled in red) indicates that the average global temperature was more heavily impacted when this particular grid point was warmed for 30 years, in comparison to the lighter coloured grid points on the map.

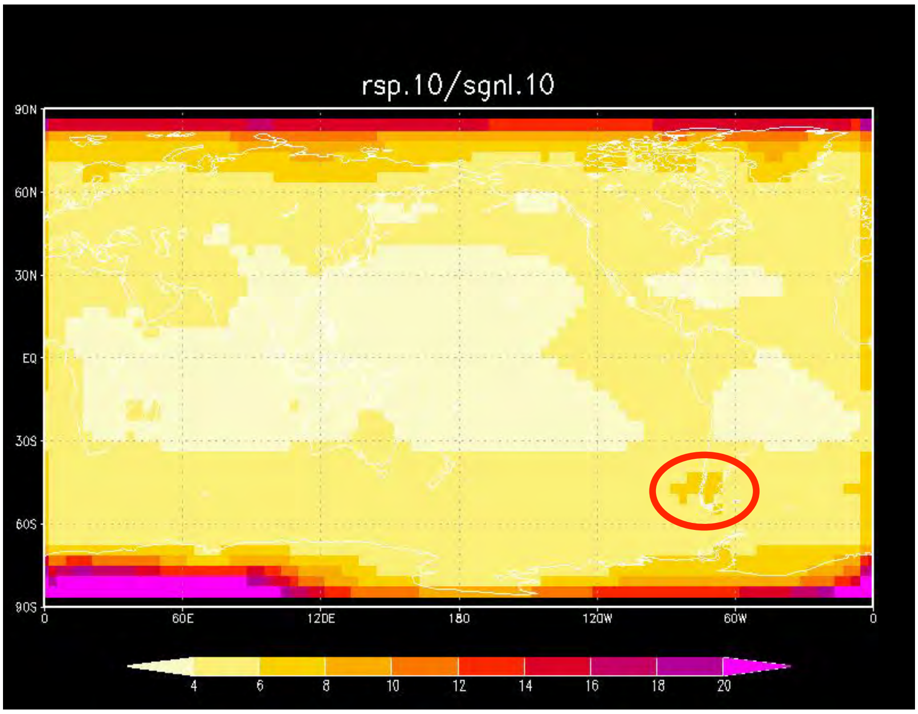
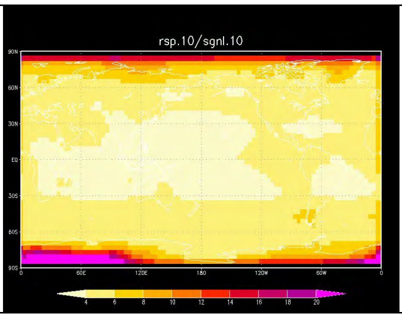


Figure 3: Response Exp. 5

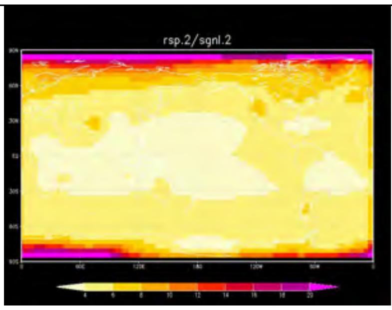
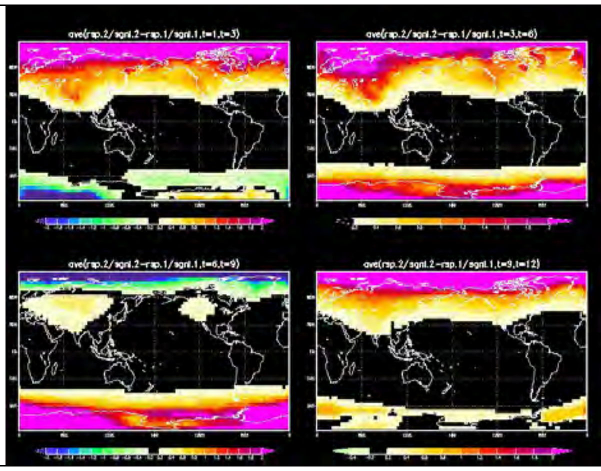
Table of Results + Discussion

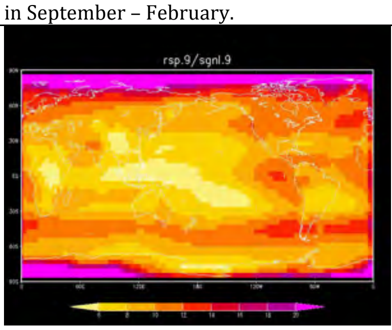
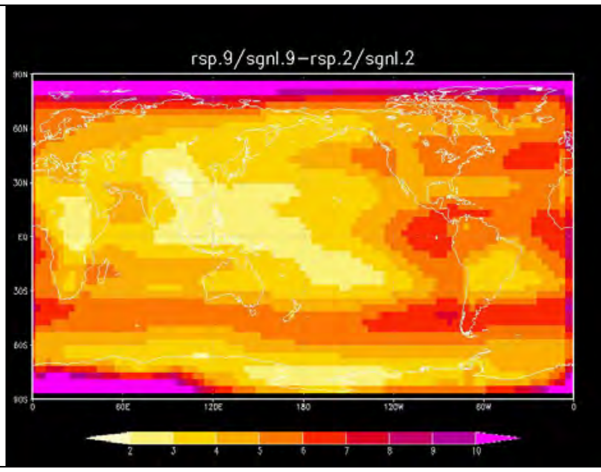
Following is a table of the results including response graph, difference graph and brief analysis:

Table 2: Results

Experiment	Response Graph	Difference Graph
log_exp 5 Solar + Thermal Radiation, non-constant cloud cover and water vapour content.		N/A
Analysis 5	• No comparison on previous experiment available. • Weaker response in tropics, stronger over subtropics and poles. • Slight correlation between lower rainfall and higher response (eg mid lat Pacific Ocean, Mid East) As stated above this is the most simple of experiments and does not include any feedback process. We are not surprised then to see a simple response pattern that seems to be more of a function of latitude than anything else. This is perhaps because incoming solar radiation is mostly a function of latitude and hence extreme latitudes show more of a relative reaction to the 1°C warming than equatorial grid points.	

<table>
<tr><td>log_exp 6

Above + Ice-albedo feedback</td><td>
</td><td>
</td></tr>
<tr><td>Analysis 6</td><td colspan="2">Note: The difference graph is a seasonal average difference graph
Increased sensitivity near poles correlated with seasonal ice regions
Larger area in Northern Hemisphere corresponding to larger ice covered regions
The seasonal difference graph shows a strong effect when including the Ice- Albedo feedback in the simulation. The ice-albedo feedback describes a strong but local positive feedback. Decrease in average temperature leads to increase in average ice cover, which increases the albedo. Increased albedo causes more solar radiation reflected and hence a net decrease in thermal radiation that then leads to a decrease in temperature. This is the feedback loop. It greatly increases the sensitivity of the local regions: South pole in March – August, North pole in September – February.</td></tr>
<tr><td>log_exp 7

Above + Local hydrological cycle for latent heat, water vapour</td><td>
</td><td>
</td></tr>
<tr><td>Analysis 7</td><td colspan="2">Increase overall
Strongest increase over subtropics and equatorial oceans
Least increase over land
This is a very strong increase overall because the water vapour feedback WVF was introduced into the simulations. The WVF is the strongest positive feedback in the model. Water vapour acts as a greenhouse gas trapping heat and increasing the average temperature. This net increase in temperature leads to higher average evaporation and thus a higher water vapour content. However, the feedback is still relatively local because water vapour transport has not been introduced yet. Introducing the hydrological cycle allows evaporation and precipitation which is very active in the mid tropics and sub tropics which explains the drastic increase in sensitivity in those regions.</td></tr>
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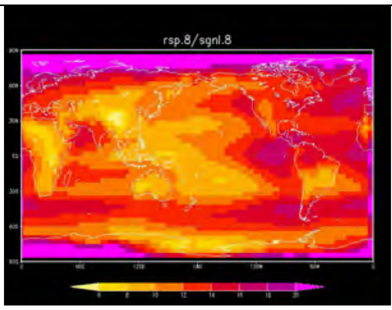
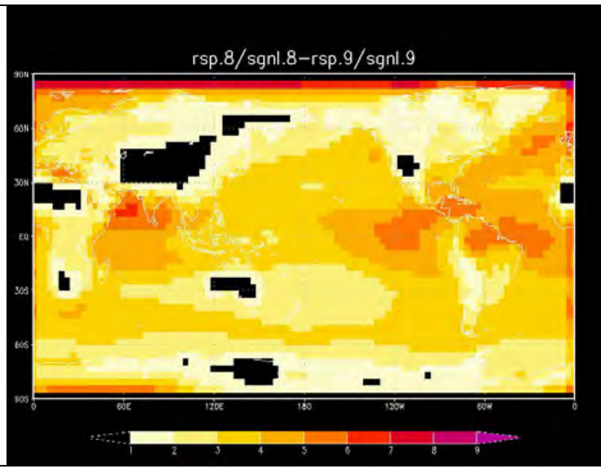
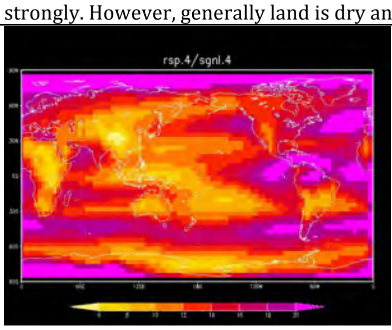
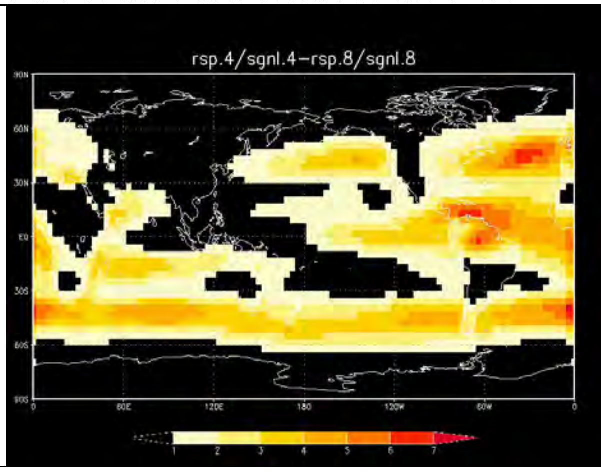
<table>
<tr><td>log_exp 8

Above +
Diffusion of
heat and
water</td><td>


</td></tr>
<tr><td>Analysis 8</td><td>Large increase overall (scale is large)
Strongest increase over tropics
Increase over oceans
Very little difference over land
Now that diffusive transport of heat and water vapour is allowed there is an increase in sensitivity in the tropics again as well as generally over all oceans. This is due to there being an abundance of water available for evaporation over oceans. Thus, the evaporated water has an even stronger effect from being able to spread and diffuse. Over land there is little evaporation with a few exceptions. Note that tropical South America, East of the Andes, Central Americas and South East Asia are all hot, damp places where evaporation still contributes quite strongly. However, generally land is dry and hence land areas are less sensitive to the effect of diffusion.</td></tr>
<tr><td>log_exp 9

Above +
Advection of
heat and
water
vapour</td><td>


</td></tr>
<tr><td>Analysis 9</td><td>Discrete longitudinal increases in sensitivity
Strongest increase over subtropics and mid latitudes
Mostly over oceans
The introduction of advection of heat and water vapour creates an interesting effect. The horizontal strips of increased sensitivity follow the same pattern as the large scale advection patterns of the atmosphere. The Hadley cell and trade winds would explain the increased sensitivity near the equator as the evaporated water and heat is moved by advection (and convection) around the globe. The Ferrel cells explain the strong sensitivity increase in the sub-tropic regions as the water vapour and heat are chaotically carried by the westerlies.</td></tr>
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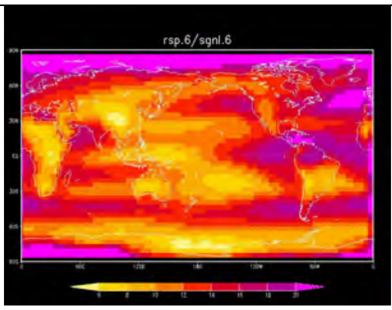
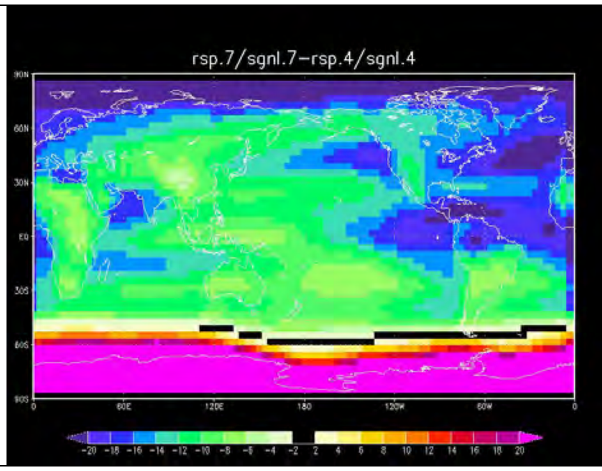
log_exp 10 As 9 + Deep Ocean circulation and feedback		
Analysis 10	• Reduced sensitivity everywhere except South Pole • Least decrease over land This is the only process that produced a negative effect in terms of sensitivity. It seems that introducing the deep ocean circulation makes the globe less sensitive to changes in temperature. This is expected, a complete cycle of deep ocean convection is approximately 50 years, causing effects to be lagged by this amount when the ocean feedback is turned on. Because the simulation was only run for 30 years (due to computing time constraints) the circulation cycle has not completed and thus the deep ocean has only absorbed heat from the surface and not yet brought it back. The increase in sensitivity at Antarctica is due to the significant upwelling of deep ocean at the south pole. At the end of the deep ocean cycle the heat from the warming globe is brought to the sensitive ice shelfs of Antarctic that involves the strong positive ice-albedo effect.	

Further Discussion

An overall trend in the results is an increasing sensitivity when the climate model becomes more complex and more processes are added. With exception to the introduction of the deep ocean circulation and feedback, there was always a net increase in sensitivity.

Another clear trend is the discrepancy between land and ocean sensitivity. With almost every process introduced, the oceans became increasingly sensitive to temperature change. It is explained by the strong water vapour feedback being fuelled by the water abundance in the ocean, however it is important to note the danger in this observation. The most sensitive regions are also the ones we have least contact with in day-to-day life. This stresses the importance of oceanic and pole meteorological research and careful monitoring of these regions.

One of the more technical difficulties was attempting to normalise the response graphs over all grid points. The problem of splitting a sphere into a Cartesian matrix is that not all grid points have the same area. The mid latitudes have much larger area than the more extreme latitude grid points. To counter this, we created a Signal matrix that was proportional to the relative size of each grid point. This was basically a function of latitude with slight contortion from land topology. We then normalised the responses by dividing each pattern by the signal pattern. It was almost a perfect solution, however, due to round off errors being propagated through computations within each simulation, extreme values popped up near the boundaries of the map. This is why each response has disproportionately large “pink” values at the poles and often on the East and West boundaries. The signal is considered close to zero and so dividing by it causes extremely large values. This could not be addressed simply and so it was ignored for most of the analysis. In the future, the normalisation problem might be met with a more elegant solution that does not cause unrealistic extreme values.

Conclusion

The effects of introducing each process into the simulation were well explained by the climatological understanding of each process. In other words, all the changes in sensitivity were expected! This shows that the GREB model is indeed a useful tool in understanding the concepts of climate change. The trends in the results showed us the strength of positive climate feedbacks and stressed the importance of understanding both the oceanic and ice affecting processes.

References

Dommenget, D., and J. Floeter 2011. Conceptual Understanding of Climate Change with a Globally Resolved Energy Balance Model. *Climate dynamics*, 2011, 37, 2143-2165.