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ATM S 380
18 February 2025

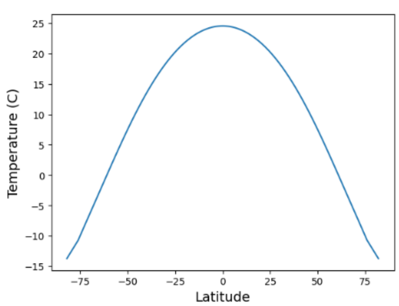
Homework 3

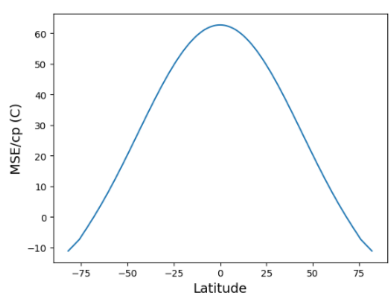
Part 1) Climatology of the MEBM

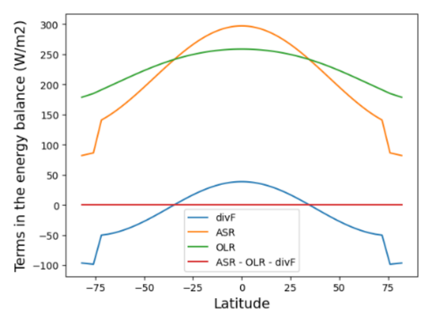
Use MEBMclimo hydro.ipynb for this problem. The model takes in a pattern of solar radiation and predicts the pattern of surface temperature (T) and atmospheric heat transport (AHT) assuming linear, down-gradient diffusion of moist static energy (MSE). The model also includes an ice albedo feedback.

(a) Run the code as is. How does the plot of temperature (T) as function of latitude compare to the plot of MSE/cp as a function of latitude? Describe the shape of the atmospheric heat transport divergence and explain why it has a kink around 75° north and south.

The plot of temperature (T) as a function of latitude and the plot of MSE/cp as a function of latitude have the same shape, just on a different scale. Both plots follow a normal curve centered around 0 latitude, though the width of MSE/cp is narrower. Additionally, both plots feature a slight kink at $\pm$75 degrees, where the slope becomes abruptly slightly shallower. The atmospheric heat transport divergence also follows a normal curve centered around 0 latitude, though around $\pm$75 degrees, there is a steep drop down about 50 W/m2, and then the divergence shallowly increases as the absolute value of latitude increases. This kink exists because our albedo shifts to that of ice-covered land when T < -10^{O}C, which occurs about at $\pm$75.



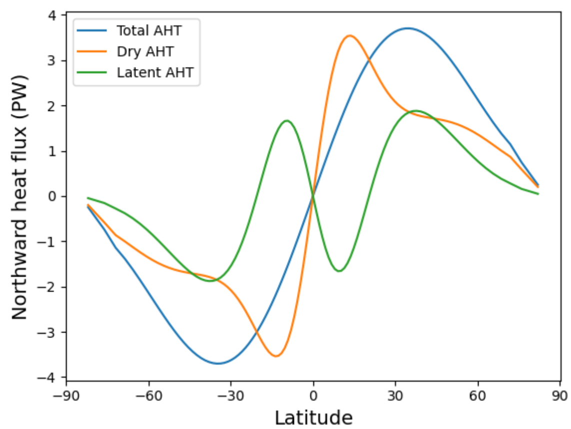


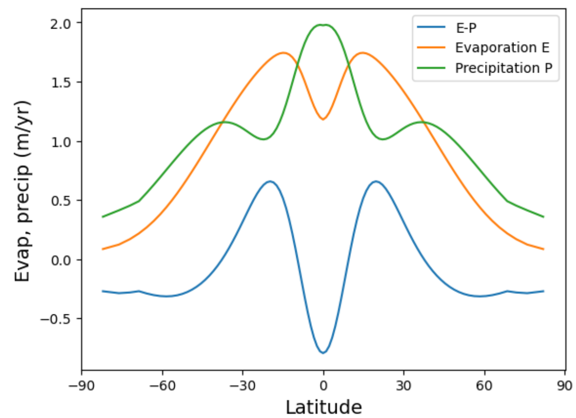


(b) Now consider the atmospheric heat transport (units of PW) and hydrologic cycle produced by the model. Describe the shape of the total, latent, and dry heat transport (units of PW). Why do evaporation minus precipitation (E-P), evaporation (E), and precipitation (P) have the shapes that they do, in the context of the MEBM?

The total AHT looks like a negative cosine function, starting around -90 and ending at 90 degrees latitude. The dry AHT, from -90 to positive 90, starts out flat, then decreases to a local minimum around -40, increases to a local max around -15, then decreases again to a local min around 10, and finally hits a local max around 40 before flattening out again by 90. The local max/mins have values of ~$\pm$2 PW. Finally, the dry AHT starts at 0 PW when latitude is -90 sharply decreasing, then levels off to a flat point around -45, and decreases again to a local min around -15. It then increases to a local max around 10, then decreases to a flat point around 40, and decreases sharply back to 0 PW by 90 degrees north. The local max/mins have values of ~±3.5 PW, and flat points ~ ±1.5 PW.

E-P, E, and P have much different shapes: E-P and E both start flat, increase to a local max by -20, decrease to a local min by 0, increase back to a local max by 20, and then flatten out again by 90 degrees north. P has a very similar shape, though with the center local min split into two with a max in between. In the context of the EBM: These shapes make sense due to the Hadley cell that draws precipitation equatorward, yielding the max at 0 latitude. Precipitation is also drawn out by eddies, causing the local maxes poleward from ±30 degrees north.



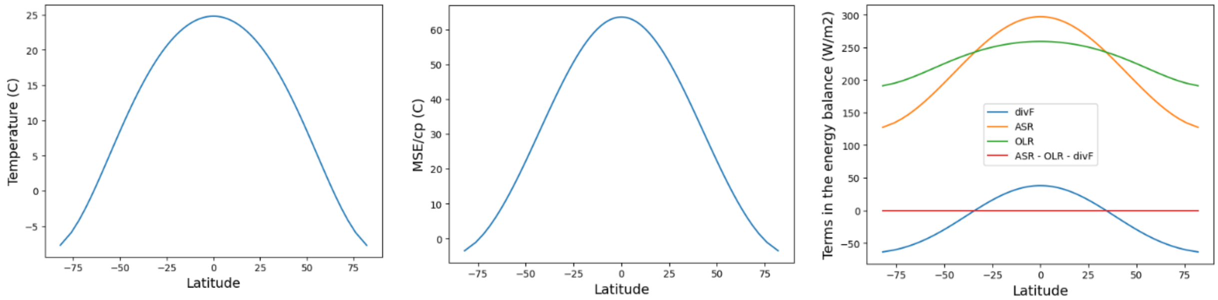


(c) How do all of the curves (temperature, heat transport, E-P, E, P) qualitatively compare to the figures we've seen in class for Earth's climatology?

Overall, the curves match up well to an averaged version of the figures we've seen for Earth's climatology. They don't get the longitudinal variation, especially in terms of temperature and precipitation, but provide a smoothed version that matches up well to real life. Temperature is largely similar, with extra local variations, and the warmest temperature is shifted due to the cold tongues created by upwelling that move warmest temperatures to just north or just south of the equator. Heat transport is very similar, as the figures we've seen in class are a lot more wobbly, but follow the same overall shape. E-P, E, and P follow broad trends, but smoothed and without extra up and down noise and potential smaller local mins and maxes. They also are centered around latitude 0, whereas the figures we've seen in class are shifted over, just like temperature.

(d) Modify the model to set the ice covered albedo to that of the ice free albedo (0.3 to account for a blend of atmospheric and surface reflectivity), then run the model again. How do your answers to part (a) change?

If we edit the ice-covered albedo to be the same as the ice-free albedo, we remove the kink at 75 degrees north and south, as now we have a constant albedo everywhere no matter what the temperature is. Now all of our curves are smooth Gaussian curves, with similar widths as previously, and slightly decreased ranges, as we no longer have the kink extending the range downwards.

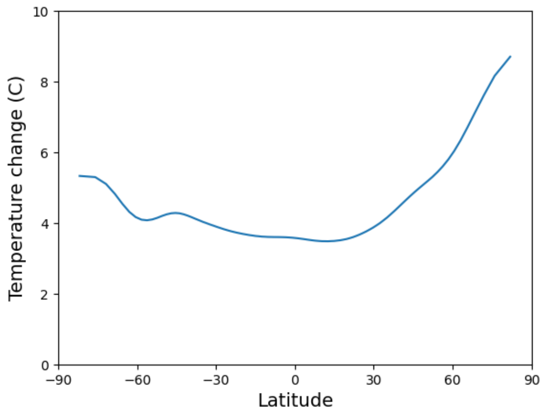


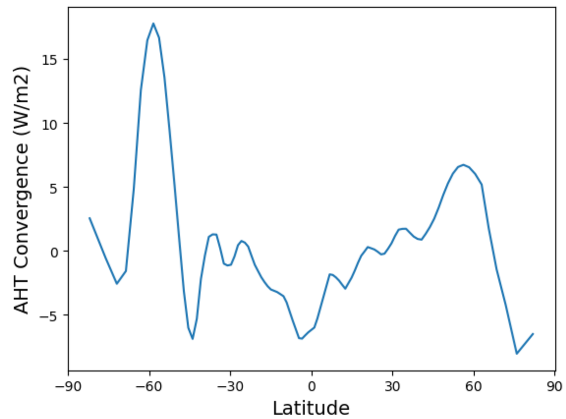
Part 2) Global warming in the MEBM under CO_2 quadrupling

Use MEBMpert hydro.ipynb for this problem, which uses the spatial pattern of feedbacks, radiative forcing, and ocean heat uptake from CMIP5 models and predicts the pattern of warming (T) and anomalous atmospheric heat transport (AHT) assuming linear, down-gradient diffusion of MSE. You should only have to comment out different lines of code and re-run the model (look for comments in the code for where to do this for each part).

(a) Run the model as it comes. Plot the warming (T) and AHT convergence as function of latitude, and describe their shapes. How does the overall pattern of T compare to that from CMIP5 models we saw in class? What is the approximate magnitude of polar amplification (local T at the pole divided by global T) at both poles? From the convergence plot, does AHT enhance or reduce polar warming?

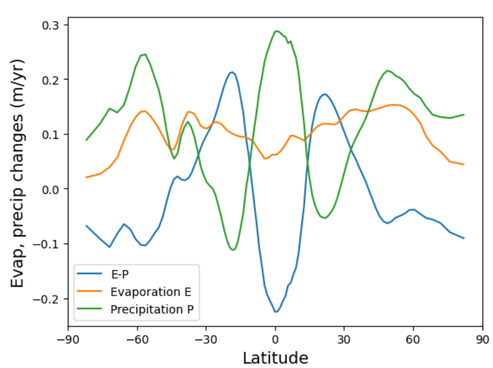
The plot of temperature change as a function of latitude is overall concave up, with a small local min around -60 degrees north. The global max is around 20 degrees north, and the change furthest south is only about two thirds of the change furthest north. AHT convergence as a function of latitude is much different, with lots of noise. Overall, there are two main local maxes at -60 and 60 degrees north, with several local mins between them. The overall pattern of T matches the CMIP6 models, as they also predict polar amplification especially in the North Pole. The approximate polar amplification at the South Pole is 5.5/4.25 = 1.3 and at the North Pole is 9/4.25 = 2.11. From the convergence plot, AHT enhances polar warming because we have higher convergence leading up to the poles, which then gets trapped there.





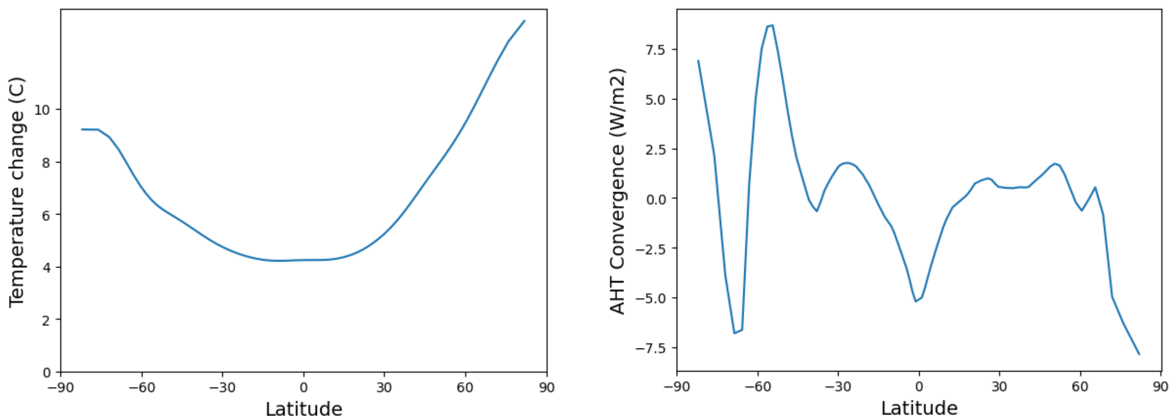
(b) Now consider the hydrologic cycle changes predicted by the model. Why do changes in evaporation minus precipitation (E-P), evaporation (E), and precipitation (P) have the shapes that they do, in the context of the MEBM? How do these patterns compare to those of CMIP models seen in class? Why does the 'wet gets wetter, dry gets drier' paradigm occur in the context of the MEBM?

The changes in evaporation are much flatter than precipitation and tends to be low in the poles and on the equator. The changes in precipitation have three local maximums, around 0 latitude and ± 60, with local minimums at ± 20, and relatively low increases at both poles. Since evaporation is so flat, E-P is essentially P flipped across a horizontal axis. In the context of the MEBM, we have rewritten evaporation as a function of surface temperature, which then allows us to predict precipitation based on moisture transport. Since the MEBM includes a Hadley cell, it displays moisture transport well. Thus, we get E-P at a minimum just offset from the equator, then increasing towards the bounds of the tropics, until it reaches a maximum in the subtropics before decreasing again out towards the mid-lats, which reflects the moisture transport out from the equator via a Hadly Cell. The CMIP models that we've seen in class have very similar shapes. The 'wet gets wetter, dry gets drier' paradigm occurs in the context of the MEBM due to the shape of our change in E-P. The wetter areas in the tropics get even wetter, whereas drier areas get even less precipitation and thus a higher E-P. Overall, this is due to increased temperature allowing for more water vapor in the air. Since precipitation increases with more water vapor, evaporation must increase as well, so the drier areas get drier to compensate for more rainfall in other areas.



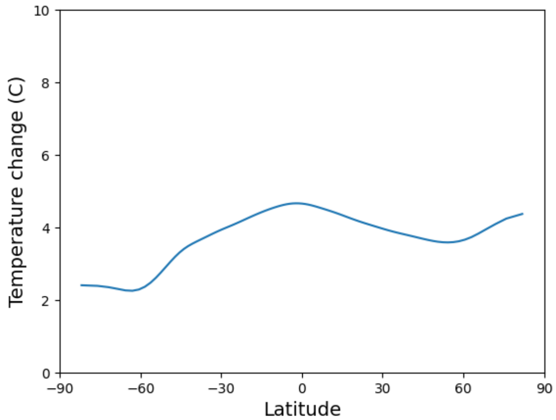
(c) Modify the code to run with zero ocean heat uptake by uncommenting the relevant line (still using the full spatial patterns of feedbacks and radiative forcing from CMIP5 models). Plot the warming (T) and AHT convergence as function of latitude, and describe their shapes. How do they compare to the overall patterns of T and AHT convergence in part (a)? What is the approximate magnitude of polar amplification (local T at the pole divided by global T) at both poles? What does this tell you about the role of ocean heat uptake in the spatial pattern of global warming?

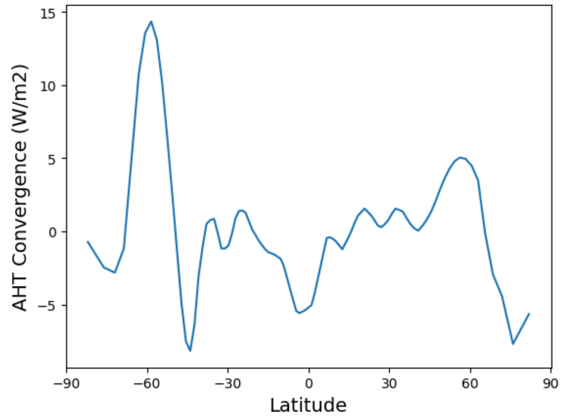
If we modify our code to now run with zero ocean heat uptake, then we significantly change the scale but not the overall shape of warming (T) and AHT convergence. AHT has changed more significantly but still has relative mins and maxes at the same latitudes, but now with very different in-between behavior. The approximate magnitude of polar amplification at the South Pole is 9.2/5.84 = 1.57, and at the North Pole is 14/5.84 = 2.40. Thus, ocean heat uptake significantly changes how much warming the globe experiences overall, especially in the poles. Since there is more land cover in the northern hemisphere, there was more convergence in the southern hemisphere, but now we have more similar magnitudes of convergence across the globe.



(d) Using the same CMIP5 feedbacks, forcing, and ocean heat uptake as in part (a), now run the dry version of the EBM (representing linear, down-gradient diffusion of sensible energy) by uncommenting the relevant lines. Plot the warming (T) and AHT convergence as function of latitude, and describe their shapes. How are they different from what you found in part (a). What is the approximate magnitude of polar amplification (local T at the pole divided by global T) at both poles? What does this tell you about the role of moist AHT in polar amplification?

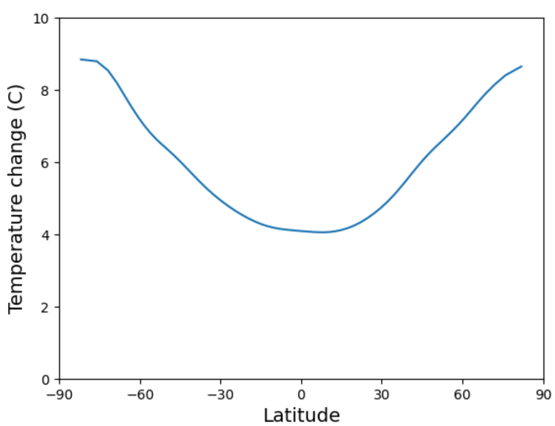
If we run a dry version of the EBM, the shape of the warming has completely changed. Now we have a maximum around 0 latitude, with an overall concave down structure, but with a small uptick near each pole as there is a small amount of polar amplification. AHT convergence, however, looks very similar to AHT from part (a), with only minor changes in magnitude. This tells us that moist AHT is very important in informing the temperature changes as distributed along latitudes, as without moisture transport we don't get the same transport of heat that pushes most of the warming to the poles, where it coalesces.

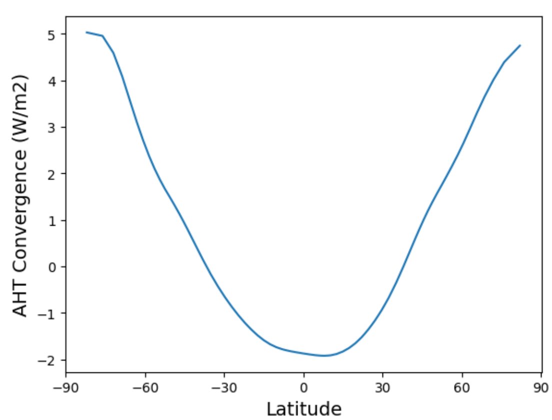




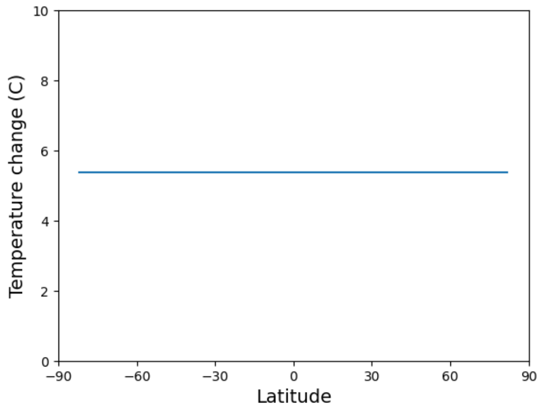
(e) Run the model with uniform forcing, uniform feedback, and no ocean heat uptake by uncommenting the relevant lines. Do this for both moist and dry versions of the model. For both moist and dry versions, plot the warming (T) and AHT convergence as function of latitude, and describe their shapes. For both, what is the approximate magnitude of polar amplification (local T at the pole divided by global T) at both poles? Can polar amplification occur in the absence of a spatial pattern in feedbacks, and if so by what mechanism?

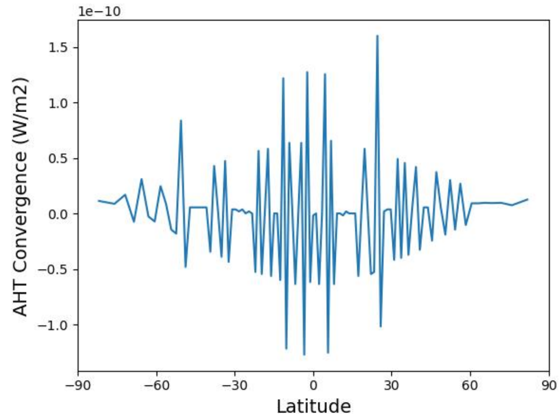
For the moist version: If we have uniform forcing and feedback, and no ocean heat uptake, then our graph of the temperature change is concave up, without the same difference of height in the poles as in part (a). AHT convergence has a very similar shape, though with a different magnitude. The approximate magnitude of polar amplification in the South Pole is 9/5.38 = 1.67, and in the North Pole is also 1.67.





For the dry version: If we have uniform forcing and feedback, and no ocean heat uptake, then there is uniform temperature change. We have very noisy AHT convergence, which seems to have random spikes coming up from an overall elliptical trend. However, since the magnitude is so small it is essentially flat. The magnitude of polar amplification at both poles is 1.

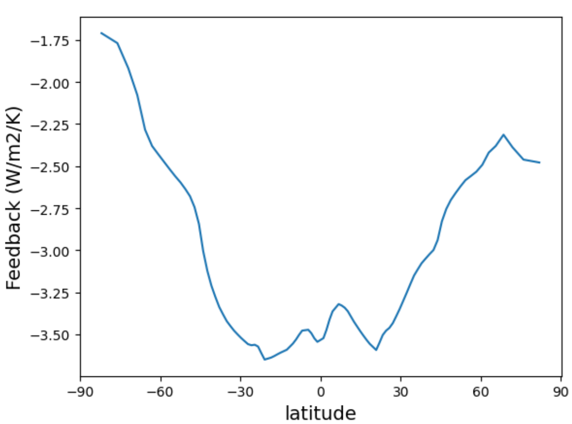


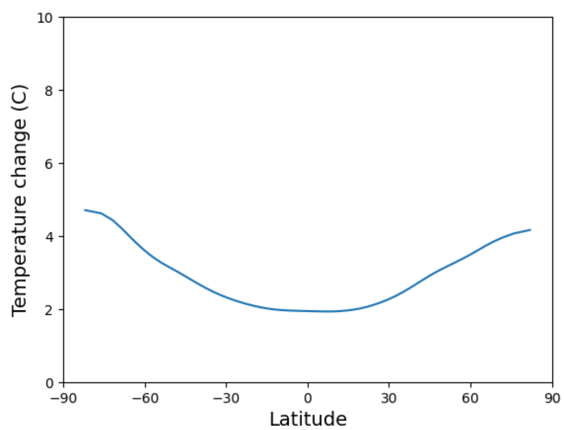


Based on this analysis, we see that it is possible to get polar amplification, but only if we are running the moist version of the model (by linear, down-gradient diffusion of MSE).

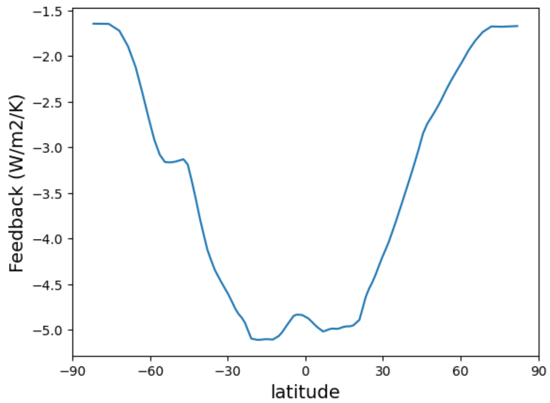
(f) Now let's consider how individual radiative feedbacks shape the magnitude of polar amplification. Make sure you are using the moist version of the model again. Run the model with uniform radiative forcing, no ocean heat uptake, and one feedback at a time by uncommenting the relevant lines. Run the model with just the Planck feedback; just the Planck + lapse rate feedback; just the Planck + water vapor feedback; just the Planck + cloud feedback; and just the Planck + albedo feedback. For each of these, plot the net radiative feedback and warming (T) as function of latitude, and report the approximate magnitude of polar amplification (local T at the pole divided by global T) at both poles. From this analysis, which of the feedbacks enhances polar amplification, and which reduces polar amplification?

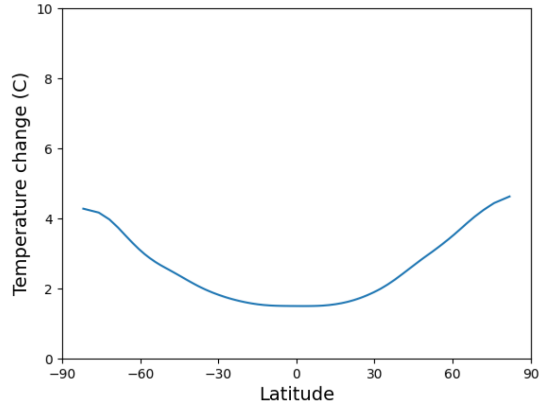
Planck feedback: The approximate polar amplification at the South Pole is 4.7/2.60 = 1.8, and at the North Pole is 4/2.60 = 1.54.



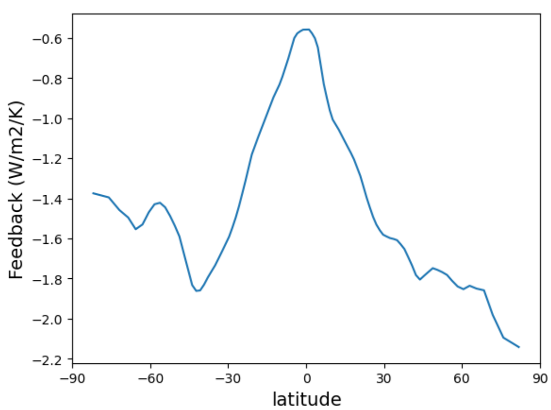


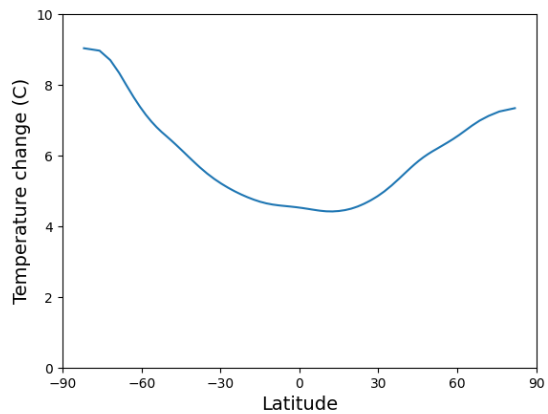
Planck + lapse rate feedback: The approximate polar amplification at the South Pole is 4.3/2.22 = 1.94, and at the North Pole is 4.9/2.22 = 2.21.



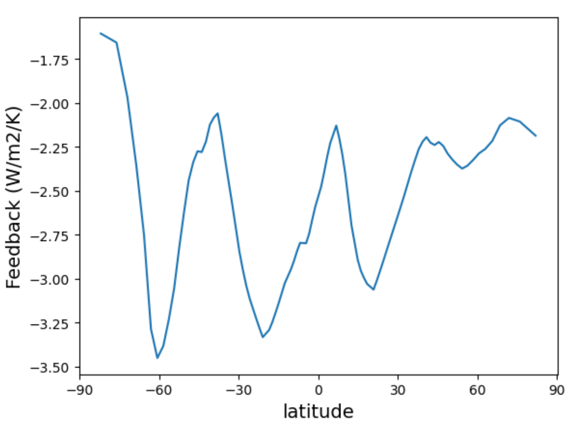


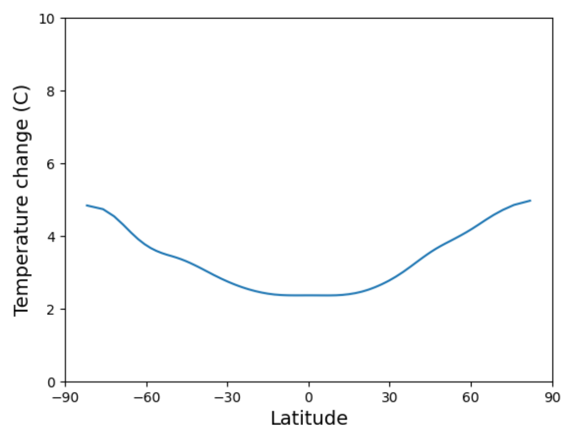
Planck + water vapor feedback: The approximate polar amplification at the South Pole is 9/5.5 = 1.64, and at the North Pole is 7.2/5.5 = 1.31.



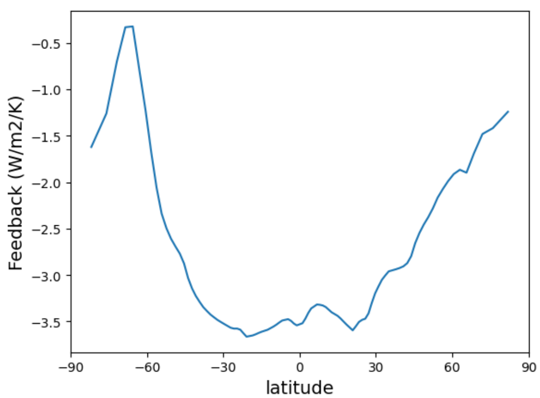


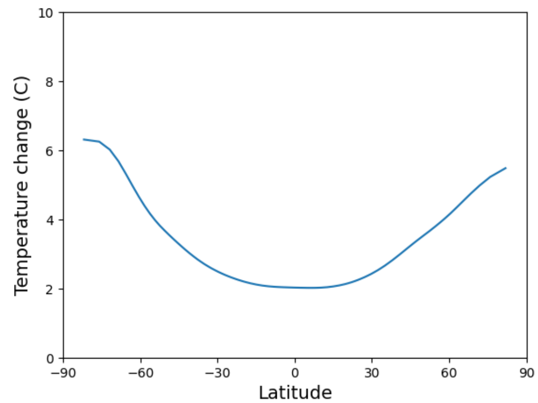
Planck + cloud feedback: The approximate polar amplification at the South Pole is 4.9/3.04 = 1.61, and at the North Pole is 5.1/3.04 = 1.67.





Planck + albedo feedback: The approximate polar amplification at the South Pole is 6.3/2.94 = 2.14, and at the North Pole is 5.4/2.94 = 1.84.

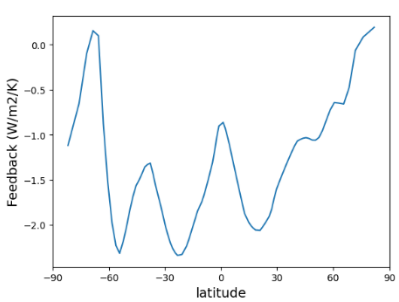




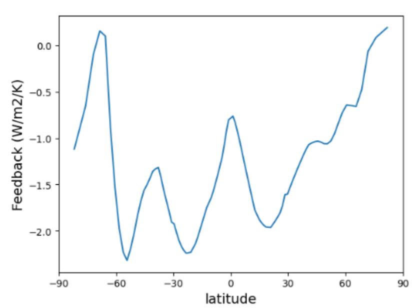
Based on these analyses, all of these feedbacks enhance polar amplification, as in every graph where have higher temperature changes at the poles. However, the lapse rate and the albedo enhance it more than the others.

(g) Return to using the CMIP5 spatial patterns of feedbacks, radiative forcing, and ocean heat uptake as in part (a). Use the moist version of the model. Modify the code to change the net radiative feedback by a small amount in the tropics (between 30◦S and 30◦N, say) and at the poles (poleward of 30◦N, say) – do one new run for each. Make plots showing how you changed the feedback, and how the spatial pattern of T changed compared to part (a). How does uncertainty in tropical feedbacks affect polar warming? How does uncertainty in polar feedbacks affect tropical warming? What does this tell you about the role of tropical vs polar feedback uncertainty in contributing to uncertainty in polar amplification?

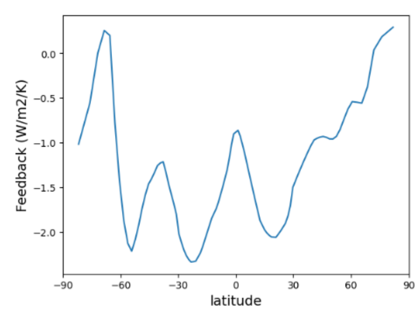
I changed the net radiative feedback between 30◦S and 30◦N by +0.1, and then poleward of 30◦N and 30◦S by +0.1.



Original Feedbacks

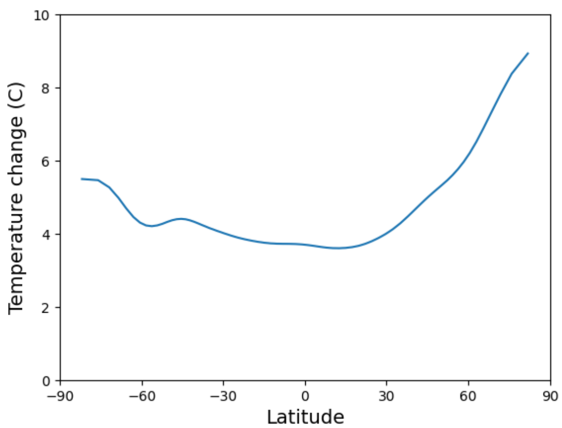


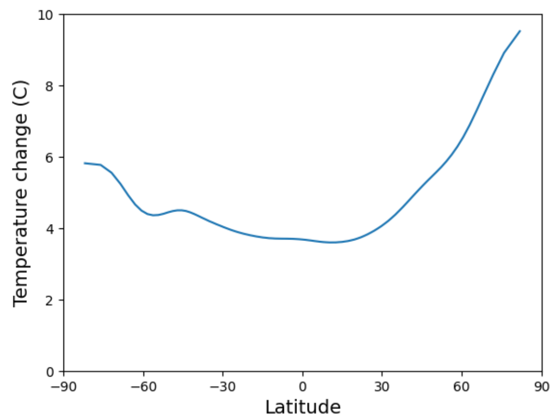
Tropics Increase



Pole Increase

After changing the feedbacks by a little bit in the tropics, the temperature change graph did not change by much, but did increase slightly in the poles. However, changing the feedbacks in the poles changed the pole temperatures by more, as shown below. This tells us that uncertainty in polar feedback contributes more towards uncertainty in polar amplification.


Temperature change (C)
Latitude
10
8
6
4
2
0
−90
−60
−30
0
30
60
90


Temperature change (C)
Latitude
10
8
6
4
2
0
−90
−60
−30
0
30
60
90