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Experiments in Orographic Forcing

The purpose of my experiment was to analyze the effects of orographic forcing through graphs of zonal wave numbers and to analyze the effects it has on the zonal and meridional winds. The primary function of Rossby Waves is to help transfer heat from the tropics to the poles and cold back to the tropics, and they are intimately tied to orographic forcing. Though this transport from the equator to the poles and back again is also the primary effect of the mean meridional circulation and eddy component of general circulation, stationary eddies and Rossby waves all play a particularly interesting role in this process because they explain the atmospheric effects of mountain ranges on the general circulation and winds. In the northern hemisphere, the dominant large scale stationary wave pattern has a zonal wave number of two. This two represents the orographic forcing produced by the Rocky Mountains and the Himalayas which creates two trough-ridge pairs spanning the latitudes between 30 to 60 degrees north. The premise of my experiment is rooted in the hypothesis that the zonal wave number will be altered from two to three when the presence of the third experimental mountain range is introduced in the middle of the Pacific Ocean. This is because the experimental range will add a third forcing location. I also aim to explore possibility that this mountain range may potentially add constructive or destructive interference both upstream and/or downstream of its location. This will potentially occur due to the resonances from the experimental mountain range and may also have effects on the amplitude of the existing waves generated by the Rockies and the Himalayas.

A primary assumption in the hypothesis is that these resonances primarily depend on the longitudinal spacing and vertical scale of the topographic features. A baseline run of the model without the experimental mountain(s) present will be used to compare the effects of the experimental mountain range on the zonal wave number and effects the different variables present in the data set. Each model run and its output will be evaluated on the same time frame of January 1st, 1950, to February 2nd, 1954, which is 1500 days. This period was chosen due to time constraints and data processing limitations on my machines. However, the period should suffice to see meaningful changes in topographic forcing over time and to explore the possibilities put forth in this hypothesis. I ran the model for both the control and the experiment with 11 elevation levels and a zonal wave number of 42. To create my experimental mountain range, I edited the global elevation model being used in the Telekinetic Atmospheric Model provided in the beginning of the class. In the *preprocess.ipynb* file I was able to edit the .75 degree elevation/topography layer that can be found online at the address http://research.jisao.washington.edu/data_sets/elevation/elev.0.75-deg.nc to add a third mountain range in the middle of Pacific Ocean spanning from 15 to 50 degrees north latitude and from -169 to -179 degrees west longitude (Figure 1). No other data sets were edited between the two model runs. This area was chosen as a midpoint between the two mountain ranges that are roughly 13000 km apart. Since the interaction between the two is well documented it made sense to insert this mountain range here to observe how the zonal waves

would change in its presence. Due to negative elevation level values in the dataset representing areas below sea level, the area of the experimental third mountain range was raised to sea-level first, then a gaussian gradient was applied making it tapered on the sides, rising to the middle of the area at a peak height of 6000 meters. The gradient from any one side to the middle longitude of the area being 0 to 6000 meters. This was done intentionally to mimic realistic topographic features on the earth surface to avoid artificial wave refraction and reflection from sharp edges. The peak height was chosen based on the relative height of the highest peaks of the two mountain ranges. The Himalayas are the tallest in the world with many peaks being in the 6000-8000-meter range and The Rockies are mostly in the 4000-meter range. Averaging between 8000-meters and 4000-meters to 6000-meters was reasonable for the experimental range and was intended to ensure that strong measurable topographic forcing would be produced relative to the other large forcing features with a realistic height profile. Though it is intended to mimic a mountain range, it can also be thought of as one extremely large mountain stretched longitudinally and placed in a prime latitude range to interact with the waves generated from existing features between 30 and 60-degrees north latitude.

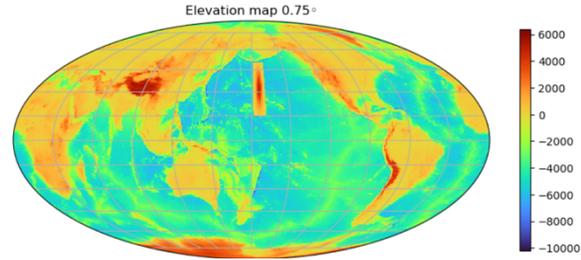


Figure 1- Experimental Range shown in the center of image.

A good place to start exploring this hypothesis was to look at the geopotential height anomalies for both the control and the experiment data sets separately. I sliced the geopotential data set for each to get only the values for the 30-to-60-degree latitudes. The goal being to generate a Charney-Eliasson style graph to help me compare the zonal wave numbers and present them in a way that was familiar from class. I started at the 500mb pressure level and what I found was very similar to the Charney-Eliasson response, but the experiment set did not contain the signature of strong forcing in the form of a wave peak that I was expecting at that level (Figure 2). The data set was modified as such: $\Phi.\text{mean}(\text{dim}=["\text{time}", "\text{lat}"])$ or ΦMean . The experiment and control were calculated in Figure 2 using the formula $\Phi\text{Mean} - \Phi\text{Mean}.\text{mean}(\text{dim}=["\text{lon}"])$. This could be described as the mean of geopotential with respect to latitude and time, minus the mean of geopotential with respect to latitude and time averaged by longitude. In this calculation, it was only applied at the 500mb level. My analysis found that the control set contained larger peaks and troughs in the anomaly overall, but the phase and amplitude of the wave high associated with the Rockies in the experimental set changed dramatically to extend to where the experimental mountain range was inserted. The

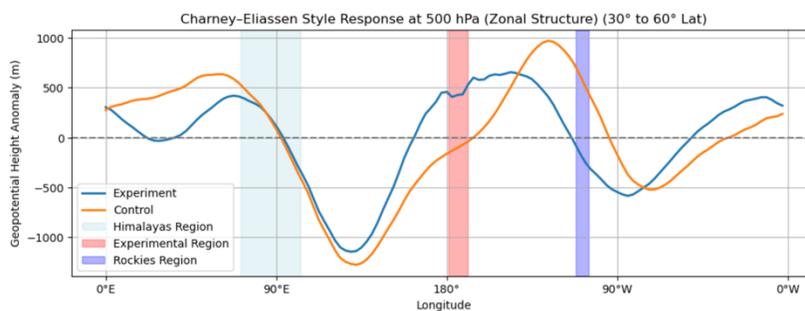


Figure 2

additional experimental mountain range had moderating effects on both the low geopotential associated with the Himalayas that preceded it and the intensity of the high geopotential after it associated with the Rockies.

At the 500mb level, the geopotential anomaly rises in association with the experimental range and does not come back down until after the Rockies except for a very slight dip in the experimental data set right after the experimental range. Although, it is interesting to think that this experiment does move the low slightly west closer to the Rockies themselves when compared to the control. The zonal wave number was still two though. This analysis was interesting but left me curious as to where I could observe the effect and changes in the zonal wave number inside of the geopotential anomaly. This led me to compare the responses for each individual pressure level, but to also super impose the averages of all the pressure levels together on top, and to display the column means for both the experimental and control datasets and compare them side by side (Figure 3). This set of graphs shows wave responses that align with the topography that are especially strong over the Himalayas and the Rockies in both graphs. These are a planetary scale waves that are displayed as a two-wave feature in the control and three-wave feature in the experiment. Most interestingly to me, the wave response of the experimental range appeared as expected at around the 180-degree mark. This signal was absent in the control data and confirms the presence of a new stationary Rossby wave at the experiment location due to orographic forcing. Perhaps, due to the uniform meridional directionality of the experimental mountain range, there seems to be a lot more wave interference both preceding and directly after the wave. This seems to severely disrupt the low along the 180-degree meridian. It appears that this wave response is baroclinic and varies with height becoming stronger as pressure decreases vertically. The interference pattern also displays this characteristic. The baroclinic response of this data set seems to be consistent with the quasi-geostrophic theory, with vertical wave propagation being influenced by static stability and mean flow shear.

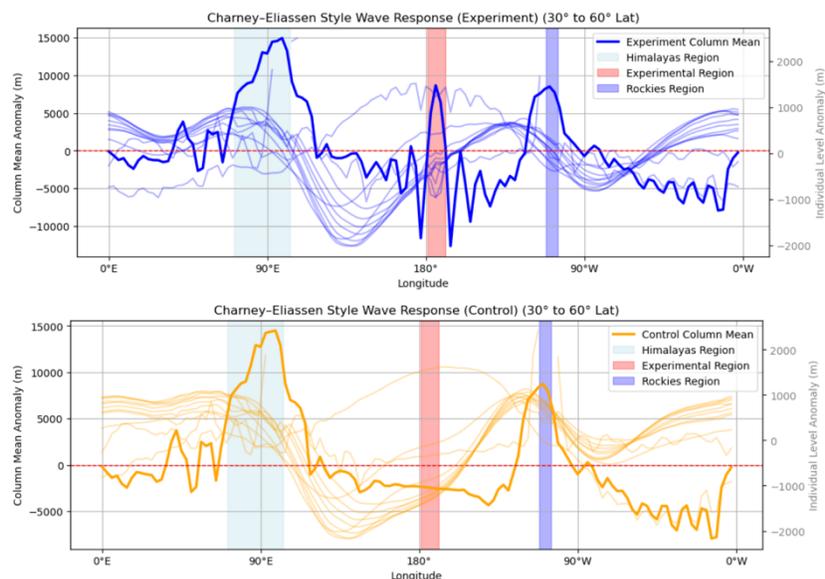


Figure 3

Another idea I had was to observe the effect of the three Rossby waves in the experimental set on other factors such as the zonal or meridional wind (Figure 4). The meridional wind is important in the formation of eddies and stationary eddies. What was apparent in the analysis is that there would be a large increase in the mean meridional winds over the eastern Pacific Ocean and an approximately one-third decrease in the average meridional wind velocity (v) off the coast of western North America. This decrease implies that there would be less interaction between eddies and the meridional flow, which would weaken the baroclinic conversion of potential energy to kinetic energy. A weaker “ v ” translates to less

energy being transported poleward, weaker ridges and troughs, but with the unusual effect of making blocking highs less likely to form or persist due to the reduced wave amplification. It is also suggested by the graph that the jet stream or geostrophic flow becomes more zonal in this area due to the decreased “v” and a slightly increased “u.” The reduction of meridional winds (v) in the location off the U.S. West Coast could therefore not only reduce the formation of blocking highs but also make existing ones weaker or shorter in duration. In essence, in areas with a weaker “v,” high-pressure ridges that typically linger over the western or eastern U.S. might not be sustained as easily because they depend on sustained meridional momentum flux to maintain their structure.

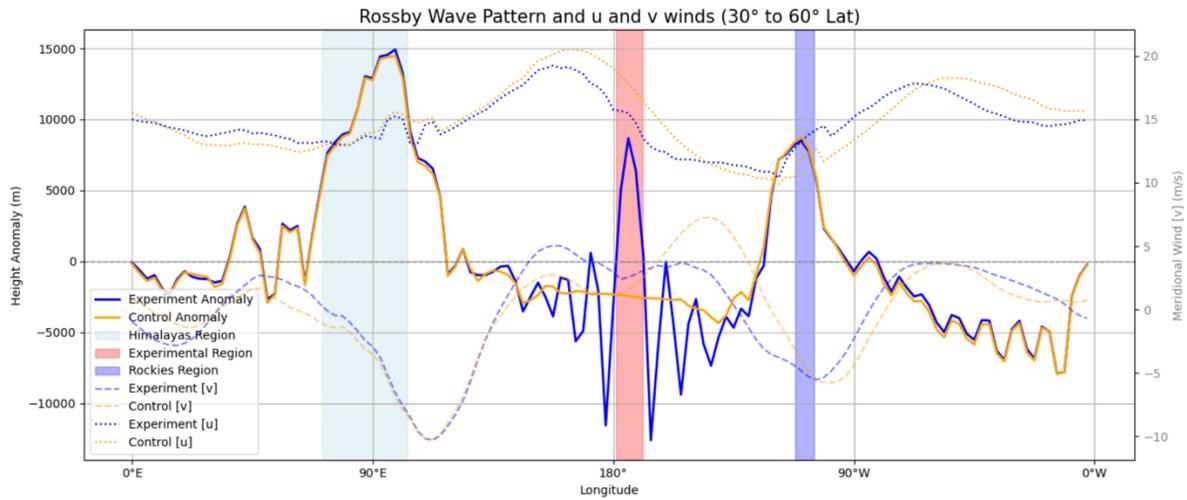


Figure 4

In contrast, the area upstream from the experimental ridge shows signs of a very different response. The increase in meridional winds there may result in more frequent and intense interactions between eddies and the mean flow, leading to greater conversion of potential to kinetic energy and potentially increasing the likelihood of persistent stationary waves. This could result in more frequent blocking events in the central to western Pacific, especially near island regions. These findings appear to me to be consistent with quasi-geostrophic theory, in which the balance between zonal and meridional winds controls the vertical and horizontal propagation of Rossby waves. The graph supports this, with a relative weakening of the zonal wind (u) just upstream of the experimental ridge, consistent with wave energy absorption or slowing, and a strengthening of zonal flow downstream, where the reduced v leads to a more uniform and less perturbed jet. This spatial shift in the mean wave flow interaction exemplifies the sensitivity of large-scale circulation to changes in topography and the resulting changes in u and v.

In conclusion, if possible in my career, I would like to expand this analysis in the future to explore other effects related to orographic forcing and Rossby waves on general atmospheric circulation. There are more qualified people to perform this sort of work though, but I am curious. Though potentially obvious, I was pleased to observe that introducing an artificial mountain range in the central Pacific successfully generated a three-wave stationary Rossby pattern, consistent with wave theory. What was especially interesting was the way the new feature attenuated and reshaped the global wave response. Not only locally, but downstream

and upstream from the experimental mountain range as well. The experimental mountain appeared to elongate the stationary wave downstream from the Rockies, enhance the zonal advection, and weaken meridional winds over western North America, while simultaneously strengthening meridional flow over the eastern Pacific. This altered wind pattern likely would suppress the formation and persistence of blocking highs near the West Coast of the U.S. but may promote increased eddy activity and energy conversion upstream, possibly affecting storm systems over the Pacific and intensifying wave structures in the subtropics. These findings suggest several possibilities for further study. For instance, an analysis of energy and momentum transport by Rossby waves could offer a clearer view into how mountain induced waves exchange energy with the mean flow. Similarly, exploring how mountains redirect zonal winds and reshape circulation cells like the Hadley, Ferrel, and Polar cells could reveal additional climate scale consequences of topographic forcing. Or there could be a deeper look at the ways in which the presence of artificial orographic forcing can be used to influence storm tracks through the manipulation of temperature gradients and jets in a way that is beneficial to humanity. As this project has shown, targeted orographic changes have the potential to modify the amplitude and phase of quasi-stationary waves, leading to large scale impacts on temperature gradients, jet stream behavior, and the persistence of meso-scale systems. Although I did not incorporate thermal forcing into this experiment, it is known that a warming climate, especially in an enhanced ENSO climate phase, can lead to amplified and stationary Rossby waves that lock regional weather patterns into place, exacerbating droughts or floods. In my opinion, this experiment/analysis also beckons broader questions of geoengineering. Though constructing artificial mountains is currently infeasible, it raises the possibility that if we better understood how topography shapes wave behavior, we might one day be able to design artificial topographic features as atmospheric interventions to steer planetary flows for the benefit of humanity. Though further research would be needed, and it is technologically infeasible now, this type of geoengineering could offer a route to mitigate persistent climate extremes. However, the results upstream from the artificial range tell the opposite story, that while artificial topography can be used to modify wave behavior, it may just as easily amplify undesirable blocking if not precisely tuned. Any geoengineering strategy would require extensive thought and thorough analysis forecasting tools. Still, this exploration was a valuable opportunity to apply theoretical knowledge from class to a practical, dynamic, and difficult to understand system. One that tickled my imaginative curiosity about humanity's relationship with the atmosphere and the potential applications of Rossby waves to geoengineering.