Effects of Snow Boundary Generated Baroclinicity on Middle Latitude Disturbances

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Abstract

It is understood that snow cover has the potential to influence synoptic dynamics through latent heating and surface albedo effects. Gaining a deeper understanding of these interactions is important in order to predict how a changing climate will affect these feedback mechanisms. Previous work has shown that a temperature gradient can be set up across the snow pack boundary, generating baroclinicity, and influencing mid-latitude storm tracks. In this work, we will discuss if the previously found relationship has a storm size dependency such that enhanced baroclinicity generation only holds for small mid-latitude cyclones. This will be determined by statistical analysis of case studies and further investigation using the Weather Research and Forecasting Model (WRF). Preliminary outputs of the WRF simulations will be discussed along with the conclusions from the case study analyses.

Introduction

Climate change is on track to significantly alter the global energy balance in ways never observed before. Much of the focus of climate research has been on the response of climate feedback systems to anthropogenic induced warming, but less so on how weather systems might be influenced. The equator to pole temperature baroclinicity drives middle latitude cyclones (MLC) through the buildup of available potential energy, eliminating the surplus of energy realized at the equator and transporting it northward (Orlanski and Sheldon, 1995). Baroclinic regions can be formed however by other processes such as snow cover, a highly variable seasonal phenomenon that has huge implications for energy balance (Rydzik and Desai, 2014). Snow cover has been shown to locally cool due to direct reflection of shortwave radiation through its high albedo (Namias, 1985), (Baker et al., 1992). A significant feature that is evident is the often abrupt boundary between a snow covered surface and a snow free surface as seen in Figure 1. As a result of the local cooling effect of snow, a low level baroclinic region is create shown in Figure 2. The low level cooling can also diabatically generate potential vorticity, an important quantity for synoptic dynamics. It has been hypothesized previously that snow boundaries can influence an MLC (Namias, 1962) (Ross and Walsh, 1986). Rydzik and Desai, 2014, showed that the low level baroclinic regions generated by snow cover are statistically correlated with MLC storm tracks as seen in Figure 3. The low-level thermal field as well as the potential vorticity has the ability to feedback into the circulation patterns of a collocated MLC (Namias, 1962).

The purpose of this study is to investigate the mechanisms responsible for MLC storm track and intensity changes as a result of the low-level baroclinicity and the potential vorticity using a numerical weather model. The MLC intensity should change as a result of the increased circulation from the ingestion of the low-level potential vorticity.

Methods

Case Study Selection

To investigate the mechanisms behind modification of MLC trajectories by snow boundaries, case studies were identified and modelled using idealized numerical model simulations. The pressure tracking algorithm and snow boundary identification algorithm from

Rydzik and Desai (2014) was utilized to generate a dataset of all storms and associated snow boundaries. The meteorological data was obtained from the North American Regional Reanalysis (Mesinger et al., 2006) Only November through March was utilized as these months have been previously shown to be the most significant for snow boundary-MLC interactions (Rydzik and Desai, 2014). A collection of cases was generated by visual inspection of the the pressure tracking data points plotted over a calculated snow boundary for a given day. The 00 UTC snow boundary was plotted for each day and then for each storm that started during the following 24 hours, the 3-hour pressure center locations were plotted.

Since trajectory modification by snow boundaries is likely to be a less significant forcing than the upward vertical motion field produced by a strong upper-level jet for example, we expected weaker storms to have greater trajectory modification than stronger ones. Snow cover data was found to be inconsistent across different model reanalysis datasets, so observed snow cover was used as verification to ensure the quality of the data using the SNODAS database (Barrett et al., 2003).

Model Experiment Design

Table 1. Abbreviated methods for each case.

Real Data Case	Modified Snow Cover	Absent Snow Cover
Control with no modification	1m of snow applied north of 43N	Snow was removed in the whole domain

The model used to investigate the identified cases was the Weather Research and Forecasting (WRF) model, a fully compressible, non-hydrostatic model. A set of 3 experiments were conducted that simulated a real data case, modified snow cover case, and a case with all of the snow removed as demonstrated in Table 1. The purpose of the 3 cases was to correlate removed snow cover with changes in intensity of MLC's as well as the low-level baroclinicity and potential vorticity.

The real data control case was run for 6 days with a 20km grid, default physics parameters, and 6 hourly boundary conditions provided using the GFS FNL .5-degree dataset. Both the absent snow cover case and the modified snow cover case were modified using restart files from the control case at 2 days, 12 hours into the simulation. The modified snow cover case had 1 meter of snow with 200 kg/m^3 snow density applied everywhere north of 43N latitude. 43N latitude was chosen due to the position of the simulated MLC related to this boundary, as the greatest effect demonstrated by Rydzik and Desai (2014) was just south of the snow line, shown in Fig. 4.

WRF Details

WRF is the most commonly used research model and offers many sets of physics parameters. The NOAH land surface model was used to simulate accurate snow physics. The domain for the model runs was chosen to highlight the Colorado storm track with the snow-boundary interaction likely occurring in the northern Great Plains. The western boundary of the domain excludes the Rocky Mountains themselves while the eastern boundary stops at the eastern extent of the United States. The goal of this domain setup was to avoid possible confounding terrain features such as mountain ranges and the Laurentian great lakes. The snow cover was modified by taking the WRF restart file2.5 days after the model start, and applying 1 M of snow to every grid point north of 43 North.

Analysis

The low-level potential vorticity field was analyzed to identify differences due to snow cover and the interaction of an MLC. Python was used to evaluate potential vorticity at the lowest eta levels in the model. The use of eta levels when looking at potential vorticity means that a constant height above the surface will be analyzed which ensures that the potential vorticity analyzed is being generated at the surface. Two -meter temperature is used to verify that the low-level baroclinicity is evident in the model. A potential temperature cross section allows the vertical effect of the snow boundary to be investigated.

Results

Case Study Identification

The case study date was January 3rd, 2006-January 4th, 2006. The output of the case study identification process showed the case as possible candidate. The pressure tracking algorithm showed an MLC approximately moving along a snow boundary. Upon verification it was determined that the MLC actually moved just south of a snow boundary, though the different snow data products disagreed on exactly where the snow was located. The result of the case study identification algorithm is seen in Figure 5.

Case Study Analysis

Comparing the output from the 3 model simulations, the central pressure track was not modified and the strength of the storm was also unmodified. It is clear that the modification of the snow had an effect on the domain as the temperature, moisture gradients were very intense across the snow boundary shown in Figure 6. The potential vorticity (PV) gradient across the snow boundary is also very intense in the modified snow simulation shown in Fig 7. The PV gradient seemed to intensify behind the passing MLC, a surprising finding. This indicates that for a short period of time behind an MLC, the PV gradient is intensified. Though all of the hypothesized pre-conditions for the modification of the MLC storm track are present in these simulations, no modification is observed.

Discussion

Snow Cover Effects

It is evident that snow cover does have an influence on low level processes, mainly temperature and potential vorticity. The setup of a baroclinic region is critical for the proposed mechanisms, and that is exactly what occurred. The potential vorticity gradient intensification is also something that would affect an MLC. The setup of an intense gradient by a leading MLC would potentially influence a closely following MLC. This might have implications that an MLC drops snow, intensifies the potential vorticity gradient which would then influence another MLC.

Areas of Uncertainty

One possibility for the absence of MLC intensification is that the model does not have the necessary physics for this connection to occur, but given the sophistication of the WRF model, this seems unlikely. A more likely possibility is that the center of circulation was actually too far displaced from the snow line for the effect of the boundary to influence it. This would mean that the strength of the circulation was no great enough to pull in potential vorticity. The final possibility is that the depth of the influence of the snow is too shallow for it to affect the the whole vertical structure of the MLC.

Future work

Several more case studies will need to be included to provide conclusive evidence of an interaction. Choosing different initial intensity MLC's and initial snow conditions would provide a larger sample of conditions to see if the interaction differs between cases. Further analysis on the low-level potential vorticity would allow a more detailed look at the advection processes that could amplify and MLC. Potential vorticity is invertible, meaning it can be calculated at every grid point, and the diabatically generated potential vorticity separated. A complication however is the surface friction and boundary layer processes that would make this calculation very difficult.

Conclusion

The experiment at this point is inconclusive as to whether snow boundaries affect MLC circulations. The pre-conditions for the hypothesized interaction are met with the increase in low level temperature and PV gradients across the boundary. The storm track for the simulation was not modified and neither was the storm intensity. The center of the circulation for the MLC center was perhaps too far removed from the snow boundary for interaction between the two. More cases will need to be added to the sample size to create a more conclusive result.

Figures

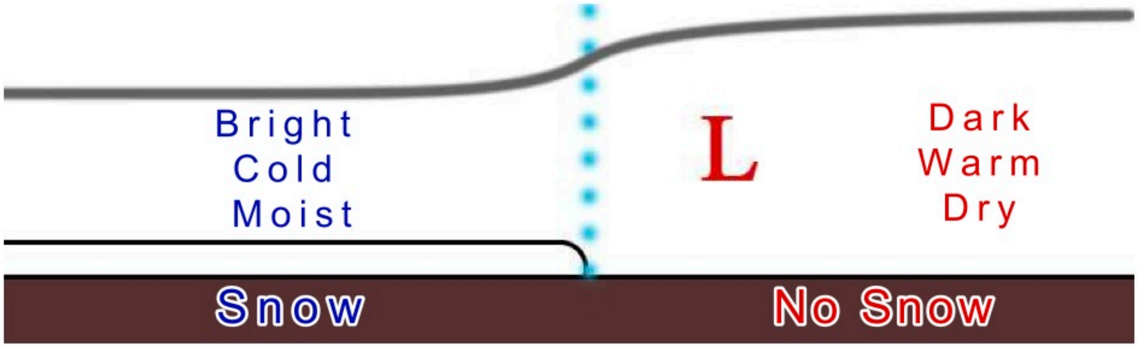

Figure 1. Diagram of the snow boundary processes. (Rydzik and Desai, 2014)

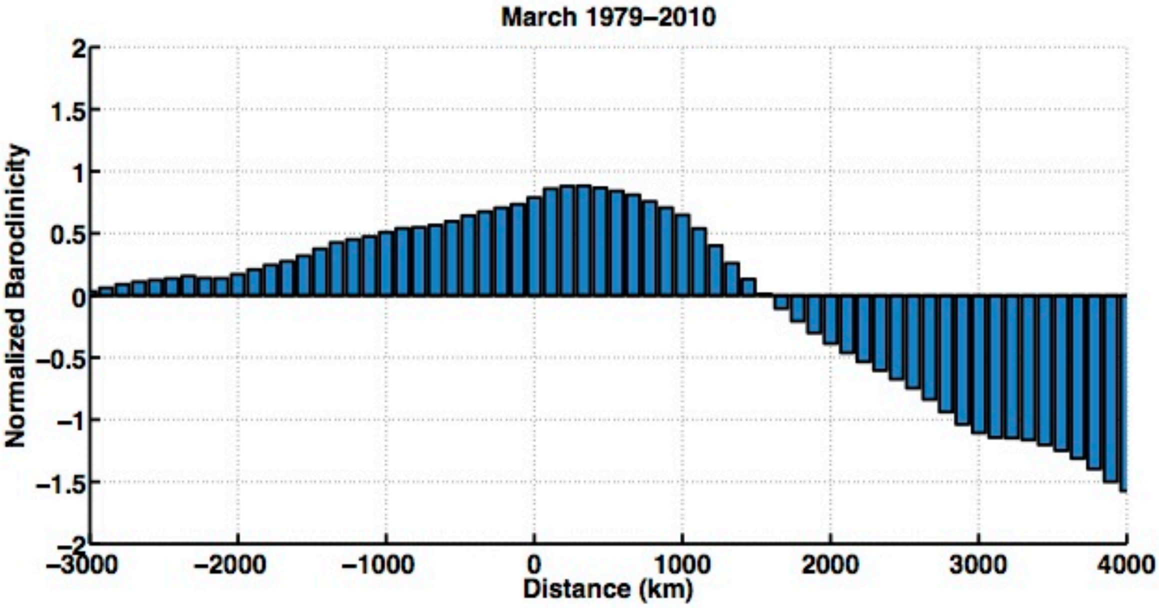

Figure 2. Normalized low-level baroclinicity relative to the snow cover extent for March. Low-level baroclinicity peaks in the region south of the snow cover extent where MLCs are most frequent. (Rydzik and Desai, 2014)

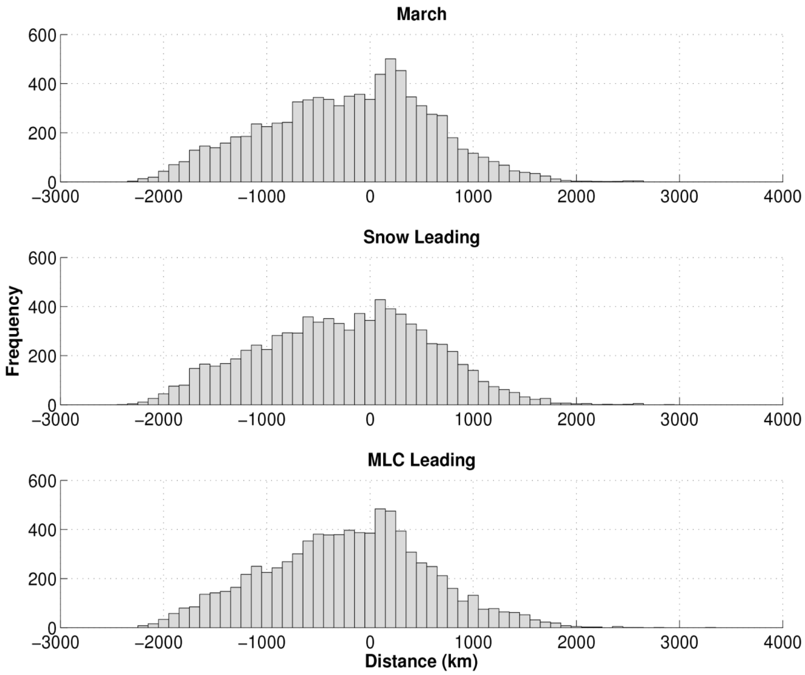

Figure 3. MLC center distance from snow cover extent for storms lasting longer than 24 hrs using various lags in March for 1979 to 2010. Negative distances are MLC centers that are over snow and positive distances are MLC centers that are over ground without snow. MLC cyclone frequency exhibits a stronger peak south of the snow cover extent than in November for snow cover and MLCs on the same day. (b) Snow cover leading the MLCs by two days. (c) A shift to the left, consistent with snow being deposited by the storm itself is seen when the MLC leads the snow cover by two days. (Rydzik and Desai, 2014)

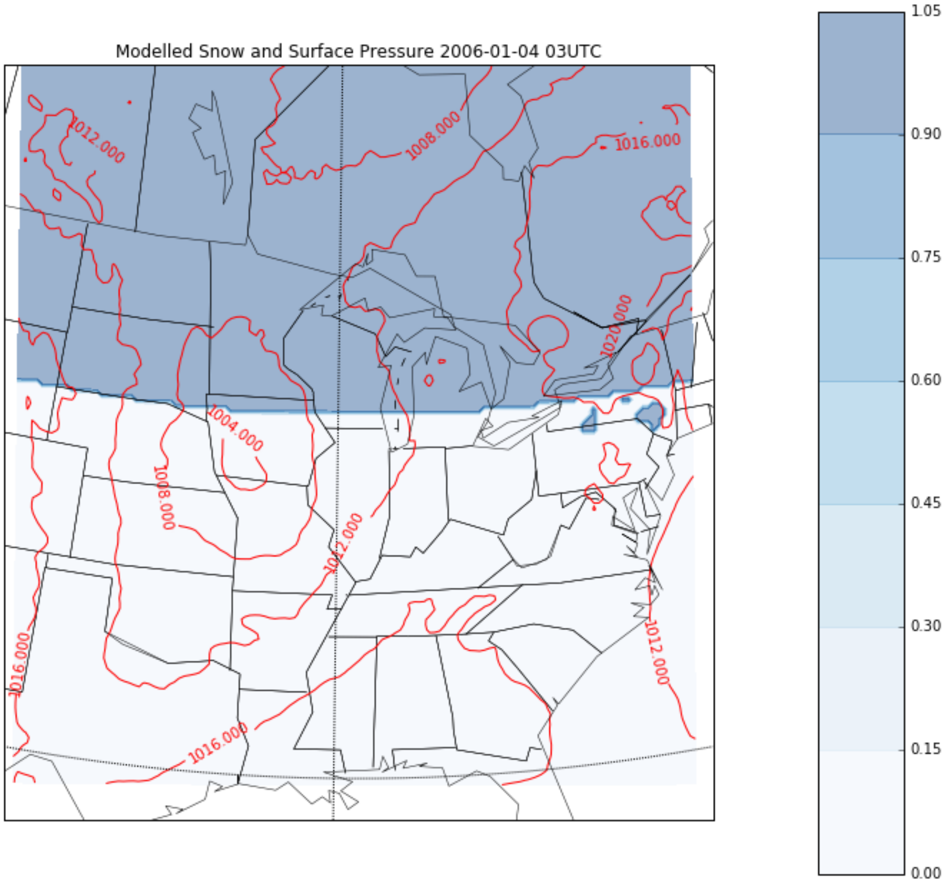

Figure 4. The modified snow cover case, with sea level pressure and snow depth plotted. 1 m of snow was applied at all grid points north of the 43N latitude line.

Figure 5. The blue line is the 00 UTC snow line for this particular day. The red circles are the locations of central pressure minima for this particular storm. This was done for storms November – March, 1979-2010.

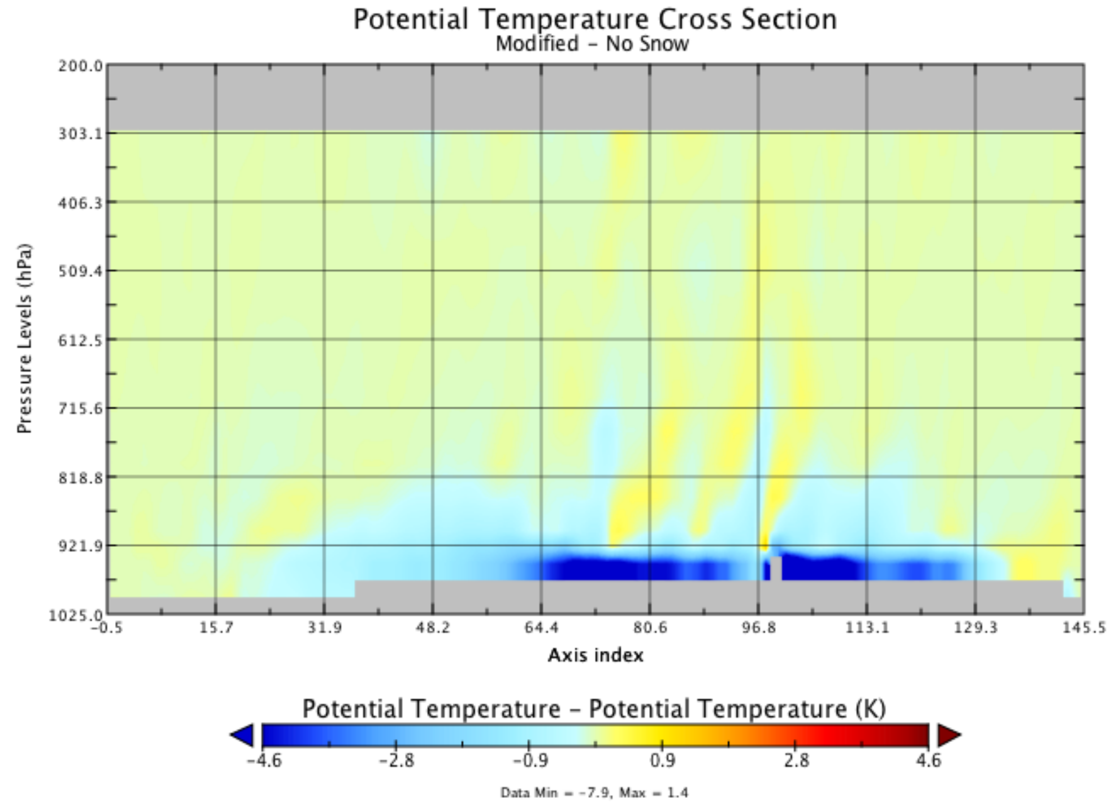

Figure 6. Cross section difference map of the modified snow cover potential temperature and the snow free potential temperature, with the snow free subtracted from the modified snow cover case. Notice the depth of the potential temperature anomaly is not very deep, but is quite intense.

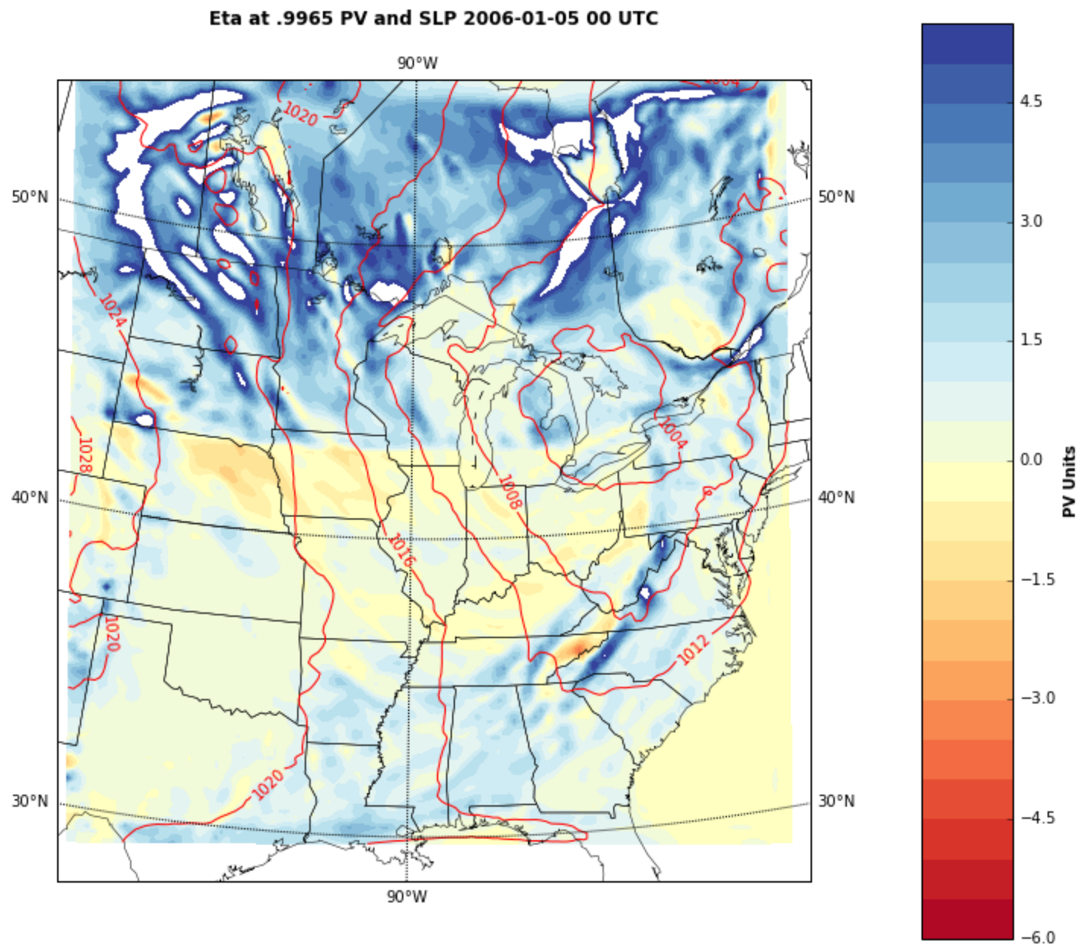

Figure 7. The shading is potential vorticity (PV) and the red contours are sea level pressure for the modified snow simulation. The PV gradient is nearly 3 PV units at the surface.

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