An Ensemble-Based Examination of Extratropical Cyclone Characteristics in Future Climates

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Introduction

Throughout the mid-latitudes, extratropical cyclones (ETCs) are a significant mechanism by which changing climate conditions and their associated societal impacts are felt in some of the most populated regions of the planet. With wide-ranging impacts on agriculture, commerce, and society at large, understanding the changes to ETC strength in a warming climate is crucial.

Changes to the climate system, such as increasing temperatures and increasing atmospheric moisture content, along with a modification of baroclinic zones across the globe, will modify current extratropical cyclogenetic environments to an unknown extent. Such uncertainty makes understanding future ETC characteristics and impacts difficult, given the wide range of possible future environments, depending on emission scenarios and other climate adaptation and mitigation techniques employed.

Analysis of future ETCs is also complicated by the complex web of feedbacks between scales within any one system. Processes from the molecular to planetary scale all exert influence on ETC development to varying degrees. Therefore, we utilize numerical modeling techniques in this study to address the following questions:

- **How do ETC properties evolve with changes to two environmental characteristics: moisture content and baroclinicity?**
- **Are there feedbacks when both characteristics are changed simultaneously?**
- **How do these environmental changes affect the ETC from a process-based perspective?**

Model Setup

The Weather Research and Forecasting (WRF), version 3.5.1, is run in an idealized mode with the following settings:

- Channel configuration with periodic eastern/western boundaries
- 161x361 horizontal grid points at 25km spacing with 65 levels.
- 14 day runtime, with ETC intensity peaking between days 9-11.
- Relevant parameterization schemes used are as follows:
  - Microphysics - Morrison double-moment
  - Cumulus – Kain-Fritsch scheme
  - Boundary Layer – YSU scheme.

Our initial conditions are a modified version of the baroclinic wave test case used in Booth et al. 2013, with two variations:

1. Simulations are run on a beta-plane, rather than on an f-plane.
2. Modifications are made so that vertical lapse rates are nearly identically preserved as bulk temperature is increased/decreased.

To test ETC sensitivity, we devise two controllable parameters:

1. Bulk Temperature
   - Shifts entire initial temperature profile in steps of ±2 K between profiles with initial surface temperatures of 288 K – 308 K at the southern boundary.
   - **Use of a constant relative humidity profile results in a realistic sensitivity test for changes in moisture content when bulk temperature is modified.**
2. Jet Amplitude Factor
   - Controls initial jet velocity by applying a multiplicative factor to the entire jet profile in steps of ±0.04 between 0.8 and 1.2.
   - **Use of thermal wind balance in the initialization results in a sensitivity test for changes in baroclinicity when the jet amplitude factor is modified.**

Sensitivity tests over 11 steps for both of these variables are combined to create an ensemble of 121 runs over the tested parameter space.

Results

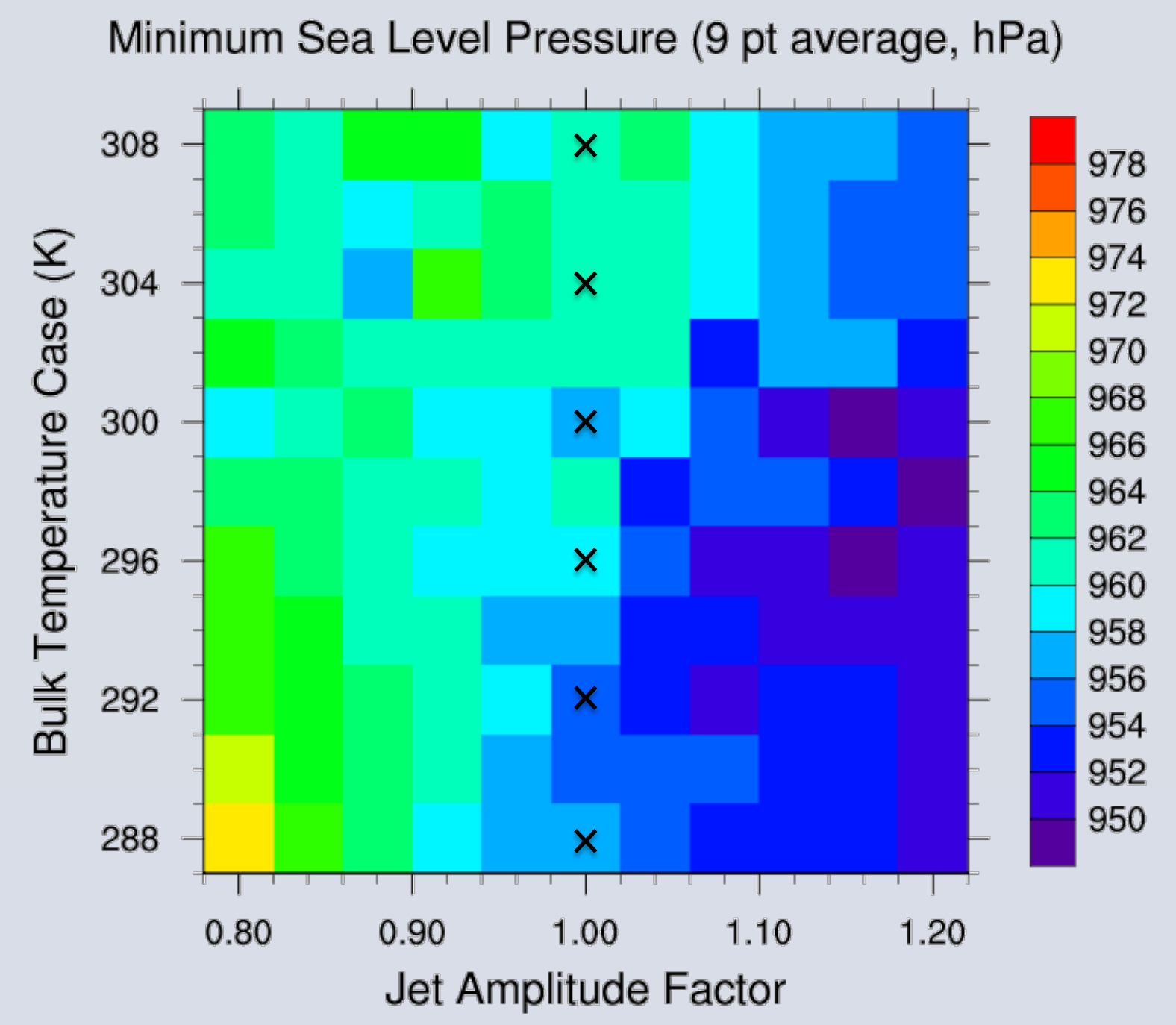


Figure 1:
Minimum Sea Level Pressure [hPa} for each of the 121 runs, calculated by using a 9 point box average centered on the minimum point

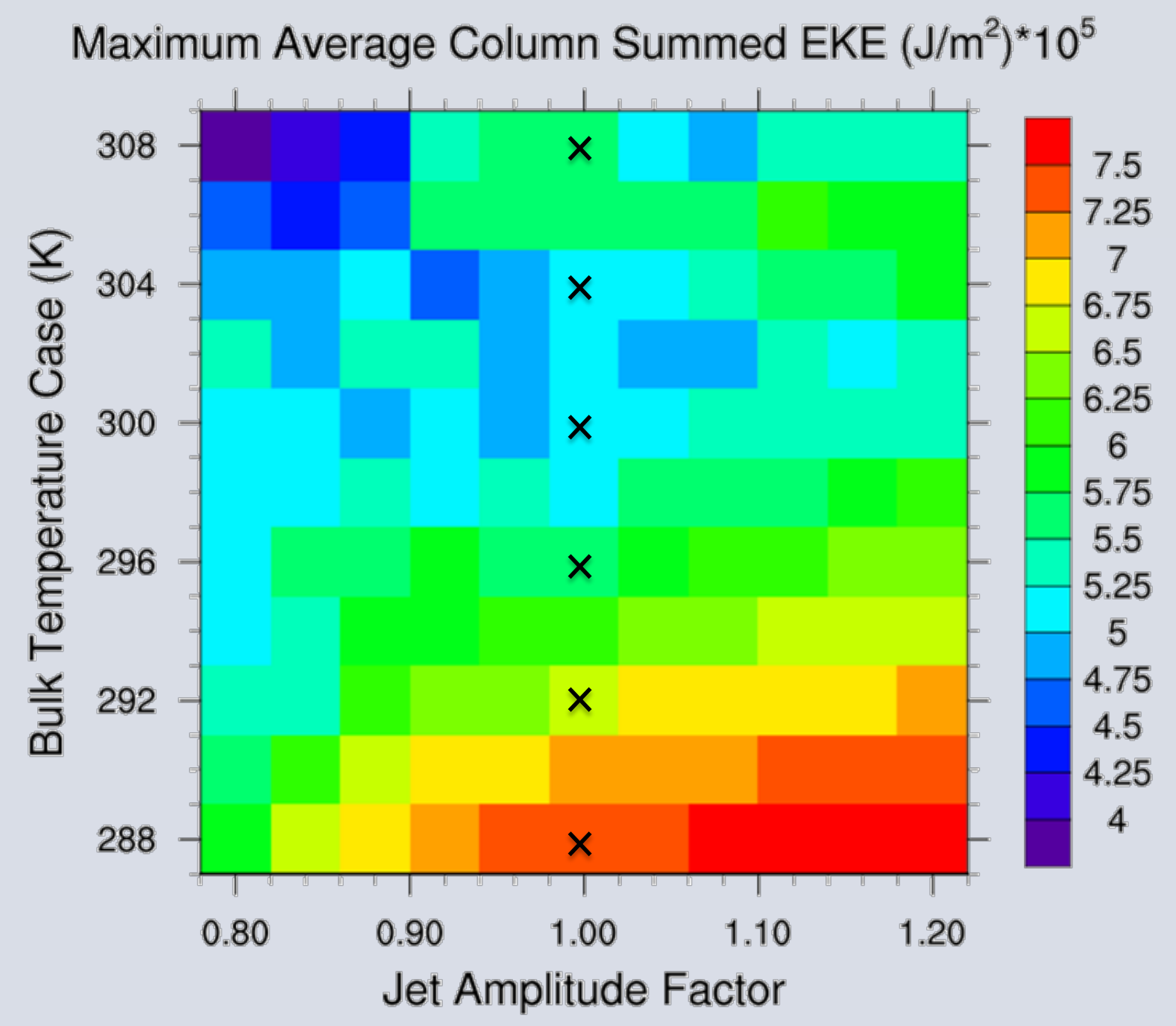


Figure 2:
Maximum Average Column-Summed Eddy Kinetic Energy (EKE) [J/m^2)*10^5] for each of the 121 runs.

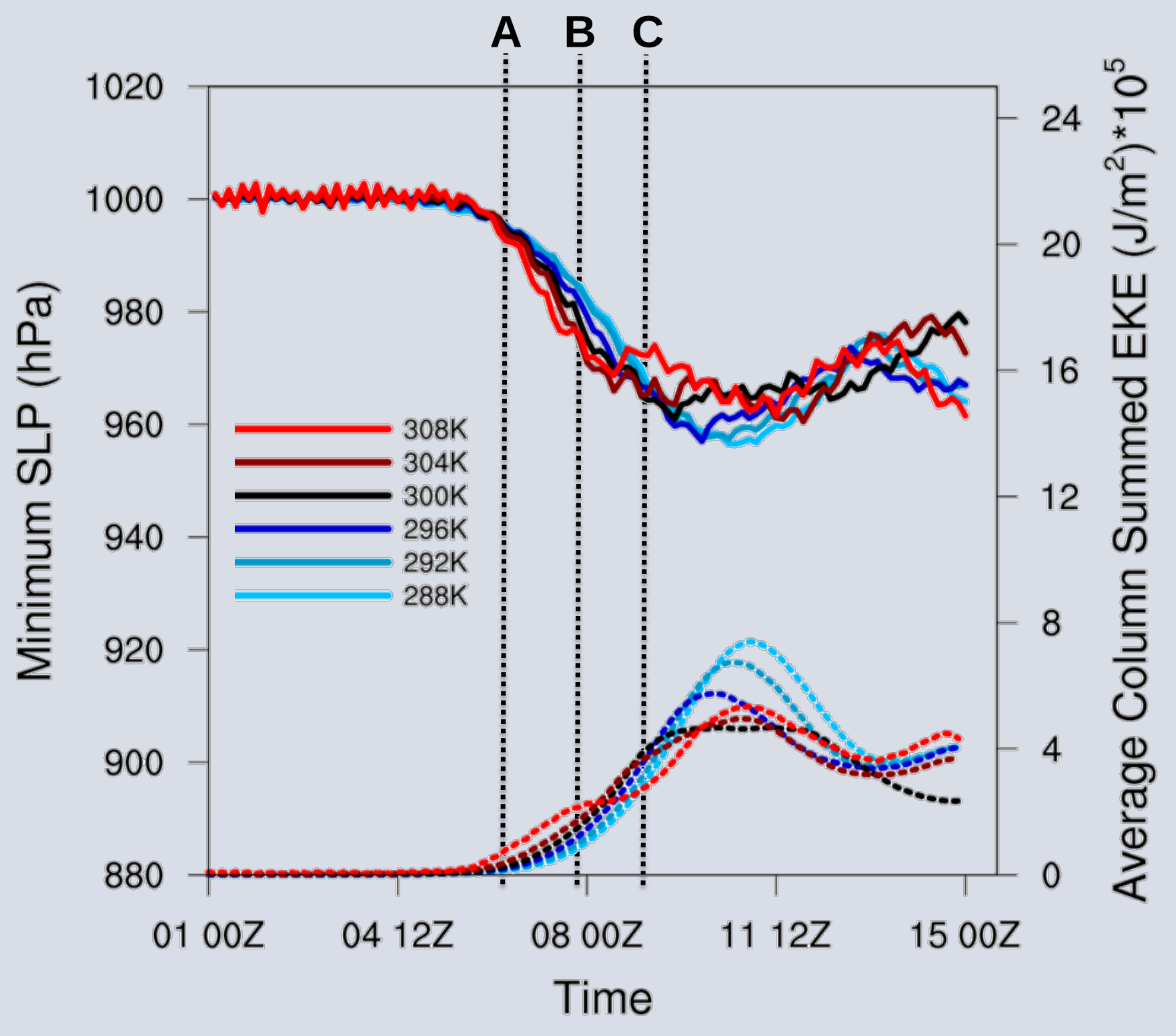
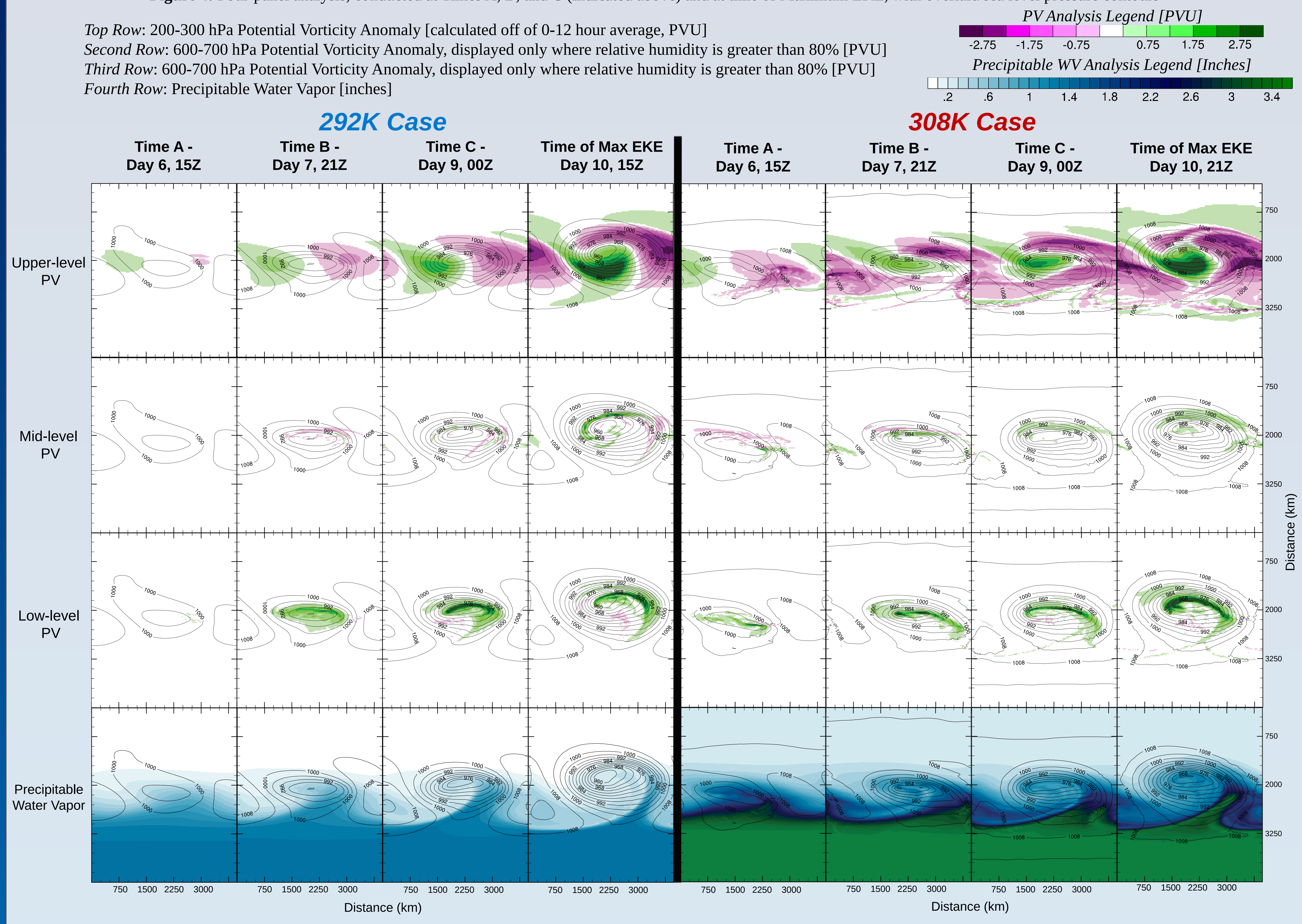


Figure 3:
Minimum SLP and Maximum EKE timelines for 6 selected runs, marked by an X in Figured 1 and 2

Figure 4: Four-panel analysis, conducted at Times A, B, and C (indicated above) and at time of Maximum EKE, with overlaid sea level pressure contours

Top Row: 200-300 hPa Potential Vorticity Anomaly [calculated off of 0-12 hour average, PVU]
Second Row: 600-700 hPa Potential Vorticity Anomaly, displayed only where relative humidity is greater than 80% [PVU]
Third Row: 600-700 hPa Potential Vorticity Anomaly, displayed only where relative humidity is greater than 80% [PVU]
Fourth Row: Precipitable Water Vapor [inches]



Discussion & Conclusions

- ➢ With increasing moisture content (via temperature controls), minimum sea level pressure values decrease at lower baroclinicities, but increase at higher baroclinicities.
  - Increasing convection plays a larger role in the early stages of cyclogenesis, disturbing the conversion of environmental baroclinic energy in moister/warmer runs.
- ➢ With increasing moisture content (via temperature controls), maximum eddy kinetic energy generally decreases, although there is non-monotonic behavior to the maximum at higher baroclinicity values.
- ➢ Warmer/moister cyclones exhibit two maxima during their EKE timelines, indicating two main periods of cyclogenesis
  - These maxima are caused by the generation of a Diabatic Rossby Wave early in the ETC lifecycle, followed by more traditional methods of cyclogenesis
- ➢ Bivariate response in maximum EKE exhibits two separate regimes, with a shift at an initial surface temperature of ~300 K at the southern boundary.
- ➢ As demonstrated in Figure 5 (below), the non-monotonic response of maximum EKE to changes in temperature/moisture content is similar regardless of the Coriolis configuration utilized.
  - Differences arise due to the changes in Coriolis force modifying the amount of rightward momentum imparted on parcels traveling towards the convectively-initiated low pressure center.

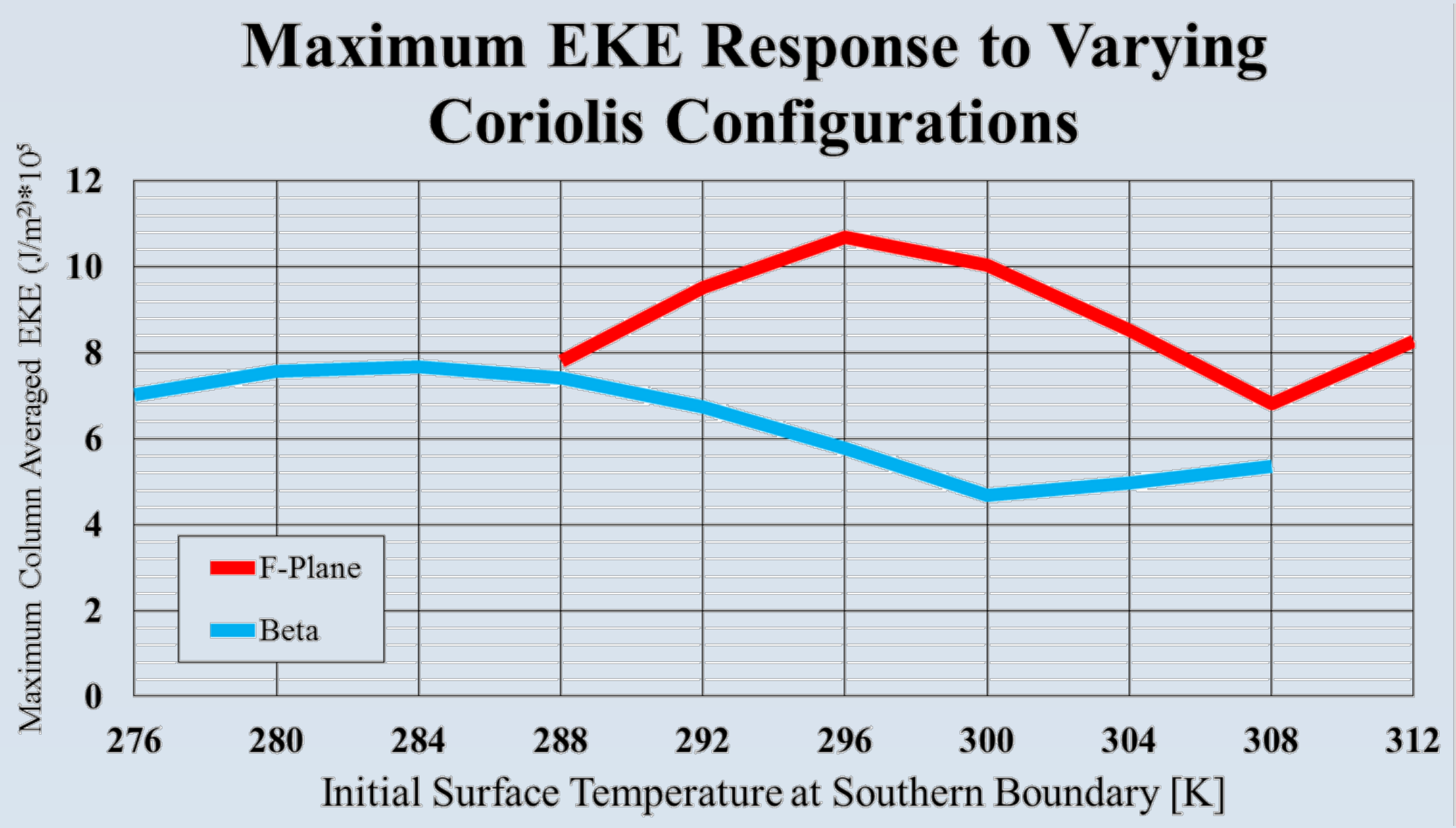


Figure 5:
Maximum EKE Responses to changes in temperature/moisture content in both f-plane and beta-plane configurations

With increasing temperature & moisture content, convection occurs earlier along the baroclinic zone, leading to greater modification of traditional cyclogenesis processes.

Acknowledgments

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