PROJECT SUMMARY

Overview:

Prediction of mid-latitude cyclone trajectories and intensity is a primary occupation of synoptic weather forecasting and understanding its drivers is a fundamental challenge to modeling the impacts of global climatic variability and change on mid-latitude weather dynamics. One long theorized driver of mid-latitude disturbances is the location of southern extent of Northern Hemisphere snow cover. But, while snow cover anomalies have been used as a forecasting rule of thumb for quite some time, neither the validity nor the physical mechanisms underlying this rule have been rigorously investigated. Recent work, by one of the PIs, has shown that, statistically over the past 30 years, antecedent snow cover in North America is a strong predictor of subsequent mid-latitude disturbance locations. The ensuing manuscript hypothesized a mechanism driven by the snow cover albedo gradient, which develops boundary-layer-free-troposphere interaction through enhancing low-level baroclinicity, a dynamical surrogate for boundary layer potential vorticity gradients. Therefore, building on this work, the objectives of this proposal are to expand the initial retrospective statistical analysis to a greater range of snow and cyclone observations, focus on central/eastern North America where the strength of the relationship was most robust, evaluate the mechanistic basis of the relationship by piece-wise inversion low-level potential vorticity in numerical model case study simulations with altered snow cover, and benchmark the likelihood of this relationship in a large ensemble of climate models to address implications for future changes to the mid-latitude storm trajectories with retreating snow extent.

Intellectual Merit :

The intellectual merit of this proposal is new insights and robust testing of mechanisms that drive boundary-layer to free-troposphere interaction through one of the planet’s most notable and temporally variable surface albedo, temperature, and moisture gradients. This proposal will build on preliminary findings with a focused central North American analysis of snow cover, cyclone trajectory, intensity, and potential vorticity relationships. Statistical analysis of mid-latitude weather systems and central North America snow cover, along with mesoscale numerical modeling with altered snow cover extent will be used to evaluate theories of the dynamical impact of lower lever circulation anomalies on synoptic systems as a function of cyclone intensity, position, and external environment. Favored mechanisms will be further evaluated with a large ensemble of modern and future climate simulations to understand the relative impact of this effect on current and future projections of the mid-latitude storm track.

Broader Impacts :

Broader impacts of this research extend to both the weather/climate prediction and boundary-layer meteorology communities. Societal relevance is found in better understanding of how climate change manifests in weather, which could lead to improvements in both weather and climate forecasting and benefit risk management of weather hazards. Numerical mesoscale and climate models will be analyzed for snow cover and storm track variability, contributing a new diagnostic to the modeling community. Quantification of the conceptual theory proposed here would allow for more robust forecasting of changes to cyclone behavior as a function of pre-existing snow cover, which has significant economic implications for warning and mitigation of storm related risk. Further, this project would support a PhD student and undergraduate students who will be trained in the emerging fields of the weather-climate interface and boundary layer-synoptic interaction and recruited from under-represented groups in the sciences. Harmonized databases on snow cover and mid-latitude storm tracks will be made publicly available. Finally, this proposal supports outreach through weather forecaster presentations, public talks, and enhancing classroom education at the undergraduate level.

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Conceptual Framework

The seasonal southward advance and northward retreat of Northern Hemisphere snow cover is one of the most dynamic and regular oscillations in Earth's surface energy balance. The presence of snow increases albedo, decreases surface skin temperature, and enhances moisture fluxes into the planetary boundary layer (PBL). The PBL is on average, colder and moister over a snow-covered surface (Fig 1).

Consequently, the equatorward edge of the snow cover is a region of substantial low-level temperature and moisture gradients. The overarching question driving this proposal is: **to what extent does this dynamic snow extent boundary drive boundary-layer baroclinicity and surface potential vorticity advection, and, in turn, influence larger scale synoptic dynamics?**

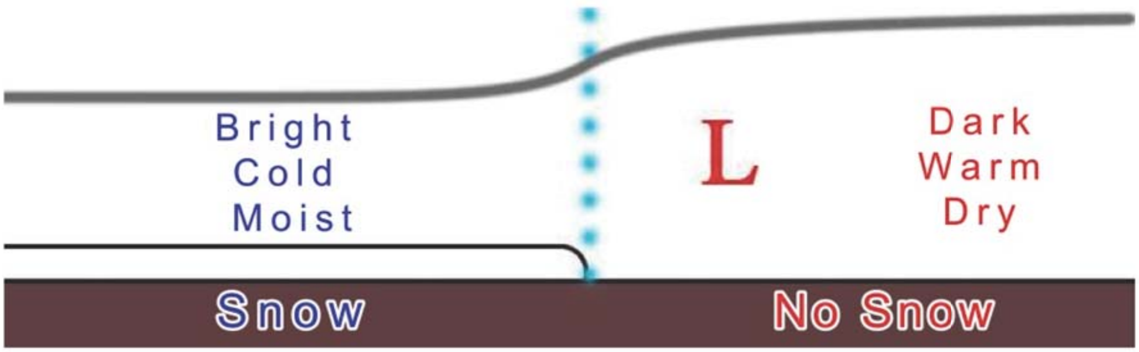

Figure 1. Conceptual diagram of the southern extent of snow cover gradient and interaction with synoptic systems.

It has long been hypothesized that snow cover and snow extent have an influence on the development or steering of synoptic mid-latitude cyclones (MLC) via boundary layer to free troposphere interaction both locally (Namias, 1962) and remotely (Gong *et al*., 2003). While most studies have focused on the influence of area extent of snow on the radiation budget or the tendency to generate blocking, a less tested claim is whether the albedo gradient that drives a surface energy balance gradient induces low-level baroclinicity and advection of low-level potential vorticity, thus acting as a favored growth region for mid-latitude cyclones. As discussed in the next section, our preliminary work hints at a robust relationship between MLC location and snow cover extent.

If this relationship is generalizable, it has transformative implications for climate dynamics and change of the mid-latitudes. While idea that such surface forcing might have a substantive *direct* influence on the dynamics of cold season synoptic waves is counterintuitive, a relationship between snow cover extent and MLCs has been discussed in the literature for almost 50 years. However, it has not been explicitly analyzed with high-resolution, long-term observations of both variables. *The goals of our proposal are to (1) extend and focus our initial retrospective statistical analysis of snow extent and MLCs to the more data sets in central/eastern North America, (2) evaluate understanding of the mechanistic basis of the relationship with analysis of low-level potential vorticity (PV) in numerical model case study simulations, and (3) benchmark the likelihood of this relationship in a large ensemble of climate models to address implications for future changes to the mid-latitude storm track.*

Detailed analysis over past and future climate history of the mid-latitudes will significantly aid the climate modeling community in bridging the weather-climate divide and better articulating the role of boundary layer forcing and land-atmosphere interactions on larger scale synoptic dynamics over climate timescales. Additionally, this proposal would develop and evaluate high-resolution mid-latitude cyclone and snow cover datasets that can be used by the broader climate science community.

Response to Prior Reviews

We submitted a previous version of this proposal in July 2013 that received favorable reviews but also highlighted a few weaknesses that we have addressed. Reviewers noted the usefulness and practical implications of the research to test this long theorized relationship, but found aspects of the experimental design to be overly broad. Here, we addressed these concerns in several ways. We have added additional snow cover data comparisons, reduced the spatial scope of analyses away from mountains and limited it to North America, developed a more focused plan and domain for numerical simulation, and revised plans for analysis of climate model simulations, within the scope of a 3 year proposal. We also expanded the literature review, connected our outreach program more closely to the proposed work, and added two investigators with specific expertise in global climate model analysis (Vavrus) and numerical regional land-atmosphere modeling (Notaro). Finally, since the development of the proposal, the primary motivating manuscript (Rydzik and Desai, 2014) is now published in *J. Climate* and this academic year, an undergraduate atmospheric sciences student is conducting preliminary modeling case study analyses for his thesis work, which has motivated the revised experimental design below.

The current proposal narrows focus to central North America, instead of the entire hemisphere, to put our effort on testing hypotheses of drivers that link terrestrial snow cover-induced lower-level circulation anomalies to upper-level atmospheric state. We use an observational low-level potential vorticity inversion approach to isolate boundary-layer anomalies. The numerical modeling domain has been expanded to avoid concerns regarding nudging from lateral boundary conditions and experimental cases have been added to test the atmospheric response to varying snow cover anomalies. We now limit the global climate model analyses to the Large Ensemble of the Community Earth System Model, which allows us to directly test signal-to-noise and robustness of relationships in an evolving climate.

Motivation

Impacts of snow on the atmosphere

Snow and ice cover, through its high albedo and insulation effects, has significant climate implications through planetary energy balance (Cohen and Rind, 1991; Groisman, 1994, Vavrus, 2007) (Fig. 2). Early studies showed the impact of snow cover on intensifying cold air masses (Cox, 1916; Wagner, 1973; Walsh *et al*., 1982; Heim and Dewy, 1984; Namias, 1985; Leathers and Robinson, 1993; Kocin *et al*., 1998), and recent work has linked changes in snow cover to acceleration of temperature trends (Peng *et al*., 2013). Other studies have related regional snow depth to cooling (Baker *et al*., 1992; Ellis and Leathers, 1999; Mote, 2008; Alexander and Gong, 2011; Dutra *et al*., 2011). These impacts of snow cover on mid-latitude thermodynamics have also been known anecdotally for quite some time and a variety of forecasting rules of thumb have arisen to correct numerical weather prediction temperature and moisture biases related to snow cover presence or absence (Dewey, 1977; Wojcik and Wilks, 1992).

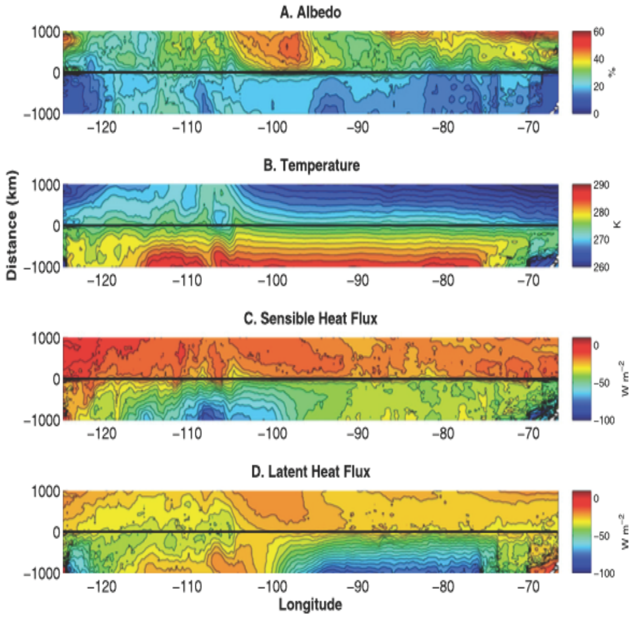

Figure 2. Analysis of difference in North American gradient of winter a) surface albedo (%), b) 2-m air temperature (K), c) sensible heat flux (W m^{-2}), d) latent heat flux (W m^{-2}) normalized in distance relative to the snow extent line, from Rydzik and Desai (2014). Note largest anomalies in Great Plains (100^{o} longitude).

However, while the connection between snow cover and boundary layer climate is physically straightforward, the impact and mechanism of influencing synoptic dynamics are poorly understood. A host of research has shown that the short-term temperature gradient induced by the snow margin is substantial enough to create its own mesoscale circulation, sometimes known as the snow breeze, mostly in spring (e.g., Johnson *et al.*, 1984; Taylor *et al.*, 1998; Segal *et al.*, 1991). But these circulations alone are unlikely to generate significant forcing for synoptic dynamics. The question remains, **to what extent can surface forcing, modulated by the boundary layer, influence upper-air dynamical processes on relevant spatial (> 10^3 km) and temporal (days-months) scales***?*

Observationally, a relationship between low-level baroclinicity and snow extent is evident (Fig. 3), but it is difficult to assign causation given the similar seasonal co-variations of jet position, storm track, and snow extent. While we recognize that there are co-occurring planetary scale variations in snow extent and the position of the polar jet and mid-latitude storm track, we have evidence to believe that the variation of snow extent within this dynamically active system can substantially influence both lower tropospheric cyclogenesis as well as the subsequent direction of individual storm trajectories (Rydzik and Desai, 2014).

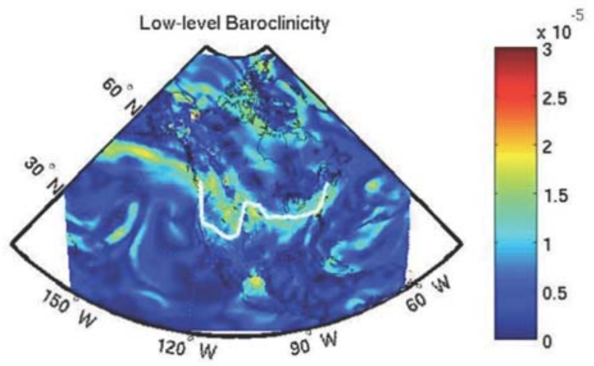

Figure 3. Comparison of low-level baroclinicity (s^{-1}) computed after Rydzik and Desai (2014) and the snow extent (white line) on a single day. Note the correspondence between the region of higher baroclinicity and snow extent.

Namias (1962) was one of the first to suggest a direct relationship between MLC trajectories and pre-existing snow cover. Using the abnormal southern extent of snow during February-March 1960, Namias showed an anomalous climatological high pressure over much of North America. The largest bias between the surface temperature extrapolated from upper-air observations and actual observed surface temperature occurred along the southern edge of the snow extent, with the difference reaching up to 6°C. The finding suggests that snow cover is significantly affecting the mid- and lower tropospheric temperature near the snow extent boundary. Namias then postulated that enhanced baroclinicity near the edge of the snow extent can lead to a positive reinforcement of the temperature contrast and thus, baroclinicity, due to developing MLCs within this region. Namias (1978) cites a similar mechanism of enhanced baroclinicity near the east coast of the United States due to anomalous snow cover for the winter of 1976-1977, consistent with Ross and Walsh (1986), who found that snow cover near a coastal boundary plays a larger role in MLC trajectories than snow over inland areas.

This mechanism is based on a region of enhanced low-level baroclinicity along the snow cover margin, arising from an enhanced temperature and moisture gradient, which then promotes increasing sea-level pressure over the snowpack, leading to a non-local negative 500 hPa height anomaly (Walland and Simmonds, 1996). The altered free tropospheric height gradients then increase the upper tropospheric gradients in vorticity and potential vorticity (PV). Regions of enhanced baroclinicity are also more favorable for MLCs because the eddy growth rate is enhanced, potentially transmitted by vertically propagating Rossby waves (Fletcher *et al.*, 2009; Allen and Zender, 2011). Considered from the PV perspective (Hoskins *et al.* 1985), the enhanced low-level baroclinicity associated with the snow boundary is manifest as an enhanced near-surface Rossby wave-guide, which in analogy to the tropopause-level PV gradient, renders it a particularly favorable region for synoptic development (Riviere *et al.*, 2012). Mid-latitude cyclones derive energy from the operation of thermally direct vertical circulations centered on local regions of large thickness gradient (e.g. Orlanski and Sheldon, 1995). The attendant vertical motions occur in response to rearrangements of vorticity in the vertical and subsequent geostrophic adjustment (Sutcliffe, 1947). Additionally, low-level thermal anomalies, acting as surface edge waves, are an important component of the PV view of baroclinic instability. Counter-propagating Rossby waves at the tropopause and surface can phase lock and mutually amplify (Hoskins *et al*. 1985).

Numerical model studies also confirm a strong impact of snow cover on mid-latitude disturbances. Early work found direct impacts of snow cover variation on sea-level pressure (Walsh and Ross, 1988), diabatic heating rate (Cohen and Entekhabi, 2001), local (Walland and Simmonds, 1997) and remote (Yasunari *et al*., 1991) circulations, and available potential energy (Elguindi *et al*., 2005). In the case of Elguindi *et al*. (2005), the authors modified snow cover under observed MLCs using a mesoscale model (MM5) in the Great Plains. Using two simulations, one with observed snow cover and one in which the entire model domain was snow-covered, they found that there was little change to MLC trajectories and weakened intensity. It is important to note, however, that by filling the entire domain with snow, the MLC is no longer near the snow cover boundary that both Namias (1962) and Ross and Walsh (1986) postulated is necessary for a positive feedback mechanism. In contrast, Sobolowski *et al*. (2010) confirmed a transient eddy response to anomalous snow forcing and that the response was a result of enhanced baroclinicity in existing storm track entrance regions of the North Atlantic. Alexander *et al* (2010) noted a more modest circulation response. The largest driver of the stationary wave response is the cooling from increased snow cover and vice versa (Sobolowski *et al*., 2011). In many respects, this is analogous to findings from a linear, stationary wave model (Hoskins and Valdes, 1990), which suggest that baroclinicity generated by ocean heating off the east coast of continents acts to help maintain a storm track.

Beyond direct links, there is also a line of research that has shown that snow cover anomalies excite remote responses at both the regional (e.g., the East Asian Monsoon in Zhang *et al*., 2004) and hemispheric scales (e.g., Walland and Simmonds, 1996; Cohen and Entekhabi, 2001; Gong *et al*., 2003). The impact of North American snow cover on Northern Hemispheric circulation has been studied less frequently than more expansive Eurasian snow cover effects on the Siberian High and teleconnections (Watanabe and Nitta, 1998; Cohen and Entekhabi, 1999; Clark and Serreze, 2000; Saito *et al*., 2001). However, recent work has shown that the effect of North American snow cover is not negligible on atmospheric blocking (Leathers *et al*., 2002; Sobolowski *et al*., 2007, 2010; Garcia-Herrera and Barriopedro, 2006; Klingaman *et al*., 2008), similar to findings on sea ice (Handorf *et al*., 2015). Leathers *et al*. (2002) showed that the frequency of North American air mass types was influenced by snow cover extent, and that snow cover exerts its most substantial impact on surface cyclogenesis and MLC trajectory during times within the annual snow cover season in the Northern Hemisphere when the upper tropospheric wave activity is relatively weak and less frequent, such as in early fall or early spring. It is notbable that Leathers *et al*. (2002) specifically encouraged research on snow cover and air mass relationship seasonality, which serves as a strong motivation for this proposal.

Recent evidence of snow cover-MLC interaction

In 2012, we conducted an analysis of snow cover extent and mid-latitude cyclone trajectory over North America to statistically establish the strength of this relationship and provide the preliminary basis for this proposal (Rydzik and Desai, 2014). As noted, most of the prior research was based on short time periods or numerical model experiments. In our study, we developed a North American snow cover atlas based on the assimilated snow depths in the National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis, derived form the Airforce Snow Data Assimilation System (SNODAS). Further, we applied a standard pressure algorithm for the tracking of low pressure minima. For each day, we normalized the locations of mid-latitude cyclone centers to north-south distance of the southern edge of the snow cover extent. We repeated this analysis over 1979-2010.

A histogram of the distance between the snow extent and the MLC centers for March (Fig. 4), where albedo gradients are the strongest shows the center of the distribution to be related to the snow extent line (zero distance). The maximum frequency occurs just south of the snow margin and exhibits a longer tail south of the snow extent than to the north. The enhanced peak in frequency is about 50-350 km south of the snow extent line. Weaker but significant relationships were also found in fall and winter. The tail south of the snow extent line is not as large as in November (no shown), but the frequency north of the snow extent line retains its shape.

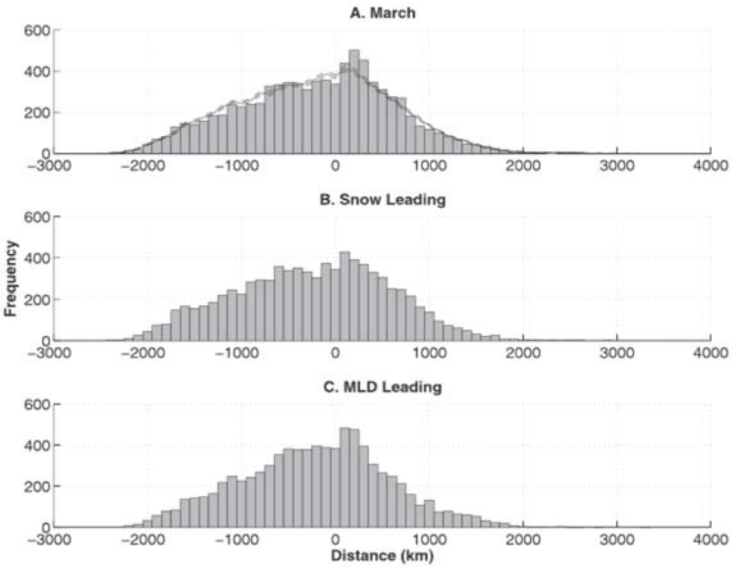

Figure 4. MLC center distance from snow cover extent for storms lasting longer than 24 hrs in March for 1979 to 2010. Negative distances are MLC centers that are over snow and positive distances are MLC centers that are over ground without snow. (a) MLC cyclone frequency exhibits a stronger peak south 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.

Still, one might expect a relationship between mid-latitude cyclone tracks and snow cover extent because it is anticipated that snow would be produced on the northern side of MLCs. To test this effect, we examined lagged relationships between snow cover extent and the antecedent location of the mid-latitude cyclone. The results suggest that it is pre-existing snow cover that is related to the mid-latitude cyclone tracks and this is shown in the middle and bottom panels of Fig. 4. Rydzik and Desai (2014) further conducted a random shuffling test and substantiated the statistical robustness of this relationship.

Further, this pre-existing snow is related to low-level baroclinicity, providing mechanistic support for the statistical correlation. Normalized mean low-level baroclinicity in 100 km bins surrounding the snow extent are presented in Fig. 5. It is evident that baroclinicity peaks in a region just south of the snow extent in March (and similarly in all months). The structure of baroclinicity is almost identical for all months with the smallest values in a region approximately 1500 km south of the snow extent and the largest values occurring in a region from the snow extent to approximately 1000 km south of the snow extent.

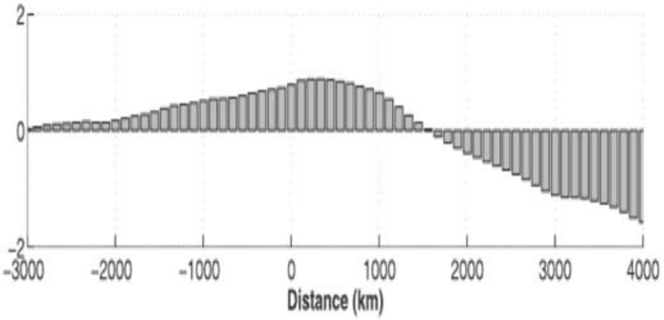

Figure 5. Normalized low-level baroclinicity relative to the snow cover extent for March from Rydzik and Desai (2014). Normalized Low-level baroclinicity peaks in the region south of the snow cover extent (positive x-axis values) where MLCs are most frequent.

The area of enhanced baroclinicity is much broader (from approximately the snow extent to 800 km south of the snow extent) than the peaks observed in MLC cycle frequency relative to the snow extent that tended to be very pronounced and limited to a few hundred kilometers. The region of largest baroclinicity just south of the snow extent provides support for the mechanism proposed by Namias (1962) and Ross and

Walsh (1986). The region immediately south of the snow extent will experience maximum eddy growth rates, making it a favorable region for the development and growth of MLCs. The identified regions of maximum baroclinic instability are, in fact, regions of strongest low-level PV gradient by definition (Bretherton, 1966). Consequently, MLCs will tend to propagate and develop along these regions, as they are the most dynamically active zones in the lower troposphere.

Past and future changes in snow cover and mid-latitude cyclones

Given these snow cover links to climate dynamics, the implications of snow cover are far reaching. Frei *et al*. (1999) find a general increase in wintertime snow cover extent during 1930 to 1980 and then a negative trend from 1980 to 1994. However, there is no clear trend in the monthly mean latitude of North American snow cover from 1979 to 2010 (Notaro *et al.,* 2014; Knowles, 2015). The analysis of climate models from the Coupled Model Intercomparison Project Phase Three (CMIP3) by Brown and Mote (2009) show that continued reductions in snow cover extent through the year 2100 is likely, especially in coastal regions. However, where snow cover does remain, there will likely be an increase in the amount of snowfall due to increased precipitation (Brown and Mote, 2009).

Recent observations and models suggest a general decrease in MLC frequency over time and a poleward shift (Wang *et al.,* 2006; Jiang and Perrie, 2007; Long *et al*., 2009), but increases in the frequency of strong MLCs that exhibit a central pressure below 980 mb (Gulev *et al*., 2001). Bengtsson *et al*. (2006) found a poleward shift of storm tracks, but no change in intensity. Results using the National Center for Atmospheric Research (NCAR) Community Climate System Model Version Three (CCSM3) show a decrease in MLC frequency, no significant poleward shift, and changes in intensity confined to the North Pacific (Finnis *et al*., 2007). More recent work with CMIP5 models have found covariance in trends in storm tracks with significant shifts in snow cover extent (Derksen and Brown, 2012; Harvey *et al*., 2012; Palmer, 2014; Zappa *et al*., 2014), although the ability to represent frontal dynamics within coarse global climate models remains questionable (Chang *et al*., 2012; Catto *et al*., 2015).

Objectives

The literature and our preliminary work all strongly suggest links of the snow cover boundary to synoptic dynamics. In a changing climate, as noted above, there is a clear need to better investigate the strength and implications of this mechanism. Our hypothesis is that the combination of radiational cooling and insulation provided by the snow cover not only increases low-level baroclinicity, but also tends to produce a low-level film of very high PV over the snow surface by virtue of the strong inversion that develops there. Under the right conditions, this "film" of high boundary layer PV might get ingested into a developing low-level cyclone, giving it a potent circulation boost that it would not get in the absence of the snow cover. We suspect the development boost may be more easily detectable in small, relative weak cyclones, as the larger synoptic-scale disturbances would be dominated by vertical motion couplets associated with larger scale mid- and upper-tropospheric waves. **The objective of this study is to critically evaluate mechanisms that drive the statistically observed relationship of gradients in snow-related surface forcing to tropospheric baroclinicity and mid-latitude dynamics.** Early studies on this topic have been limited to case studies, while later studies have not focused on our proposed snow extent mechanism. A deeper understanding of these mechanisms would facilitate more effective evaluations and improvements to the representation of climate dynamics and variability within models.

The primary questions proposed here are:

1. How robust are the relationships between snow extent, low-level baroclinicity, potential vorticity, and mid-latitude cyclone trajectorie across the Northern Hemisphere as a function of season and cyclone intensity?
2. What do statistical climate observations and numerically simulated case-studies indicate about mechanisms of this relationship and under what climate state conditions, surface forcing magnitude, boundary layer structure, and cyclone characteristics are these mechanisms most

likely to be dominant for coupling between mid-latitude cyclone eddy growth rate and surface low-level potential vorticity generation?

3. Can we develop observational metrics of the relationship between snow cover extent and MLCs that inform how significant this process is in Earth system models relative to other forcings?

The questions will guide our investigation as we confront observations and models with these hypotheses:

- H1. Daily Northern Hemisphere extent of pre-existing snow cover directly correlates to the mean **trajectory** of subsequent mid-latitude cyclones.
    - Alternate H1a. This relationship only holds for small mid-latitude cyclones, requiring pre-conditioning of the storm track by large mid-latitude cyclones, which first entrain boundary layer air into the free troposphere.
- H2. Snow cover extent anomalies lead to enhanced regions of low-level baroclinicity and potential vorticity, which provide tropospheric forcing for enhancing the **intensity** of mid-latitude synoptic systems
    - Alternate H2a. Snow cover anomalies are limited to mesoscale circulations (snow breeze), which enhance turbulence within mid-latitude cyclones but do not influence mid-troposphere forcing.
    - Alternate H2b. The primary fuel from snow cover is in the form of enhanced latent heat flux provided by enhanced vertical mixing along the cold conveyor belt (low-level cold air flow), irrespective of snow extent location.
    - Alternate H2c. Low-level baroclinicity exists across the mid-latitude storm track, regardless of snow cover.
- H3. Multiple realizations from an ensemble of climate model simulations will confirm the dominance of observed snow cover – mid latitude cyclone relationships, showing a large signal (snow cover influence on mid-latitude disturbance) to noise (alternative forcing) ratio across the ensembles.
    - Alternate H3a. Any snow cover to mid-latitude cyclone relationships are only found in a minority of ensembles, indicting the dominance of other mechanisms on mid-latitude cyclone trajectory and intensity.

To address these questions and hypotheses, we propose a three-year project with 4 co-PIs, one graduate student, and one undergraduate to conduct three major activities that investigate snow cover and MLCs in past and future climates. Our approach couples a long-term retrospective statistical analysis with numerical modeling of case studies and evaluation of climate model output. Briefly, we propose to:

1. **Develop a publically accessible global snow extent and MLC trajectory database, extending existing records with higher spatial resolution and longer time periods.** The satellite era has allowed for global monitoring of snow cover with observations dating back to 1966 (Brown and Armstrong, 2008). Complementary to that is the use of long-term reanalyses data to identify and track individual mid-latitude cyclone trajectories, togethger which make up the storm track region. Furthermore, for statistical identification, related products on the surface energy forcing and extent of the 2 potential vorticity unit (PVU) isertel on the 330K surface will be extracted from these databases.

2. **Extend existing analysis on snow cover extent and mid-latitude cyclones with observations and models**. Our analysis in Rydzik and Desai (2014) focused on North America and statistical links between snow extent and mid-latitude disturbances. Here, we will focus these analyses across central to eastern North America, developing a normalized snow extent-MLC database, and using statistical and simulation techniques to identify mechanisms. Numerical simulations will involve a range of realistic snow

anomalies. We will also further extend our analysis beyond low-level baroclinicity to look for lagged links among external forcing and MLC intensity and position.

3. **Evaluate ensemble climate change scenarios to assess how hypothesized mechanism are represented in climate model simulations.** Finally, we will use the statistical analysis and case studies to develop metrics on the fidelity of snow cover extent to MLC trajectory and use this to evaluate climate of the 20th century experiments from the Community Earth System Model (CESM) Large Ensemble (Kay *et al.*, 2015). These will be used to identify the fidelity (signal to noise ratio) of the observed and simulated mechanisms on disturbance intensity and track and identify potential changes in future cyclone activity with shifts in snow cover.

Detailed Methods

Development of database of snow extent and storm trajectories

Several databases on snow cover and a few databases on storm trajectories exist, but they have not been systematically evaluated, updated to present, nor compared. Also, storm trajectory databases have mostly been coarse resolution, not evaluated with multiple observations, nor extended to recent decades.

Snow cover: Regular measurements of snow cover properties date back to the late 1800s and typically were based on the presence of snow cover or lack of snow cover (Brown and Armstrong, 2008). Station observations in the United States can be reliably traced back to 1900 with some caveats about data quality that make identifying trends difficult (Kunkel *et al*., 2007). Satellite observations were a large improvement over the point measurement interpolation techniques used before one could observe global snow cover directly (Matson and Wiesnet, 1981). Passive microwave observations can be used to overcome limitations of visible sensors by penetrating clouds, operating without sunlight, and estimating snow depth (Brown and Armstrong, 2008). Grody and Basist (1996) uses passive microwave observations to determine snow cover by looking for the ratio of scatter between high and low frequencies and then implementing other criteria to screen out precipitating clouds and frozen soil, both of which produce scatter ratios similar to snow cover.

Harmonized long-term snow cover extent products exist from several sources and are input into several reanalyses (e.g., Modern-Era Retrospective Analysis for Research and Applications (MERRA), Japanese 25-year ReAnalysis (JRA-25), Climate Forecast System Reanalysis (CFS), North American Regional Reanalysis (NARR)). There is also the National Aeronautics and Space Administration (NASA) Making Earth System Data Records for Use in Research Environments (MEaSUREs) Northern Hemisphere Snow and Ice Climate Data Records and derived products at 100 km resolution from 1966-2010 and 25 km from 1999 to present (http://climate.rutgers.edu/measures/snowice/). We will compare these products to our main proposed product, based on the National Operational Hydrologic Remote Sensing (NOHRSC) Center Snow Data Assimilation System (SNODAS). SNODAS is a modeling and data assimilation framework to estimate snow cover and related variables (Barrett, 2003). SNODAS incorporates (1) quality controlled and downscaled numerical weather prediction output, (2) a snow pack model, and (3) a data assimilation scheme. The data assimilation scheme takes observations from satellite, airborne instruments, and surface observations. The dataset has one-hour temporal resolution and one km horizontal grid spacing. These products will be compared and evaluated on trends and variations in snow cover extent and also for case study initialization and directly compared to NASA Moderate Resolution Imaging Spectroradiometer (MODIS) satellite snow cover imagery for reliability and consistency of SNODAS for use in simulations and analyses.

For analysis of MLC distance to snow, we objectively determine maximum snow cover extent by locating the latitude of continuous snow cover, after accounting for discontinuities, such as lakes and mountains (Rydzik and Desai, 2014). Categorical snow cover is linearly interpolated to account for noisy data. In a situation where a storm deposits snow significantly far away from the existing extent, a swatch of non snow-covered ground may appear between the new snow and old snow. For the purpose of this study, we are interested in the southern extent of the snow. Our algorithm searches each longitude bin, from south to north, looking for ten consecutive snow covered points (320 km). The snow extent is then set to the first (most southern) point in the snow covered region. After finding the latitude of snow cover extent at each longitude bin, the line is smoothed by running a ten-point filter forward and backward to prevent phase shifting. We will further test the optimum number of points for estimating southern extent.

Storm trajectories: Numerous subjective and objective MLC identification methods have been developed based on sea-level pressure, upper air pressure, and maximum cyclonic vorticity, but most are over limited domains or apply coarse resolutions, such as the Atlas of Extratropical Storm Tracks (Chandler and Jonas, 1999), which make it difficult to test relationships for distance to snow extent. A comprehensive review on MLC identification, tracking, and frequencies is presented in Ulbrich *et al.* (2009). The most common automated MLC detection methods are minima location detection methods. Most common fields for analysis are mean sea-level pressure (e.g., Lambert, 1988; Murray and Simmonds, 1991; Chandler and Jonas, 1999; Lionello *et al*., 2002; Bauer and Del Genio, 2006) and 1000 hPa geopotential height (e.g., Alpert *et al*., 1990; Konig *et al*., 1993; Blender *et al*., 1997). One issue with the minima methods is that centers are often reported as the grid cell where the minimum is observed, neglecting the fact that coarse grids may not be able to accurately represent the true center of a MLC. Numerous identification methods have been proposed in recent years. Hoskins and Hodges (2002) reviews identification methods ranging from those best suited for small scales (vorticity and potential vorticity), medium scales (meridional wind, temperature, vertical velocity), and large scales (mean sea-level pressure and geopotential height) further evaluated in Hodges *et al.* (2011).

We propose to compare several techniques with several global reanalyses of sea-level pressure and vorticity fields from the previously discussed reanalyses (MERRA, JRA-25, CFS, NARR), to be consistent with their respective snow cover fields. If we maintain our current method (Rydzik and Desai, 2014), MLC trajectories will be identified by finding a local minimum in sea-level pressure and tracking it at subsequent time steps. The sea-level pressure field at each time step was linearly interpolated to two grids with spacing of 0.25° (fine) and 2.5° (coarse). Critical points were found at both grid spacings by taking derivatives in the north-south and east-west orientations and then finding the intersection of the zero derivative contours. Minima, maxima, and saddle points are differentiated by the second derivative in both orientations at the critical points. The minima are then set to be at the closest grid point. The coarse resolution identifications were then refined by changing their location to the nearest fine resolution minimum. Relating the coarse resolution to the fine resolution is done to improve the accuracy of the coarse resolution and to ignore noise (small fluctuations) in the fine resolution.

After identifying MLCs at each time step, it is necessary to link MLCs at subsequent time steps. Most tracking methods follow some variation of the nearest-neighbor approach (e.g., Murray and Simmonds, 1991; Chandler and Jonas, 1999; Lionello *et al*., 2002) that finds the closest MLC center at the next time step. We conducted our tracking in a similar way. At every time step, we attempt to relate all pressure minima to a pressure minimum at the next time step. At subsequent 3 hourly time steps, storms are searched for within a radius of 361 km, equating to a cyclone maximum speed of approximately 120 km hr^{-1}, similar to thresholds used by Blender and Schubert (2000) and Chandler and Jonas (1999). The nearest pressure minimum, within the search radius, is set to be part of the same storm as the previous minimum. To prevent pressure minimum from unrealistically backtracking, future pressure minimum must be located in a region generally to the east of the previous location. If in any six-hour period, a storm has not moved more than 0.25°, then the track is terminated. The tracking creates a North American storm database that contains the latitude, longitude, pressure, date, and time of the storm center at each three-hour time step of the MLC, which we intend to share with the broader community.

Numerical case study simulations

Comparing the runs with altered snow covers will permit analysis of how the trajectory is modified due to the snow cover feedbacks as well as replicate previous findings (Elguindi *et al*., 2005). We will use model output to directly identify to what extent varying snow extent and jet position has any effect on hemispheric coupling of MLCs to snow (Fig. 6). By investigating models with upper waves of varying threshold strength and position, we can see how a given potential vorticity anomaly evolves and diagnose variation in diabatic PV generation.

For the proposed modeling of the North American snow line and its impact on baroclinicity and resulting cyclone intensity and track, we will apply the upcoming version 8 of the Advanced Research Weather Research and Forecasting (WRF) Model (Skamarock and Klemp, 2008; Skamarock *et al*., 2008). WRF is a fully compressible, non-hydrostatic model, which applies terrain-following hydrostatic pressure coordinates in the vertical. It is likely the most commonly used model for dynamical downscaling (Caldwell *et al*., 2009; Salathé *et al*., 2010; Racherla *et al*., 2012; Mearns *et al*., 2012; Gao *et al*., 2012; Vautard *et al*., 2013; Harkey and Holloway, 2013; Spero *et al*., 2016) and has been successfully applied for cold season analyses across North America (Shi *et al*., 2010; Gula and Peltier, 2012; Gutmann *et al*., 2012; Wright *et al*., 2013; Milrad *et al*., 2014).

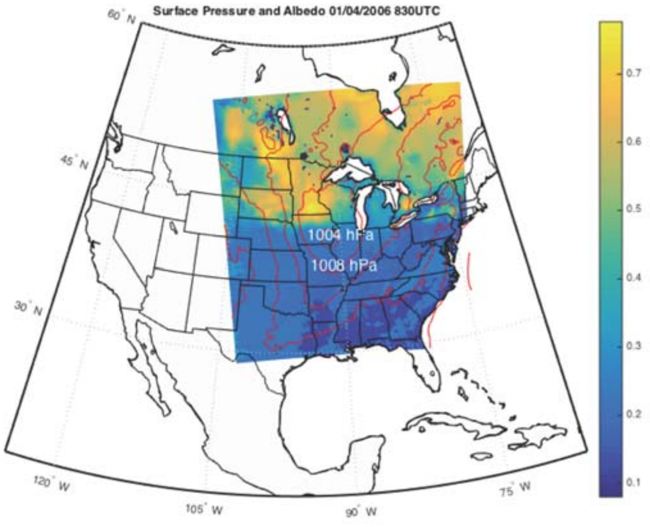

Figure 6. Example 20-km resolution WRF-NOAH output from 7-day run showing domain, fractional snow cover (color) and sea level pressure (contours). Central minimum pressure is close to snow boundary. Experiments would alter this snow cover extent.

Modeling experiments will focus on case studies in which cold season cyclones, along the Colorado storm track (Reitan 1974; Whittaker and Horn 1981; Mercer and Richman 2007), approach the snow line around the Northern Great Plains, namely from eastern Montana to Minnesota, away from complicating factors from the Rocky Mountains and Laurentian Great Lakes, but a prototypical region for many similar locations of the globe where we expect these responses to be most robust. Given that we plan to run experiments with a modified latitudinal position of the snow line near the northern Great Plains, we propose to apply a large domain of 30-65°N, 130-65°W. In doing so, the surrounding buffer zone (where the simulated climate is continually nudged toward the lateral boundary conditions (LBCs)) will be positioned far away from the region of imposed land surface modification (Notaro and Zarrin, 2011), thereby allowing the atmosphere to respond to the snow cover anomalies without being restricted by nudging from the buffer zone. LBCs will be provided to WRF by from NARR (Mesinger *et al*. 2006).

In order to select the optimal model configuration for cold season simulations over North America using WRF, we propose a series of three-year runs (e.g. 2013 to 2015), each applying different selections of land surface models (LSMs) [e.g. National Center for Atmospheric Research (NCAR) Community Land Model (CLM, Oleson *et al*. 2010; Lawrence *et al*. 2010) and Noah land surface model (Sellers *et al*., 1997; Chen and Dudhia, 2001; Ek *et al*., 2003; Barlage *et al*. 2010)], cumulus parameterizations [e.g. modified Kain-Fritsch scheme (Kain, 2004), Tiedtke scheme (Tiedtke, 1989; Zhang *et al*., 2011), and Betts-Miller-Janjic scheme (Janjic, 1994, 2000)], and planetary boundary layer (PBL) schemes [e.g. Mellor-Yamada-Janjic scheme (Mellor and Yamada, 1982; Janjic, 1990, 1996, 2002), Medium Range Forecast Model scheme (Hong and Pan, 1996), and Yonsei University scheme (Hong *et al*., 2006)]. Based on the prior analysis of WRF over the western United States by Jin *et al*. (2010), we expect that the more sophisticated treatment of snow, soil, and hydrology in CLM, compared to the other LSMs coupled to WRF (e.g. Noah land surface model), will result in the best simulation of snow cover (Oleson *et al*., 2010; Lawrence *et al*., 2010). Likewise, we will explore the representation of cyclone track and intensity and the seasonal advance and contraction of the snow line in three-year simulations with differing grid spacing (single domain with hydrostatic 20-km versus nested domain with 20-km in the outer domain and non-hydrostatic 3-km in the inner domain) and differing vertical resolution (e.g. number of levels within the PBL, to capture snow-atmosphere exchanges within the boundary layer). The fidelity of each three-year simulation will be assessed in terms of the spatial and temporal variability of near-surface air temperature, precipitation, sea-level pressure, snow cover, and surface albedo, compared to stations observations from the United States Historical Climate Network, NARR, 500-m MODIS, and 1-km SNODAS. We will apply standard performance metrics, as used in the international coordinated regional climate downscaling experiment (CORDEX, Giorgi *et al*. 2012), namely mean absolute bias, mean bias, and pattern correlation coefficient. All subsequent case study and snow modification simulations will apply the most successful model configuration.

The impact of snow cover anomalies around the northern Great Plains on cold season cyclone intensity and track, along the southwest-to-northeast Colorado storm track, will be examined through 20 case studies. The set of case studies will consist of two weak cyclones and two strong cyclones, as determined based on minimum central pressure or maximum cyclonic vorticity (Sinclair, 1997; Sinclair and Watterson, 1999; Flaounas *et al*., 2014) from NARR, per calendar month from November to March, in order to understand the sensitivity of cyclones of differing intensity to seasonal snow anomalies and associated albedo feedbacks. It is expected that weak cyclones will be more sensitive to land surface conditions (Xiao *et al*., 2016) and the impact will be most pronounced during March, as greater insolation amplifies the snow albedo feedback in spring (Robock, 1983; Hall, 2004; Qu and Hall, 2007). Case studies will be limited to cyclones that pass within 200 km of the snow line across the northern Great Plains and are therefore likely sensitive to a latitudinal shift in the snow line's position.

For each cyclone case study, we will run a control simulation, CTL, beginning at the time of cyclogenesis across the western United States, in which initial snow cover in WRF is obtained from MODIS. Restart files will be saved daily from the CTL simulations. Furthermore, using restart files from each CTL case study, we will perform two experiments, EXP_{north} and EXP_{south}, in which the snow line near the northern Great Plains will be shifted poleward or equatorward by 400 km, respectively, roughly 1-2 days prior to the cyclone reaching the snow line in CTL. If we encounter the situation where we shift the snow line poleward in EXP_{north} but newly falling snow quickly covers the imposed bare ground, we will consider an additional code modification in which all newly fallen precipitation over the region will be restricted to liquid form. In order to investigate the mesoscale-to-synoptic scale impacts of the snow line, we will quantify changes in air temperature, radiation budget (e.g. sensible and latent heat fluxes, shortwave and longwave radiation, and surface albedo), baroclinicity, sea-level pressure, PBL height, vorticity, and vertical motion between CTL and both EXP_{north} and EXP_{south}, with the opposing experiments permitting an exploration of potential non-linear impacts on cyclone intensity and track. We will apply an extratropical cyclone tracking algorithm to all simulations to quantify impacts to each cyclone case study. The vertical fingerprint of anomalies in the latitudinal position of the snow line will be investigated through a comparison of air temperature, specific humidity, and winds by height between CTL and the experiments in order to determine if a statistically significant signal is detected far above the PBL, into the mid-upper troposphere (Walsh and Ross, 1988; Vavrus, 2007).

Time permitting, we will further decompose the contribution of snow cover versus depth anomalies towards modifying propagating cyclones by either imposing very shallow (e.g. 2 cm) versus very deep (e.g. 1 m) snowpacks in EXP_{south}, thereby affecting turbulent fluxes. This is motivated by prior studies that demonstrated the regulation of air temperature by snow depth anomalies (Baker *et al*., 1992; Ellis and Leathers, 1999; Mote, 2008; Alexander and Gong, 2011).

Diagnostic analysis on snow cover extent and mid-latitude cyclones

Hypotheses on upper-air disturbance trajectory and intensity will be tested through diagnostic analysis of both observations and models. Analyses will allow us to establish the strength of this effect, the role of pre-conditioning by larger MLCs, the difference in relationships on high and low baroclinicity days, the impact of the external environment, and development of storm track trajectories. Similar types of analysis with the numerical model output will allow us to more directly test mechanisms by tracking PV anomalies and how those change with differing snow cover anomalies given the same external forcing.

In both reanalysis and models, we will compare MLCs relative to snow cover extent. The distance from the MLC center to the nearest snow cover extent point is calculated using the snow cover and MLC position with one to three day lag to test for the role of pre-existing snow cover on MLCs and avoid snow being deposited by the storm itself. If the MLC center is over snow, then the distance value is set to be negative. If the MLC is not over snow, then the distance is set to be positive. Low-level baroclinicity will be calculated within the study domain using a measure of baroclinicity in the lowest two model or observational pressure levels (Rydzik and Desai, 2014) based on earlier work on numerical analysis of upper-level baroclinicity (Lindzen and Farrell, 1980; Hoskins and Valdes, 1990).

The variable strength of the simulation's upper waves is quantifiable using PV diagnostics. Presumably weaker, smaller-scale waves will have less substantial tropopause-level PV anomalies than stronger, larger-scale waves. Investigation of the influence of low-level, diabatically induced PV on the development of small-scale circulations on the snow cover boundary will be undertaken using the piecewise potential vorticity (PV) inversion technique introduced by Davis and Emanuel (1991) (DE). Analysis of reanalyses and model simulations using the piecewise PV inversion will shed considerable light on the nature of the dynamical interactions between the low-level baroclinicity and the development and propagation of the simulated mid-latitude cyclones.

Effective use of piecewise potential vorticity inversion requires a meaningful partitioning of the atmosphere. The goals of partitioning are 1) to account for nearly all of the perturbation PV, while not inverting any of it more than once, and 2) to select the minimum number of partitions that adequately describe the features in question. One way to accomplish these goals is by grouping together potential vorticity anomalies with a common history (Davis, 1992). We plan to adopt a conventional three-way partitioning involving an upper layer, an interior layer, and a surface layer, separated based upon isobaric and relative humidity criteria as employed in our prior work (e.g. Korner and Martin, 2000; Martin and Marsili, 2002; Posselt and Martin, 2004; Martin and Otkin, 2004; Winters and Martin 2016). This three-way partition provides insight into the roles that the lower troposphere, upper troposphere, and latent heating can have in the near surface development. In our proposed analysis, we will also employ the isentropic PV partition recently introduced by Winters (2015), in which the PV is partitioned by isentropic layer. Isolation of the influence of PV residing in near-surface isentropic layers can thus be precisely measured – a likely important advantage in the proposed analysis.

To test alternate hypotheses of snow breeze circulation and pre-conditioning, we will also extract surface latent heat flux forcing and boundary layer turbulent kinetic energy profiles and compare these across MLCs. MLCs and associated forcing can then be segregated by type, strength, location, season, and jet position to test for mechanisms that drive patterns. We will identify in observations and models "trailer events" (small MLC following a large MLC) that pre-condition the dynamical environment such that smaller MLCs are more likely to follow existing snow cover after the passage of a large MLC.

Climate ensemble model analysis and implications

While observations provide a single realization of cyclone trajectories and intensity, climate model ensembles allow us to test the robustness of this relationship against other potential drivers across a much longer record of varying initial conditions. We will investigate the North American snow cover-cyclone relationship in a state-of-the-art climate model by utilizing simulations from the new CESM Large Ensemble (Kay *et al*. 2015). This collection contains 40 independent realizations of the CESM-Community Atmosphere Model Version Five (CAM5) global climate model (GCM) at 1° resolution and spans both the past and future (1920 to 2100) using historical radiative and the representative concentration pathway 8.5 (RCP8.5) greenhouse forcing. Though the resolution may limit some analyses, the large ensemble allows us to directly evaluate how likely this mechanism of snow cover on MLC dominates over others. Daily output of snow cover will be used to evaluate the simulated relationship between snow pack and MLC trajectories and to determine the relative importance of snow extent versus snow depth. Atmospheric fields of temperature, sea-level pressure, and geopotential heights will be used to calculate near surface baroclinicity and PV and how it relates to snow cover and cyclone growth rates. Importantly, the Large Ensemble will provide a clear signal-to-noise ratio, since we expect that stochastic variability will be superimposed on the actual physical relationship between snow cover and MLCs. We will perform cyclone-snow cover analyses in select 30 year chunks from 1920-2100 as a test of the robustness of the observational and case study findings. Furthermore, the simulation of past and future conditions will reveal how this relationship may change as a function of greenhouse warming.

Broader Impacts

Databases on snow cover and mid-latitude cyclones, training of students in weather-climate links, and engagement of professional scholars, students, and the public on the topic of climate change impacts to mid-latitude storms all have broad impacts that benefit society and scientific progress. Similarly, societal relevance is found in better understanding of how climate change manifests in weather, which could lead to improvements in both weather and climate forecasting and benefit risk management of weather hazards.

Dataset development and dissemination

An outcome of our work is development of a snow cover and MLC database. While some of these databases are already available online, they are often of limited domain or have relatively coarse spatial resolution. We hope to catalyze new research in mid-latitude cyclones, snow cover trends, and linkages by making our databases freely available for use and developing a citable data product and publication.

Student training

The Atmospheric and Oceanic Sciences program at the University of Wisconsin (UW)-Madison is a highly regarded and well-known program for the training of atmospheric scientists. We will focus on global recruiting of underrepresented, highly qualified students for the graduate program whose thesis research will be supported by this project. Additionally, we will support undergraduate summer hourly or thesis students to provide exposure to climate and weather systems research and participate in key project activities with a focus on observational and experimental studies to evaluate modeled relationships, database development, and numerical modeling. We will provide training to allow the graduate student to gain mentoring experience through shared supervision of undergraduate students.

NWS outreach

We intend to complement our scientific conference presentation with more direct outreach to the forecaster community, both locally and nationally. We have budgeted travel to the National Weather Association conference to present results and also will coordinate a visit to the local National Weather Service local forecast office to discuss implications of findings on forecasting.

Undergraduate education

In addition to undergraduate courses in synoptic meteorology (Martin), climate dynamics (Desai), and senior thesis supervision (Desai/Martin), where results from this research would be incorporated, Desai also teaches a course on meteorological instruments with a focus on student-led field experiment development at local research study sites. We currently have eddy covariance, meteorological, radiation, and upper air profiling sensors to test relationships relevant to this proposal. We have budgeted funding here to acquire acoustic snow depth sensors to enhance the course's ability to analyze boundary layer modification by snow cover, which would provide an observational focus to the diagnostic and modeling goals here and be potentially useful to the proposed undergraduate senior thesis projects.

Public outreach

There is general public interest in winter storms, mid-latitude weather dynamics, and climate change. We will continue outreach with the general public through lectures, media interviews, and public workshops and enhance those with results from this project. Co-PI Martin co-hosts a monthly call-in radio show (The Weather Guys) and a weekly newspaper column and will address our findings in those venues.

Management Plan

Personnel

Ankur Desai is professor of Atmospheric and Oceanic Sciences at UW-Madison and an expert on surface-atmosphere interaction, boundary layer dynamics, spatiotemporal data mining, and terrestrial ecosystem forcing of climate system dynamics. He will be responsible for overall project management, co-supervision of the graduate student and undergraduate interns, and training and implementation of database development, statistical analysis, modeling, and related publications. Desai will also oversee online database publication, public and practitioner community outreach, and course material acquisition and implementation for undergraduate courses.

Jon Martin is professor of Atmospheric and Oceanic Sciences at UW-Madison and is a leading expert on winter storms and synoptic dynamics. Martin will co-supervise the graduate student and lead the project's development of PV inversion of observations, numerical models, and climate model benchmarking as well as the PV analyses central to aspects of the experimental plan.

Michael Notaro, senior scientist and associate director of the Center for Climatic Research at UW-Madison, is an expert in dynamical downscaling across North America and the study of cold season processes and surface-atmosphere interactions (Notaro and Zarrin 2011; Notaro *et al*. 2013a,b, 2014, 2015a,b; Vavrus *et al*. 2013). He will lead WRF model experimental design and assist the student on model implementation and analysis.

Steve Vavrus, senior scientist at the Center for Climatic Research at UW-Madison, has extensive experience with global climate model analysis of climate dynamics and large-scale snow-cover/sea-ice and climate teleconnections. He will lead the CESM analysis and assist the student on acquiring CESM output and interpretation of these data.

The **graduate student** will focus her thesis research on interactions of climate systems, land surface forcing, and synoptic dynamics. The student will be jointly advised by Desai and Martin and be recruited to work specifically on this project. The student will also help mentor **undergraduate students** during summer or the academic year to conduct independent research projects relevant to this proposal.

Timeline

We propose a three-year project to implement our methods as follows with PI lead noted in parentheses:

- Recruitment and supervision of graduate student and undergraduate interns (Desai, all years)
- Development and publication of snow extent and mid-latitude cyclone database (Desai, Year 1)
- Analysis of PV isentropic anomalies in observational database and models (Martin, Year 1-2)
- Analysis and publication of snow extent and MLC relationships (Desai, Year 2-3)
- Numerical model set up, case study identification, and model experiments (Notaro, Year 1-3)
- CESM acquisition, harmonization, and analysis (Vavrus, Year 1-3)
- Publications on databases, numerical modeling, and climate model benchmarking (All, Years 2-3)
- Public outreach and classroom material development (Desai and Martin, Year 2-3)

Outcomes

We expect to deliver at least four manuscripts on observational PV analysis, statistical snow cover and MLC analysis, numerical simulation, and climate ensemble model analysis. Furthermore, we will make the snow extent and MLC databases available publicly on the web upon submission of manuscripts. Model benchmarking results and other findings will also be published online. Conference presentations on these topics, public lectures, and reflections on experimental snow experiments in undergraduate field courses will all be documented on the website. We hope through these activities to engage a community of research scholars working at the intersection of climate and weather dynamics and also on boundary layer/snow hydrology to tropospheric forcing.

Results from prior NSF support

DESAI: **CAREER: Contrasting environmental controls on regional CO_2 and CH_4 biogeochemistry - Research and education for placing global change in a regional, local context (NSF DEB**), PI A Desai, 8/1/2009-7/31/2014, $693,862, DEB-0845166, **Intellectual Merit**: We conducted a combined observational and modeling study to produce the first long-term record of tall-tower based regional CH4 and CO2 exchange, investigations of regional environmental controls on them, and impacts on regional atmospheric chemistry and global climate. Twenty-six publications include those on calibration, tall tower methane flux variability, scaling, and global synthesis. **Broader Impacts**: The project produced and continually updates Fluxnet/Ameriflux open-access high-frequency flux data from the tall tower site, which were also contributed to an organized global workshop and manuscript on methane wetland fluxes. Support and training was provided for one research technician, three graduate students, two of whom were female, and 5 REU students, two of whom were female, and two Native American. Public talks, course development, and engagement with local landowners were held. The primary outreach was a three-year field-based education program and summer field course with a local tribal college.

MARTIN: **Studies of the Structure, Evolution and Dynamics of Lower Stratospheric Frontal Zones Associated with Upper-level Jet/Front Systems and their Influence on Tropopause Deformation**, 6/15/2008-5/31/2012, ATM-0806430 and **Investigations of the Structure, Evolution, and Life Cycles of Intraseasonal Fluctuations of the north Pacific Jet Stream,** 8/1/2013-8/31/2016, ATM-1265182 **Intellectual merit:** During the term of these grants we have made a number of significant advances in understanding the structure, evolution and dynamics of upper tropospheric and lower stratospheric jet/front systems as well as the structure, dynamics, and sensible weather consequences that characterize vertical superposition of the polar and subtropical jets, including wok on investigation of the life cycles of lower stratospheric fronts in northwesterly and southwesterly flow, the intensification of the ageostrophic secondary circulation about a superposed jet and its influence on lower tropospheric moisture flux in a high impact flooding event in North Americam analysis of the areal extent of the Northern Hemisphere wintertime cold pool at 850 hPa, and diagnosis of inter-model variability of 20th century Northern Hemisphere jet portrayal in a set of CMIP3 global climate models (GCMs). **Broader Impacts:** The work has thus far resulted in 10 scholarly publications, 5 M.S. theses, and 3 recent Ph.D. dissertations, with 2 more coming in spring 2016.

NOTARO/VAVRUS: **Role of low-level clouds in the accelerated warming of the Great Lakes – A dual observational and regional modeling assessment**, PI S. Kravtsov, 7/15/2012-6/30/2016, $680,937, AGS-1236620, **Intellectual merit:** We are exploring the physical drivers of accelerated warming of the Laurentian Great Lakes during 1982-2012 using observations, remote sensing, and Regional Climate Model Version Four (RegCM4), interactively coupled to a one-dimensional lake model (Zhong *et al*. 2016a). We are also investigating the large spatial heterogeneity in lake temperature trends (Zhong *et al*. 2016b) and have found lake depth and background mean air temperatures are the two primary factors determining the distribution of warming trends. The recent accelerated warming could be attributed to non-linear dynamics rooted in the ice-albedo feedback (Sugiyama *et al*. 2016). Variations in Lake Michigan-Huron water levels are explored and attributed to the Atlantic Multidecadal Oscillation and Pacific North American pattern (Hanrahan *et al*. 2014). **Broader impacts:** Our dynamically downscaled set of climate projections for the Great Lakes Basin has led to collaborative and stakeholder opportunities with the Great Lakes Indian Fish and Wildlife Commission, Long Point Waterfowl, Ducks Unlimited, United States Geological Survey, Michigan Department of Natural Resources, Ontario Climate Consortium, and the Wisconsin Initiative on Climate Change Impacts. Drs. Notaro and Vavrus are actively engaging with the Global Lake Temperature Collaboration, developing a multi-model paper on historic lake warming and mechanisms, and will participate in the Superior Challenge Summit, focused on lake impacts from the current ENSO episode.

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Yasunari, T., A. Kitoh, and T. Tokioka, 1991: Local and remote responses to excessive snow mass over Eurasia appearing in the northern spring and summer climate - A study with the MRI-GCM. *J. Meteor. Soc. Japan,* **69**, 473-487.

Zappa, G., G. Masato, L. Shaffrey, T. Woollings, and K. Hodges, 2014: Linking Northern Hemisphere blocking and storm track biases in the CMIP5 climate models, *Geophys. Res. Lett.,* **41**, 135–139, doi:10.1002/2013GL058480.

Zhang, C., Y. Wang, and K. Hamilton, 2011: Improved representation of boundary layer clouds over the Southeast Pacific in ARW-WRF using a modified Tiedtke cumulus parameterization scheme. *Mon. Wea. Rev.*, **139**, 3489-3513.

Zhang, Y., Li, T., and Wang, B., 2004: Decadal Change of the Spring Snow Depth over the Tibetan Plateau: The Associated Circulation and Influence on the East Asian Summer Monsoon*. *J. Climate*, ***17*****,** 2780–2793. doi:10.1175/1520-0442(2004)017<2780:DCOTSS>2.0.CO;2

Zhong, Y., M. Notaro, S. Vavrus, and M. Foster, 2016a: Physical drivers of recent accelerated warming of Laurentian Great Lakes. *Limnology and Oceanography*, in review.

Zhong, Y., M. Notaro, and S. Vavrus, 2016b: Attributing the heterogeneous warming of the Laurentian Great Lakes to lake depth and background climate zones. *Limnology and Oceanography*, in preparation.

BIOGRAPHICAL SKETCH FOR ANKUR R DESAI

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E-mail: desai@aos.wisc.edu
Website: http://flux.aos.wisc.edu

(A) PROFESSIONAL PREPARATION

Oberlin College (Ohio) B.A., Environmental Studies and Computer Science (double major), 1997
University of Minnesota, M.A., Geography, 2000
Pennsylvania State University, Ph.D., Meteorology, 2006
National Center for Atmospheric Research (Colorado), ASP Postdoctoral Fellow, 2006-2007

(B) APPOINTMENTS

2016-	Professor, Dept. of Atmospheric & Oceanic Sciences, U. Wisconsin
2014	MICMoR Visiting Scientist, KIT IMK-IFU, Garmisch-Partenkirchen, Germany
2011-2016	Associate Professor, Dept. of Atmospheric & Oceanic Sciences, U. Wisconsin
2009-	Faculty affiliate, Limnology and Marine Sciences, College of Engineering
2008-	Faculty affiliate, Center for Climatic Research, Nelson Institute
2007-2011	Assistant Professor, Dept. of Atmospheric & Oceanic Sciences, U. Wisconsin
2006-2007	Postdoctoral Fellow, Advanced Study Program, NCAR
2002-2006	Graduate Research Assistant, Dept. of Meteorology, Pennsylvania State U.
2000-2001	Research Fellow, Dept. of Forest Resources, University of Minnesota
1998-2000	ICGC MacArthur Scholar Fellow, Dept. of Geography, University of Minnesota

(C) PRODUCTS

FIVE RELEVANT PUBLICATIONS AND PRODUCTS (BOLD DEONTES DESAI LAB AUTHORS)

Bagley, J.E., **Desai, A.R.**, Harding, K.J., Snyder, P.K., and Foley, J.A., 2014. Drought and deforestation: Has land cover change influenced recent precipitation extremes in the Amazon? *J. Climate*, 27, 345-361,doi:10.1175/JCLI-D-12-00369.1.

Desai, A.R., 2014. Influence and predictive capacity of climate anomalies on daily to decadal extremes in canopy photosynthesis. *Photosynthesis Research*, 119, 31-47,doi:10.1007/s11120-013-9925-z.

Desai, A.R., Wohlfahrt, G., Zeeman, M.J., Katata, G., Eugster, W., Montagnani, L., Gianelle, D., Mauder, M., and Schmid., H.-P., 2016. Montane ecosystem productivity responds more to global circulation patterns than climatic trends. *Environ. Res. Lett.* 11(2):024013 doi:10.1088/1748-9326/11/2/024013.

Rydzik, M. and **Desai, A.R.**, 2014. Relationship between snow extent and midlatitude disturbance centers. *J. Climate*, 27, 2971–2982, doi:10.1175/JCLI-D-12-00841.1.

Serbin, S.P., Singh, A., **Desai, A.R.**, DuBois, S.G., Jablonski, A.D., Kingdon, C.C., Kruger, E.L., and Townsend, P.A., 2015. Remotely estimating photosynthetic capacity, and its response to temperature, in vegetation canopies using imaging spectroscopy, *Rem. Sens. Environ.*,167, 78-87, doi:10.1016/j.rse.2015.05.024.

FIVE OTHER PUBLICATIONS AND PRODUCTS (BOLD DEONTES DESAI LAB AUTHORS)

Becknell, J.M., **Desai, A.R.**, Dietze, M.C., Schultz, C.A., Starr, G., Duffy, P.A., Franklin, J.F., Pourmokhtarian, A., Hall, J., Stoy, P.C., Binford, M.W., Boring, L.E., and Stuadhammer, C.L., 2015. Assessing interactions among changing climate, management, and disturbance in forests: A macrosystems approach. *Bioscience*, 65:263-274, doi:10.1093/biosci/biu234

Desai, A.R., **Xu, K.**, Tian H., Weishampel, P., **Thom, J.**, Baumann, D., Andrews, A.E., Cook, B.D., King, J.Y., and Kolka, R., 2015. Landscape-level terrestrial methane flux observed from a very tall tower. *Agricultural and Forest Meteorology*, 201, 61-75, doi:10.1016/j.agrformet.2014.10.017.

Dietze, M.C., Serbin, S.P., Davidson, C., **Desai, A.R.**, Feng, X., Kelly, R., Kooper, R., LeBauer , D., Mantooth, J., McHenry , K., and Wang, D., 2014. A quantitative assessment of a terrestrial biosphere model's data needs across North American biomes. *J. Geophys. Res-G*, 119, 286–300, doi:10.1002/2013JG002392.

Petrescu, A.M., Lohila, A., Tuovinen, J.P., Baldocchi, D.D., **Desai, A.R.**, Roulet, N.T., Vesala, T., et al., 2015. The uncertain climate footprint of wetlands under human pressure. *Proc. Natl. Acad. Sci.*, 112, 4594-4599, doi:10.1073/pnas.1416267112.

Whitaker, E., **Reed, D.E.**, **Desai, A.R.**, 2016. Lake ice measurements from soil water content reflectometer sensors. *Limnology and Oceanography: Methods*, in press,doi:10.1002/lom3.10083.

(D) SYNERGISTIC ACTIVITIES

- Journal of Geophysical Research, Biogeosciences, Editor, 2015-, Associate Editor, 2011-2014
- Lead instructor and manager, Forest and Climate Leaders in Menominee and the Environment (For-CLIMATE), NSF-support field-based outreach course for Native American students at tribal college and high school, 2010-2013
- Chair, American Meteorological Society (AMS), Agricultural and Forest Meteorology, Science Technical and Advisory Committee (STAC), 2010-2016
- Chair, National Ecological Observatory Network (NEON, Inc.), Fundamental Instrument Unit Working Group, Flux and Micrometeorology, 2010-
- AMS Clarence Leroy Meisinger and AMS Early Career Achievement Awards, 2016

Biographical Sketch

Jonathan E. Martin
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University of Wisconsin
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Madison, WI 53706-1695
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A. Professional Preparation

BA, Saint Louis University, Applied Mathematics, 1986
BS, Saint Louis University, Meteorology, 1986
PhD, University of Washington, Atmospheric Sciences, 1992
  Thesis topic: Structure, dynamics, and precipitation distribution of wintertime frontal structures east of the Rocky Mountains.

B. Appointments

Professor, Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, 2004-
Chair, Department of Atmospheric and Oceanic Sciences, 2004-2013
Associate Professor, Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, 2000-2004
Assistant Professor, Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, 1994-1999
Research Associate, Department of Atmospheric Sciences, University of Washington, 1992-1994

C. Publications most relevant to this proposal

1. Martin, J. E., 2015: Contraction of the Northern Hemisphere, lower tropospheric, wintertime cold pool over the last 66 years. *J. of Climate*, **28**, 3764-3778.
2. Martin, J. E., 2014: Quasi-geostrophic diagnosis of the influence of vorticity advection on the development of upper level jet-front systems. *Quart. J. Roy. Meteor. Soc.*, **140**, 2658-2671.
3. Winters, A. C., and J. E. Martin, 2014: The role of a polar/subtropical jet superposition in the May 2010 Nashville Flood. *Wea. Forecasting*, **29**, 954-974.
4. Winters, A. C., and J. E. Martin, 2015: Synoptic and mesoscale processes supporting vertical superposition of the polar and subtropical jets in two contrasting cases *Quart. J. Roy. Meteor. Soc.*, **141**, (in press).
5. Wu. L., J. E. Martin, and G. W. Petty, 2011: Piecewise potential vorticity diagnosis of the development of a polar low over the Sea of Japan. *Tellus*, **63A**, 198-211**.**

Other Recent Publications

1. Martin, J. E., S. J. Vavrus, F. Wang, and J. A. Francis, 2016: Sinuosity as a measure of middle tropospheric waviness. *J. Climate*, **29**, (submitted).
2. Karnauskas, K. B., J. P. Donnelly, H. C. Barkley, and J. E. Martin, 2015: Coupling between air travel and climate. *Nature Climate Change*, **5**, doi:10.1038/NCLIMATE2715.

3. Delcambre, S. C., D. J. Lorenz, D. J. Vimont, and J. E. Martin, 2013: Diagnosing Northern Hemisphere jet portrayal in 17 CMIP3 global climate models: Twentieth-century intermodel variability *J. Climate*, **26**, 4910-4929.
4. Jaffe, S. C., J. E. Martin, D. J. Vimont, and D. J. Lorenz, 2011: A synoptic-climatology of episodic, sub-seasonal retractions of the Pacific jet. *J. Climate*, **24**, 2846-2860.
5. Hulme, A. L., and J. E. Martin, 2009a: Synoptic and frontal scale influences on tropical transition events in the Atlantic basin. Part I: A six case survey, *Mon. Wea. Rev.*, **137**, 3605-3625.

D. Synergistic Activities

Martin is a renowned educator having won high-profile teaching awards on the campus (Mark H. Ingraham Distinguished Faculty Award), state (UW-Systemwide Underkofler Excellence in Teaching Award), and national (American Meteorological Society's Edward N. Lorenz Teaching Excellence Award) levels.

He disseminates analyses of partitioned quasi-geostrophic omega, polar and subtropical jet identifications, as well as perturbation pressure depths on isentropic surfaces from daily NCEP model data on a series of well-maintained web sites.

His graduate advisees regularly come from diverse backgrounds. 10 of the 32 students he has advised to completion of an advanced degree have been members of underrepresented minorities in STEM fields testifying to the consistency of his efforts in that regard.

For over 18 years, he has been a regular guest, along with colleague Prof. Steve Ackerman, on a monthly call-in radio show on Wisconsin Public Radio (WHA) – Ask the Weather Guys – in which they field all manner of weather and climate science questions from a broad statewide and national audience. Over the last 8.5 years, this activity has been supported by a weekly newspaper column in the *Wisconsin State Journal* which has focused on communicating weather and climate science, as well as the more general nature of scientific inquiry, to a large audience.

He is the author of a leading textbook in mid-latitude synoptic-dynamics (*Mid-Latitude Atmospheric Dynamics: A First Course*) and plans to add a chapter on tropical/extratropical interactions – educational materials that will be informed by the proposed work. He is currently writing a biography of the famous British meteorologist, Dr. Reginald C. Sutcliffe. In the process he has been called upon to give lectures regarding the history of modern synoptic-dynamic meteorology as well as the importance of government sponsorship of basic scientific research.

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email: mnotaro@wisc.edu

(a) Professional Preparation

Ph.D in Atmospheric Science, State University of New York at Albany	1998-2002
M.S. in Atmospheric Science, State University of New York at Albany	1995-1998
B.S. in Atmospheric Science, State University of New York at Albany	1992-1995

(b) Appointments

2011-2016	Associate Director, Center for Climatic Research, University of Wisconsin-Madison
2014-2016	Senior Scientist, Center for Climatic Research, University of Wisconsin-Madison
2008-2014	Associate Scientist, Center for Climatic Research, University of Wisconsin-Madison
Summer 2010	Interim Director, Center for Climatic Research, University of Wisconsin-Madison
2005-2008	Assistant Scientist, Center for Climatic Research, University of Wisconsin-Madison
2002-2004	Research Associate, Center for Climatic Research, University of Wisconsin-Madison
1995-2002	Research Assistant, Atmospheric Sciences Research Center, State University of New York-Albany
1995, 1997	Teaching Assistant, Dep't of Earth & Atmospheric Sciences, State University of New York-Albany

(c) Products

Five most relevant to the proposed project

Notaro, M., V. Bennington, and B. Lofgren, 2015: Dynamical downscaling-based projections of Great Lakes' water levels. *J. Climate*, **28**, 9721-9745.

Notaro, M., V. Bennington, and S. Vavrus, 2015: Dynamically downscaled projections of lake-effect snow in the Great Lakes Basin. *Journal of Climate* (IF=4.9), **28**, 1661-1684.

Notaro, M., D. Lorenz, C. Hoving, and M. Schummer, 2014: Twenty-first century projections of snowfall and winter severity across central-eastern North America. *Journal of Climate* (IF=4.9), 27, 6526-6550.

Notaro, M., A. Zarrin, S. Vavrus, and V. Bennington, 2013: Simulation of heavy lake-effect snowstorms across the Great Lakes Basin by RegCM4: Synoptic climatology and variability. *Monthly Weather Review* (IF=3.6), 141, 1990-2014.

Notaro, M., and A. Zarrin, 2011: Sensitivity of the North American monsoon to antecedent Rocky Mountain snowpack. *Geophysical Research Letters* (IF=4.5), 38, L17403, doi: 10.1029/2011GL048803.

Five other significant publications

Zhong, Y., M. **Notaro**, and S. J. Vavrus, 2016: Physical drivers of recent accelerated warming of the Laurentian Great Lakes. Limnology and Oceanography, in review.

Vavrus, S., M. **Notaro**, and D. Lorenz, 2015: Interpreting climate model projections of extreme weather events. *Weather and Climate Extremes*, **10**, 10-28.

Vavrus, S., **M. Notaro**, and A. Zarrin, 2013: The role of ice cover in heavy lake-effect snowstorms across the Great Lakes Basin as simulated by RegCM4. *Monthly Weather Review* (IF=3.6), 141, 148-165.

Notaro, M., K. Holman, A. Zarrin, E. Fluck, S. Vavrus, and V. Bennington, 2013: Influence of the Laurentian Great Lakes on regional climate. *Journal of Climate* (IF=4.9), 26, 789-804.

Notaro, M., D. Lorenz, D. Vimont, S. Vavrus, C. Kucharik, and K. Franz, 2010: 21st century Wisconsin snow projections based on an operational snow model driven by statistically downscaled climate data. *International Journal of Climatology* (IF=3.4), DOI: 10.1002/joc.2179.

(d) Synergistic Activities

62 scientific publications, 106 oral presentations, and 38 interviews and media releases.

Granted permanent PI status for academic staff by the University of Wisconsin-Madison Office of the Vice Chancellor for Research and Graduate Education

Advised 1 MS student, 3 PhD students, 4 interns, and 6 postdoctoral researchers.

Member of: (1) Climate Working Group and Working Group Council of the Wisconsin Initiative on Climate Change Impacts, (2) Steering Committee for the Nature Conservancy's Conserving Nature's Stage for the Great Lakes Region, and (3) Advisory Board for the Great Lakes Integrated Sciences and Assessment (GLISA).

International collaborations with King Saud University, University of Western-Australia, Abdus Salam International Centre for Theoretical Physics, and Long Point Waterfowl.

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University of Wisconsin-Madison
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Professional Preparation

University of Wisconsin-Madison	Climatology	Postdoctoral Associate	1997-99
University of Wisconsin-Madison	Atmospheric Science	Ph.D.	1997
University of Wisconsin-Madison	Atmospheric Science	M. S.	1992
Purdue University	Atmospheric Science	B. S.	1989

Appointments

Senior Scientist (Center for Climatic Research)	2009-
Interim Director (Center for Climatic Research)	2008-2009
Associate Scientist (Center for Climatic Research)	2002-2009
Research Associate (Beloit College)	2001-2007
Visiting Assistant Professor (Beloit College)	2004
Assistant Scientist (Center for Climatic Research)	1999-2002
Consultant (Center for Ocean-Land-Atmosphere Studies, COLA)	1999-2000
Postdoctoral Research Associate (Center for Climatic Research)	1997-1999
Graduate Fellow (NASA)	1995-1997
Research Assistant (Southampton Oceanography Centre; Southampton, England)	1993
Graduate Research Assistant (Center for Climatic Research)	1992,1994,1995
Graduate Fellow (National Science Foundation)	1990-1994
Research Associate (Climatic Research Unit, University of East Anglia, England)	1989-1990

Publications

Five Most Related to Proposed Project

Notaro, M., V. Bennington, and **S. Vavrus**, 2014: Dynamically downscaled projections of lake-effect snow in the Great Lakes basin. J. Clim., 28, 1661-1684.

Vavrus, S., 2013: Extreme Arctic cyclones in CMIP5 historical simulations. *Geophys. Res. Lett.*, 40, 6208-6212.

Vavrus, S., M. Notaro, and A. Zarrin, 2013: The role of ice cover in heavy lake-effect snowstorms over the Great Lakes basin as simulated by RegCM4. *Mon. Wea. Rev.*, 141, 148-165.

Notaro, M., D. Lorenz, D. Vimont, **S. Vavrus**, C. Kucharik, and K. Franz, 2010: 21st century Wisconsin snow projections based on an operational snow model driven by statistically downscaled climate data. *Int. J. Climatol.*, doi: 10.1002/joc.2179.

Vavrus, S., 2007: The role of terrestrial snow cover in the climate system. *Clim. Dyn.*, **29**, 73-88.

Five Other Significant Publications

Vavrus, S. J., M. Notaro, and D. J. Lorenz. 2015. Interpreting climate model projections of extreme weather events. *Weather and Climate Extremes*, 10, 10-28.

Vavrus, S. J., and R. Behnke, 2014: A comparison of projected future precipitation in Wisconsin using global and downscaled climate model simulations: Implications for public health. *Int. J. Climatology*, 34, 3106-3124.

Vavrus, S., M. M. Holland, A. Jahn, D. A. Bailey, and B. A. Blazey, 2012: 21st-century Arctic climate change in CCSM4. *J. Climate*, 25, 2696-2710.

Francis, J. A., and **S. J. Vavrus**, 2012: Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophys. Res. Lett.*, 39, L06801, doi:10.1029/2012GL051000.

Vavrus, S., J. E. Walsh, W. L. Chapman, and D. Portis, 2006: The behavior of extreme cold-air outbreaks under greenhouse warming. *Int. J. Climatology*, 26, 1133-1147.

Selected Synergistic Activities

- Science Steering Committee Member SEARCH (Study of Environmental Arctic Change)
- Science Steering Committee Member CESM (Community Earth System Model)
- CLIVAR Working Group Member: Arctic Change and Possible Influence on Mid-latitude Climate and Weather
- Organized AMS 10th Conference on Polar Meteorology and Oceanography (2009)
- Member of Community Earth System Model's Polar and Paleoclimate Working Groups

DESAI LAB FACILITIES

Computation: Computational infrastructure in the Desai lab includes 3 Linux (CentOS) servers with a combined 52 AMD Operton and Intel Xeon 64-bit cores, 112 GB of RAM, 65 TB of storage, and licenses for standard compilers and analysis packages, including MatLab, IDL, PGI Fortran, and Adobe Creative Suite. Lab computers include networked desktop, laptop, and OEM systems. Additional large-scale cluster high performance computation support and data storage is available for little or no charge through the University of Wisconsin Advanced Computing Initiative (ACI) and the SSEC high-performance data center (Zara), the largest single compute installation at UW-Madison.

The University of Wisconsin-Madison Center for Climatic Research maintains a computing facility that includes over 150 TB of network-attached storage, 1 48-processor Linux server, 1 20-processor Linux cluster, 1 16-processor Linux server, 45 Macintosh workstations, 3 Linux workstations, 4 Microsoft Windows workstations, and 15 printers, including a 42-inch poster printer. Software used at the center includes Vis-5D, IDV, GrADS, NCAR Graphics (NCL), Matlab, NCVIEW, NCO, Ferret, Fortran, C, MySql, Apache, PHP, Microsoft Office, and Adobe. Operating systems include Mac OS X, from 10.3 to 10.8; Linux, including Centos, Fedora, and Redhat; and Microsoft Windows, including XP, Vista, and Windows 7. Networked systems are located on a gigabit Ethernet network with high-bandwidth connectivity to external computing resources. The center has access to major computing facilities at the National Center for Atmospheric Research (NCAR), the National Center for Supercomputing Applications (NCSA), and the Department of Energy (DOE) National Energy Research Scientific Computing Center. The center employs one full time computer systems administrator who maintains departmental and PI computers, and is available for consultation regarding computer purchases, software installation and education, and data management and acquisition. The center also provides office spaces and meeting rooms for faculty, scientists, staff, post docs and graduate students.

Lab: The Desai Ecometeorology lab includes support for installation, repair, and calibration of micrometeorological and eddy covariance flux instrumentation with facilities at UW-Madison and at the Kemp Natural Resources Station in Woodruff, WI. Additionally, at UW-Madison, the renovated Desai Lab Greenhouse Gas Calibration Lab includes WMO-traceable calibration standards for CO_2 and CH_4 in dry air and a Picarro, Inc. multi-species gas analyzer (Model G2401) for high-accuracy determination of cylinder, analyzer, and air sample $CO_2/CH_4/H_2O$. UW SSEC also includes machine and electrical shops and technical staff for support of components and calibration or installation of instrumentation

Field: Field resources include four Dept of Energy Ameriflux core site facilities in northern Wisconsin (US-PFa very tall tower, US-WCr mature hardwood forest, US-Los shrub wetland, and US-Syv old-growth forest) and one flux observation facility on Lake Mendota. All sites include tower hardware ranging in height from 10 m to 450 m, CO_2, H_2O and CH_4 open and closed path infrared or laser-based gas analyzers, 3-D sonic anemometers, data loggers, incoming and reflected radiation spectrometers, soil and atmospheric temperature, CO_2, light profile instruments, and associated biometric and physiological observations of soil and plant carbon and water pools and fluxes. All sites serve data in near real-time to UW servers via cellular or DSL internet access and have power via solar, propane generator, or AC installation. Eddy flux measurements are made with combination of LiCor, Inc. LI-6262, LI-7500, LI-7200, LI-7700, and Picarro G-1301f infrared gas analyzers, and ATI Type K and Campbell Scientific, Inc. CSAT-3 sonic anemometers, Campbell Scientific, Inc. CR-10X, 23X, 1000, and 3000 data loggers, and associated hardware.

Data description and format

Storm track trajectory and location results will be processed into ASCII readable files, and use standard conventions from previous storm track databases. Metadata in the form of ASCII readme files will be provided.

Snow extent analyses will be derived from existing snow cover databases and stored in ASCII as a linear transect identifying the most equatorward latitude of snow cover for each longitude bin for each day.

WRF model run case studies will be output as needed for the experiments and provided in NetCDF format. We expect to generate output for model control files, driver files, and output for central and eastern US for several dozen case studies with three-six differing configuration each, expect 10-20 GB of output. These models will be run locally on Desai lab cluster and on the Space Science and Engineering Center (SSEC) Zara compute cluster, with each run take 1 or 2 days of wall clock time. If additional runs are needed that take significant computation time, we will request allocation on the NSF/NCAR supercomputing facility.

Responsibility

The Co-Principal Investigators will be responsible for carrying out the data processing, storage, access, and archiving described in this data management plan. Desai will have overall oversight for ensuring compliance with the data management plan, training students on best practices, hosting the website, and acquiring necessary archival resources.

Designated Archive

Short-term: Storm track, snow extent analyses, and WRF model output will be stored locally at the University of Wisconsin Atmospheric and Oceanic Science servers operated by the Desai lab. These servers are backed up daily by the Center for Climatic Research.

Long-term: Upon publication of results from these analyses, we will submit formatted, human and machine readable data files to Dryad or another atmospheric science based long-term data repository.

Access, Sharing, and Archiving

Upon submission of manuscripts for review, we will make full set of observational analysis and model output available locally on the Desai lab wiki (http://flux.aos.wisc.edu/twiki/bin/view/Main/LabData), including author versions of manuscript, proposal narrative, project reports, and associated documents. Further, access will be made available to the core data sets archived at the repository.

All output will follow our standard lab sharing policy as started clearly on top of the website: “Any data you can access here was collected with public funding and thus belong to the public domain. Thus, all data and code that can be accessed here are available for you to view, download, and use in your own scholarship. You are under no obligation to seek permission. We do kindly ask that you contact us and inform us of your intentions, mostly because we like to hear (and tell our funding agencies) about how our data are being used, keep track of citations, provide advice on analyses or draft manuscripts, and maybe even develop a collaboration, especially if there is strong overlap with our own existing research. In limited cases, there may be a request for more involvement, which could lead to co-authorship - but this is not a requirement for use of our data. Some of the datasets include readme files or wiki pages that include citation and acknowledgment information. We request that you include those in your publications and presentations that use those datasets. Large synthesis datasets from multi-investigator groups or derived datasets based on other people's observations may have separate data policies, which supersede these, except for the data contributed by our group, which remain public domain. If needed, we include those policies in the folders with the data.”