**TempestExtremes: Indicators of change in the characteristics of extreme weather**

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# Contents

# 1 Scientific / Technical / Management

## 1.1 Motivation and Objectives

This research proposal targets **NASA Strategic Research Objectives** (ROSES-2014) "*Climate Indicators and Data Products for Future National Climate Assessments*." This proposal incorporates aspects of both *Climate indicators*, by developing and improving indicators based on characteristics of extreme weather events, and *Assessment capabilities and products*, by supporting the development of a new software pipeline for the analysis of data sets and model output.

**Overview:** The next century will see unprecedented changes to the climate system, which are in turn expected to drive changes to the characteristics of meteorological extremes. These changes will have direct impact on populations throughout the United States; as stated by third National Climate Assessment (NCA), "changes in extreme weather and climate events, such as heat waves and droughts, are the primary way that most people experience climate change." The characteristics of extreme weather are key climate indicators, and addressing observed (lagging) and projected (leading) changes in these quantities will be important across multiple sectors, in multiple regions, and highly useful input to future NCAs. This project tackles the pressing need for a better understanding of changing extremes, including tropical cyclones (TCs), extratropical cyclones (ETCs), atmospheric blocks, atmospheric rivers (ARs), temperature extremes and precipitation extremes.

**Objectives:** The **central objective** of this proposal is the **development of a catalogue of past extremes, their characteristics and trends in these characteristics**. The **secondary objective** of this proposal is to provide a new **assessment capability** in the form of an **automated pipeline for detection and characterization of extreme weather events**. These objectives are expanded as four research tasks:

(T1) Implement expanded functionality for **detection and characterization** of atmospheric blocks, atmospheric rivers, extreme temperature and extreme precipitation events in the extreme weather detection/characterization framework TempestExtremes.

(T2) Assess differences in new and existing detection and characterization algorithms. Using reanalysis and model data, provide a **comprehensive assessment of past changes in the characteristics of these extremes**.

(T3) Using large ensemble simulations from the Climate of the 20th Century (C20C) project, determine how the characteristics of extreme weather events under historical climate simulations differ from hypothetical climate simulations with preindustrial greenhouse gas concentrations.

(T4) Through the NASA Earth Exchange (NEX), provide scientists with the capability for **automatic analysis of datasets** using a suite of detection and characterization algorithms.

### 1.1.1 Central Theme: Discrete Extreme Weather Events

This proposal targets a broad class of regional-scale **extreme weather** events that appear in climate datasets, with a particular emphasis on the North American continent. These events include both “nodal” features with a specific geographic location, such as the sea-level pressure minimum associated with both extratropical and tropical cyclones, and “areal” features, including atmospheric rivers, atmospheric blocks, heat waves and precipitation extremes. All events have both a spatial location (or extent, for areal extremes) and a temporal component, including a distinct start and end time. Extreme weather events include both propagating events (those that change spatial position over time) and stationary events. The **climate indicators** targeted by this proposal are the characteristics of these features, and are itemized in section 1.2.

### 1.1.2 Central Theme: Efficient Mining of Big Data

Over the past century there has been an explosive growth in the number of meteorological observations, more recently augmented by multi-terabyte datasets from climate models and climate analysis. Analysis of this vast reservoir of climate data is a pressing challenge for climate researchers over the next decade [1, 2]. Forthcoming high-resolution global atmospheric simulations at scales of 10km will each require roughly a petabyte of active storage, and post-processing of this data will be an inevitable bottleneck in the process of understanding regional climate change. The need for rapid, high-throughput data analysis tools that have been validated on climate data is now greater than ever. Addressing this need is a major focus of this proposal. Current technologies include an array of competing algorithms for detection and characterization that typically address only a single type of extreme weather, frequently require disparate input data formats and generally only work for data on a specific type of grid [3]. Consequently, the proposed work has the potential to dramatically simplify and streamline the process of detection and characterization of synoptic scale phenomena in large-scale climate datasets, and so will lead to a better understanding of how these features are represented within climate simulations.

### 1.1.3 Impact and Relevance to NASA

According to the Intergovernmental Panel on Climate Change (IPCC), since 1980 annual losses from extreme weather events have ranged from several billion to over 200 billion dollars. Weather-related disasters have also caused a significant loss of human life since the turn of the century, including over 146,000 fatalities in Burma (Myanmar) from Tropical Cyclones Nargis (2008), over 14 million displaced by the Pakistan flooding of 2010 (including 1200-2200 fatalities), and 70,000 deaths from the European heat wave of 2003. Consequently, future extreme weather events will have direct socioeconomic impact that must be investigated as part of any climate assessment.

The assessment of extreme weather characteristics in this proposal will augment existing studies that have only targeted specific types of extreme weather events or have only dealt with singular datasets. This project instead proposes the development of a comprehensive catalogue of past events and their characteristics. Consideration of multiple event types under a single umbrella also allows for analysis and identification of connections between these phenomena. For instance, atmospheric blocking in the Eastern Pacific is responsible for redirecting atmospheric rivers, and can in turn lead to a modification of precipitation patterns.

This project will fill in many of the gaps that exist within the last National Climate Assessment (NCA) associated with extreme weather events, and will improve our confidence in reported trends from existing extreme weather studies. The development of a climate data analysis pipeline for extreme weather will position NASA as a cornerstone agency for the analysis of climate data from national and international sources, and will assist in the analysis and assessment of future climate data products produced from future NASA missions. This project further aims to increase the number of researchers performing assessment-relevant science by training of two graduate student researchers (GSRs). NASA also has an ongoing effort to develop and improve climate datasets. Accordingly, this proposal includes a component addressing verification of MERRA and intercomparison with other global reanalysis datasets using previously unassessed criteria.

## 1.2 Extreme Weather Events, Sectors, Regions, and Indicators

This section provides a brief overview of each of the extreme weather events that will be targeted by this proposal along with affected sectors and regions. The key characteristics (indicators) that will be identified and catalogued for each feature are provided.

**Tropical Cyclones (TCs):** Tropical cyclones (TCs) are severe storms originating in warm, tropical, ocean basins which are characterized by their strong surface winds and low pressure center. Storm sizes can range anywhere from 100 km to 2,000 km in diameter. Landfalling TCs produce intense winds, heavy rain, high waves, and damaging storm surge in coastal locations [4]. They are currently estimated to be responsible for 19,000 fatalities per year and $26 billion/year in damages worldwide [5], making them one of the most devastating natural phenomena.

Key sectors affected by tropical cyclones include human health, energy, urban environments, and transportation, primarily via infrastructural vulnerability. Regions in the United States affected by TCs include the southeast, mid-Atlantic, and northeast, particularly along the coast.

Key characteristics targeted by this proposal include counts, wind intensity, radius of maximum wind, precipitation intensity, total overland precipitation, genesis location, probability of landfall and spatial density of storms. These characteristics will also be analyzed by seasonality and region. Annual characteristics also include date of hurricane season onset and completion.

**Extratropical Cyclones (ETCs):** ETCs are phenomena associated with transient low-pressure systems occurring in the mid-latitudes of both hemispheres, and are sometimes known for producing damaging levels of wind, precipitation, low temperatures, and flooding [6, 7]. In the span of a few hours, ETCs can travel across large areas and develop into massive potentially damaging storms. Intense ETC events, such as the 1993 "Storm of the Century" in the eastern United States and the 1999 Windstorm Lothar in northern France, can cause hundreds of fatalities and impact regional infrastructure. Past studies examining ETCs have argued that winter extratropical storm frequency and intensity has increased since 1950 [8], with a slight shift in storm tracks towards the poles [9, 10], but large uncertainties remain.

Key sectors affected by extratropical cyclones include energy, transportation, urban environments and human health. Infrastructural vulnerabilities to extreme winter snowfall remain persistent, but winter weather can also affect energy demand and human health. In the US, ETCs cause significant weather hazards for the northern west coast, central, and Atlantic coast region.

Key characteristics include wind intensity, radius of maximum wind, precipitation intensity, total overland precipitation, proportion of precipitation as snowfall, and spatial density of storms. Again characteristics will be analyzed by seasonality and region.

**Atmospheric Blocking:** Formally, atmospheric blocking is a meteorological phenomenon defined by an anti-cyclonic quasi-stationary high-pressure system persisting for several days to weeks. Blocking events are well characterized in the literature [11], and their connection with prolonged extreme temperatures, drought conditions and poor air quality is well known. Sustained extreme temperatures, including heat waves and cold spells, which arise from atmospheric blocking have been responsible for significant socioeconomic damage (see, for example, Extreme Heat Events below). As stated by the third NCA, "conclusions about trends in blocking have been found to depend on the method of analysis," suggesting the need for a multi-pronged approach in addressing blocking.

Key sectors affected by atmospheric blocking include water, energy, agriculture and human health. Persistent weather conditions caused by atmospheric blocks can affect precipitation patterns and lead to increases in local and regional air pollution. Within the US, the northwest, southwest and Alaska are strongly affected by blocking over the Pacific. The Great Plains, midwest, northeast and southeast are also affected by omega blocks, which are responsible for a range of extreme weather phenomena such as tornadoes and winter storms.

Key characteristics include intensity (for instance, measured by the strength of the anomaly), lifetime, genesis location and meridional and latitudinal extent.

**Atmospheric Rivers (ARs):** ARs are meteorological phenomena characterized by long, narrow plumes of increased atmospheric moisture stretching between the subtropics and the midlatitudes regions [12]. These features are responsible for 30%-50% of total US west coast precipitation, particularly during winter months, and 30%-40% of total seasonal snow water [13, 14]. ARs are usually between 400 to 600 km wide, and so at global model resolutions of $1^\circ$ they are mostly unresolved, occupying as few as four grid cells in the latitudinal direction. Those ARs with highest moisture content and strongest winds can induce extreme rainfall and flooding. Notable AR events include the 2010 "Snowmageddon" event [15], responsible for record-breaking snowfall in the US northwest and the February 1986 atmospheric river that resulted in 13 fatalities, 50,000 people displaced by flooding and $400 million dollars in damage [16]. ARs are not addressed in the third NCA.

Key sectors affected by atmospheric rivers include water, energy and agriculture, particularly for their role in the water cycle along the US West Coast, but these features are nonetheless relevant throughout the US.

Key characteristics include wind speed, total column integrated water vapor, precipitation intensity and point of landfall.

**Extreme Heat Events (EHEs):** Heat waves have led to tens of thousands of deaths since the turn of the century, including roughly 70,000 casualties from the 2003 European heat wave [17], 220 deaths from the 2006 North American heat wave, over 15,000 casualties from the 2010 Russian heat wave and 760 fatalities from the 2013 British heat wave [18]. The economic cost of these events has been estimated to be in the tens of billions of dollars. Historically, heat waves and droughts are often experienced in tandem, such as the 1980 heat wave and drought over the central US that led to $55 billion in losses (in 2009 dollars) [19].

Various measures of extreme heat have been used in past studies. For heat waves, often a percentile threshold is used like 99% [20], 97.5% ([21]; with other conditions), 95% [22], 90% [23]. Other definitions exist, some with, some without a minimum duration; however, there is no set definition [24, 25]. The WCP and CLIVAR sponsored development of 27 indices by ETCCDI committee (see: `http://etccdi.pacificclimate.org/list_27_indices.shtml`). ETCCDI indices maxima in monthly periods, percentile exceedances, tropical nights (daily minimum temperature >20C). The NCA uses a variety of measures of extremes: Hard thresholds (T>90F, T>95F, T<32F, in various regions), return period values (hottest once in 20 years), and highest percentages (top 5%, hottest 2% of daily max and min temperature). These are all easy to understand measures tailored to the NCA's broad audience, so we propose to track similar quantities.

Key sectors affected by heat extremes include energy, agriculture and human health. Energy infrastructure is particularly susceptible to extreme heat outbreaks, largely due to the increased energy demand from air conditioning. Extreme heat can also devastate crop yields and, in conjunction with high humidity, is a major cause of heat stroke and fatality among children and the elderly, especially in disadvantaged communities. All regions of the US are affected by extreme heat.

Key characteristics include spatial extent, duration of heat events, average daily maximum temperature, temperature-humidity index, and average overnight recovery temperature. These characterizations can then be used to compute return values for certain heat extremes.

**Extreme Precipitation Events (EPEs):** Compared with heat extremes, precipitation extremes are more difficult to isolate: First, the distribution of precipitation is highly skewed since it is single signed and has a very long tail most places. Second, precipitation has finer structure than does temperature (with the exception of mountainous regions, of course). It is common for extreme precipitation to hit one station and miss the adjacent one. This behavior is seen in high resolution models (e.g. GFS precipitation). So it is common practice to examine precipitation extremes over regions, and that will be done here.

Various measures of extreme precipitation events exist. Several types of grouping exist based first on the time interval over which the extreme precipitation occurs: a flash flood from a thunderstorm to a seasonal accumulation. For example, a robust ETCCDI index for climate model simulations

[26] is the maximum 5-day interval precipitation during a month (RX5day); [27] claim that extreme values of this index are a useful indicator for large scale flooding events over Europe. Other ETCCDI indices target 1 day maxima up to annual amounts exceeding 95%. The NCA uses percentiles (top 2% of daily rainfall in a year, heaviest 1% of all daily events each year), return period threshold (the 2-day total that occurs once in a 5 year period).

Key sectors affected by extreme precipitation events include water, energy, transportation and agriculture. All regions of the US are affected by extreme precipitation events.

Key characteristics include spatial extent, total precipitation and maximum sustained precipitation rate. These characterizations can then be used to compute return values for specified precipitation extremes.

### 1.3 Datasets

For the set of extreme weather events targeted by this proposal, accurate detection and characterization requires spatially gridded datasets with at least daily temporal resolution. For features which are governed by the large-scale circulation, 6-hourly or higher temporal resolution is required. Consequently, the key datasets for analysis will include MERRA, CFSR and ERA-Interim global reanalysis products, NARR regional reanalysis, and C20C ensemble simulations. CMIP5 hindcasts covering the period 1979-2008 will be used to determine if observed trends are also present in climate model simulations. For temperature and precipitation extremes, daily output will be used from Daymet and PRISM.

Follow-up efforts targeting leading indicators will also leverage CLIVAR experiments, which include multi-year static climatologies with (a) present-day greenhouse gas concentration and sea-surface temperatures (SSTs), (b) doubled atmospheric CO2 concentration (2xCO2), (c) increased global sea-surface temperatures by 2 degrees (SST+2) or (d) a combination of (b) and (c). Future projections from CMIP5 (and upcoming sixth assessment) will also be used to assess trends in indicators over the coming century.

**MERRA / CFSR / ERA-Interim / C20C:** Reanalysis products represent climate model hindcasts which are tightly constrained to known observational data. More than a dozen global and regional reanalysis products are now available. However, these datasets have the potential to differ significantly depending on the choice of model, model parameters, the number and type of observations and the methodology by which data is assimilated into the model. The focus of this proposal is on MERRA data [28], a NASA reanalysis product that integrates satellite measurements over the period 1979 - present. This dataset provides 3D data products at 6-hourly intervals and 2D products (including surface fluxes, single level meteorology, vertical integrals and land states) at 1-hour intervals. The spatial resolution is $1/2^\circ$ latitude by $2/3^\circ$ longitude ($\sim$ 55 km resolution in the midlatitudes), sufficient for capturing most extreme weather events (although higher resolutions may be desired for TCs and in regions with strong topographic drivers). This proposal will also include MERRA-2 as data becomes available.

This proposal also aims to assess trends in other reanalysis datasets, including NCEP CFSR [29], ERA-Interim [30] and C20C [31]. Differences in TC structure and intensity between various reanalysis products have been highlighted using a manual tracking method [32]. These differences are postulated to arise from factors such as horizontal resolution, use of vortex bogusing and relocation, and the addition of synthetic TC winds. As observed by [33], there are some notable differences in the appearance of ETCs in these datasets, including more intense storms observed in MERRA and large differences in southern hemisphere ETC count. We will also examine trends with high-resolution North American Regional Reanalysis (NARR) data to evaluate resolution sensitivity. The use of multiple datasets is important for identifying and overcoming biases associated with specific atmospheric models that may contaminate the results [34], and hence will lead to a set of more robust scientific conclusions.

**NARR:** The North American Regional Reanalysis (NARR) [35] provides dynamically downscaled data over North America at $\sim 32$ km resolution and 3 hourly intervals from 1979 through present. All major climatological variables are present in NARR, making it an excellent candidate for assessment of regional extremes. Nonetheless, some inaccuracies have been identified in NARR that must be accounted for, including deficiencies in precipitation fields away from the continental US [36].

**CMIP5 Hindcasts:** The fifth Climate Model Intercomparison Project (CMIP5) represents a major international collaboration, having brought together 19 global Earth-system models from various global centers to better understand the effect of changing climate over the next century. Key for the analysis of lagging indicators, the CMIP5 experiments include simulations covering the period 1979-2008 with prescribed SSTs at resolutions ranging from 25km to 200km. These experiments provide alternate historical climatologies that are consistent with observed SSTs, and therefore can be leveraged to provide a larger statistical sample of associated extreme weather events. Results from the multi-model ensemble are now available for scientific analysis.

**Climate of the 20th Century:** As part of the Climate of the 20th Century (C20C) project, over 50 simulations of possible climate scenarios using historical sea-surface temperature (SST) forcings covering the period from 1959 to 2011 have been performed [`http://portal.nersc.gov/c20c/`]. Each of these simulations represents one possible atmosphere that is consistent with known historical greenhouse gas emissions and ocean temperatures. A further ensemble of 50 simulations have been computed using historical data that has been adjusted to remove anthropogenic forcing, including greenhouse gas emissions and warming of SSTs, to mimic the state of the pre-industrial atmosphere. These two ensembles are commonly referred to as "the world that was" and "the world that could have been." The goal of the proposed project is to leverage these datasets to better understand the role that humans have played in affecting extreme weather over the past century.

**Daymet:** Daymet is an extremely high resolution (1 km) gridded dataset with daily outputs covering the period of 1980 through 2013 and including total precipitation, humidity and minimum and maximum temperatures [37, 38, 39]. The dataset is produced using an algorithmic technique that ingests point station measurements in conjunction with a truncated Gaussian weighting filter. Daymet is supported by funding from NASA and available through the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC). This dataset will be used for detection and characterization of temperature and precipitation extremes.

**PRISM:** The Parameter-elevation Regressions on Independent Slopes Model (PRISM) [40] supports a 4km gridded dataset obtained by taking point measurements and applying a weighted regression scheme that accounts for many factors affecting the local climatology. The datasets include total precipitation and minimum, maximum and (derived) mean temperatures. Monthly climatological variables are available for 1895 through 2014. Daily data is available for the period 1981 through present, although the documentation is careful to state that since the observational input changes over time this data is not intended for multi-decadal trends. Higher spatial resolutions (800m) are available for a charge, but will not be used in this proposal. This dataset will be used for detection and characterization of temperature and precipitation extremes.

## 1.4 Methods, Detection and Characterization

A key focus of this proposal is the **investigation and intercomparison of detection criteria for extreme weather events**. The goal of this proposal is the identification the best algorithm(s) for each extreme weather feature. The capability to address such a wide array of extremes hinges on the TempestExtremes software package, a new suite of flexible detection and characterization algorithms developed by the PI for processing large climate datasets. This package uses an algorithmic framework known as "MapReduce" to first detect candidate events at individual times using specified criteria. Stitching is then used to track pointwise and areal detections in time. The result is a catalog of extreme weather events and associated characteristics (here treated as climate indicators) whose generation can be automated and parallelized for multiple datasets.

### 1.4.1 Tropical cyclones and extratropical cyclones

The vast majority of existing TC detection algorithms identify storms on a time-independent basis based on some combination of collocated sea level pressure minimum, low-level vorticity maximum, and upper-level temperature maximum (e.g., [41, 42, 43, 44, 45, 46, 47]). Detected candidates which are close in both space and time are stitched together to form trajectories. Wind speeds are then used to isolate systems considered intense enough to fit the standard definition of TCs. While the minimum sustained surface wind speed for a system to be named by the World Meteorological Organization is 17.5 m/s, this threshold is frequently relaxed when assessing climate data for reasons such as insufficient resolution and different heights where the wind measurement is assessed [45].

Detection algorithms for ETCs have been proposed by [10, 48, 49] and others (see, for example, the review paper by [7]) using a procedure analogous to that of TCs. As shown by [3] as part of the IMILAST project, ETC counts can vary by up to an order of magnitude depending on the choice of detection algorithm, even when assessing a single reanalysis dataset. When controlling for the detection algorithm, significant differences were also observed between reanalysis datasets [10, 49, 50]. These studies motivate the need for a comprehensive approach that considers a suite of detection algorithms and datasets in order to draw conclusions on the character of ETCs.

In TempestExtremes, detection of both ETCs and TCs is handled by first searching for minima in the sea-level pressure field. Thresholds can then be specified on the pointwise Laplacian of pressure, maximum or minimum latitude and topographic height at the point of detection. Additional criteria are also available, including requirement or elimination of candidates based on the presence of a warm core aloft, the presence of a relative vorticity maximum, or the presence of a closed pressure contour. Once candidate storms have been identified, stitching of candidates to form cyclone tracks is performed. The stitching algorithm provides options for maximum distance between candidate points, minimum track duration, minimum distance between begin and endpoint, minimum path length, and other user-specified thresholds on quantities such as windspeed or surface pressure. The stitching algorithm also provides an option for identifying trajectories with detection gaps, for example when candidates are present at times 1,2,3,5,6, and 7. These criteria amalgamate a wide range of detection and stitching algorithms specified in the literature, including those criteria discussed above. A plot of ETC densities for one possible configuration is depicted in Figure 1. This proposal will apply this existing detection and stitching technology to the datasets in section 1.3 so as to isolate historical trends of ETC and TC characteristics, and improve statistical confidence in previously observed trends.

#### 1.4.2 Atmospheric blocks

Various algorithms have been developed in the literature for the identification of blocking events in atmospheric model data [52, 53, 54, 55, 51, 56, 57, 58]. Most of these approaches use either geopotential height, 500mb velocity or potential vorticity as indicators (with a variety of thresholds). However, robust algorithmic detection of atmospheric blocking events has been particularly difficult due to the fact that atmospheric blocking manifests in many different forms [59], such as Rex Blocks, Omega Blocks, etc. Notably, the focus of the majority of past studies has also been on Euro-Atlantic blocking, with only a few studies assessing atmospheric blocking over North America. Consequently, assessing blocking over North America will be a major focus of this proposal.

No prior analysis has examined trends in atmospheric blocking based on tracking and characterizing discrete blocking episodes, and existing work that uses diagnosed dynamical quantities are largely limited to a single dataset. ERA-40 reanalysis was used to document an observed decrease in blocking over Greenland and the North Pacific [60]. Others have claimed that the duration of blocking events and associated heat waves may increase under global warming [61, 62]. However, there are also arguments that the duration of blocks remained roughly constant whereas frequency decreased [58]. Another study compared atmospheric blocking events from 15 atmospheric general circulation models and found that models, at the time, tended to underestimate both blocking frequency and the average duration of blocks [63].

To determine how blocking detection schemes behave for North American blocks, we will apply three blocking detection algorithms to the reanalysis datasets to determine how blocking formulations vary. To demonstrate the detection technology, preliminary global detection and tagging results showing regions of anti-cyclonic column-integrated potential vorticity (PV) anomalies using a detection approach analogous to [51] are shown in Figure 2.

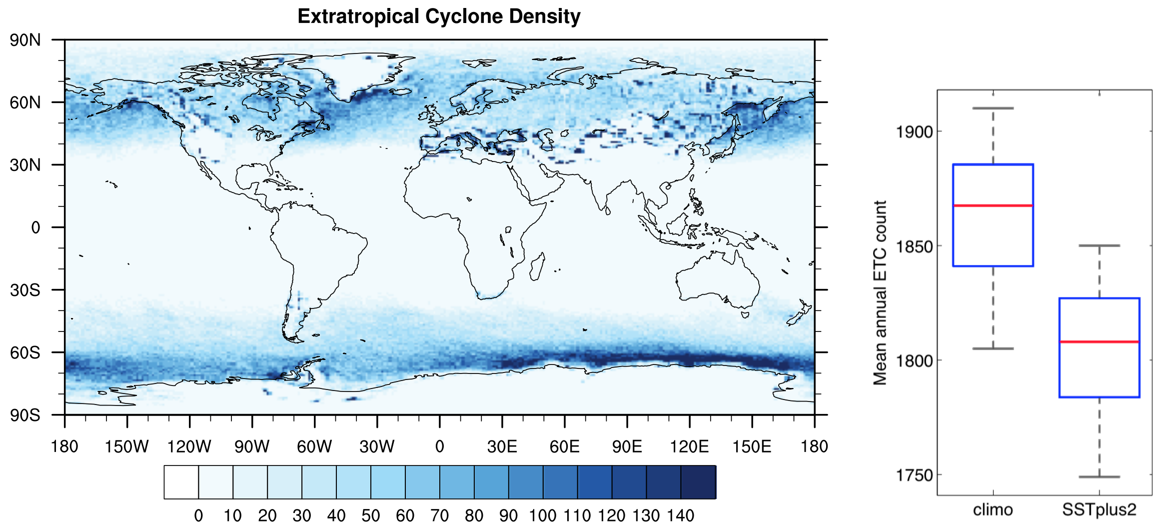


Figure 1: **(Left)** Example ETC counts from a 20-year CLIVAR climatological simulation, as obtained by selecting only pressure minima that (a) do not have an upper level warm core, (b) are within 4 degrees of a vorticity maximum, (c) are present over topography of maximum elevation 1500 m, (d) are persistent for at least 2 days, (e) increase in pressure by at least 0.1 hPa over a distance of 1 degree in all directions, and (f) are in the latitude interval [90S, 20S] or [20N, 90N]. **(Right)** An example of differences between average annual ETC counts from a control simulation (climo) and a simulation with increased sea-surface temperatures (SSTplus2).

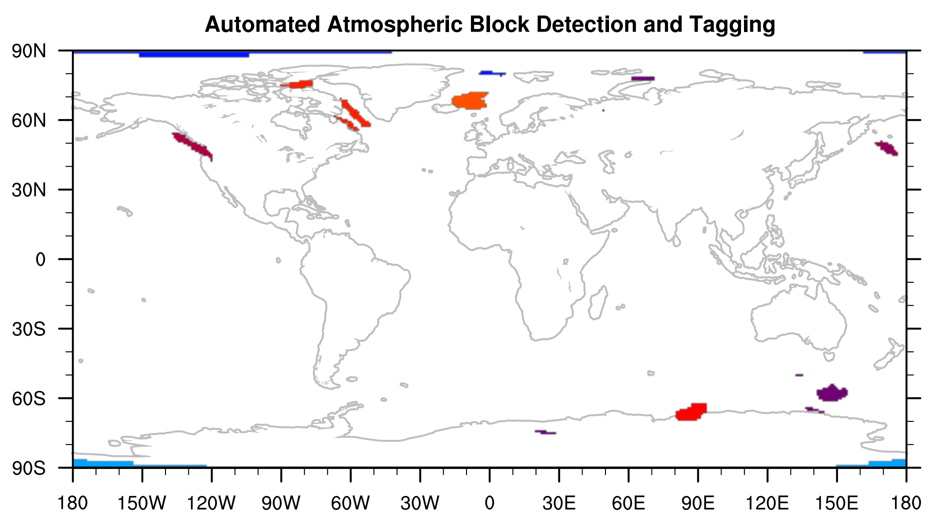


Figure 2: Anti-cyclonic column-integrated potential vorticity (PV) anomalies (against a 15 year monthly averaged background state taken from 1979 to 1993), identifying regions where the column integrated PV is less than $-1.3$ PVU (northern hemisphere) and greater than $+1.3$ PVU (southern hemisphere). This criteria for blocking event detection is described by [51], as applied to the ERA-Interim reanalysis data for 11 June 2005. Discrete blocking events are tagged with a unique identifier based on spatial and temporal connectivity.

### 1.4.3 Atmospheric rivers

Algorithms for detection of ARs generally use their basic properties [12], including (a) an integrated column water vapor of 2 cm, (b) wind speeds greater than 12.5 m/s in the lowest 2 km and (c) a long, narrow shape of length at least 2000 km and width less than 1000 km. This definition is typically augmented algorithmically via image processing techniques such as edge detection, for identifying the structure of the event [64]. Other algorithms include [65, 66, 67, 68, 69]. Notably, detection algorithms have had some difficulty assessing point of landfall, possibly attributed to insufficient model resolution [70].

### 1.4.4 Temperature extremes

People, plants, animals, power demand, and infrastructure are affected by high heat in different ways. For living things severity depends on a combination of high temperature and high humidity. For power demand, road surfaces, and other infrastructure, one may focus upon high temperatures. As our measure of high extreme temperature relevant to many living things we shall use values of the temperature-humidity index (THI). Specific examples include: identifying areas of THI>79F and THI>90F the former is an extreme discomfort threshold, the latter to mortality of some animals and groups of people. Given its use in the last NCA, we shall track T>90F and T>95F occurrences.

Another threshold we shall track is the highest 5% of the THI (THI95x). THI can be calculated from air temperature and any of these three quantities: relative humidity, dew point, or wet-bulb temperature (AMS Glossary). Since overnight recovery is important to people, plants, and animals, tracking the highest 5% of daily minimum temperatures (THI95n) is also included. As our measure of high extreme temperature we shall use the threshold of the highest 5% (T95x). Since overnight recovery is important to people, plants, and animals, tracking the highest 5% of daily minimum temperatures (T95n) is also included. These percentages are with respect to a reference period that will need to be specified. Typically a historical period is used (ETCCDI uses 1961-1990) but this depends on the simulation time period available and will need to be user-specified.

The post-detection analysis will allow comparison between two groups of datasets by including calculation of significance (using a t-test) to highlight areas that are significantly different (between comparison groups) in these parameters. Generally speaking, significance is more likely to be found when the size of the region increases, so this test might only be applied to combinations of NOAA climate divisions where those divisions are small and conterminous and those stitched together to produce a map to see geographical patterns.

This task seeks to implement and analyze several algorithmic approaches for the detection and characterization of heat waves and cold spells. Part of the goal of this work will be to determine if detection indicators of heat waves are correlated with typical indicators for blocking events in the reanalysis datasets. An analogous study was performed [71], which examined summer heat waves over western Europe over the 20th century and showed that many European heat waves are correlated with anomalous high pressure systems over Scandinavia characteristic of an atmospheric blocking event. This proposal aims to expand this study to the global scale using the previously developed framework of multiple reanalysis datasets and detection algorithms.

### 1.4.5 Precipitation extremes

We propose to calculate highest 1-day, 2-day, and 5-day extreme precipitation amounts occurring each year, defined as exceeding the 95% level for the season in which that period occurs. As with the temperature extremes, these percentile-based indices will require specification of a reference period. Alternatively, when a control period is not available for comparison, hard thresholds can be used, so we shall calculate the ETCCDI R10 and R20 indices (counts of days exceeding 10mm and 20mm over the course of a year).

### 1.4.6 Visualization

This proposal aims to produce both tabulated and graphical data representations of the results (event severity, location, and duration). Maps will show changing extreme weather density over North America, along with informational labels identifying changes in characteristics that will affect key regions and sectors and an indication of statistical significance. Maps for the next NCA will focus on climatically-consistent regions, specifically the 344 NOAA climate devisions. Regions that are most affected by changes in extremes (those with "high extreme weather potential") will be emphasized. Box-and-whisker plots will be produced showing changes in characteristics when breaking the sample period into two (for example, 1979-1997 and 1998-2016). Time series of individual characteristics by region will be produced, as appropriate.

## 1.5 Research Tasks

### 1.5.1 (T1) Implementation of new detection and characterization algorithms

This research task focuses on the implementation and evaluation of new detection and characterization algorithms in the TempestExtremes framework, augmenting the existing set of algorithms.

**Atmospheric Blocks:** Two methods for blocking detection have already been implemented in TempestExtremes: specifically, [55], using column integrated potential vorticity, and [54], using a blocking indicator based on Rossby wave overturning. We will augment these algorithms with a simple gradient of geopotential height scheme to detect flow reversal [52].

**Atmospheric Rivers:** This proposal aims to implement the method of [72], which is based off of the AR definition of [73] and incorporates a number of modern features of AR detection algorithms. AR structures will be agglomerated in space using a graph traversal algorithm, and then connected in time by determining overlaps in detections at adjacent time points.

**Heat Extremes and Precipitation Extremes:** This proposal will implement detection of heat and precipitation extremes by detecting exceedance of specified percentile thresholds. Events will be stitched in space and time to quantify discrete episodes.

### 1.5.2 (T2) Assessment of lagging indicators

The climate indicator focus of this proposal will assess past trends in the characteristics of extreme weather events. This will be the first comprehensive study of discrete extreme weather events in reanalysis data, and will lead to a catalogue of events and associated characteristics. Reanalysis products, as described in section 1.3 will be key to assess past changes, including the Modern Era Retrospective-analysis for Research and Applications (MERRA), CFSR, ERA-Interim and North American Regional Reanalysis (NARR) (for all extreme events), Daymet (for temperature and precipitation extremes) and PRISM precipitation data (for precipitation extremes). CMIP5 hindcast simulations will be used to determine if observed trends in the characteristics of extremes also appear in standalone climate model simulations with prescribed SSTs. This project will also require the development of a pre-processing tool that is capable of transforming input climate data into a single standard compatible with TempestExtremes. In addition, the following special topics will be tackled by this work:

**Tropical Cyclones:** Atmospheric reanalysis data (MERRA and CFSR) will be used in conjunction with the International Best Track Archive for Climate Stewardship (IBTrACS) tropical cyclone best track database [74] to assess the performance of commonly-used tracking parameter combinations. Sensitivity tests which perturb the thresholds used to define tropical cyclones in climate data will be completed to assess sensitivity of the storm detection process to the choice of criteria.

**Extratropical Cyclones:** Accurate detection of ETCs over high topography, such as the Rocky Mountains, remains an outstanding question addressed with this work. This issue has been an obvious hurdle in the ETC community [3], but the impacts of winter storm systems on communities throughout North America require accurate knowledge of possible trends in storm tracks.

**Atmospheric Blocks / Heat Waves:** This proposal aims to determine if detection indicators of heat waves are correlated with typical indicators for blocking events in reanalysis. It has been shown that summer heat waves over western Europe during the 20th century are correlated with anomalous high pressure systems over Scandinavia which are characteristic of an atmospheric blocking event [71]. This proposal aims to expand this study to the North America using the previously developed framework of multiple reanalysis datasets and detection algorithms.

### 1.5.3 (T3) Assessing Human-Induced Climate Change (Attribution)

The question of the influence human activity on the frequency and magnitude of extreme weather events of the past decade has remained largely unanswered. To address this question, this proposal will apply the TempestExtremes suite of detection and characterization algorithms to the ensemble of "world that was" and "world that could have been" simulations from the C20C (see section 1.3). By contrasting the character of extreme weather events within these two datasets, anthropogenic influences can be separated from natural variability. The size of the ensemble (55 members) is key in this regard; these ensemble runs enlarge the statistical sample of inherently rare extreme events. These data can be further used to analyze the time series of observation-based historical data and improve estimates of frequency distributions for extreme events with specific characteristics.

The results of this task would also provide enlightenment on specific atmospheric events of the past (other such studies include [75] and [76]). Namely, it would address questions such as "what was the probability of the 1993 Storm of the Century in a world with and without anthropogenic forcing?" Statistically significant differences between the probability in the forced and unforced simulations would drive conclusions on the influence of human activity on the likelihood of these

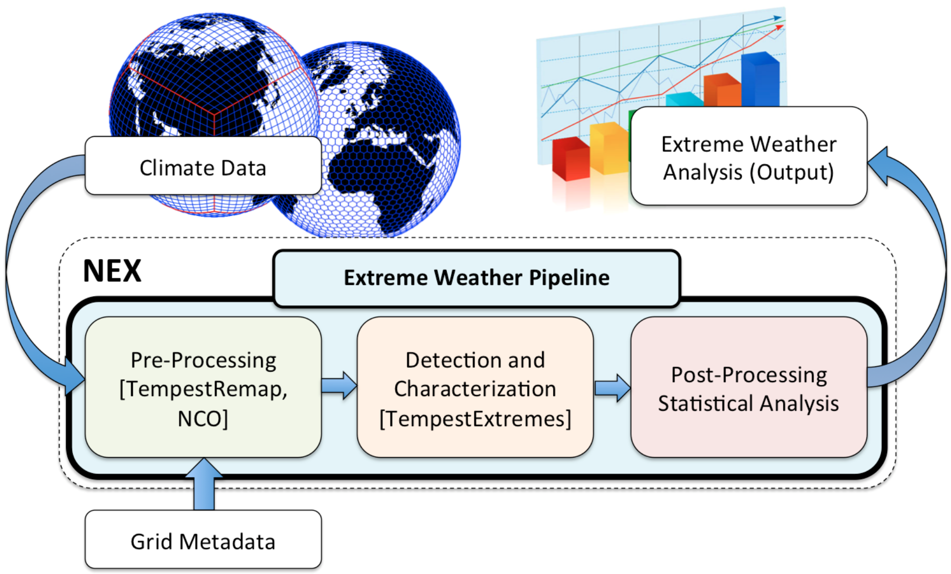


Figure 3: A depiction of the Extreme Weather Pipeline for supporting analysis of climate data through the NEX system.

events. The large ensemble that will be leveraged as part of this project is necessary in order to provide accurate statistics on relatively infrequent events such as these.

#### 1.5.4 (T4) Integration of the Extreme Weather Pipeline in NEX

We propose the integration of the TempestExtremes detection and characterization software into the existing NASA Earth Exchange (NEX) infrastructure, to provide a capability for scientists to quickly obtain information and statistics on extreme weather events from their climate datasets. A depiction of the software data pipeline is given in Figure 3. First, gridded climate data and grid metadata are provided to the pre-processor so as to convert the data to a format compatible with the detection and characterization toolset. This step entails both regridding of the climate data and computation of additional diagnostic variables (for instance, computation of vorticity from wind vectors). When remapping coarse resolution input data to a finer grid, one must be careful to respect features (such as topographically-driven rain shadows and coastal inversions) that will affect interpolated quantities. We will investigate algorithms for improving the quality of these routines (for example, one such algorithm is described in the PRISM documentation). Once pre-processing is complete, the processed input data is then fed into the detection and characterization software (TempestExtremes), where the user may specify the set of extreme weather events to identify and their characteristics (indicators) of interest. Multiple detection algorithms (even for the same extreme weather event) or parameter choices can be specified at this stage. The results of the detection and characterization step is then fed into a statistical post-processor, where the user again has the option of computing statistical quantities of interest.

The software associated with this proposal will be implemented using C++. Execution will be performed on NASA's computing systems via the NEX interface. Software integration with NEX will involve collaboration with Weile Wang and Ramakrishna Nemani, leads on the NEX project.

| | Year 1 | | | | Year 2 | | | | Year 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1st | 2nd | 3rd | 4th | 1st | 2nd | 3rd | 4th | 1st | 2nd | 3rd | 4th |
| (T1) Detection algor. | | | | | | | | | | | | |
| (T2) Indicators | | | | | | | | | | | | |
| (T3) Attribution study | | | | | | | | | | | | |
| (T4) NEX Integration | | | | | | | | | | | | |

Table 1: Expected timeline of (split in quarters for each year) for all major activities.

### 1.6 Management Plan and Timetable of Activities

PI Ullrich will provide leadership for this project and coordinate activities for atmospheric blocks and ARs. Co-PI Grotjahn will coordinate activities for temperature and precipitation extremes and provide advisement on activities for atmospheric blocks. Collaborator Zarzycki will coordinate activities for TCs, and will provide advisement on activities for ETCs. PI Ullrich will also be in charge of coordinating software development and ensuring that this work meets the necessary software engineering guidelines. The graduate student researchers involved in this project will work on assessment and evaluation of detection criteria. Communication between partners will be managed via telecon, one annual meeting at UC Davis between all project members, and once annually at the American Geophysical Union Fall Meeting.

The approximate timeline of the research component of this proposal is as follows (see Table 1): The first year will be dedicated towards the development of new detection and characterization algorithms (section 1.5.1). Characterization and assessment of trends in these indicators is the major focus of this project, and will cover a 2.5 year period (section 1.5.2). This task involves assessments of reanalysis data, gridded data and CMIP5 hindcast data. The attribution study (section 1.5.3) will be carried out beginning in year 2 and will proceed through the beginning of year 3. Finally, NEX integration (section 1.5.4) will be carried over the last half of the project as the codebase converges on a specific suite of algorithms.

### 1.7 Data Sharing Plan

The sum total of the research conducted under this grant application will be linked from the Climate and Global Change Group at UC Davis, available online at `http://climate.ucdavis.edu`. Along with being accessible via the NEX system, the software produced in conjunction with this project will released as part of the Tempest codebase under the Lesser GNU Public License (LGPL). Members of the public will have access to this codebase via GitHub (`https://github.com/paullric/tempestextremes`). Implementation details will be described in the Tempest implementation document, which is freely distributed along with the source code. Catalogued extreme weather data will be available via the NEX system. We also anticipate public data will also be deposited and backed up in Merritt, a repository service from the University of California Curation Center (UC3). Merritt allows access to the public via persistent URLs, provides tools for long-term data management, and permits permanent storage options. Merritt has built-in contingencies for disaster recovery including redundancy and recovery plans.

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# 3 Biographical Sketches

## Biographical Sketch: Dr. Paul Ullrich

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### (a) Professional Preparation

| | | |
|---|---|---|
| University of Waterloo (Canada) | Applied Mathematics and Computer Science | B.Math 2005 |
| University of Waterloo (Canada) | Applied Mathematics | M.Math 2007 |
| University of Michigan (Ann Arbor, USA) | Atmospheric Science and Scientific Computing | Ph.D. 2011 |
| University of Michigan (Ann Arbor, USA) | Atmospheric Science and Scientific Computing | Postdoc 2011-2012 |

### (b) Appointments and Professional Experience

| | |
|---|---|
| 09/12 - Present: | Assistant Professor, Regional and Global Climate Modeling, University of California Davis |
| 05/11 - 08/12: | Postdoctoral Researcher / Adjunct Lecturer, University of Michigan, Ann Arbor, MI |
| 09/04 - 12/04: | Mathematics Developer, Maplesoft Inc., Waterloo, Canada |
| 01/04 - 04/04: | Senior Software Engineer, RapidLabs Microsystems, Waterloo, Canada |
| 01/01 - 08/02: | Software Engineer, Sonic Foundry Canada, Waterloo, Canada |

### (c) Products

- **Ullrich, P.A.** (2014) “A global finite-element shallow-water model supporting continuous and discontinuous elements.” Geosci. Model Dev. Discuss., Vol. 7, 5141–5182, doi: 10.5194/gmdd-7-5141-2014.

- **Ullrich, P.A.** (2014) “Understanding the treatment of waves in atmospheric models, Part I: The shortest resolved waves of the 1D linearized shallow water equations.” Quart. J. Roy. Meteor. Soc., Vol. 140, 1426–1440, doi: 10.1002/qj.2226.

- **Ullrich, P.A.** and M.R. Norman (2014) “The Flux-Form Semi-Lagrangian Spectral Element (FF-SLSE) method for tracer transport.” Quart. J. Roy. Meteor. Soc., Vol. 140, 1069–1085, doi: 10.1002/qj.2184

- **Ullrich, P.A.**, T. Melvin, C. Jablonowski and A. Staniforth (2014) “A proposed baroclinic wave test case for deep- and shallow-atmosphere dynamical cores.” Quart. J. Royal Meteor. Soc., Vol. 140, 1590–1602, doi: 10.1002/qj.2241.

- **Ullrich, P.A.**, P.H. Lauritzen and C. Jablonowski (2013) “Some considerations for high-order ‘incremental remap’-based transport schemes: edges, reconstructions and area integration.” Int. J. Numer. Meth. Fluids., Vol. 71, 1131–1151, doi: 10.1002/fld.3703.

- **Ullrich, P.A.** and C. Jablonowski (2012) “MCore: A non-hydrostatic atmospheric dynamical core utilizing high-order finite-volume methods.” J. Comput. Phys., Vol. 231, 5078–5108, doi: 10.1016/j.jcp.2012.04.024.

- **Ullrich, P.A.** and C. Jablonowski (2012) "Operator-Split Runge-Kutta-Rosenbrock Methods for Nonhydrostatic Atmospheric Models." Mon. Wea. Rev., Vol. 140, 1257–1284, doi: 10.1175/MWR-D-10-05073.1.
- **Ullrich, P.A.** and C. Jablonowski (2011) "An analysis of finite-volume methods for smooth problems on refined grids." J. Comput. Phys., Vol. 230, 706–725, doi: 10.1016/j.jcp.2010.10.014.
- Lauritzen, P.H., **P.A. Ullrich** and R.D. Nair (2011) "Atmospheric transport schemes: Desirable properties and a semi-Lagrangian view on finite-volume discretizations." In Numerical Techniques for Global Atmospheric Models, Springer-Verlag: Heidelberg, pp. 185–250.
- **Ullrich, P.A.**, C. Jablonowski and B. van Leer (2010) "High-order finite-volume models for the shallow-water equations on the sphere." J. Comput. Phys., Vol. 229, 6104–6134, doi: 10.1016/j.jcp.2010.04.044.

## (d) Synergistic Activities

- Associate Editor of the AMS journal Monthly Weather Review (MWR). Reviewer for Journal of Computational Physics (JCP), Communications in Computational Physics (CiCP), SIAM Journal on Scientific Computing (SISC), Quarterly Journal of the Royal Meteorological Society (QJRMS), Journal of Advances in Modeling Earth Systems (JAMES), International Journal of Numerical Methods in Fluids (IJNMF) and Geoscientific Model Development (GMD).
- Lead co-organizer of the Dynamical Core Model Intercomparison Project (DCMIP). Also lead co-organizer and invited lecturer of the DCMIP 2012 summer school held at NCAR. Lead designer of the DCMIP 2012 test case suite for dynamical core inter comparison.
- Co-organizer of the Partial Differential Equations (PDEs) on the Sphere conference (2014, Boulder, CO). Co-organizer of "Traversing New Terrain in Meteorological Modeling, Air Quality and Dispersion" (2013, Davis, CA). Session organizer at 2012-2014 AGU Fall Meeting and 2013-2015 SIAM Computer Science and Engineering (CS&E) conference.
- Lead developer of the Tempest finite-element Earth-system modeling framework. Co-developer of the Chombo/MCore finite-volume dynamical core (at Lawrence Berkeley National Lab).
- Developer of comprehensive course notes for mixed undergraduate / graduate courses "Introduction to Scientific Computing" and "Numerical Methods for Partial Differential Equations."

## (e) Collaborators and Other Affiliations

Christiane Jablonowski (University of Michigan, Graduate Advisor, Postdoctoral Sponsor)

Phillip Colella (LBNL)
Hans Johansen (LBNL)
Smadar Karni (University of Michigan)
James Kent (University of Michigan)
Peter Lauritzen (NCAR)
Peter McCorquodale (LBNL)
Thomas Melvin (UK Met Office)
Ram D. Nair (NCAR)
Matthew Norman (Oak Ridge National Lab)
Kevin Reed (American Geophysical Union)
Andrew Staniforth (UK Met Office)
Mark Taylor (Sandia National Laboratories)
Bram van Leer (University of Michigan)
Michael Wehner (LBNL)

# Biographical Sketch: Richard Grotjahn

Professor (upper level) of Atmospheric Science and Climate Dynamics, UC Davis.
Department of L.A.W.R, University of California (530) 752-2246; fax: 752-155
One Shields Avenue : e-mail grotjahn @ucdavis.edu
Davis, CA 95616 website: http://grotjahn.ucdavis.edu//

**Education:**

University of Washington, Seattle, Washington: Atmospheric Science (B.S. cum laude, 1973)
Florida State University, Tallahassee, Florida: Meteorology (M.S. 1975; Ph.D. 1979)

**Prior Work Experience (only listed since 2010):**

Professor, UCDavis 7/92-6/12, Upper Level Professor, 7/12-present
Visiting Scientist, LASG (Beijing, China) 5/10-6/10

**Recent refereed publications** relevant to proposal

**Grotjahn, R**., and G. Faure. 2008: Composite Predictor Maps of Extraordinary Weather Events in the Sacramento California Region. *Wea. and Forecasting*. **23**: 313-335. doi:10.1175/2007WAF2006055.1

**Grotjahn, R**., 2011. Identifying extreme hottest days from large scale upper air data: a pilot scheme to find California Central Valley summertime maximum surface temperatures *Climate Dyn*., 37:587–604 DOI 10.1007/s00382-011-0999-z

**Grotjahn, R**., 2013. Ability of CCSM4 to simulate California extreme heat conditions from evaluating simulations of the associated large scale upper air pattern *Climate Dyn.* **41**, 1187-1197. DOI: 10.1007/s00382-013-1668-1

**Grotjahn, R**, 2014. Western North American extreme heat, associated large scale synoptic-dynamics, and performance by a climate model. In: *Dynamics and Predictability of Global and Regional High-Impact Weather and Climate Events*, Cambridge Univ. Press. (Li, Swinbank, **Grotjahn**, and Volkert, editors)

**Grotjahn, R**. 2008: Different Data, Different General Circulations? A Comparison of Selected Fields in NCEP/DOE AMIP-II and ECMWF ERA-40 Reanalyses. *Dyn. Atmos. and Oceans* **44**:108-142. doi:10.1016/j.dynatmoce.2007.08.001

**Synergistic Activities (partial list)**

**1**. Lead author for Chapter 6: Agriculture of The National Climate Assessment (2013)
**2**. Member of US CLIVAR Predictability, Predictions, and Applications Interface (2010-2012)
**3**. US CLIVAR Working Group on Extremes (Chair, 2011-prsent)
**4**. International Commission on Dynamic Meteorology, IAMAS (member 2005-present, Secretary: 2011-2015, President-elect)
**5**. Books: *Global Atmospheric Circulations* (1993, Oxford Univ. Press), also Ref 4 above.
**6**. On editorial Board and editor of 2 special editions *Dynamics of Atmospheres and Oceans*.

Biographical Sketch
**Dr. Colin M. Zarzycki**

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Advanced Study Program (ASP), Climate and Global Dynamics Division (CGD)
National Center for Atmospheric Research (NCAR), E-mail: zarzycki@ucar.edu, Phone: (303) 497-1381

## Education

Cornell University, Ithaca, NY; Earth and Atmospheric Science; B.S., 2008
University of Illinois, Urbana, IL; Civil and Environmental Engineering; M.S., 2010
University of Michigan, Ann Arbor, MI; Atmospheric, Oceanic, and Space Sciences; Ph.D., 2014

## Appointments

2014–present: **Advanced Study Program (ASP) Postdoctoral Fellow**, National Center for Atmospheric Research, Boulder, CO

2014: **Postdoctoral Researcher**, University of Michigan, Ann Arbor, MI

## Recent publications

1. **Colin M. Zarzycki**, Christiane Jablonowski, Diana R. Thatcher, Mark A. Taylor (2015), "Effects of localized grid refinement on general circulation and climatology in the Community Atmosphere Model." *J. Clim*, in press.
2. Kevin J.E. Walsh, [...], **Colin M. Zarzycki**, *et al.*, (2014), "Hurricanes and climate: the U.S. CLIVAR working group on hurricanes." *B. Am. Meteorol. Soc.*, in press. doi:10.1175/BAMS-D-13-00242.1.
3. **Colin M. Zarzycki**, Christiane Jablonowski (2014), "A multidecadal simulation of Atlantic tropical cyclones using a variable-resolution global atmospheric general circulation model." *J. Adv. Model. Earth Syst.*, **6**(3), 805–828, doi:10.1002/2014MS000352.
4. **Colin M. Zarzycki**, Michael N. Levy, Christiane Jablonowski, Mark A. Taylor, James Overfelt, Paul A. Ullrich (2014), "Aquaplanet experiments using CAM's variable-resolution dynamical core." *J. Clim.*, **27**(14), 5481–5503, doi:10.1175/JCLI-D-14-00004.1.
5. **Colin M. Zarzycki**, Christiane Jablonowski, Mark A. Taylor (2014), "Using variable-resolution meshes to model tropical cyclones in the Community Atmosphere Model." *Mon. Wea. Rev.*, **142**(3), 1221–1239, doi:10.1175/MWR-D-13-00179.1.
6. Tami C. Bond, **Colin Zarzycki**, Mark G. Flanner, Dorothy M. Koch (2011), "Quantifying immediate radiative forcing by black carbon and organic matter with the Specific Forcing Pulse", *Atmos. Chem. Phys.*, **11**, 1505–1525, doi:10.5194/acp-11-1505-2011.
7. **Colin M. Zarzycki**, Tami C. Bond (2010), "How much can the vertical distribution of black carbon affect its global direct radiative forcing?", *Geophys. Res. Lett.*, **37**, L20807, doi:10.1029/2010GL044555.

## Synergistic Activities

Co-convener and chair of sessions at both American and European Geophysical Union Annual Meetings; Reviewer for Journal of Climate, Journal of Geophysical Research-Atmospheres, Journal of Advances in Modeling the Earth System, Science of the Total Environment, Michigan Journal of Sustainability; Member of the NCAR Thompson Lecture Series Committee.

# 4 Current and Pending Support

## 4.1 PI Ullrich

### 4.1.1 Current

| | |
|---|---|
| Title: | Identifying the Influence of Anthropogenic Forcing on Extreme Weather Events |
| PI: | P. Ullrich |
| Agency: | Hellman Foundation |
| PI months/year: | 1.0 |
| Dollar value: | $30,000 |
| Period: | 1 August 2014 – 31 July 2015 |

| | |
|---|---|
| Title: | Multiscale Methods for Accurate, Efficient, and Scale-Aware Models of the Earth System (Supplement) |
| PI: | W. Collins |
| Agency: | Department of Energy |
| PI months/year: | 1.0 |
| Dollar value: | $80,000 |
| Period: | 1 August 2014 – 31 July 2015 |

### 4.1.2 Pending

| | |
|---|---|
| Title: | Application sector-based climate indicators, from the past into the future |
| PI: | R. Grotjahn |
| Agency: | NASA |
| PI months/year: | 1.0 |
| Dollar value: | $575,022 |
| Period: | 1 September 2015 – 31 August 2018 |

| | |
|---|---|
| Title: | A New Approach for the Computational Needs of Next-Generation High-Resolution Climate Simulations |
| PI: | P. Ullrich |
| Agency: | National Science Foundation |
| PI months/year: | 1.0 |
| Dollar value: | $481,735 |
| Period: | 1 July 2015 – 30 June 2018 |

| | |
|---|---|
| Title: | Diagnosing and Advancing Scale-Aware Convection Parameterizations for Unified Multi- Scale GCMs |
| PI: | C. Jablonowski |
| Agency: | Department of Energy Office of Science |
| PI months/year: | 1.0 |
| Dollar value: | $343,476 |
| Period: | 1 March 2015 – 29 February 2018 |

| | |
|---|---|
| Title: | Advancing the Frontiers of Variable and High-Resolution GCMs for Regional Climate Assessments and Extreme Events |
| PI: | C. Jablonowski |
| Agency: | Department of Energy Office of Science |
| PI months/year: | 1.0 |
| Dollar value: | $366,738 |
| Period: | 1 September 2014 – 31 August 2017 |

| | |
|---|---|
| Title: | Understanding Human Influence on Atmospheric Blocking and Extratropical Cyclones |
| PI: | P. Ullrich |
| Agency: | Department of Energy Office of Science |
| PI months/year: | 1.0 |
| Dollar value: | $457,950 |
| Period: | 1 October 2014 – 30 September 2017 |

## 4.2 Co-PI Grotjahn

### 4.2.1 Current

| | |
|---|---|
| Title: | Large scale dynamics and statistics of California extreme weather in the atmosphere and in global models |
| PI: | R. Grotjahn |
| Agency: | National Science Foundation |
| Grant number: | 1236681 |
| PI months/year: | 1.5 (0.5 to be paid) |
| Dollar value: | $603,843 |
| Period: | 1 October 2012  30 September 2015 |

### 4.2.2 Pending

| | |
|---|---|
| Title: | Synoptic-Dynamics Processes-based Metrics for Hot and Cold Spells Simulations in Climate Models |
| PI: | R. Grotjahn |
| Agency: | NOAA |
| PI months/year: | 1.5 (0.5/year on average to be paid) |
| Dollar value: | $442,553 |
| Period: | 1 May 2015  30 April 2018 |

| | |
|---|---|
| Title: | Application sector-based climate indicators, from the past into the future |
| PI: | R. Grotjahn |
| Agency: | NASA |
| PI months/year: | 1.5 (0.5 in years 1 and 3, 1.5 in year 2) |
| Dollar value: | $575,022 |
| Period: | 1 September 2015  31 August 2018 |

# 5 Letters of Collaboration

UNIVERSITY OF CALIFORNIA, DAVIS

BERKELEY • DAVIS • IRVINE • LOS ANGELES • MERCED • RIVERSIDE • SAN DIEGO • SAN FRANCISCO • SANTA BARBARA • SANTA CRUZ

PROF. RICHARD GROTJAHN
DEPARTMENT OF LAND, AIR AND WATER RESOURCES
231 HOAGLAND HALL

ONE SHIELDS AVENUE
DAVIS, CALIFORNIA 95616-8627

PHONE: (530) 752-2246
FAX: (530) 752-1793
EMAIL: grotjahn@ucdavis.edu
WEB: http://grotjahn.ucdavis.edu

14 January 2015

To whom it may concern:

I acknowledge that I am identified by name as Co-Principal Investigator to the investigation entitled "TempestExtremes: Indicators of change in the characteristics of extreme weather", that is submitted by Dr. Paul Ullrich to the NASA Research Announcement NNH14ZDA001N-INCA, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. I have read the entire proposal, including the management plan and budget, and I agree that the proposal correctly describes my commitment to the proposed investigation. For the purposes of conducting work for this investigation, my participating organization is the University of California, Davis.

Sincerely,

Dr. Richard Grotjahn
Professor (upper level) of Climate Dynamics
University of California, Davis

February 5, 2015

Colin Zarzycki
Advanced Study Program Postdoctoral Fellow
National Center for Atmospheric Research
P.O. Box 3000
Boulder, CO 80307

I acknowledge that I am identified by name as Collaborator to the investigation entitled "TempestExtremes: Indicators of change in the characteristics of extreme weather," that is submitted by Dr. Paul Ullrich to the NASA Research Announcement NNH14ZDA001N-INCA, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. I have read the entire proposal, including the management plan and budget, and I agree that the proposal correctly describes my commitment to the proposed investigation. For the purposes of conducting work for this investigation, my participating organization is the National Center for Atmospheric Research.

Sincerely,

Colin Zarzycki

National Aeronautics and
Space Administration

**Ames Research Center**
Moffett Field, CA 94035-1000

February 02, 2015

Dear Dr. Ullrich,

We acknowledge that the NASA Earth Exchange (NEX) facility is identified as an enabling tool in supporting the investigation, entitled "TempestExtremes: Indicators of change in the characteristics of extreme weather" that is being submitted by Dr. Paul Ullrich to the NASA ROSES-14 Announcement NNH14ZDA001N-INCA (A.29: Climate Indicators and Data Products for Future National Climate Assessments), and that we (the NEX team) intend to carry out all responsibilities identified for us in this proposal. We understand that the extent and justification of our participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. We have read the entire proposal, including the management plan and budget, and we agree that the proposal correctly describes our commitment to the proposed investigation.

Sincerely,

Ramakrishna Nemani
NEX, Principle Investigator
NASA Ames Research Center
Moffett Field, CA 94035
Phone: (650) 604-5574
Fax: (650) 604-4680

Weile Wang
NEX, Research Scientist
CSUMB&NASA Ames Research Center
Moffett Field, CA 94035
Phone: (650) 604-3916
Fax: (650) 604-4680

# 6 Budget Justification

## 6.1 Award Instrument

It is expected that this award will be in the form of a Grant.

## 6.2 Personnel ($235,583)

Salaries are based on Fiscal Year 2014/2015 levels and assume a 3% increase in each subsequent fiscal year.

## 6.3 Salaries ($224,812)

### 6.3.1 Principal Investigator (Dr. Paul Ullrich) $25,333

PI Dr. Paul Ullrich will be direct charging the project 1 month (8.33% of his annual effort) of salary in project years 1, 2 and 3. Anticipating a forthcoming merit increase, this amounts to salary costs of $8,196 in year 1, $8,442 in year 2 and $8,695 in year 3 or 1/11 of his annual salary each year based on 11/12 appointment. .

### 6.3.2 Co-Principal Investigator (Dr. Richard Grotjahn) $22,093

co-PI Dr. Richard Grotjahn will be direct charging the project a ? month of salary (4.17% of his annual effort) in project years 1, 2 and 3. This amounts to salary costs of $7,148 in year 1, $7,362 in year 2 and $7,583 in year 3 (Monthly salary is based on 1/11 of his annual salary each year based on 11/12 appointment).

### 6.3.3 Graduate Student Researcher IV (TBN x2) $177,386; $88,693 each

Two graduate student researchers (GSR IVs; 9 months at 48%, 3 summer months at 100%) will be funded for the duration of this project, conducted as part of their degree with a thesis option. The current annual salary rate for a GSR IV is $45,300. Based on 9 months at 48% and 3 months at 100% this amounts to a total of $57,390 ($28,695 each) in project year 1, $59,112 ($29,556 each) in year 2 and $60,884 ($30,442 each) in year 3.

## 6.4 Benefits ($10,771)

Employee Benefits are based on Federally Approved Composite Benefit Rates. The University of Californias current Composite Benefit Rates have been federally reviewed and approved through June 30, 2015. Rates for Fiscal Years 2015/2016 and 2016/2017 are projected while the rates for Fiscal Year 2017/2018 and beyond are estimates using a 3% increase over the preceding years rates as the basis of the estimate.

### 6.4.1 Principal Investigator (Dr. Ullrich): $4,522

As the direct charging of salary for Dr. Ullrich is during the summer of each project year, the projected composite benefit rates are 17% and 18% for project years 1 and 2 respectively and an estimated rate of 18.5% in year 3.

### 6.4.2 Co-Principal Investigator (Dr. Richard Grotjahn): $3,943

As the direct charging of salary for Dr. Grotjahn is during the summer of each project year, the projected composite benefit rates are 17% and 18% for project years 1 and 2 respectively and an estimated rate of 18.5% in year 3.

### 6.4.3 Graduate Student Researcher IV (TBN x2): $2,306 ($1,153 each)

The composite benefit rate for the GSR is expected to remain at 1.3% for the duration of the project.

## 6.5 Travel

The budget includes domestic travel costs associated with three annual trips to the American Geophysical Union (AGU) Fall Meeting in San Francisco, CA for the PI and two graduate students. Including registration fees, travel expenses and meal and incidental expenses, the total cost is estimated at $1,400 per traveler per year (5 days, $60 travel, $400 registration, $700 hotel, $240 meals and incidentals). Domestic travel expenses are also included for the PI to present at the American Meteorological Society (AMS) 30th annual Climate Variability and Change conference, to be held in January 2018, estimated at $2,300 in year 3 (5 days, $500 airfare, $400 registration, $700 hotel, $200 car rental, $500 meals and incidentals). International travel expenses are included to the International Association of Meteorology and Atmospheric Sciences (IAMAS) conference in Cape Town, South Africa, to be held in 2017, estimated at $4,400 for one participant (5 days, $2000 airfare, $400 registration, $1200 hotel, $800 meals and incidentals). The budget also includes domestic travel costs for project collaborator Colin Zarzycki, of the National Center for Atmospheric Research, which will amount to $2,650 for each project year to support his travel to the American Geophysical Union (AGU) Fall Meeting ($1,400 per year) and one trip each project year to UC Davis for consultation / in-person meetings ($1,250 per year).

## 6.6 Supplies: $6,277

A one-time expense of $3,550 will cover the cost of 50 TB in external hard drives to store reanalysis and model data that is generated or utilized by this project. Additionally the project requires the purchase of software licenses totaling $2,727. The software license charges are $138 / year / license for the mathematics software package Maple and $165 / year / license for the software package Matlab, for a total of $303 / year / license. Software will be provided to the GSRs (2 licenses) and PI (1 license) over the duration of the project. This amounts to $909 / year for all licenses. These software packages will be used by the students and PI for data processing, analysis and modeling.

## 6.7 Other Expenses: $96,337

### 6.7.1 Publication Charges: $6,000

Publication costs are incurred from publication of work produced by this project and the associated annual cost is expected to be $2,000 per year (16 pages at $125 per page).

### 6.7.2 Tuition and Fee Costs: $90,337

The GSR IV is expected to have residency status which amounts to $27, 292 ($13,646 per GSR) in year 1, $30,021 ($15,010.50 per GSR) in year 2 and $33,023 ($16,511.50 per GSR) in year 3. These totals factor in a 25% rebate from the Provost and an estimated 10% increase per academic year.

## 6.8 Indirect Cost: $156,440

Per the University of California, Davis Federally approved Indirect Cost Rate for on-campus research, an initial rate of 56.5% Modified Total Direct Cost will be applied to the project during the period through June 30, 2016 and 57% for the period of July 1, 2016 through June 30, 2017. As overhead rates have not been established beyond Fiscal Year 2016/2017 the last approved rate of 57% is used for the remainder of the project for budgeting purposes. The Negotiated Indirect Cost Rate Agreement can be found here: `http://research.ucdavis.edu/wp-content/uploads/F-A-Rate-Agreement-2014-update.pdf`.

## 6.9 Table of Personnel and Work Effort

| Name | Role | Effort Commitment (per year) |
|---|---|---|
| Paul Ullrich | PI | 8% |
| Richard Grotjahn | Co-I | 4% |
| Marielle Pinheiro (or other) | GSR | 62% |
| Xingying Huang (or other) | GSR | 62% |
| Colin Zarzycki | Collaborator | |
| Weile Wang | Collaborator | |
| Ramakrishna Nemani | Collaborator | |

## 6.10 Facilities

Over the course of this project computational resources for software development, testing and data analysis will be required. Several avenues for obtaining computational resources are available to the PI and co-PI, which will be pursued to ensure the success of this work. The University of California, Davis has recently invested in building a campus-wide computing cluster for the advancement of scientific research in the environmental sciences. The research team for this project will have high-priority access to this cluster, with over 1,500 processors, including full-time technical support from the campus computing team. Laptops for the graduate student researchers have been provided by the PI's start-up package. Computing resources on NASA supercomputing systems will also be pursued as part of this project.