WORKSHOP ON ANALYSES, DYNAMICS, AND MODELING OF LARGE-SCALE METEOROLOGICAL PATTERNS ASSOCIATED WITH EXTREME TEMPERATURE AND PRECIPITATION EVENTS

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COVER IMAGE:

Aerial view of cumulonimbus with rainshaft. Photo by Lester Zinser.

BACK COVER IMAGE:

Maps of (top) US surface air temperature composite anomalies (°C) and (bottom) 500 mb geopotential height composite anomalies (m) for (left) the cold air outbreak of April 6-10, 2007 and (right) the heat wave of March 13-23, 2012. Anomalies are calculated relative to the period 1981-2010.
Images provided by the NOAA Earth System Research Laboratory, Physical Science Division, Boulder from their Interactive Plotting and Analysis Tool: http://www.esrl.noaa.gov/psd/cgi-bin/data/getpage.pl
(Data Source: NCEP/NCAR Reanalysis, see Kalnay et al. 1996).

WORKSHOP ON ANALYSES, DYNAMICS, AND MODELING OF LARGE-SCALE METEOROLOGICAL PATTERNS ASSOCIATED WITH EXTREME TEMPERATURE AND PRECIPITATION EVENTS

Report from a US CLIVAR-sponsored International Workshop

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I Introduction

1.1 Context for the US CLIVAR Extremes Working Group and Workshop

Weather and climate extremes have large societal and economic consequences. Heat waves have caused a larger annual number of weather related deaths in the US (170) than hurricanes (117) or flooding (74) in a 10-year average (1997-2006). While many heat waves are short-lived (e.g., Chicago, 12-15 July 1995, 623 fatalities in Illinois[1]), longer events can have a large economic cost (e.g., $56.4B heat wave in the central part of the US during much of the summer of 1980). Similarly, cold air outbreaks (CAOs) tend to be short-lived but carry large economic losses (e.g., $6.1B during 20-30 December 1990 and $1.6B during 13-17 January 2007 in California; $4.7B in 1983 and $2.3B in 1995 in Florida2; adjusted for 2013 Consumer Price Index).

It may be tempting to think of cold air outbreaks as becoming less of a problem in the future, but even in a warming environment, freezes still occur (Tang et al. 2013) and cause large losses. In Florida during December 1989, two days of subfreezing weather were so unusually cold as to wipe out half the citrus trees, though the monthly mean temperature was *above* normal. Furthermore, the timing of the cold can be more important than the minimum temperatures of the freeze. For example, during 4-10 April 2007 low temperatures across the South caused $2.2B in agricultural losses since many crops were in bloom or had frost-sensitive buds or nascent fruit. Some might believe that the occurrences of extreme events are captured by longer-term means, such as monthly means. However, the same 2007 event also exemplifies how commonly-used monthly means can be misleading: April 2007 monthly average temperatures were near normal[2]. Similar examples of inopportune timing apply for the other extremes considered (e.g., heavy rainfall just before harvest, high heat during fruit development). Thus, short-term temperature and precipitation extremes can have high and lasting societal impacts.

Extremes in temperature and precipitation can occur over many time scales. To make the subject more manageable and reduce overlap with other CLIVAR efforts, the workshop (as does the working group, WG) focused on short-term (five-day or less) extreme precipitation and temperature events in North America. Hence this workshop addressed an important gap in knowledge by studying short-term events. Temperature extremes were defined to include both short-term hottest days (warm season) and CAOs (winter and spring), though the greater amount of research literature reflects an emphasis on extreme hot events. Precipitation extremes were considered from daily values to five-day means, which captures most of the big impact single events. Additional narrowing of the workshop scope excluded tropical-cyclone-related events.

Extreme temperature and precipitation events in both observations and models are receiving considerable attention [including Intergovernmental Panel on Climate Change (IPCC) reports, e.g., IPCC 2012; research papers, e.g., Meehl and Tebaldi, 2004; and active websites[3]: However, the large-scale meteorological patterns (LSMPs) and underlying dynamical mechanisms associated with such extreme events are less well known. Figure 1 shows illustrative LSMPs for cold, hot, and heavy precipitation events affecting central California. The figure illustrates how significant parts of the pattern extend a great distance from the location of the extreme.

[1] Source: NOAA; http://www.nws.noaa.gov/om/hazstats.shtml
[2] Source: NOAA; http://www.ncdc.noaa.gov/billions/
[3] See: http://www.esrl.noaa.gov/psd/ipcc/extremes/ and http://gmao.gsfc.nasa.gov/research/subseasonal/atlas/Extremes.html

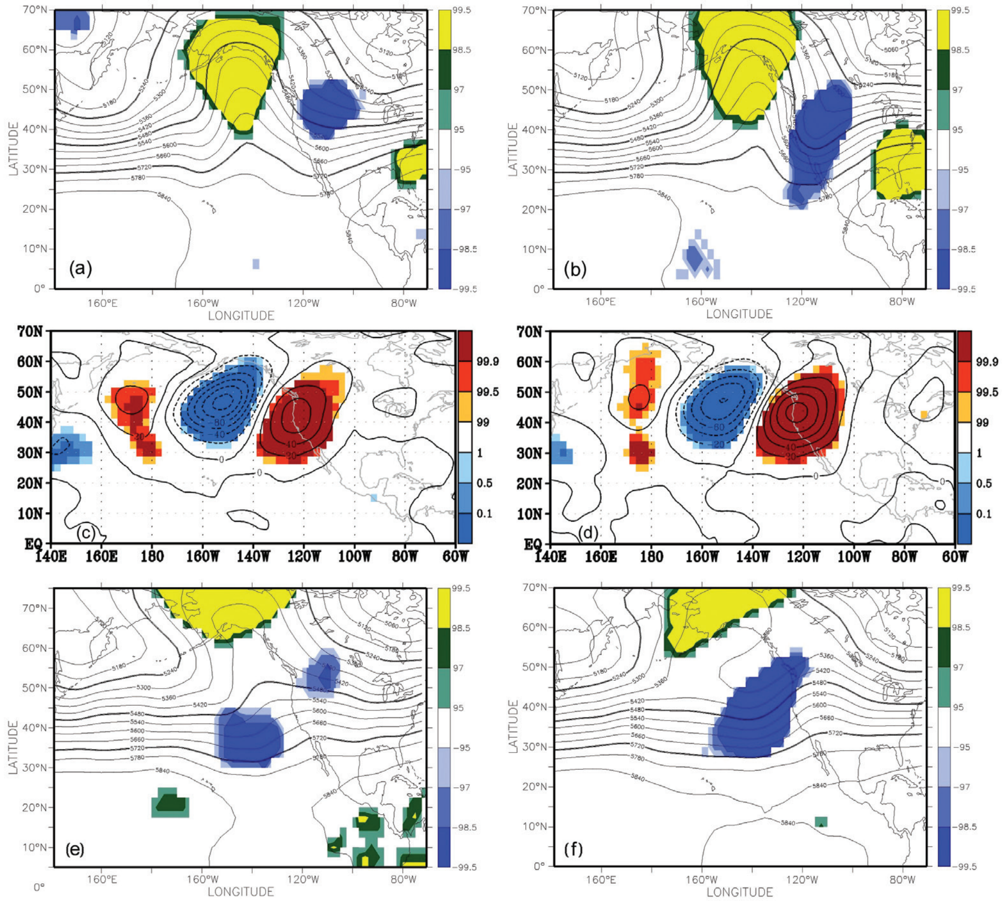

Figure 1: LSMPs for temperature and precipitation extremes of the California Central Valley. (a) and (b) geopotential height composites for cold air outbreaks; (c) and (d) geopotential height anomaly composites for heat waves; (e) and (f) geopotential height composites for extreme precipitation. All fields are at 500 hPa level. Bottom row is at event onset, while top row is 24 hours before onset. Units are m. Shading indicates significance, with darker shading at the highest (yellow) and lowest (darkest blue) 0.5% for the full fields; highest (darkest red) and lowest (darkest blue) 0.1% for the anomaly fields. Sources: (a), (b), (e), and (f) from Grotjahn and Faure (2008); (c) and (d) from Grotjahn (2014).

Establishing a link between LSMPs and extreme events that are rare and occur on a smaller space and time scale provides a means of utilizing climate model simulations to study variability of extremes under a changing climate, as current model resolution is adequate to resolve LSMPs even if local impacts are not correctly captured. However, the overall relationships between extreme events and LSMPs for North America are not well known – and we can anticipate large variations by variable (precipitation and temperature), by climatic region, and by season. Also, interactions with local topography are likely to play key roles for at least some extreme precipitation events. In addition, there is a knowledge gap in how well climate models simulate these LSMPs; if a model simulates them poorly then the model may not develop extreme weather adequately or for the wrong reason. This is a critical question for understanding the uncertainty of future projections and for directing model improvements.

The workshop occurred at an opportune time to examine the critical issues discussed above and to identify key knowledge gaps in the understanding of climate extremes and their variability and trend. The time was opportune for three reasons.

1. Evaluation of whether current climate models used for future projections are producing extremes with the correct dynamical mechanisms, which reflects directly on the appropriate confidence in the projections, is at a very early stage.
2. Identifying and understanding the creation, maintenance, and simulation of LSMPs relevant for extreme events also provides an opportunity for downscaling of extremes.
3. There has been sufficient preliminary work in a number of related areas (the four general topical categories) that joint discussion is particularly useful.

1.2 Organization of the Workshop

The workshop was organized around four general topical categories: data issues, statistical methods and applications, synoptic/dynamic methods and applications, and modeling. A "tutorial" approach was emphasized for presentations so that they would be accessible to researchers in the other areas and to the student audience. Within each topical category a balance of presentations was sought amongst research applicable to short-term temperature extremes and precipitation extremes. How to define these extreme events is not straightforward and was one focus of the workshop in all four topical categories. Some issues cut across these categories. For example, the terminology 'LSMP' was developed. The agenda for the workshop with links to oral presentations is available at http://usclivar.org/meetings/extremes-workshop-agenda.

The workshop had three principal goals. The first two, to *synthesize existing research and identify key knowledge gaps*, are discussed in this report. The presentations and discussions provided valuable information about current and recent research that is being incorporated into two survey articles (presently under development). In addition, six of the presentations were published in a special issue (Winter 2014) of US CLIVAR *Variations*. Two survey articles (one on temperature extremes, one on precipitation extremes) are in preparation for a peer-reviewed journal. These articles also address knowledge gaps uncovered during the literature review, during formal and informal discussions amongst the WG, and during the workshop.

Another stated goal was to *build a network of 'extremes' researchers*. It was noted at several times during the workshop that people present were not aware of some work presented by others at the workshop. As a trivial example, the terminology 'LSMP' came into common usage by participants. A substantive example of cross-discipline work that arose due to the workshop is a statistician, with long experience in extreme value theory (EVT), presented work that studied for the first time a measure of the intensity of a hot-spell LSMP with his various EVT tools. As another example of cross-discipline interaction, several dynamic meteorology experts suggested, during open discussion, a variety of markers (e.g., LSMP indices, E-vectors, absolute vorticity gradient, velocity potential, jet stream exit structure) that should be considered by statisticians and modelers in their extremes research. In general, there was a lot of positive feedback regarding the facilitation of interactions between researchers specializing in the different topical areas (data, statistics, synoptic-dynamics, modeling).

Beyond the goals of the WG[4], the workshop:

1. demonstrated working techniques for characterizing LSMPs;
2. showed the utility of the LSMP approach for understanding extremes and assessing model representation of them;
3. highlighted the importance of a dynamical approach to extremes analysis; and
4. produced a clear set of recommendations to advance the field.

[4] See WG webpage: http://www.usclivar.org/working-groups/extremes

2 Present State of Knowledge and Methodologies

2.1 Data Issues and Methodologies

Three lectures about "data" opened the workshop. Ken Kunkel explored the differing classes of storms leading to extreme precipitation in the US and summarized how station data were collected and quality controlled. As two examples, very extreme precipitation reports (>10 inches) are likely invalid and an increasing trend (17% / century) in 20 year return values is mainly in frontal systems and tropical cyclones. Figure 2 from his presentation shows the result of five years of effort from his team to categorize US extreme precipitation. Pasha Groisman further explored observed precipitation data limitations. His main message was that observed mid-latitude precipitation has become more intense but more sporadic over the past several decades. He further concluded that different sources of intense precipitation do not combine linearly and that precipitation distributions reflect that non-linearity (Figure 3). Pardeep Pall shifted the focus from observational data to model output data. He presented the basic methodology to attribute the change in risk of severe weather as the overall climate changes (using model simulations with and without 20th century greenhouse gas increases). He related extreme flooding in the UK in 2000 to a strong Scandinavian low frequency pattern. One of the many challenges in these techniques is the analysis of multi-terabyte model output datasets.

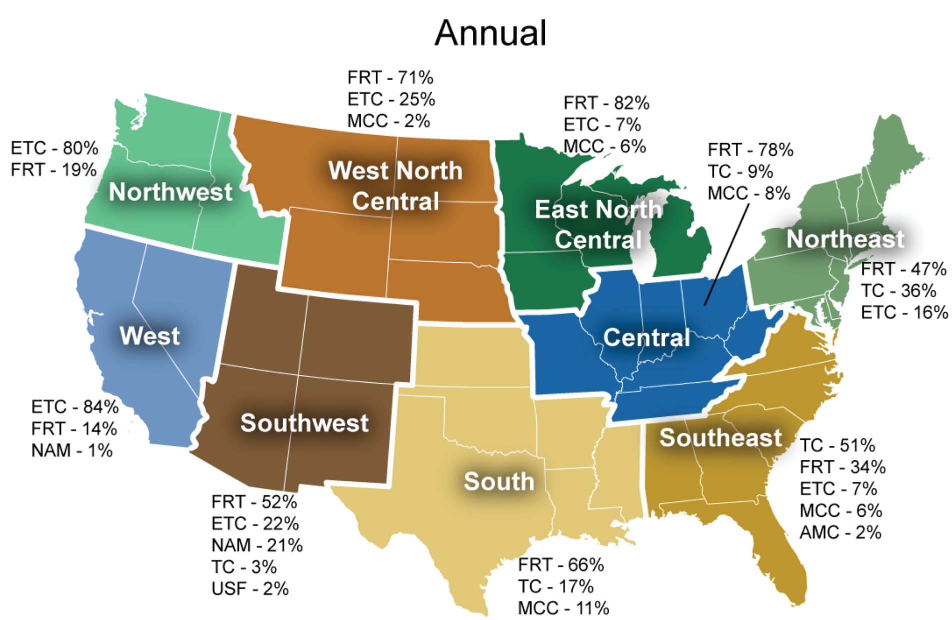

Figure 2: Sources of observed extreme precipitation events in varying parts of the contiguous United States. Type of storms considered are Non-frontal Extratropical Cyclones (ETC), Frontal Extratropical Cyclones (FRT), North American Monsoon (NAM), Tropical Cyclones (TC), Mesoscale Convective Systems (MCC), Air Mass Convection (AMC). Source: Kunkel et al. (2012).

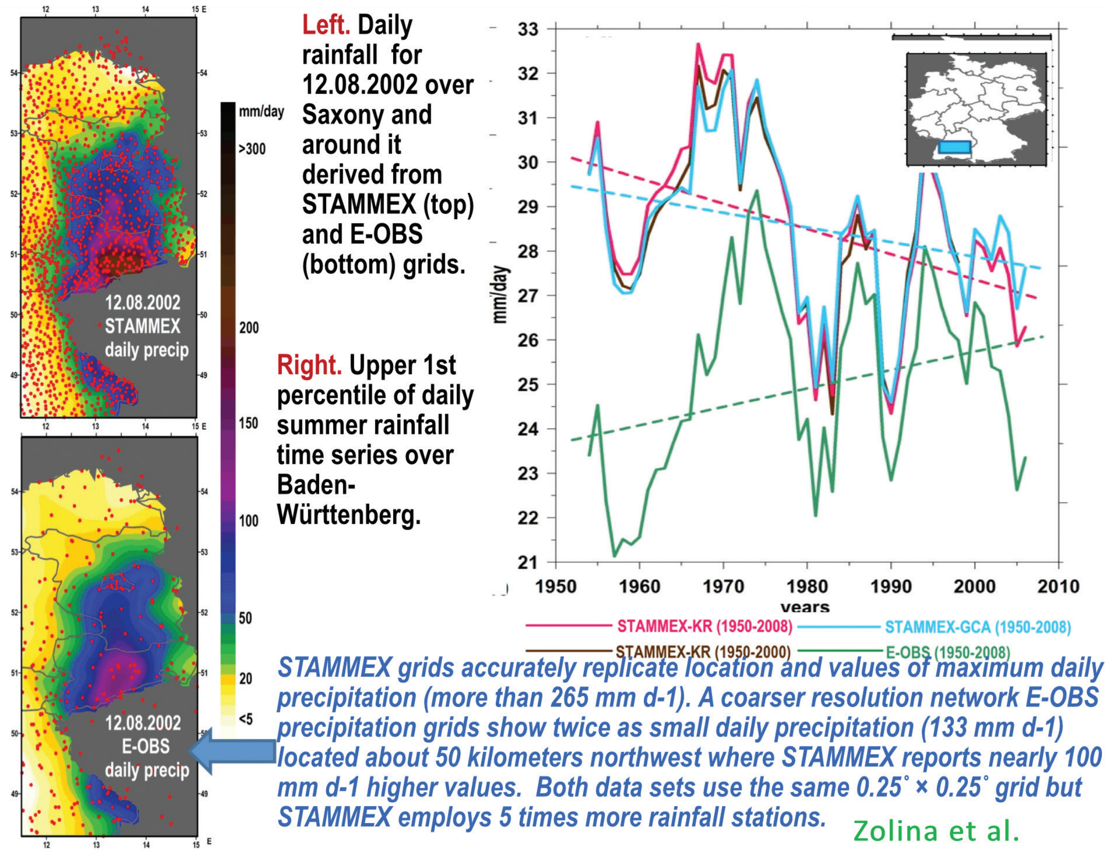

Figure 3: Extreme rainfall is compared from two gridded products over Germany (Spatial and Temporal Scales and Mechanisms of Extreme Precipitation Events over Central Europe, STAMMEX, 0.1° x 0.1° and the European Climate Assessment and Dataset E-OBS dataset of several hundred stations, 0.25° x 0.25°). The comparison shows significant deficiencies in reporting by a relatively coarse network (E-OBS) of extreme rainfall pattern such as the catastrophic storm of August 2002 in Saxony as well as of systematic changes of very heavy rainfall intensity (the upper first percent of daily rainfall). The deficiencies come from two sources: (a) an inability of sparser station networks (red dots) to accurately report extreme rainfall peak and location and (b) a failure of the common data assimilation technique (used in E-OBS, when all valid data on a given date are used to "better" represent the current day precipitation pattern) to secure the homogeneity of regionally-averaged heavy precipitation time series. Source: Zolina et al. (2014).

Several interesting ideas were floated in the data discussion breakout sessions. The data necessary to understand the role of LSMPs in extreme precipitation and temperature events come from both observations and models. Model output, by its very nature, can be made as complete as necessary. Observed data, however, is limited to that actually available and is incomplete.

Another important discussion centered on the uncertainties of observed data records. Information about uncertainty is often difficult to discern from the published datasets. The groundbreaking "perturbed physics" approach used by the HadCru team and the ensemble of 20th century reanalyses were strongly encouraged as good examples attempting to quantify observational uncertainties, as well as raising the general awareness about observational uncertainties.

The connection to the applications community and the relevance of sub-daily fields, particularly temperature, to certain sectors (such as energy and agriculture) was raised. The availability of high quality sub-daily observations is critical. Also, standards for distribution and formatting of observed fields, similar to the CF compliance standard[5] used for model output, would enable more widespread use of the observations. Furthermore, comparison of observations to model output necessitates a gridding step. Standard techniques for comparing averages may not be appropriate for extremes, particularly precipitation, and further statistical research into this subject is needed.

Multi-dimensional analyses of extremes, particularly when using high-resolution global models, quickly become 'Big Data' challenges. An emerging generation of parallel analysis tools (e.g., parallel R, VisIT, UVCDAT, TECA) is enabling such analyses for those privileged with access to large high-performance computing platforms. Further development of these tools and wider access to appropriate hardware is encouraged. The multi-petaflops computer systems currently being used to generate petabytes of model output are not generally suitable to analysis tasks. Rather than expensive fast networks between 100s of thousands of processing cores, large memory systems of 10s of thousands of processing cores are more suitable in many cases.

What issues arise in data quality or quantity?

Much of the historical data analysis in climate studies utilizes global or regional reanalyses. Examples of these reanalyses include the NCEP/NCAR Reanalysis-2 (Kanamitsu et al. 2002), updated from the original NCEP/NCAR Global Reanalysis (Kalnay et al. 1996). This dataset has global coverage, a spatial resolution of 2.5° x 2.5°, a temporal resolution of 6-h, and is available from 1979 to present. Additionally, there exists the NCEP North American Regional Reanalysis (NARR; Mesinger et al. 2006), which has a 32 km grid spacing and a temporal resolution of 3-h, available from 1979 to present, and the NCEP Climate Forecast System Reanalysis (CFSR; Saha et al. 2010), which has a 0.5° grid spacing and a temporal resolution of 6-h, and is also available from 1979 to present. The original NCEP/NCAR Global Reanalysis is available for the period from 1948 to the present. Global analyses are also provided at approximately 0.7° by the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis Interim (ERA-Interim; Dee et al. 2011) and at 1/2° latitude x 2/3° longitude by the NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al., 2011). The use of satellite data assimilation for the reanalyses increased markedly after 1978. Because this satellite data assimilation improves the analyses, particularly over the otherwise data sparse oceanic regions, many of the recently released reanalysis products begin in 1979.

The global reanalyses are generally credible sources for the examination of synoptic- and planetary-scale features. However, more complicated (and often more interesting) metrics, such as precipitation, near-surface temperatures, and atmospheric stratification, are typically not as credibly reproduced in the global reanalyses. The primary reason for this problem is that these reanalysis metrics are more heavily weighted on model physical parameterizations, such as moist convection, and planetary boundary layer schemes.

Regional reanalyses, such as the NARR, provide more reliable precipitation analyses than those provided by the global reanalyses, primarily because of the NARR's assimilation of the Unified Gauge-based daily precipitation over the continental US at 0.25°resolution. However, such detail is available over only the continental US, and a few other countries in Europe that use similarly high-resolution reanalyses. Although better than some of the global reanalyses, the NARR precipitation has issues as well (Bukovsky et al. 2007).

[5] See http://cf-convention.github.io/

It may be possible to use data assimilation techniques in the historical records to modify the gridded data from its current form. For example, the quality control utilized for accepting specific stations into the analyses could be adjusted to reflect a new, perhaps more realistic standard of acceptance to modify the model's first guess. Adjustments could also be made to homogenize the assimilation techniques among the various regions of the globe.

How well do station observations compare with reanalyses?

Although soundings and satellite data are assimilated into the reanalyses, surface data are not as often assimilated. It is, however, valuable to compare station observations with reanalysis data in order to facilitate improvements in modeling.

A particularly interesting tool is the 20th century reanalysis (Whitaker et al. 2004; Compo et al. 2006, 2011) that is based primarily upon surface pressure analyses. These reanalyses can be useful to diagnose large-scale atmospheric circulations from 1871 into 2011. These reanalyses may be especially valuable in discerning the atmosphere's natural variability and quantifying observational and analysis uncertainty.

The existing mismatch between observation-based extremes and reanalysis-based extremes presents a particular challenge in extreme identification. A more rigorous examination of reanalysis proxies for extremes may facilitate improved identification.

What observation-based or model data are needed for extreme event identification?

Generally, the use of surface-based datasets is recommended for identification of temperature and precipitation extremes. As suggested above, high-resolution models and observations will have point values of extremes (small-scale features) that a reanalysis would not capture. Therefore, identifying reanalysis proxies for the observed extremes is recommended.

An example of the difficulty in identifying extreme precipitation events relates to the relative roles of extratropical cyclones versus frontal systems in triggering extreme events. For example, Milrad et al. (2014) illustrate the very disparate synoptic and mesoscale structures (including both cyclones and fronts) associated with extreme warm-season rainfall events in the Montreal, Quebec (~ 45°N). Though examining synoptic-scale circulation structures does typically point to extreme rains, it is not obvious that moist convection is universally identified with large-scale atmospheric structures that are documented by the reanalyses. The issue was raised of whether synoptic-scale structures, air mass characteristics, fronts, and tropical influences on extratropical precipitation are changing.

Relatively new remote sensing technologies can be used to document both precipitation and aerosols. For example, the global precipitation measurement (GPM; http://pmm.nasa.gov/GPM) mission, along with other satellite-based remote sensing tools, including radar, can improve precipitation analyses. Both MODIS and MISR provide aerosol optical depth information useful for monitoring long-range transport of aerosols. Creamean et al. (2013) documented the presence of dust particles transported from the Sahara and Asia in glaciated high-altitude clouds during an atmospheric river landfall in northern California. Arriving from high altitude and serving as ice nuclei, both measurements (Creamean et al. 2013) and modeling (Fan et al. 2014) suggested that dust enhances orographic precipitation associated with the atmospheric river, and increases the ratio of snowfall to total precipitation, both with important implications to California's water resources that are derived primarily from snowpack in the mountains.

What ETCCDI indices are relevant?

The commonly used Expert Team on Climate Change Detection and Indices (ETCCDI) indices were developed under the auspices of the World Meteorological Organization's Commission for Climatology and the International CLIVAR Program for detection and attribution purposes, but their development was *not for the purpose of exploring the role of LSMPs in extreme events*. Furthermore, it was pointed out that these global indices were designed in the face of limited and low quality observations over many parts of the world. This is not the case for North America where high quality observations are available for a relatively dense network of stations. The possibility of developing multidimensional indices (such as blocking and temperature) to explore the relationship of LSMPs and extreme events was found to offer much promise.

There was discussion of applying extreme statistical techniques to ETCCDI indices, to identify and analyze extreme events. New techniques, involving the usage of physically based covariates, such as ENSO, blocking indices, or LSMP-based indices, offer the promise of added insight into the roles of LSMPs and certain classes of extreme weather.

2.2 Statistical methodologies and applications

Richard Grotjahn started the session by illustrating what the LSMPs look like for extreme temperature events affecting California, both hot spells and cold air outbreaks (e.g., Figure 1). He also described the steps in a compositing approach to find the LSMPs both in reanalysis and climate model data. Rick Katz introduced various extreme value analysis (EVA) statistical methods including such as generalized extreme value (GEV) and peaks over threshold (POT) concepts. He described their bases, parameters, and general issues. He then illustrated an application where a covariate, an index measuring the LSMP strength, is included in the EVA. Francis Zwiers showed work with block maxima (in set time periods) applied to precipitation extremes and to detect human influences. He emphasized that a physical basis is needed when using covariates. Robert Black discussed several low frequency phenomena (PNA, NAO, and ENSO) as modulating the seasonal cold events. Christopher Paciorek showed trends and patterns in extreme precipitation by applying GEV and POT to observational, gridded, and model data. For example, he found spatial smoothing to give a clearer pattern and reduce uncertainty. Sasha Gershunov described a technique for characterizing how 'heavy' a tail is, in extreme precipitation, at different locations and seasons. He noted that most models have exponential instead of heavy tails, thereby under-predicting extreme values.

What data-handling techniques are relevant – self-organizing maps, composites, etc. – to identify LSMPs?

One basic question concerns whether to condition on the extreme event or on the LSMP. (a) The compositing approach involves examining the LSMP conditional on an extreme event occurring. It has advantages in terms of dynamical interpretation, including facilitating the identification of an LSMP, but the disadvantage of lumping all the extreme events (i.e., of varying intensity) together. (b) The extreme value analysis approach instead conditions on the LSMP. It has the advantage of statistically modeling both the rate of occurrence and intensity of the extreme event, but the disadvantage of not providing a convenient means of identifying LSMPs. Thus these two approaches should be viewed as complementary.

Compositing, EOFs, self-organizing maps (SOMs), and cluster analysis are all useful techniques for identifying LSMPs, with the attendees expressing no strong preference for any one of these being superior to the others. Techniques that segregate data, like EOFs, SOMs and cluster analysis offer the potential for conditional compositing that lumps together only extreme events with similar large-scale characteristics. In order to treat complicated phenomena, such as "atmospheric rivers," in an automated fashion (i.e., when processing large files of output from climate model experiments), machine learning is another promising technique.

Considering the demonstrated links between weather/climate extremes and LSMPs, the desire was expressed to focus on the assessment of LSMP predictability. Such a focus would facilitate an enhanced understanding of large-scale processes responsible for producing an environment conducive to producing extremes.

What statistical methods apply to these extreme events?

As discussed under the previous question, methods using extreme value distributions with covariates (that is, conditioning on the LSMP) are advantageous (at least once a candidate LSMP has been identified). Prototypical studies of the relationship between climate extremes and LSMPs using this approach include Sillmann et al. (2011) and Photiadou et al. (2014). One can go further and develop an index based directly on the LSMP as Grotjahn (2011) did for California hot spells.

Of course, a number of challenges remain in making use of techniques based on extreme value statistics. Including non-stationarity in statistical models may be desirable, but accounting for it involves trade-offs between precision of fit and comprehension of complexity. Extreme phenomena such as cyclones require the statistical modeling of both their path and intensity. See Stephenson and Economou (2012) for an extension of extreme value statistics to this situation.

Multivariate approaches can provide insight into the physical behavior of extremes by identifying links between different fields, including LSMPs. Although the statistical theory of multivariate extremes is well established, it requires the assumption that all variables be extreme. Yet extreme climate events involve more than one climate variable, not all of which need be simultaneously extreme. Recently, a "conditional" approach that relaxes this assumption has been introduced. One of the first applications of this conditional approach to climate is Gilleland et al. (2013), in which the variables are indicators of severe weather.

Finally, a scale mismatch (i.e., area versus point) with observations makes the evaluation of gridded model output for precipitation extremes difficult. In principle, methods based on extreme value theory could be applied to devise an adjustment for this mismatch (Mannshardt-Shamseldin et al. 2010).

What statistical connections are there between extreme event and large-scale phenomena such as low frequency phenomena like the El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), etc.?

The same approach of extreme value distributions with covariates should still be applicable to low frequency (LF) phenomena. In fact, so far this approach has been applied more for covariates that are indices of LF phenomena than for LSMPs per se (e.g., Brown et al. 2008).

One issue concerns whether the assumption of linearity is justified (e.g., the location parameter of the generalized extreme value distribution is commonly assumed to be a linear function of any covariate such as an LSMP). In principle, this approach can handle nonlinear relationships too, but the additional complexity required may limit its feasibility for large datasets. A way to examine the linearity assumption would be via experiments using climate models.

What are limitations in the observational record and how can they be overcome?

Gaps in observations undermine analysis of extreme events, which are by definition rare. Gaps are particularly problematic when trying to identify trends in extremes. This may be especially true if gaps are systematic. For example, extreme events may be poorly observed if observing sites tend to close or are damaged during severe weather.

Decadal variability of extremes also needs better analysis. Thus, there is need to analyze multiple phases of phenomena such as the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) and their influence on the statistics of extremes on weather time scales. Data gaps undermine such efforts. There is also some suggestion that behavior of extremes during 1910-1970 differs from post-1970 statistics. Some observing networks, such as the Cooperative Observing Network, rely on volunteers and appear to function best when there is a state or regional person promoting the efforts of participants and inspiring their continued, careful involvement.

There are various approaches one might consider for alleviating problems created by the gaps. Programs to recover old observational archives can help fill some of the gaps. Proxy data for some types of extremes (e.g., tropical cyclones, pluvials) might also provide opportunities to infer the missing observational data. Modeling, such as through reanalysis might also allow inferring values for missing observations. Any methods used, however, need to account for the approximations and thus uncertainty of gap-filling techniques.

2.3 Synoptic and Dynamic Methodologies and Applications

The presentations and breakout discussions mainly focused on (a) characterizing the LSMPs linked to extreme weather events (EWEs) and (b) understanding the physical linkages between LSMPs and EWEs. Considerable emphasis was placed upon the how to optimally isolate LSMP-EWE links, both in terms of EWE metrics used as well as most effectively characterizing LSMPs. Some presentations studied the physical processes leading to LSMPs, themselves, and mechanistic influences of LSMPs on EWEs.

Various metrics for defining extreme precipitation events were discussed. In particular, Shawn Milrad presented the extreme precipitation index (EPI; Gyakum 2008) as a novel proxy for precipitation rate. A substantial advantage of this proxy is that it is based upon resolved dynamical measures found in model output and reanalysis data. Russ Schumacher overviewed results based upon a measure of widespread heavy precipitation (Schumacher and Davis 2010). During summer, widespread extreme rainfall events are quite rare over the continental US and are most often associated with tropical storms or anomalous synoptic-scale trough patterns.

Presentations by Steven Feldstein and Bill Gutowski use SOMs (Cavazos 2000) to identify LSMPs associated with regional EWEs. Although composite analyses are quite useful for EWEs with simple and repeatable dynamics, SOMs enable the identification of more complex LSMP-EWEs linkages involving differing LSMP patterns. SOMs also encapsulate some of the desired behavior of EOF-type analyses (spanning pattern space and favoring high variance behavior). Besides SOMs, Richard Grotjahn described an 'LSMP index' (Grotjahn, 2011) for characterizing the strength and similarity of the current weather pattern to the pattern associated with hot spells affecting California. The characterization methodology was a significant topic in the breakout discussions and deemed an important consideration in framing the LSMP-EWEs problem.

What are the physical mechanisms responsible for LSMPs?

It was generally recognized that considerable uncertainties remain in our knowledge of the physical mechanisms responsible for implicated LSMPs. Although internal atmospheric variability is considered to be the main intraseasonal forcing mechanism for many LSMP patterns, including common patterns, such as the NAO and Arctic Oscillation (AO), it was also suggested that surface boundary conditions provide an important modulation of this behavior. A key result of Randy Dole's talk was that remote forcing, local dynamics, and boundary forcing can all play a role in forcing LSMPs.

Gutowski illustrated that widespread extreme precipitation events occurring over the upper Midwest during winter are commonly linked to an east-west mid-tropospheric circulation dipole with an anomalous cyclone (anticyclone) located over the Southwest (Northeast). This dipole pattern leads to anomalous southerly flow emanating from the Gulf of Mexico into the Mississippi valley region. Similar east-west circulation dipole features were isolated in Schumacher's analysis of warm season extreme precipitation events. Milrad further emphasized the significance of downstream anticyclones during heavy rain events in Montreal during summer. The anticyclone feature helps provide a warm unstable air mass and enhanced moisture transport.

Linkages between LSMPs, remote phenomena, and extreme temperature events were presented and discussed by several speakers. Feldstein used various dynamical tools to link various low frequency phenomena (such as MJO to PNA to negative NAO) and to high predictive skill in parts of North America. He then surmised whether the higher skill during certain combinations of LF phenomena, further modulated by the stratospheric polar vortex and Arctic sea ice, to probabilistic forecasts of extreme 2m temperatures. Focusing on the March 2012 warm wave, Dole illustrated the important proximate role of sustained poleward heat transport in producing this event. This transport was part of a broader large-scale circulation anomaly pattern extending upstream to the North Pacific. The breakout discussion emphasized the role of blocking events in producing temperature extremes.

The role of the AO in boreal cold air outbreaks was a key focus of Steve Vavrus' presentation. It is becoming well recognized that the negative phase of the AO tends to favor prominent cold air outbreaks over North America and Europe (Francis and Vavrus 2012) as the weakened jet stream allows cold air masses to more readily meander southward. One issue illustrated by Vavrus, however, is that current projections of likely future changes in the mean winter circulation project upon the AO pattern, itself. Thus, at least in this case, the future behavior of EWEs is clouded by uncertainty in the combined impact of changes in (a) the seasonal mean background state and (b) LSMP behavior. Although climate models currently suggest that the behavior of key LSMPs will not change appreciably, changes in the background state are likely to impact future EWE behavior (as well as how they are best defined). This will be influenced by changes in surface boundary conditions such as snow cover and soil moisture.

Physical linkages between LSMPs and EWEs were touched on in several presentations. One result presented by Steven Feldstein is that the LSMP influence on extreme precipitation events over the Mediterranean is mediated via associated variability in the mid-latitude storm tracks, leading to synoptic wave breaking, PV intrusions, and large amplitude moisture transports. The important role of mesoscale dynamical processes in producing extreme precipitation events was also emphasized. Many of the above elements were effectively merged in Dole's synthesis presentation on using weather-climate linkages to understand better (and ideally predict) EWEs. Within a case study framework, Dole illustrated the respective roles of long-term climate trends, anomalous boundary conditions, and initial conditions (partly linked to remote forcing), leading to the regional LSMP responsible for the March 2012 US heatwave. The event predictability was enhanced by each of these factors in the manner schematically illustrated in Figure 4 taken from Dole et al. (2013).

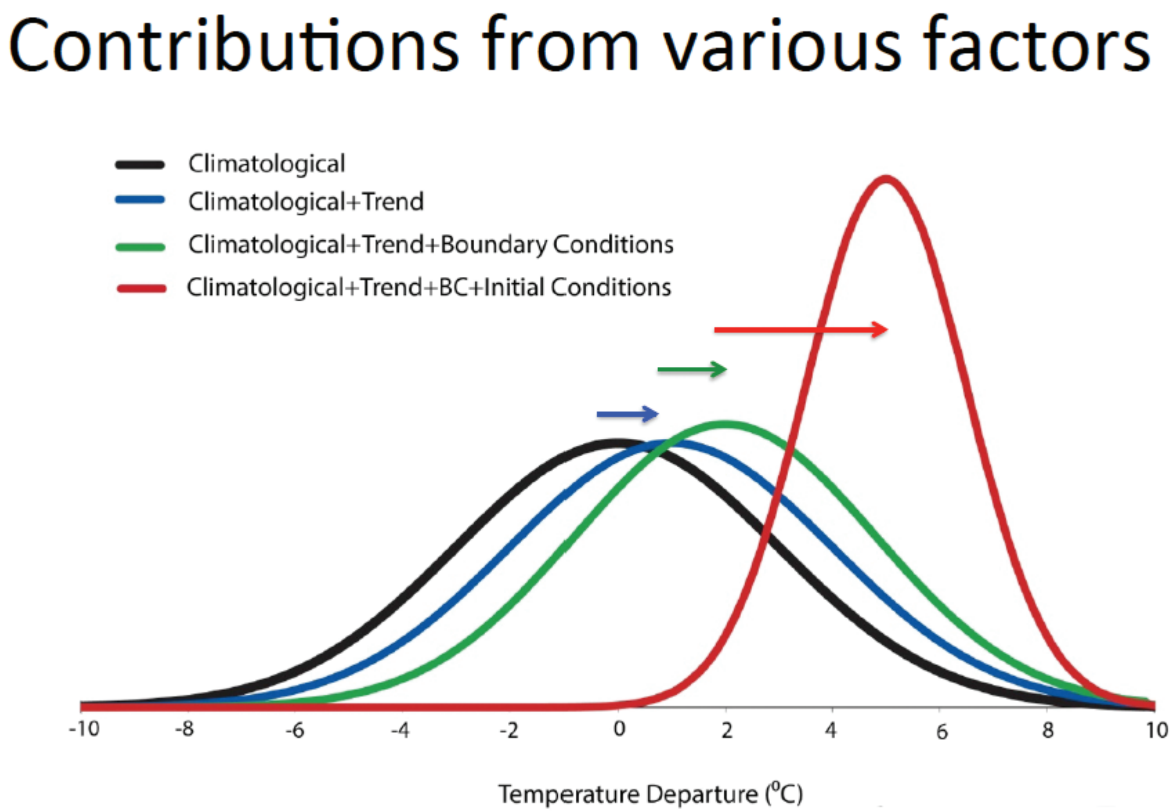

Figure 4: A schematic representation of how predictions for the March 2012 temperature (averaged over the central and eastern US) PDF shifted away from the climatological distribution (black) in response to different factors. These include long term trends and multi-decadal variations that evolve on time scales much longer than a season (blue), sea surface temperatures and other boundary forcings varying on seasonal-to-interannual time scales (green), and the Madden Julian Oscillation and other shorter time-scale phenomena dominated by atmospheric processes varying on subseasonal-to-daily time scales (red). Source: Dole et al. (2014).

What roles do local dynamical processes and remote forcing play?

While the role of local dynamical processes is emphasized in the section above, it is also well recognized that regional LSMPs impacting EWEs are often connected to remote forcing via recurring large-scale teleconnection patterns, particularly during winter. Evidence was presented that links some North American LSMP patterns to remote forcing from the tropical Pacific via a quasi-stationary Rossby wave train. On intraseasonal time scales, North American LSMPs are impacted by the Pacific-North American (PNA) pattern, the AO/NAO, and blocking patterns (Walsh et al. 2001, Celitti et al. 2006). On interannual and longer time scales additional climate modes such as ENSO and the PDO are implicated (Westby et al. 2013).

Feldstein illustrated that the remote influences of ENSO and the Madden-Julian Oscillation (MJO) on extreme temperature events over North America are often mediated by a PNA-like teleconnection pattern, with links to the stratospheric circulation and the state of the NAO. Thus, the net extratropical response to tropical forcing, such as that associated with the MJO, is impacted by the pre-existing state of the stratosphere. Feldstein also determined that the behavior of mid-latitude teleconnection patterns is sensitive to variations in Arctic sea ice. In some cases, predictive information can be obtained from a combined consideration of different remote forcing (Figure 5). Dole's presentation illustrated how remote forcing can physically interact with local processes in producing large amplitude local LSMP patterns.

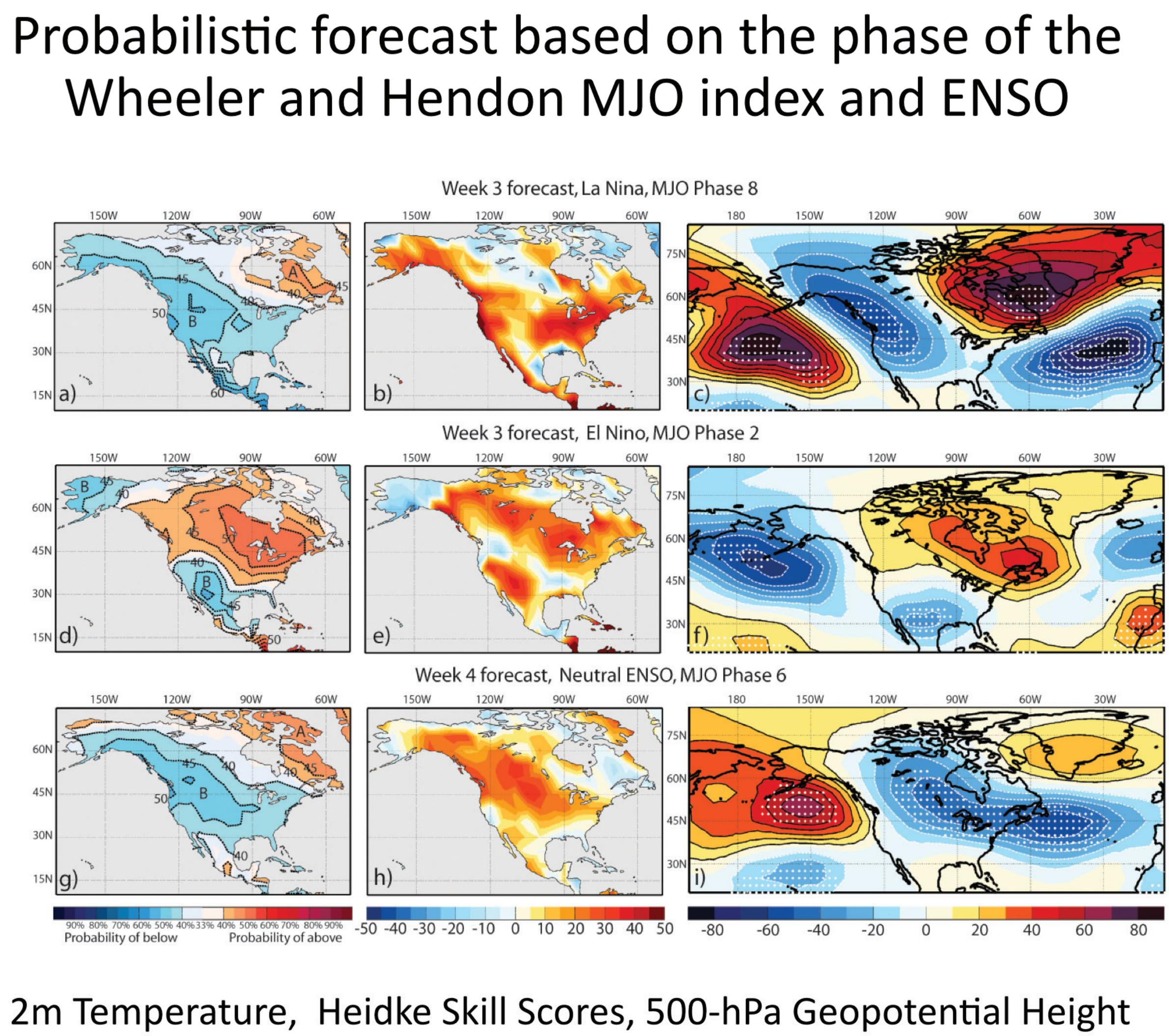

Figure 5: Three and four week probabilistic forecast of 2-meter temperature based on the phase of the Madden-Julian Oscillation and the El Nino/Southern Oscillation; (left column) probabilities for the top and bottom terciles, (middle column) Heidke skill score, (right column) anomalous 500-hPa geopotential height. Source: Steven Feldstein.

What dynamical diagnostic tools – such as wave activity flux, E-vectors, energy budgets etc. – are useful to understand the formation and maintenance of LSMPs?

The large-scale nature of the LSMPs and their common connection to low frequency phenomena suggests the utility of several diagnostic tools. Several presentations used Hovmöller diagrams to characterize time evolving behavior. For example Dole used this approach to illustrate the link between a Midwest heat wave and a slow moving MJO. The onset and decay of LSMP structures linked to EWEs occur on relatively short intraseasonal time scales. One can consider the diagnosis of LSMP dynamics as a two-stage process: first it is of interest to assess whether the main energy source(s) are local or remote in nature. Once the energy source location is determined, the second task is to assess the physical nature of the proximate energy source in this location. An effective means for assessing the source regions for large-scale atmospheric waves is the application of wave activity flux analyses (Plumb 1985, Takaya and Nakamura 2001). The wave activity flux is parallel to the Rossby wave group velocity and thereby traces out a three-dimensional pathway between a wave source region (where flux divergence occurs) and a wave sink region (where flux convergence occurs). Past studies have been successful in applying this diagnostic to make inferences about the wave source regions for various large-scale circulation patterns.

Possible physical mechanisms providing local sources of wave activity in this context include large-scale barotropic growth, baroclinic growth/instability, and nonlinear forcing by synoptic-scale eddies (e.g., Evans and Black 2003). These mechanisms may be augmented via feedbacks related to diabatic processes or interactions of the LSMP with the local topography or land surface. Past studies have introduced comprehensive dynamical frameworks for studying the physical mechanisms leading to the local growth and decay of LSMPs (Feldstein 2002, 2003). These are based upon a local analysis of large-scale circulation tendencies (Feldstein 2002, Evans and Black 2003). In these studies, local tendencies are decomposed into separate forcing terms that are related to distinct physical mechanisms including those discussed above. The two-stage process outlined above is a means for quantitatively diagnosing the dynamics of LSMP life cycles in both observations and climate model simulations.

There are other more simple diagnostic metrics that can be applied to make inferences about the nature of individual dynamical processes and these were discussed in the breakout sessions. Barotropic growth occurs when horizontally anisotropic eddies interact with a background deformation field (for example, a zonally elongated LSMP can grow in a jet exit region with strong diffluence). A suitable eddy diagnostic in this context is the barotropic E-vector (Simmons et al. 1983), while the background deformation field can be assessed in terms of the deformation pseudovector (Mak and Cai 1989). In a similar fashion, inferences about baroclinic growth can be made in terms of the eddy heat flux vector (associated with the LSMP) in relation to the background mean temperature gradient (e.g., Dole and Black 1990). A useful diagnostic measure of local storm track variability associated with LSMPs is the envelope function (Nakamura and Wallace 1990).

The tropical forcing, say by the MJO or ENSO, of extratropical Rossby wavetrains generally involves the interaction of the upper tropospheric divergent outflow (emanating from anomalous tropical convection) with pre-existing subtropical vorticity gradients leading to a local Rossby wave source within the subtropics (Sardeshmukh and Hoskins 1988). Divergent outflow is readily diagnosed in terms of velocity potential while key background vorticity structures can be isolated in terms of threshold magnitudes in the absolute vorticity gradient. The methods and diagnostic tools discussed above are well developed and frequently applied in the literature. An outstanding practical issue is the engagement of the atmospheric dynamics community in diagnostic assessment specifically targeting those LSMPs linked to EWEs.

In summary, the existing body of knowledge regarding LSMP mechanisms is currently uneven and incomplete. Greater uniformity in EWE metrics, LSMP characterization, and dynamical diagnostic approaches is needed to bridge this knowledge gap and enable systematic diagnosis of relevant LSMP behavior in coupled climate models.

2.4 Modeling Approaches and Issues

In this session Noah Diffenbaugh considered how the thunderstorm environment may change for simulated climate change. Increased convective available potential energy and decreased shear were found in an ensemble of CMIP5 model simulations. Anthony Broccoli used composites to define LSMPs in four temperature categories and then assessed how some properties of corresponding grand composite LSMPs differed across North America. He compared individual models and a multi-model mean for highest and lowest temperature events in both January and July. Figure 6 shows how the LSMPs for unusual winter cold look for 4 regions of North America. In Gary Lackmann's presentation, he proposed one method for conducting high-resolution simulations of extreme weather events in future climate scenarios. This technique, which has been called "pseudo-global-warming", compares a high-resolution model simulation initialized with the observed conditions in today's climate with a simulation initialized with the large-scale meteorological conditions but includes projected changes in SSTs and air temperature. Lackmann compared a credible simulation of a historical event to a simulation that included future climate increments of moisture, temperature, etc.; in his A2 simulations, he found the increase in extreme precipitation rates to exceed the water vapor increase.

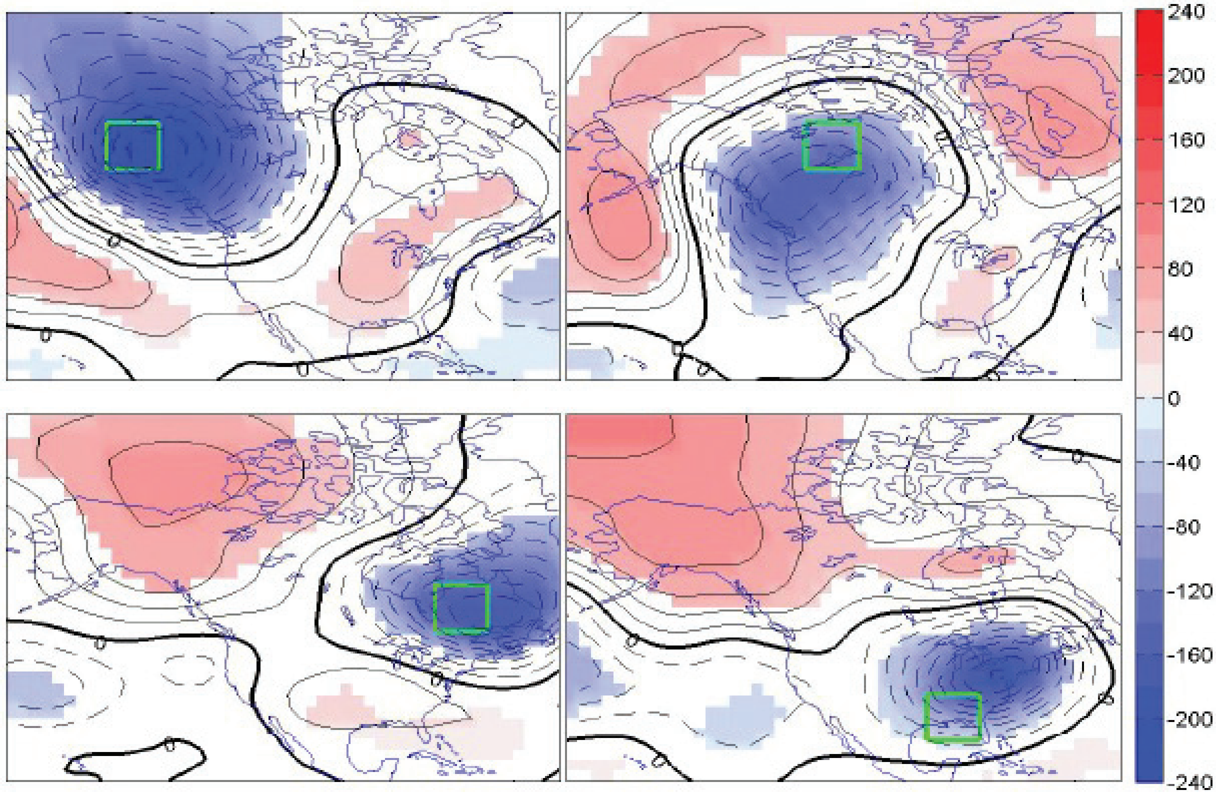

Figure 6: Composite maps of 500 hPa geopotential height anomalies during coldest 5% of January dates in the NCEP/NCAR Reanalysis 1. 20m contour interval used, with dashed lines for negative values. Shading denotes statistical significance (t-test) at the 5% level. Related information can be found in Loikith and Broccoli (2012).

How well can models simulate LSMPs and the associated T/P extremes? What are the uncertainties in simulating/predicting the LSMP and extreme T/P?

There are several issues that were presented and discussed during the modeling sessions. The consensus was that CMIP5 models are better than expected in simulating LSMPs (better than CMIP3). They capture the broad features of the LSMPs, but there are substantial inter-model differences. Models tend to produce blocking events, but generally have lower persistence than observed features. Grotjahn showed a heat wave 'LSMP index' and LSMPs for the NCAR model CCSM4. CCSM4 develops LSMP-like patterns (with specific biases) but not as often as observed (Grotjahn 2013). Vavrus concluded that climate models can reasonably simulate LSMPs associated with cold air outbreaks (CAOs) in current climate and that the patterns won't change fundamentally in the future. Broccoli found that all models, even the 'poorer' model, simulated well the 500 hPa geopotential height LSMPs for winter cold and warm events in the continental interior; for other areas shown, the model results resembled the LSMPs but the poorer model had noticeable amplitude errors, especially for regions near the continental edge. Perhaps in contrast to temperature events, Lackmann stated that synoptic precursors to extreme precipitation are often poorly resolved by global climate models (GCMs provide lateral boundary conditions for the RCM).

The model discrepancies in simulating cold extremes are generally larger than those for warm extremes, as discussed by Kharin et al. (2013), and warm extremes are reasonably well simulated when compared against the reanalyses. Storm track results for the Northern Hemisphere have been mixed in CMIP5 simulations due to differences in sea surface temperatures (SSTs) and parameterizations (microphysics, radiation). Moderate resolution general circulation models (GCMs) appear to do about the same as finer resolution models (e.g., in NARCCAP; Bukovsky et al. 2013). Finer resolution models do a little better with extremes, but results depend on the parameterizations and model physics. Vavrus mentioned that CAO LSMPs are affected by soil moisture and snow cover.

Numerical models produce heavy tails for precipitation, but not as heavy as observations. Uncertainty in extreme precipitation in the tropics and subtropics remains very large, both in the models and reanalysis (Kharin et al. 2013).

What insights can models provide to better understand the relationships between LSMP and extreme T/P?

Model simulations capture the broad features of the LSMPs, but there are substantial inter-model differences. In general, GCMs, due to lower resolution, are better at simulating LSMPs than corresponding climate extremes themselves. One can take advantage of this fact in developing statistical downscaling methods to (a) get usable information on climate extremes from the simulation of LSMPs; (b) use such relationships in extended-range prediction of climate extremes; and (c) use the techniques in quantifying uncertainties in projections of climate extremes. Climate simulations also have the advantage of providing physically consistent datasets for developing better understanding about LSMPs and climate extremes, something that is lacking in observations. On the negative side, however, models have biases that can influence the LSMPs-climate extreme relationship.

Moreover, LSMPs and extreme temperature and precipitation may be better captured in winter than in summer. An important issue to understand inter-model differences and the events is to look at key ingredients (metrics) that explain LSMPs or extreme temperature or precipitation events. Sometimes a key ingredient is necessary but not sufficient to produce an extreme; in other cases it may be necessary to look at the temporal evolution of an event.

Many models show systematic strong cold or warm biases as compared to observations. This is a problem that was seen in CMIP3 and was not resolved in CMIP5 (for the Southwest US and Mexico); this problem is discussed in Bukovsky et al. (2013).

Future extreme precipitation may not respond to current convective parameterization schemes (model physics); this is an issue that needs to be discussed between modelers and atmospheric scientists. Moreover, with the availability of finer scale models (regional dynamical models) there are several downscaling challenges: (a) what kind of convection-related errors may appear with increasing fine resolution?; (b) how does one decide what is the "best" global model to force a regional model?; and (c) what kind of metrics should we use to make those decisions? In Gary Lackmann's presentation, he proposed one method for conducting high-resolution simulations of extreme weather events in future climate scenarios. This technique, which has been called "pseudo-global-warming", compares a high-resolution model simulation initialized with the observed conditions in today's climate with a simulation initialized with the large-scale meteorological conditions but includes projected changes in SSTs and air temperature.

3 Knowledge Gaps, Research Priorities, and Recommendations

The final morning of the workshop reviewed summaries of the discussion breakouts and engaged participants in a plenary discussion of knowledge gaps, research priorities, and recommendations to accelerate progress on understanding LSMPs and their connection to extreme weather events. The following set of recommended actions were distilled from that discussion.

3.1 Data Needs and Recommendations

- Develop *indices* specific to exploring the causes of extreme temperature and precipitation that exploit the high quality North American observations. These metrics would be supplemental to the ETCCDI indices designed for climate change detection purposes and sparse data. These indices should *include measures of the LSMPs* associated with various regional extreme events.
- Better quantify and present the *uncertainties in observed datasets* as part of the downloadable datasets.
- Increase *investments in "Big Data" technologies* focused on climate and weather applications. These investments should include both software and hardware technologies.
- Promote efforts to *maintain current observing networks*, especially those with long observing records.
- Enlist scientists to engage and provide strong encouragement to *volunteers* who are *maintaining cooperative observing networks*.

3.2 Statistical Tool Needs and Recommendations (e.g., Tools Beyond ETCCDI Indices)

- Promote the use of *multiple data-analysis approaches* (e.g., clustering techniques, self-organizing maps, simple composites) to identify and analyze LSMPs associated with extreme events.
- Develop and promote techniques to *assess uncertainty in climate model predictions* of extreme events, especially uncertainty in the application of extreme values (e.g., relative to some threshold), LSMP indices, and other metrics of extreme events.
- Identify *limits of techniques* including, not only those listed in Recommendation 1, but also those based on extreme value statistics.
- Think globally when studying extreme events and explore the potential for *including low-frequency phenomena* (e.g., ENSO, NAO, PDO, annular modes) that may influence episodes of extreme events (but have a different time scale) in statistical analyses.

3.3 Synoptic and Dynamical Knowledge Gaps and Recommendations

- Establish *general uniformity* and *relative simplicity* in characterizing LSMPs, as there is no commonly accepted practice for isolating LSMPs (although there are multiple approaches for this purpose).

- Study *atmospheric blocking events*, identified as an important LSMP relative, as blocks (a) have no unique definition, (b) are strongly linked to extreme weather events and (c) are difficult for climate models to accurately represent.

- Characterize for precipitation EWEs the specific *physical role of mid-level trough LSMPs* in modulating regional precipitation strength.

- Develop a *coordinated research effort* on deducing the physical mechanisms responsible for the *formation and maintenance* of targeted LSMPs linked to particular types of EWE events.

- Engage the *atmospheric dynamics community* in the study of key LSMPs. This effort should include synoptic and dynamical diagnosis along with hierarchical modeling experiments to delineate among local dynamics, remote/boundary forcing, and low frequency modes.

- Identify *specific markers/metrics* for model diagnosis, buiding upon the above research efforts to *identify atmospheric features* (such as local vorticity gradients, stationary wave structure, and storm track variability) and *physical processes* (tropical heating anomalies, Rossby wave generation/propagation, local dynamical processes) related to the life cycles of critical LSMPs.

- Train *students* able to carry on the necessary research, particularly linking the fundamental dynamical mechanisms, thermodynamic processes in the planetary boundary layer, moist convection, and radiation.

3.4 Modeling Needs and Recommendations

- Create a database of *model runs with higher temporal resolution* (e.g., sub-daily instantaneous fields) but not as complex as the CMIP5 database. A problem with CMIP3 and CMIP5 datasets was that daily data in the vertical (and even for surface variables) were not readily available in a sufficiently timely manner to facilitate analyses of synoptic-scale processes; some models still do not have daily information available.

- Develop *large-scale circulation indices* for LSMPs that lead to temperature and precipitation extremes; and that can be used for diagnosing model output.

- Foster a *community consensus approach* to comparing model data at different model grid sizes with observational station data and/or observed gridded datasets. Should one interpolate all gridded data to a common grid (for example to the observed gridded dataset) to make easier metric comparisons? Should there be a common interpolator?

- Advance beyond the global extreme climatic indices developed by Kharin et al. 2013 (and Michael Wehner, LBNL) at the annual time scale, to *develop seasonal indices* to study heat and cold waves in specific seasons.

- Identify *standard outputs* for relevant LSMPs indices for the CMIP6 archive.

- Consider *time-evolution of LSMPs*. At present, most analyses are looking at simultaneous occurrence of LSMPs and extremes. This will help advance research into the predictive domain.

- Work with the *community of extreme weather researchers* to establish best approaches for identifying LSMPs in model simulations. Provide guidance to users when working with model data in efforts to understand LSMPs-climate extreme relationships.

- Organize an effort in *identifying biases* in extremes-LSMPs connections *in model simulations*.

- Address the question of *how variability in LSMPs is changing* under changing climate, which might provide useful information on the assessment of changes in climate extremes.

- Develop *metrics* as to how good is good enough when connecting LSMPs with relevant extremes in climate simulations.

- Build a *library of extreme climate events* for each index that includes the date and location of every event, so that it would be possible to go back to create and analyze the LSMPs of the events.

3.5 Additional General Recommendations

Questionnaires were given to attendees that posed six questions as possible input to the discussion sessions and for individual responses:

1. *What are the key scientific questions for short-term temperature and precipitation extremes?*
2. *Are there any infrastructure needs (e.g., data availability and storage, pre-processing of indices, field campaigns) that are holding back progress?*
3. *Are there any community activities (e.g., workshops, conference sessions, discussions of metrics and definitions, interaction among the numerous different national and international groups doing work related to extremes) that would help speed progress?*
4. *Is there anything that needs to be added to the current consideration of extremes in the US National Climate Assessment and the IPCC?*
5. *Are there any other follow-on activities that would be useful?*
6. *In the process of drafting the US CLIVAR Science Plan, we found a broad range of opinions on what "climate extremes" and/or "climate and weather extremes" meant: how would you define "climate extreme" and do you think it should be separate from "weather extreme"?*

Ten responses were received. A wide range of topics were mentioned but there were several common themes:

- enthusiasm for the workshop and a strong interest in further activities that bring together the different communities working on extremes;
- an interest in relating more to societal impacts, especially in terms of user needs and user-relevant definitions; and
- an emphasis on the importance of considering extremes from a dynamical point of view.

A summary of the responses to individual questions follows.

For question one, responses related to *key scientific questions* include: (a) whether the basic statistical distributions for all seasons and locations in North America had been investigated yet, (b) what are the physical mechanisms underlying trends in extreme events, and whether models adequately simulate those processes. Several questions directly relate to LSMPs, including: (c) what are the monthly to seasonal predictability of LSMPs, (d) what are the relative importance of multidecadal variability as compared to high-frequency variability and to anthropogenic forcing, (e) whether LSMPs can be defined for other extreme weather, (f) what are the mechanisms for generating and maintaining the LSMPs, and (g) how can LSMPs be used to diagnose models. Other questions included (h) whether definitions of extremes could also be made based on societal impact and (i) how relevant the range of current definitions are to impacts.

For question two on *infrastructure needs*, a key issue is (a) managing and analyzing the large amount of data ('Big Data') needed to capture and analyze the conditions during extreme events. Other responses included the (b) usefulness of descriptions (including data quality) and references for all methodologies (including extreme value statistics) and data discussed in the workshop, (c) an extremes resources website, (d) preprocessing of extremes indices for models and reanalyses, (e) gridded aerosol estimates, (f) computer resources for running sufficiently high resolution experiments, and (g) information on related extremes with high societal impact (wind, snow, freezing rain).

For question three on *community activities*, 9 of the 10 responses (one blank) emphasized (a) the importance of continuing communication on the topic of extremes and LSMPs, and 5 specifically requested (b) follow-on workshops or meetings, including on dynamical metrics, user needs, and applied extreme value statistics. These efforts could be leveraged by coordination with other efforts like: WCRP's 'Grand Challenge' in climate extremes, WWRP's interest in high impact weather (e.g. THORPEX), and other groups like ICDM-organized sessions at IAMAS meetings.

For question four on *the National Climate Assessment and the IPCC*, the responses noted a need for (a) more focus on dynamically-oriented indices and analysis, (b) more understanding of trends and projections of other extreme weather (severe convective storms-related weather, high winds, turbulence, blizzards), and (c) more emphasis on understanding blocking and models' struggles with correctly reproducing it.

For question five on *follow-on activities*, the responses suggest (a) briefing program officers on the workshop results, in particular on the importance of dynamical understanding and observational analysis and incorporation of those efforts into model design and evaluation. An effort (b) to develop extreme indices beyond just temperature and precipitation is valuable, involving dynamicists, modelers, and application sector communities. (c) Another workshop on predictability of extremes is favored. The possibility of special sessions at AGU/AMS meetings was also mentioned.

For question six, on *definitional issues with weather and climate extremes*, there was an overall agreement on (a) the importance of the weather-climate interface but a split vote on (b) whether there is a distinction between climate extremes and weather extremes – with some not drawing an essential distinction (e.g. the climate extreme being an aggregation of extreme events over time), while others considered a climate extreme to involve timescales longer than weather and a weather extreme consisted of a single synoptic event.

4 Concluding Thoughts

The Berkeley workshop was highly successful in helping the Extremes WG make progress towards its goals. It demonstrated working techniques for characterizing LSMPs, showed the utility of the LSMP approach for understanding extremes and assessing model representation of them, and highlighted the importance of a dynamical approach to extremes analysis. Several key knowledge gaps were identified for this critical societally-important research area and a detailed set of recommendations were developed for addressing these gaps. Given the broad nature of the problem – spanning data issues, statistics, observational analysis, and modeling – there was also general agreement and enthusiasm on the need for further efforts like this workshop that span multiple areas of expertise and help to build and support a network of extremes researchers.

5 Acknowledgements

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6 References

Brown, S.J., J. Caesar, and C.A.T. Ferro, 2008: Global changes in extreme daily temperatures since 1950. *J. Geophys. Res.*, **113**, DO5115, doi:10.1029/2006JD008091.

Bukovsky, M.S., and D J. Karoly, 2007: A brief evaluation of precipitation from the North American Regional Reanalysis. *J. Hydrometeor.*, **8**, 837–846, doi:10.1175/JHM595.1.

Bukovsky, M.S., D. J. Gochis, and L. Mearns, 2013: Towards assessing NARCCAP regional climate model credibility for the North American monsoon: Current climate simulations. *J. Climate*, **26**, 8802-8826, doi:10.1175/JCLI-D-12-00538.1.

Cavazos, T., 2000: Using Self-Organizing Maps, **13**, 1718–1732.

Cellitti, M.P., J.E. Walsh, R. M. Rauber, and D.H. Portis, 2006: Extreme cold air outbreaks over the United States, the polar vortex, and the large-scale circulation, *J. Geophys. Res.*, **111**, D02114, doi:10.1029/2005JD006273.

Compo, G.P., J.S. Whitaker, and P.D. Sardeshmukh, 2006: Feasibility of a 100 year reanalysis using only surface pressure data. *Bull. Amer. Met. Soc.,* **87**, 175-190, doi:10.1175/BAMS-87-2-175.

Compo, G.P., J.S. Whitaker, P.D. Sardeshmukh, N. Matsui, R.J. Allan, X. Yin, B.E. Gleason, R.S. Vose, G. Rutledge, P. Bessemoulin, S. Brönnimann, M. Brunet, R.I. Crouthamel, A.N. Grant, P.Y. Groisman, P.D. Jones, M. Kruk, A.C. Kruger, G.J. Marshall, M. Maugeri, H.Y. Mok, Ø. Nordli, T.F. Ross, R.M. Trigo, X.L. Wang, S.D. Woodruff, and S.J. Worley, 2011: The Twentieth Century Reanalysis Project. *Quarterly J. Roy. Meteorol. Soc.*, **137**, 1-28.Dee, D.P., and Coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.*, **137**, 553–597, doi:10.1002/qj.776.

Creamean, J.M., and co-authors, 2013: Dust and biological aerosols from the Sahara and Asia influence precipitation in the western U.S. *Science*, doi:10.1126/science.1227279.

Dole, R.M., and R.X. Black, 1990: Life cycles of persistent anomalies. Part II: The development of persistent negative height anomalies over the North Pacific Ocean. *Mon. Wea. Rev.*, **118**, 824–846.

Dole, R., M. Hoerling, A. Kumar, J. Eischeid, J. Perlwitz, X.W. Quan, G. Kiladis, R. Webb, D. Murray, M. Chen, K. Wolter, and T. Zhang, 2014: The making of an extreme event: Putting the pieces together. *Bull. Amer. Meteor. Soc.*, **95**, 427–440, doi:10.1175/JCLI-D-12-00270.1.

Evans, K.J., and R. Black, 2003: Piecewise tendency diagnosis of weather regime transitions. *J. Atmos. Sci.,* **60**, 1941–1959, doi:10.1175/1520-0469(2003)060<1941:PTDOWR>2.0.CO;2.

Fan, J., L.R. Leung, P. DeMott, J. Comstock, B. Singh, D. Rosenfeld, J.M. Tomlinson, A. White, K.A. Prather, P. Minnis, J.K. Ayers, and Q. Min, 2014: Aerosol impacts on California winter clouds and precipitation during CalWater 2011: Local pollution versus long-range transported dust. *Atmos. Chem. Phys.*, **14**, 81–101, doi:10.5194/acp-14-81-2014.

Feldstein, S.B., 2002: Fundamental mechanisms of the growth and decay of the PNA teleconnection pattern. *Quart. J. Roy. Meteor. Soc.*, **128**, 775-796, doi:10.1256/0035900021643683.

Feldstein, S.B., 2003: The dynamics of NAO teleconnection pattern growth and decay. *Quart. J. Roy. Meteor. Soc.*, **129**, 901-924, doi:10.1256/qj.02.76.

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.

Gilleland, E., B.G. Brown, and C.M. Ammann, 2013: Spatial extreme value analysis to project extremes of large-scale indicators for severe weather. *Environmetrics*, **24**, 418-432, doi:10.1002/env.2234.

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. *Dynamics and Predictability of Global and Regional High-Impact Weather and Climate Events*, J. Li, R. Swinbank, H. Volkert and R. Grotjahn, Eds. Cambridge Univ. Press, in press.

Grotjahn R, and G. Faure, 2008: Composite predictor maps of extraordinary weather events in the Sacramento, California, region. *Wea. Forecasting,* **23**(3), 313–335, doi:10.1175/2007WAF2006055.1.

Gyakum, J. R., 2008: The Application of Fred Sanders' teaching to current research on extreme cold-season precipitation events in the Saint Lawrence River Valley region. *Meteor. Monogr.*, **33**, 241–250, doi:10.1175/0065-9401-33.55.241.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*, Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley Eds., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77,** 437–471.

Kanamitsu, M., and Coauthors, 2002: NCEP-DEO AMIP-II Reanalysis (R-2). *Bull. Amer. Meteor. Soc.*, **83**, 1631-1643.

Kharin, V.V., F.W. Zwiers, X. Zhang, M.F. Wehner, 2013: Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Climatic Change*, **119**, 345-357, doi:10.1007/s10584-013-0705-8.

Kunkel, K.E., D.R. Easterling, D.A.R. Kristovich, B. Gleason, L. Stoecker, and R. Smith, 2012: Meteorological causes of the secular variations in observed extreme precipitation events for the conterminous United States. *J. Hydromet.*, **13**, 1131-1141, doi:10.1175/JHM-D-11-0108.1.

Loikith, P. C., A. J. Broccoli, 2012: Characteristics of observed atmospheric circulation patterns associated with temperature extremes over North America. *J. Climate*, **25**, 7266–7281. doi:10.1175/JCLI-D-11-00709.1.

Mak, M., and M. Cai, 1989: Local barotropic instability. *J. Atmos. Sci.*, **46**, 3289–3311.

Mannshardt-Shamseldin, E.C., R.L. Smith, S.R. Sain, L.O. Mearns, and D. Cooley, 2010: Downscaling extremes: A comparison of extreme value distributions in point-source and gridded precipitation data. *Ann. Appl. Stat.*, **4**, 484-502, doi:10.1214/09-AOAS287.

Meehl, G, and C. Tebaldi, 2004: More intense, more frequent, and longer lasting heat waves in the twenty-first century. *Science,* **305**, 994–997, doi:10.1126/science.1098704.

Mesinger, F., and Coauthors, 2006: North American Regional Reanalysis. *Bull. Amer. Meteor. Soc.*, **87**, 343–360, doi:10.1175/BAMS-87-3-343.

Milrad, S. M., E. H. Atallah, J. R. Gyakum, and G. Dookhie, 2014: Synoptic typing and precursors of heavy warm-season precipitation events at Montreal, Quebec. *Wea. Forecasting*, in press.

Nakamura, H., and J.M. Wallace, 1990: Observed changes in baroclinic wave activity during the life-cycles of low-frequency circulation anomalies. *J. Atmos. Sci.*, **47**, 1100–1116.

Photiadou, C., M. Jones, D. Keellings, and C. Dewes, 2014: Modeling European hot spells using extreme value analysis. *Climate Res.*, **58**, doi:10.3354/cr01191.

Plumb, R.A., 1985: On the three-dimensional propagation of stationary waves. *J. Atmos. Sci.*, **42**, 217–229.

Rienecker, M.M., and Coauthors, 2011: MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. *J. Climate*, **24**, 3624-3648, doi:10.1175/JCLI-D-11- 00015.1.

Saha, S., and Coauthors, 2010: The NCEP Climate Forecast System Reanalysis. *Bull. Amer. Meteor. Soc.,* **91,** 1015-1057, doi:10.1175/2010BAMS3001.1.

Sardeshmukh, P.D., and B.J. Hoskins, 1988: The generation of global rotational flow by steady idealized tropical divergence. *J. Atmos. Sci.*, **45**, 1228–1251.

Schumacher, R.S., and C.A. Davis, 2010: Ensemble-based forecast uncertainty analysis of diverse heavy rainfall events. *Wea. Forecasting*, **25**, 1103-1122, doi:10.1175/2010WAF2222378.1.

Sillmann, J., M. Croci-Maspoli, M. Kallache, and R.W. Katz, 2011: Extreme cold winter temperatures in Europe under the influence of North Atlantic atmospheric blocking. *J. Climate*, **24**, 5899-5913, 10.1175/2011JCLI4075.1.

Simmons, A.J., J.M. Wallace, and G. Branstator, 1983: Barotropic wave propagation and instability and atmospheric teleconnection patterns. *J. Atmos. Sci.*, **40**, 1363–1392.

Stephenson, D., and T. Economou, 2012: Spatial extreme-value modelling of European and Atlantic storms, *Workshop on Statistical Applications to Climate Extremes, Zurich, Switzerland,* (presentation at www.mmm.ucar.edu/people/mingge/DOWNLOAD/stephenson-new.pdf).

Takaya, K., and H. Nakamura, 2001: A formulation of a phase-independent wave-activity flux for stationary and migratory quasigeostrophic eddies on a zonally varying basic flow. *J. Atmos. Sci.*, 58, 608–627.

Tang, Q., X. Zhang, X. Yang and J.A. Francis, 2013: Cold winter extremes in northern continents linked to Arctic sea ice loss. *Environ. Res. Lett.*, 8, 014036, doi:10.1088/1748-9326/8/1/014036.

Walsh, J.E., A.S. Phillips, D.H. Portis, and W.L. Chapman, 2001: Extreme cold outbreaks in the United States and Europe, 1948–99, *J. Climate*, 14, 2642–2658.

Westby, R.M., Y.-Y. Lee, R.X. Black, 2013: Anomalous temperature regimes during the cool season: Long-term trends, low-frequency mode modulation, and representation in CMIP5 simulations. *J. Climate*, 26, 9061–9076, doi:10.1175/JCLI-D-13-00003.1.

Whitaker, J.S., G.P. Compo, X. Wei, and T.M. Hamill, 2004: Reanalysis without radiosondes using ensemble data assimilation. *Mon. Wea. Rev.*, 132, 1190-1200, doi:10.1175/1520-0493(2004)132<1190:RWRUED>2.0.CO;2.

Zolina, O.G., P. Shapovalov, C. Simmer, A. Kapala, P. Becker, H. Maechel, S.K. Gulev, and P.Ya. Groisman, 2014: New view on precipitation variability and extremes in Central Europe from a high resolution German daily precipitation dataset: Results from the STAMMEX project. *Bull. Amer. Meteorol. Soc.*, in press, doi:10.1175/BAMS-D-12-00134.1.

Appendix A: Scientific Organizing Committee

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Appendix B: Workshop Agenda

U.S. CLIVAR Workshop:
Analyses, Dynamics, and Modeling of Large Scale Meteorological Patterns
Associated with Extreme Temperature and Precipitation Events

Lawrence Berkeley National Laboratory, Berkeley, CA
August 20-22, 2013

20 August - Tuesday

8:00 Continental Breakfast

8:30 **Welcome & Introductions**

Session 1: Data Talks

8:40 **Kenneth Kunke**l, NOAA CICS-NC/North Carolina State
"Meteorological Causes of Observed Extreme Precipitation Trends in the U.S."

9:10 **Pavel Groisman**, UCAR at NOAA NCDC
"The impact of data paucity and handling techniques on intense precipitation analyses"

9:40 **Pall Pardeep**, Lawrence Berkeley National Laboratory
"Using large climate data sets for Probabilistic Weather-Event Attribution"

10:10 Coffee Break

10:30 **Data Breakout Sessions** (2 parallel)

Session 2: Statistics Talks

11:30 **Richard Grotjahn**, University of California, Davis
"The why, how, and what of large scale meteorological pattern"

12:00 **Richard Katz**, NCAR
"Statistical Methods for Relating Temperature Extremes to Large-Scale Meteorological Patterns"

12:30 Catered Lunch

Session 2: Statistics Talks cont.

1:30 **Francis Zwiers**, Pacific Climate Impacts Consortium
"Applications of extreme value theory in climate science"

2:00 **Robert Black**, Georgia Institute of Technology
"Boreal Cool Season Temperature Regimes: Recent Trends and Low Frequency Mode Modulation"

2:30 **Christopher Paciorek**, University of California, Berkeley
"Analyzing trends and patterns in extreme precipitation in observations and models using statistical extreme value analysis"

3:00 **Sahsa Gershunov**, University of California, San Diego/Scripps
"Diagnosing probability models for observed daily precipitation extremes"

3:30 **Poster Session** (**Data** and **Statistics**) with Coffee Break

4:30 **Statistics Breakout Sessions** (2 parallel)

5:30 End of Day 1

6:30 Collaborative Discussion Time at Hotel Shattuck Plaza

21 August - Wednesday

8:00 Continental Breakfast

Session 3: Synoptics/Dynamics Talks

8:30 **Steven Feldstein**, The Pennsylvania State University
"A methodology for examining the relationship between teleconnections and extreme precipitation"

9:00 **Bill Gutowski**, Iowa State University
"Understanding Synoptic Weather Yielding Extreme Daily Precipitation"

9:30 **Shawn Milrad**, Embry-Riddle Aeronautical University
"On the synoptic-scale mechanisms of extreme precipitation events: The role of the anticyclone and a dynamically based event identification method"

10:00 **Russ Schumacher**, Colorado State University
"Wet weeks in the warm season: Patterns and processes supporting widespread multi-day heavy rainfall episodes"

10:30 Coffee break

Session 3: Synoptics/Dynamics Talks cont.

10:50 **Steve Vavrus**, University of Wisconsin
"Relating Extreme Weather Events to Large-Scale Meteorological Patterns: Is the Glass Half Full or Half Empty?"

11:20 **Randall Dole**, NOAA ESRL PSD
"The Making of An Extreme Event: Putting the Pieces Together"

11:50 **Synoptics/Dynamics Breakout Sessions** (2 parallel)

12:50 Catered Lunch

Session 4: Modeling Talks

2:00 **Noah Diffenbaugh**, Stanford University
"Robust increases in severe thunderstorm environments in response to greenhouse forcing"

2:30 **Anthony Broccoli**, Rutgers University
"Observed and Model Simulated Atmospheric Circulation Patterns Associated with Extreme Temperature Days over North America"

3:00 **Gary Lackmann**, North Carolina State University
"Climate Change and Mesoscale and Synoptic-Scale Precipitation Events" (by phone)

3:30 **Poster Session** (**Synoptics/Dynamics** and **Modeling**) with Coffee Break

4:30 **Session 4: Modeling Breakout Sessions** (2 parallel)

5:30 End of Day 2

6:00 Extremes WG Meeting at Hotel Shattuck Plaza (by invitation)

22 August - Thursday

8:00 Continental Breakfast

8:30 **Reports and Discussion from Breakouts Sessions** (45 min/each)
Data
Statistics

10:00 Coffee Break

10:30 **Reports and Discussion from Breakouts Sessions** cont. (45 min/each)
Synoptics/Dynamics
Modeling

12:00 **Meeting Wrap-up**

12:30 Adjourn

Poster Session (Data and Statistics) Tuesday, 8/20 @ 3:30

Data:

Rick Lader, University of Alaska Fairbanks
"Evaluating daily reanalysis temperature and precipitation for Alaska"

Michael Wehner, Lawrence Berkeley National Laboratory/University of California, Berkeley
"Extreme Event Attribution"

Statistics:

Elizabeth Cassano, Cooperative Institute for Research in Environmental Sciences
"Analysis of synoptic forcing for widespread surface temperature extremes across Alaska"

Brandon Fisel, Iowa State University
"Multi-Regime States and Extreme Behavior of Arctic Atmospheric Circulation"

Justin Glisan, Iowa State University
"A SOM-based approach for analyzing daily precipitation extremes over the North American Arctic"

Soyoung Jeon, Lawrence Berkeley National Laboratory
"Analysis of Spatial Dependence Patterns in Precipitation Extremes"

Megan Kirchmeier, University of Wisconsin-Madison, Atmospheric and Oceanic Sciences, Center for Climatic Research
"The use of probabilistic downscaling in relating local-scale extreme events to large-scale meteorological conditions"

Ken-Chung Ko, National Kaohsiung Normal University
"Circulation patterns for southern Taiwan's summer monsoon rainfall during July to September"

Yun-Young Lee, Georgia Institute of Technology
"Extreme Temperature Regimes in association with two types of El Niño"

Bo Madsen, University of Copenhagen
"Comparison of Relationship between Weather Regimes and Precipitation in Observations and Models"

Diandong Ren, Curtin University
"Extreme precipitation events in AR5 models and implications for flash floods"

Deepti Singh, Stanford University
"Precipitation extremes over the continental United States in a transient, high-resolution, ensemble climate model experiment"

Poster Session (Synoptics/Dynamics and Modeling) Wednesday, 8/21 @ 3:30

Synoptics/Dynamics:

Laurie Agel, University of Massachusetts - Lowell
"Dynamical Analysis of Extreme Precipitation Events in the Northeast"

Bradford Barrett, U.S. Naval Academy
"Intraseasonal variability of large-scale meteorological patterns and tornado activity"

Benjamin Lintner, Rutgers, The State University of New Jersey
"Impact of land-atmosphere interactions on surface temperature distributions"

Chihhua Tsou, National Taiwan Normal Univ.
"Role of Multi-scale Interaction in Tropical cyclones Eddy Kinetic Energy"

John Walsh, University of Alaska, Fairbanks
"Atmospheric circulation patterns associated with extreme events in Alaska"

Modeling:

Tereza Cavazos, Department of Physical Oceanography, CICESE
"Present and future daily precipitation extremes in the North American monsoon region"

Anthony DeAngelis, Rutgers University
"Evaluation of CMIP3 and CMIP5 Simulations of Heavy Precipitation and its Associated Physical Mechanisms over North America"

Sho Kawazoe, Iowa State University
"Regional, Very Heavy Daily Precipitation in Global and Regional Climate Simulations of North America"

Arun Kumar, NOAA / Climate Prediciton Center
"Do Extreme Climate Events Require Extreme Forcings?"

Paul Loikith, Caltech/JPL
"Evaluating Extreme Temperatures and Associated Mechanisms in NARCCAP Hindcast Experiments"

Appendix C: List of Participants

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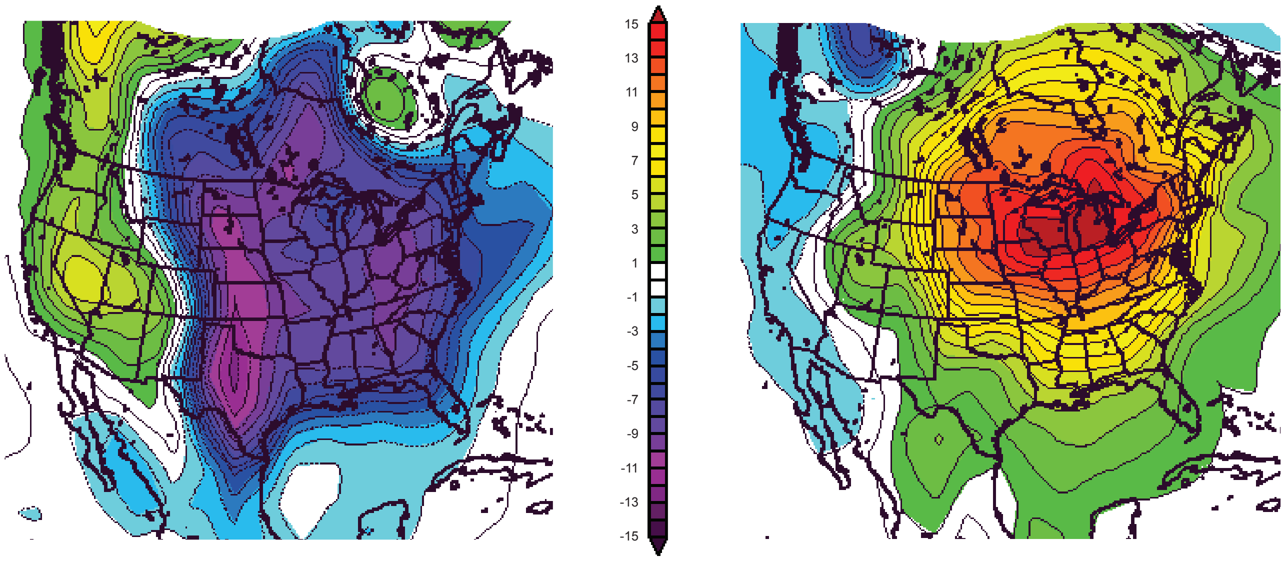
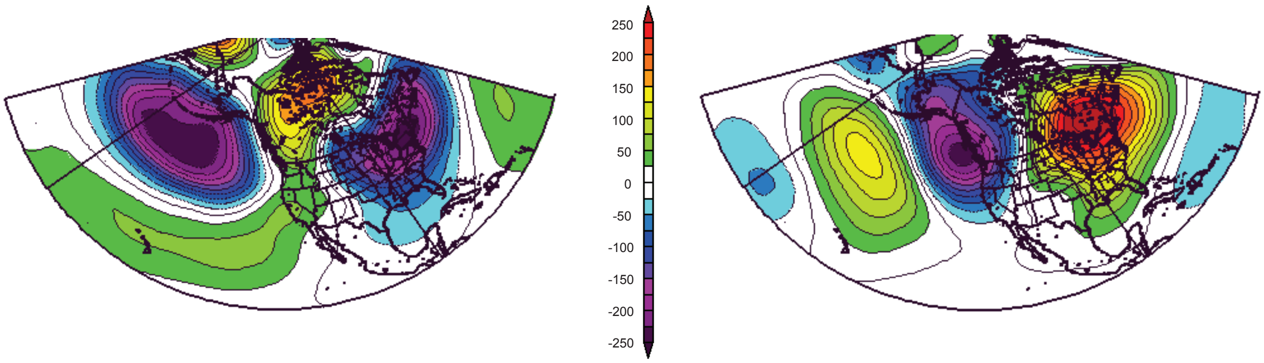
COLD AIR OUTBREAK
APRIL 6-10, 2007

HEAT WAVE
MARCH 13-23, 2012



Composite surface air temperature anomaly (°C)



Composite 500mb height anomaly (m)

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