Low Frequency Modulation of Extreme Temperature Regimes in a Changing Climate

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We review research activities supported by "Low Frequency Modulation of Extreme Temperature Regimes in a Changing Climate" (DOE/BER Award Number DE-SC0004942, PI: Robert Black). Our project examined the long-term modulation of extreme temperature regime (ETR) events by large-scale low frequency modes (LFMs) in both observations and CMIP5 model simulations.

1) Observed ETR behavior and ETR-LFM linkages

We completed a comprehensive climatological and statistical analysis of wintertime cold air outbreaks (CAOs) and warm waves (WWs) occurring over the continental United States during the past 60 winters. No significant long-term trends in either WWs or CAOs are observed over the continental United States. Winter-mean CAO frequency is modulated by the (i) North Atlantic Oscillation (NAO) over the Southeast and (ii) Pacific–North American (PNA) pattern over the Northwest. WW frequency is modulated by the (i) NAO over the eastern United States and (ii) combined influence of the PNA, Pacific decadal oscillation (PDO), and ENSO over the southern United States. Linear statistical analysis reveals that the collective influence of low-frequency modes can account for as much as 50% of the year-to-year regional variability in ETR frequency. This research is reported in Westby, Lee and Black (2013).

A second research effort in this topical area is related to *annular* low frequency modes, associated stratosphere-troposphere coupling and regional impacts on tropospheric weather, including temperature extremes. The Polar Annular Mode (PAM) is a stratospheric mode linked to the north-south movement of the stratospheric polar vortex during boreal winter. The structure, physics and tropospheric impact of PAM was studied via composite analyses of large amplitude PAM events. PAM events are found to be initiated in the stratosphere via the breaking of anomalous Rossby wave activity emanating from the troposphere. PAM onset is subsequently characterized by an abrupt change in the circumpolar jet stream with a coherent structure that extends from the mid-stratosphere downward through the troposphere to the Earth's surface. The tropospheric impact of PAM events persists for 2-3 weeks with a significant regional impact upon surface air temperature and midlatitude storm activity. These research results were published in Black, McDaniel and Lee (2012).

2) Synoptic characterization

Rebecca Westby, a PhD student supported under the grant, performed a thorough synoptic-dynamic characterization of ETRs occurring in the southeast US via composite time-evolution analyses categorized by the sign and amplitude of relevant low frequency modes. Synoptic-scale and large-scale disturbances both contribute to ETR onset. During CAO (WW) onset, negative (positive) geopotential height anomalies are observed in the upper troposphere over the SE with oppositely-signed anomalies in the lower troposphere over the central US. In most cases, there is a surface east-west height anomaly dipole, with anomalous northerly (CAO) or southerly (WW) flow into the SE leading to cold or warm surface air temperature anomalies, respectively. One distinction is that CAOs involve substantial air mass transport while WW formation is more regional in nature.

The primary differences among case categories are in the origin and nature of the circulation anomaly features linked to ETR onset. In a subset of WWs, the North American height anomaly pattern arises in part as a downstream manifestation of the negative PNA pattern. Conversely, in some CAOs, the height anomaly pattern over eastern North America is a regional expression of the negative NAO pattern that contributes to both CAO onset and demise. The results indicate that low frequency modes help to both trigger ETR formation and modulate ETR duration. Companion potential vorticity (PV) anomaly analyses reveal PV anomaly features in the mid to upper troposphere consistent in structure with the coincident geopotential height anomaly patterns. These results have been submitted for publication (Westby and Black 2014).

3) Physical mechanisms for ETR onset

We have performed detailed diagnostic studies of ETR onset in order to infer the proximate physical sources for regional temperature anomalies. A composite heat budget analysis of CAO onset indicates that linear advective transport near the surface is the primary contributor to the regional temperature decreases. This is partly offset by (a) anomalous nonlinear transport and (b) adiabatic warming associated with lower tropospheric subsidence. The linear advective transport is partitioned into pieces via piecewise PV inversion methods. This approach is based on a PV dynamical framework and allows a separation of the large-scale wind field into components associated with distinct dynamical features (each connected to individual PV anomaly elements). Applying this method to southeastern US cold air outbreaks, we have discovered the interesting (and nonintuitive) result that the lower tropospheric northerly winds enacting the event onset over the southeast can be partly attributed to the dynamical influence of a pre-existing shallow cold pool located along the east side of the Rocky Mountains. A journal article based upon this diagnostic research is currently under preparation.

4) Diagnosis of CMIP5 simulations

The main thrust of this research effort is in studying the representation of ETRs, LFMs and LFM-ETR linkages in state-of-the-art coupled climate models. We first assessed the ability of CMIP5 models to represent the structure and regional impact of the NAO and PNA patterns during boreal winter. While all models qualitatively replicate the basic structure of the PNA, a small minority of models fails to replicate the NAO pattern. Interestingly, models with a well-resolved stratosphere generally perform more poorly than those without. Model biases in representing the NAO and PNA patterns provide important consequences for representing associated regional variability in surface air temperature and storm track behavior. Model deficiencies in the NAO and PNA patterns are related to underlying model inadequacies in replicating the climatological stationary waves. These results are reported in Lee and Black (2013)

We also studied the structure and dynamics of the stratospheric northern annular mode (SNAM) in CMIP5 simulations. Models with a poorly-resolved stratosphere typically underrepresent SNAM amplitude at stratospheric altitudes, consistent with weaker polar vortex variability. However, this distinction does not carry over to the associated tropospheric signature. More specifically, a regional analysis illustrates that most CMIP5 models (with or without a well-resolved stratosphere) have anomalously weak and eastward shifted (versus observations) storm track and sea level pressure anomaly patterns during SNAM events. Dynamical analyses of stratosphere–troposphere coupling reveal that stratospheric planetary wave activity is anomalously weak in CMIP5 models with poorly-resolved stratospheres, due to correspondingly weak vertical propagation of planetary-scale Rossby wave activity upward into the stratosphere. This suggests that such models are characterized by anomalously weak vertical dynamical coupling during SNAM events. Paradoxically, however, there is little apparent impact upon attendant tropospheric variability. These results will be published soon (Lee and Black 2014).

We have also studied general ETR behavior and LFM-ETR linkages in CMIP5 models. Although CMIP5 models qualitatively replicate observed ETR behavior, WW (CAO) frequency is overestimated (underestimated). The collective influence of low-frequency modes upon ETRs is underestimated in CMIP5 models. Further, none of the models are able to replicate observed linkages between ETRs and the PDO, which is due to the misrepresentation of the PDO structure in most CMIP5 models. Our results suggest that predictions of future CAO and WW behavior are limited by the ability of climate models to accurately represent the primary natural modes of low-frequency variability (thereby limiting our ability to make specific projections on the future behavior of LFM-ETR linkages). These results are contained in Westby et al. (2013). Parallel research on assessing the role of stratospheric resolution in determining the realism of tropospheric climate in CMIP5 models was pursued in separate collaborative research efforts relating to the PI's involvement in the WCRP SPARC Dynvar project. These research efforts are contained in part of two journal submissions (Charlton-Perez et al. 2013, Manzini et al. 2014).

5) Related professional and academic activities

During the grant period the PI became a member of the US CLIVAR Extremes Working Group. The charge of the working group is evaluate whether current climate models produce extremes for the right reasons and whether they can be used for predicting and projecting short-term extremes in precipitation and temperature over North America (http://usclivar.org/working-groups/extremes). Our participation has provided an excellent opportunity to foster a synergistic interaction between grant research activities and a broader multi-agency scientific focus on the weather-climate nexus. Grant-related results were presented at a related CLIVAR Extremes Workshop and are included in the follow-up workshop report and review paper (Grotjahn et al. 2014). Our grant has provided support for (a) the mentorship of a graduate student (Ms. Rebecca Westby) and post-doctoral fellow (Dr. Yun-Young Lee) and (b) research activities reported in 8 journal articles (2 under review), 12 contributed presentations and 7 invited presentations. LFM and LFM-ETR linkages have been incorporated as elements of a Georgia Tech course the PI teaches on large-scale atmospheric circulations. For example, there is a particular emphasis on delineating the role of various LFMs and physical forcings in producing extremes occurring during recent boreal winters.

Grant Supported Publications (* indicates graduate student or postdoctoral advisee):

Black, R.X., B.A. McDaniel, and Y-Y. Lee*, 2012: The structure, dynamics and tropospheric signature of the Polar Annular Mode. *J. Geophys. Res.,* **117,** D19115, doi:10.1029/ 2012JD017900.

Charlton-Perez, A.J., et al.*, 2013: On the lack of stratospheric dynamical variability in low-top versions of the CMIP5 models. *J. Geophys. Res.,* **118,** 2494-2505, doi: 10.1002/jgrd.50125.

Grotjahn, R., et al., 2014: North American Extreme Temperature Events and Related Large Scale Meteorological Patterns: Statistical Methods, Dynamics, Modeling, and Trends. *Clim. Dyn.,* (submitted).

Lee*, Y-Y., and R.X. Black, 2013: Boreal Low Frequency Variability in CMIP5 models. *J. Geophys. Res. Atmos.,* **118,** 6891-6904, doi: 10.1002/jgrd.50493.

Lee*, Y-Y., and R.X. Black, 2014: The Structure and Dynamics of the Stratospheric Northern Annular Mode in CMIP5 Simulations. *J. Climate* (in press).

Manzini, E., et al.*, 2014: Northern winter climate change: Assessment of uncertainty in CMIP5 projections related to stratosphere-troposphere coupling, *J. Geophys. Res.,* **119,** 7979–7998, doi:10.1002/2013JD021403.

Westby*, R.M., and R.X. Black, 2014: Development of Anomalous Temperature Regimes over the Southeast United States: Synoptic Behavior and Role of Low Frequency Modes, *Wea. Forecasting,* (submitted).

Westby*, R.M., Y-Y. Lee* and 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.

Grant Related Non-Refereed Papers/Presentations (* indicates graduate student or postdoctoral advisee):

Black, R.X., R.M. Westby* and Y.-Y. Lee* 2014: The Low Frequency Modulation of Anomalous Temperature Regimes during Winter. *U.S. CLIVAR Variations,* **Vol. 12,** No. 1, 13-16. (Paper at: http://www.usclivar.org/sites/default/files/documents/2014/Variations-winter-2014-v3.pdf)

Westby*, R.M. and R.X. Black 2014: Anomalous Temperature Regimes during the Cool Season: Triggers and Physical Connections to Low Frequency Modes. 26th Conference on Climate Variability and Change, American Meteorological Society.
(Abstract at: https://ams.confex.com/ams/94Annual/webprogram/Paper232945.html)

Lee*, Y.-Y., and R.X. Black 2013: Boreal low frequency variability in CMIP5 models. 19th Conference on Atmospheric and Oceanic Fluid Dynamics, American Meteorological Society. (Abstract at: https://ams.confex.com/ams/19Fluid17Middle/webprogram/Paper227215.html)

Black, R.X., and Y.-Y Lee* 2013: Boreal low frequency variability, annular modes and stratosphere-troposphere coupling in CMIP5 models. Third SPARC DynVar workshop/ First SPARC SNAP workshop, World Climate Research Program. (Abstract at:
http://www.met.reading.ac.uk/~pn904784/DynVar_SNAP_Workshop/abstract/black.pdf)

Westby*, R.M., Y.-Y. Lee*, and R.X. Black 2013: Extreme Temperature Regimes in the United States: Long-term Trends and Low Frequency Mode Modulation in Observations and CMIP5 Models. 25th Conference on Climate Variability and Change, American Meteorological Society.
(Abstract at: https://ams.confex.com/ams/93Annual/webprogram/Paper220229.html)

Lee*, Y-Y., and R.X. Black, 2012: Boreal Low Frequency Variability in CMIP5 models. 45th Annual Fall Meeting, American Geophysical Union.
(Abstract at: http://fallmeeting.agu.org/2012/eposters/eposter/a53l-0320/)

Black, R.X., R.M. Westby*, and Y-Y. Lee*, 2012: Extreme Temperature Regimes during the Cool Season: Low Frequency Modulation and Representation in CMIP5 Models. Asia Oceania Geosciences Society – AGU (WPGM) Joint Assembly. (Abstract at:
http://www.asiaoceania.org/aogs2012/mars2/pubViewAbs.asp?sMode=oral&sectionIdO=4&dayRank=2&submit=Browse+Abstracts)

Black, R.X., R.M. Westby*, and Y.-Y. Lee*, 2012: Extreme Temperature Regimes During the Cool Season Part II: Simulated Behavior in CMIP5 Simulations. 24th Conference on Climate Variability and Change, American Meteorological Society.
(Abstract at: http://ams.confex.com/ams/92Annual/webprogram/Paper194941.html)

Westby*, R.M. and R.X. Black, 2012: Extreme Temperature Regimes During the Cool Season Part I: Recent Observed Behavior and Low Frequency Modulation. 24th Conference on Climate Variability and Change, American Meteorological Society.
(Abstract at: http://ams.confex.com/ams/92Annual/webprogram/Paper194940.html)

Black, R.X., R.M. Westby* and Y.-Y. Lee*, 2011: Extreme Temperature Regimes during the Cool Season: Recent Observed Behavior and Low Frequency Modulation. Department of Energy Climate and Earth System Modeling Meeting.

Black, R.X., B.A. McDaniel and Y.-Y. Lee*, 2011: Stratosphere-troposphere coupling: The stratospheric seasonal cycle in CMIP5 models. WCRP Open Science Meeting.
(http://conference2011.wcrp-climate.org/abstracts/C34/Black_C34_W176A.pdf)

Black, R.X., and R. Westby*, 2011: Extreme temperature regimes during the cool season, 23rd Conference on Climate Variability and Change, American Meteorological Society.
(Abstract at: http://ams.confex.com/ams/91Annual/webprogram/Paper180666.html)

Grant Related Invited Presentations

US CLIVAR - Workshop on Analyses, Dynamics and Modeling of Large-Scale Meteorological Patterns Associated with Extreme Temperature and Precipitation Events, August 2013 (Invited Presentation)

MIT - Cool Season Temperature Regimes: Low Frequency Modulation and Representation in CMIP5 Models, November 2012 (Invited Seminar).

National Taiwan University - Extreme Temperature Regimes during the Cool Season: Low Frequency Modulation and Representation in CMIP5 Models, August 2012 (Invited Seminar).

AOGS - AGU (WPGM) Joint Assembly, August 2012 (Invited Speaker).

NCAR - Advance Study Program Summer Colloquium. The Weather-Climate Intersection: Advances and Challenges, June 2012 (Invited Speaker).

University of Georgia – Extreme Temperature Regimes during the Cool Season: Recent Observed Behavior and Low Frequency Modulation, November 2011 (Invited Seminar).

North Carolina State University – Extreme Temperature Regimes during the Cool Season, April 2011 (Invited Seminar).