Boreal Cool Season Anomalous Temperature Regimes: Trends and Low Frequency Modulation

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Presentation Overview

- ♠ Introductory remarks/General issues/Background
- ♥ Data & methods applied in the current study
- ♣ Interannual variability and long-term trend analysis
- ♦ Interannual modulation by low frequency modes
  - ➙ Correlation and linear regression analysis
- ♠ Assessment of CMIP5 model performance:
  - ➙ Representation of low frequency modes
  - ➙ LFM modulation of temperature regimes
- ♥ Summary and concluding remarks

General Issues for Consideration

- ♠ ***What datasets to analyze?*** *(e.g., station data vs. reanalyses)*
- ♥ ***How to define anomalous temperature regimes (ATRs)?*** *(local or regional?; absolute temperature vs anomalies; how anomalous/"extreme"?; how long-lived/persistent?)*
- ♣ ***How to address non-stationarity?*** *(Accounting for non-stationarity in defining extremes, assessing trends, etc.)*
- ♦ ***How to characterize linkages between ATRs and Large Scale Meteorological Patterns (LSMPs)?*** *Begin with ATRs and work toward LSMPs? Start with known LSMPs (e.g., PNA, NAO) and assess impact on ATR behavior?*
- ♠ ***What is required of CGCMs to enable predictive utility?*** *(hindcast validation tests; general behavior of ATRs; general behavior of LSMPs; LSMP-ATR linkages)*

Winter ATRs in the Continental US: General Behavior

- ♠ *Considerable body of research on cold air outbreaks (CAOs) but limited research on warm waves (WWs)*
- ♥ *Both CAOs and WWs provide substantial regional impacts upon regional energy consumption, agriculture & health (Cellitti et al. 2006, Gu et al. 2008, Peterson et al. 2013)*
- ♣ *Little evidence of long term trends in frequency of CAOs (Walsh et al. 2001, Portis et al. 2006, Andrade & Santos 2012, Westby et al. 2013)*
- ♦ *Paradox: Significant warming trends *are* occurring in regions of cold air mass formation (Hankes & Walsh 2011)*
- ♠ *Recent winters (09/10; 10/11) have exhibited prominent regional CAOs (e.g., Guirguis et al 2011) within a back-ground consisting of anomalously warm hemisphere-average winter temperatures (Cohen et al. 2010).*

Winter ATRs in the Continental US: LSMP linkages

- ♠ ***It is well known that major low frequency modes (LFMs) modulate the behavior of CAOs over the CONUS (Walsh et al. 2001, Vavrus et al. 2006, Lim & Schubert 2011).***
- ♥ ***Both the Pacific North American (PNA) pattern and North Atlantic Oscillation (NAO) play key roles in this behavior (Cellitti et al. 2006, Guirguis et al. 2011, Westby et al. 2013)***
- ♣ ***The role of ENSO in modulating ATRs differs from earlier findings with a stronger connection to WWs than CAOs (Lim & Schubert 2011, Westby et al. 2013).***
- ♦ ***Recent focus on role of high latitude warming (Arctic amplification), weakening jet (negative AO/NAO) and amplified Rossby wave patterns (enhanced blocking) leading to increased ATRs (e.g., Francis & Vavrus 2011)***

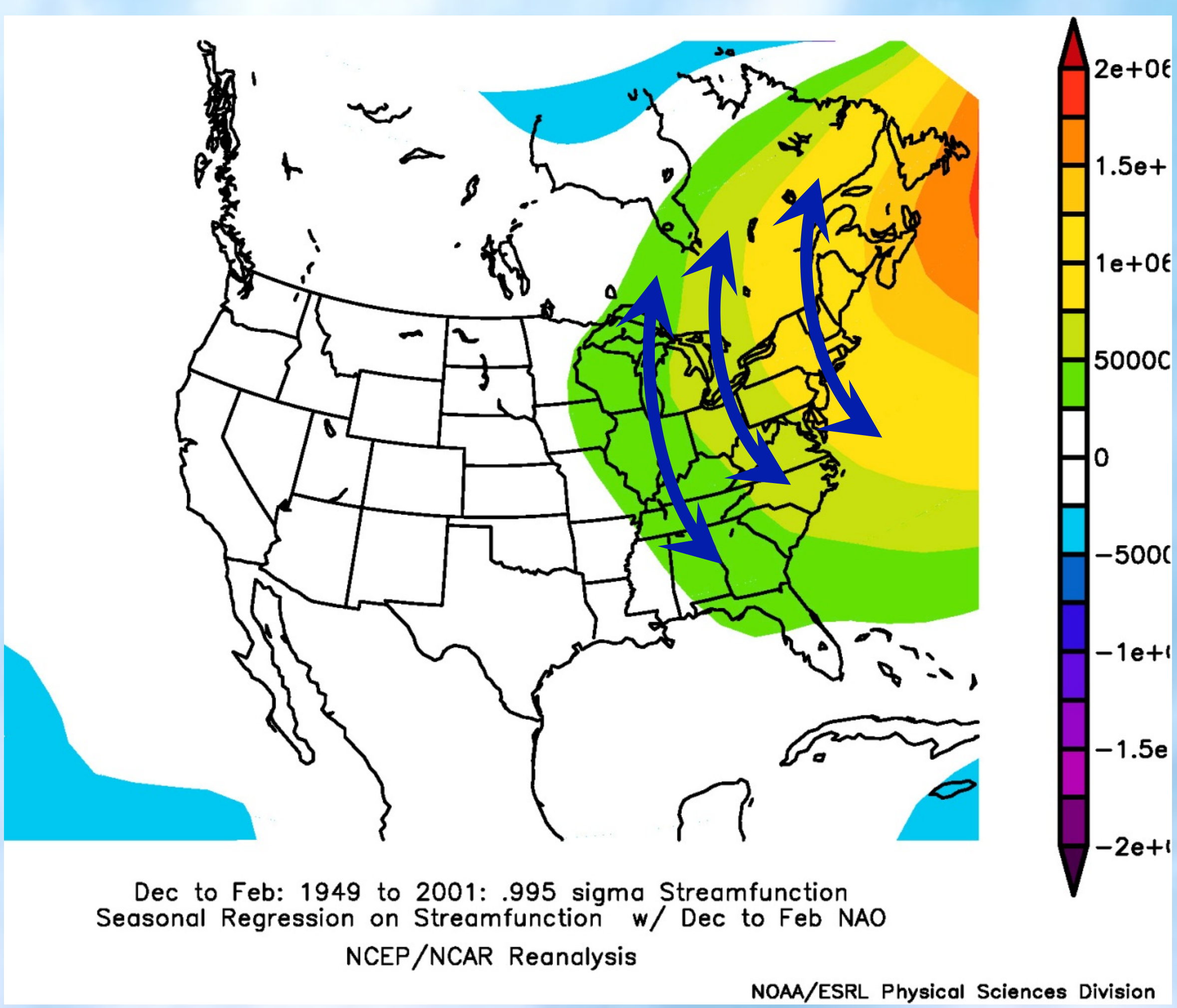
(Less cold air but greater latitudinal mobility?)

Underlying Physics of LSMP-ATR linkages

- ♠ ***Large-scale impacts*** ***(Dynamically driven):***
  - ➙ ***Linear: Direct contribution of large-scale circulation to alterations in regional temperature advection***
  - ➙ ***Nonlinear: Low frequency modulation of synoptic time/space scale variability (e.g., storm tracks)***
- ♥ ***Local impacts*** ***(local response):***
  - ➙ ***Interaction of large-scale circulation with local topography and/or coastal interface***
  - ➙ ***Introduction of asymmetric local ATR response (e.g., Loikith and Broccoli 2012)***
- ♣ ***Possible feedback*** ***of ATRs upon LSMP?***

Regional Influence of Low Frequency Mode: NAO

- ♠ *Linear regression of near surface streamfunction w/NAO*
- ♥ *Positive NAO: Anomalous southerly flow over Eastern US*
- ♣ *Negative NAO: Anomalous northerly flow over Eastern US*



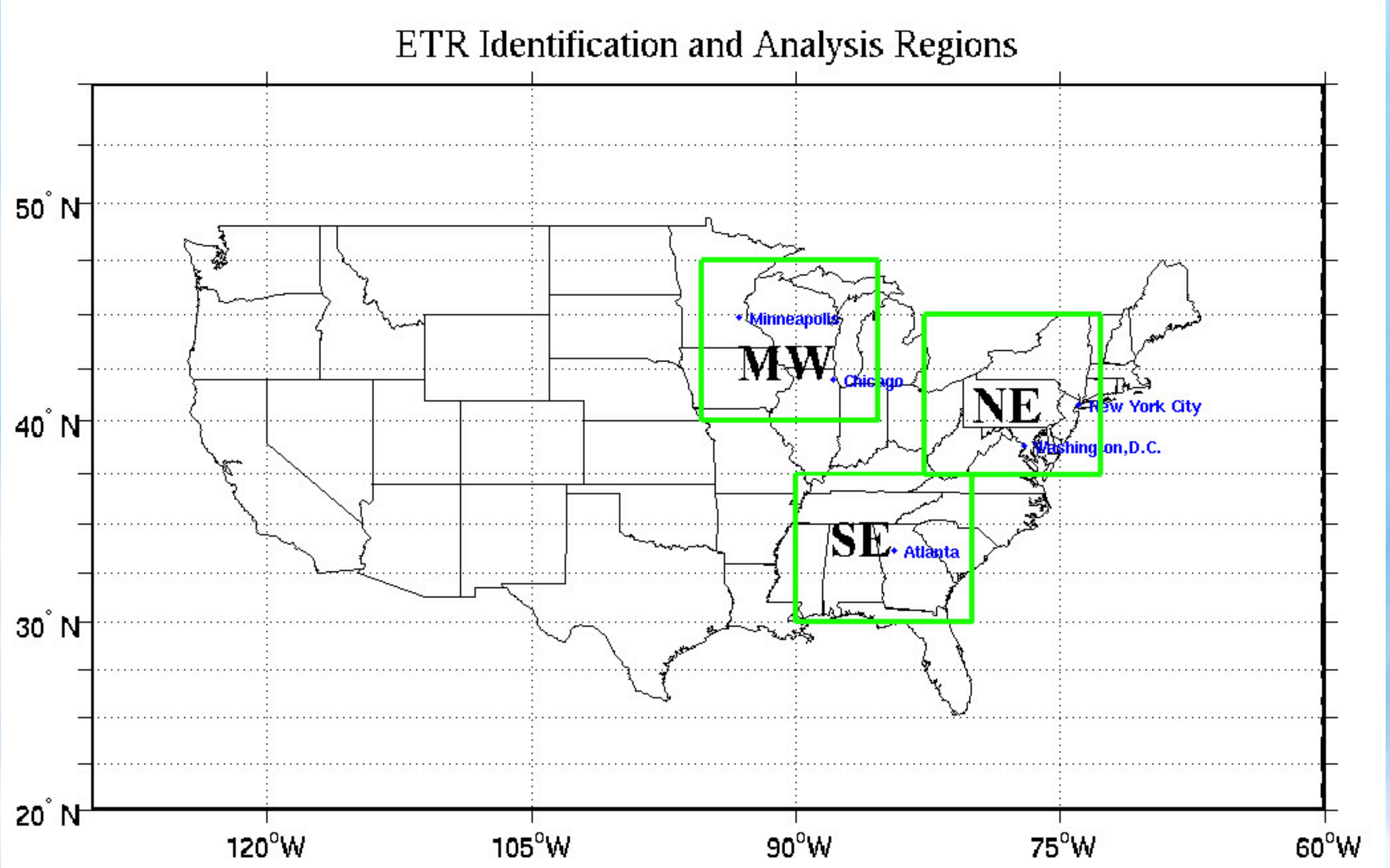
General Research Approach & Datasets

- ♠ Identify anomalous temperature regimes (ATRs) in terms of anomalies in surface air temperature (Walsh et al. 2001)
- ♥ Basic data: Daily averaged data
  - ➞ NCEP/NCAR Reanalyses (NNR; 1949 – 2011)
  - ➞ CMIP5 historical simulations (1950 – 2005)
- ♣ Anomalies are normalized departures of temperature from daily normal values during December, January & February
- ♦ Daily normal values obtained by smoothing climatological seasonal cycle (retain 1st 6 harmonics of seasonal cycle)
- ♠ Daily averaged data is detrended prior to calculating anomalies (remove trend in DJF mean temperature)

(Westby, Lee & Black 2013; [in press @ Journal of Climate])

Research Approach: Local and Regional Metrics

- ♠ *Our approach includes a consideration of **local (gridpoint) temperatures** as well as analyses based upon **areal-average temperature** over the following regions (MW, NE, SE):*



Research Approach: Temperature Metrics

- ***Temperature metrics are then used to identify episodes of anomalous temperature, leading to seasonal metrics:***

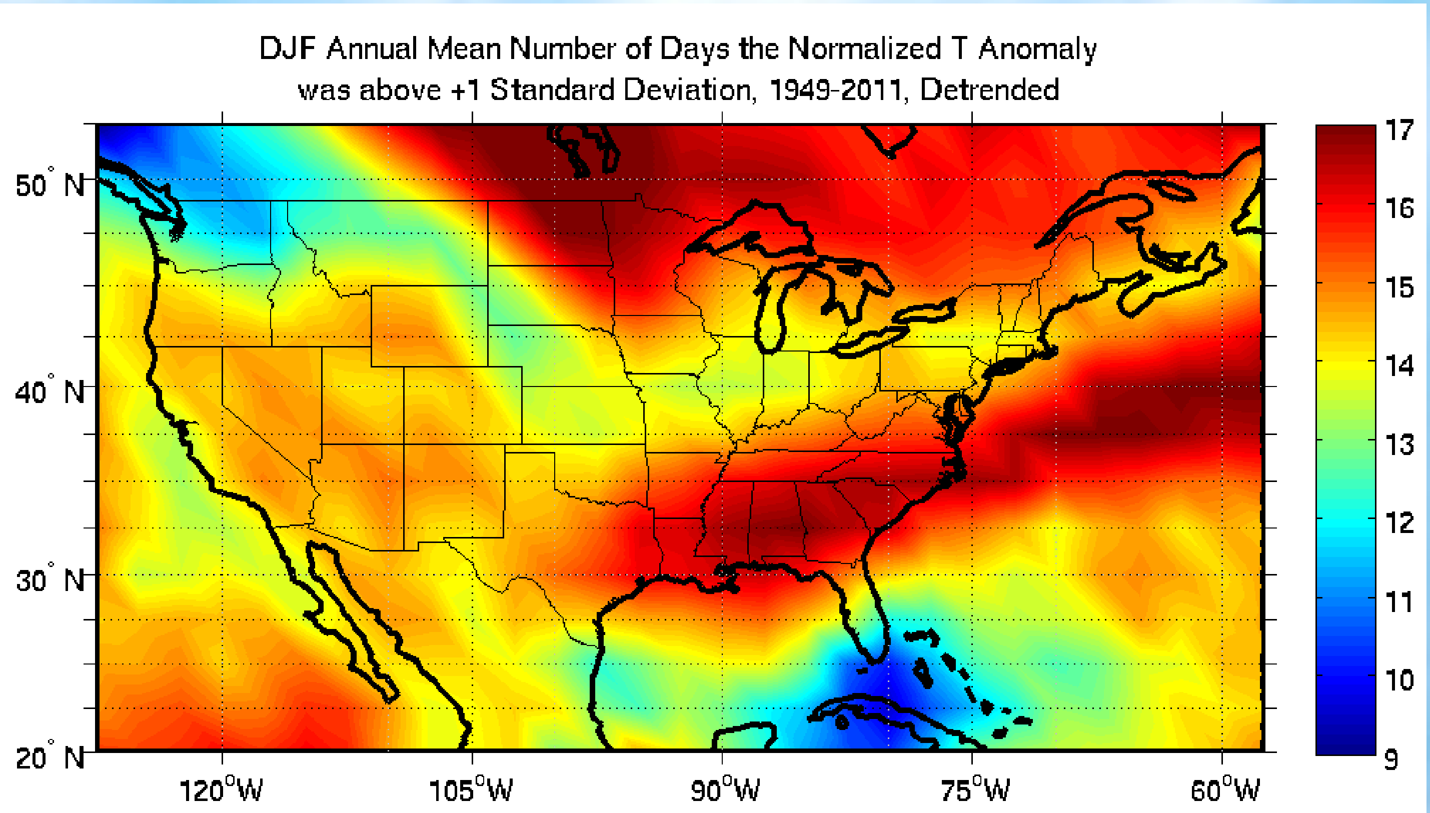
1) Number of days: N = # days temperature anomaly is:
above +nσ (warm days) or below –nσ (cold days)
where n = 1, 1.5 or 2 (we focus on using n = 1)

2) Impact Factor: Sum normalized anomaly values for all days exceeding threshold value during each winter (i.e., amplitude weighted measure)

$$\text{Impact Factor} = \sum_{i=1}^{N} \left(\frac{T_i'}{\sigma_i} \right)$$

Regional Statistical Behavior

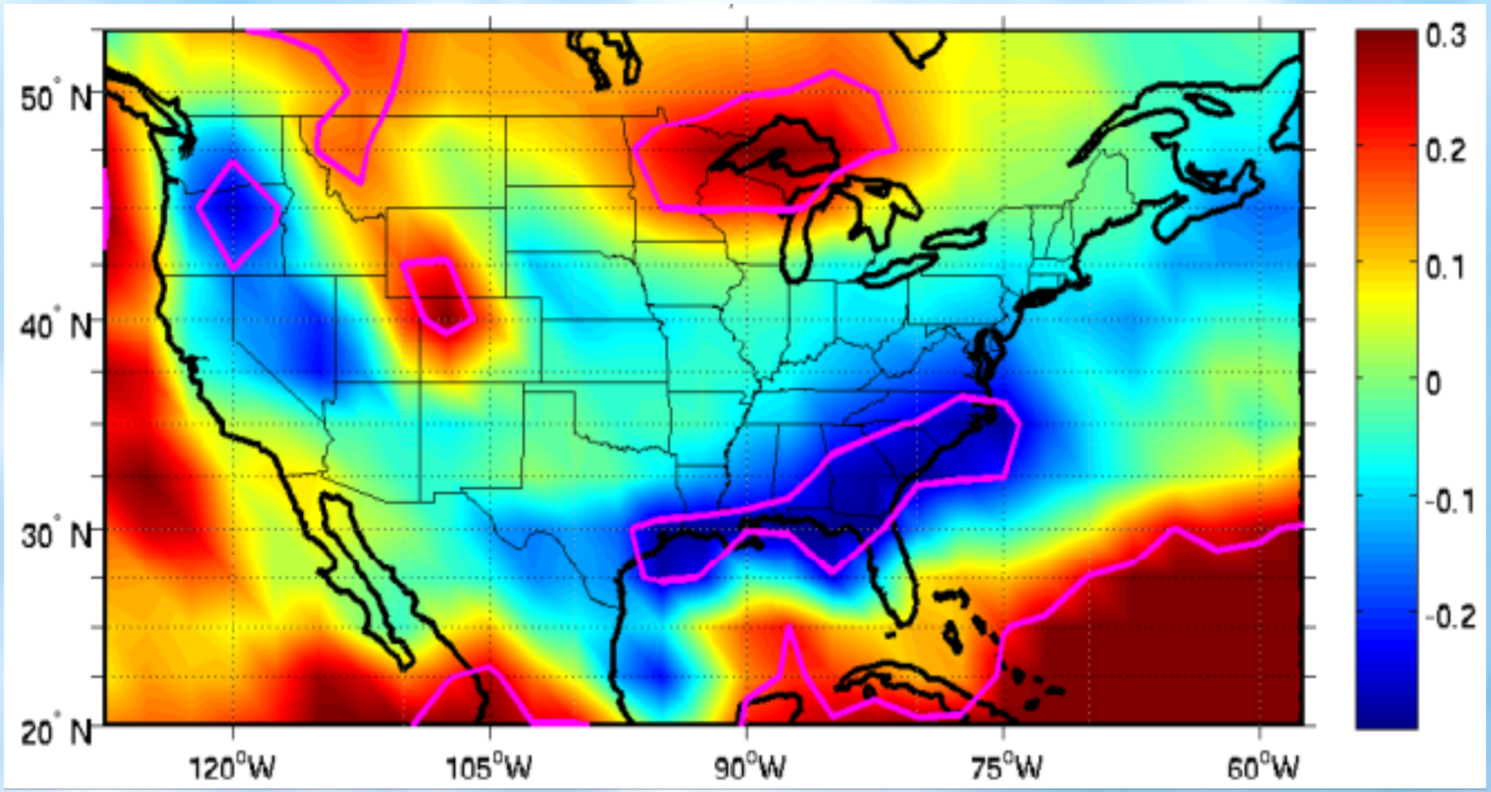
Gridpoint Analysis of Warm Wave Frequency



- ♠ *Typical annual frequency ~ 15 days in eastern US*
- ♥ *Events most frequent in southeast & upper midwest*

Regional Statistical Behavior

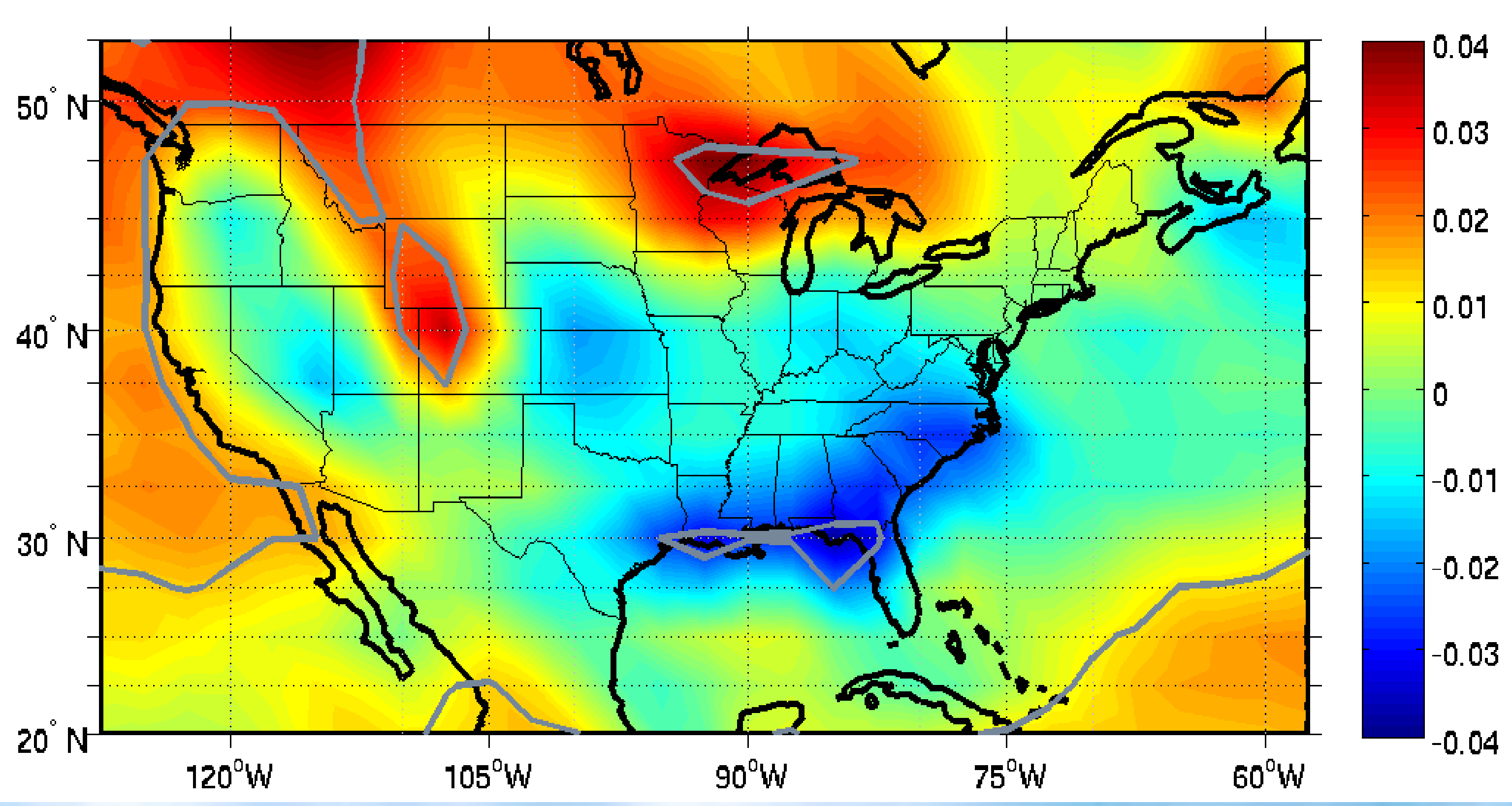
Trend in DJF Warm Wave Impact Factor (yr $^{-1}$)



- ♠ ***Significant decrease in WWs over Southeast US***
- ♥ ***Significant increases over Upper Midwest and Rockies***

Regional Statistical Behavior

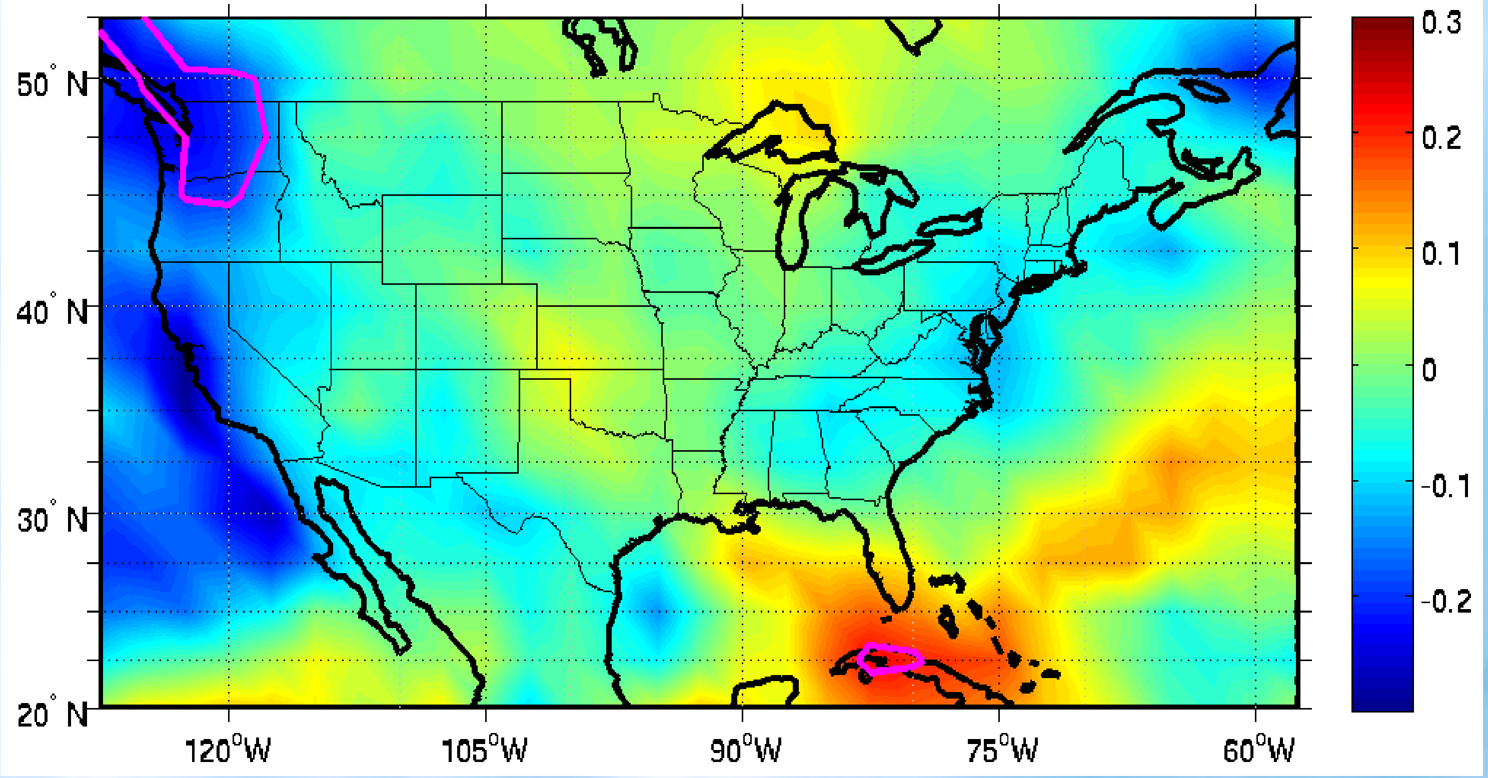
Trend in DJF Mean Temperature (1949-2011; K/year)



- ♠ *Statistically significant cooling trend in deep South*
- ♥ *Regional warming trends in Upper Midwest and Rockies*

Regional Statistical Behavior

Trend in DJF Warm Wave Impact Factor (Detrended)



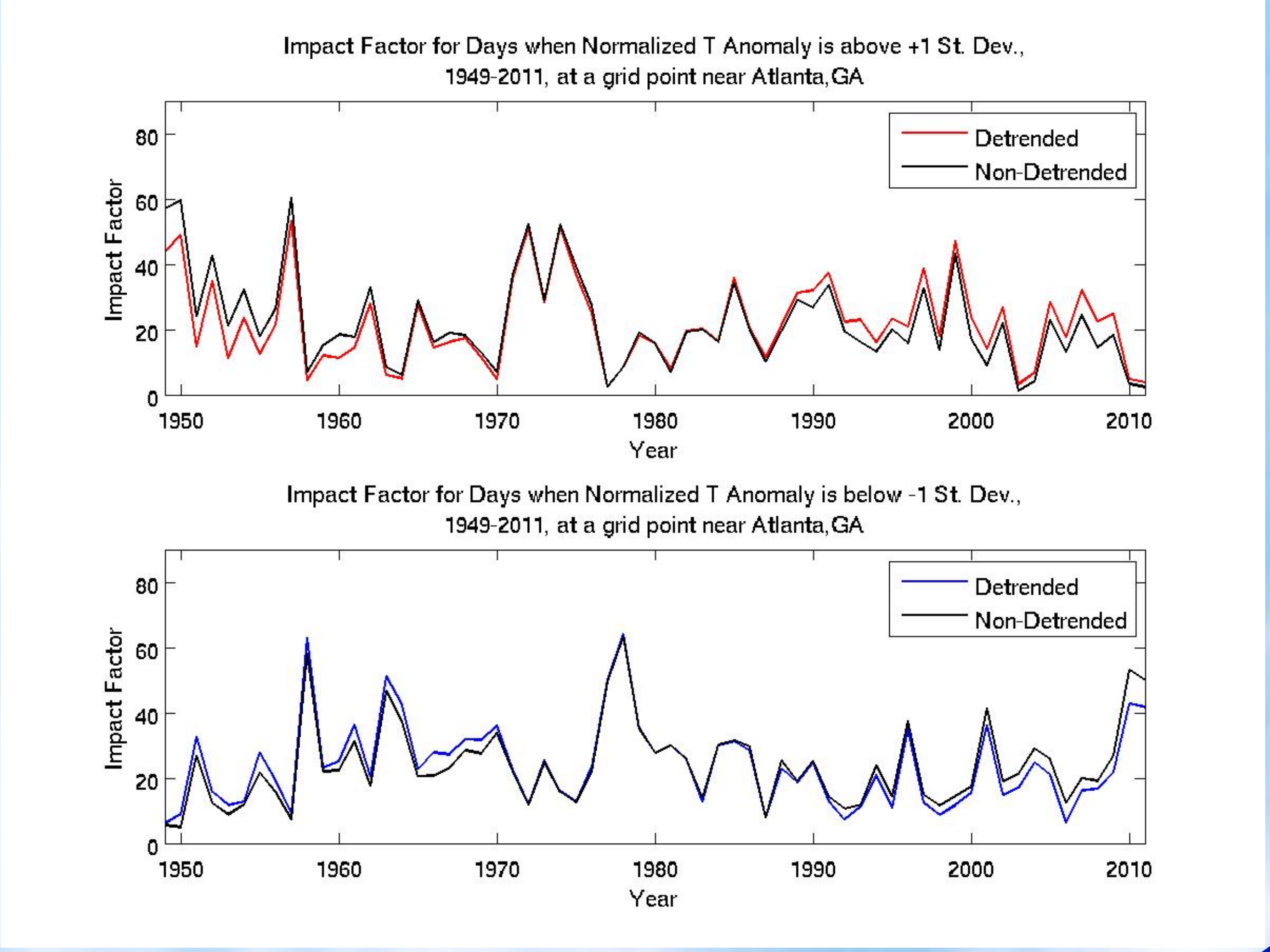
- ♠ *Most significant WW trend signatures are eliminated*
- ♥ *Virtually no local ATR trends identified (WWs or CAOs)*

ATR Impact Factor near Atlanta: Impact of Detrending

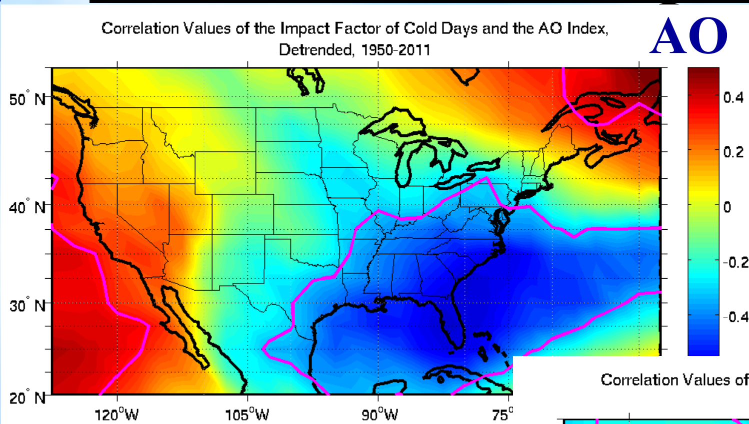
- ♠ *Remove long-term trend in seasonal mean temperature*
- ♥ *Little change in interannual variability of ATRs*

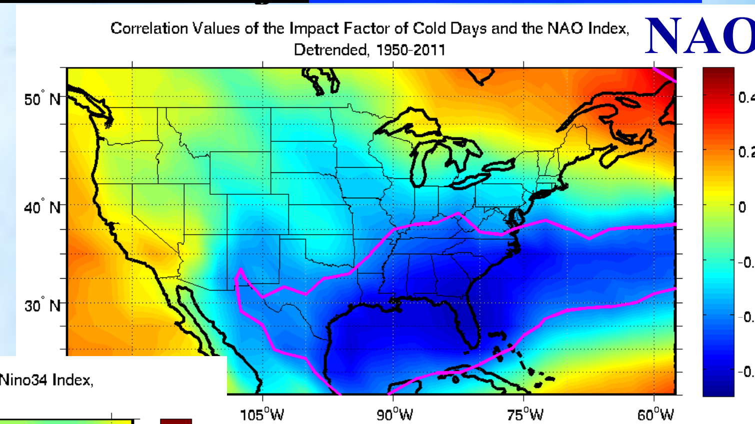
Warm Days

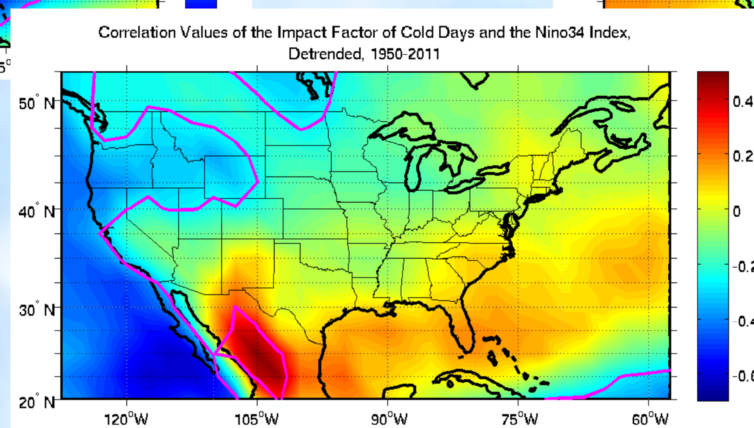
Cold Days



Seasonal Low Frequency Modulation of Cold Events







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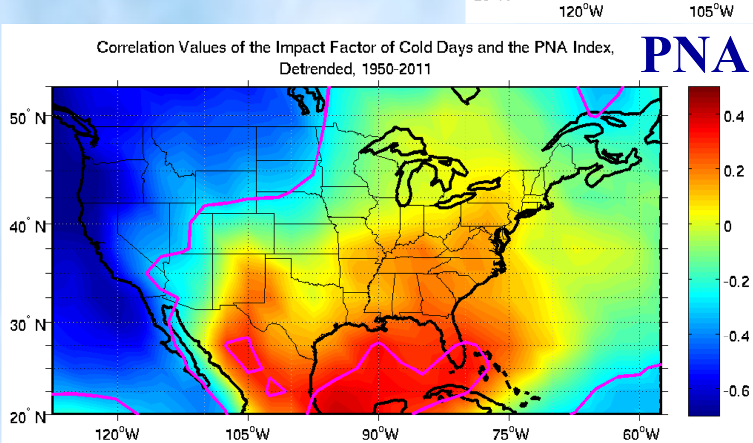
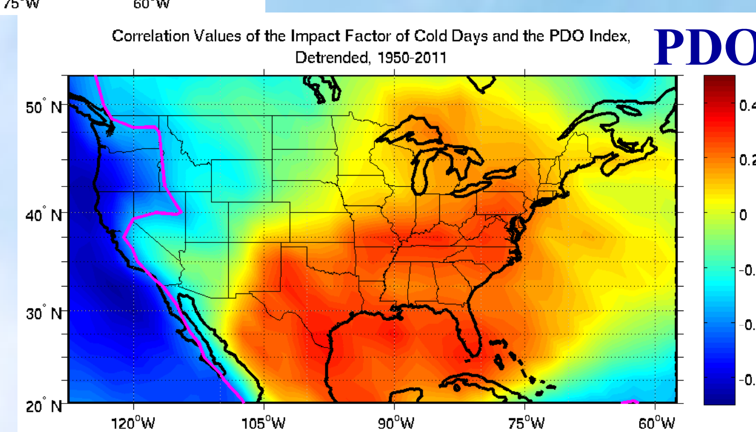
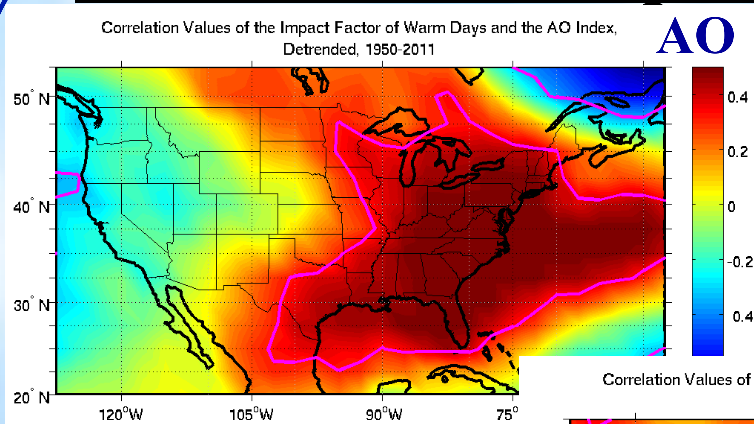
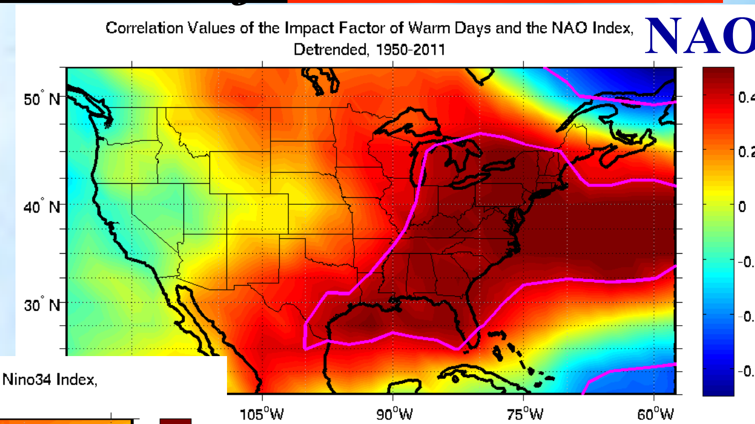
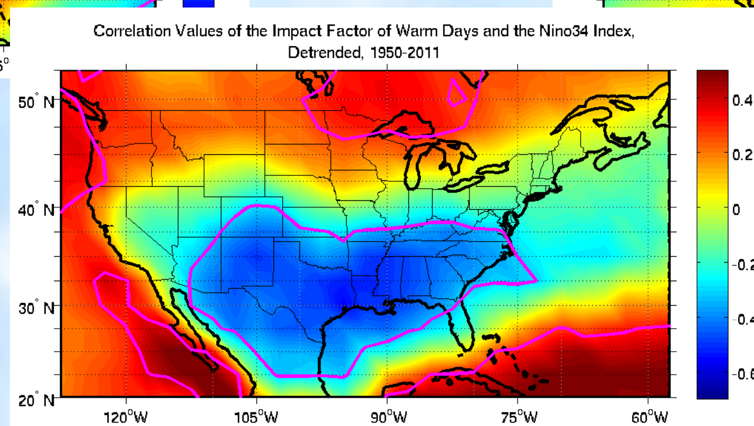




Seasonal Low Frequency Modulation of Warm Events







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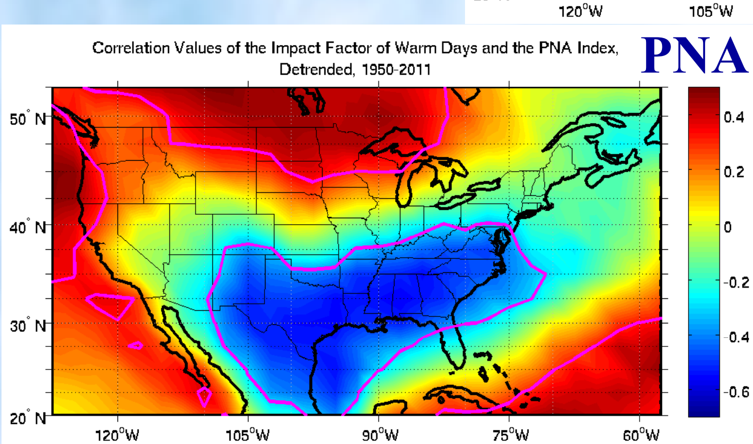
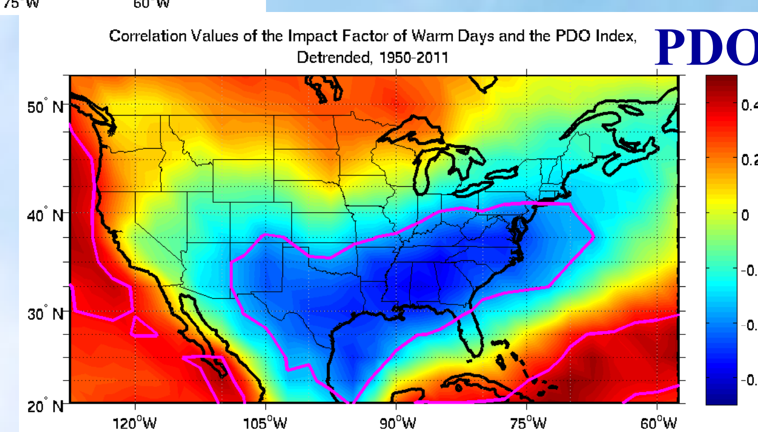




Low Frequency Modulation of Temperature Regimes

Correlation Assessment for the Southeast Region

SE Region Correlations	Number of Cold Days	Number of Warm Days	Cold Days Impact Factor	Warm Days Impact Factor
Seasonal Mean AO Index	-0.48	0.45	-0.47	0.43
Seasonal Mean NAO Index	-0.51	0.41	-0.49	0.40
Seasonal Mean PNA Index	0.27	-0.60	0.26	-0.59
Seasonal Mean PDO Index	0.32	-0.63	0.32	-0.60
Seasonal Mean MEI Index	0.08	-0.46	0.07	-0.44
Seasonal Mean Nino 3.4 Index	0.06	-0.45	0.05	-0.43
Seasonal Mean SOI Index	-0.01	0.31	-0.01	0.28
NPGO	0.25	-0.30	0.23	-0.29
AMO	-0.12	-0.11	-0.13	-0.11

- ♠ **Blue (green) shading indicates statistical significance at the 95% (90%) confidence level**
- ♥ ***Warm waves more strongly linked to low frequency modes***
- ♣ ***AO/NAO significantly modulate number of Cold Days***
- ♦ ***AO/NAO, PNA, PDO & ENSO modulate Warm Days***

Low Frequency Modulation of Temperature Regimes

Multiple Linear Regression Analysis

Region	Metric	Best Combination of Predictors	Variance Explained
MW	Number of Cold Days	--	--
	Number of Warm Days	AO & PNA	30%
	Cold Days Impact Factor	--	--
	Warm Days Impact Factor	AO & PNA	28%
SE	Number of Cold Days	NAO & PDO	28%
	Number of Warm Days	NAO & PDO	54%
	Cold Days Impact Factor	NAO & PDO	33%
	Warm Days Impact Factor	NAO & PNA	51%
NE	Number of Cold Days	AO	9%
	Number of Warm Days	NAO & PDO	31%
	Cold Days Impact Factor	AO	8%
	Warm Days Impact Factor	NAO & PDO	34%

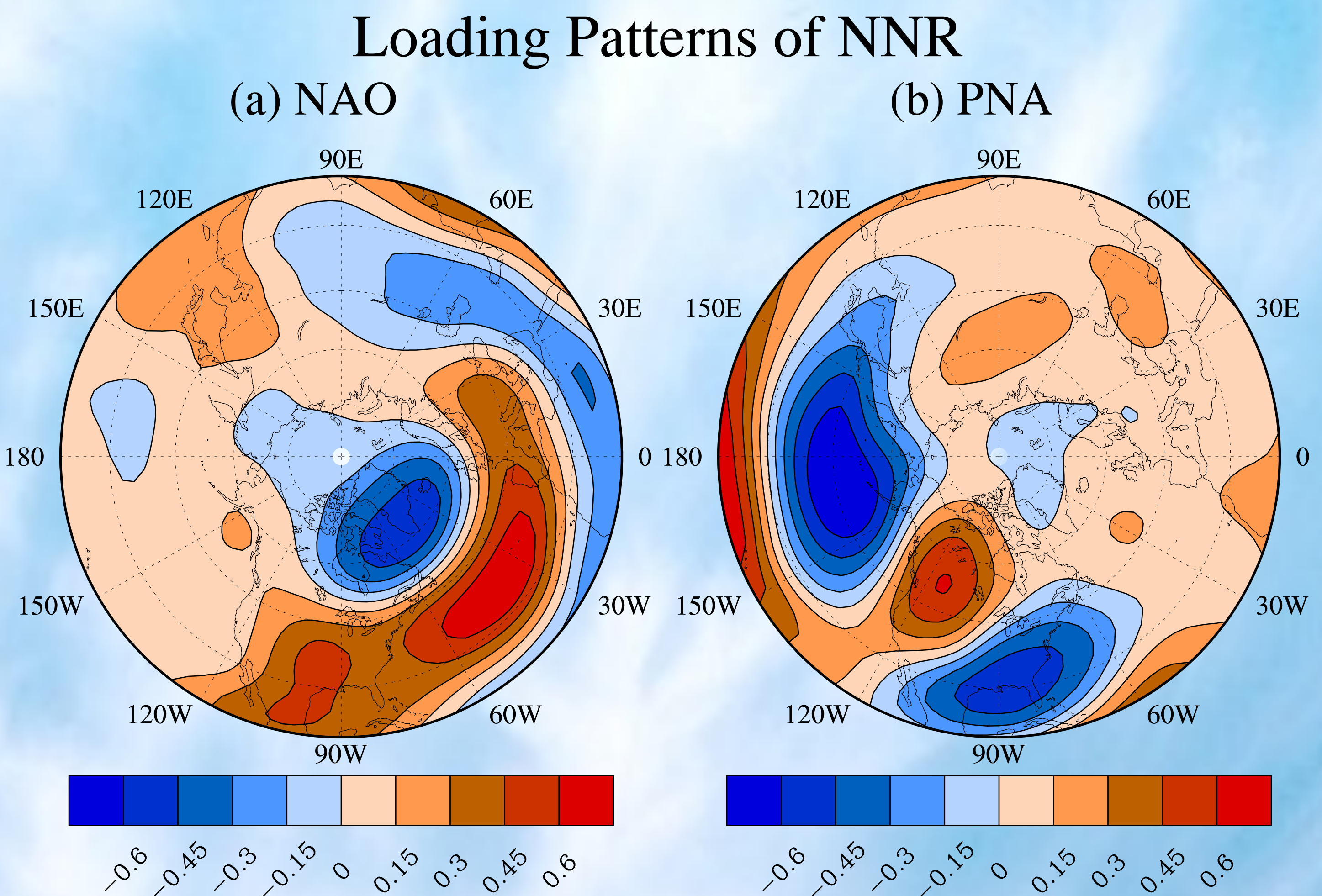
- ♠ ***Strongest low frequency modulation for warm events***
- ♥ ***Midwest region has weakest low frequency modulation***
- ♣ ***Southeast region has strongest low frequency modulation***

Validation of LFMs in CMIP5 models

- ♠ ***Observational data:*** ***NCEP-NCAR Reanalyses (NNR) for period 1950-2005 (boreal winter analysis)***
- ♥ ***Model data:*** ***Historical simulations from CMIP5 for same time period (16 models: 7 high-top; 8 low-top; 1 intermediate)***
- ♣ ***Tropospheric low frequency modes:*** ***Rotated PC analysis of monthly mean 500 hPa geopotential height anomalies (Barnston & Livezey 1987) in both NNR & model data***
- ♦ ***Apply pattern correlation analysis to identify modes in each model that are most NAO-like and PNA-like***
- ♠ ***Also employ linear regression and composite analyses along with k-means clustering (tropospheric low frequency modes)***

(Lee & Black 2013 [JGR-Atmospheres])

500 hPa Low Frequency Modes: Observed Structures



Rotated EOF #1

(Explains 9.3% Variance)

Rotated EOF #2

(Explains 9.2% Variance)

(Lee and Black 2013 [JGR-A])

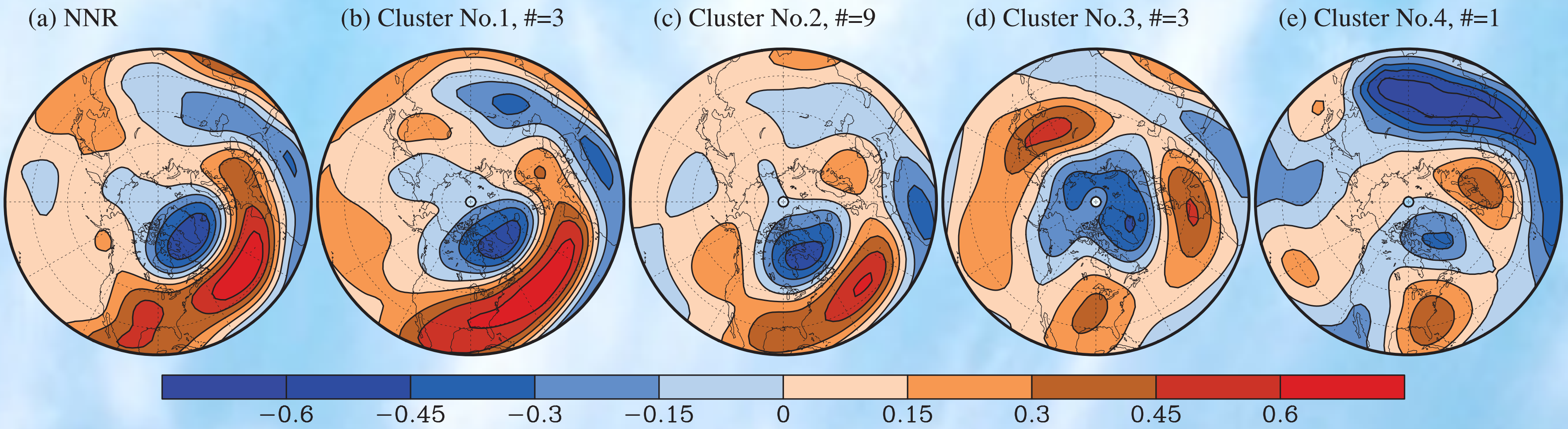
CMIP5 Rotated EOFs: Pattern Correlations with NNR

Model	NAO	PNA	Mean
"GFDL-ESM2G"	0.94	0.93	0.93
"MPI-ESM-LR"	0.83	0.92	0.88
"HadCM3"	0.90	0.82	0.86
"CSIRO-Mk3-6-0"	0.85	0.81	0.83
"CCSM4"	0.71	0.91	0.81
"CanESM2"	0.73	0.83	0.78
"CNRM-CM5"	0.78	0.77	0.78
"MIROC-ESM-CHEM"	0.73	0.78	0.75
"inmcm4"	0.72	0.76	0.74
"NorESM1-M"	0.56	0.91	0.73
"IPSL-CM5A-MR"	0.61	0.84	0.73
"MIROC5"	0.68	0.77	0.73
"HadGEM2-CC"	0.74	0.70	0.72
"MIROC-ESM"	0.72	0.70	0.71
"IPSL-CM5A-LR"	0.48	0.88	0.68
"MRI-CGCM3"	0.49	0.87	0.68
	0.72	**0.83**	**0.77**

- ***Low top models** generally outperform **high top models***
- ***Overall, PNA is better represented than NAO pattern***
- ***GFDL-ESM2G receives first prize in both categories***

Cluster Composites of Loading Vectors: NAO-like

Loading Patterns of NAO



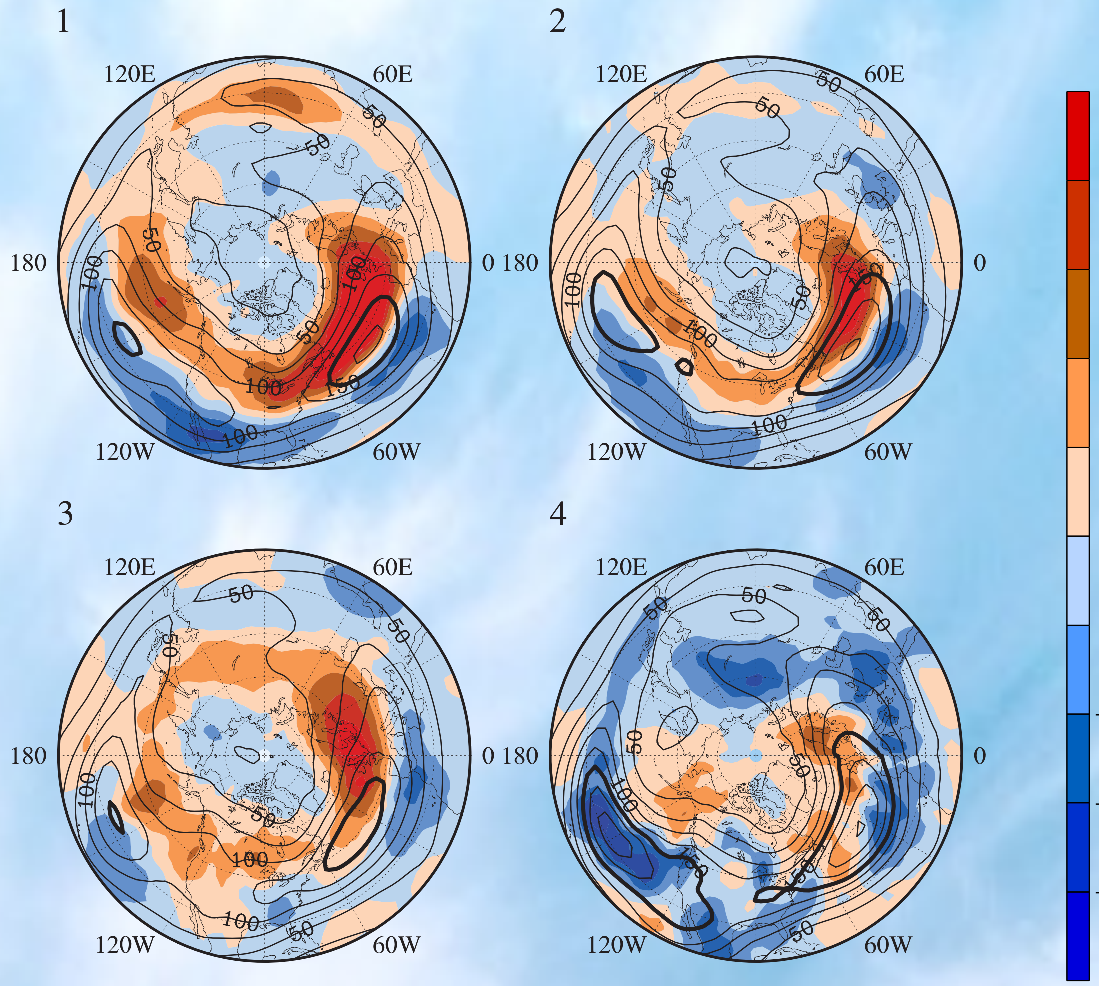
(b) Cluster No.1	(c) Cluster No.2	(d) Cluster No.3	(e) Cluster No.4
GFDL-ESM2G	IPSL-CM5A-LR	IPSL-CM5A-MR	MRI-CGCM3
HadCM3	MIROC-ESM-CHEM	inmcm4	
CSIRO-Mk3-6-0	MIROC-ESM	NorESM1-M	
	MPI-ESM-LR		
	HadGEM2-CC		
	CCSM4		
	CNRM-CM5		
	MIROC5		
	CanESM2		

- ***Longitudinal phase shifts in meridional dipole structure in clusters 2 and 3***
- ***Pronounced eastward phase shift of meridional dipole in cluster 3***
- ***Fundamental differences in anomaly structure in clusters 3 and 4***
- ***Anomalous westerly flow from N Atlantic into N Eurasia in cluster 3***

NAO-like Regional Impact: Storm Tracks

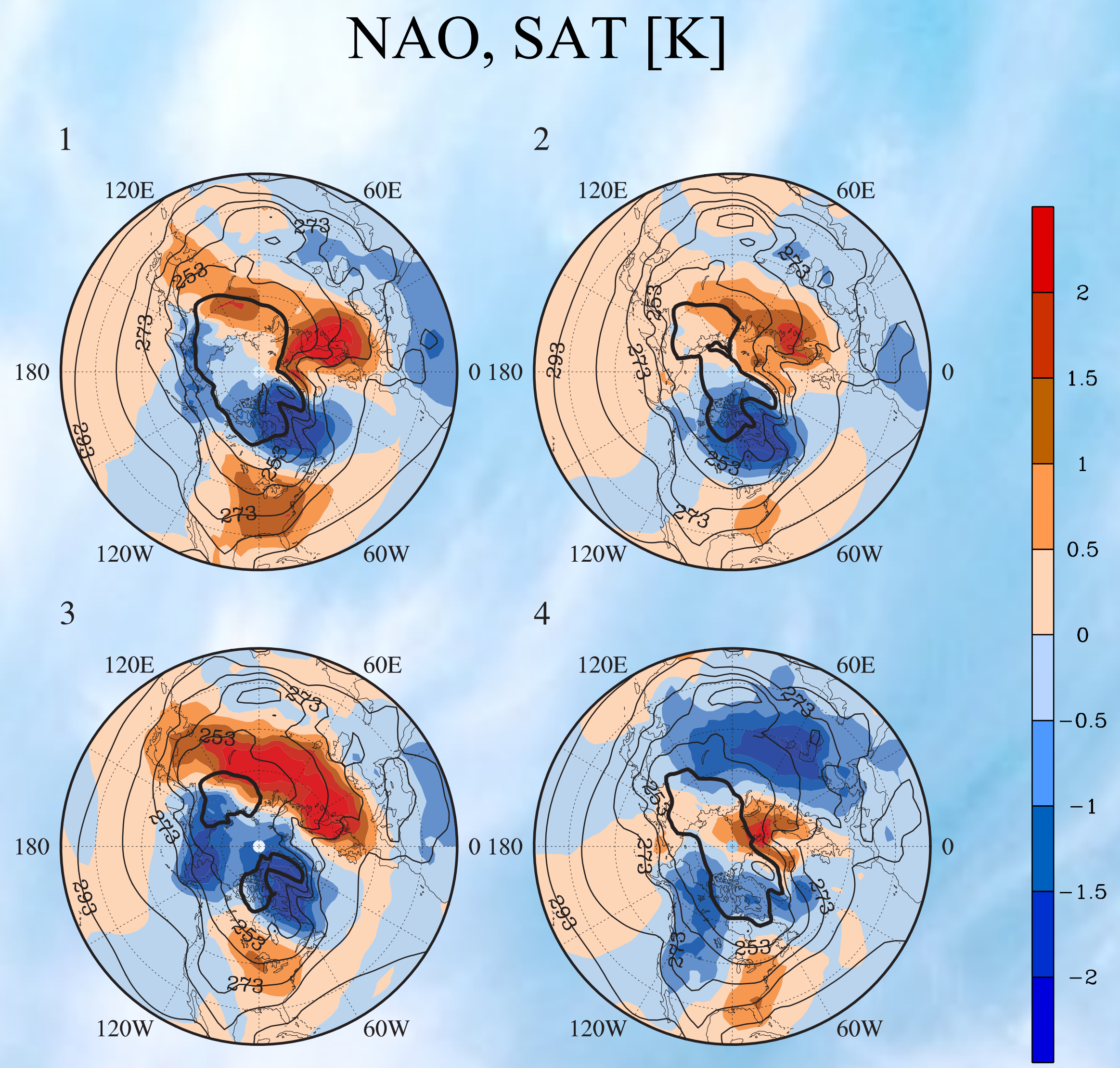
NAO, VV250 [m^2/s^2]

- ♠ ***Shading: Regressed anomaly fields***
- ♥ ***Contours: climatology***
- ♣ ***Field: Variance in high pass filtered (10 day cutoff) meridional wind***
- ♦ ***Note eastward extension of storm track anomaly in Cluster 3***



NAO-like Regional Impact: Surface Air Temperature

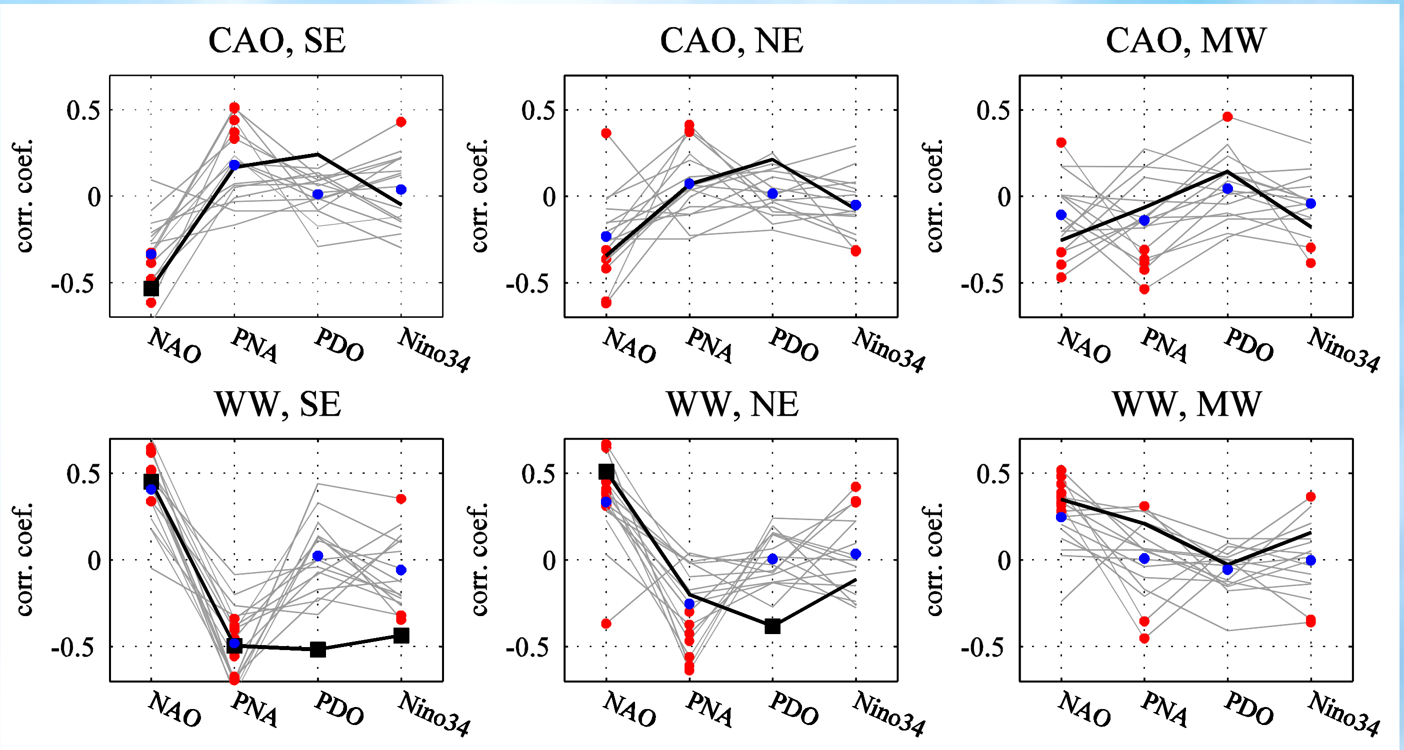
- ♠ ***Shading: Regressed anomaly fields***
- ♥ ***Contours: climatology***
- ♣ ***Field: Surface air temperature***
- ♦ ***Note amplified eastward extension of warm anomalies in Cluster 3***



Low Frequency Modulation of ATRs in CMIP5

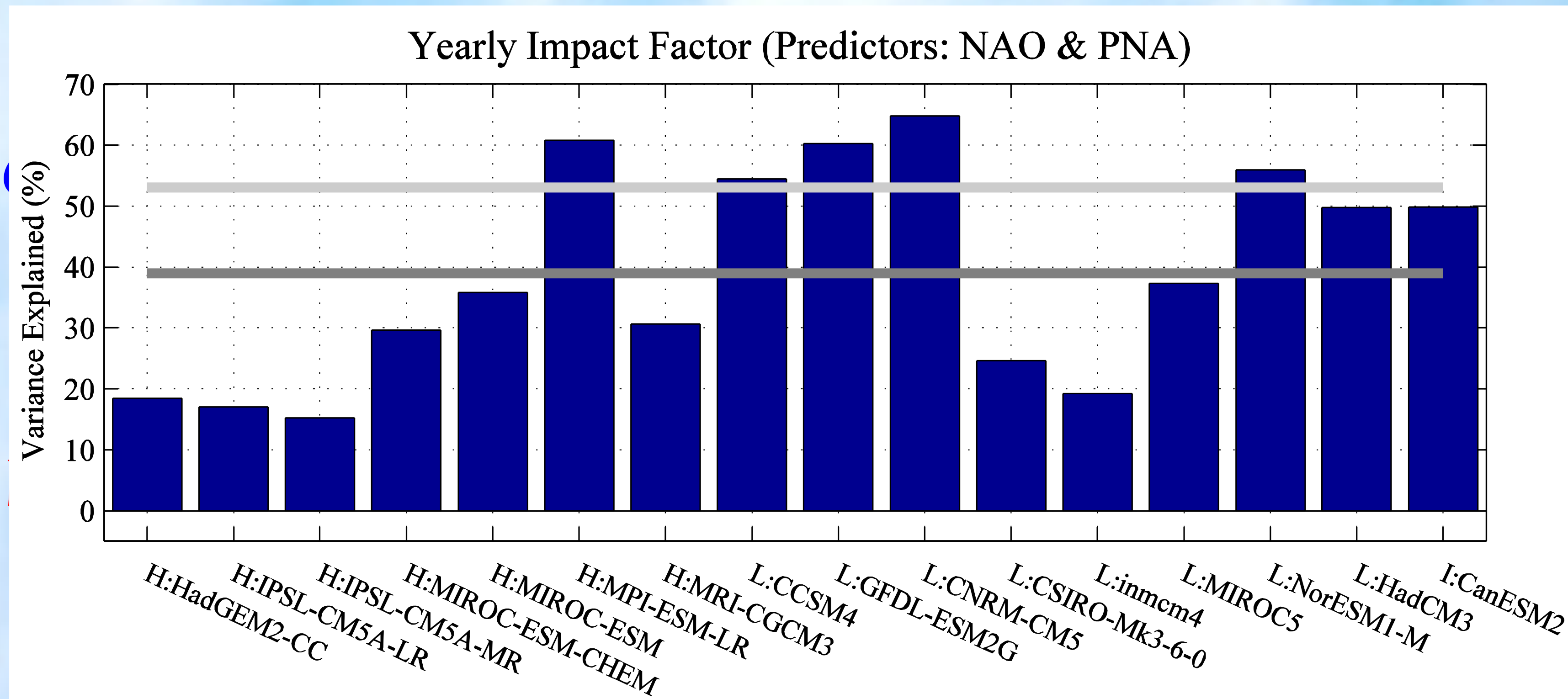
Cold Days

Warm Days



- *Black (grey) line(s): Correlation coefficients for observations (models)*
- *Black squares (red bullets): Statistically significant correlations*

Low Frequency Modulation of ATRs in CMIP5



Variance explained for the yearly Impact Factor for warm days in the Southeast Region via a multiple linear regression for DJF 1951-2005 using the NAO and PNA indices as predictors. Light and dark grey lines denote value for observations (NNR) and the model average, respectively.

Summary

- ♠ *No significant trends observed in ATR frequency (in particular: no evidence for decreases in cold events)*
- ♥ *Pronounced interannual modulation of cool season ATRs by leading modes of low frequency variability (particularly NAO & PNA/PDO/ENSO patterns)*
- ♣ *CMIP5 models qualitatively replicate structure of PNA; A small minority of models fail to replicate the NAO; PDO poorly represented in most models considered*
- ♦ *Model biases in low frequency mode structure impact the regional representation of anomalous weather conditions*
- ♠ *Linkages between low frequency modes and ATRs are well replicated for NAO & PNA (but not PDO)*


Questions?