Results from the North American Regional Climate Change Assessment Program (NARCCAP): Model projections for major U.S. cities in different climate zones, the development of a future typical meteorological year, and estimated impact of a changing climate on building energy consumption

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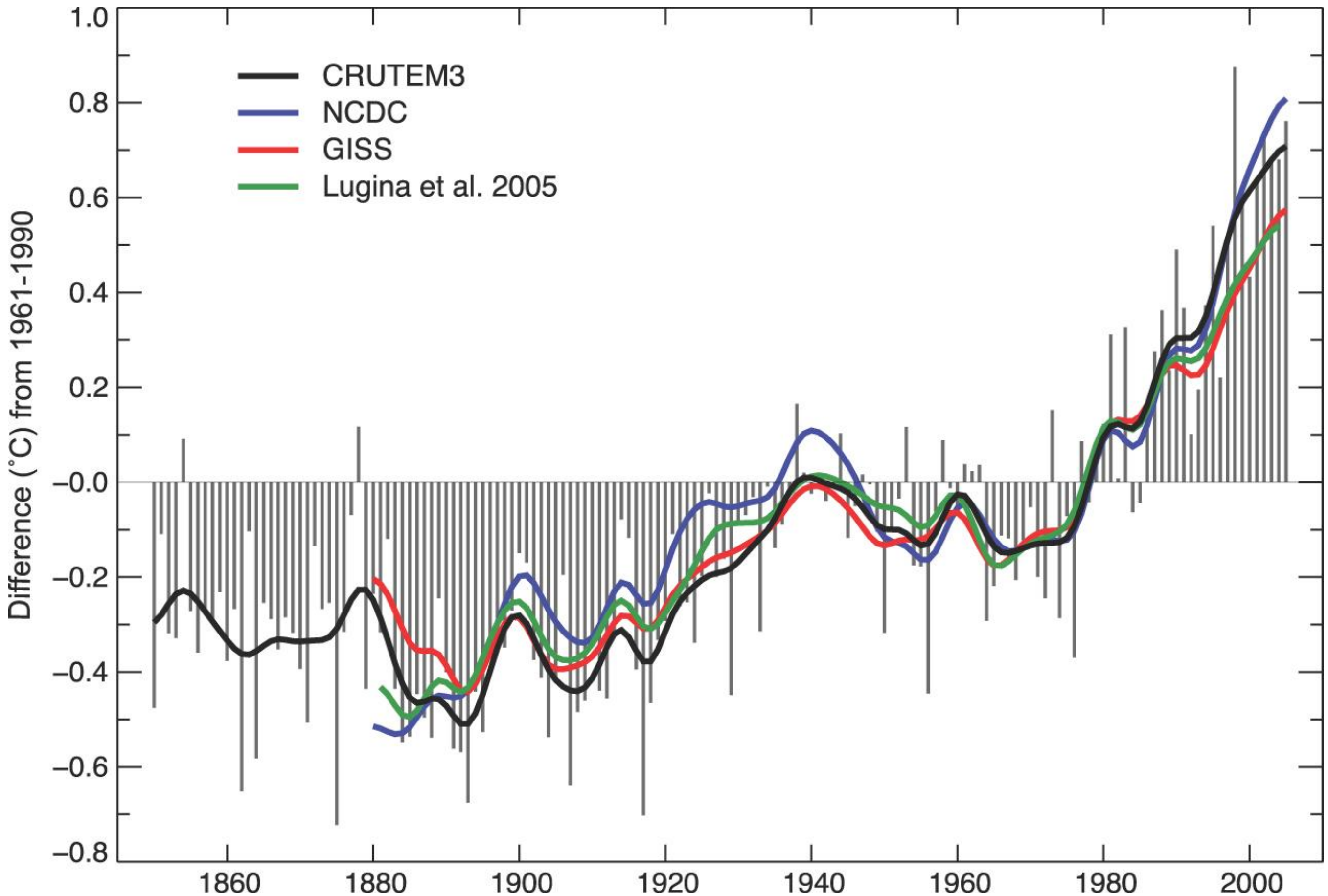
Motivation

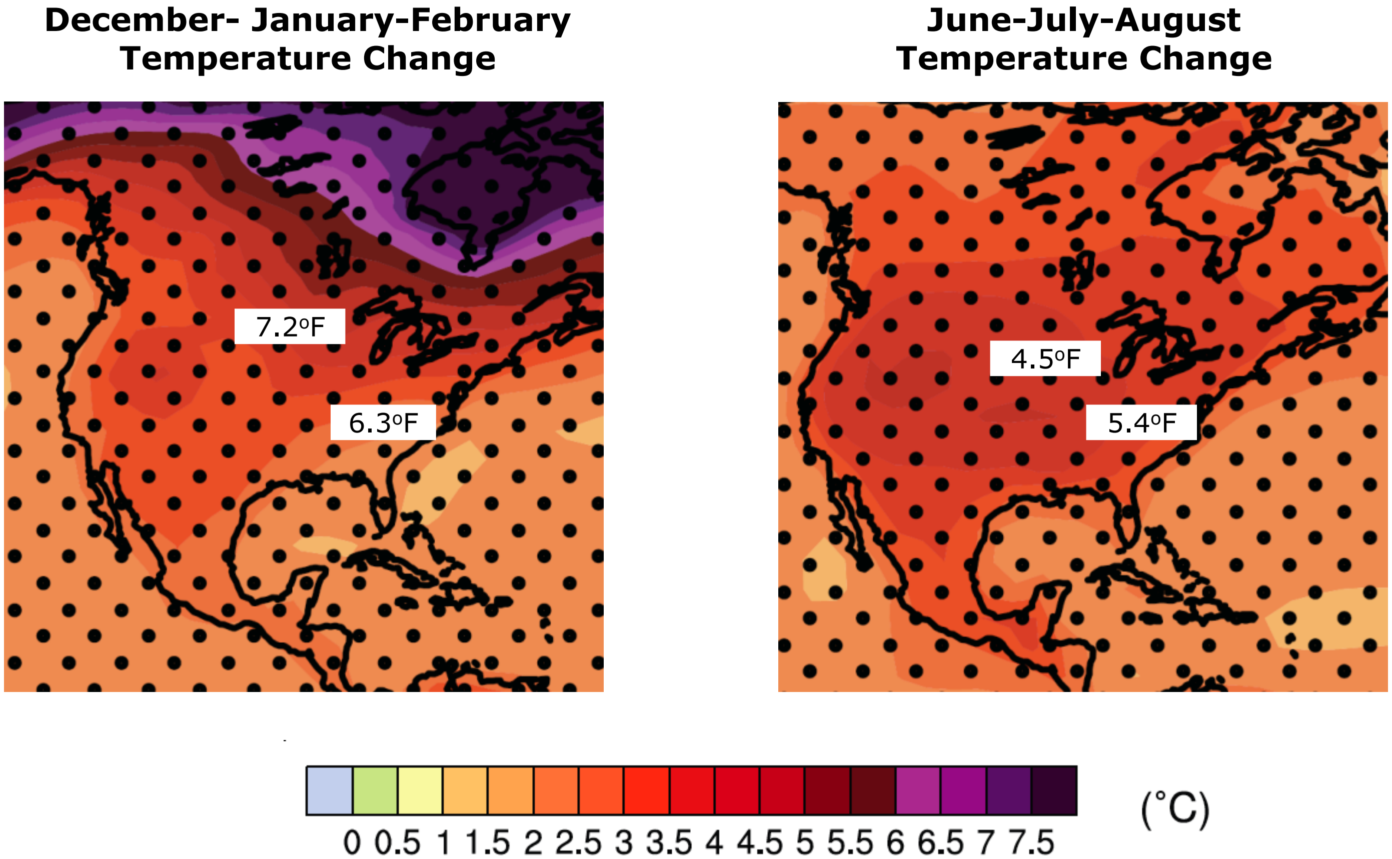
- Typical climate conditions for the 20th century may not provide adequate design parameters for the built environment of the 21st century.

Observed climate change



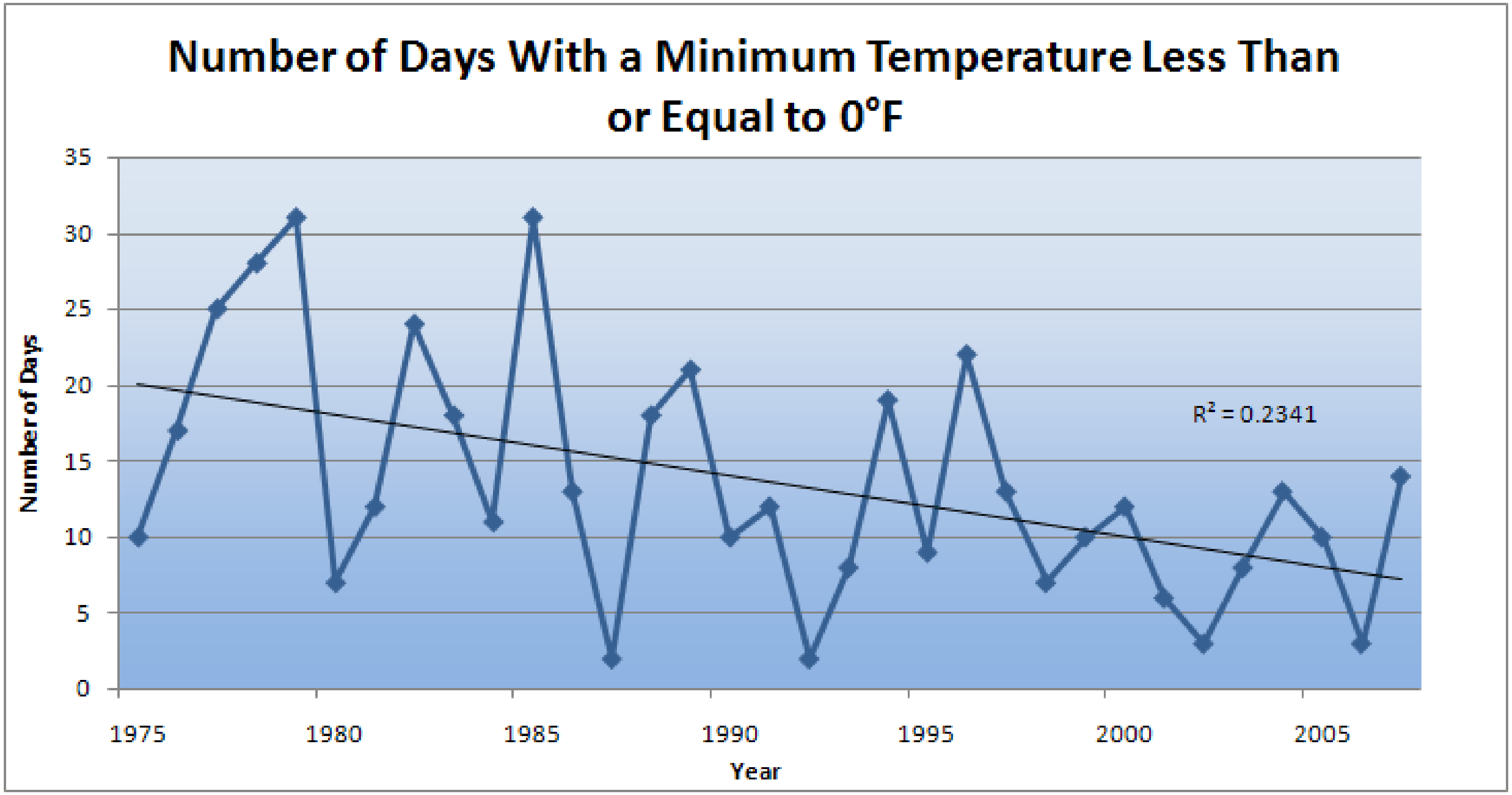
Separate analyses of the temperature record – Trends are in close agreement (IPCC 2007)

Projected temperature change



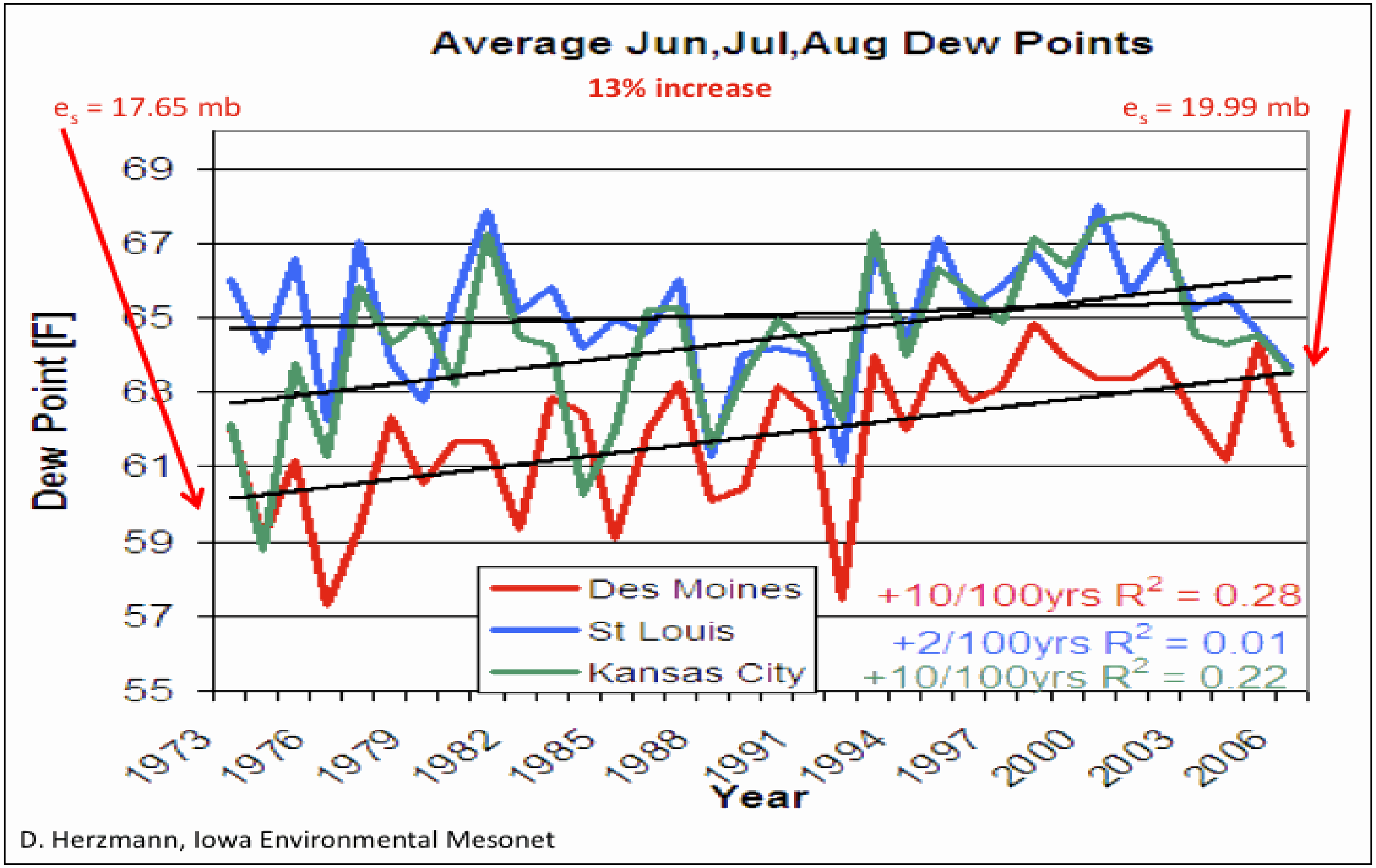
A1B Emission Scenario: 2080-2099 minus 1980-1999 (IPCC 2007)

Observed climate change: Iowa



Des Moines Airport Data

Observed climate change: Iowa



Previous work

- The currently accepted method for assessing impacts of climate change is to downscale information from GCMs and add these changes to the current climate to produce an estimate of future climate
  - Imposed offset or “morphing” method
  - Belcher et al. (2005)
  - Used by Chan (2011), Chen et al. (2012), Coley and Kershaw (2010), Holmes and Reinhart (2011), Jentsch et al. (2013)

Previous work

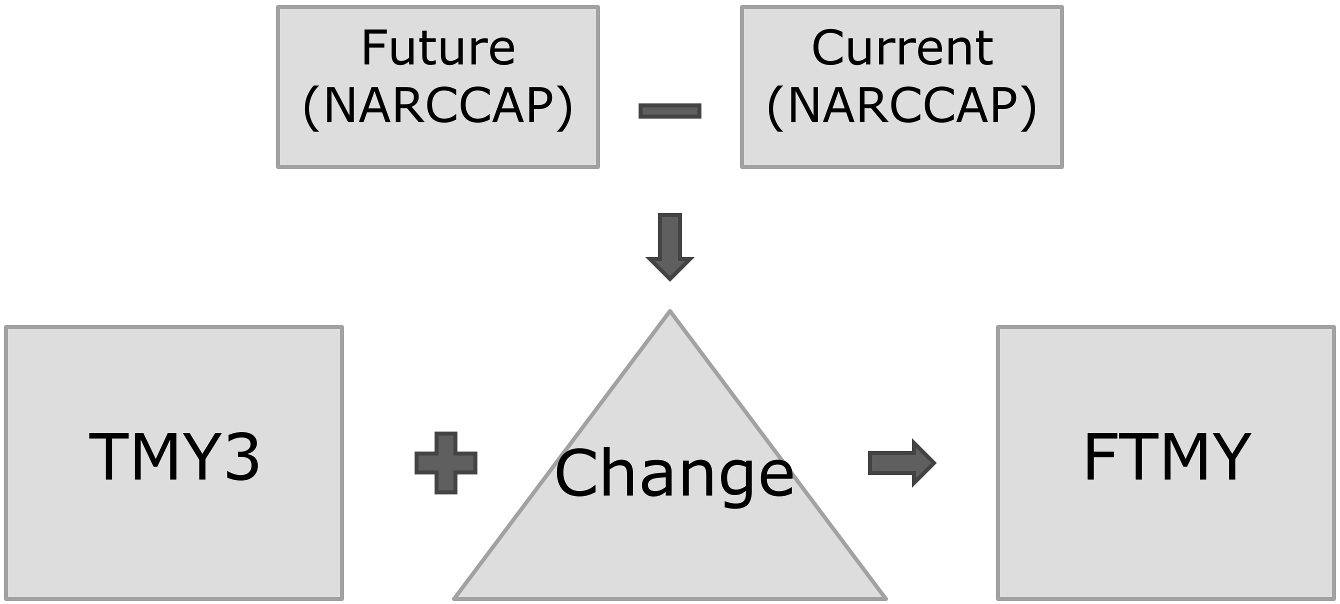
- Huang (2006)
  - Used global climate models (GCMs) for four future climate scenarios
  - Finding: Net energy use will increase by 25 - 28% by 2100 in L.A.
- Crawley (2008)
  - Used GCMs with statistical downscaling for four climate change scenarios and 25 locations
  - Finding: Change in energy use by climate:
    - Cold: -10%
    - Tropical: +20%
    - Mid-latitude: change from heating to cooling

Improvements to methodology

- Dynamical downscaling
- Results applicable to all U.S. locations available in the TMY3 database
- Use of multiple GCMs and RCMs to quantify the range of uncertainty in future climate projections

Our study methodology

- Creation of future typical meteorological year (FTMY) dataset



Selection of locations

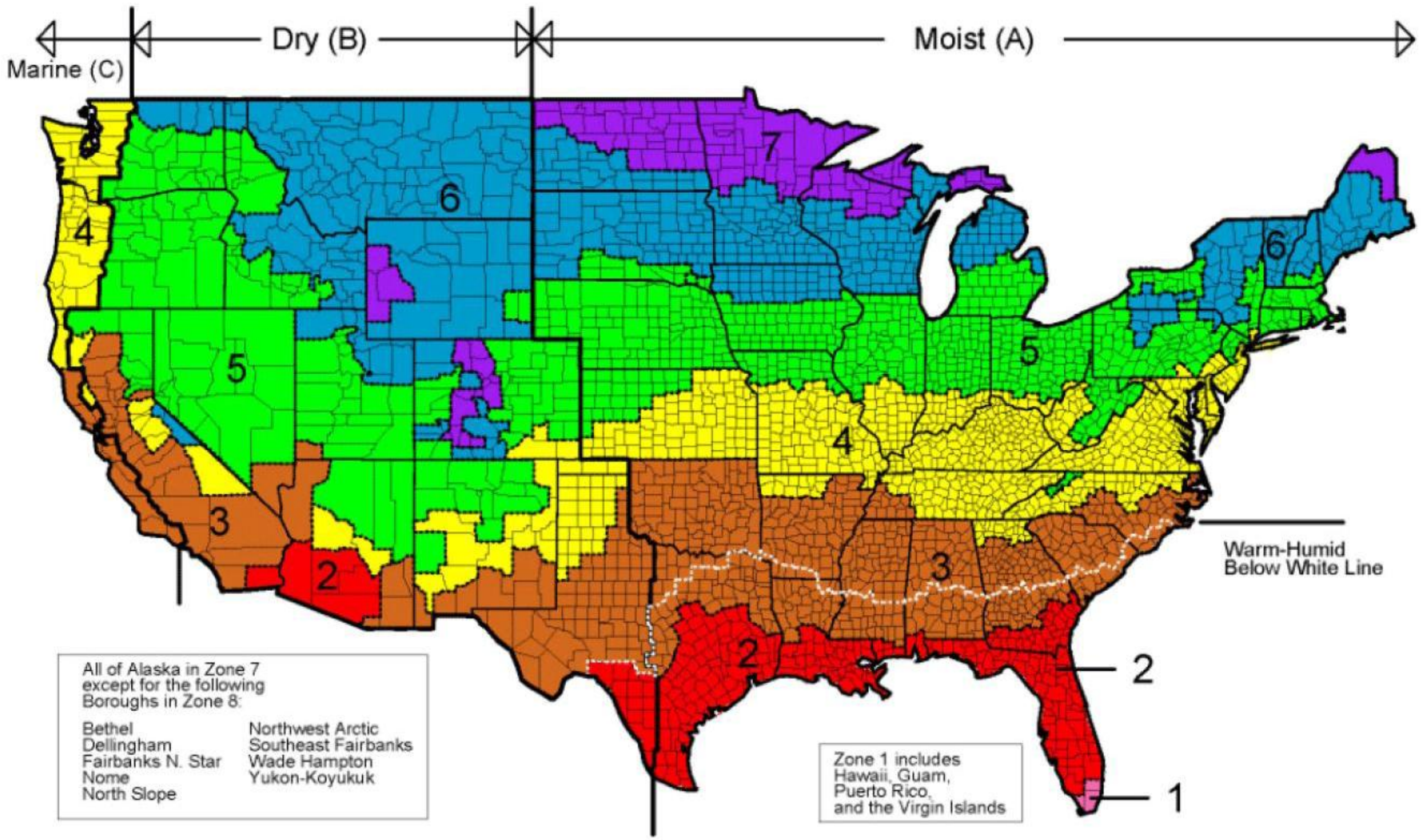


Figure 1 Climate zone classification
(Credit: Briggs et al. [2003]; DOE [2005])

Selection of locations

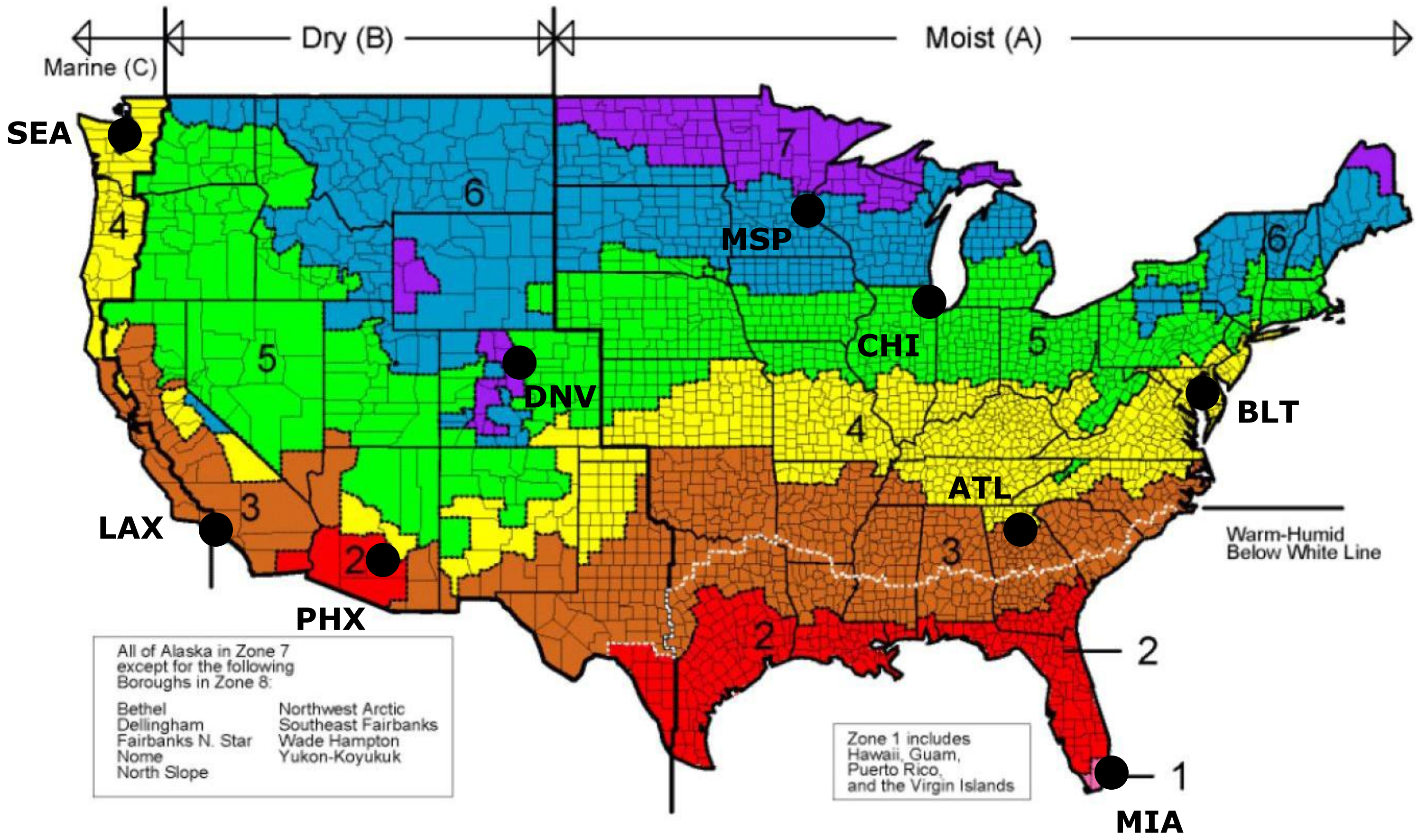
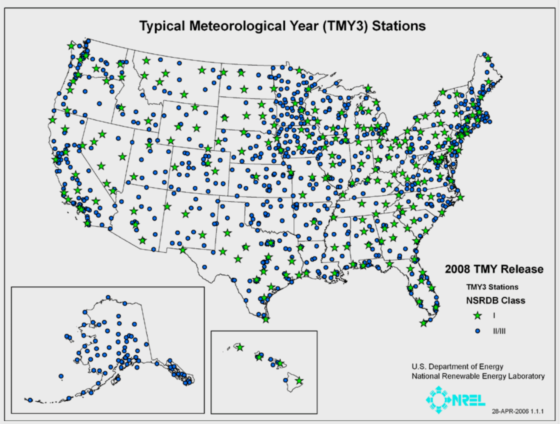


Figure 1 Climate zone classification
(Credit: Briggs et al. [2003]; DOE [2005])

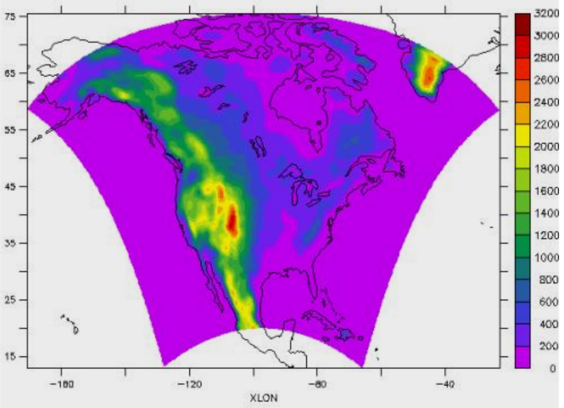
Three different datasets used

TMY 3



OBSERVATION

NARCCAP



TMY3

- TMY3 dataset (Wilcox and Marion 2008)
  - 1976 - 2005
  - Derived from observations
  - Individual months selected
    - Global horizontal radiation
    - Direct normal radiation
    - Dry-bulb temperature
    - Dew-point temperature
    - Wind speed
  - Annual dataset consisting of hourly values
  - Includes natural diurnal and seasonal variations

Observations

- Observed dataset (NCDC ISD)
  - 1976 - 2005
  - 30-year dataset consisting of hourly values
  - Months influenced by volcanoes removed
  - Same stations as used in TMY3 creation

TMY evaluation

Table 3.1 Difference Between TMY3 and Observations for Chicago, IL

Month	**Totcld** tens	**Dry-bulb** °C	**Dew-point** °C	**Rhum** %	**Ahum** g cm^{-3}	**Pressure** mbar	**Wspd** m s^{-1}	**Wdir** deg
1	-0.31	0.57	-0.07	-2.99	-0.04	1.40	-0.26	-2.85
2	-0.64	-0.07	-1.22	-6.28	-0.26	-3.81	0.04	-24.35
3	-0.25	0.47	0.82	1.89	0.08	0.61	0.17	-13.65
4	0.43	0.33	1.66	5.03	0.82	2.86	-0.30	-18.86
5	-0.46	-0.10	-1.06	-2.66	-0.70	-0.74	-0.87	-8.66
6	-0.10	0.27	-0.72	-4.19	-0.56	1.55	0.92	-34.18
7	-0.06	0.51	1.82	5.48	1.53	0.46	0.46	-29.21
8	-0.04	-0.68	-0.17	1.76	-0.19	-0.08	0.30	18.96
9	0.14	-0.33	0.57	4.37	0.21	-0.90	-0.38	23.33
10	-0.36	-0.15	-0.26	-1.00	-0.33	0.60	0.41	-13.48
11	0.71	0.07	0.95	3.98	0.81	-0.29	0.54	-11.67
12	-0.36	-1.23	-1.06	0.61	-0.40	-0.69	-0.49	-3.17
Avg	-0.11	-0.03	0.11	0.50	0.08	0.08	0.04	-9.82
Avg SD (Obs)	0.74	2.03	2.11	4.59	0.91	1.83	0.48	27.75

TMY evaluation

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Avg	-0.11	-0.03	0.11	0.50	0.08	0.08	0.04	-9.82
Avg SD (Obs)	0.74	2.03	2.11	4.59	0.91	1.83	0.48	27.75

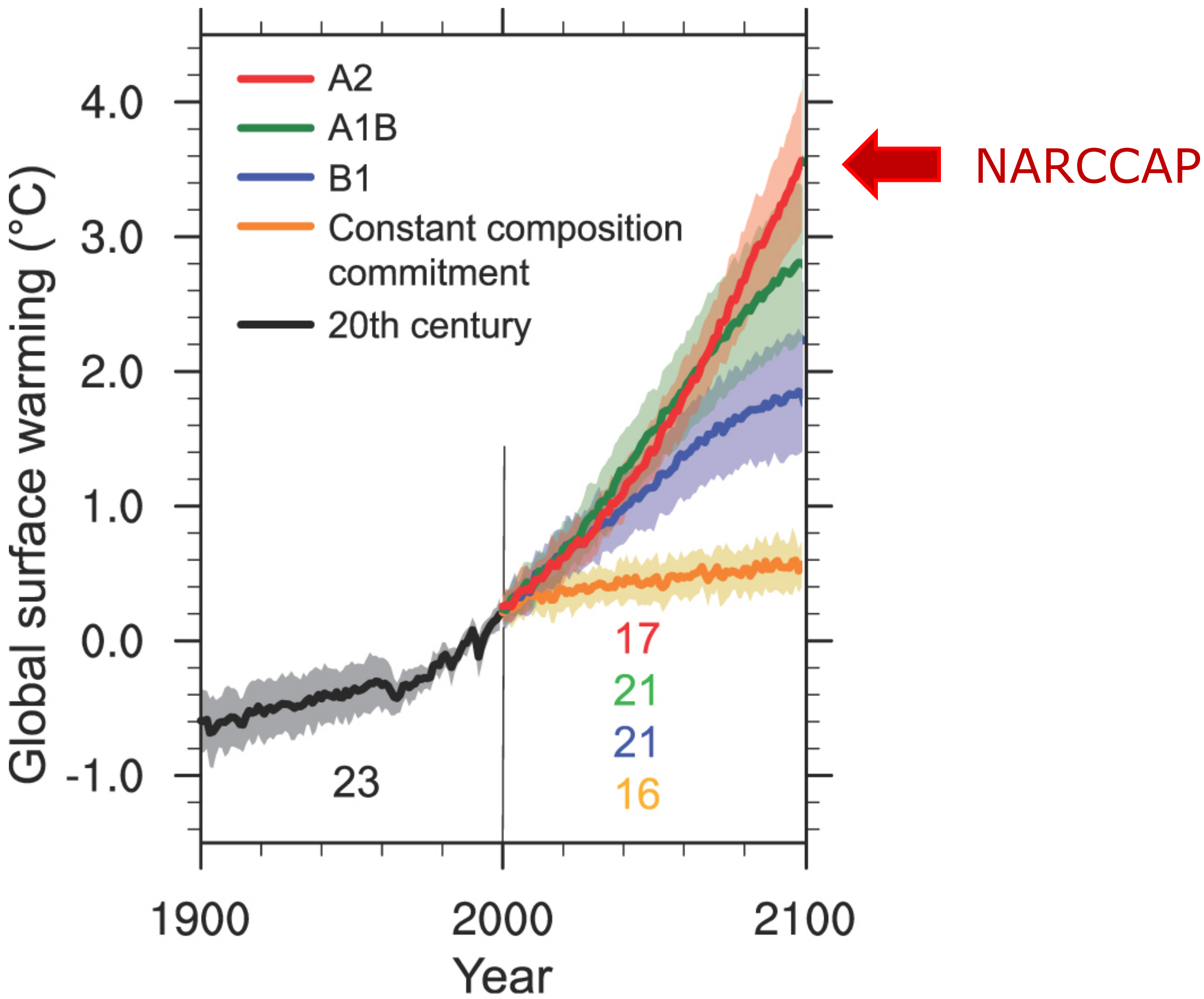
➡ Differences are generally quite small

NARCCAP

- International program to produce high resolution climate change simulations

- Configuration
  - Domain covers U.S. and most of Canada
  - 50 km spatial resolution
  - Forced with SRES A2 emissions scenario
  - NCEP Reanalysis (obs-driven; 1979-2004), current period (GCM-driven; 1971-2000), and future period (GCM-driven; 2041-2070)
  - 3-hourly values

Emission scenarios



Improvements to methodology

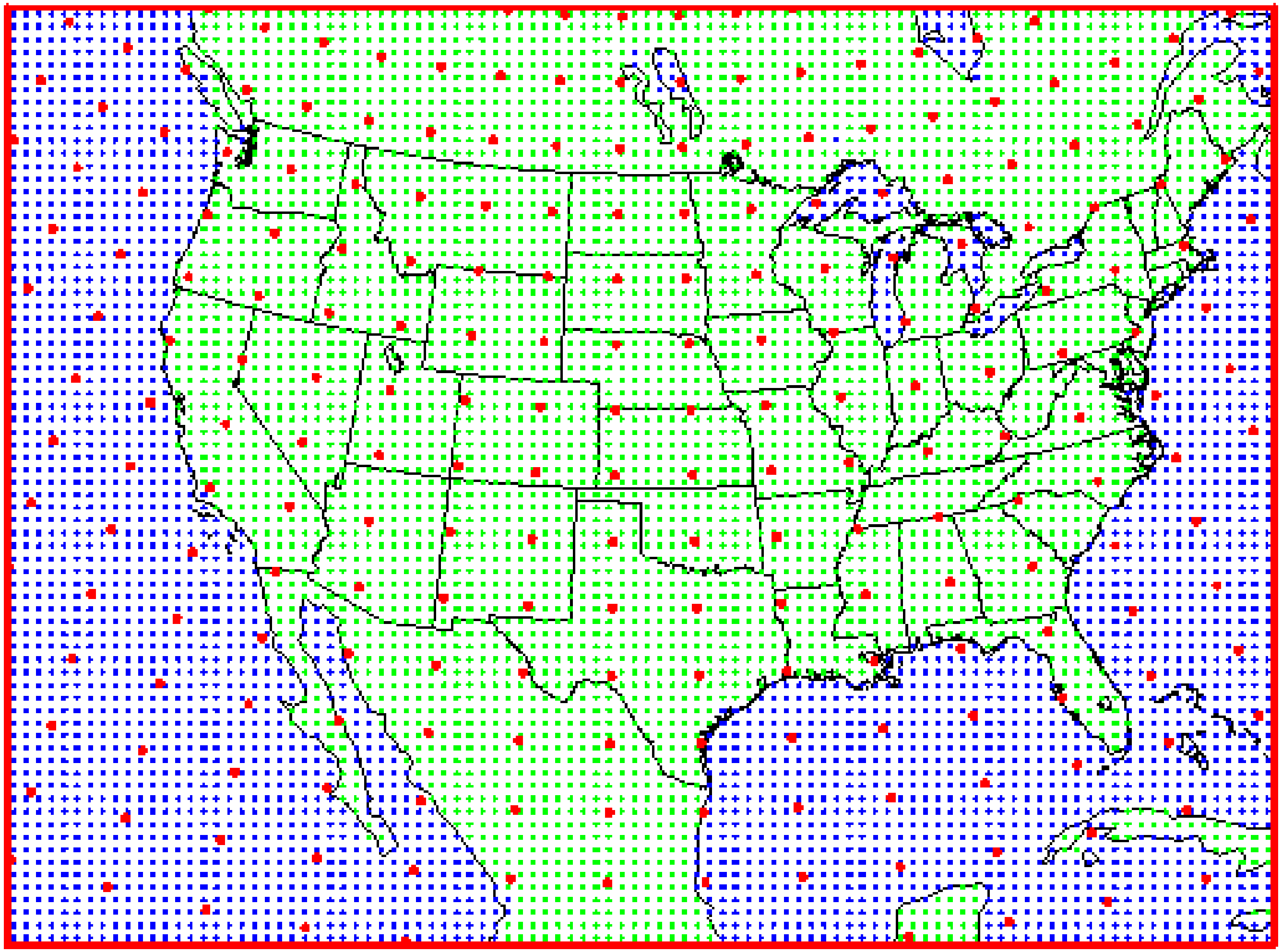
- Dynamical downscaling
- Results applicable to all U.S. locations available in the TMY3 database
- Use of multiple GCMs and RCMs to quantify the range of uncertainty in future climate projections

RCMs: Dynamical downscaling

- Impacts of climate change are currently assessed by “statistically downscaling” information produced by GCMs for specific locations.

- “Dynamical” downscaling
  - An alternative method to that used by Karl et al. (2009), Xu et al. (2009), Crawley (2008), and Guan (2009)
  - GCMs provide boundary conditions for RCMs
  - North American Regional Climate Change Assessment Program (NARCCAP, 2010)

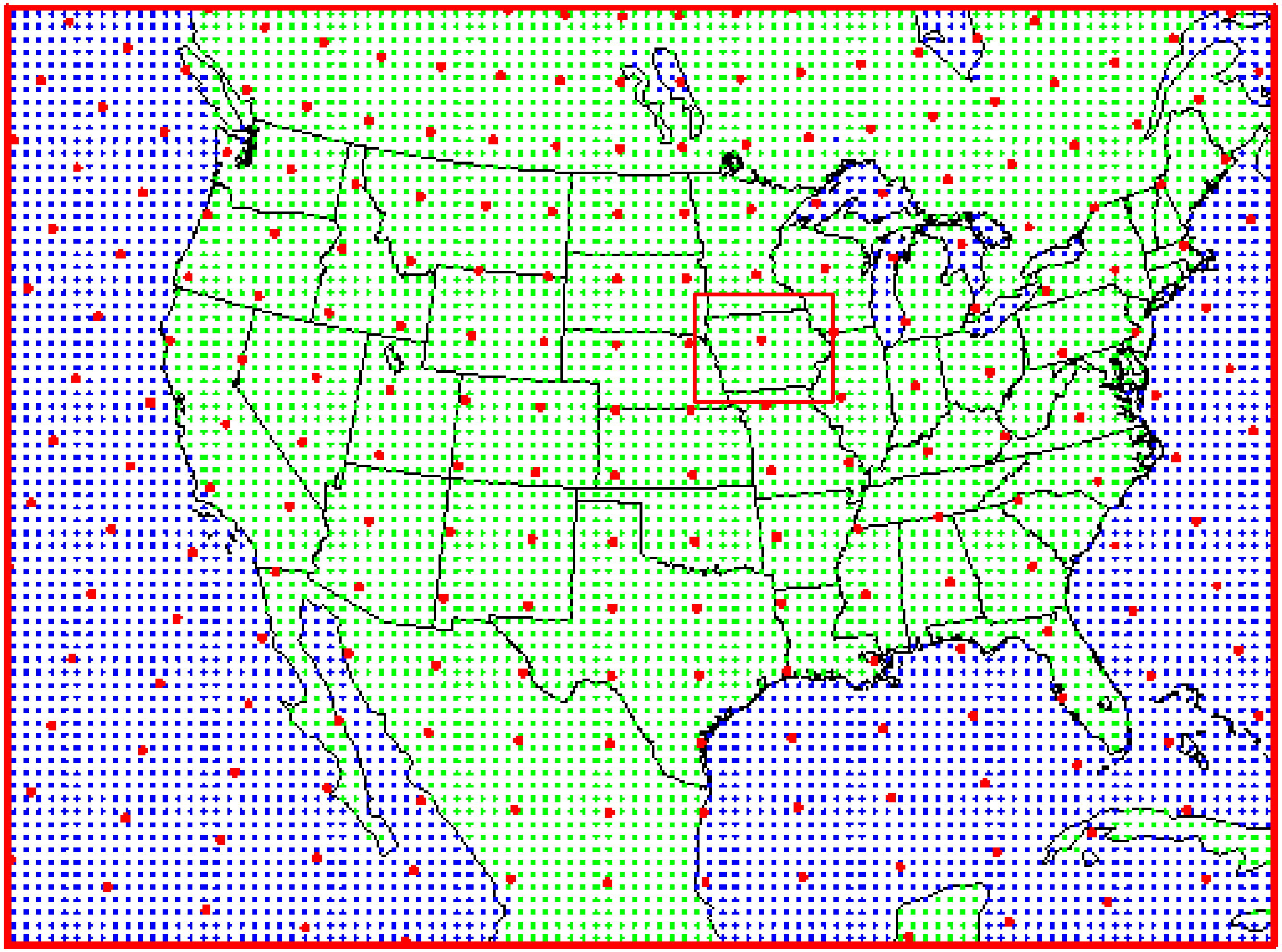
Resolution comparison



● global
● regional (land)
● regional (water)

Only every second RCM grid point is shown in each direction

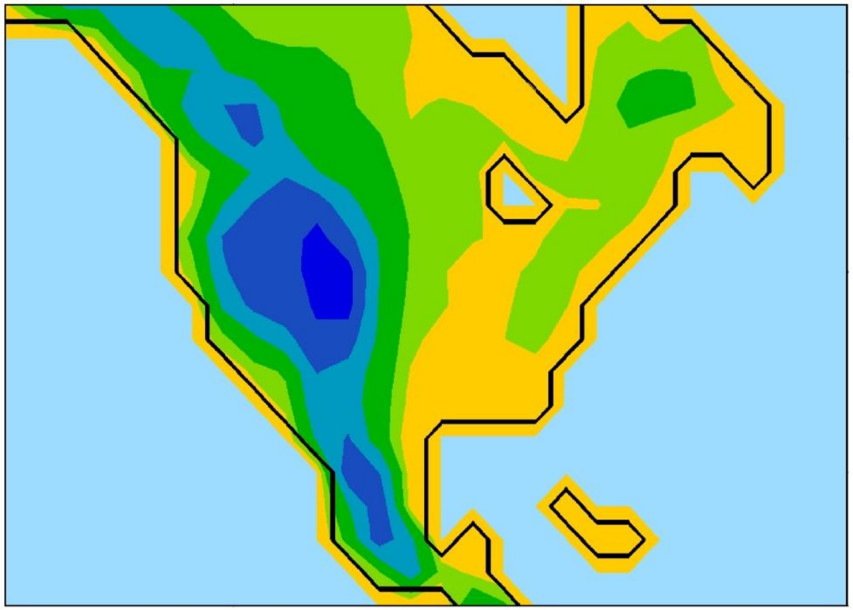
Resolution comparison



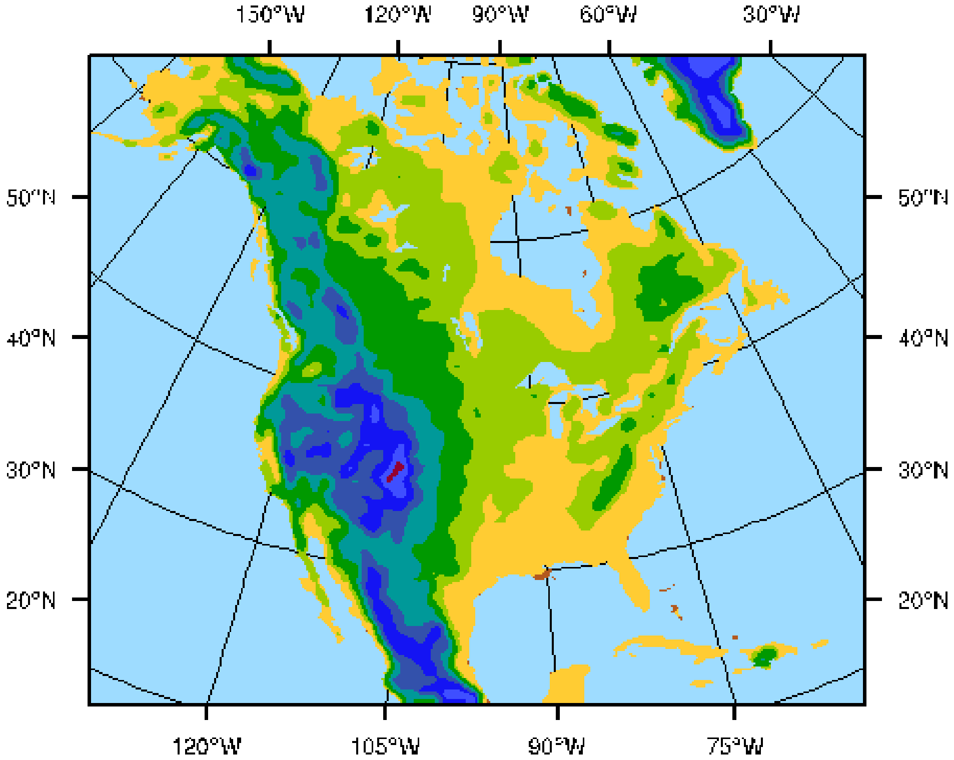
- global
- regional (land)
- regional (water)

Only every second RCM grid point is shown in each direction

Example: Modeled terrain

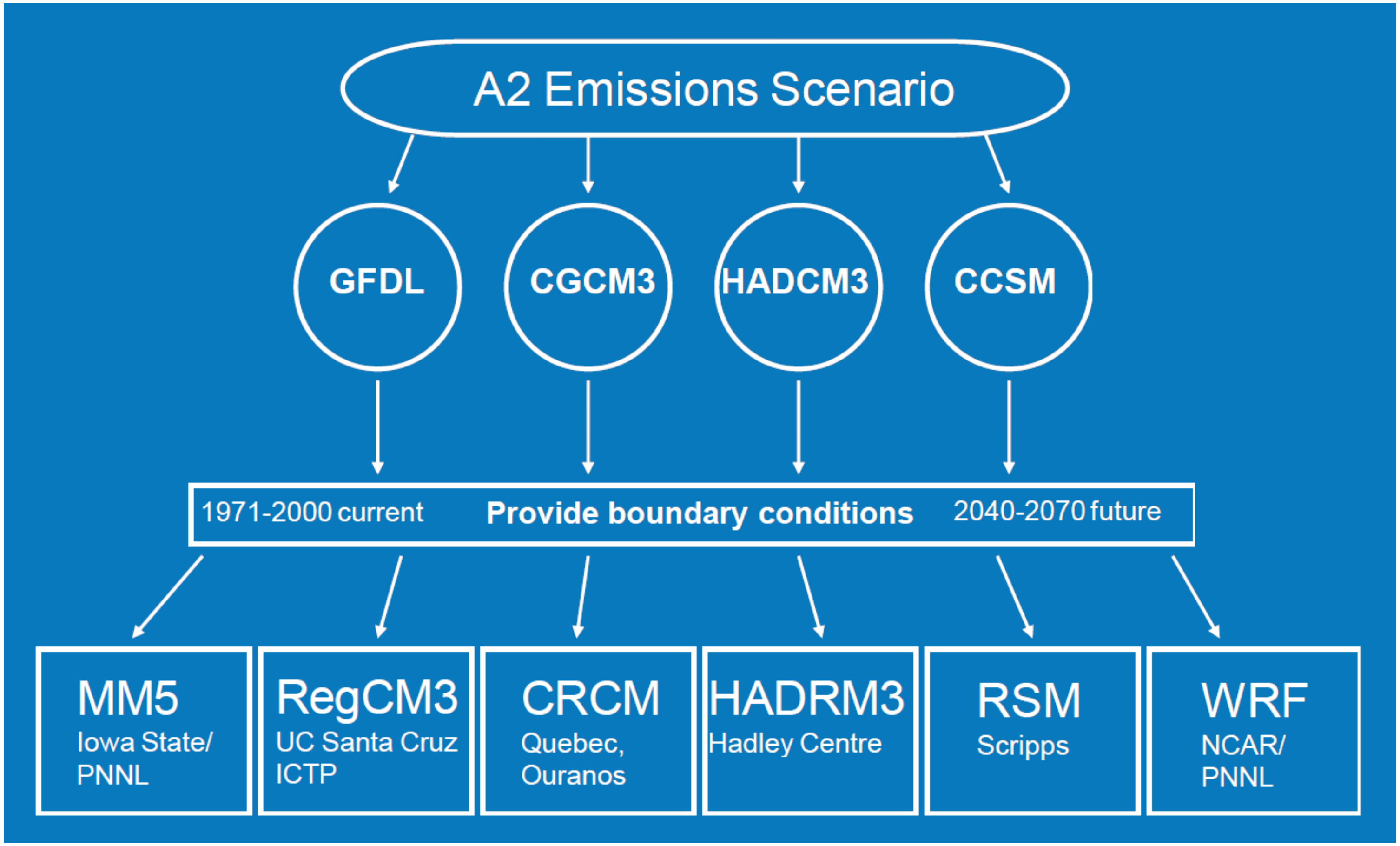


GCM

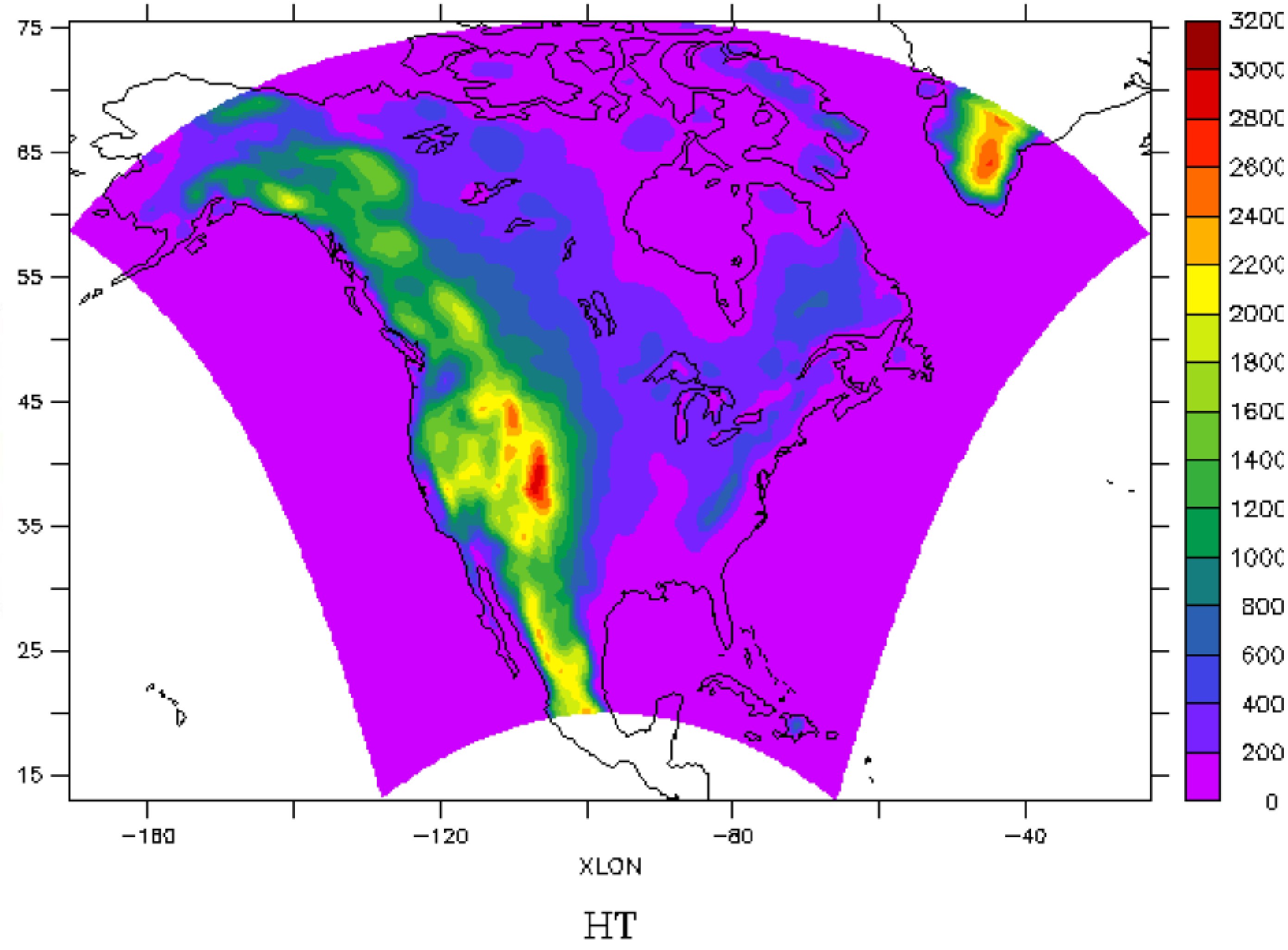


RCM

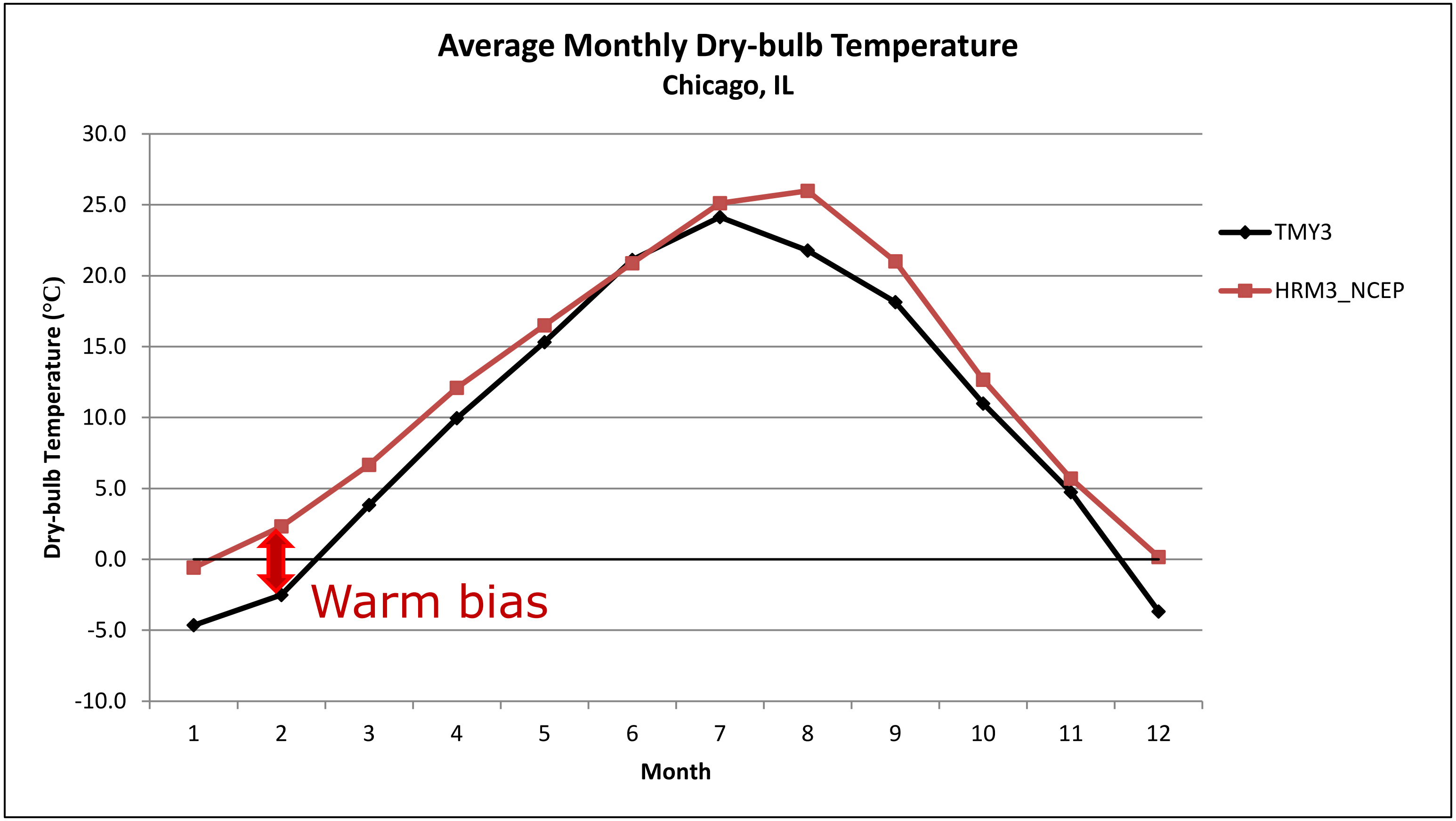
Quantification of uncertainty



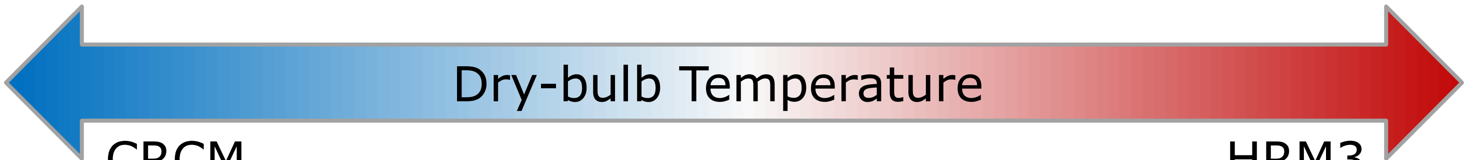
Application to locations



Model evaluation



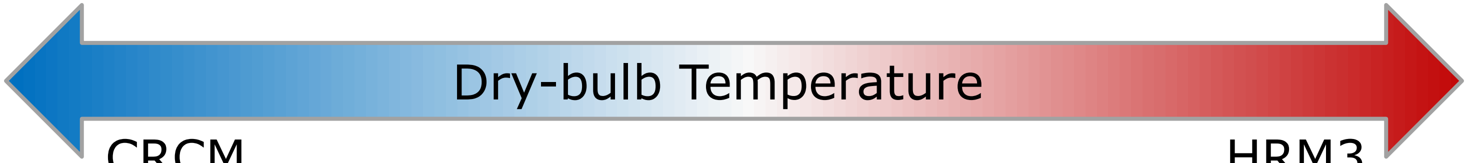
Model biases



CRCM
MM5I
RCM3
WRFG (Northeast)

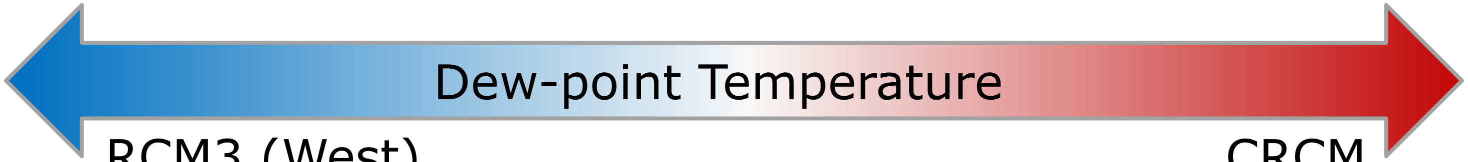
HRM3
WRFG(Midwest)

Model biases



CRCM
MM5I
RCM3
WRFG (Northeast)

HRM3
WRFG(Midwest)



RCM3 (West)
WRFG (Midwest)

CRCM
HRM3
RCM3 (East)
WRFG (Northeast)

Model biases

Dry-bulb Temperature

CRCM
MM5I
RCM3
WRFG (Northeast)

HRM3
WRFG(Midwest)

Dew-point Temperature

RCM3 (West)
WRFG (Midwest)

CRCM
HRM3
RCM3 (East)
WRFG (Northeast)

Precipitation

CRCM
HRM3
RCM3 (Coastal)
WRFG (South)

MM5I (Midwest)
RCM3
WRFG (North)

Model projected change

Table 4.1 Average NARCCAP Annual Projected Change

City	Totcld tens	Dry-bulb °C	Dew-point °C	Rhum %	Ahum g cm^{-3}	Pressure mbar	Wspd m s^{-1}	Wdir deg	Precip mm
Atlanta, GA	-0.21	2.30	1.88	-1.21	1.29	0.33	-0.05	-0.98	11.47
Baltimore, MD	-0.14	2.46	2.14	-0.77	1.25	0.27	-0.06	-5.85	3.75
Chicago, IL	-0.06	2.65	2.30	-0.70	1.06	0.23	-0.05	-3.88	22.50
Denver, CO	-0.05	2.67	1.77	-1.85	0.63	1.26	-0.10	-1.02	-37.45
Los Angeles, CA	0.04	1.89	1.82	0.10	1.08	0.09	-0.07	-5.63	-5.08
Miami, FL	-0.38	1.92	1.64	-0.92	1.71	0.27	0.02	-1.96	-129.56
Minneapolis, MN	-0.04	2.63	2.49	-0.02	1.02	0.28	-0.03	-5.02	28.72
Phoenix, AZ	-0.03	2.45	1.46	-2.09	0.67	0.40	-0.06	2.47	-51.03
Seattle, WA	-0.07	1.91	1.80	-0.11	0.83	0.42	-0.07	0.94	2.55

Model projected change

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Los Angeles, CA	0.04	1.89	1.82	0.10	1.08	0.09	-0.07	-5.63	-5.08
Miami, FL	-0.38	1.92	1.64	-0.92	1.71	0.27	0.02	-1.96	-129.56
Minneapolis, MN	-0.04	2.63	2.49	-0.02	1.02	0.28	-0.03	-5.02	28.72
Phoenix, AZ	-0.03	2.45	1.46	-2.09	0.67	0.40	-0.06	2.47	-51.03
Seattle, WA	-0.07	1.91	1.80	-0.11	0.83	0.42	-0.07	0.94	2.55

- Increasing temperatures from 1.5°C to 3.0°C
- Decreasing cloud cover, relative humidity and wind speed

Model inter-comparison

- Ranked projected changes of each model combination from 1 to 9
  - HRM3-GFDL (model combination)
    - 1 for dry-bulb temperature
    - 9 for dew-point temperature
  - CRCM (RCMs)
    - 3-4 for dry-bulb temperature
    - 1-2 for dew-point temperature
  - CCSM (GCMs)
    - 2-3 for dry-bulb temperature
    - 1-4 for dew-point temperature

Significance

- Does the model projected change exceed both the natural variability of the 20th century and inter-model variability?

Table 4.2 Average Annual Projected Change for Chicago, IL

Value	Totcld tens	Dry-bulb °C	Dew-point °C	Rhum %	Ahum g cm^{-3}	Pressure mbar	Wspd m s^{-1}	Wdir deg	Precip mm
Projected Change	-0.06	2.65	2.30	-0.70	1.06	0.23	-0.05	-3.88	22.50
SD of Model Change	0.11	0.47	0.39	2.00	0.24	0.53	0.08	1.98	51.31
SD of 20th C Obs	0.31	0.89	1.00	2.82	0.42	0.59	0.34	14.69	261.92

Significance

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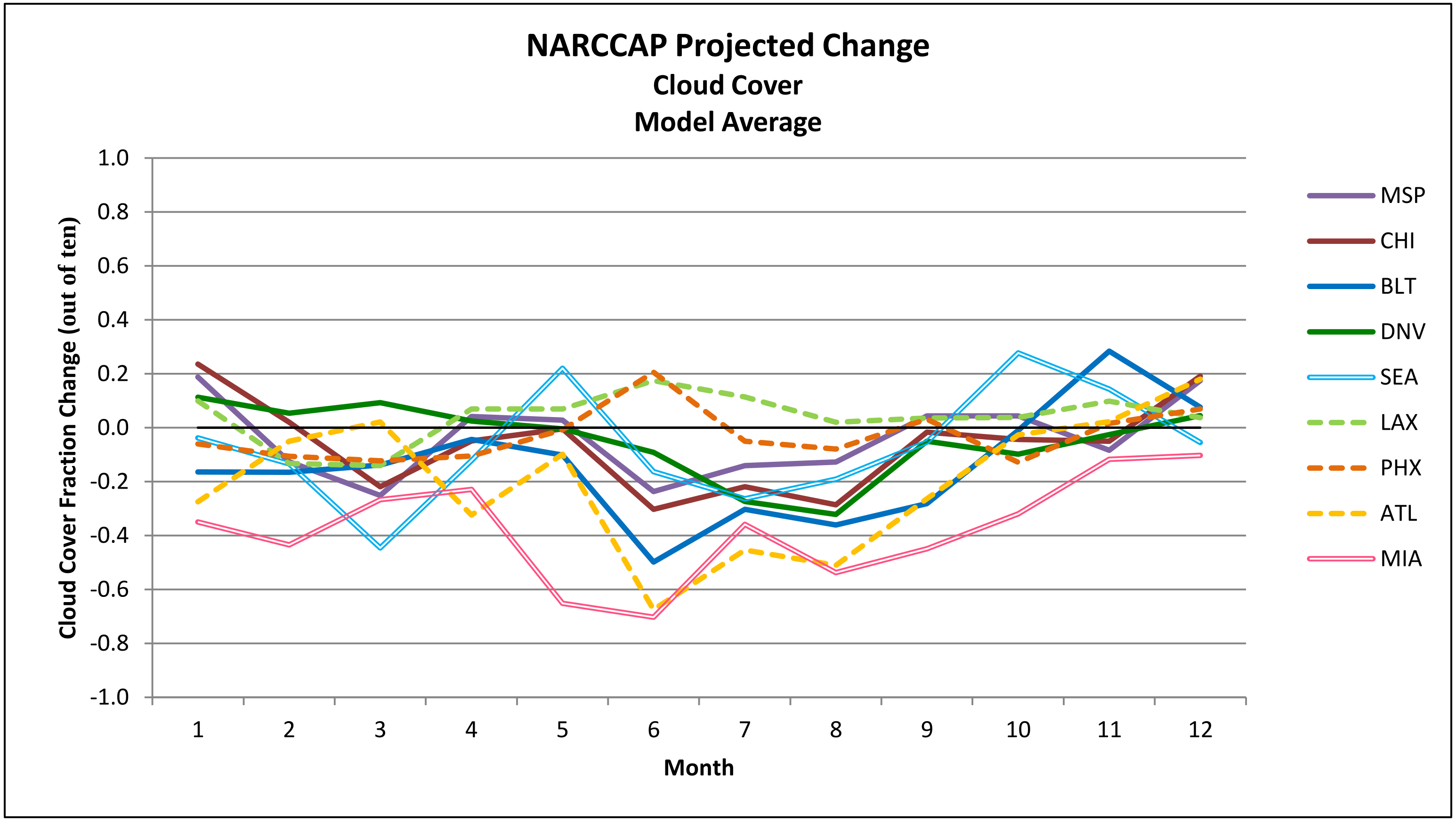
Seasonal changes



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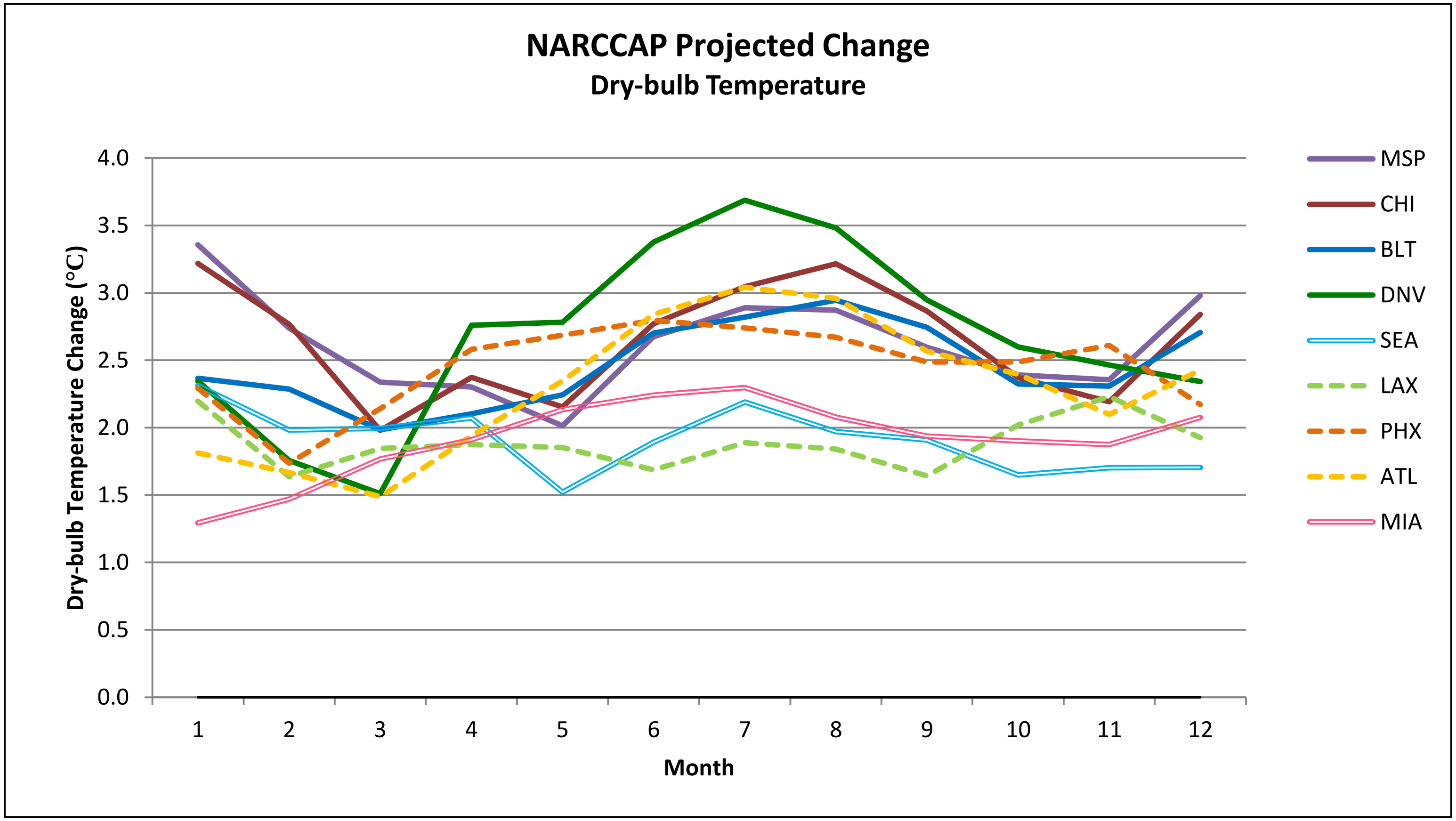

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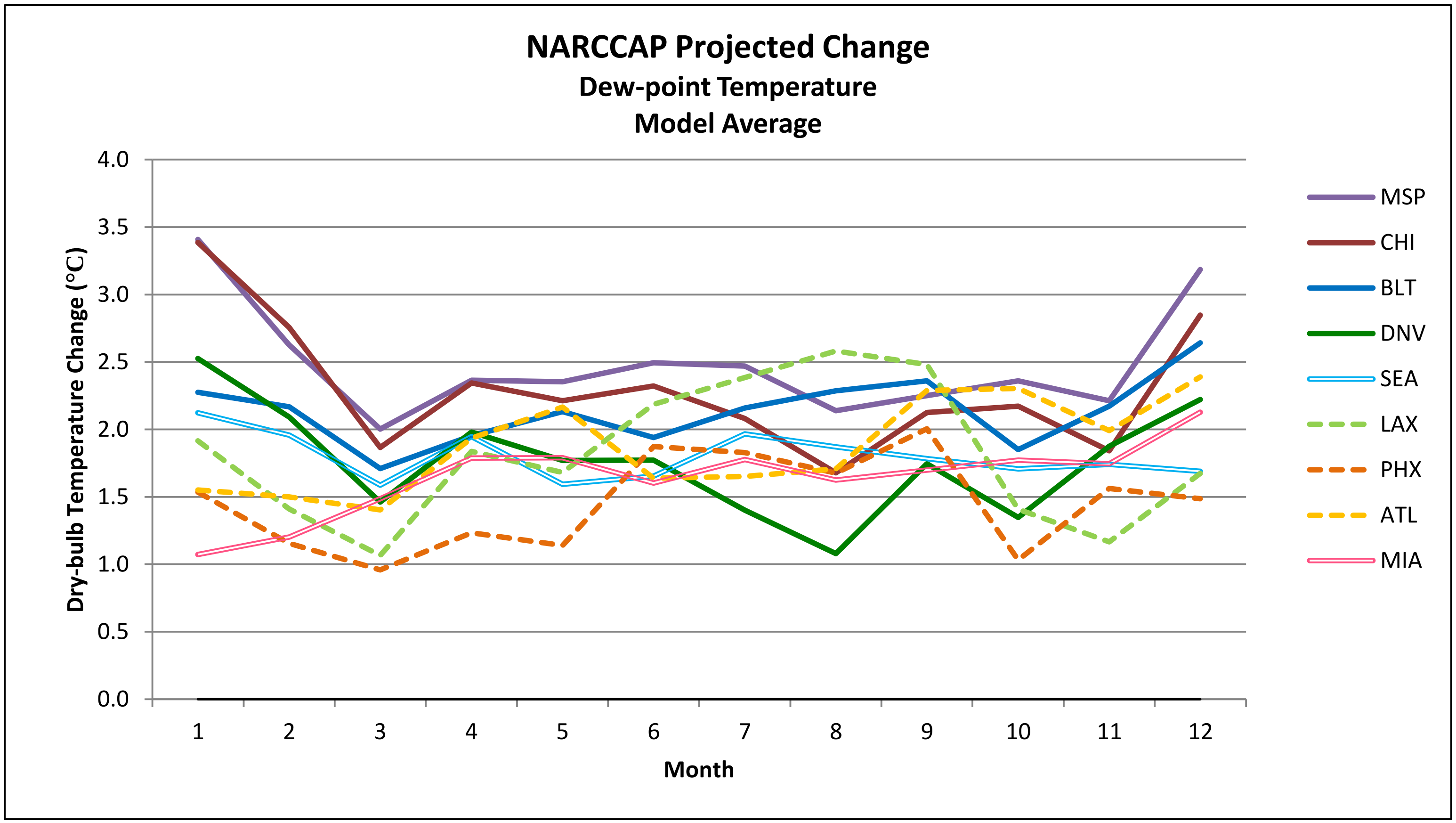

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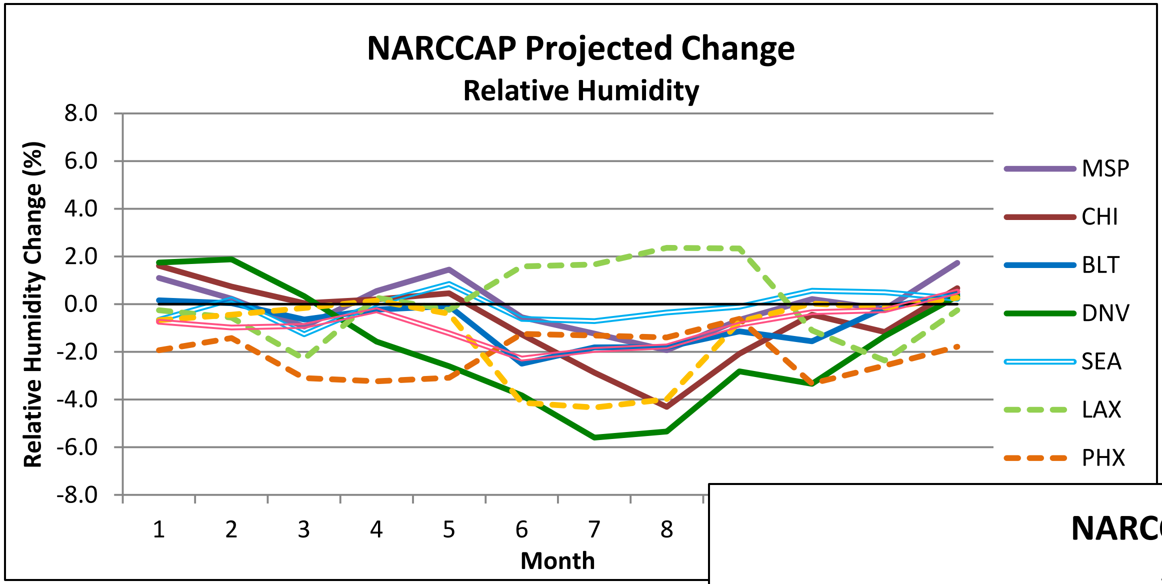
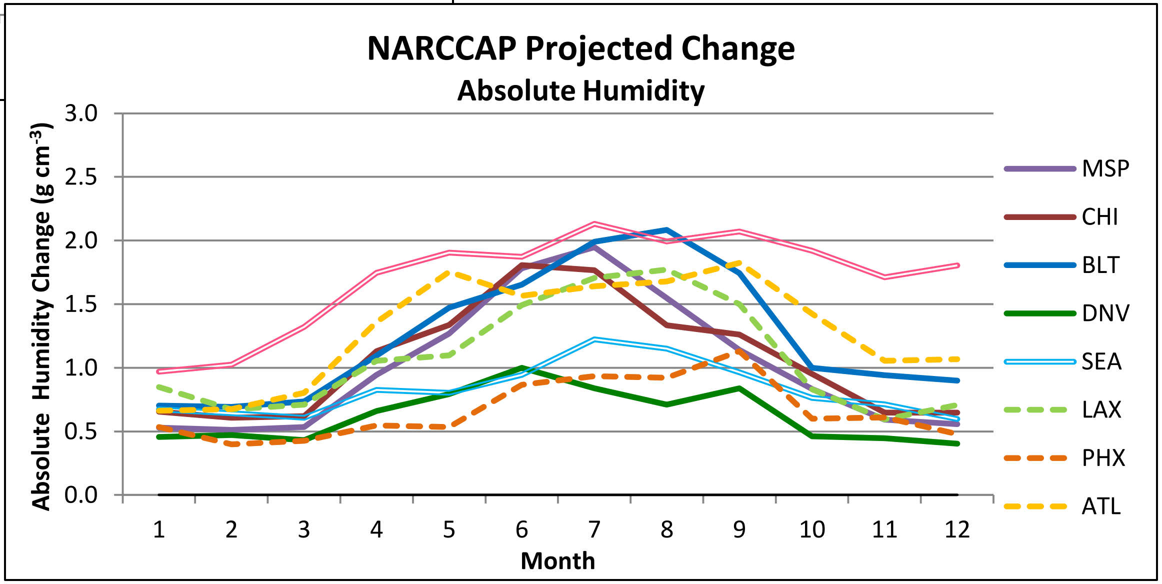


Largest *decrease* in summer

Largest *increase* in summer



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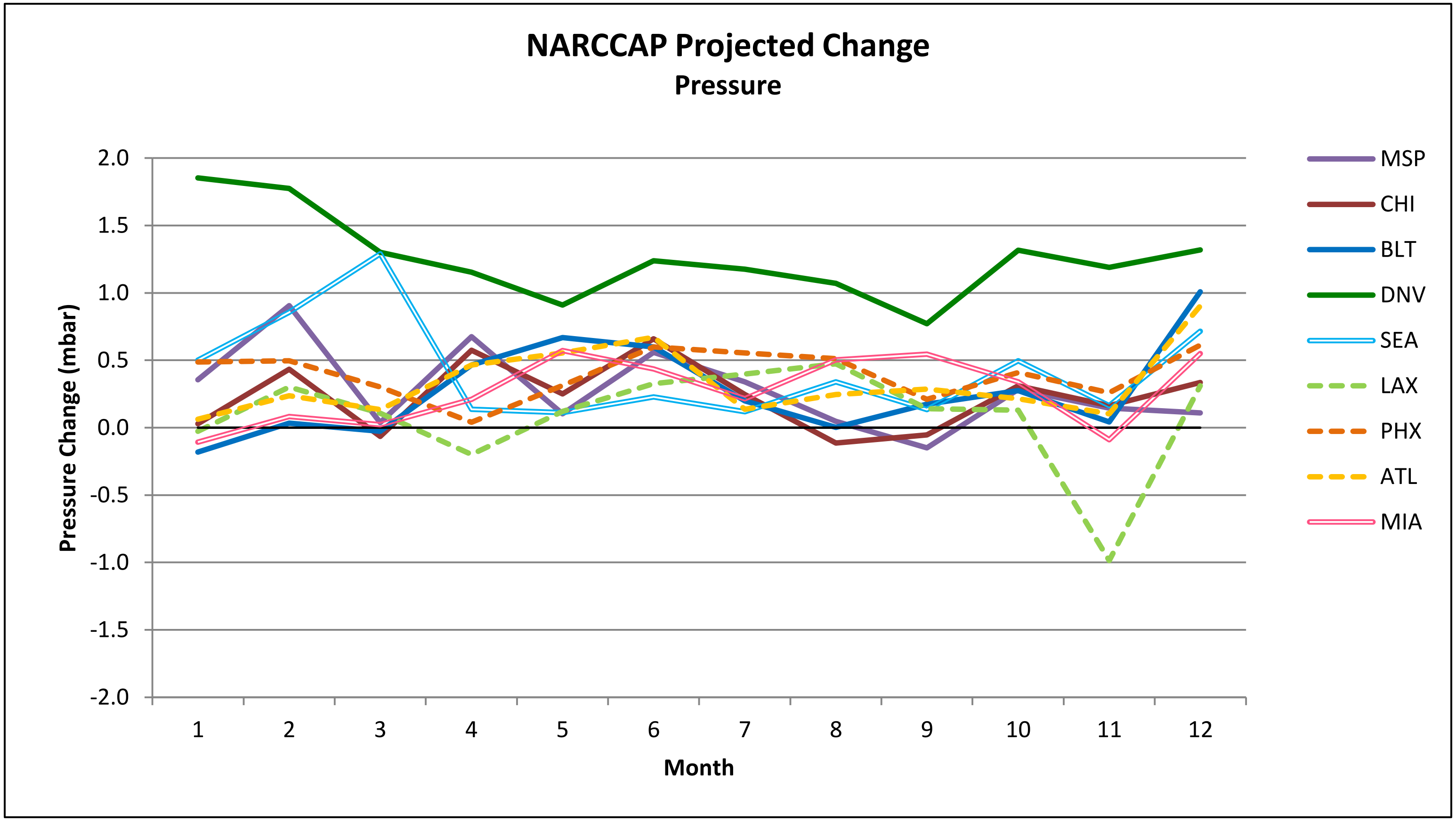
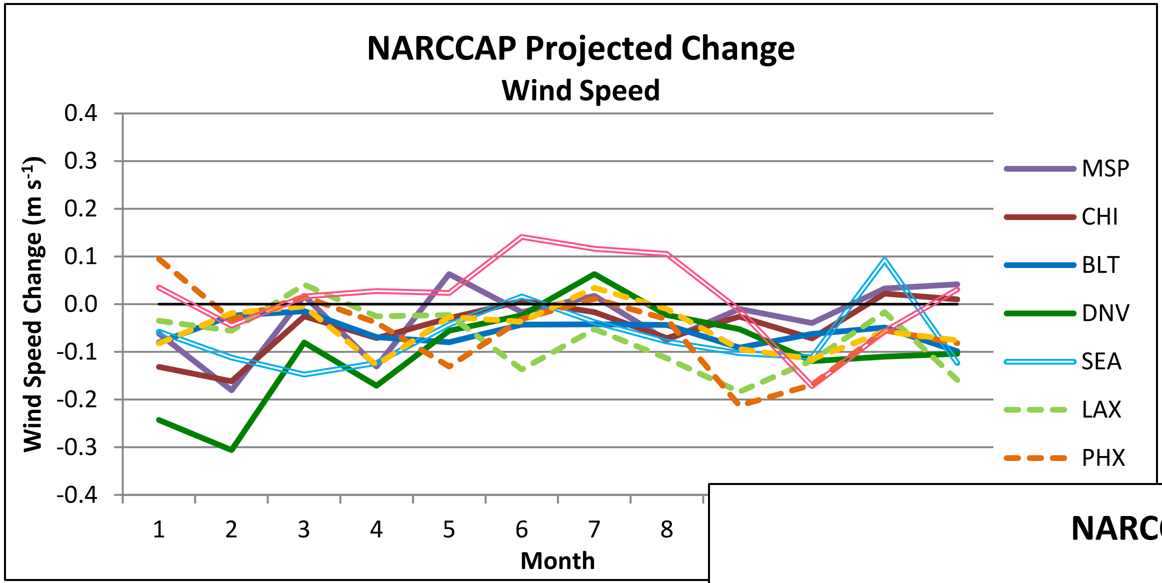
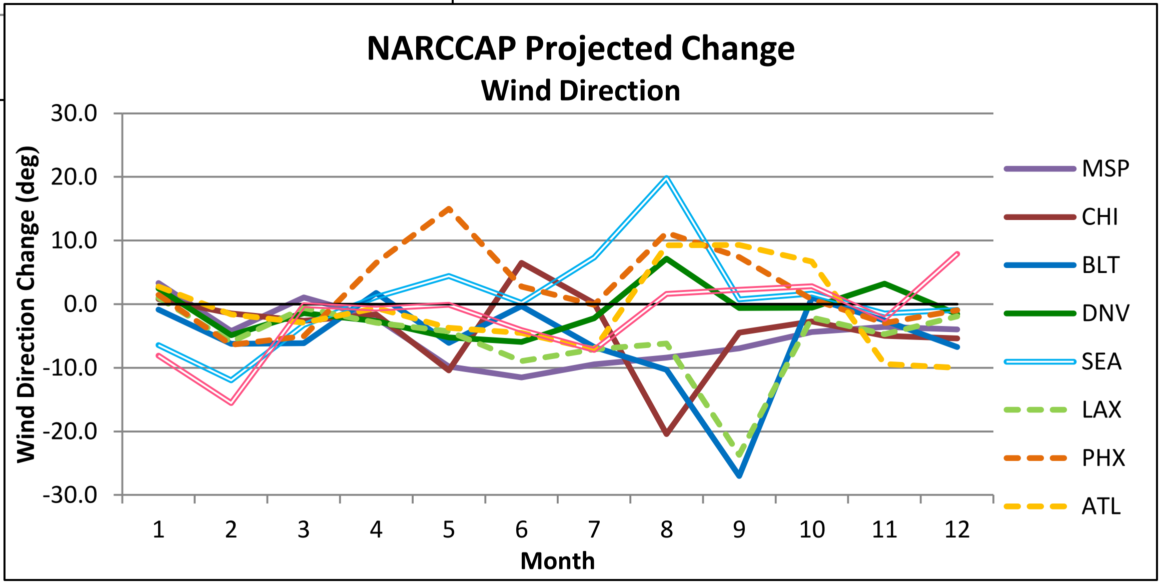


Seasonal changes



Patterns are not as obvious



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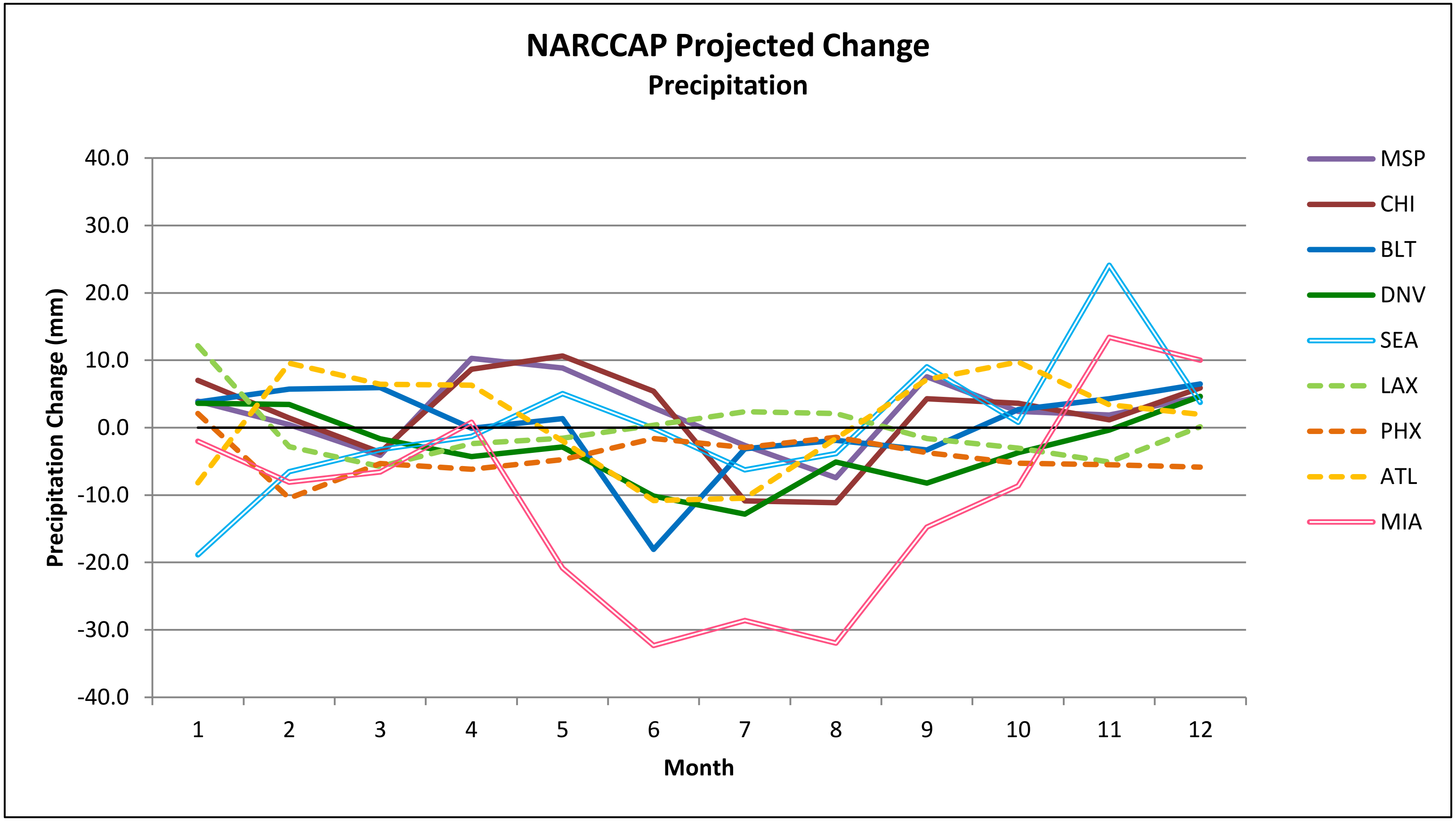
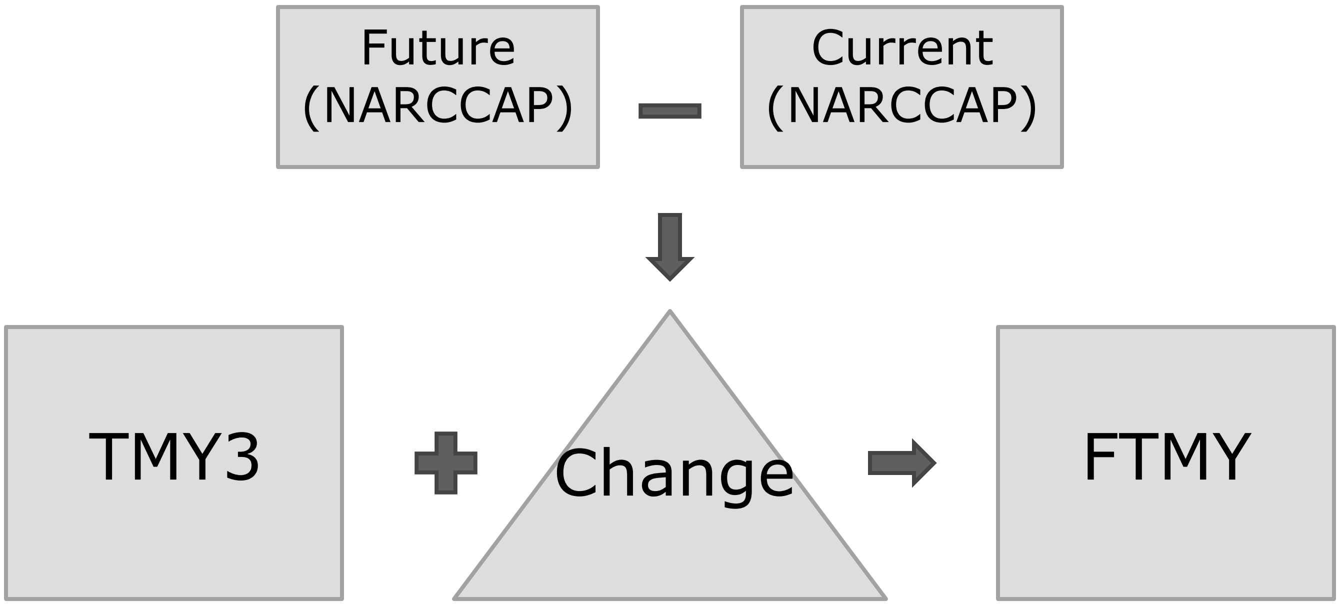


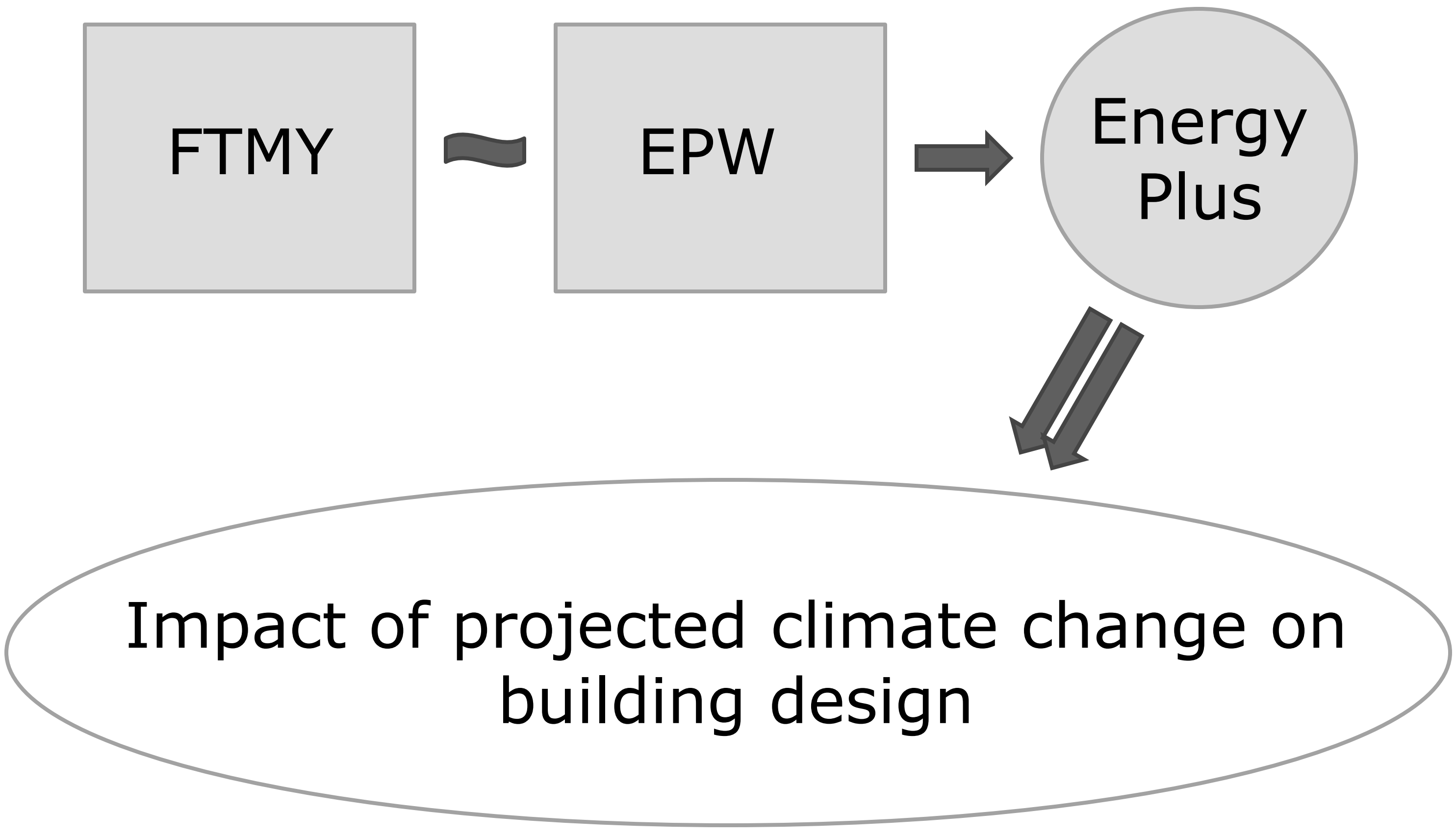
Our study methodology

- Creation of future typical meteorological year (FTMY) dataset



Our study methodology

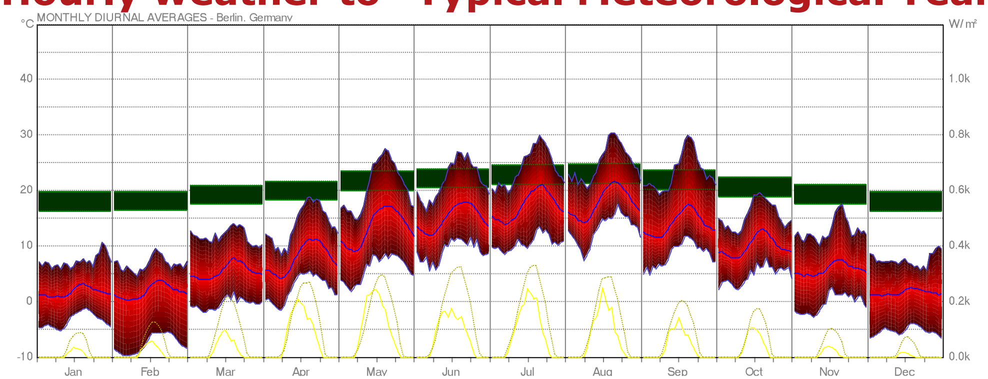
- Simulations of buildings using FTMY



Climate data in energy modeling

- Energy Plus and other modeling software pairs a building design with one weather file to predict energy performance

Hourly weather to "Typical Meteorological Year"



kWh

$$$$$$$$

Projected impact on buildings

Table 5.1 Principal Commercial Building Types (*D and R International*, 2011)

Building	Floorspace	Buildings	Energy Consumption
Office	17	17	19
Mercantile	16	14	18
Retail	6	9	5
Enclosed/Strip Malls	10	4	13
Education	14	8	11
Warehouse and Storage	14	12	7
Lodging	7	3	7
Service	6	13	4
Public Assembly	5	6	5
Religious Worship	5	8	2
Health Care	4	3	8
Inpatient	3	0	6
Outpatient	2	2	2
Food Sales	2	5	5
Food Service	2	6	6
Public Order and Safety	2	1	2
Other	2	2	4
Vacant	4	4	1
Total	100	100	100

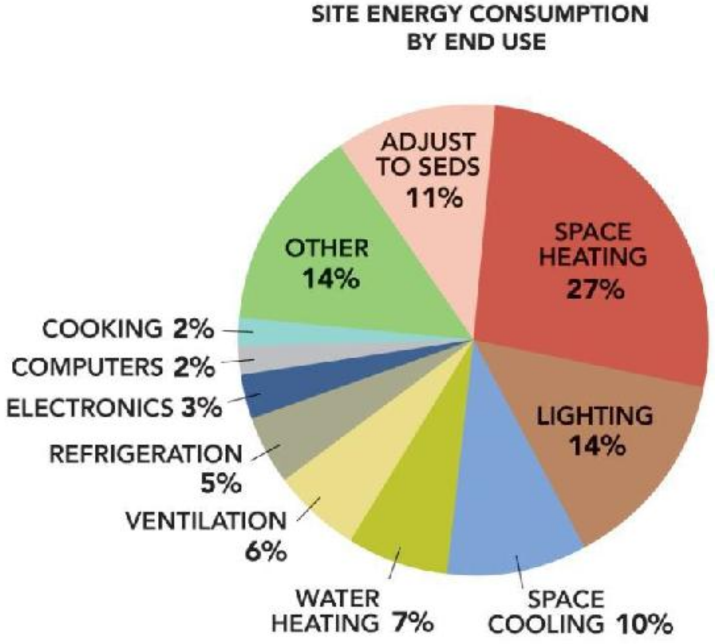


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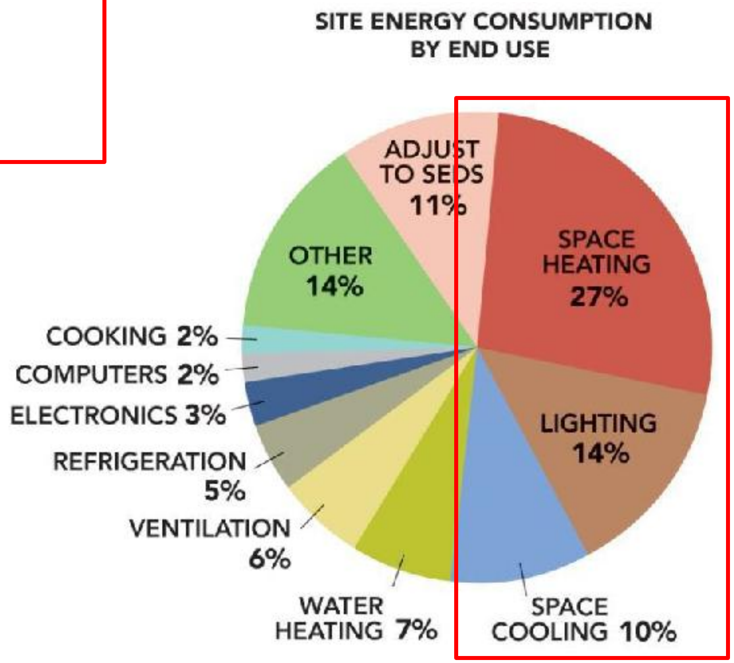
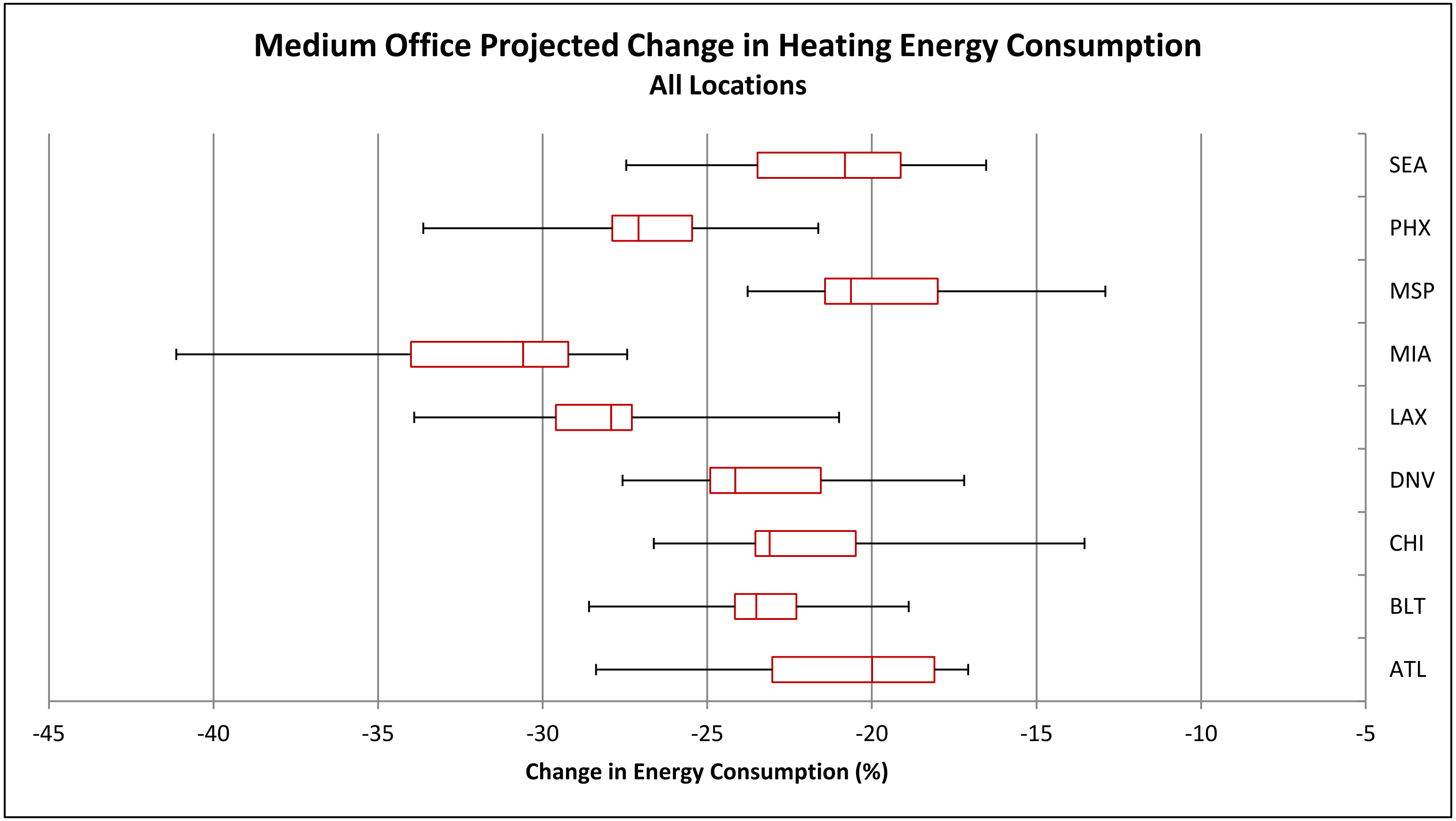
Table 5.1 Principal Commercial Building Types (*D and R International*, 2011)

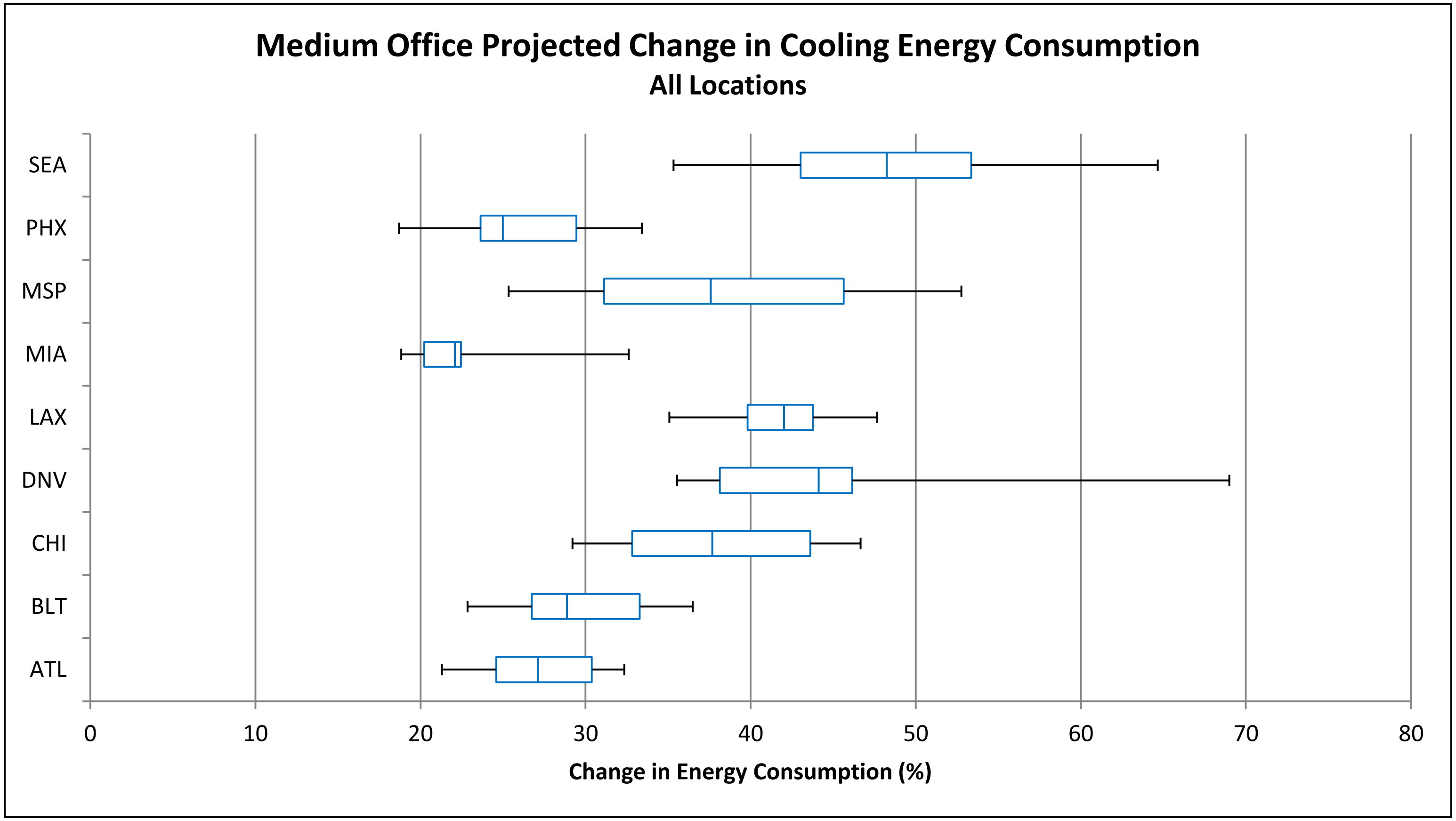
Building	Floorspace	Buildings	Energy Consumption
Office	17	17	19
Mercantile	16	14	18
Retail	6	9	5
Enclosed/Strip Malls	10	4	13
Education	14	8	11
Warehouse and Storage	14	12	7
Lodging	7	3	7
Service	6	13	4
Public Assembly	5	6	5
Religious Worship	5	8	2
Health Care	4	3	8
Inpatient	3	0	6
Outpatient	2	2	2
Food Sales	2	5	5
Food Service	2	6	6
Public Order and Safety	2	1	2
Other	2	2	4
Vacant	4	4	1
Total	100	100	100



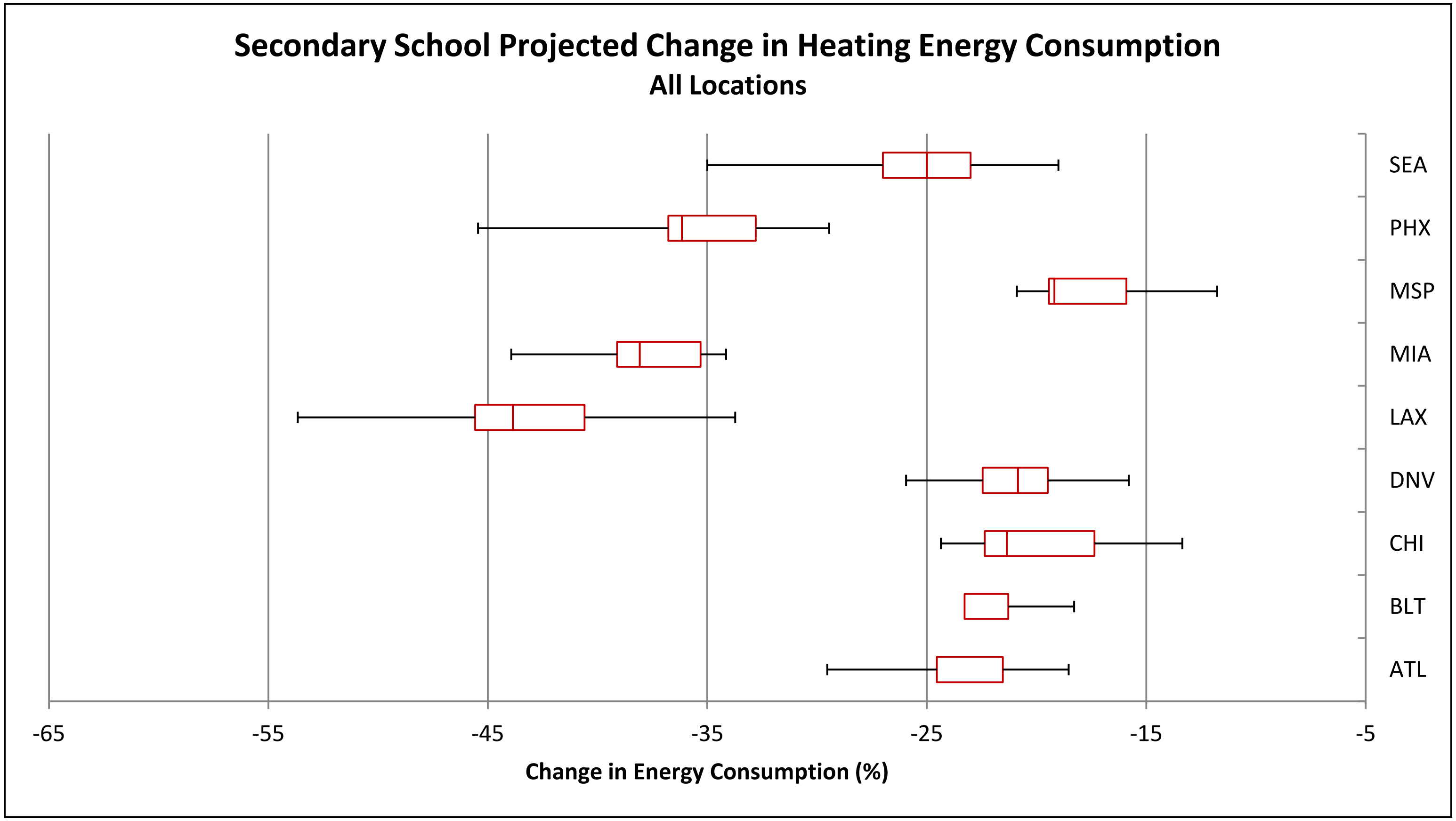
Range of projected consumption change



Range of projected consumption change

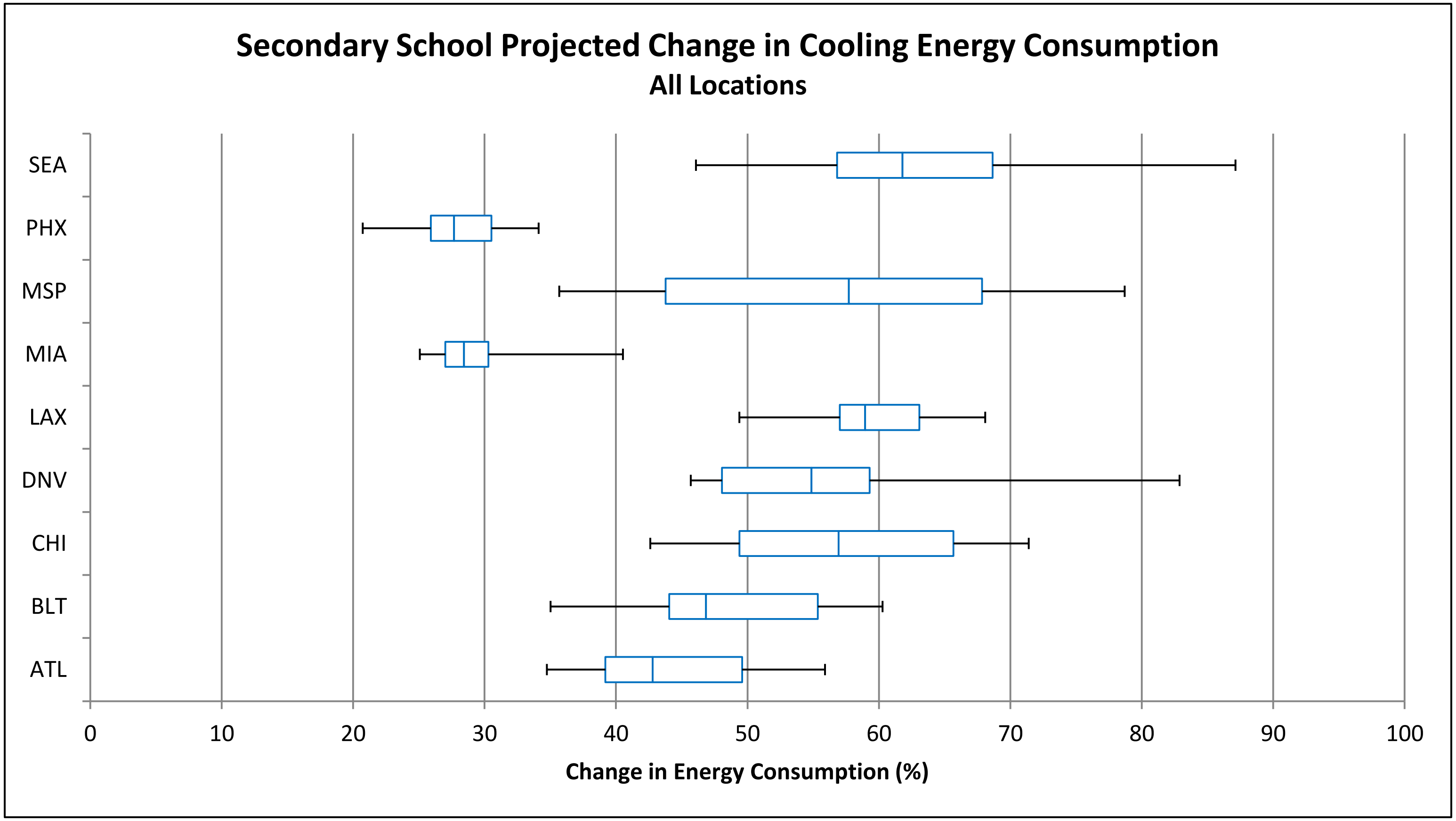


Significance

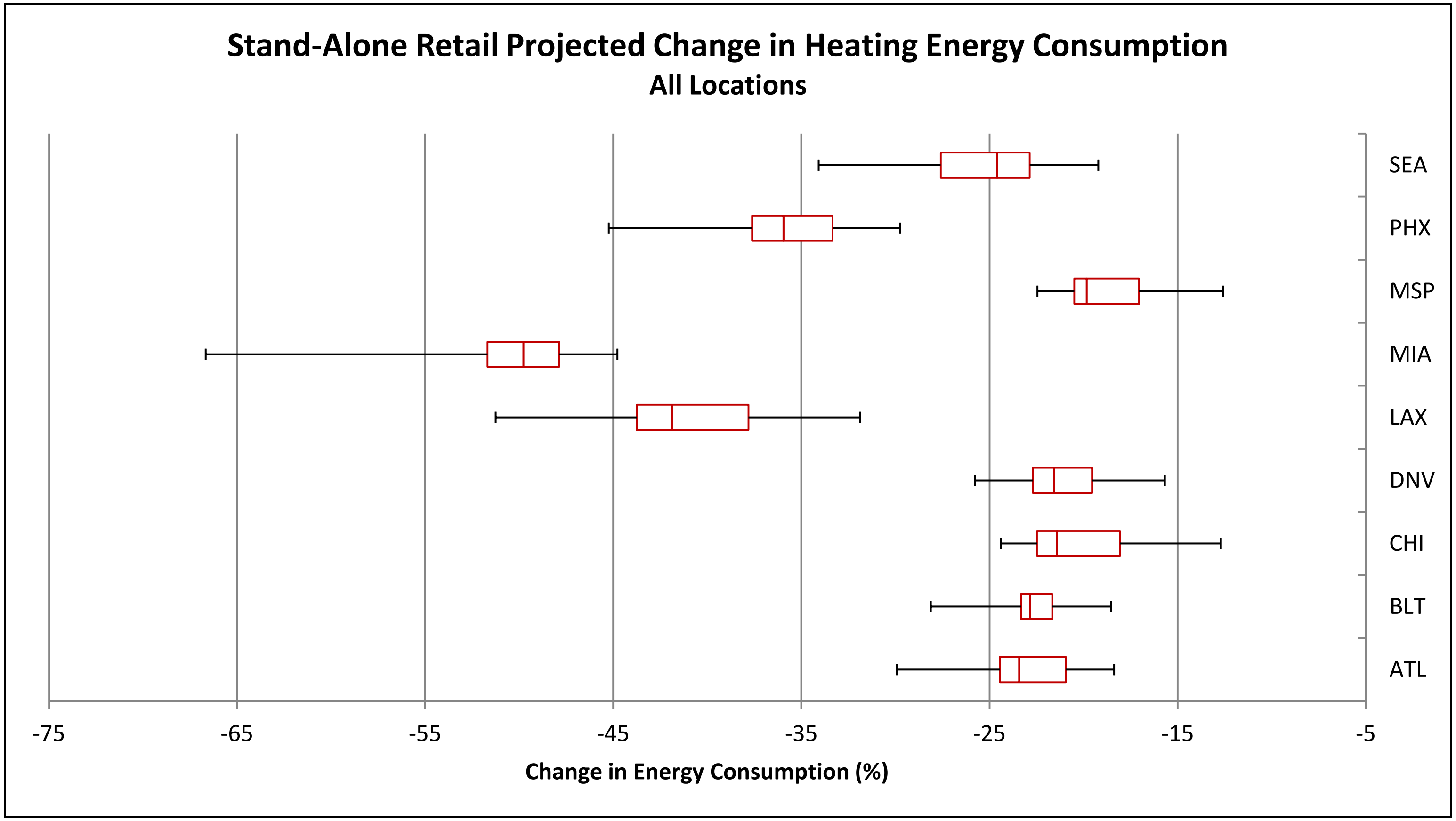


Projected changes are greater than projected ranges

Significance

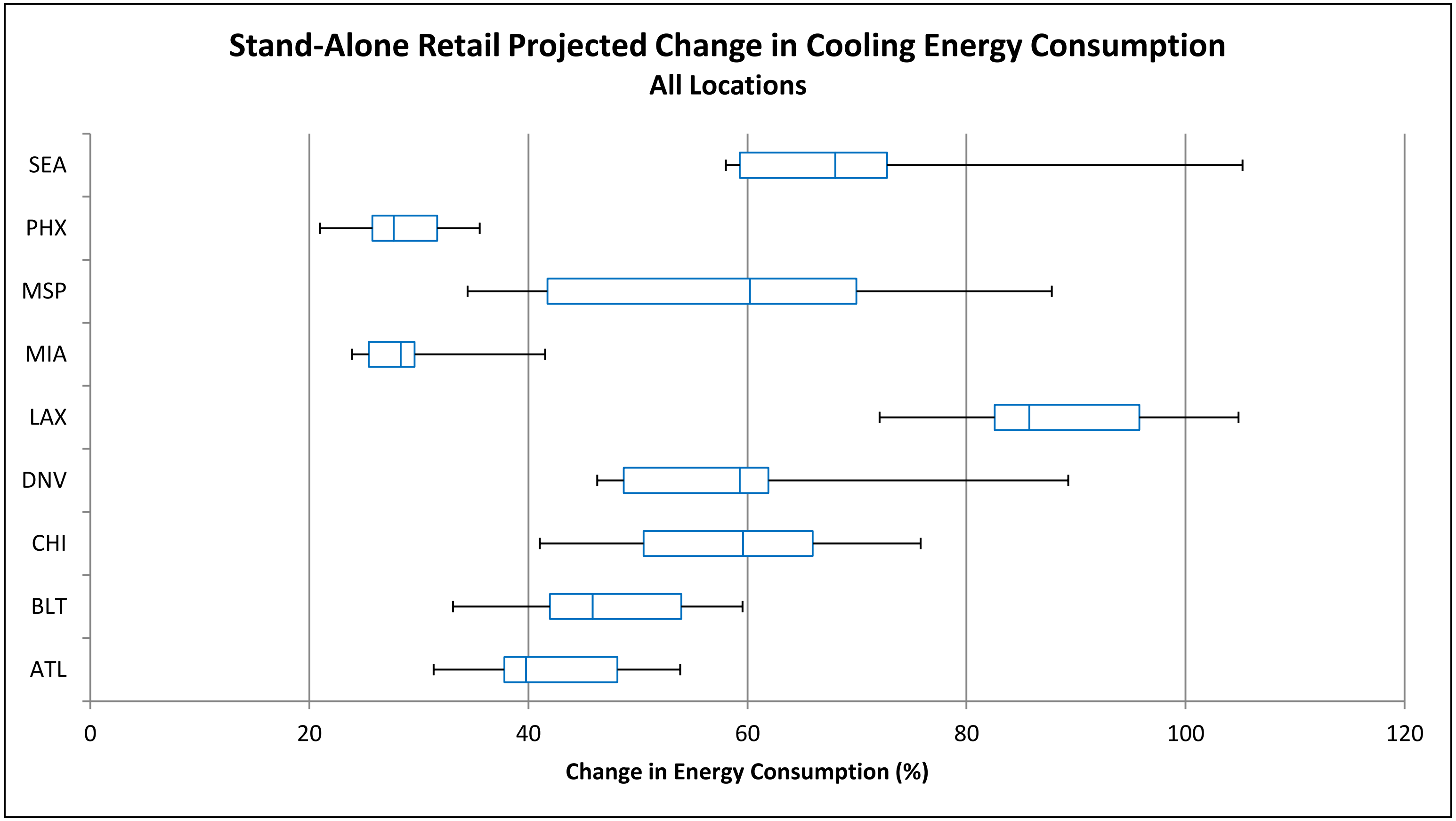


Latitudinal dependence



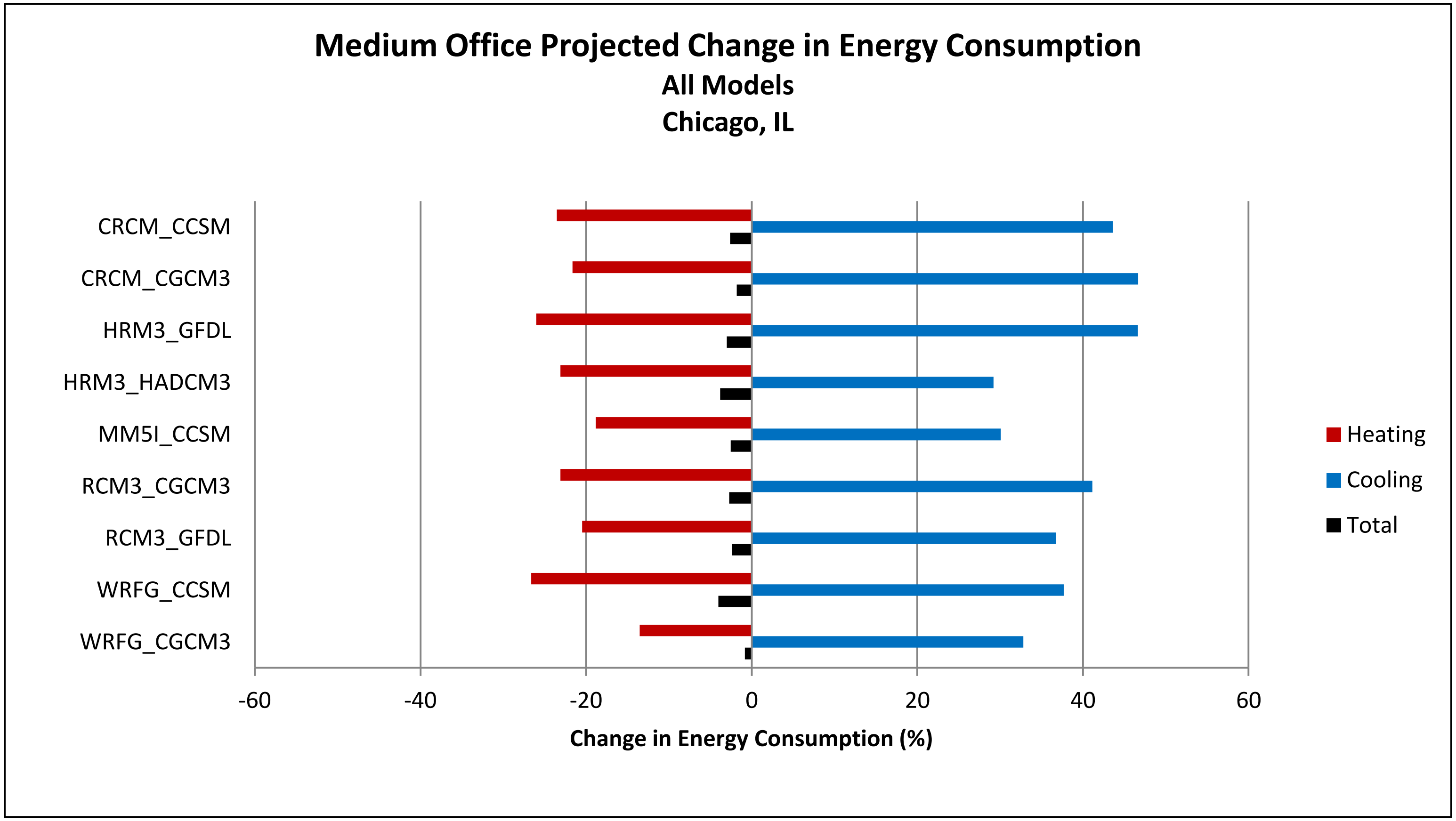
Inverse relationship between percentage and magnitude change

Latitudinal dependence



Colder locations will save enough heating energy due to warmer winters to compensate for increase in cooling usage

Balance


Medium Office Projected Change in Energy Consumption
All Models
Chicago, IL
CRCM_CCSM
CRCM_CGCM3
HRM3_GFDL
HRM3_HADCM3
MM5I_CCSM
RCM3_CGCM3
RCM3_GFDL
WRFG_CCSM
WRFG_CGCM3
-60
-40
-20
0
20
40
60
Change in Energy Consumption (%)
Heating
Cooling
Total

Concerns

- Poor quality precipitation data
- Importance of excluded variables
- Possible issue with humidity removal within EnergyPlus simulations
  - Undersized systems?
  - Reference building design flaw?
  - EnergyPlus design flaw?

Conclusions

- ✓ Heating energy consumption predicted to decrease.
- ✓ Cooling energy consumption predicted to increase.

BUT:

- ✓ Overall annual energy consumptions may increase, decrease, or remain steady depending on balance between heating and cooling.

- ✓ Future typical meteorological year data can be prepared for risk analysis of a changing climate.

Future work

- Expand study to suggested modifications or retrofits
  - Changes in materials
  - Structural changes
  - Associated costs
- Impact of extreme weather
- Application to locations world-wide

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