Climate impacts of historical deforestation in New England, USA using a WRF multi-physics ensemble


Reynoldston, NY Historical Society

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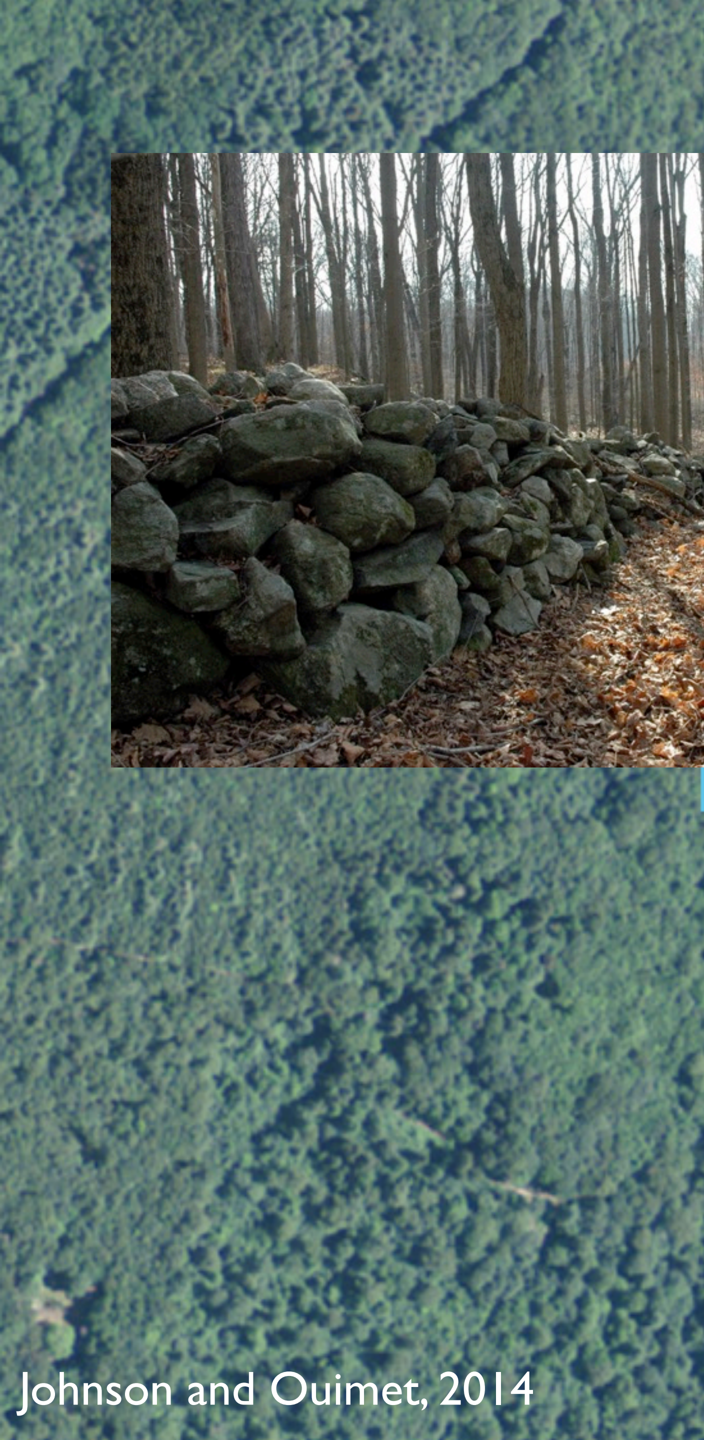
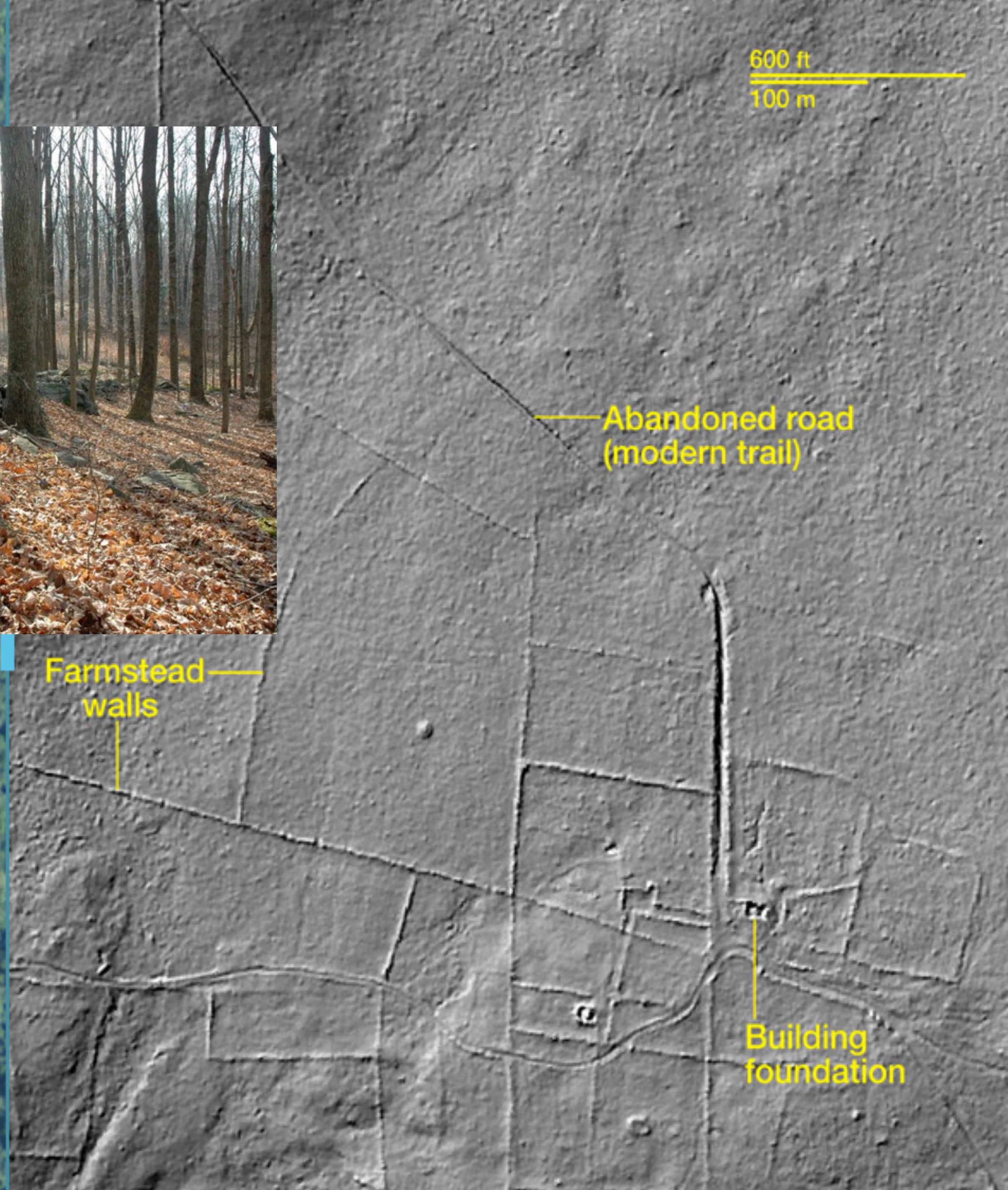
Harvard Forest Seminar 2015-03-20

Peak Deforestation in Mid-1800s

East Boston, c. 1855
Southworth and Hawes, daguerreotype

Completion of the
Great Northern Railway, 1893
Forest History Society





Johnson and Ouimet, 2014

Mid-1800s Peak Deforestation

New England Forest Cover and Human Population

- Connecticut
- Maine
- Massachusetts
- New Hampshire
- Rhode Island
- Vermont
- All New England (% of all six states)

Figure 1. *Historical changes in forest cover show that reforestation of abandoned farmland from the mid-19th through the late 20th century has provided a second chance to determine the fate of the region's forests. Recent trends show the loss of forest throughout the region.*

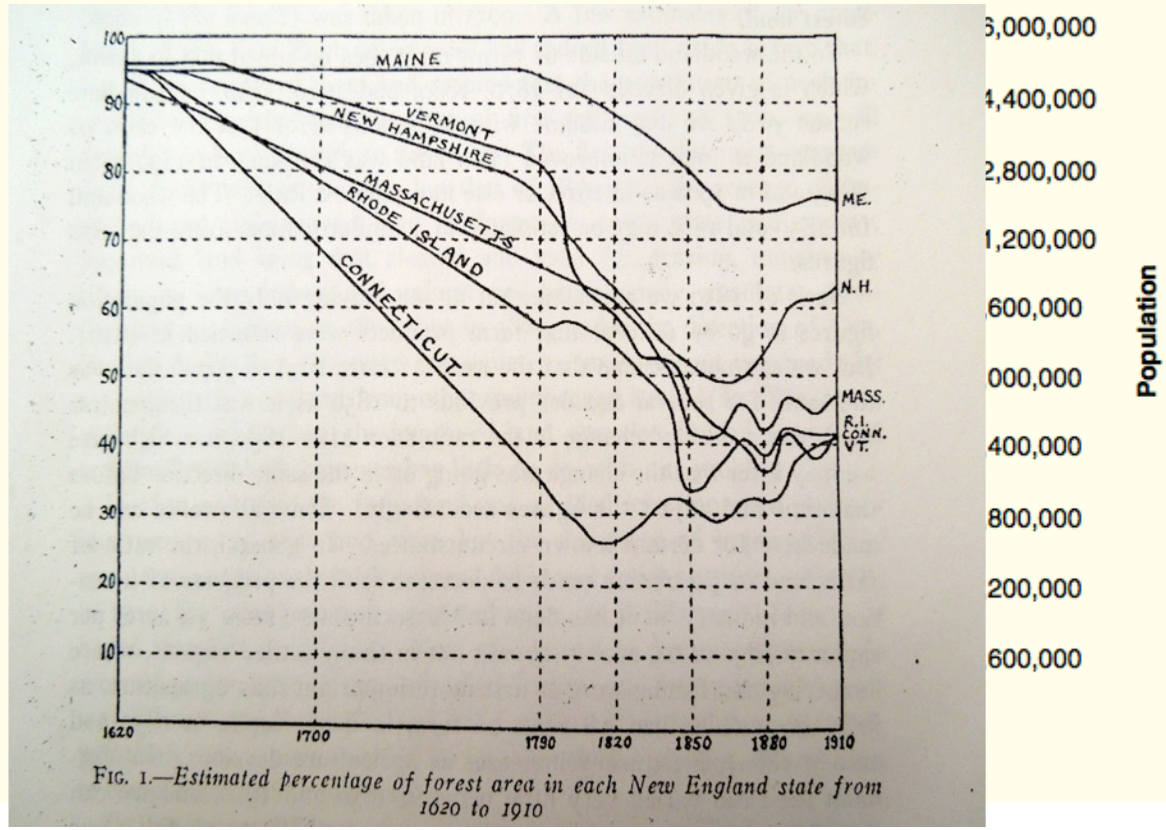


FIG. 1.—*Estimated percentage of forest area in each New England state from 1620 to 1910*

Harper, 1918

Baldwin, 1942

Foster et al. 2008

Mid-1800s Peak Deforestation

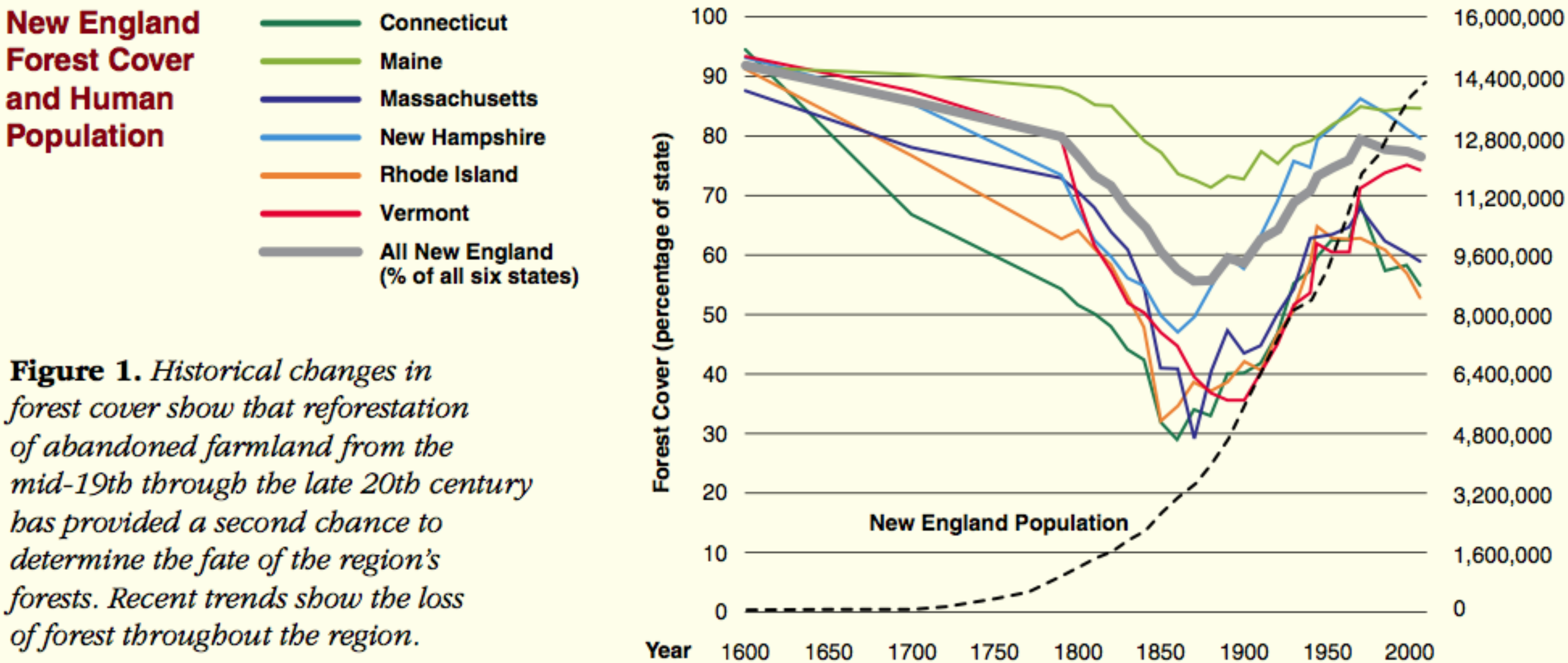


Figure 1. *Historical changes in forest cover show that reforestation of abandoned farmland from the mid-19th through the late 20th century has provided a second chance to determine the fate of the region's forests. Recent trends show the loss of forest throughout the region.*

Harper, 1918

Baldwin, 1942

Foster et al. 2008

8. MARSH SELF-BINDER DRAWN BY OXEN, DALRYMPLE FARM, RED RIVER VALLEY, D.T., 1877. *Regarded as the mechanized wonders of the day, the bonanza farms used the latest available agricultural implements that cut the amount of manpower needed during plowing, seeding, and harvest. The move toward mechanization, including the use of the revolutionary self-binder, came rapidly in frontier areas where seasoned agricultural help was often scarce and large acreages demanded a large labor force.*

Pennsylvania Coal
George Bretz, 1880s

Global Land Cover Change

Crop and Pasture Fraction Difference: 1992-1870

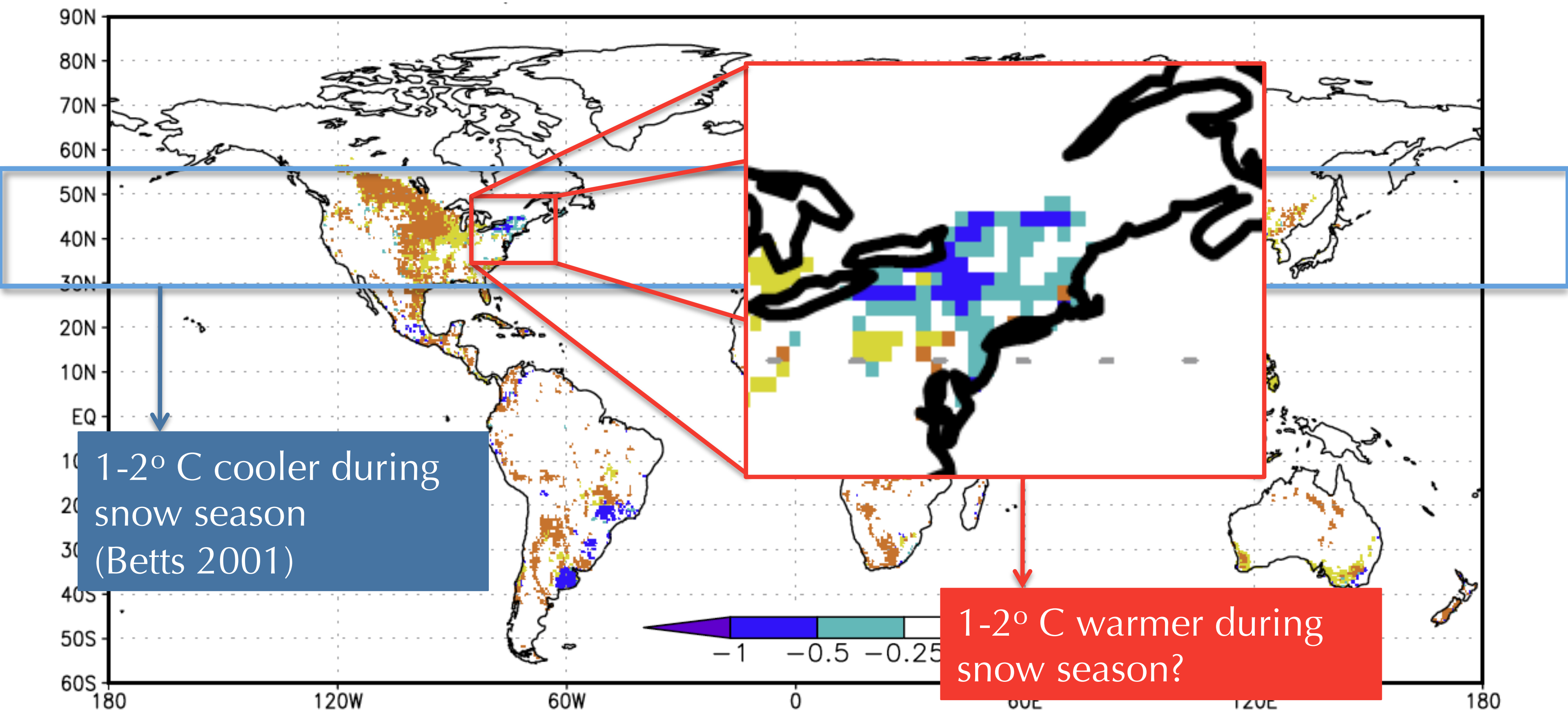


Figure from Pitman et al. (2009). Land cover map constructed using data from Ramankutty and Foley (1999) and Goldewijk et al (2001).

Lee et al. 2011

Biophysical Processes

- Evapotranspiration
- Albedo
- Surface roughness

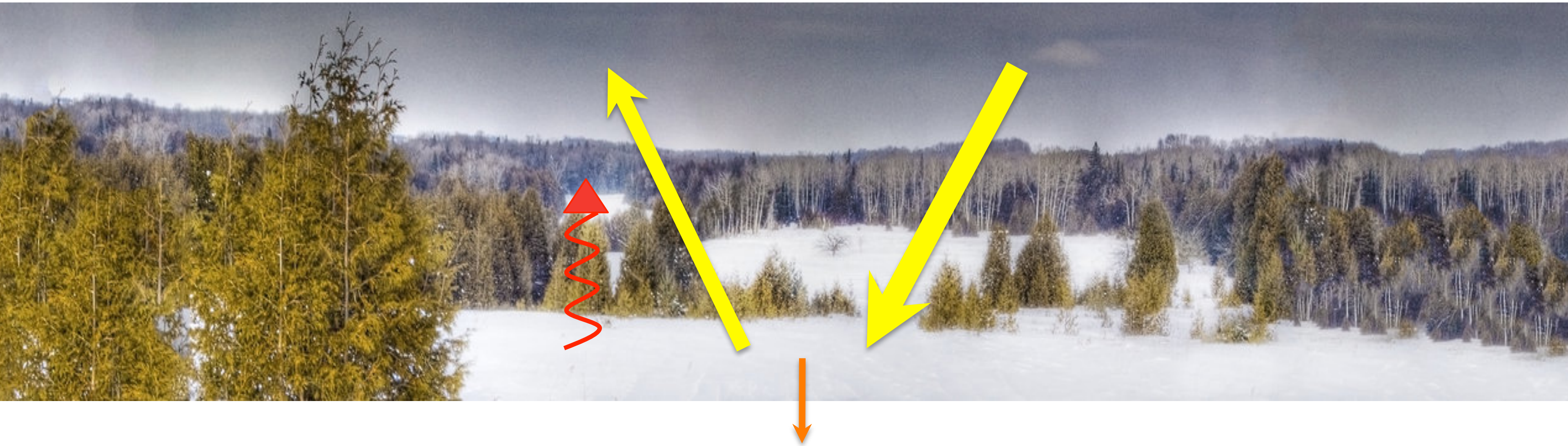
Biophysical Processes

- ~~Evapotranspiration~~
- Albedo
- Surface roughness

Biophysical Processes

- Albedo = SW_{up}/SW_{down}

Snow-Covered Field 0.85

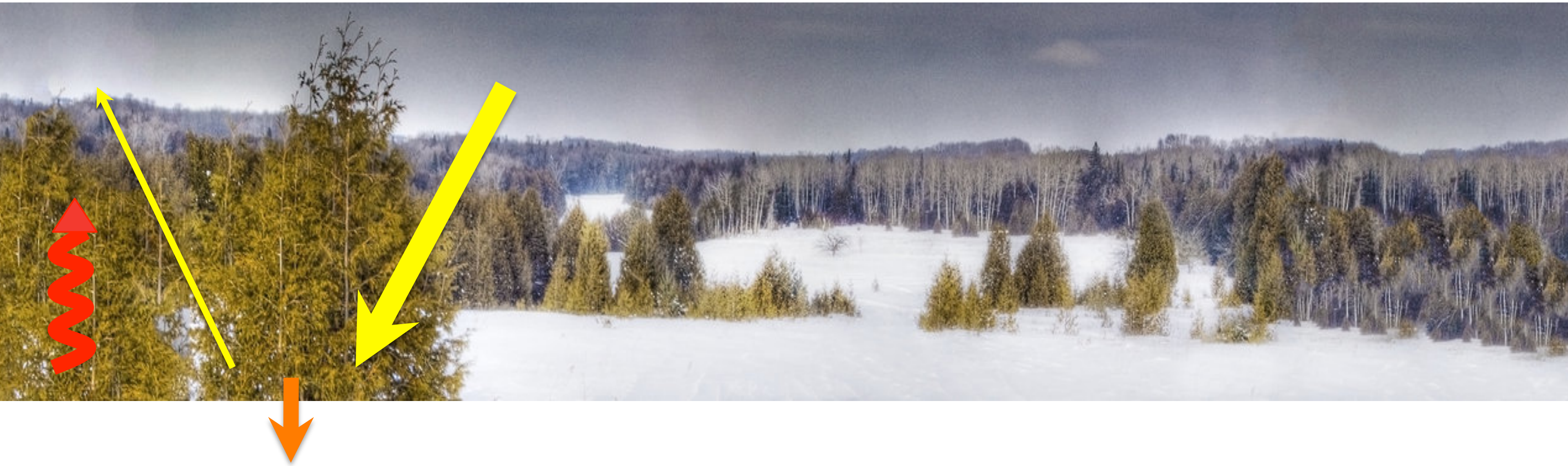


Cooler open lands due to increased shortwave being reflected when snow is present.

Biophysical Processes

- Albedo = SW_{up}/SW_{down}

Snow Covered Forest 0.25



Warmer forests due to decreased shortwave being reflected.

Lee et al. 2011

Biophysical Processes

- Albedo
- Surface roughness

Warmer forests at night from enhanced mixing and higher turbulence at night over rough canopies.

Lee et al. 2011

Biophysical Processes

- Albedo
- Surface roughness

Warmer over open land during the day from suppressed mixing; rough forest canopies dissipate sensible heat more efficiently.

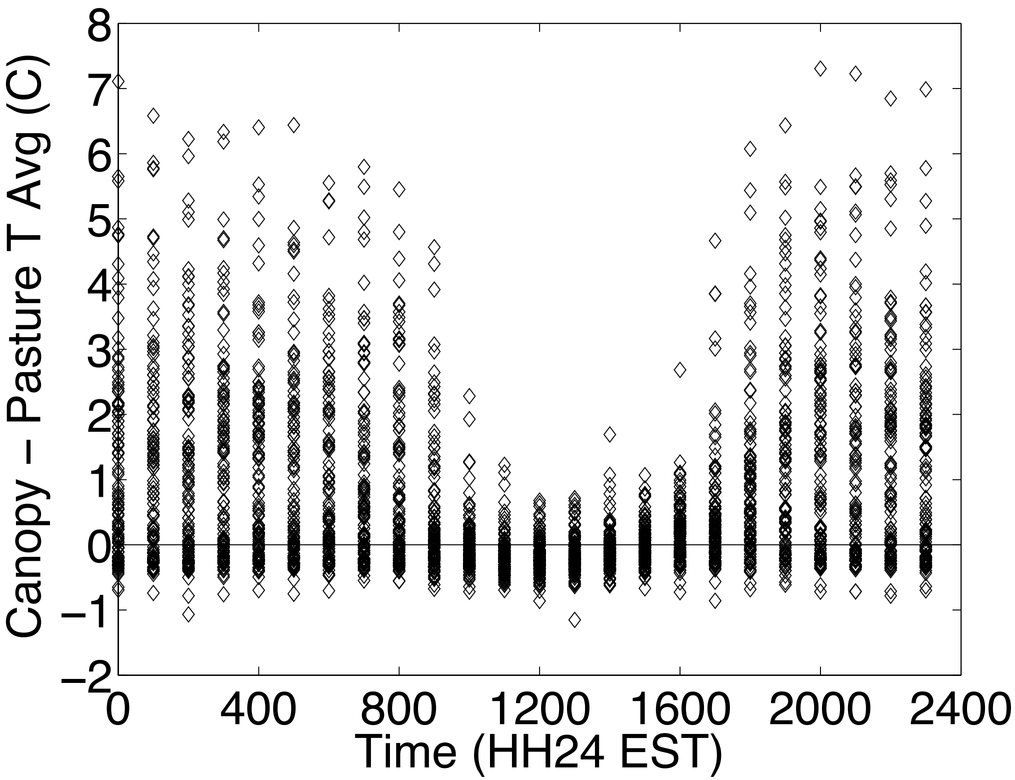
Lee et al. 2011

Biophysical Processes

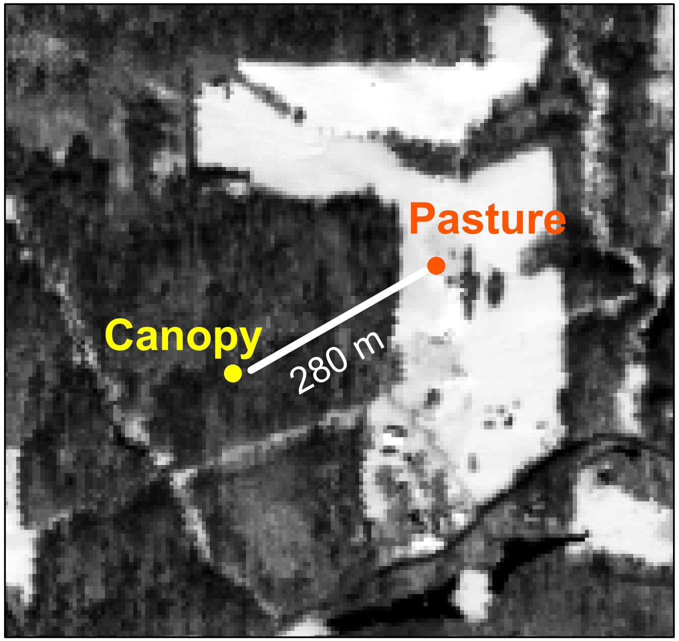
Albedo & surface roughness effects are of opposite sign.

Which dominates in temperate winter?

Diurnal Temperature Differences: Forest - Pasture



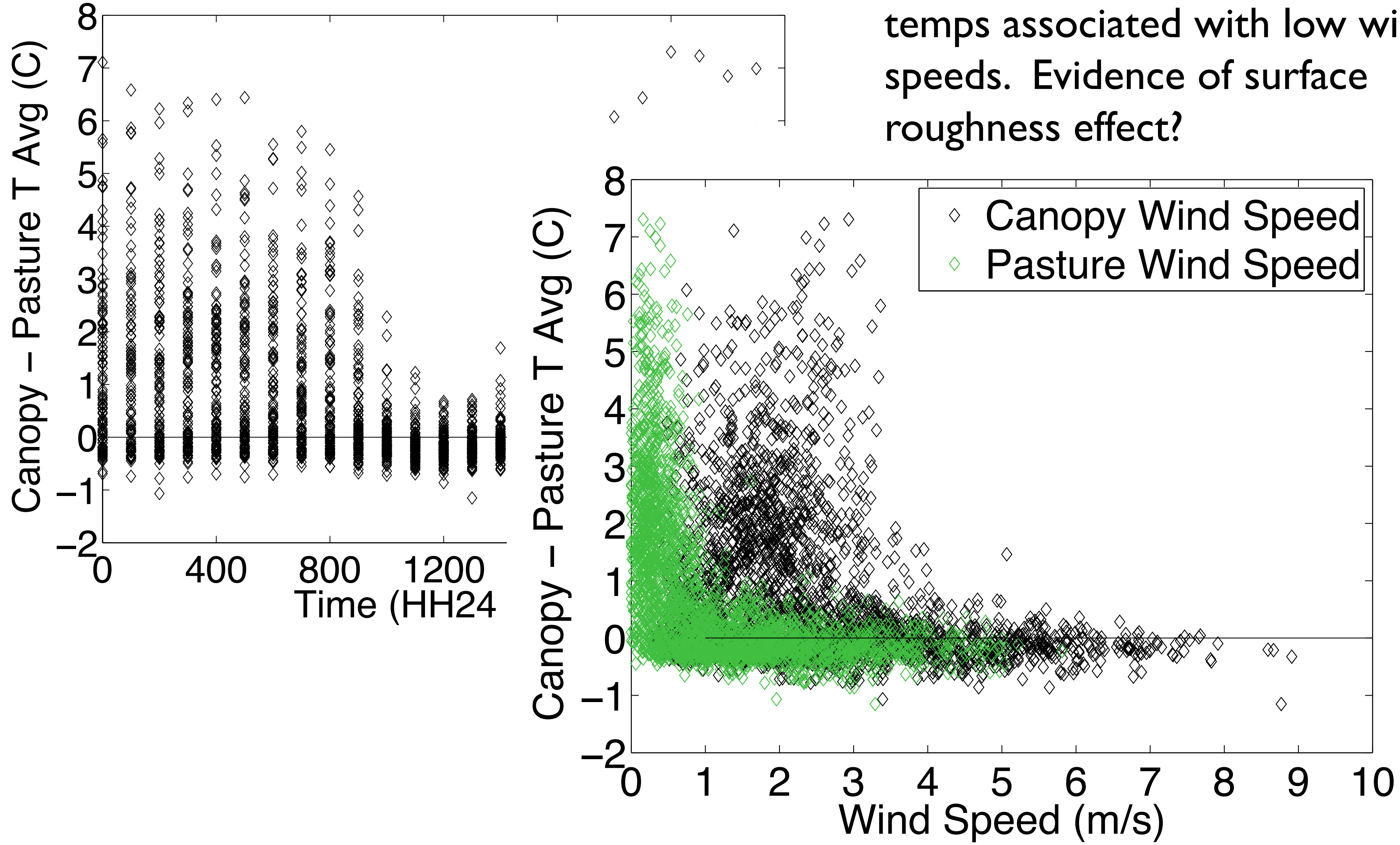
Warmer at night over canopy compared to adjacent pasture site.



Durham, NH

Diurnal Temperature Differences: Pasture – Forest

…Warmer nighttime canopy temps associated with low wind speeds. Evidence of surface roughness effect?



Weather, Research, and Forecasting (WRF) Model V3.5.1 to evaluate mid-1800's climate responses to deforestation

- How well do WRF configurations simulate extremes in cold season (Dec-Mar) climate in New England?
- Do climate responses to deforestation vary with WRF model configuration?
- What are the dominant biophysical processes controlling climate responses to deforestation?

Modeling Approach

- Simulate climatic extremes
- Develop mid-1800s deforested land cover scenario
- Use a multi-physics ensemble to evaluate response to land cover change

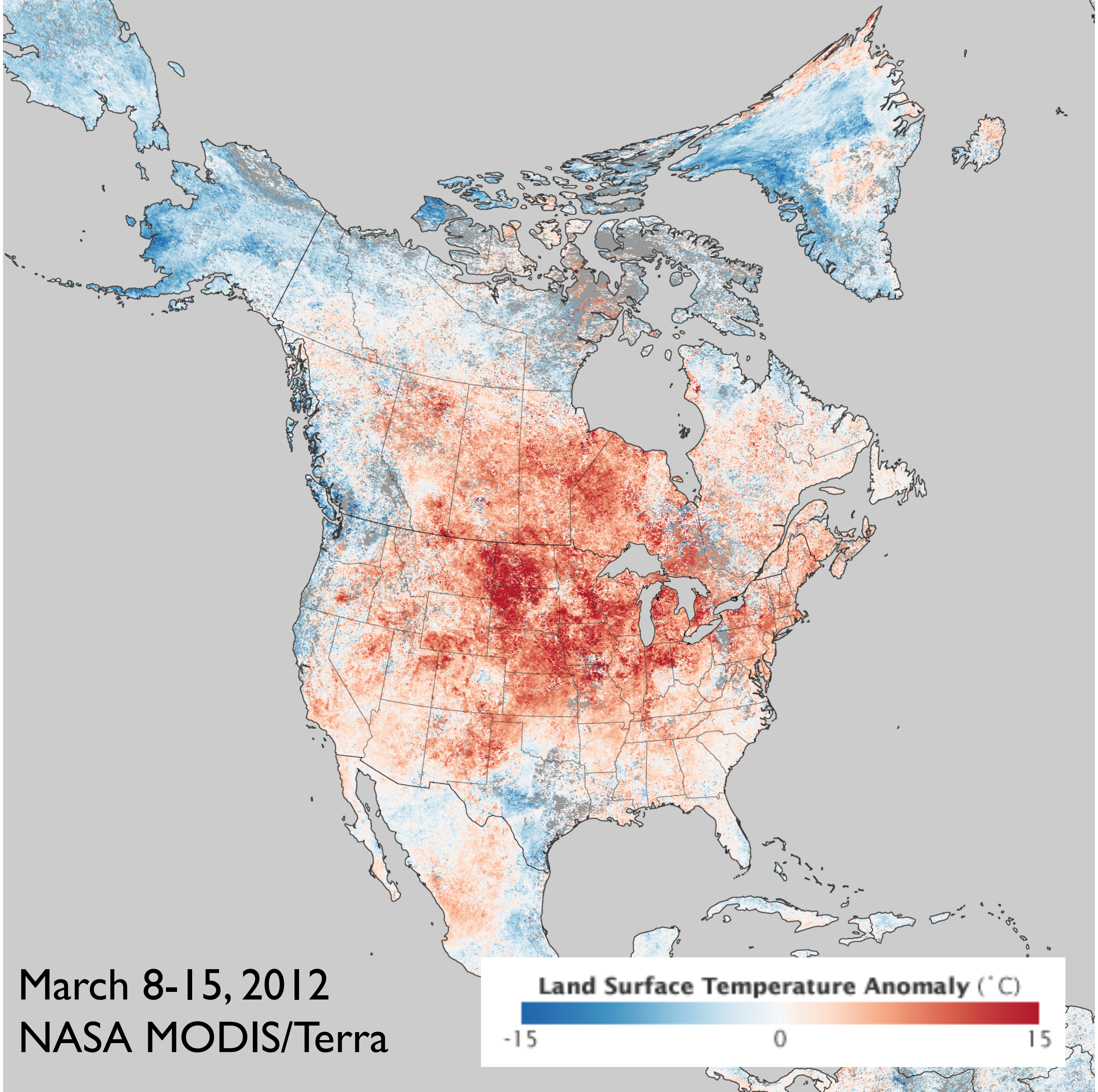
Climate Extremes

(1) Cold, Snowy: Dec 2008 through March 2009

(2) Warm, Dry: Dec 2011 through March 2012 (proxy for future climate)

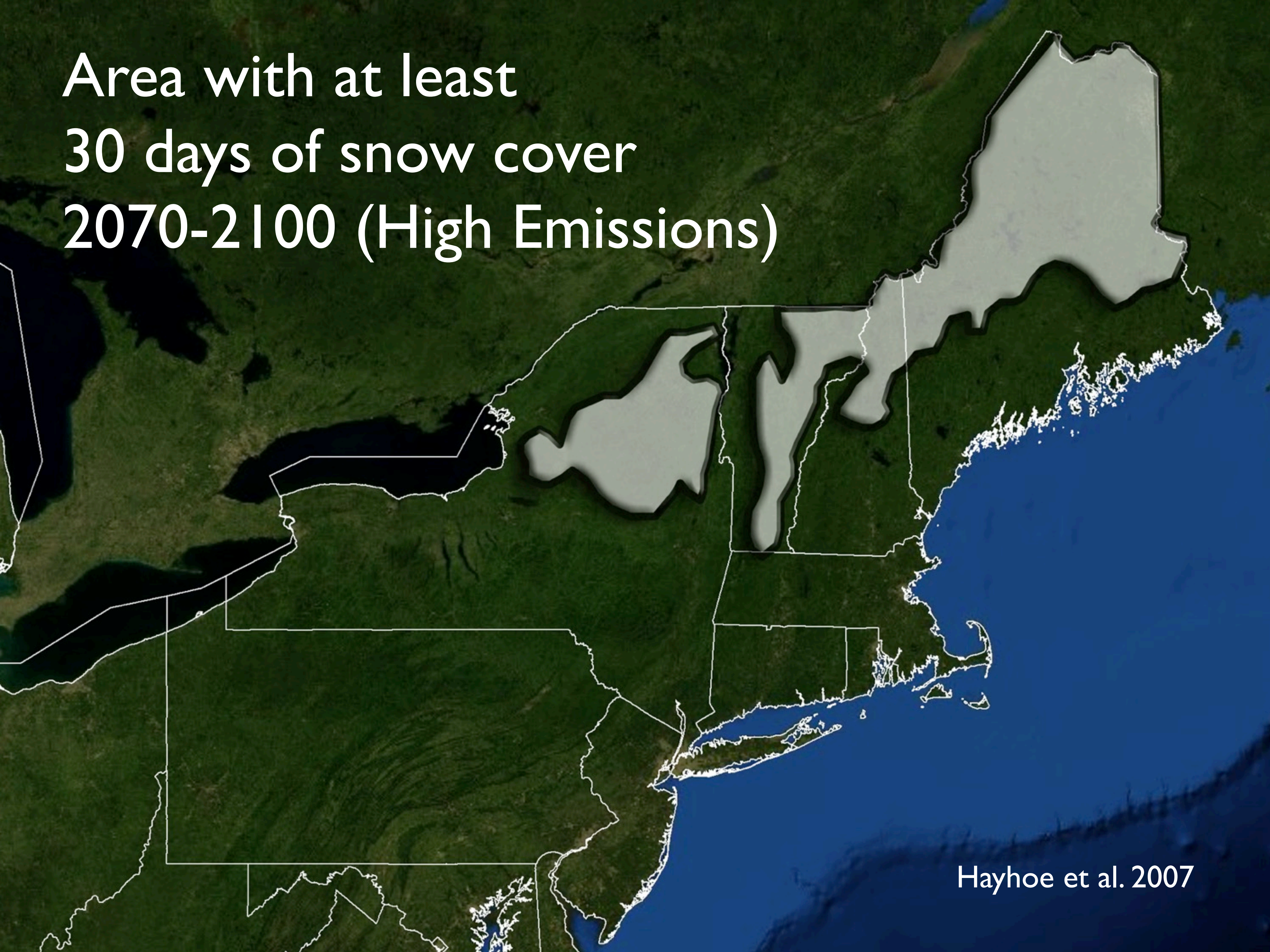
State	Temperature Departure (°C)		% Precip of normal	
	Cold, Snowy (2008/09)	Warm, Dry (2011/12)	Cold, Snowy (2008/09)	Warm, Dry (2011/12)
Connecticut	-0.6	+2.9	106%	81%
Maine	-1.4	+2.6	110%	88%
Massachusetts	-0.5	+2.7	120%	76%
New Hampshire	-0.7	+2.8	123%	88%
Rhode Island	-0.9	+2.2	115%	75%
Vermont	-0.6	+2.7	119%	82%

- ERA-Interim initial conditions, lateral boundaries, and sea surface temperature (6h)
- 4-month cold season (Dec-Mar) simulations, 1 month spin-up

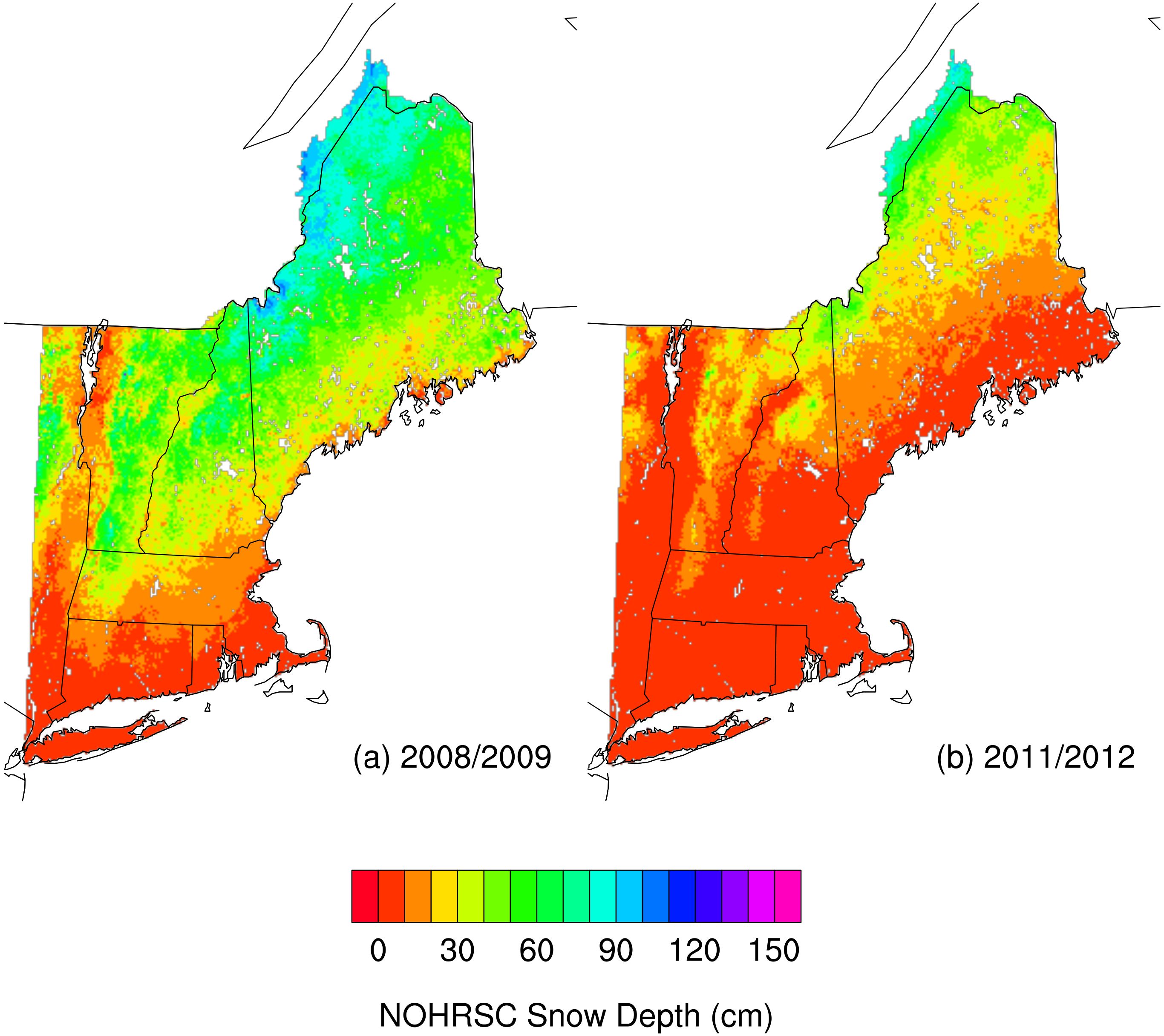


March 8-15, 2012
NASA MODIS/Terra

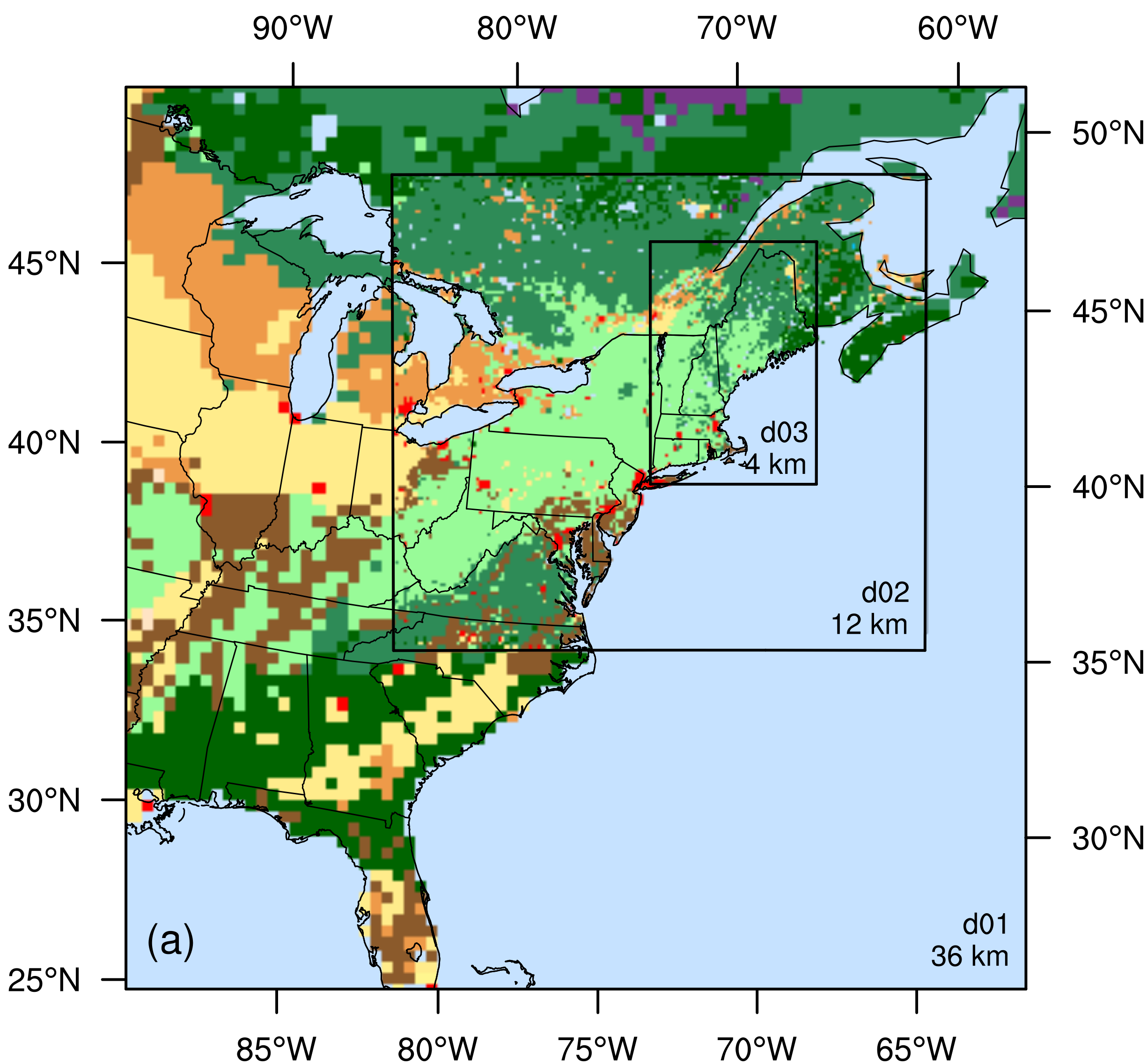

Area with at least
30 days of snow cover
1960-1990
Hayhoe et al. 2007


Area with at least
30 days of snow cover
2070-2100 (High Emissions)
Hayhoe et al. 2007

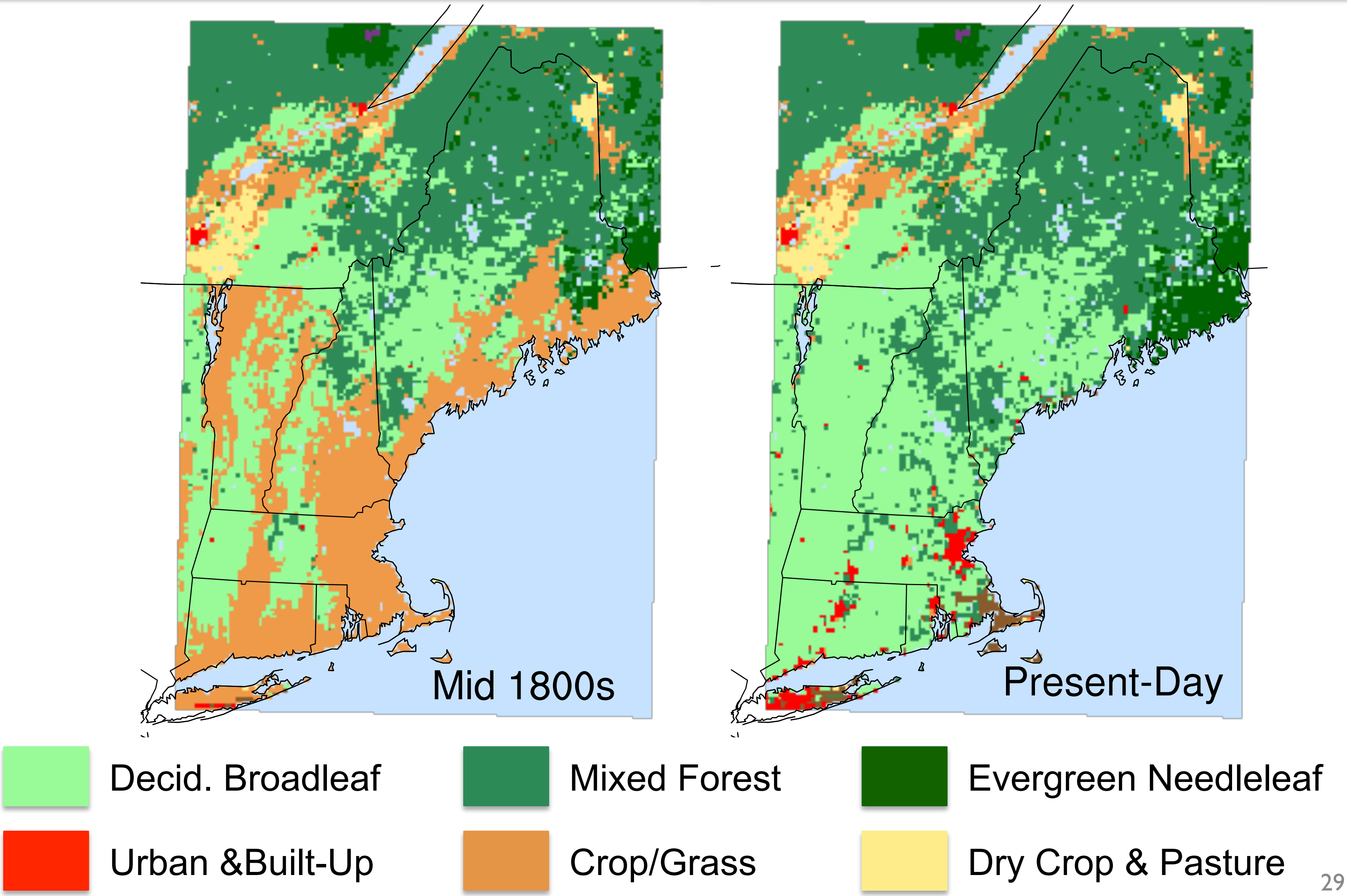
NOHRSC Snow Depth



Modeling Domains, one-way nests



Land Cover Scenarios



WRF Multi-Physics Ensemble

Three land surface models
Two longwave/shortwave (LW/SW) schemes
Two microphysics schemes

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12 ensemble members

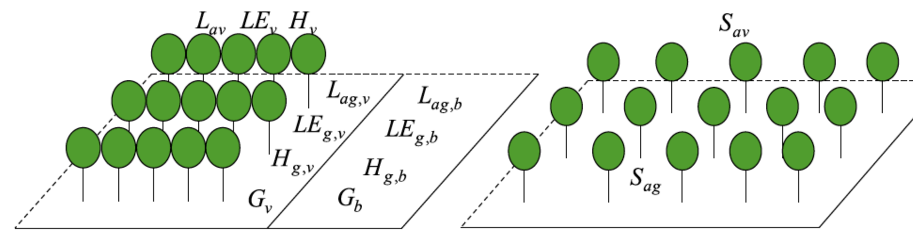
- Yonsei University Planetary Boundary Layer scheme
- Kain-Fritsch cumulus scheme (domain 1 and 2 only)

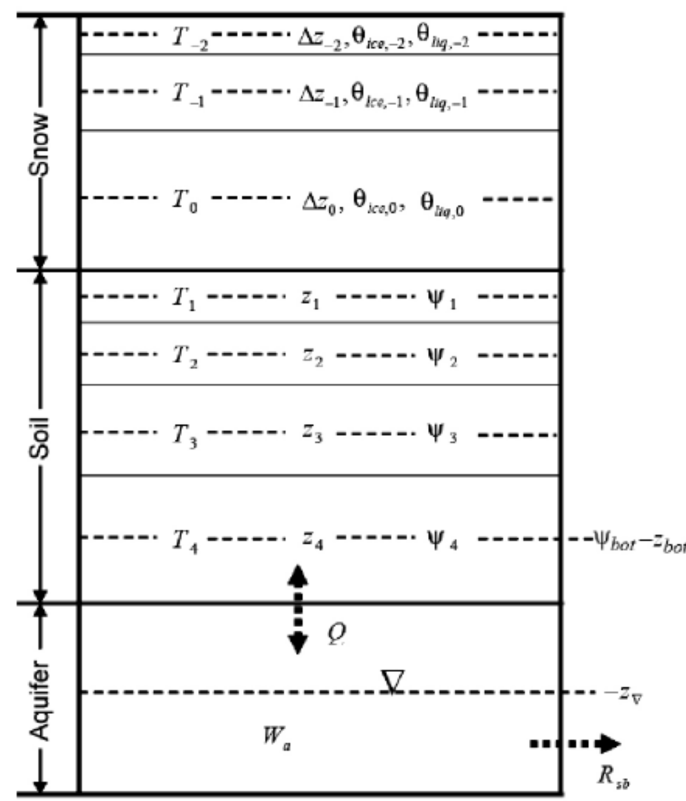
Why Use a Multi-Physics Ensemble?
Characterize uncertainty in land cover response related to physics parameterizations.

Land Surface Models: WRF/NOAH-MP

Niu et al. 2011

- Semi-tile subgrid scheme:
- Longwave (L), Latent heat (LE), Sensible heat (H), Ground heat (G) fluxes for veg and bare portions
- Shortwave fluxes entire grid cell w/ gap probabilities as function of SZA and 3D structure of canopy
- Single layer canopy
- Three-layer snowpack
- Four-layer soil column





Land Surface Models: WRF/NOAH-MP

Niu et al. 2011

Leaf Area Index	4
Turbulent transfer	2
Soil moisture stress factor	3
Canopy stomatal resistance	2
Snow surface albedo	2
Frozen soil permeability	2
Supercooled liquid water	2
Radiation transfer	3
Precipitation partitioning	2
Runoff and ground water	4

9,216
Combinations

418 billion
WRF/NOAH-MP

Land Surface Models: WRF/NOAH-MP

http://www.iges.org/lsm/Yang_S2_LSM.pdf

Niu et al. 2011

Leaf Area Index	Prescribed by veg. type
Turbulent transfer	Original Noah
Soil moisture stress factor	Original Noah
Canopy stomatal resistance	Ball-Berry
Snow surface albedo	**BATS & CLASS**
Frozen soil permeability	Linear, more permeable
Supercooled liquid water	No iteration
Radiation transfer	Modified two-stream
Precipitation partitioning	Snow when T<0C
Runoff and ground water	Original Noah

Noah MP Albedo Options

Biosphere-Atmosphere Transfer Scheme (BATS)

Direct and diffuse radiation over visible and near-infrared wave bands, accounting for fresh snow albedo, variations in snow age, solar zenith angle, grain size growth, and impurities (more CLM-like)

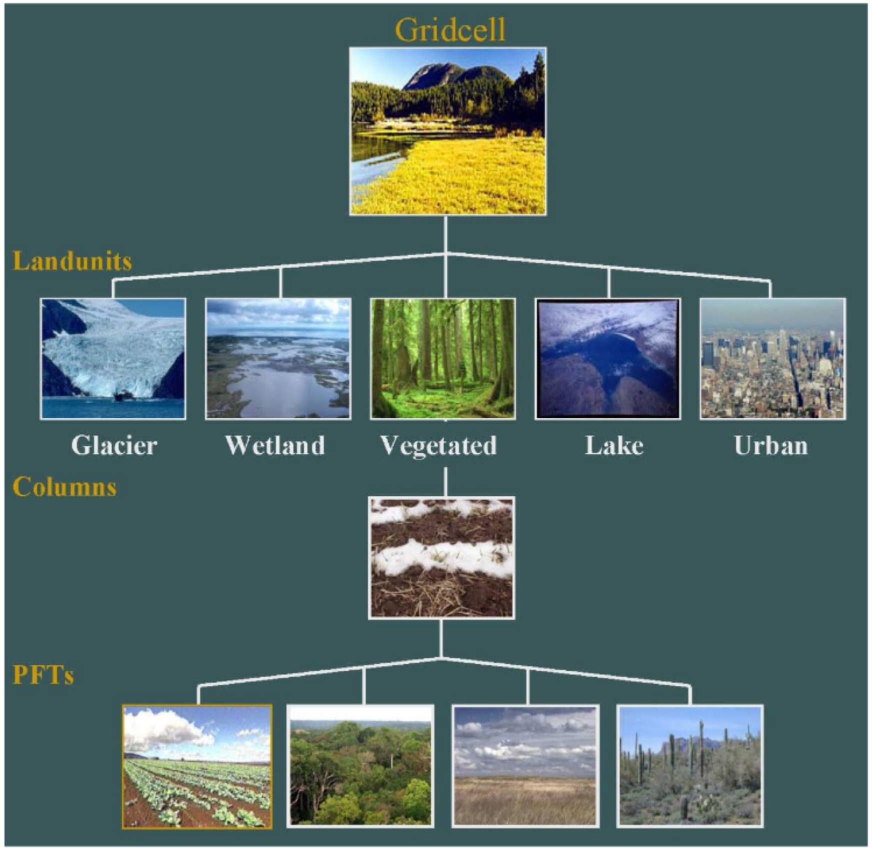
Canadian LAnd Surface Scheme (CLASS)

Accounts for fresh snow albedo and decrease in albedo with snow age.

Land Surface models: WRF/CLM4.0

Jin et al. 2010
Lu and Kueppers, 2012
Oleson et al., 2010

- Called as a sub-routine in WRF
- Five sub-grid land cover types (glacier, lake, wetland, urban, vegetated)
- Vegetated subgrid includes up to 16 Plant Functional Types
- USGS 24-class land cover translated into 5 sub-grid land cover types and/or PFTs
- Single layer canopy
- Five-layer snowpack
- Ten-layer soil column



Longwave/Shortwave Schemes:

(1) RRTM/Goddard

- Rapid Radiative Transfer Model Longwave:
  - CO_2 = 379 ppm
  - N_2O = 319 ppb
  - CH_4 = 1774 ppb

(2) CAM/CAM V5.1

- CAM Longwave:
  - CO_2 = annual values
  - N_2O = 311 ppb
  - CH_4 = 1714 ppb

Microphysics

(1) WRF Single-Moment 6-class (WSM6)

- Hong and Lim, 2004
- Mixing ratios of water vapor, cloud water, cloud ice, snow, rain, and graupel
- Spherical snow with constant bulk density
- Exponential shape for snow size distribution

(2) Thompson et al. 2008 (Thompson 08)

- cloud water, cloud ice, snow, rain, and graupel
- Non-spherical snow
- Sum of exponential and gamma snow size distributions

WRF Multi-Physics Ensemble

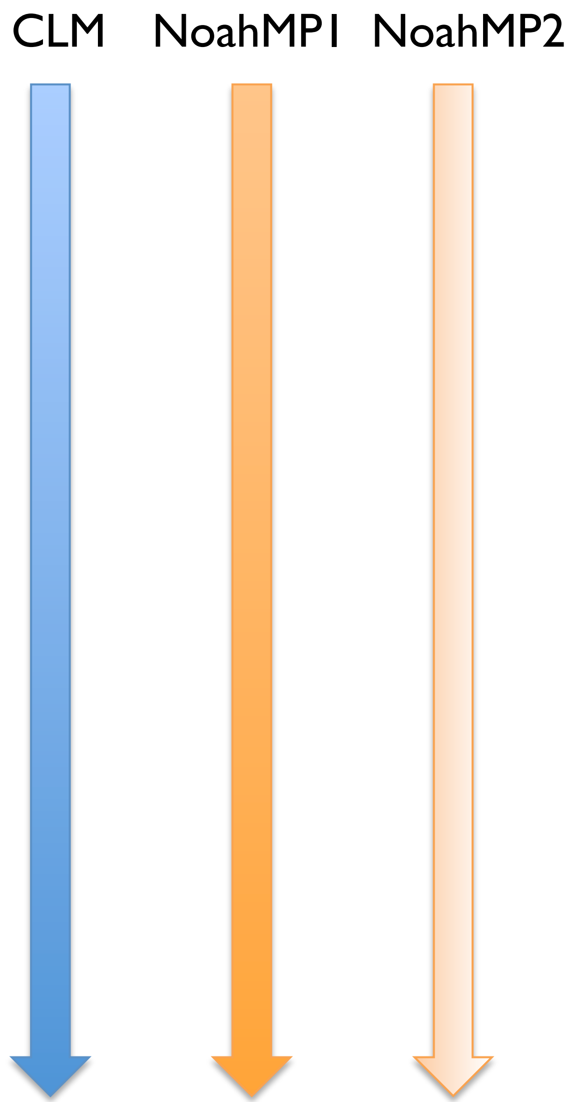
Simulation	Land Surface Model	Longwave/Shortwave	Microphysics
1	CLM	RRTM/Goddard	WSM6
2	NoahMP1 (BATS albedo)	RRTM/Goddard	WSM6
3	NoahMP2 (CLASS albedo)	RRTM/Goddard	WSM6
4	CLM	CAM/CAM	WSM6
5	NoahMP1	CAM/CAM	WSM6
6	NoahMP2	CAM/CAM	WSM6
7	CLM	RRTM/Goddard	Thompson 2008
8	NoahMP1	RRTM/Goddard	Thompson 2008
9	NoahMP2	RRTM/Goddard	Thompson 2008
10	CLM	CAM/CAM	Thompson 2008
11	NoahMP1	CAM/CAM	Thompson 2008
12	NoahMP2	CAM/CAM	Thompson 2008

*YSU PBL in all simulations

**Kain-Fritsch Cumulus in domain 1 and 2

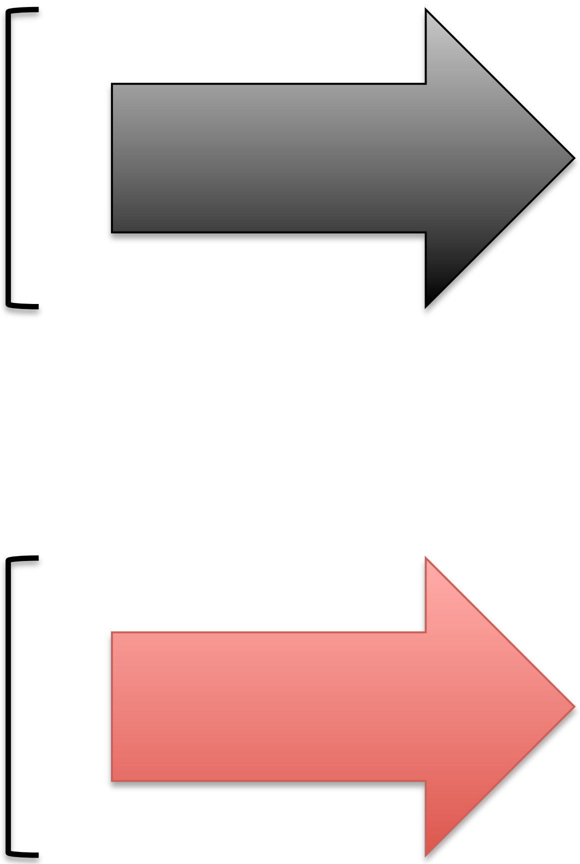
Model Validation, WRF minus PRISM

Land Surface Models



Model Validation, WRF minus PRISM

WSM6



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Model Validation, WRF minus PRISM

Longwave/Shortwave

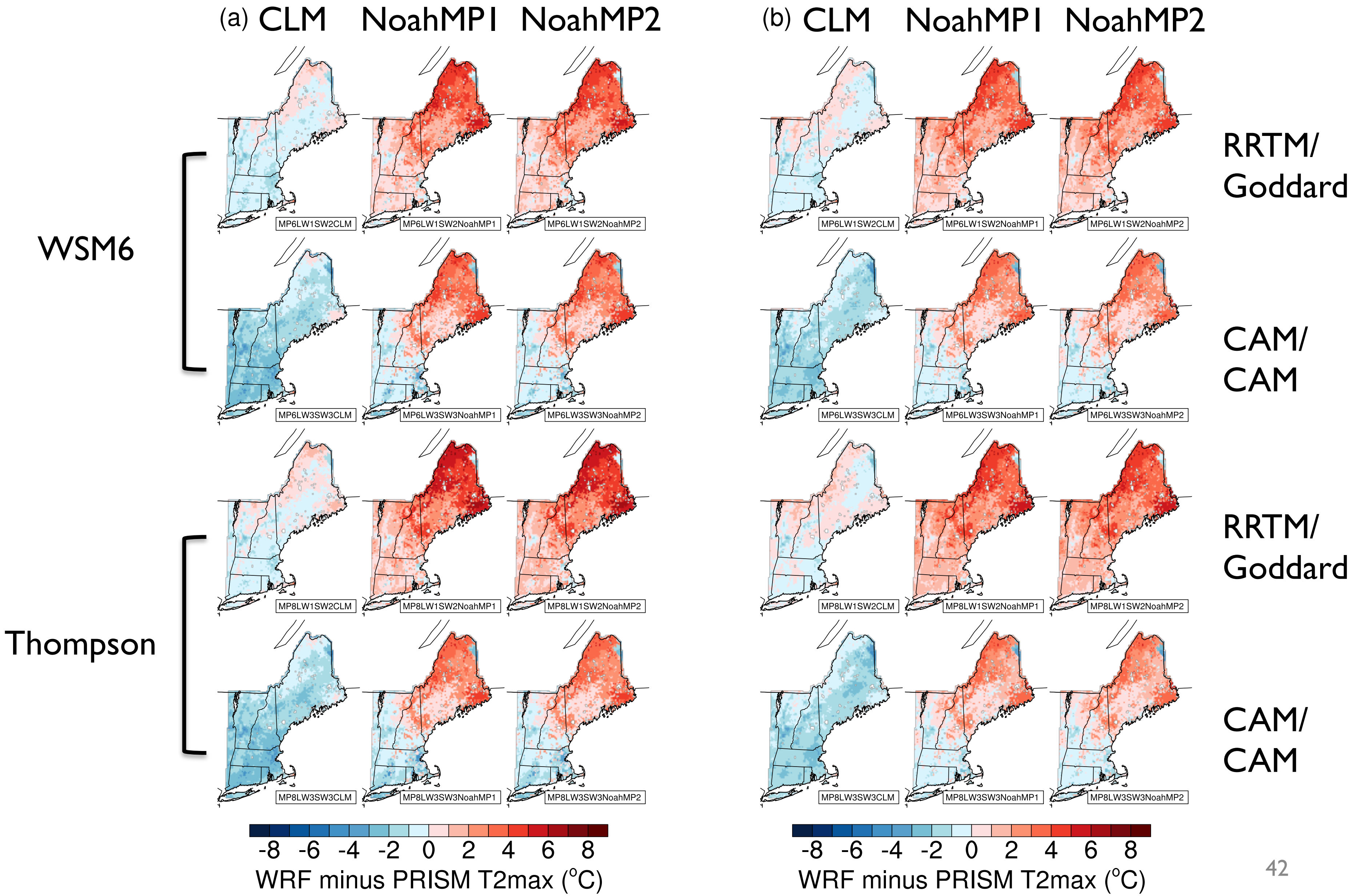
RRTM/
Goddard

CAM/
CAM

RRTM/
Goddard

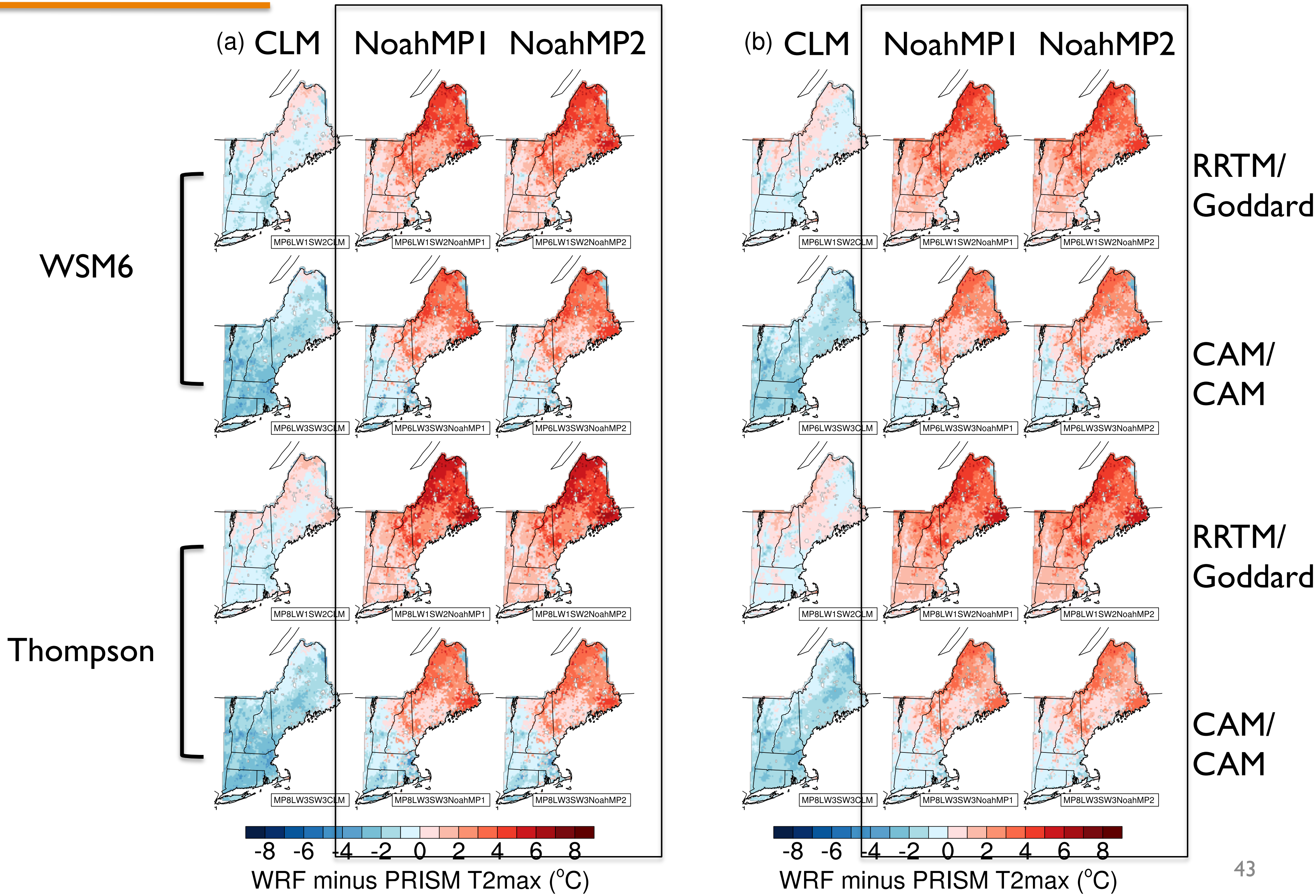
CAM/
CAM

T2max Cold, Snowy Warm, Dry

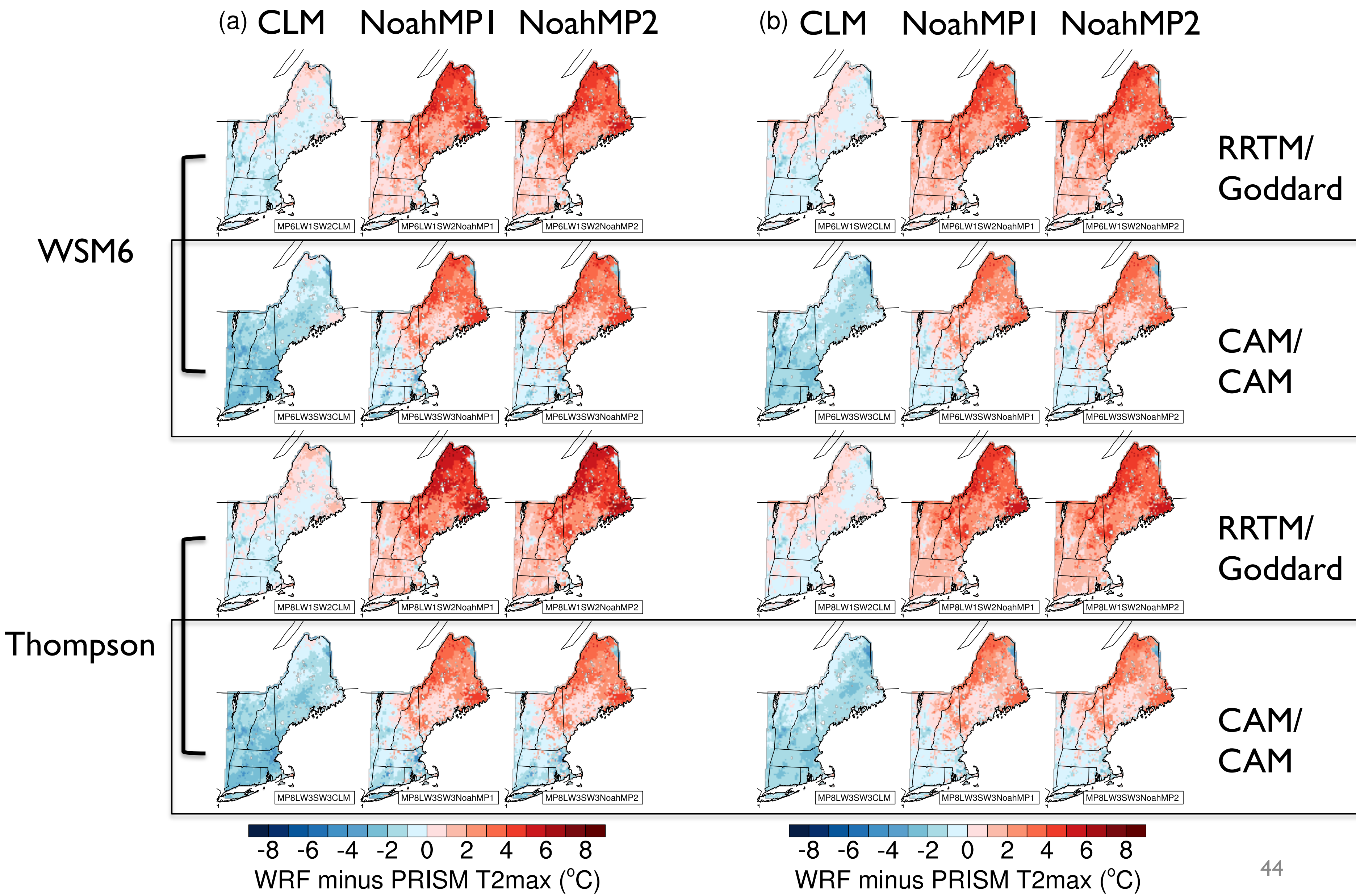


T2max

Cold, Snowy — Warm, Dry

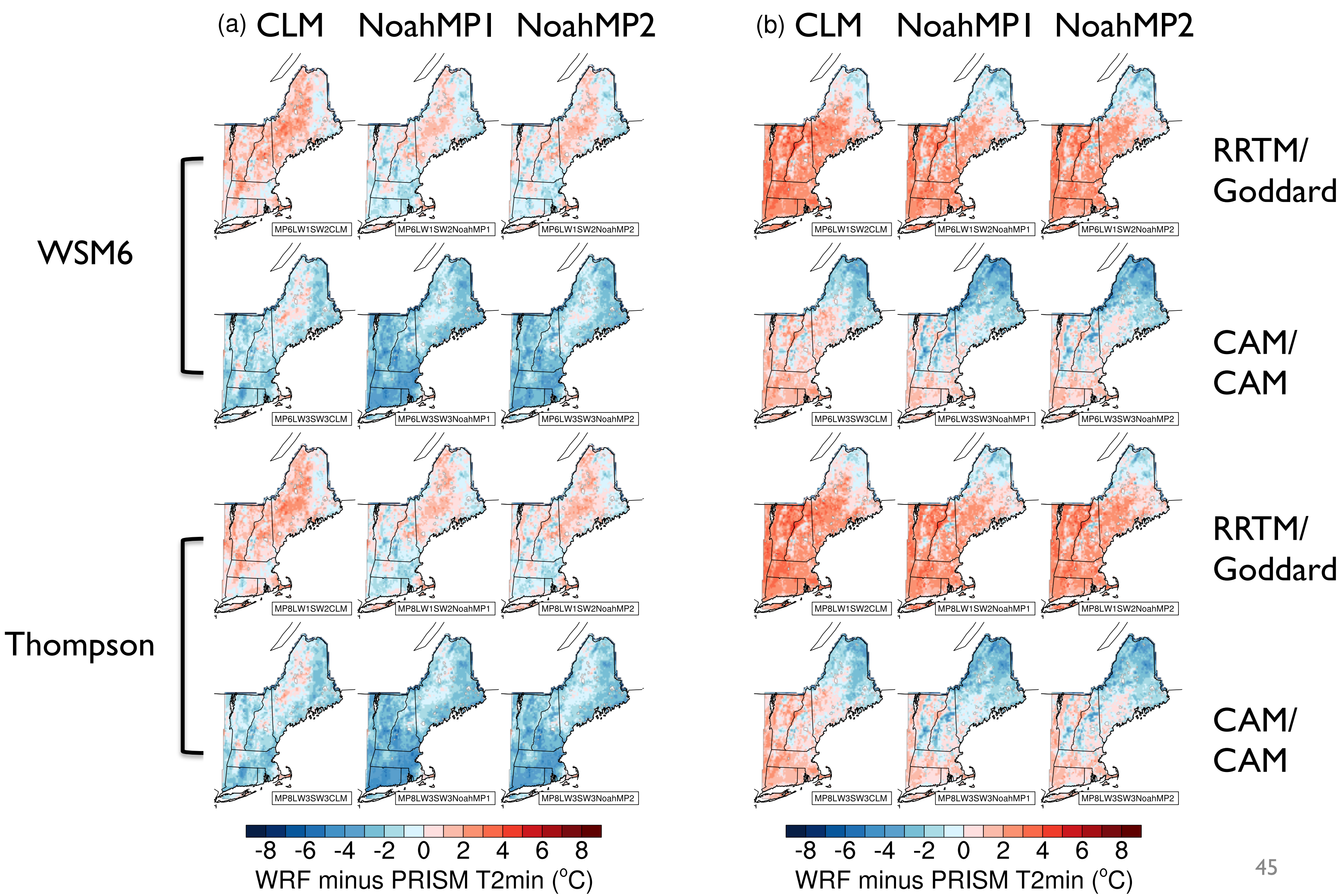


T2max Cold, Snowy Warm, Dry

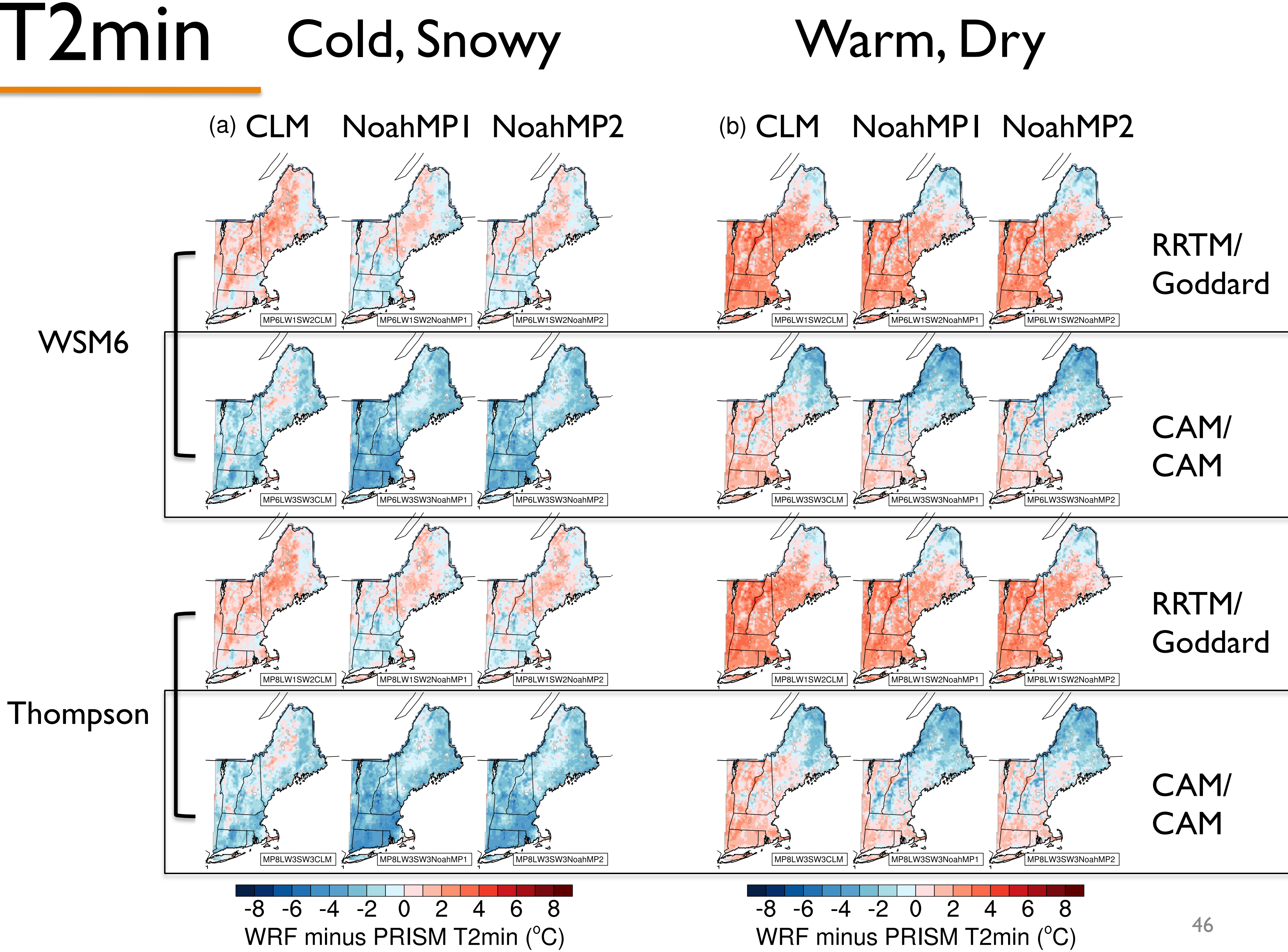


T2min

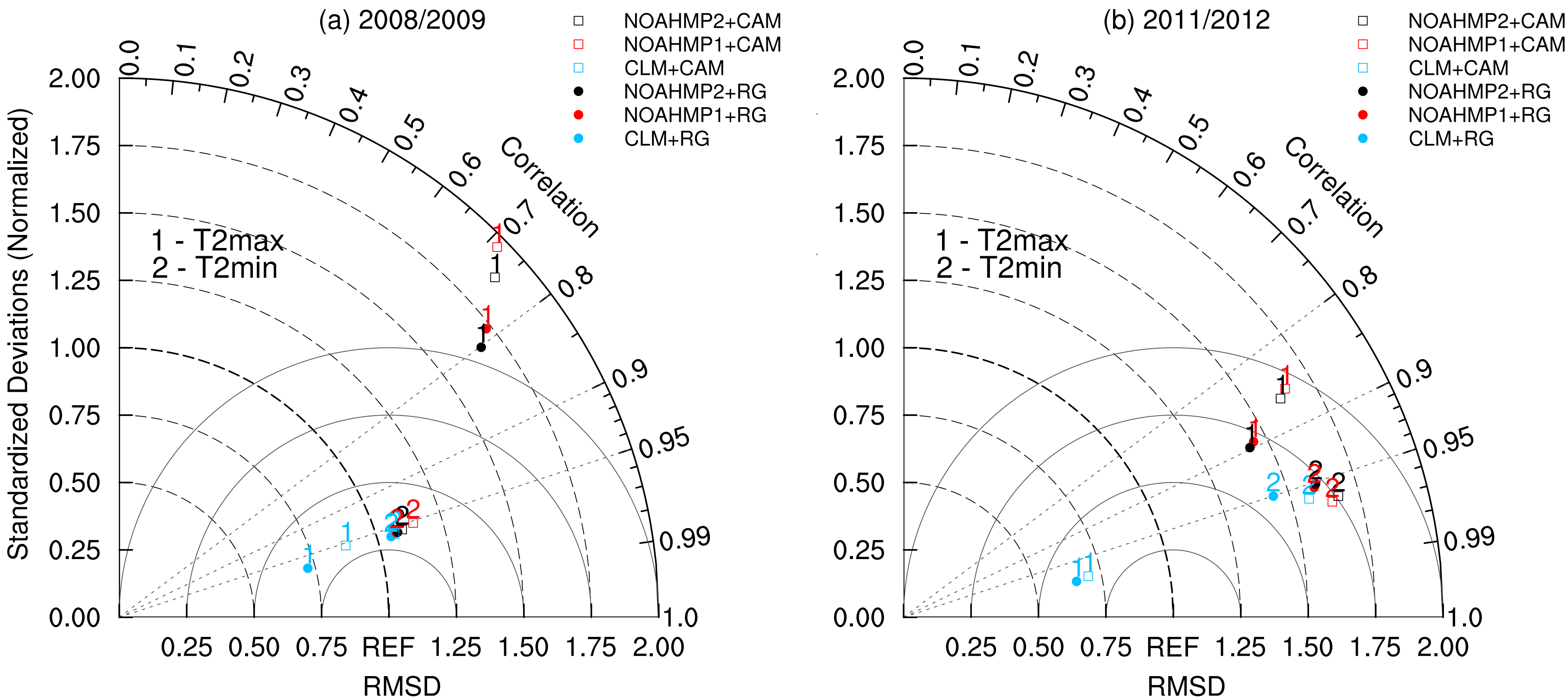
Cold, Snowy   Warm, Dry



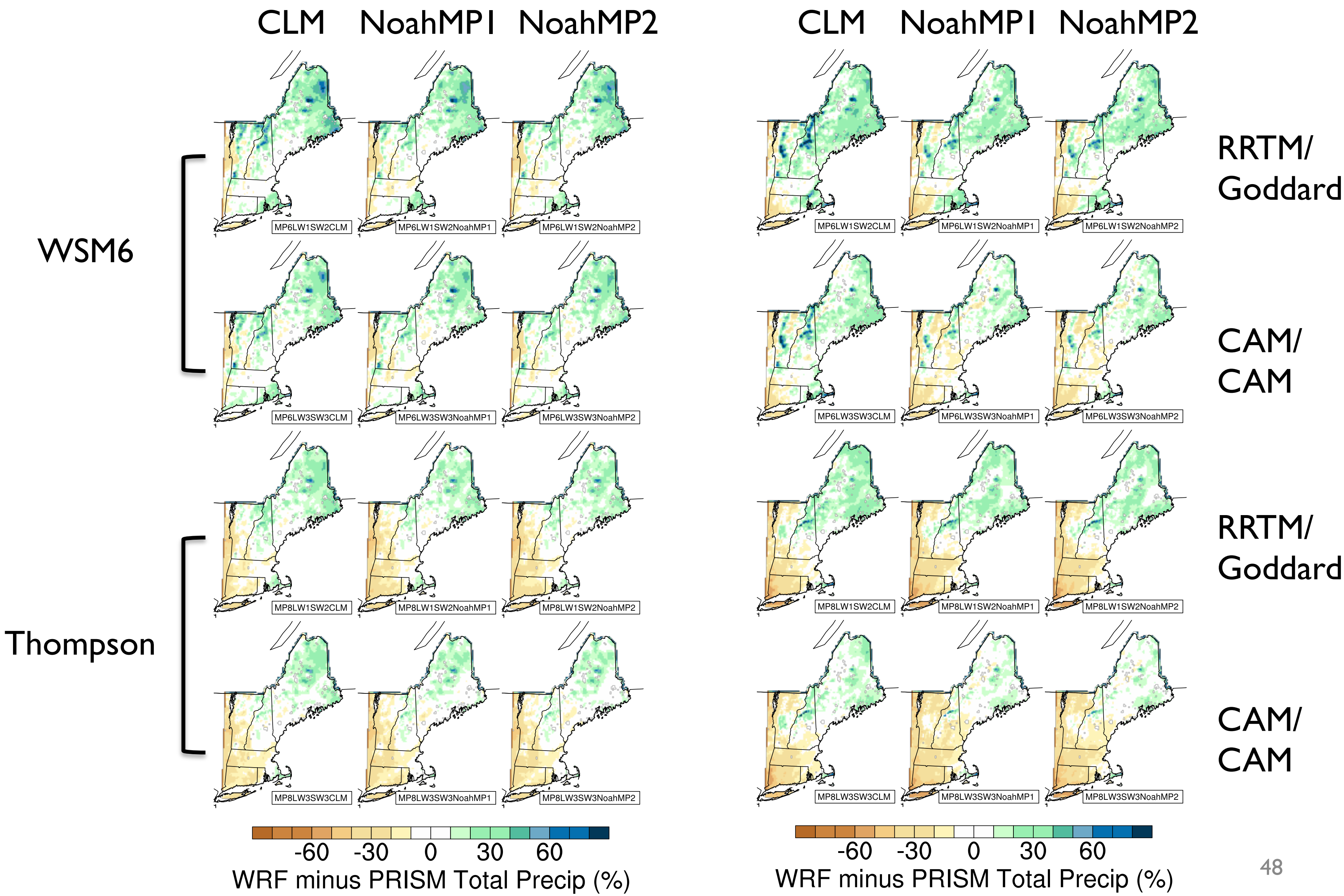
T2min


Cold, Snowy
Warm, Dry
(a) CLM NoahMP1 NoahMP2
(b) CLM NoahMP1 NoahMP2
WSM6
Thompson
RRTM/ Goddard
CAM/ CAM
RRTM/ Goddard
CAM/ CAM
MP6LW1SW2CLM
MP6LW1SW2NoahMP1
MP6LW1SW2NoahMP2
MP6LW3SW3CLM
MP6LW3SW3NoahMP1
MP6LW3SW3NoahMP2
MP8LW1SW2CLM
MP8LW1SW2NoahMP1
MP8LW1SW2NoahMP2
MP8LW3SW3CLM
MP8LW3SW3NoahMP1
MP8LW3SW3NoahMP2
-8 -6 -4 -2 0 2 4 6 8
WRF minus PRISM T2min (°C)
-8 -6 -4 -2 0 2 4 6 8
WRF minus PRISM T2min (°C)

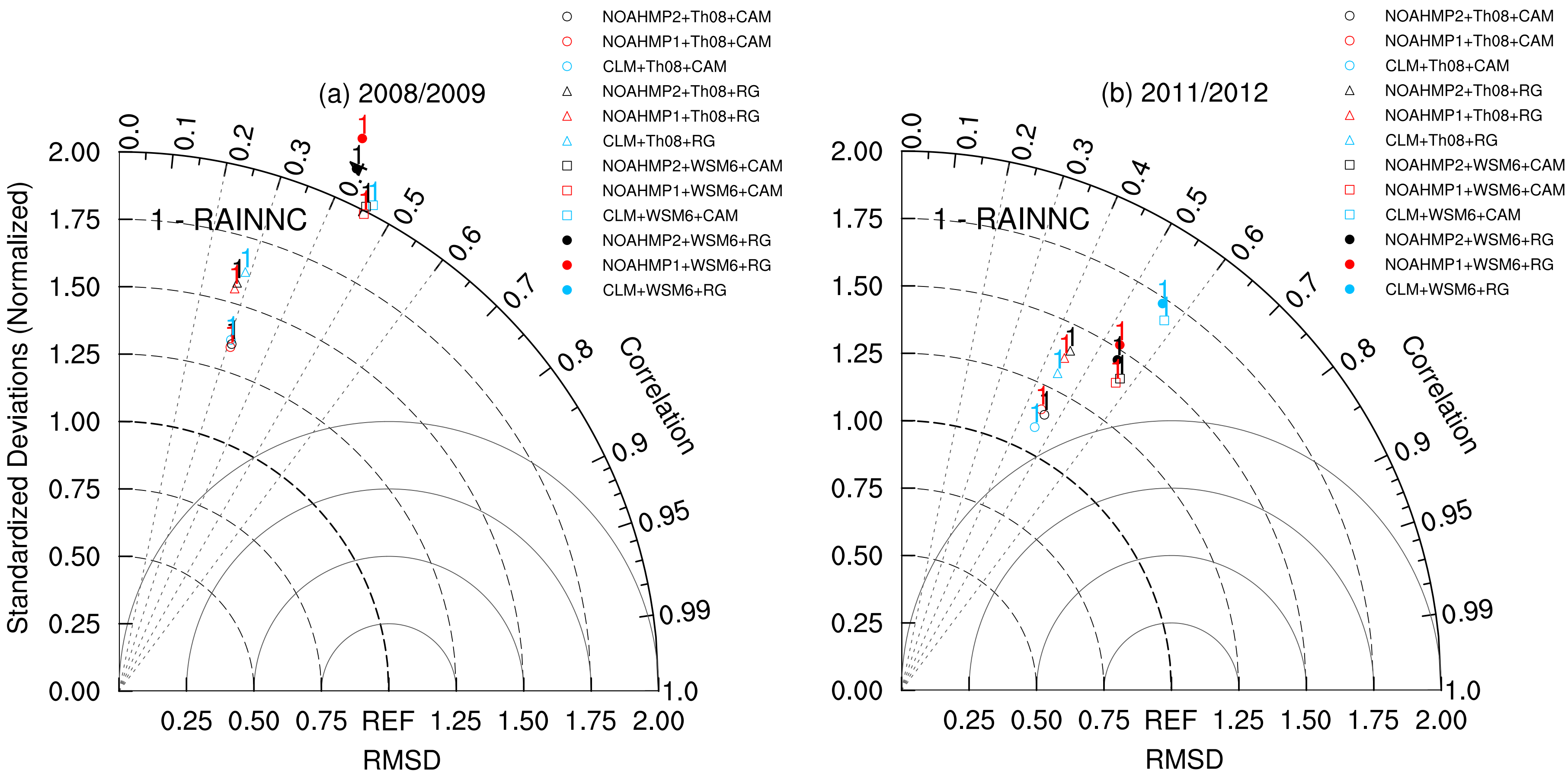
WRF/CLM4.0 generally better …



Precip. Cold, Snowy Warm, Dry



Hard to say any are "better"

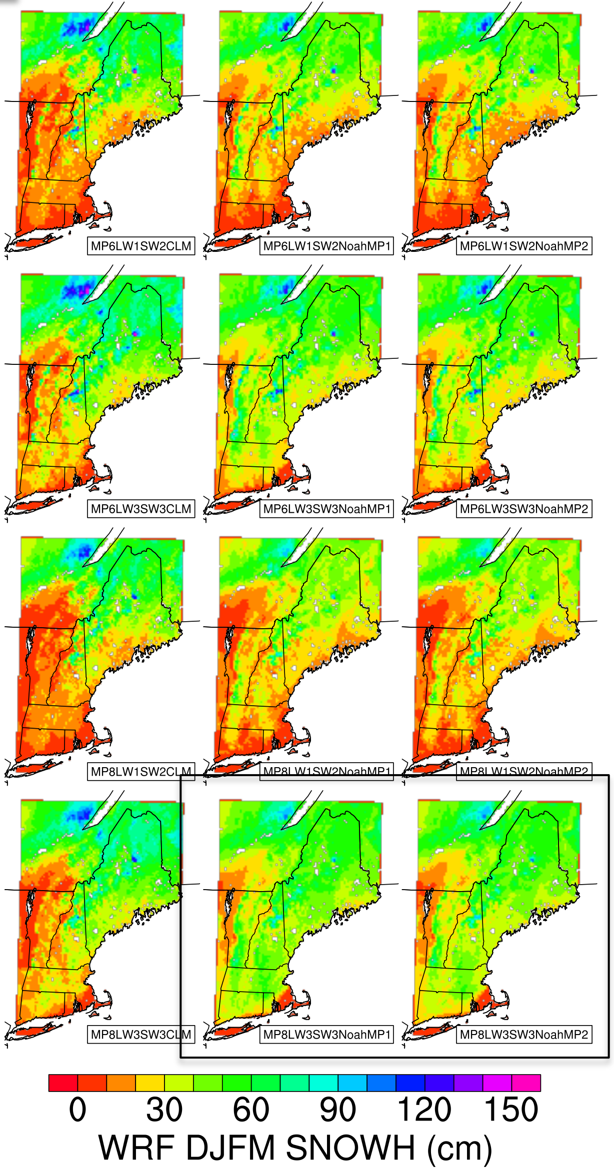


Thompson 2008 microphysics with CAM best of the worst?

Snow Depth

Cold, Snowy — Warm, Dry

CLM NoahMP1 NoahMP2



WSM6: RRTM/Goddard; CAM/CAM

Thompson: RRTM/Goddard; CAM/CAM

Deeper Snowpack

CAM/CAM Radiation
NoahMP

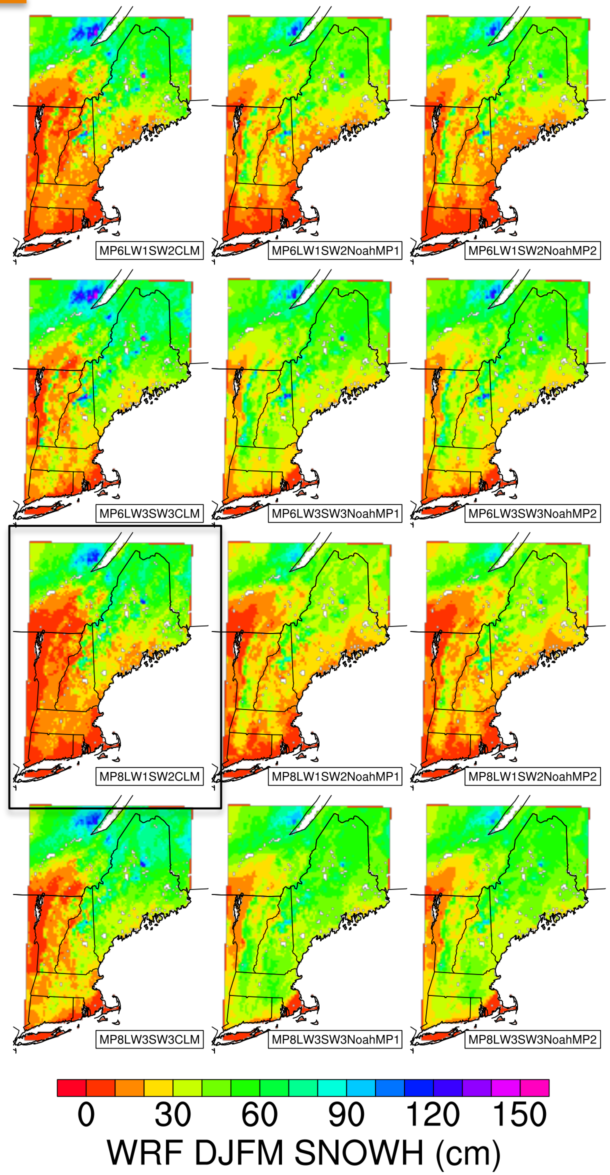
Snow Depth

Cold, Snowy — Warm, Dry

CLM NoahMP1 NoahMP2

WSM6

Thompson



RRTM/ Goddard

CAM/ CAM

RRTM/ Goddard

CAM/ CAM

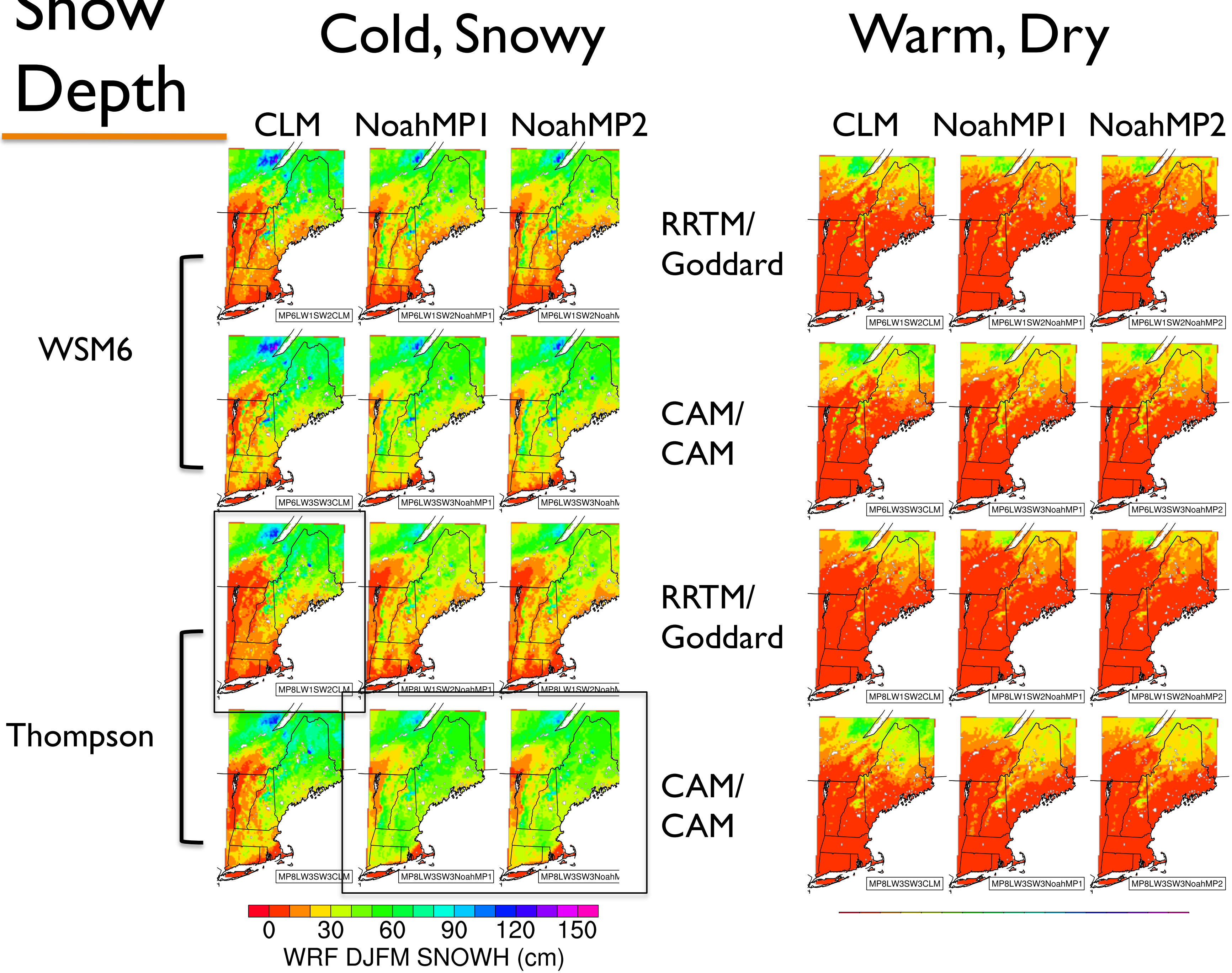
Deeper Snowpack:

CAM/CAM Radiation
NoahMP

Shallower Snowpack:

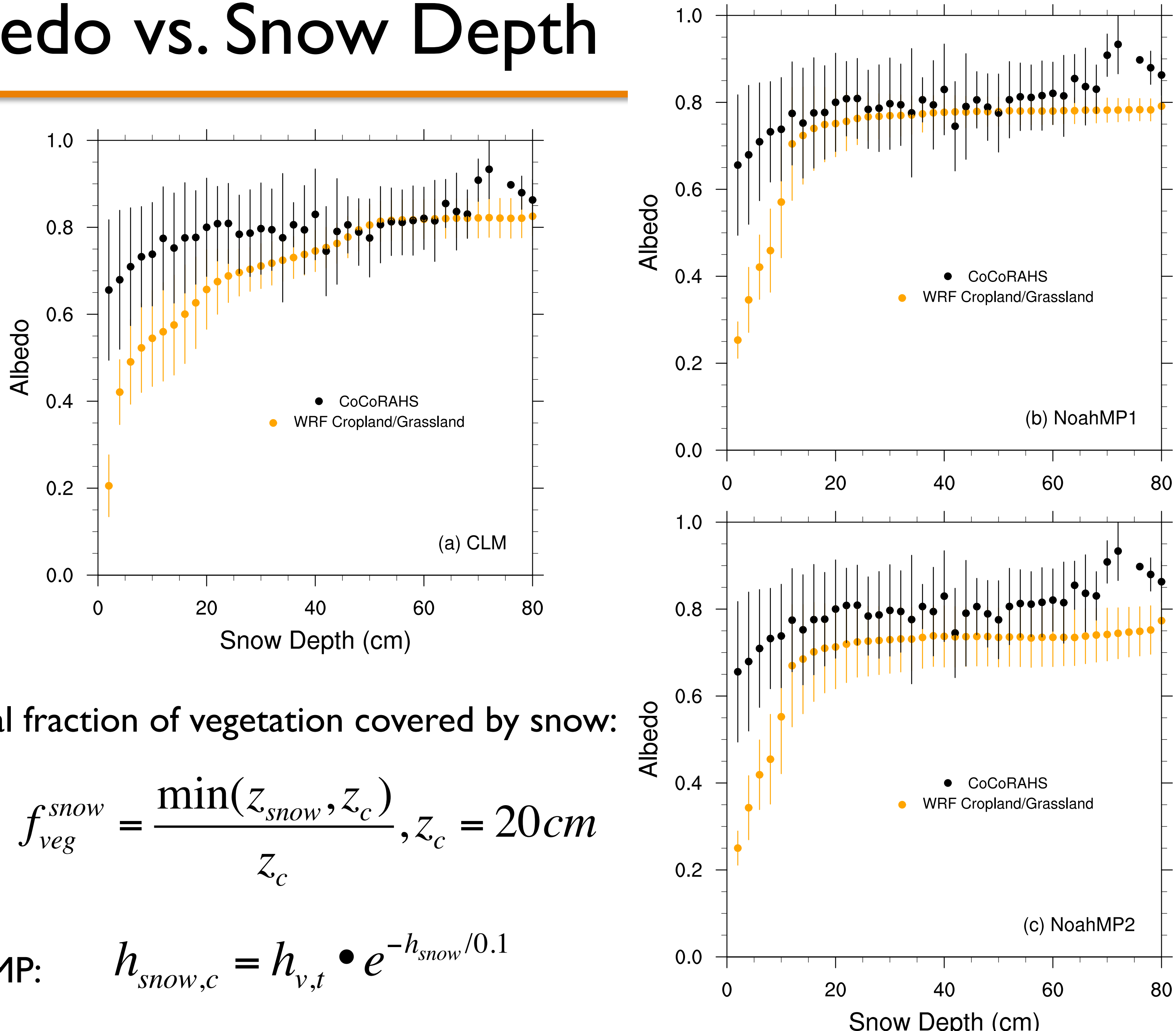
RRTM/Goddard Radiation
CLM

Snow Depth



Cold, Snowy
Warm, Dry
CLM
NoahMP1
NoahMP2
CLM
NoahMP1
NoahMP2
WSM6
Thompson
RRTM/
Goddard
CAM/
CAM
RRTM/
Goddard
CAM/
CAM
MP6LW1SW2CLM
MP6LW1SW2NoahMP1
MP6LW1SW2NoahMP2
MP6LW3SW3CLM
MP6LW3SW3NoahMP1
MP6LW3SW3NoahMP2
MP8LW1SW2CLM
MP8LW1SW2NoahMP1
MP8LW1SW2NoahMP2
MP8LW3SW3CLM
MP8LW3SW3NoahMP1
MP8LW3SW3NoahMP2
0 30 60 90 120 150
WRF DJFM SNOWH (cm)

Albedo vs. Snow Depth



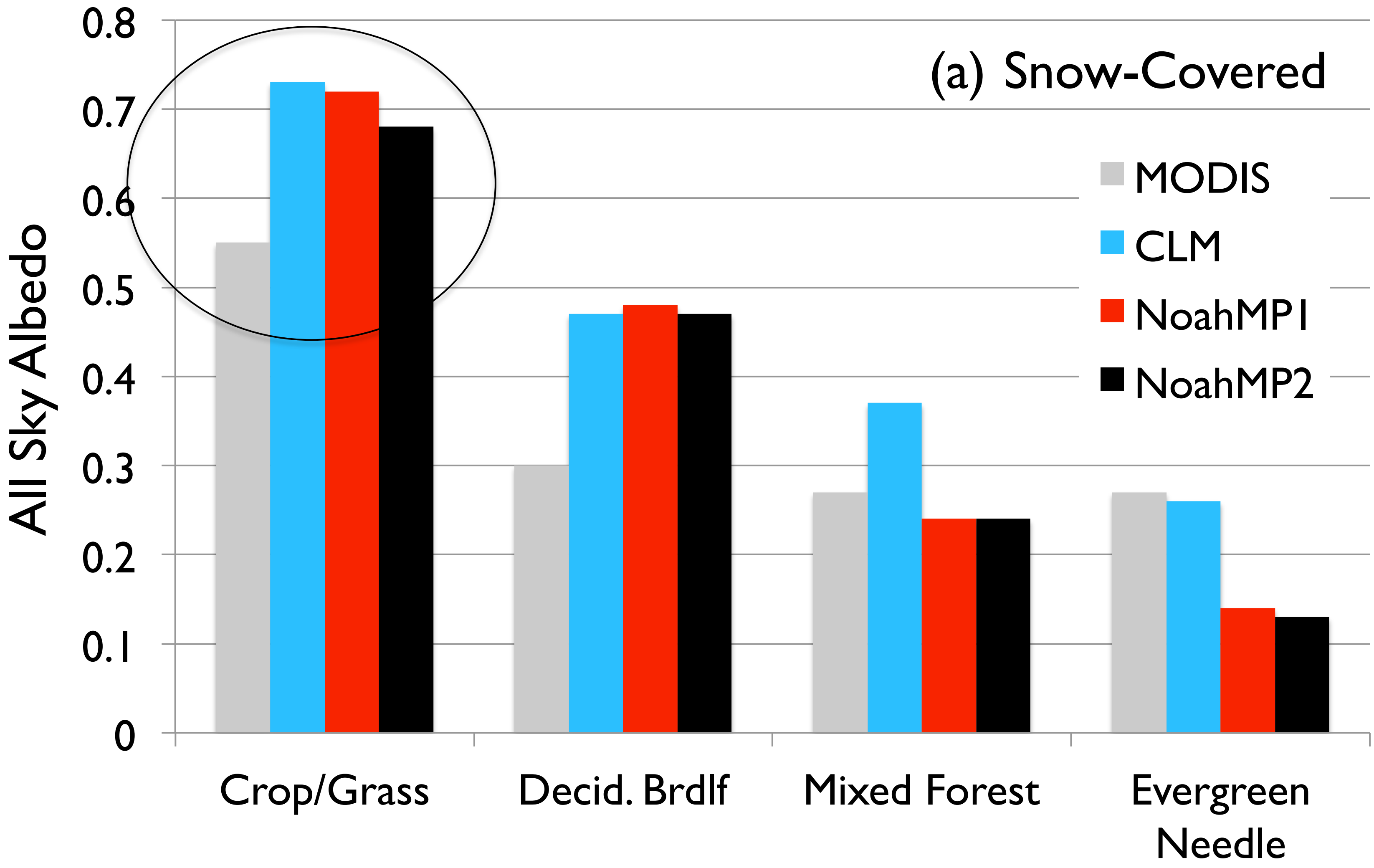
Vertical fraction of vegetation covered by snow:

CLM: $$f_{veg}^{snow} = \frac{\min(z_{snow}, z_c)}{z_c}, z_c = 20cm$$

Noah-MP: $$h_{snow,c} = h_{v,t} \bullet e^{-h_{snow}/0.1}$$

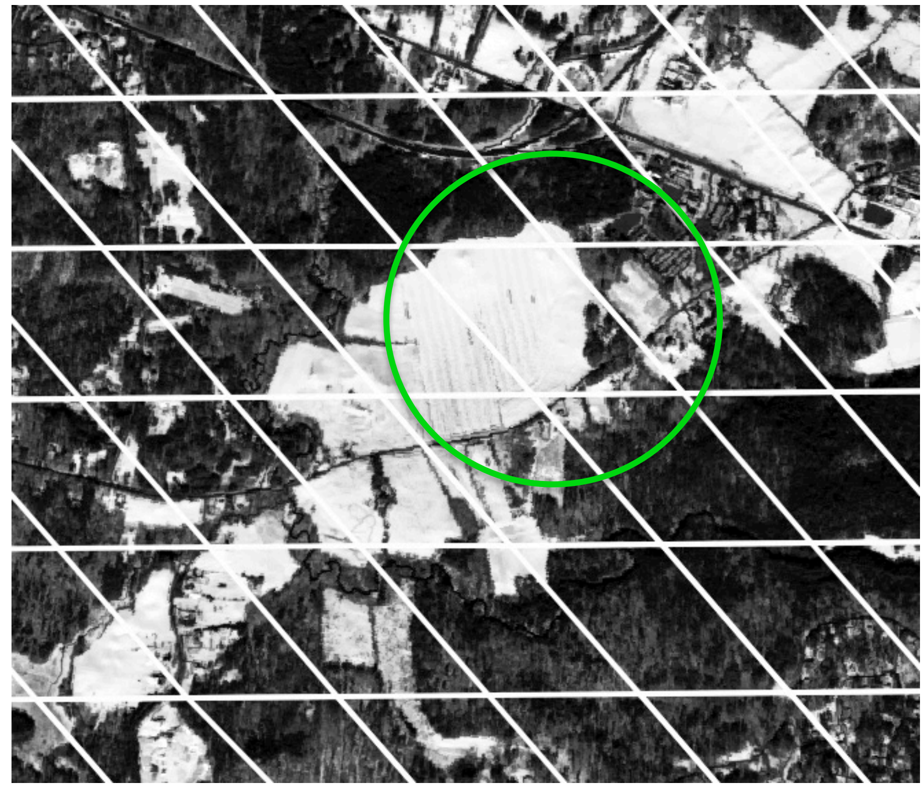
CoCoRAHS Data: Burakowski et al., 2013, *Hydrological Processes*

WRF and MODIS albedo



Schaaf et al. (2002) MCD43A3 BRDF/Albedo v5

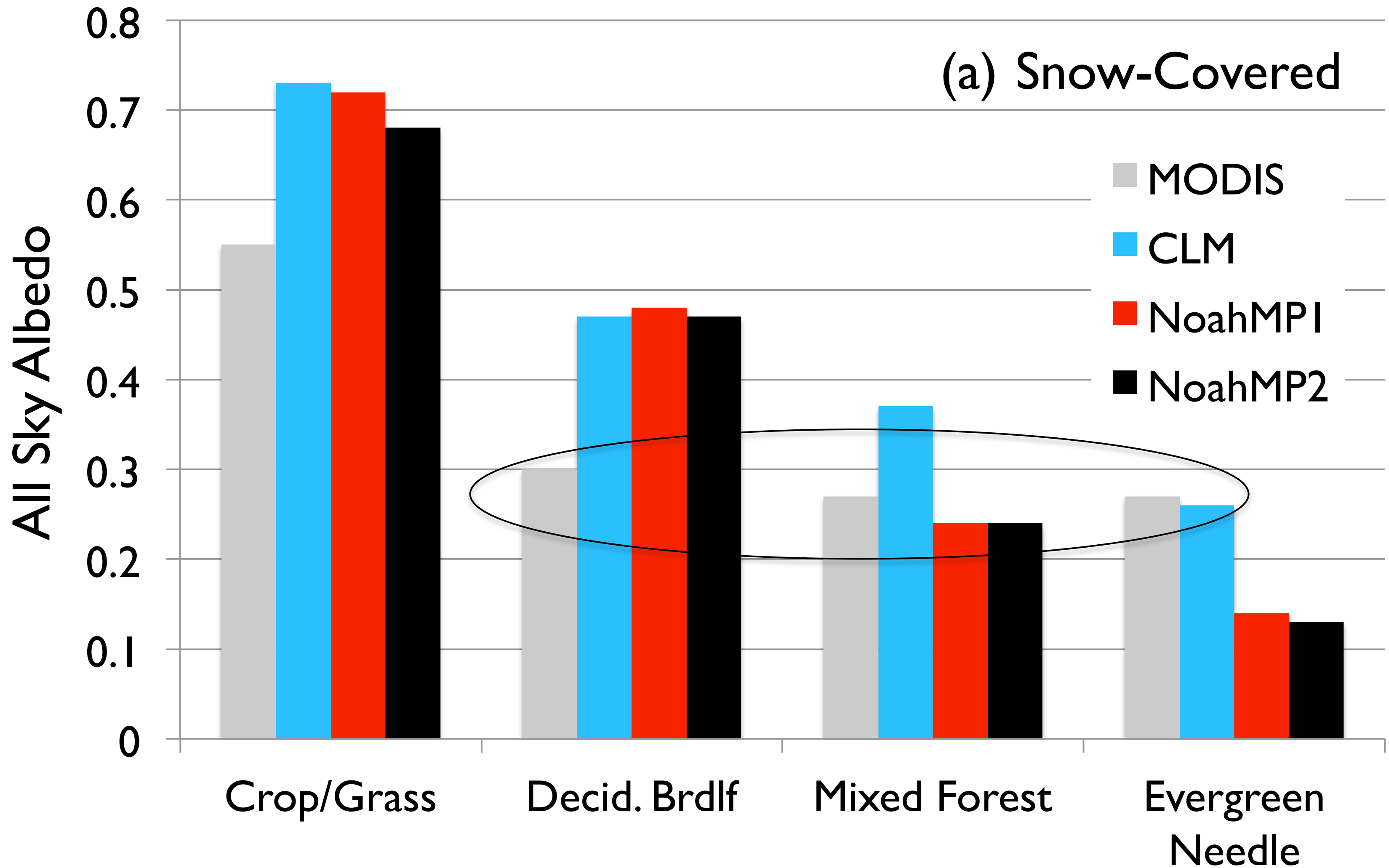
Hyperspectral Imagery and MODIS



MODIS cropland grid cells often contain darker surfaces such as trees, buildings, and roads that produce negative albedo bias.

Burakowski et al., 2013, *Remote Sensing of Environment*

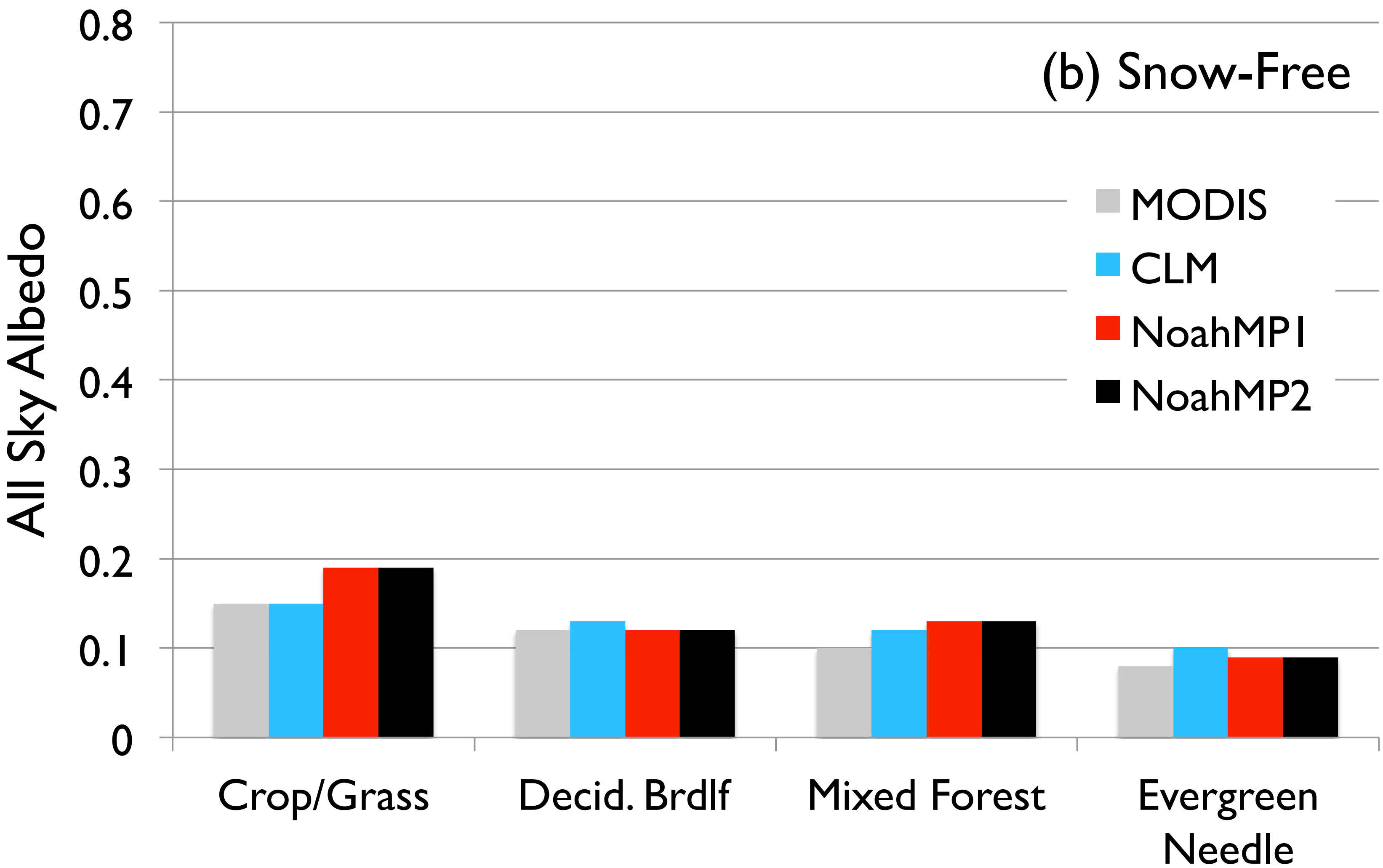
WRF and MODIS albedo



Schaaf et al. (2002) MCD43A3 BRDF/Albedo v5

Burakowski et al. 2014,

WRF and MODIS albedo



Schaaf et al. (2002) MCD43A3 BRDF/Albedo v5

How well do WRF configurations simulate extremes in cold season climate?

- WRF/CLM4.0 reasonably simulates Tmax and Tmin
- WRF/Noah-MP warm bias (+5 to +8K) in Tmax
- All configurations fail to capture precipitation
- Snow-covered deciduous broadleaf albedo overestimated in all models
- Snow-covered evergreen needleleaf albedo underestimated in WRF/NoahMP

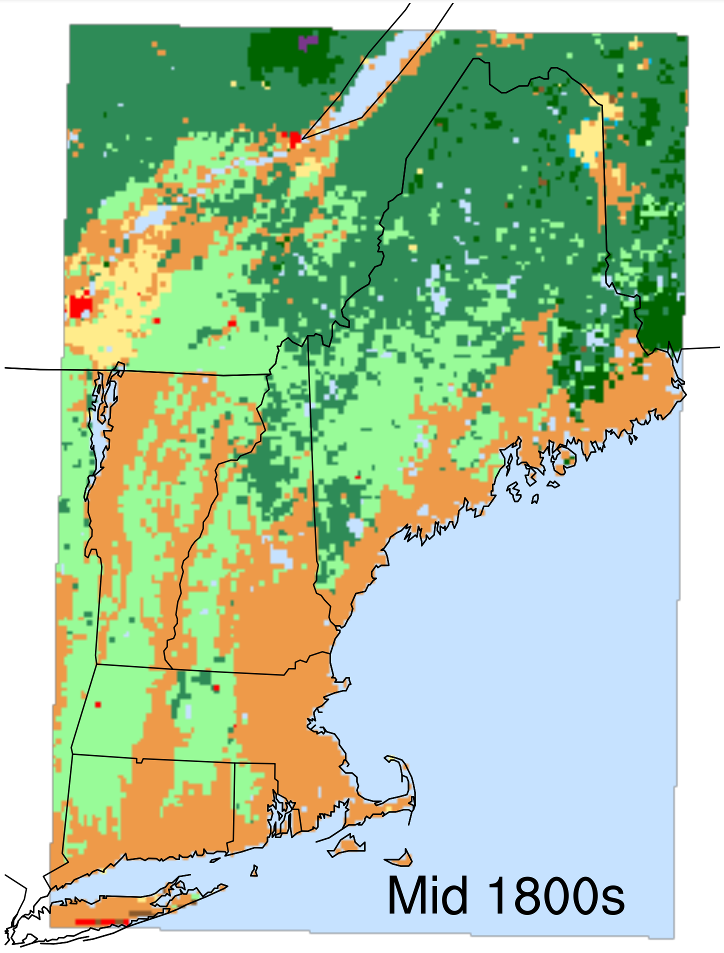
Climate responses to deforestation

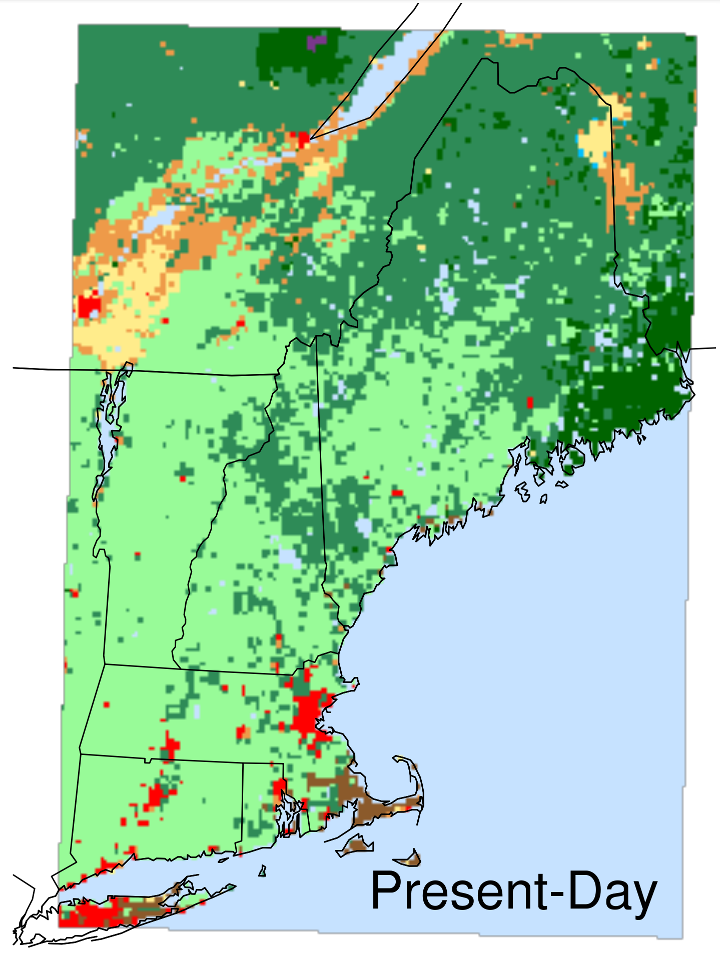
All results are Present-Day minus Mid-1800s Deforested

Expect to see:

- Warmer T2max over forest (albedo effect)
- Warmer T2min over forest (surface roughness)

Land Cover Scenarios



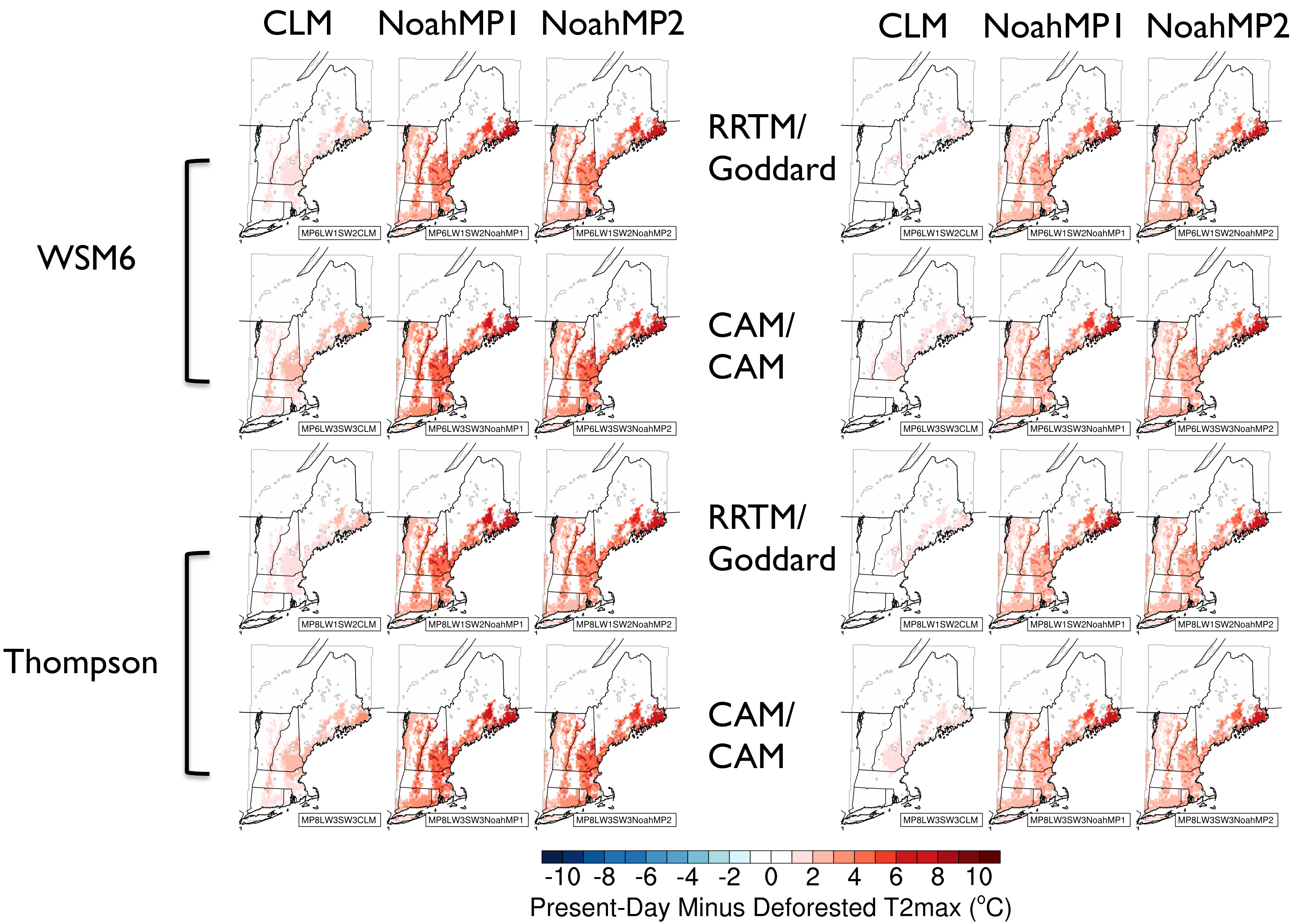


Decid. Broadleaf | Mixed Forest | Evergreen Needleleaf

Urban &Built-Up | Crop/Grass | Dry Crop & Pasture

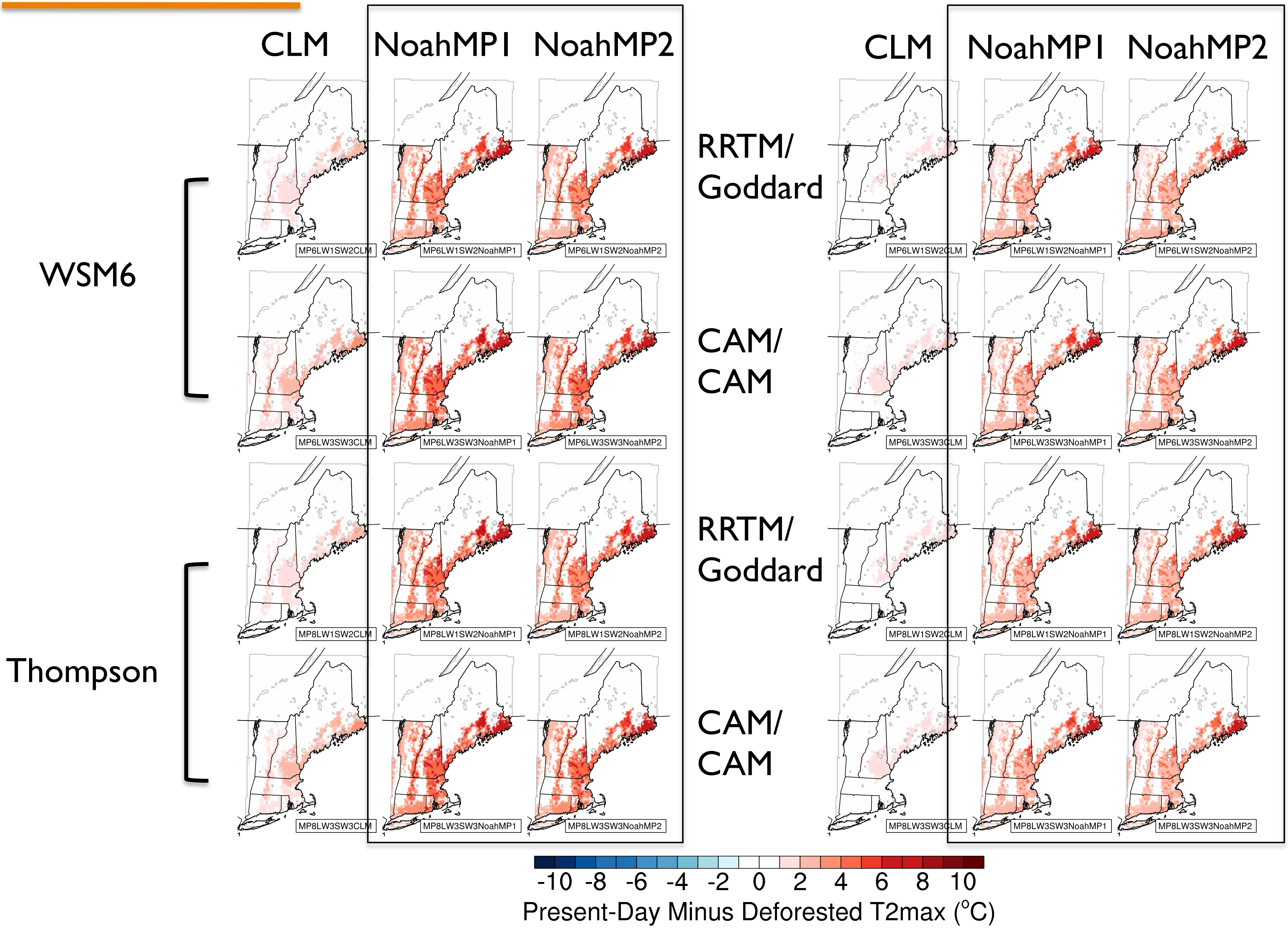
T2max

Cold, Snowy | Warm, Dry

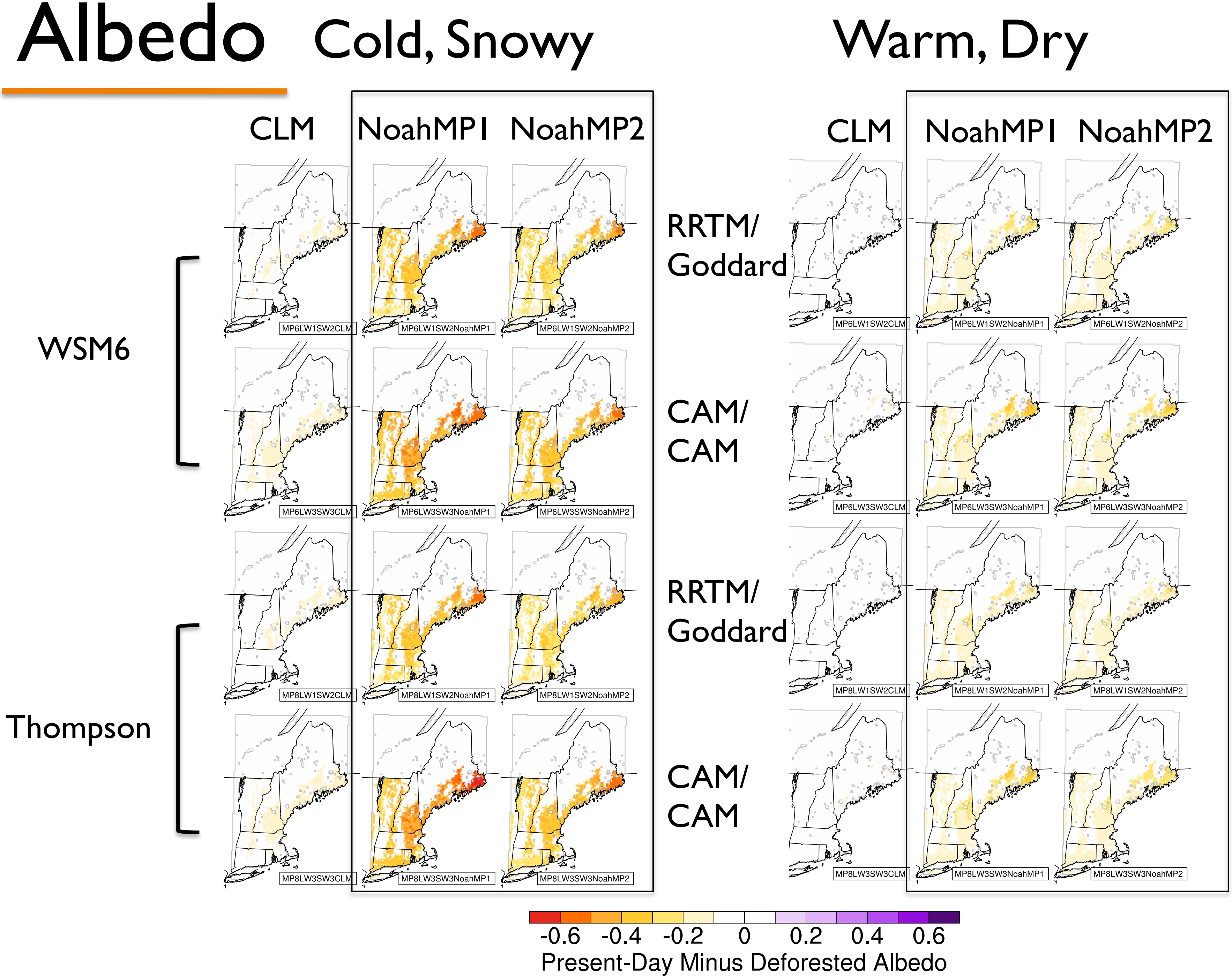


T2max

Cold, Snowy — Warm, Dry

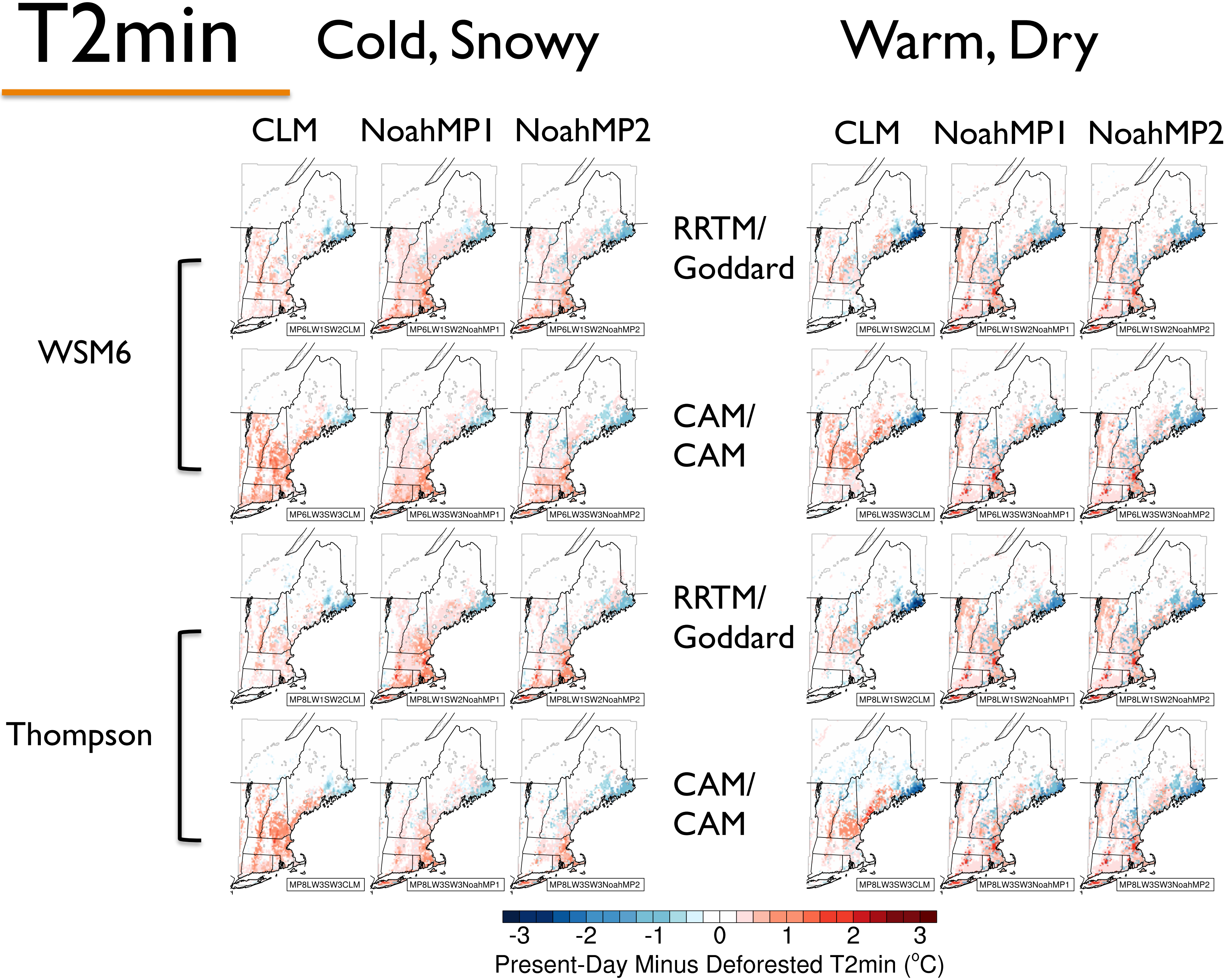


Albedo



Cold, Snowy
Warm, Dry
CLM
NoahMP1
NoahMP2
CLM
NoahMP1
NoahMP2
WSM6
Thompson
RRTM/
Goddard
CAM/
CAM
RRTM/
Goddard
CAM/
CAM
MP6LW1SW2CLM
MP6LW1SW2NoahMP1
MP6LW1SW2NoahMP2
MP6LW3SW3CLM
MP6LW3SW3NoahMP1
MP6LW3SW3NoahMP2
MP8LW1SW2CLM
MP8LW1SW2NoahMP1
MP8LW1SW2NoahMP2
MP8LW3SW3CLM
MP8LW3SW3NoahMP1
MP8LW3SW3NoahMP2
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
Present-Day Minus Deforested Albedo

T2min


Cold, Snowy
Warm, Dry
CLM
NoahMP1
NoahMP2
WSM6
Thompson
RRTM/ Goddard
CAM/ CAM
MP6LW1SW2CLM
MP6LW1SW2NoahMP1
MP6LW1SW2NoahMP2
MP6LW3SW3CLM
MP6LW3SW3NoahMP1
MP6LW3SW3NoahMP2
MP8LW1SW2CLM
MP8LW1SW2NoahMP1
MP8LW1SW2NoahMP2
MP8LW3SW3CLM
MP8LW3SW3NoahMP1
MP8LW3SW3NoahMP2
-3 -2 -1 0 1 2 3
Present-Day Minus Deforested T2min (°C)

Dominant Biophysical Processes

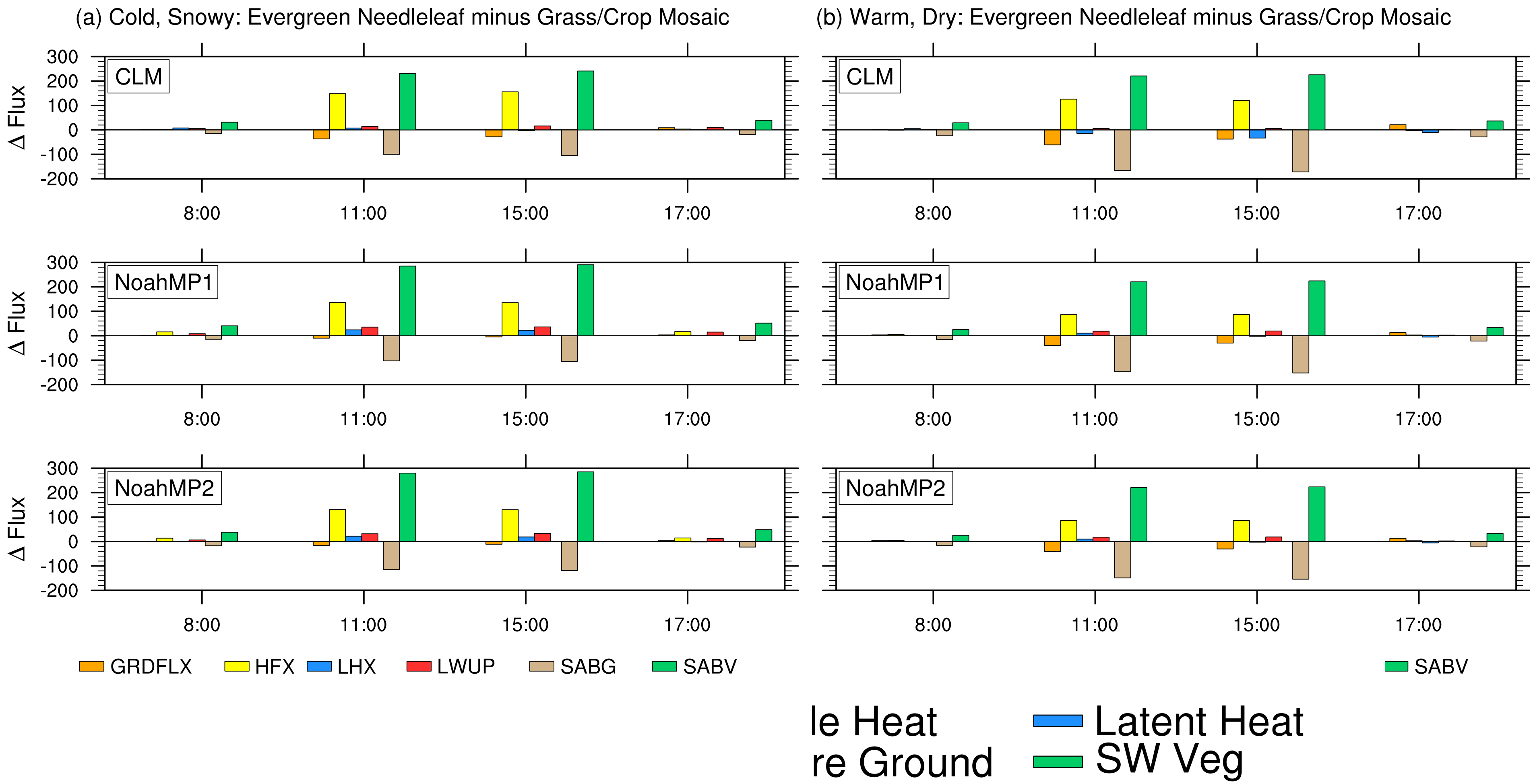
Daytime

- **Albedo:** warmer forests due to increase in SW absorbed by vegetation (albedo)
- **Surface Roughness:** cooler forests due to more efficient dissipation of sensible heat & warmer open land due to suppressed mixing

Nighttime

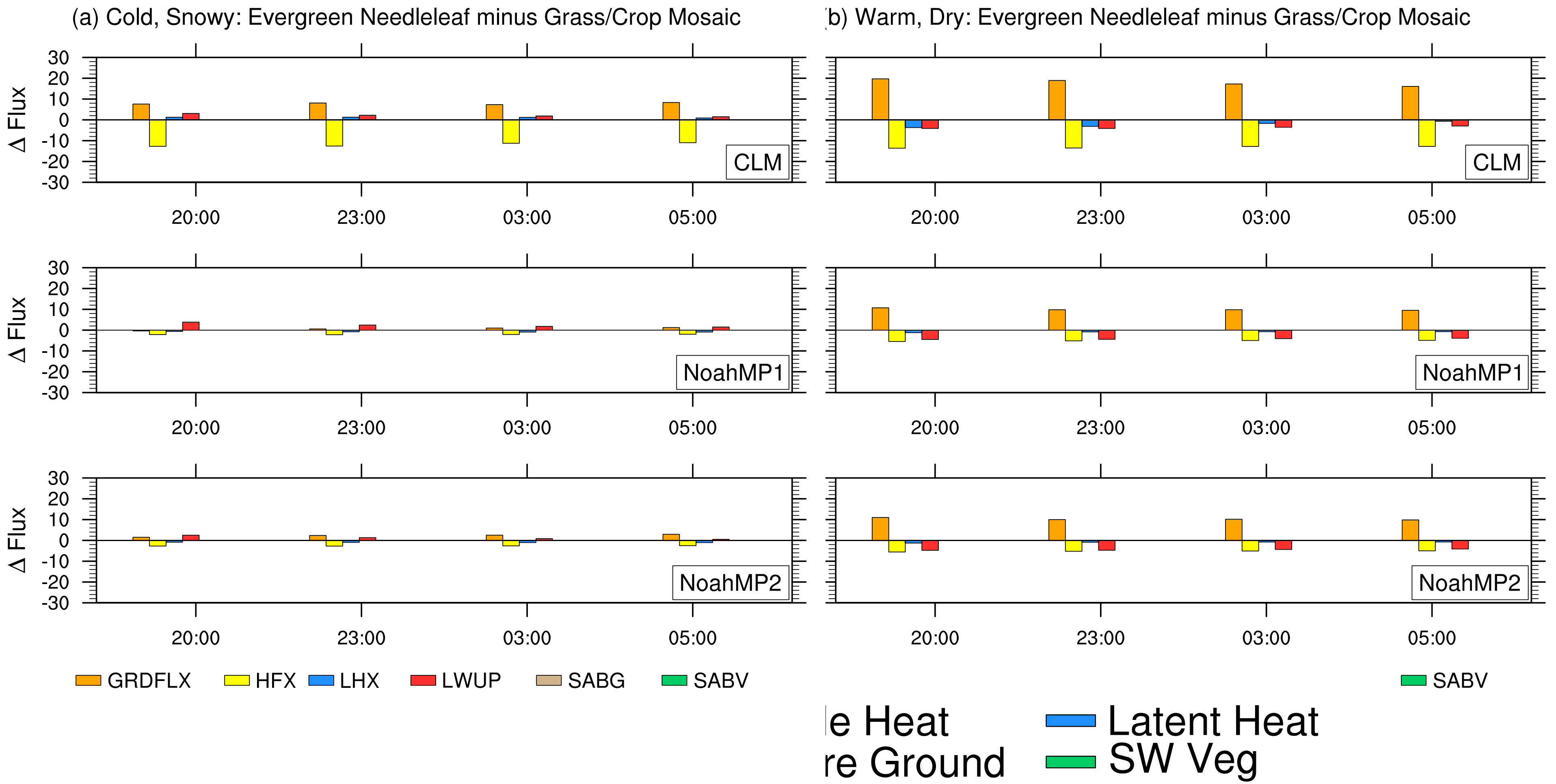
- **Surface Roughness:** warmer forests due to enhanced mixing, drawing warmer air from aloft during stable conditions

Diurnal change in surface energy fluxes: Evergreen Needleleaf minus Grass/Crop



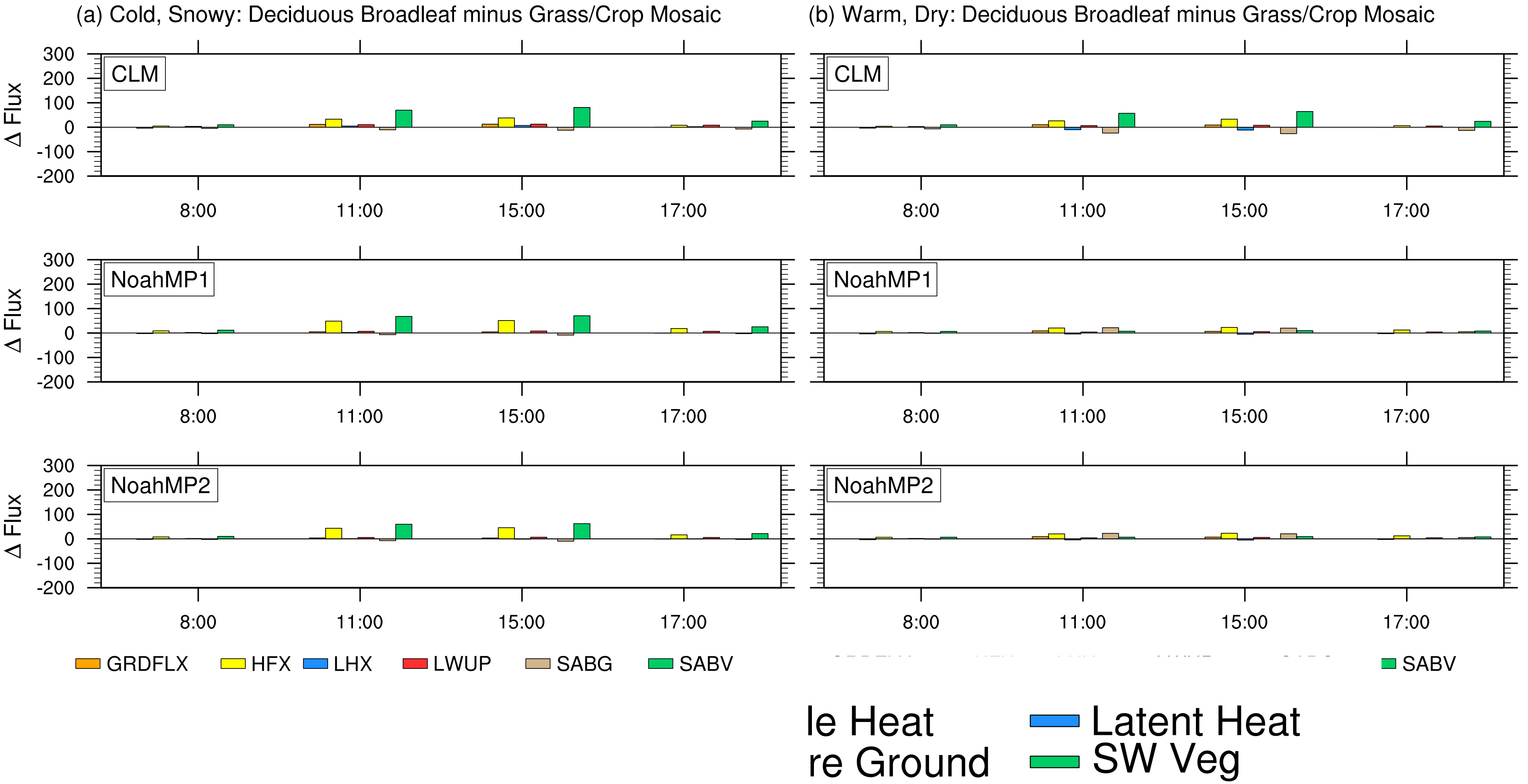
Larger increase in shortwave absorbed by vegetation (SW Veg) in Noah-MP compared to CLM.

Diurnal change in surface energy fluxes: Evergreen Needleleaf minus Grass/Crop



Larger increase in ground heat flux in 2011/2012 with low snow cover. Ground heat flux negative at night (soil cooling).

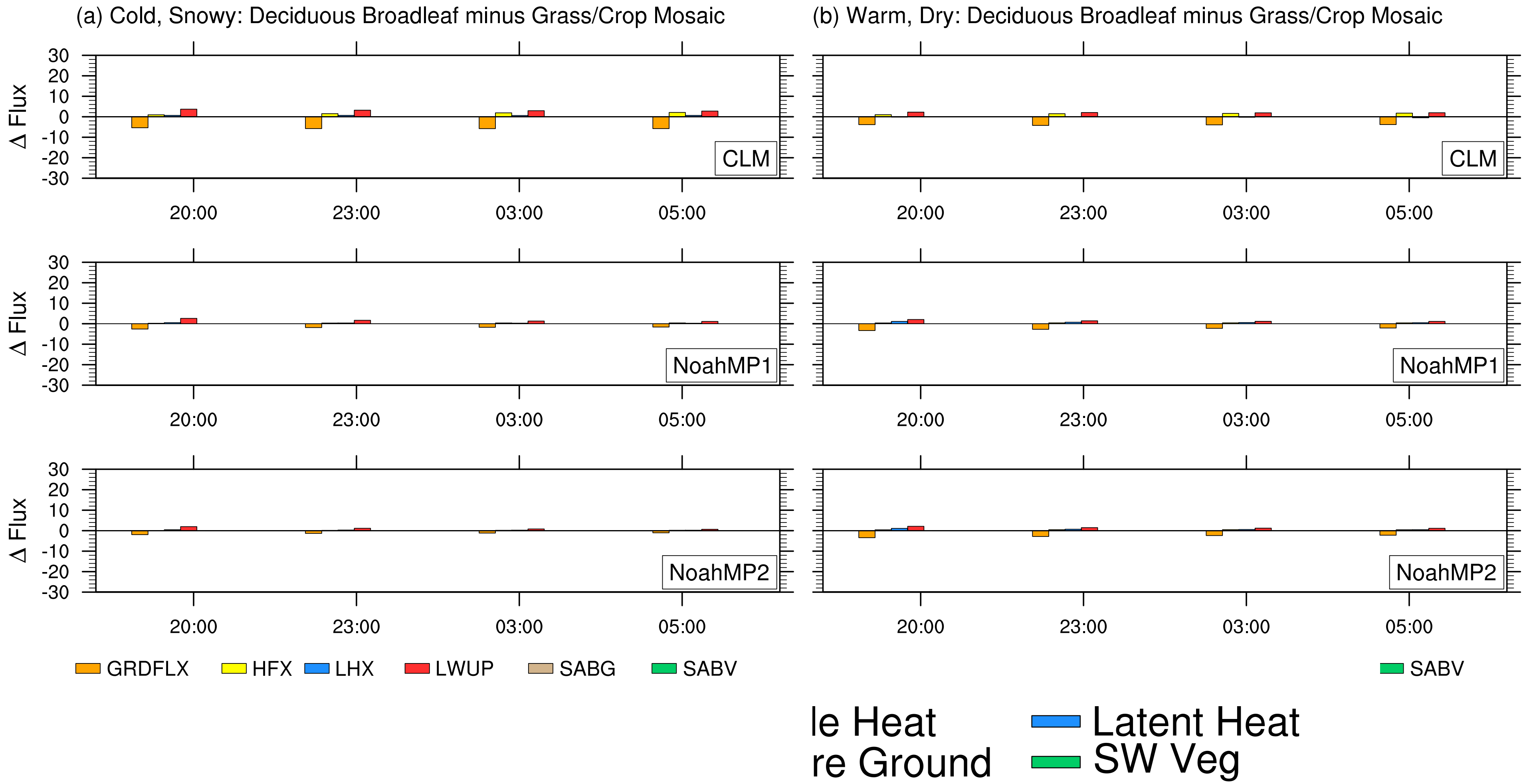
Diurnal change in surface energy fluxes: Deciduous Broadleaf minus Grass/Crop



Increase in SW absorbed by vegetation in all LSMs.

Decrease in SW absorbed by ground in CLM. *Increase* in NoahMP.

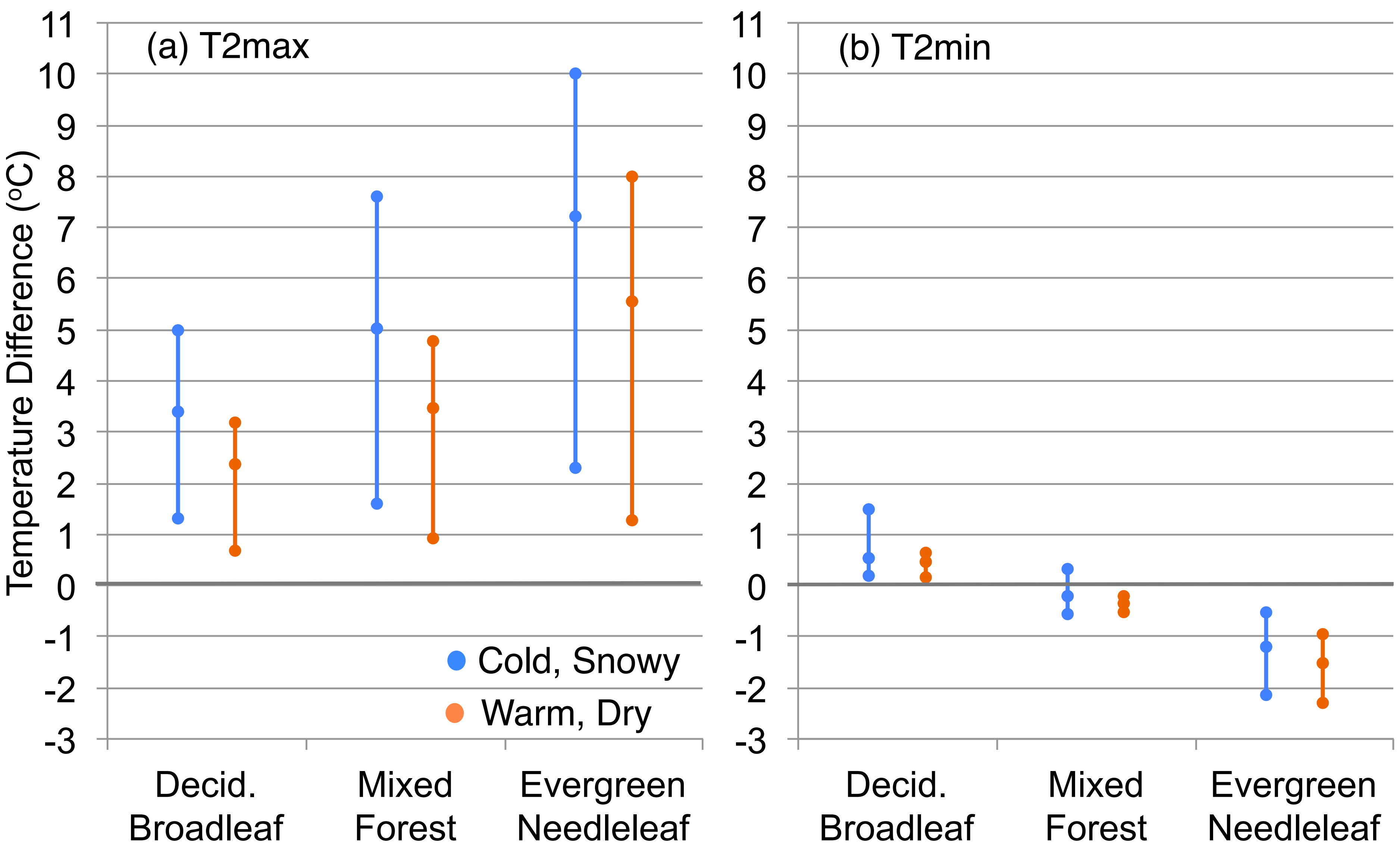
Diurnal change in surface energy fluxes: Deciduous Broadleaf minus Grass/Crop



Increase in SW absorbed by vegetation in all LSMs.

Decrease in SW absorbed by ground in CLM. *Increase* in NoahMP.

Responses to Reforestation



Summary

- How well do WRF configurations simulate extremes in cold season (Dec-Mar) climate in New England?
  - Choice of land surface model influences of T2max
  - Choice of longwave radiation scheme influences T2min
  - WRF/CLM generally better at simulating temperature extremes
  - Precipitation not simulated well by any physics configuration tested here
  - Snow-covered albedo of deciduous broadleaf forest overestimated relative to MODIS by all model configurations
  - Snow-covered albedo of evergreen needleleaf underestimated relative to MODIS by all model configurations

Summary

Do climate responses to reforestation vary with WRF model configuration?

- T2max **warms** in all physics configurations (albedo)
- T2min response is uncertain; multi-physics ensemble spans both cooling and warming responses.
- Unclear why the model does not consistently simulate the *observed* warming at night (e.g., T2min) driven by changes in surface roughness over forest compared to open land.

Future Work

Summer biophysical impacts of land cover change

Future Work

Summer biophysical impacts of land cover change

Where are New England Forests headed?

Future Work

Summer biophysical impacts of land cover change

Where are New England Forests headed?

And for that matter, climate?

Questions?