Regional Air Quality Management Aspects of Global Change: Impact of Climate-Responsive Controls and Forest Management Practices on Regional Air Quality and Associated Uncertainties

M. Trail, P. Liu, A.P. Tsimpidi*, Y. Hu, A. Nenes, Y. Wang and A.G. Russell

Georgia Institute of Technology

J. Rudokas, B. Keaveny, M.. Manion, G. Klieman, and P. Amar*

NESCAUM

K. Tsigaridis

NASA GISS

M. Bergin and D. Tian

Georgia Environmental Protection Division

Georgia Institute of Technology

NESCAUM

This research is funded by U.S. EPA - Science To Achieve Results (STAR) Program Grant # R8342801

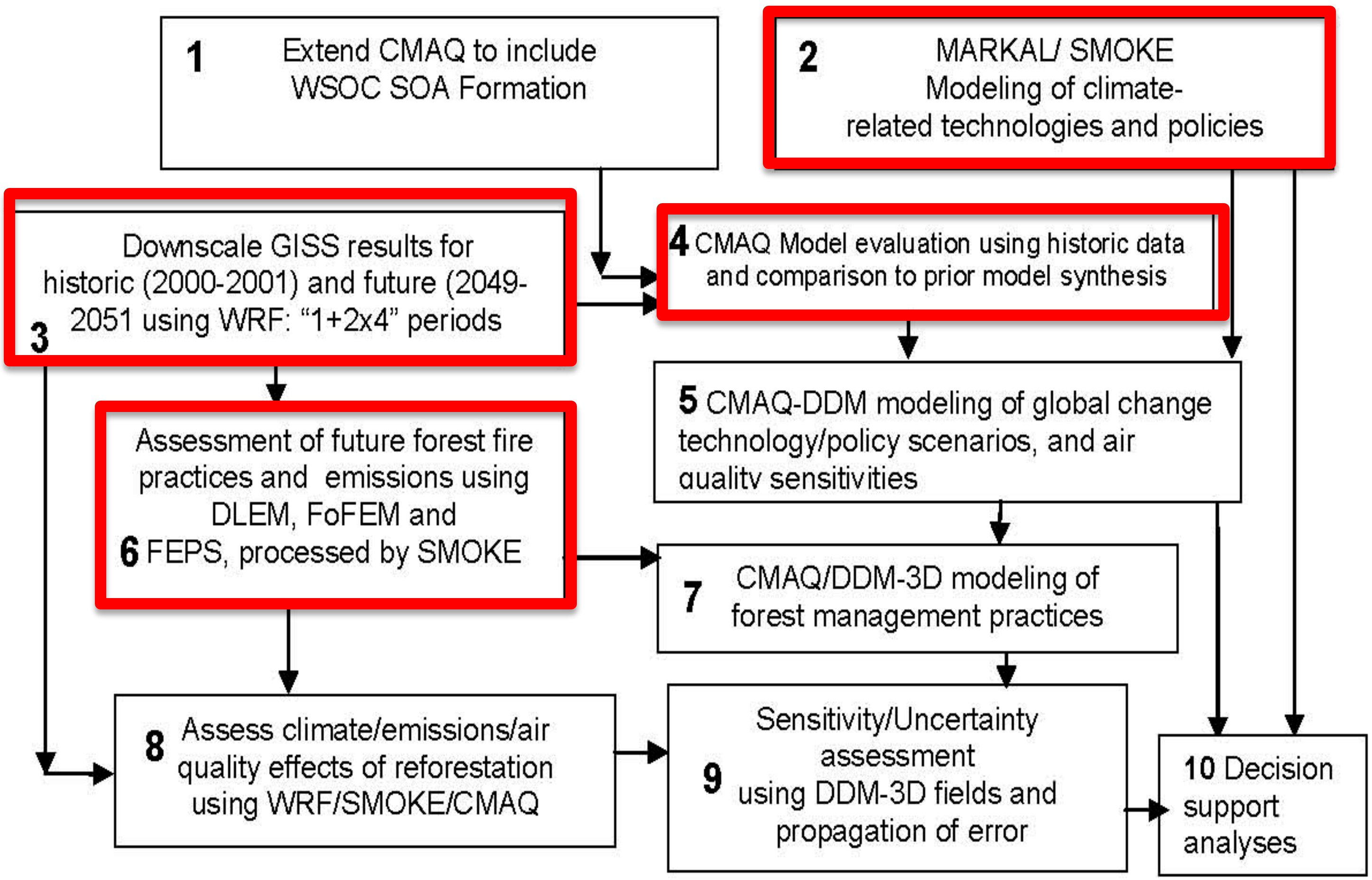
Project Overview

- Combined academic (engineering, atmospheric sciences)-state/regional planning organization team to identify and assess strategies to influence global change and air quality focusing on eastern US
  - NESCAUM (MARKAL modeling) and Georgia EPD (biofuels/biomass burning) provide information on potential strategies and emissions impacts
  - Georgia Tech conducts atmospheric modeling
- Approach
  - Assessing emission impacts of specific strategies (and combinations)
    - MARKAL: Energy systems-oriented economic linear programming model
    - Reforestation/biomass burning: Expected to be of growing importance in Southeast
      - Source emissions expected to grow while others are reduced
  - Assess air quality impacts in midterm future (2050)
    - Downscale GISS MODEL E using WRF
    - Apply extended (SOA, HDDM, Adjoint?) CMAQ
- Provide policy making organizations with specific information about the likely impacts of strategies along with sensitivities and uncertainties

Global change-motivated strategies

- Technological, regulatory and management practices
  - RGGI: Regional Greenhouse Gas Initiative (and other state/regional initiatives)
  - Renewable energy and energy conservation
  - Alternative transportation technologies (i.e. reduced petroleum fuel/increased low-carbon fuels)
  - Use of carbon capture and sequestration
  - Reforestation with cellulosic fuel production
    - Impacts regional climate directly and indirectly
  - Forest management practices
    - prescribed burning
    - liquid biofuel production
    - wildlife habitat restoration

Project flow diagram



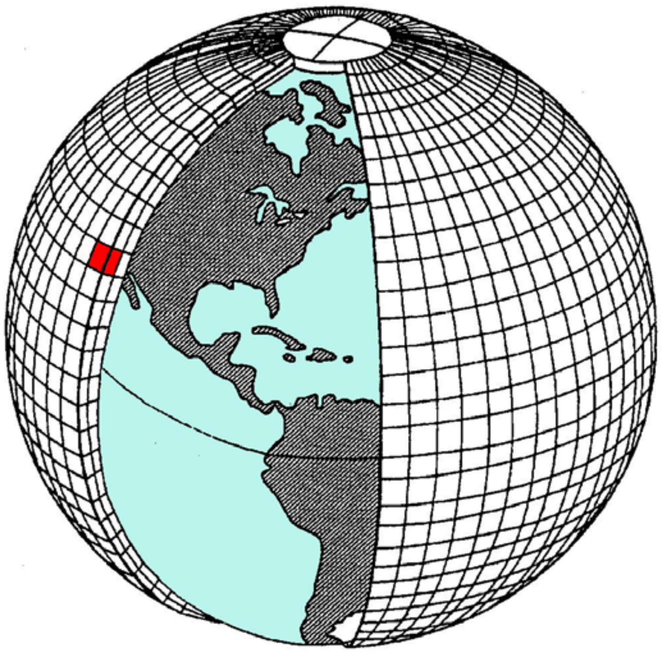
Some Diversions

- Evaluation of spectral versus grid nudging
  - Spectral nudging performed better
- Development of “loop” Noah
  - Treats each land use individually within a grid
    - Needed to consider some climate controls
  - Allows consideration of subgrid scale heat exposures

Global Climate Modeling

- **Model:** GISS Model E

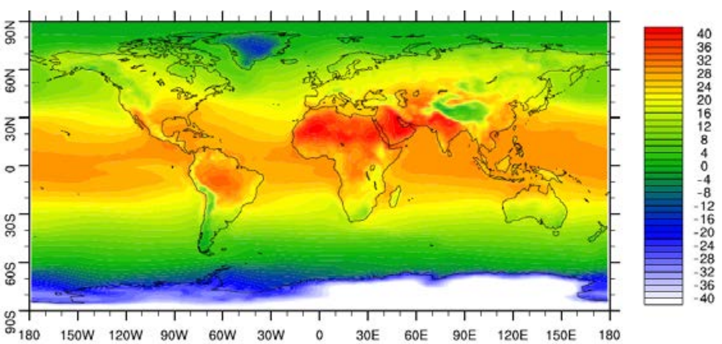
• State-of-the-science representations of advection, convection, clouds, radiation, boundary key physics, etc.



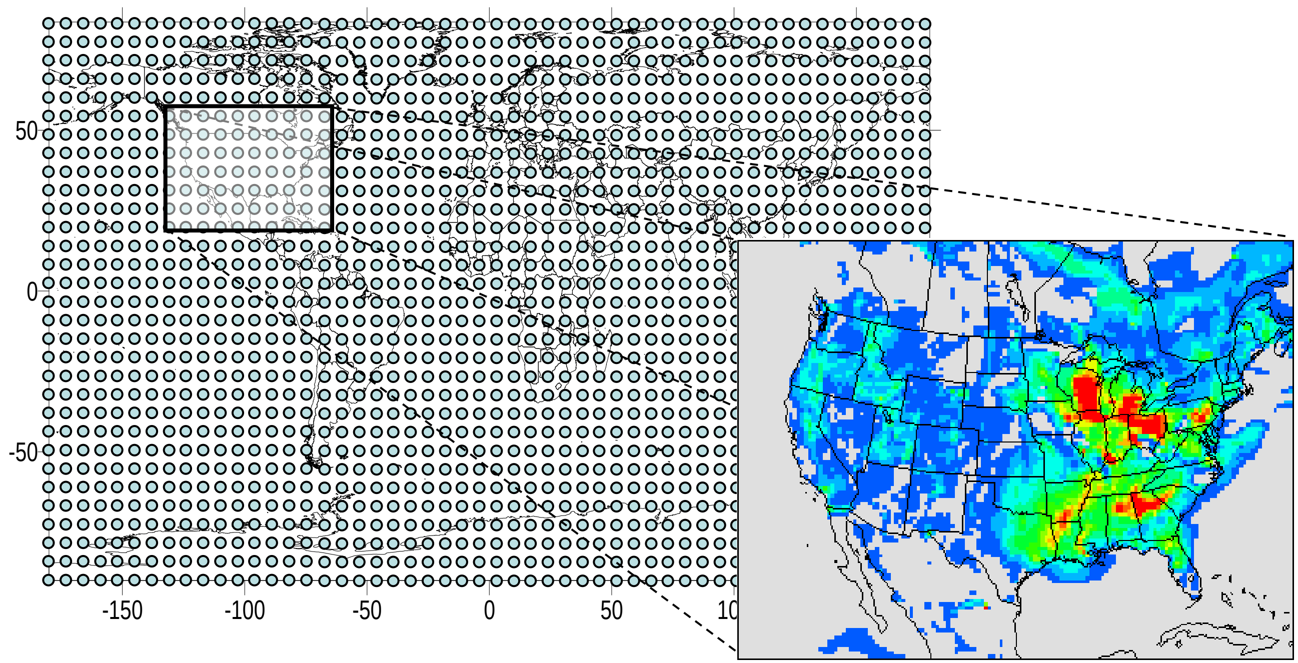
- **Grid resolution:** 2^0 x 2.5^0 latitude by longitude, 40 vertical layers up to 0.1 hPa

Emissions Scenario: RCP 4.5
(~4.5 W/m2 radiative forcing at stabilization after 2100)

- **Output Data:** Meteorological fields for the years 2006-2010 and 2048-2050 with 6-hr interval resolution (provided by our NASA GISS collaborators)



Regional downscaling of climate simulations



➢ Downscaled GISS Model E using WRF.
- GISS provides initial, surface, and lateral boundary conditions
- WRF generates gridded higher-resolution meteorological fields

➢ Spectral nudging (Liu et al., 2012 compares spectral and grid nudging)
- Accounts for longer wave information from the global model
- Small-scale details are the result of an interplay between larger-scale atmospheric flows and smaller-scale geographic features

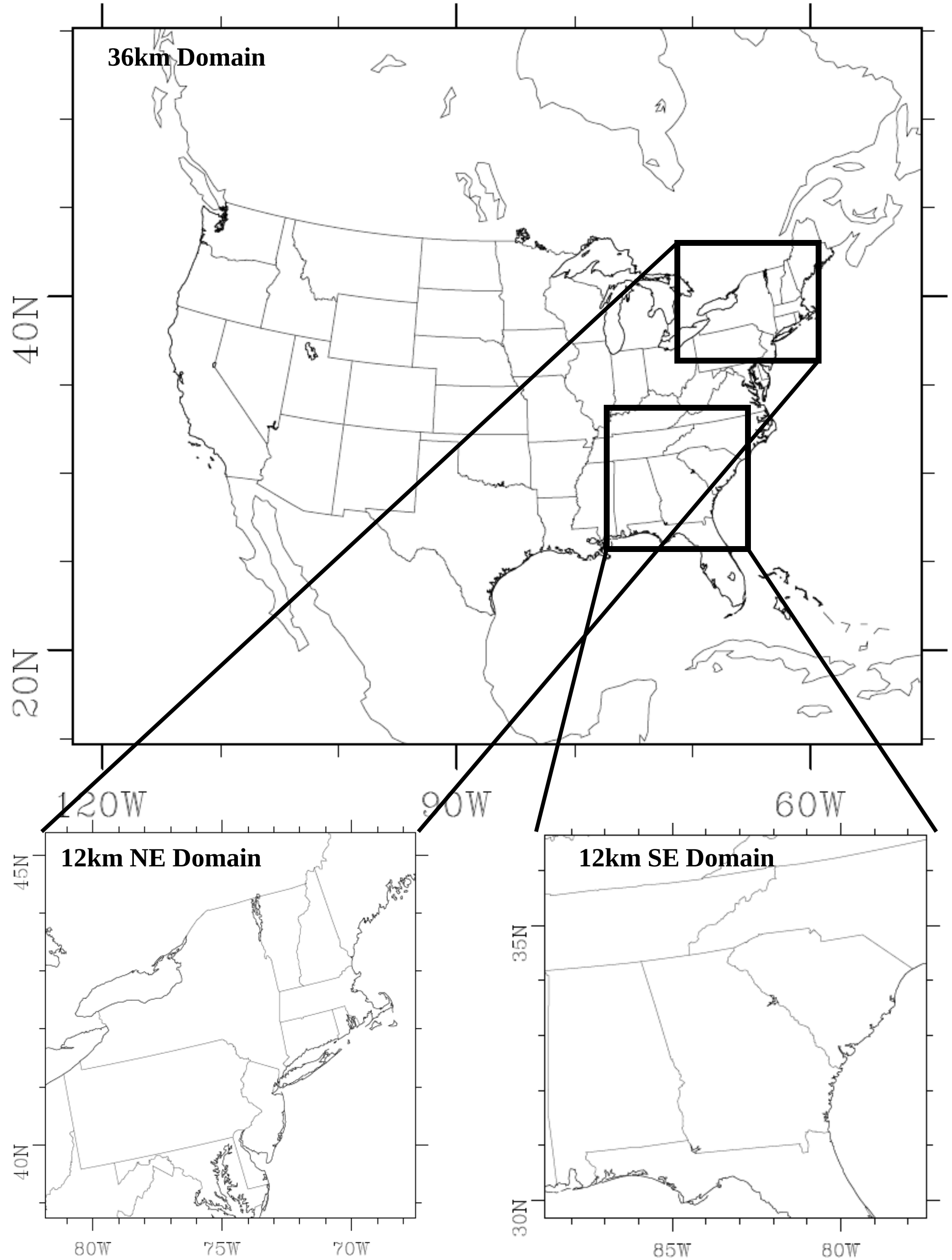
Regional Air Quality Modeling

Currently using CMAQ V4.7.1

- May move to 5, depending on DDM and adjoint availability
- Changes within the aerosol module
  - improved treatment of secondary organic aerosol (SOA) formation
    - Multigenerational
- SAPRC Mechanism
- High-Order Decoupled Direct Method (HDDM)
  - CMAQ with DDM-3D being run for the alternative scenarios and the sensitivities to NO_x, SO_x, and VOC emissions are being calculated
  - Use for uncertainty assessment
- Model development
  - Georgia Tech SOA (multigenerational) module
  - Extended DDM for the SOA module
  - Adjoint method should become available

Regional Modeling Domain

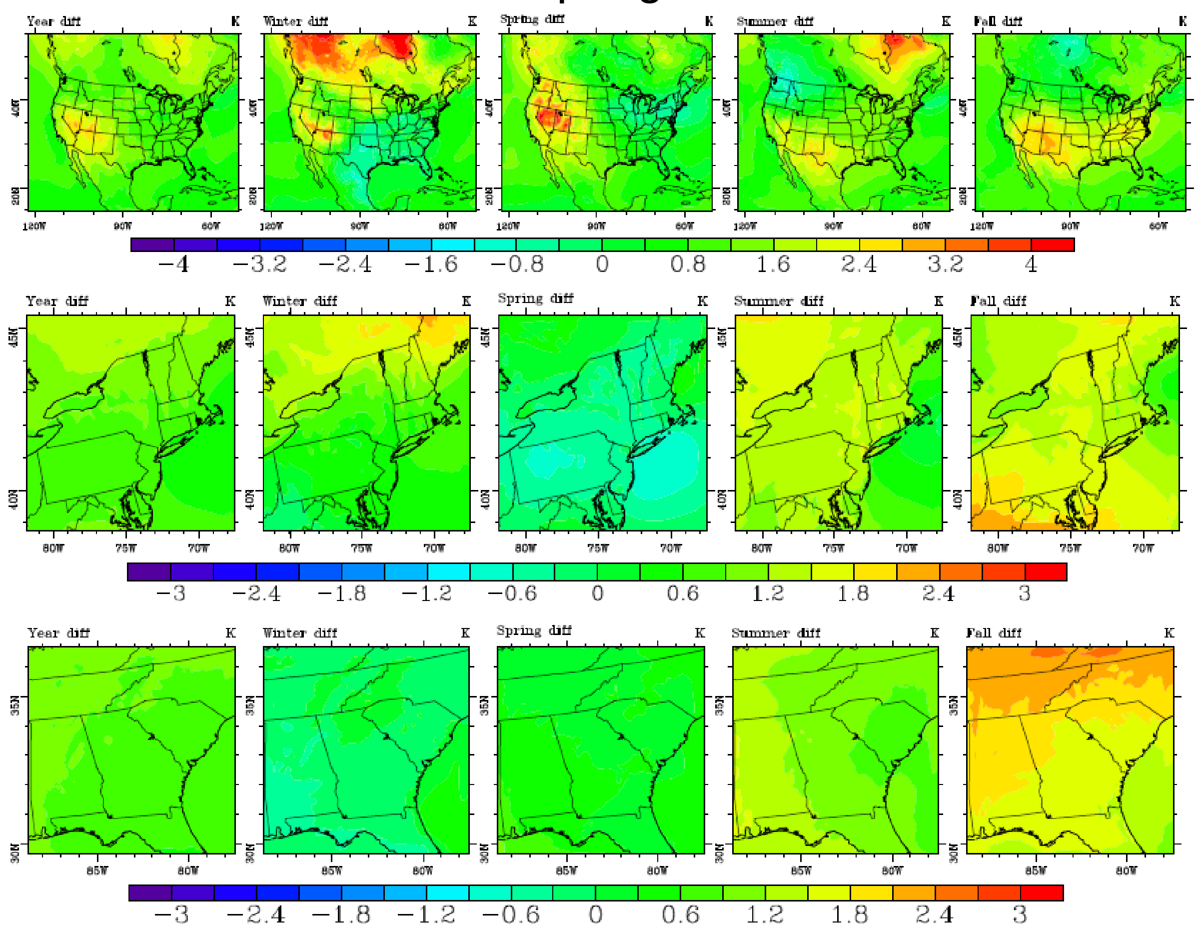
- Focus on Georgia and Northeast (NESCAUM)
- Include 4 domain km over Atlanta and New York as appropriate



Downscaling results: Temperature

- Seasonal 2km Temperature difference
  - 2006-2010 vs. 2048-2052
- Average warming of more that 1 degree
  - Midwest and Texas
  - Eastern U.S. in the Fall
  - Seasonally dependent

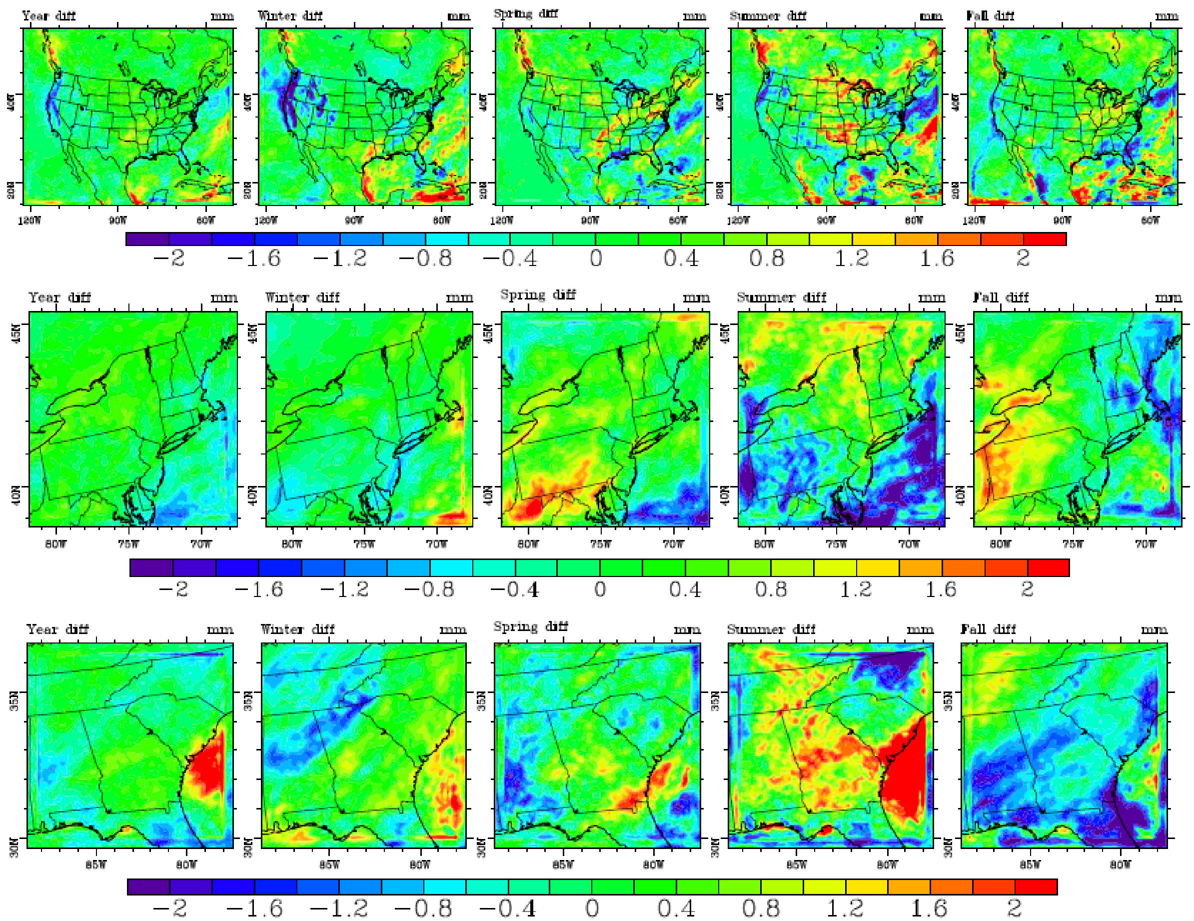
Year Winter Spring Summer Falll



Downscaling results: Precipitation

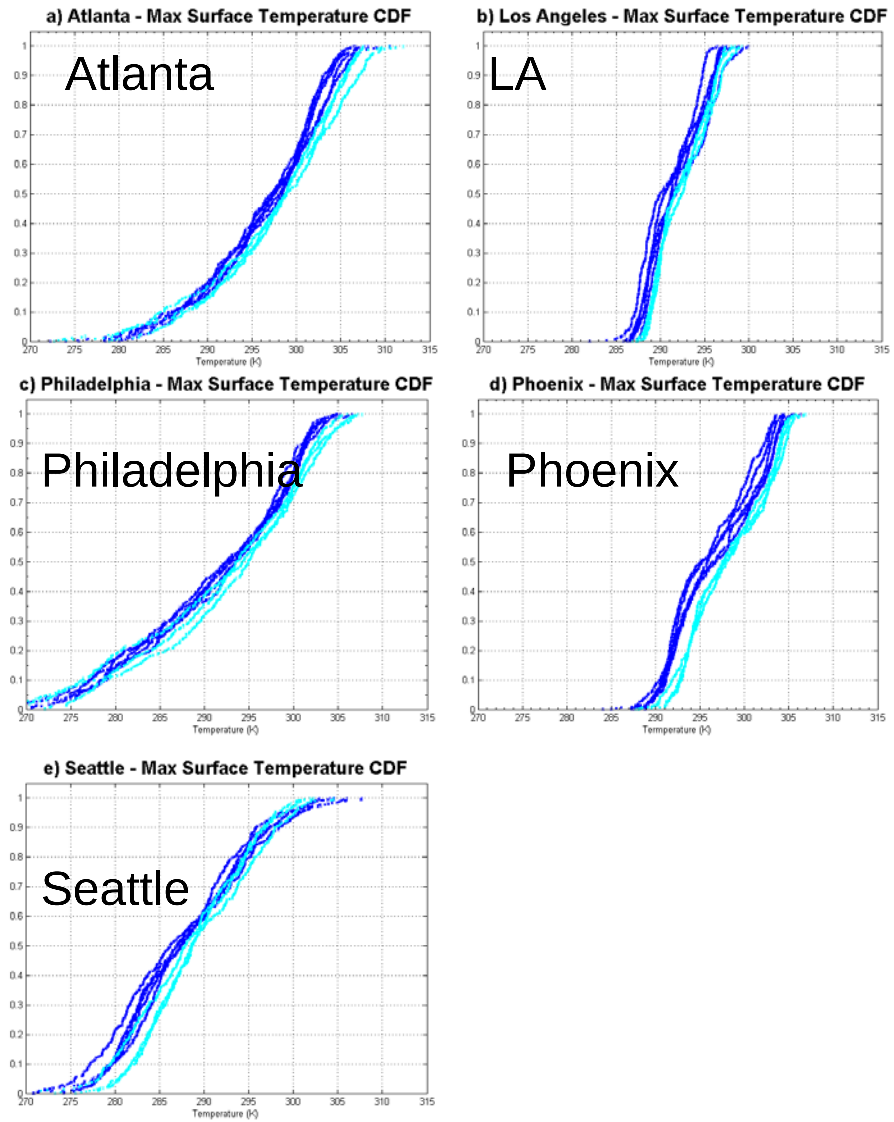
- Seasonal Precipitation difference
  - 2006-2010 vs. 2048-2052
  - Dryer West Coast
  - Dryer Southeast Fall
  - Wetter Mid-West summer
  - Wetter Southeast summer
  - Need to put in to context with longer term results

Year Winter Spring Summer Falll



Downscaling results

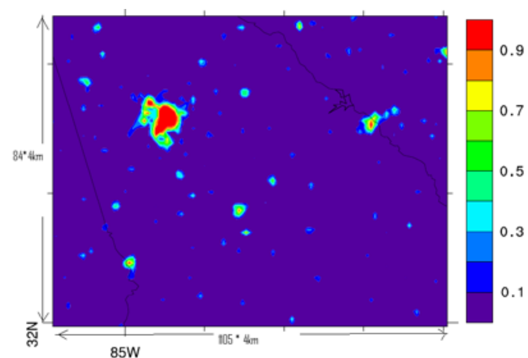
- Historic years (dark) and future years (light) maximum daily 1-hr average temperature at major U.S. cities
- Temperature extremes
  - Increased maximum temperature in most major cities
    - Seattle has cooler summers



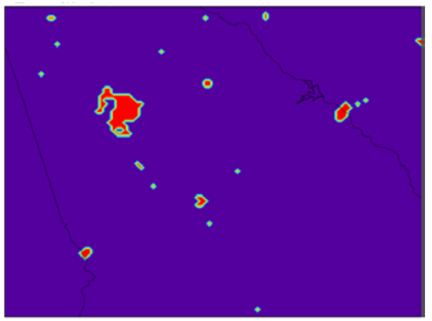
Modification to WRF/Noah Land Surface Model: Loop Noah

- Project potentially needed to treat land use changes at subgrid scales
- Noah used dominant land use to determine LSM model characteristics
- "Loop" Noah developed to track subgrid scale changes

Urban land use fraction (USGS) of northern Georgia



Grids dominated by urban



“Loop” NOAH Method-- **Motivation**

Land use change is an important forcing for regional or local climate and air quality change

SE US →

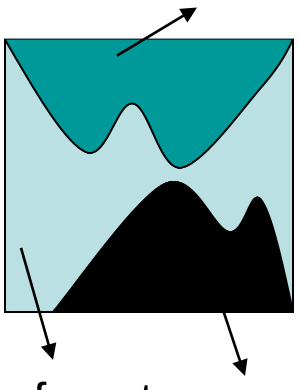
Urbanization/sprawl/ densification

Potential “cooling” strategies in cities

Reforestation and corresponding increased biomass burning

- Land use change scenarios: modify land use change at fine level (e.g. under 1km resolution)
- Land Surface Models (LSMs): provide heat and moisture fluxes of land surface, which serve as the lower boundary condition for the vertical transport

"Loop" Noah Method



Begin Land Surface Model

At each time step, for each grid cell

↓

Loop Noah LSM over all land use types

↓

- *For additive properties* (e.g. heat and moisture flux):

  $\sum wi\ Fi$ (i:land use type, w:land use fraction, F: flux)

- *For non-additive properties*: keep track the sub-grid information

- *For representative skin temperature (TSK) of the grid cell*:

  derived by energy balance, Energy in = Energy out

  $\sum w_i((1-\mathbf{a}_i)SW+e_iLW)$ =

  $\sum w_i$(sensible heat+soil heat+latent heat+ $ei*\sigma*TSK^4$)

  (i:land use type a: albedo e:emissivity σ:Stefan-Boltzman const.)

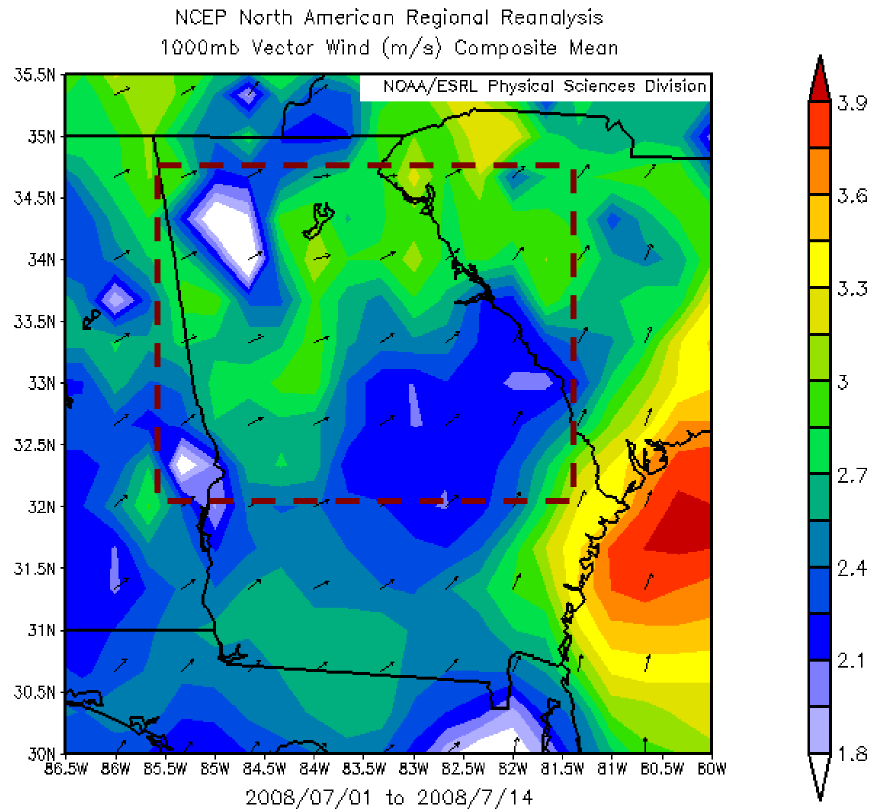
↓

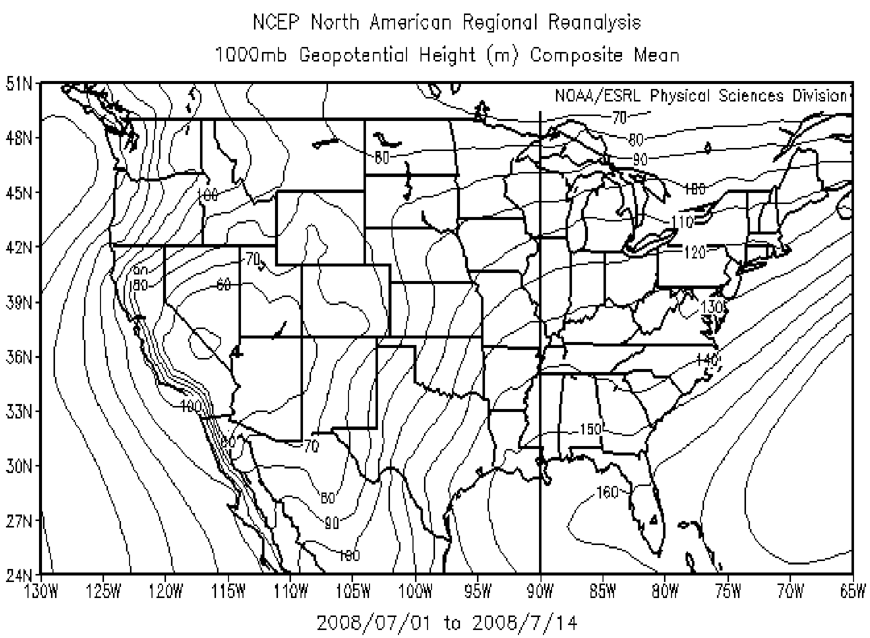
End Land Surface Model

Evaluation of Loop Noah in WRF3.1.1

Downscaling NARR data with WRF3.1.1 to 12km resolution, with a nested domain of 4km resolution (84*105) covering Atlanta, and original and loop Noah methods are applied to the 4km resolution domain

Results shown for 2008-07-01 ~ 2008-07-14

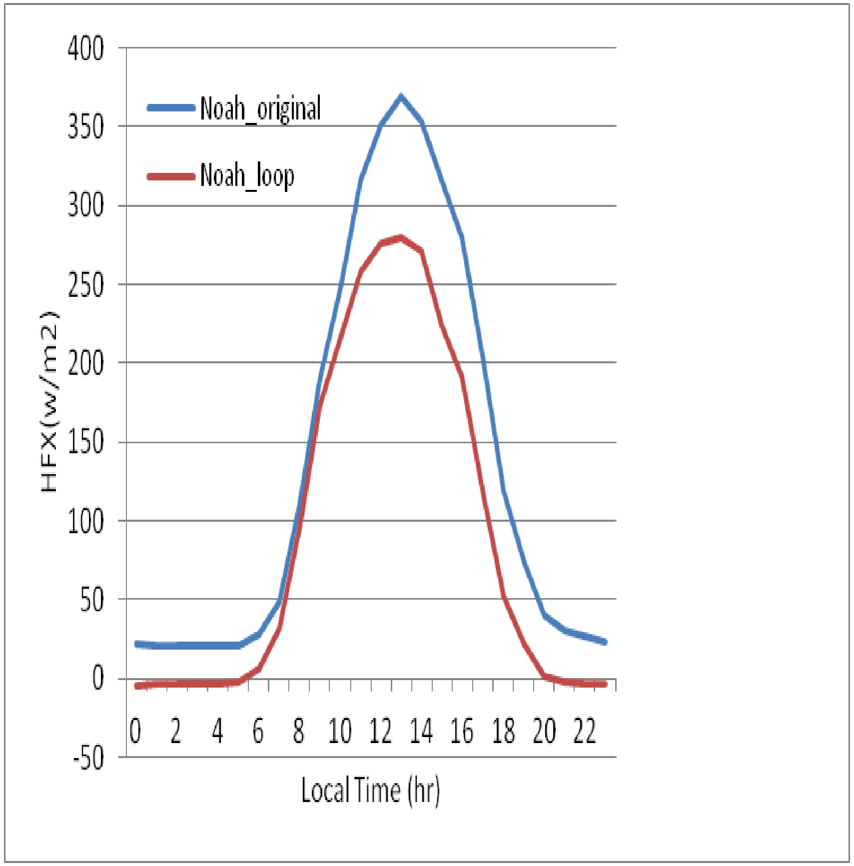


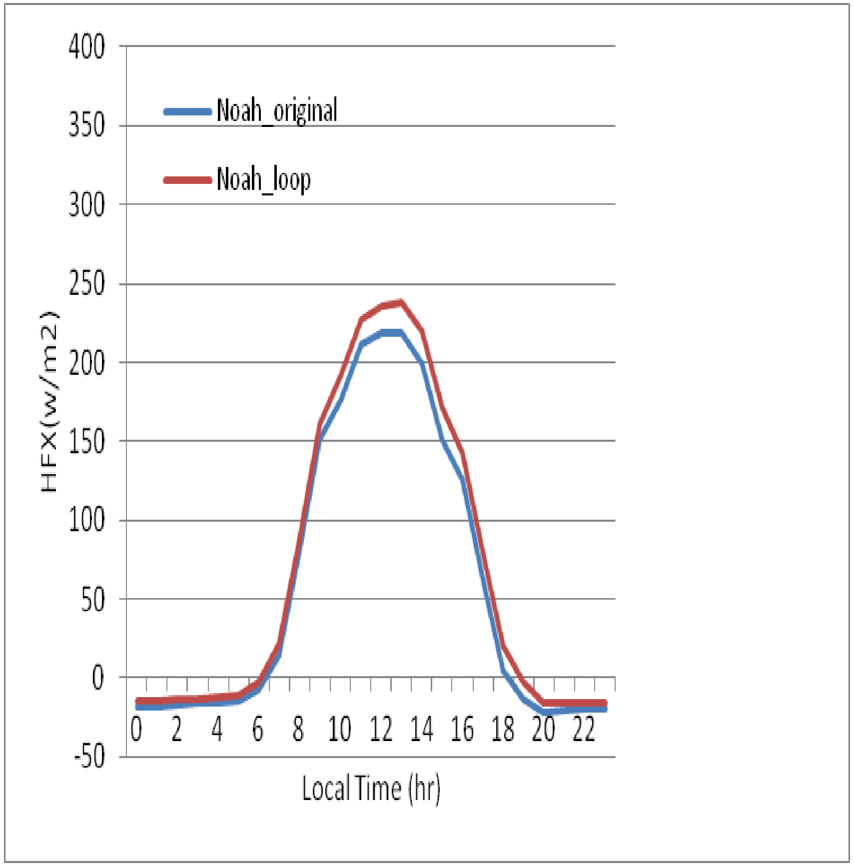


Difference of sensible heat flux (HFX) b/w original and loop Noah method

Averaged diurnal HFX of grids dominated by urban, but with urban fraction less than 60%

Averaged diurnal HFX of grids dominated by agriculture, but with urban fraction greater than 10%

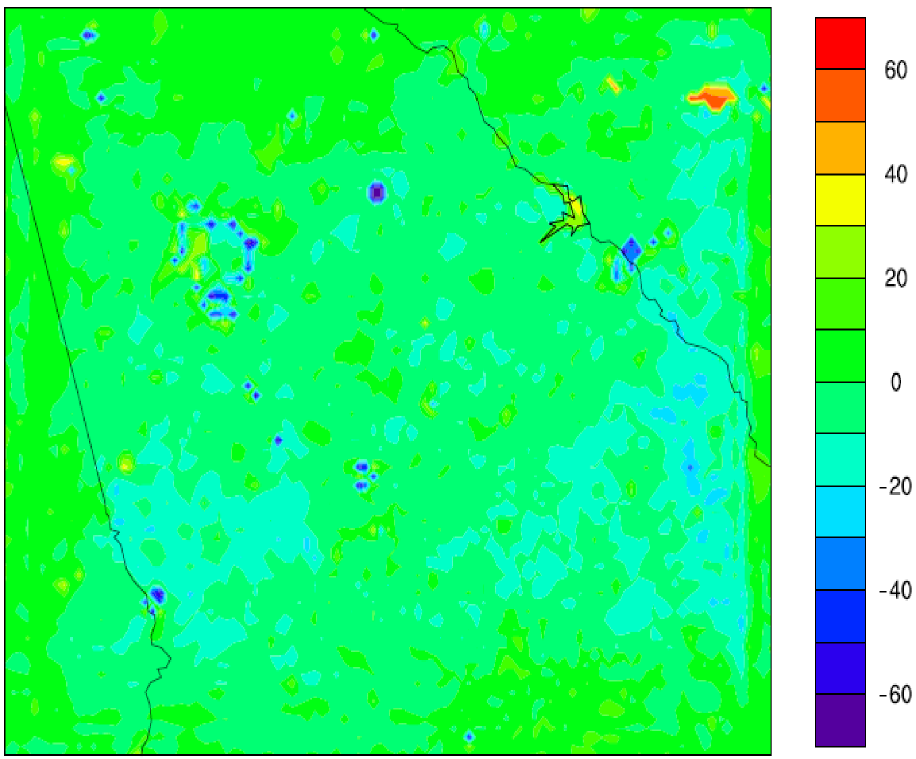




Difference of sensible heat flux (HFX) b/w original and loop Noah method

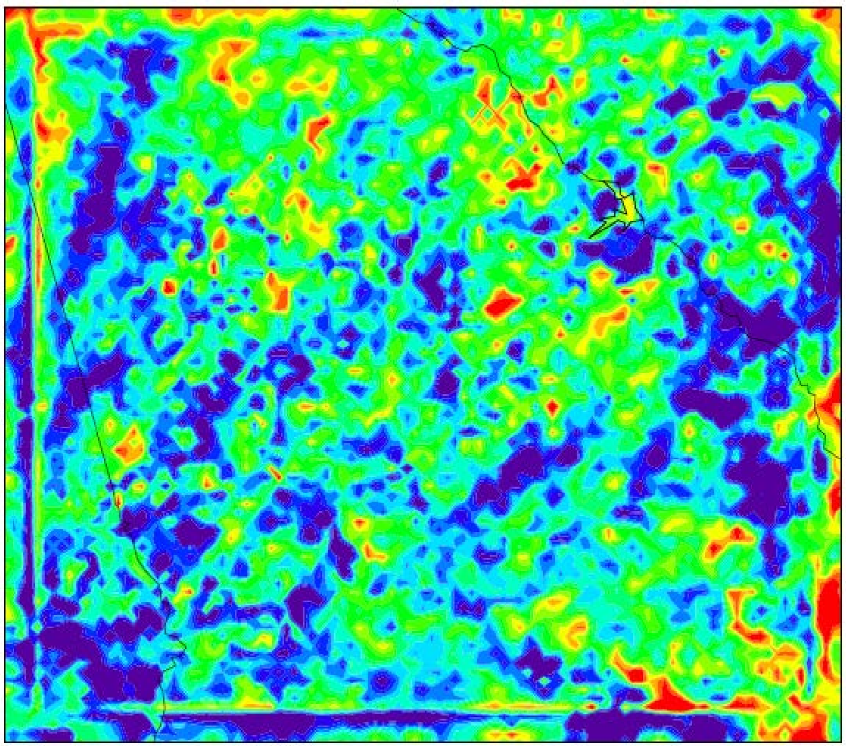
Difference in HFX (w/m²) loop minus original Noah

(UTC 00/local 19:00)



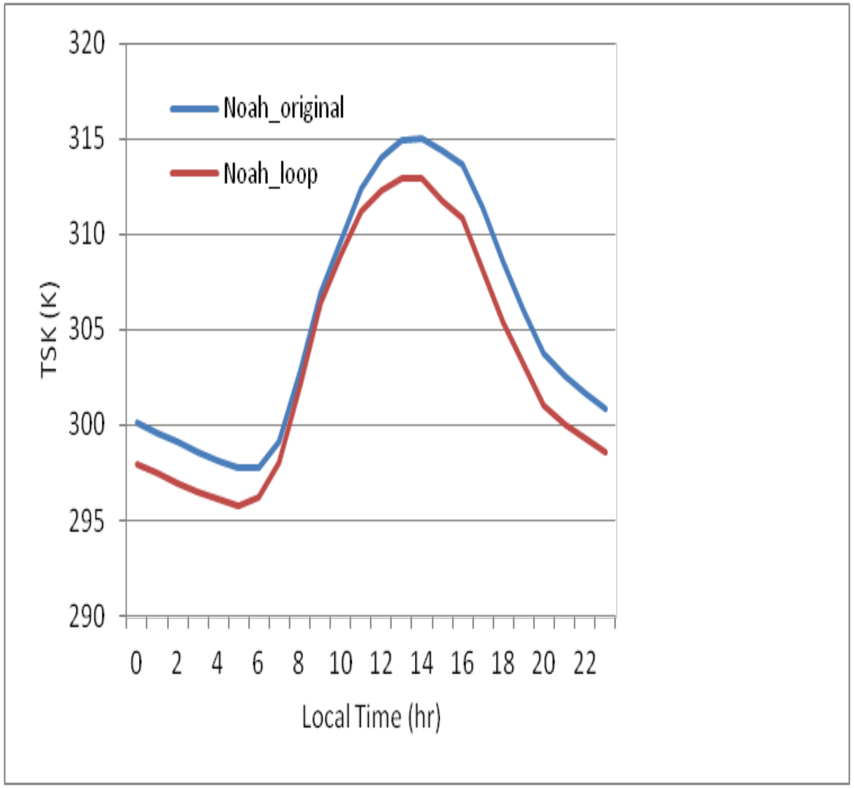
Difference in HFX (w/m²) loop minus original Noah

(UTC 16/local 11:00)

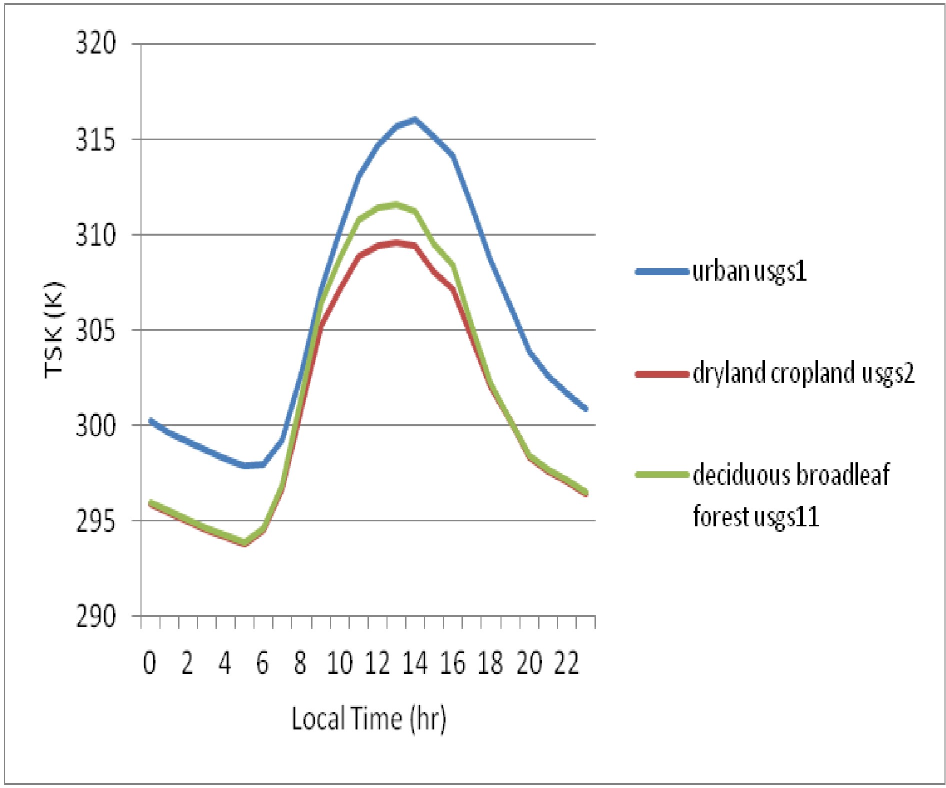


Difference of Skin Temperature (TSK) b/w original and loop Noah method

Averaged diurnal TSK of grids dominated by urban, but with urban fraction less than 60%



Averaged sub-grid diurnal TSK of different land use types for grids dominated by urban, but with urban fraction less than 60%



Energy and Emission Scenario Development

- Brian Keaveny, Climate and Energy Analyst
- Michelle Manion, Climate and Energy Team Lead
- Jason Rudokas, Climate and Energy Analyst
  - NESCAUM Office # 617-259-2000

NESCAUM

Background

- Project goal is to asses the impact of climate-responsive controls on regional air quality.

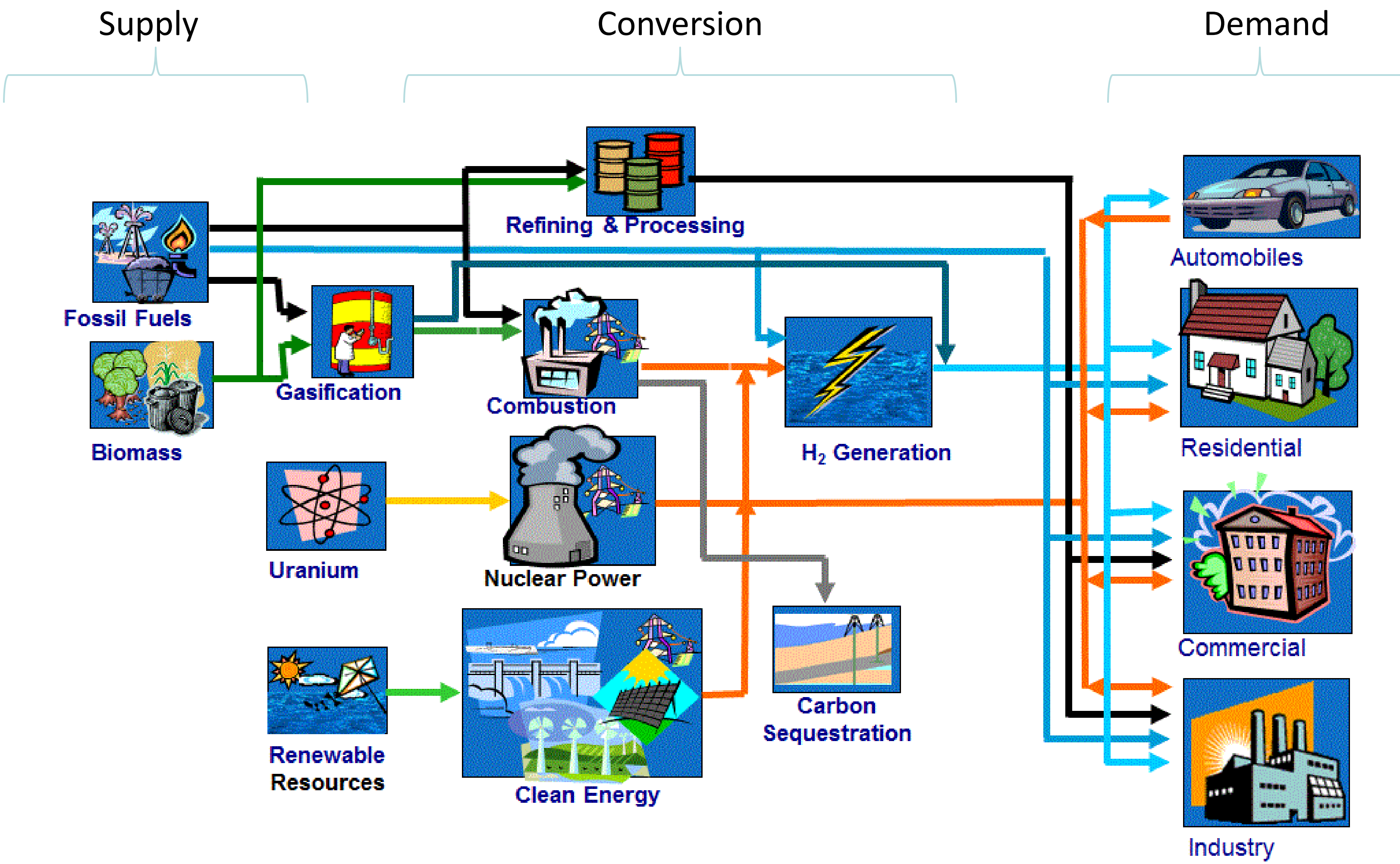
- Policy and technical staff at NESCAUM developing emission control scenarios within an integrated energy and environmental modeling framework.
  - Use MARKAL US9R
    - Identify a range of strategies
    - Comparing about 10 strategies
  - Provide representative set (~3) for detailed CMAQ analysis

- The integrated modeling framework:
  - Provides a baseline (2010 & 2050) reference case projection of air quality and climate outcomes.
  - Examines how alternative technology and policy scenarios impact future (2050) emissions of climate and air pollutants.

US9R Model Overview & Key Features

- Developed at EPA Office of Research and Development (ORD) and released in 2008.
- Bottom-up (i.e., technology-driven) regional model of the nation's energy supply and demand infrastructure.
- Model Configuration:
  - Timeframe: 2000 – 2055, solves in 5 year steps
  - Emissions Coverage: CO_2, NO_x, SO_2, PM_{10}, $PM_{2.5}$, VOC, CO
  - Spatial Domain: 9 US Census Divisions
  - Calibration: EIA, Annual Energy Outlook 2008
  - Model Logic: Linear Programming, Cost Optimization

Simplified Depiction of US9R Model Database

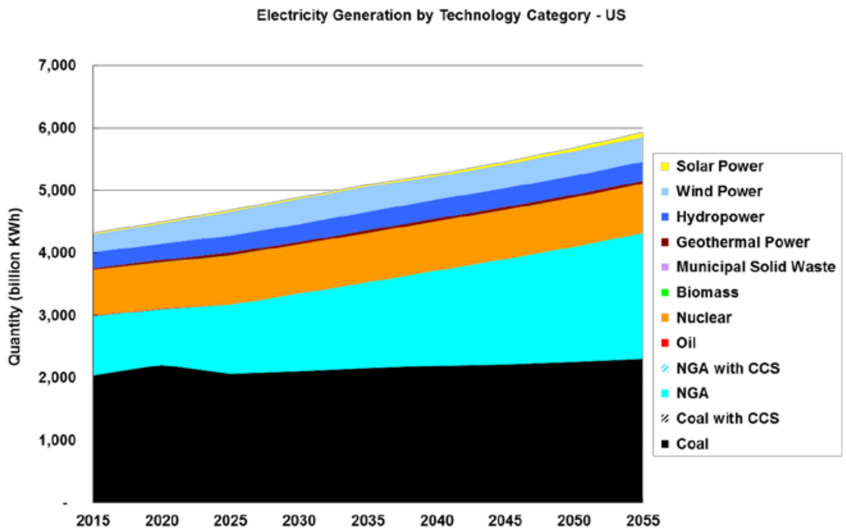


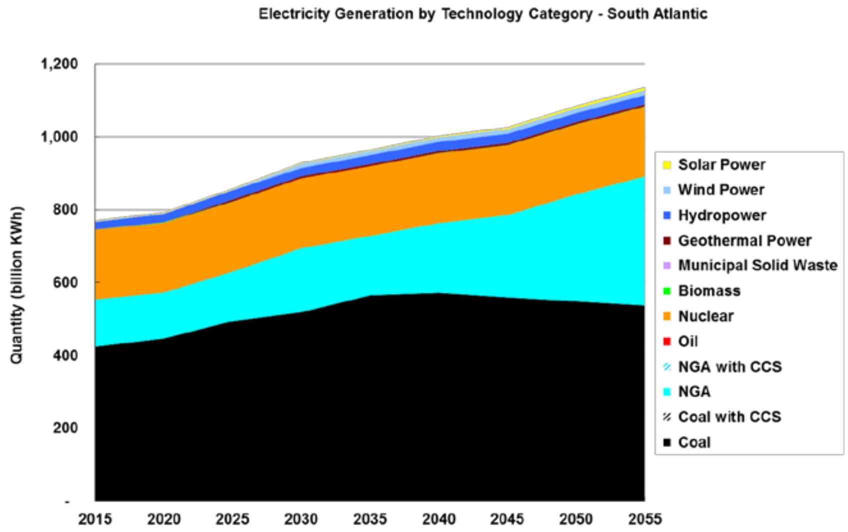
Reference Case: Policy Assumptions

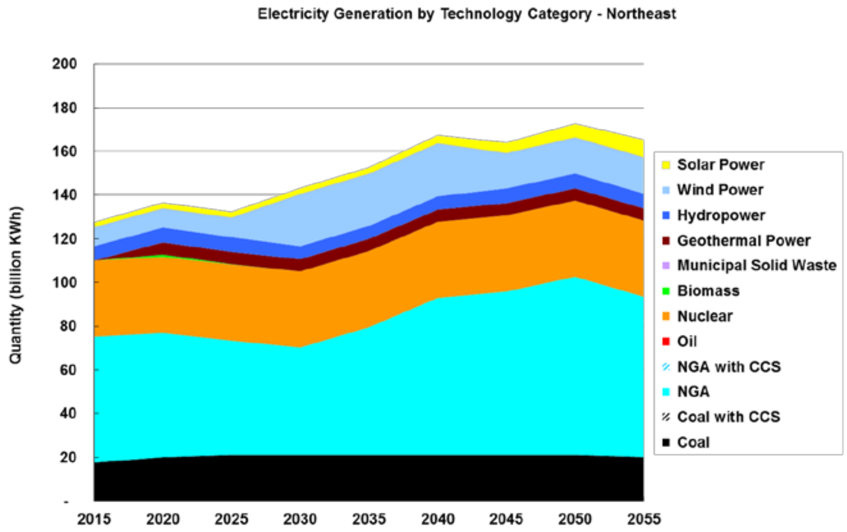
- Clean Air Act Title IV SO_2 and NO_x power sector limits
- Energy Independence and Security Act 2007
  - Renewable Fuel Standard (RFS) Fuel Mandate (36 bgy by 2022, 21 bgy advanced biofuel / 15 bgy corn based)
- Cross State Air Pollution Rule (CSAPR) rule (replacement for Clean Air Interstate Rule (CAIR))
- Aggregated state Renewable Portfolio Standards (RPS) standards by region
- Federal Corporate Average Fuel Economy (CAFE) standards as modeled in the Annual Energy Outlook (AEO) 2010
- No regional carbon policies at this time
- No efficiency or demand response programs
- Update to include MATS

Reference Case Electricity Generation

- Reminder: These are reference case results.
- South Atlantic generation profile is much more similar to the national average than to the Northeast.
- Wind is more favorable in the Northeast since in this region, wind availability is slightly more aligned with peak demand periods.
- In all regions, natural gas generation shares increase over time.

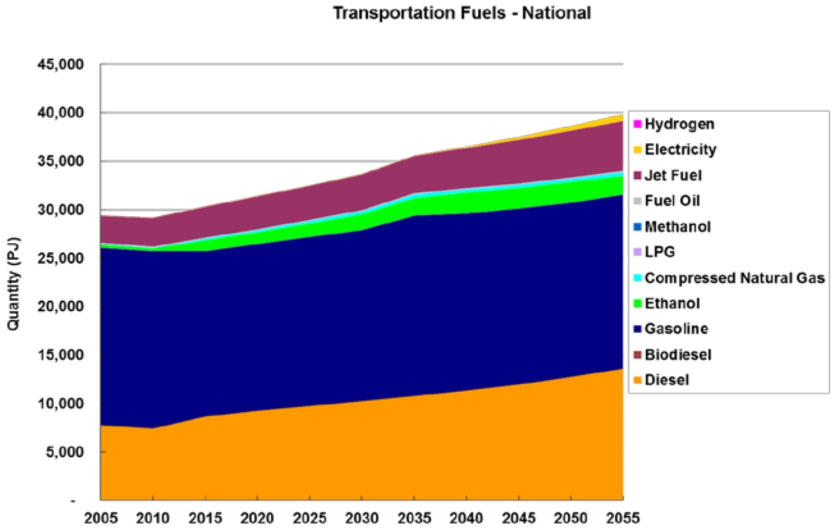


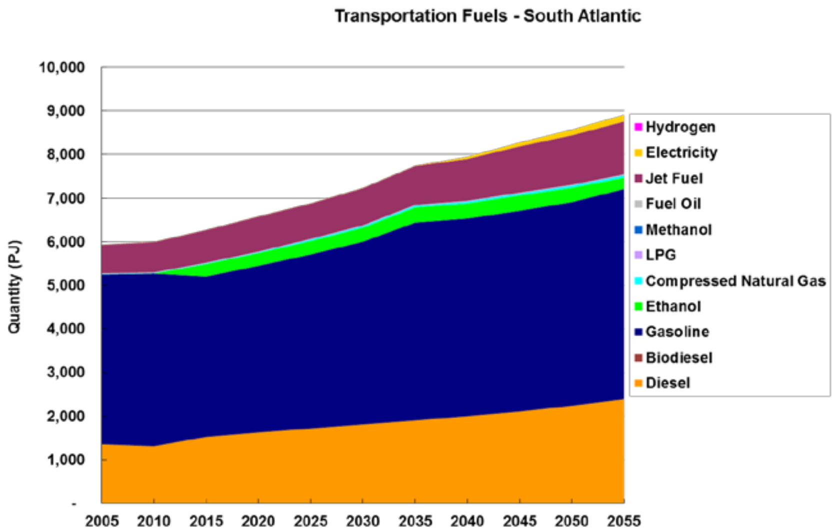


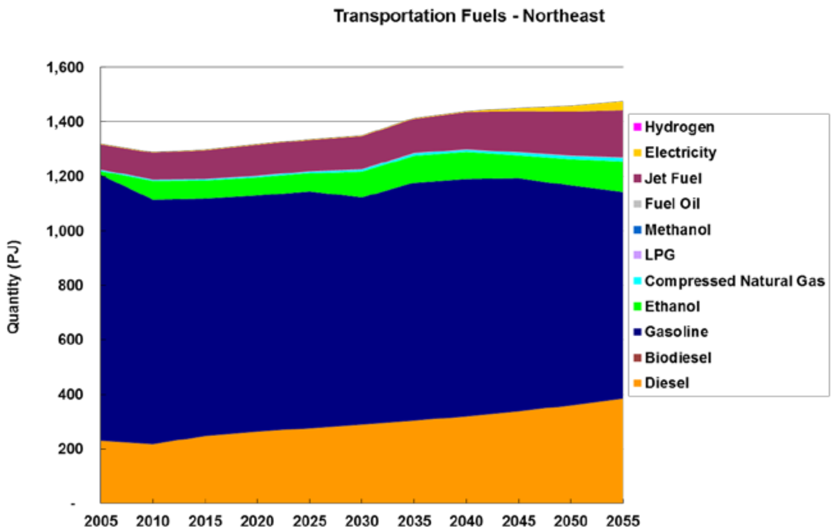


Reference Case Transportation Sector Energy Consumption

- Reminder: These are reference case results
- Ethanol consumption, mostly for E85 and higher blends, increases to meet the fuel volume requirements of the RFS.
- Increased diesel consumption mostly associated with high efficiency medium and heavy-duty diesel vehicles.

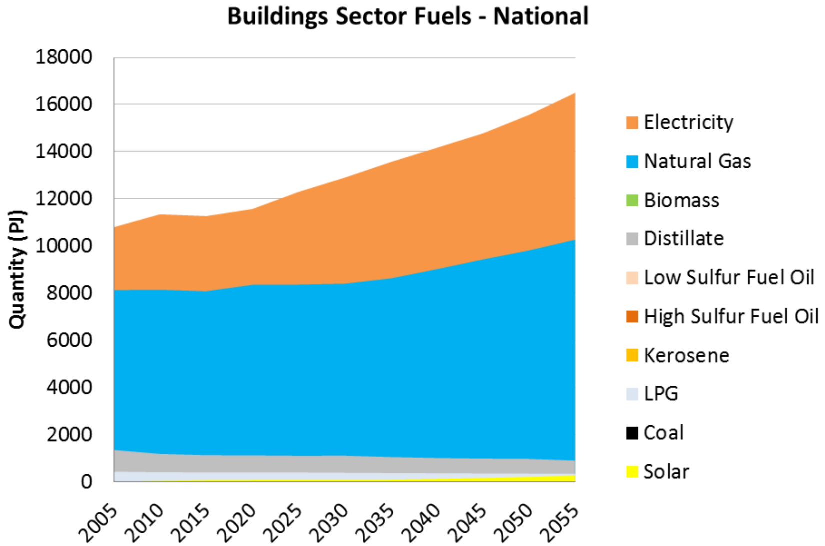


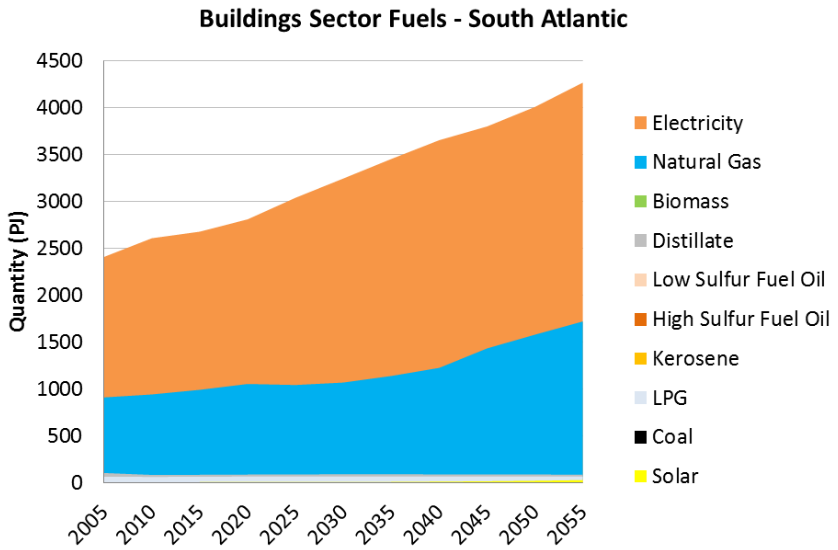


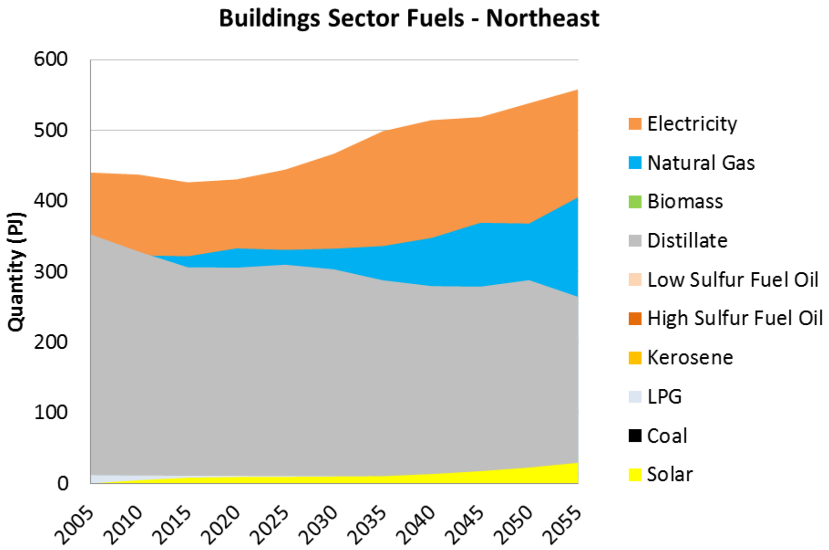


Reference Case Commercial & Residential Building Energy Consumption

- Reminder: These are reference case results
- South Atlantic buildings sector energy consumption trends are more closely aligned with the national average.
- The Northeast moves towards natural gas, but distillate fuel remains the dominant heating fuel.
- Buildings consume small amounts of renewable energy without targeted policies to overcome high upfront investment costs.

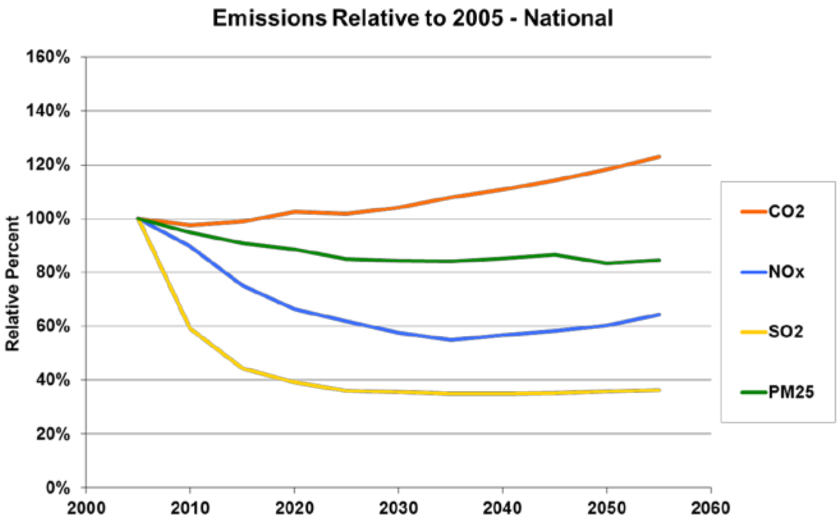


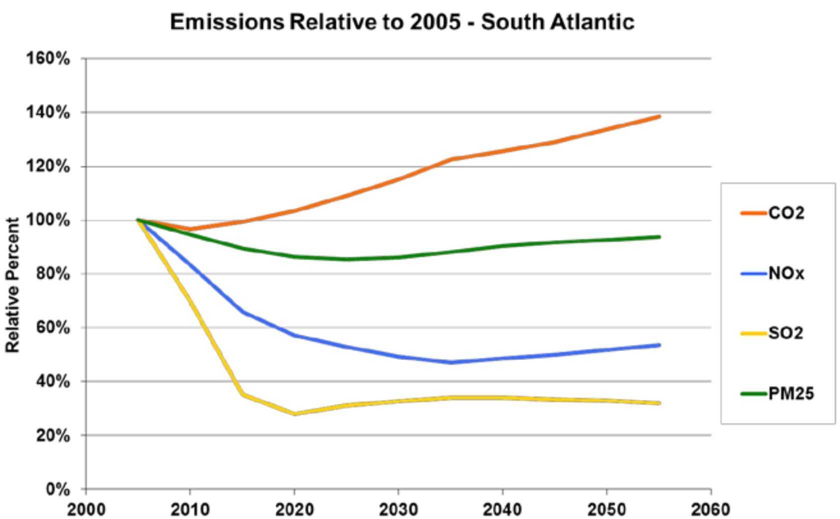


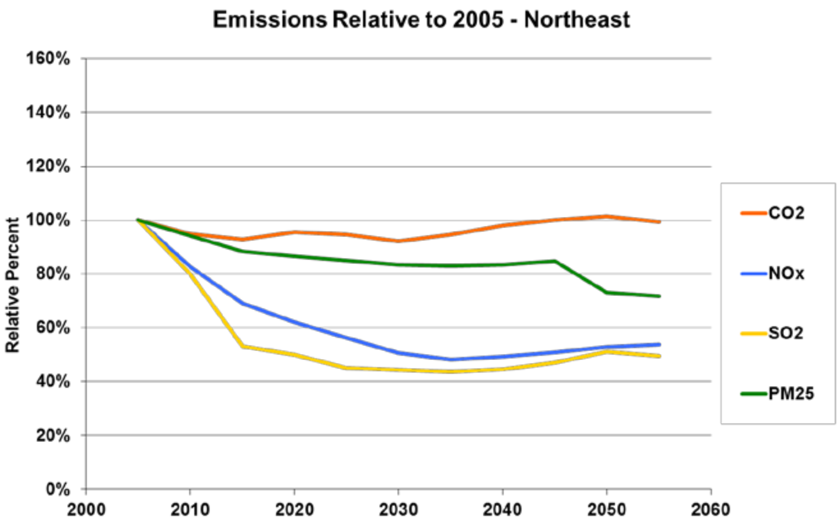


Reference Case Economy wide emission trajectories

- **South Atlantic and National reliance on coal for electricity generation leads to CO2 growth rates of over 20% by 2055.**
- **CO2 trend in the Northeast is relatively flat over the modeling timeframe.**
- **Criteria pollutants experience declining rates of growth in the short to mid-term mostly due to title IV power sector limits and CAFE standards modeled in AEO 2010.**
- **The divergence between CO2 and criteria pollutant growth trends suggests a need to explore & develop air quality and climate goals simultaneously.**







Emission Control Scenarios Under Development

Three alternative emission control scenarios targeted at the regional and national level for detailed CMAQ analysis:

- Clean Transportation Scenario
  - Aggressive deployment of alternative fuel light-duty vehicles.
    - Focus is on electric vehicles and CNG vehicle deployment.

- High Biomass Potential Scenario
  - Regional Renewable Portfolio Standards (RPS) with aggressive biomass carve-outs.
  - Higher rates of reforestation
    - Motivation for our Southeast reforestation research

- National Carbon Tax
  - Application will be economy-wide and value will escalate over time.

Impacts of Future Forest Management Practices on Air Quality

- Future forest management practices being assessed
  - Reforestation: Use of forest biomass for alternative fuel production (cellulosic ethanol biofuel)
    - Increased forest area will impact climate and emissions
  - Prescribed burning frequency scenarios
  - Forest growth responding to higher temperatures and CO_2

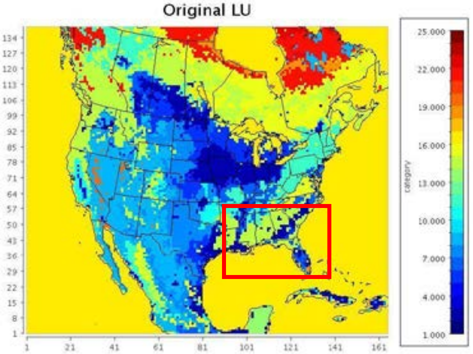
Reforestation Impacts on Temperature

Simulation period: 2050

Two cases:

-SE_for Convert all cropland to forest

-SE_crop Convert all forest to cropland



SE_crop SE_forest

1	'Urban and Built-Up Land'
2	'Dryland Cropland and Pasture'
3	'Irrigated Cropland and Pasture'
4	'Mixed Dryland/Irrigated Cropland and Pasture'
5	'Cropland/Grassland Mosaic'
6	'Cropland/Woodland Mosaic'
7	'Grassland'
8	'Shrubland'
9	'Mixed Shrubland/Grassland'
10	'Savanna'
11	'Deciduous Broadleaf Forest'
12	'Deciduous Needleleaf Forest'
13	'Evergreen Broadleaf Forest'
14	'Evergreen Needleleaf Forest'
15	'Mixed Forest'
16	'Water Bodies'

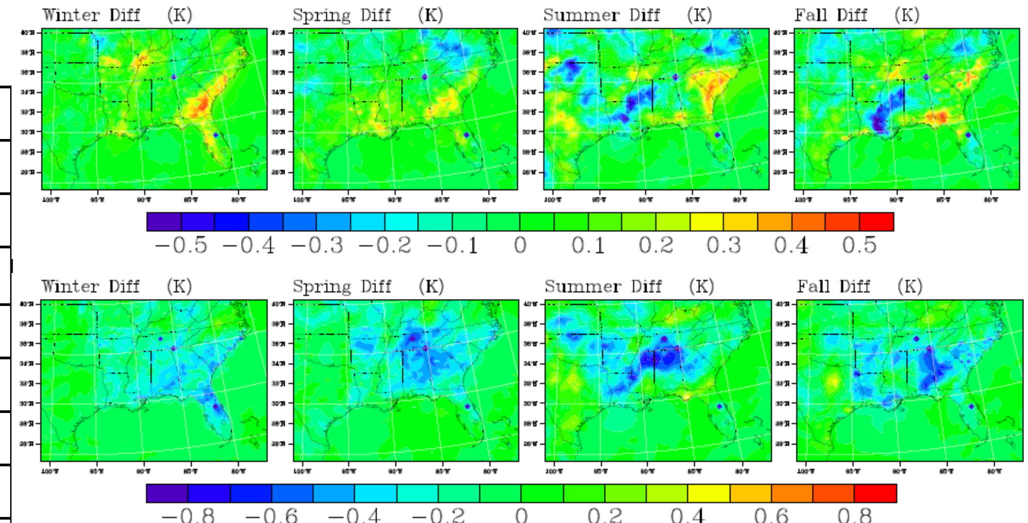


Figure Temperature difference zoomed in for the SE_foreest (top) and SE_crop (bottom) cases

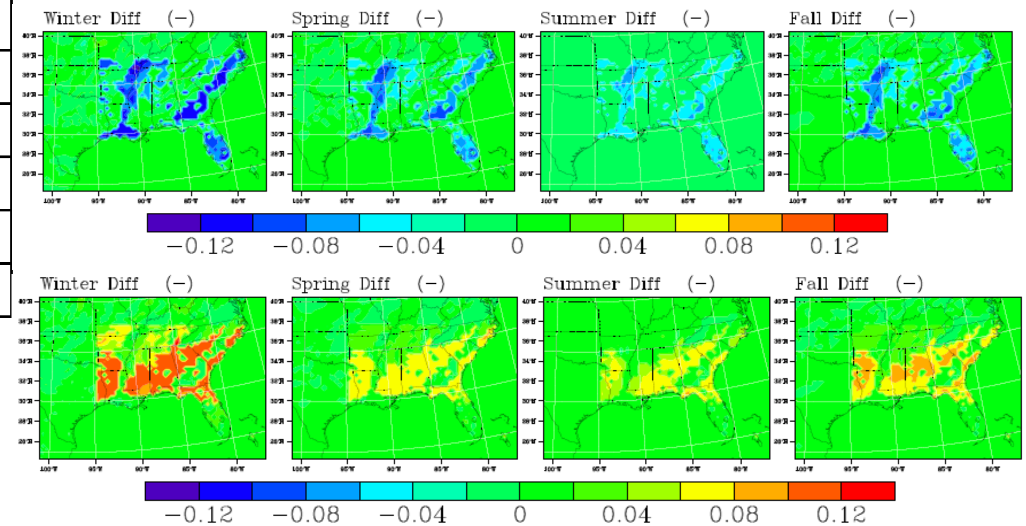


Figure Albedo difference for the SE_forest (top) and SE_crop (bottom) cases

Future Work

- Loop NOAH
  - –Loop Noah method effective for studying the impact of the fine-scale land use modification on regional or local climate.
    - •Tests of more periods are underway
  - –Sub-grid information provided by loop Noah method may further be used for health-related studies.
- Reforestation and Forest Management Practice
  - –Prepare biogenic emissions for the different landuse scenarios and perform air quality simulations
- Air quality modeling with sensitivity and uncertainty analysis
  - –Conduct air quality modeling of future emissions scenarios
  - –Sensitivity and uncertainty analysis
- Happy to share modeling products (loop Noah, CMAQ sensitivity tools, fields) with others

Thanks for your attention and support

- Thanks, also, to Prof. Brian Stone
  - Urban land use policy and climate change analysis

Outcomes and Benefits

- Provide quantitative results as to how economic/energy modeling-derived approaches to mitigate climate forcing emissions will also impact air quality in the eastern US
- Assess impacts of alternative Southeastern forest-management practices
- Assess regional climate and air quality impacts of Georgia's forest biomass fuel production policies
- Investigate the related uncertainties and sensitivities
- The results will be constructed for use in decision support analyses, linking energy paths, controls, emissions, impacts and costs

Additional Benefits

- Further development of the capabilities of the computational tools.
- Comprehensive analysis of the downscale techniques
- Development of the scientific foundation for protecting air quality

Also: Very happy to work with others and provide our data/models

US9R Mapping to SCC Codes

Sector	MARKAL Technology Group	Corresponding SCC codes
Electric	Coal boilers	10100000, 2101000000
	Gasified coal combined cycle turbines	10100000, 20100000
	Biomass combustion	10100000, 20100000, 2101000000
	Diesel turbine, combined-cycle, and CHP	10100000, 20100000, 2101000000
	Natural gas turbine, combined-cycle, and CHP	10100000, 20100000, 2101000000
	Residual fuel oil boilers	10100000, 2101000000
	Landfill gas turbines	10100000, 20100000, 2101000000
	Waste-to-energy	10100000, 10200000, 10300000, 2101000000
Industrial	All except refineries	10200000, 10500000, 20200000, 2102000000, 2390000000, 2199000000
	Refineries	2306000000
Commercial	All combustion	10300000, 10500000, 2103000000, 2199000000
Residential	All combustion	2104000000
Transportation	Airplanes	2275000000
	Buses and heavy duty trucks	2201070000, 2230070000
	Light duty vehicles	2201001000, 2201020000, 220140000, 2230001000, 2230060000
	Off-highway	2260000000, 2270000000
	Rail	2285000000
	Shipping	2282000000, 2280001000, 2280002000, 2280003000, 2280004000

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Limitation of “Loop” Noah

In each loop over all landuse categories, domain is assumed 100% covered by certain category,i, so corresponding green vegetation fraction(vegfrac(i)) is needed.

step1: 30s resolution USGS data used to get domain resolution of 1km.

step2: vegfrac(i)=average(grids with landuse fraction(i) greater than 99%)

Limitation: vegfrac(i)=f(i,t) but not x or y

Therefore, “loop” Noah method applies to the situation where simulation domain is small and no large spatial variation of vegfrac is expected

Fig.a Urban land use fraction (USGS) of northern Georgia

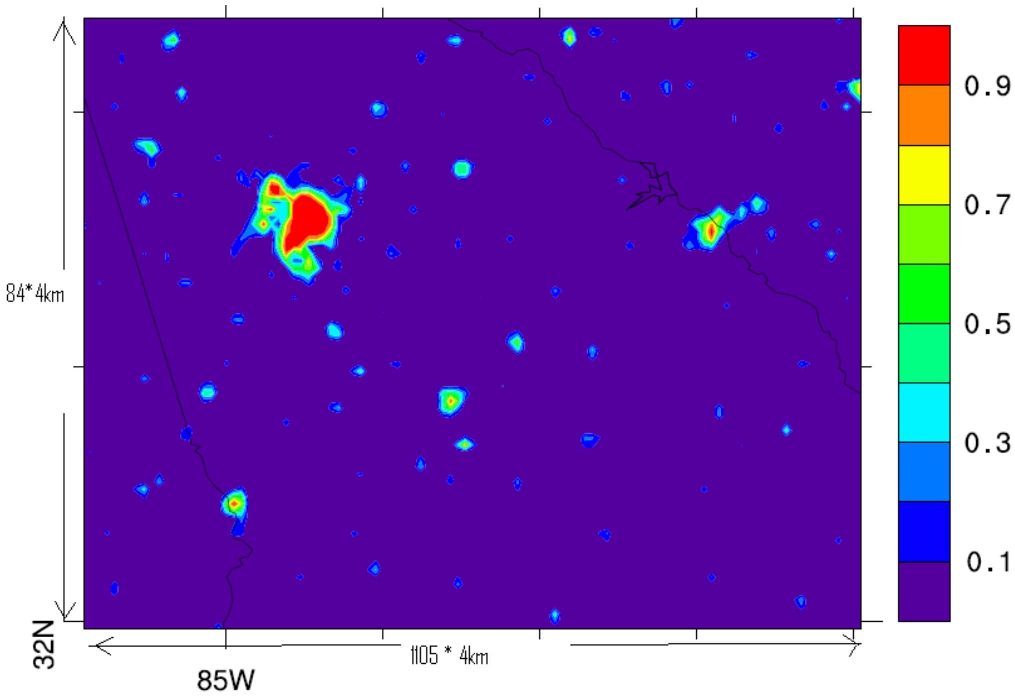
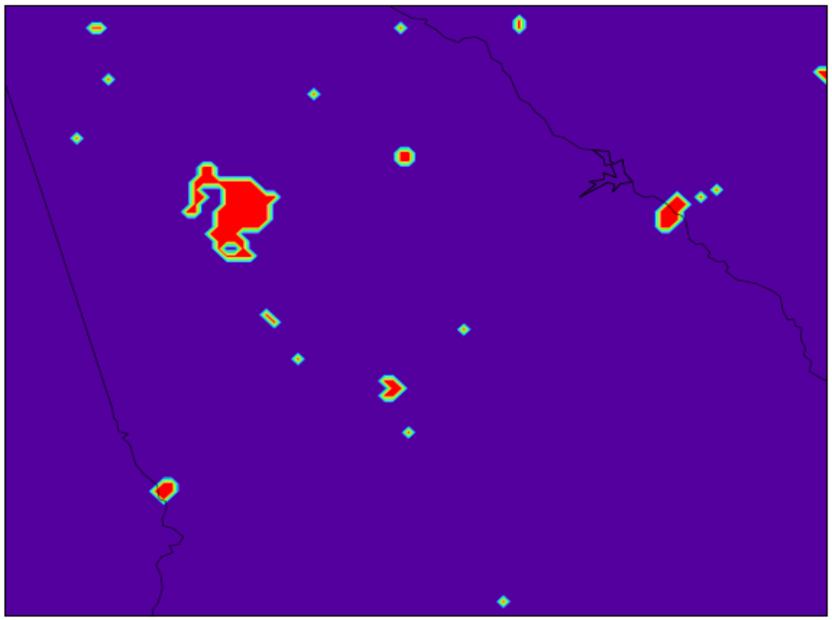


Fig.b grids dominated by unban of northern Georgia



type2: use mixing parameters, which can reflect the impact of different land use types to some extent, but may have problem because of the non-linearity of the system

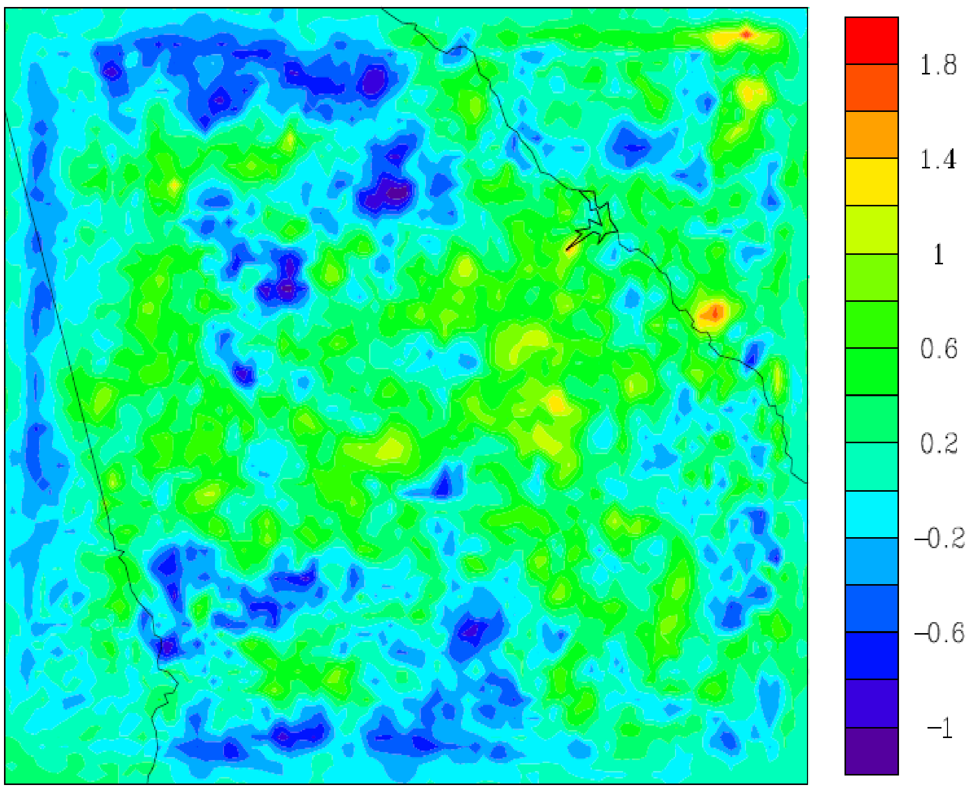
Current LSMs in WRF can barely satisfy our need to reflect the impact of land use change at fine scale.

- Goal: take into account the contributions from all land use types as much as possible without the cost of ultra-high resolution simulation

Difference of surface wind speed b/w original and loop Noah method

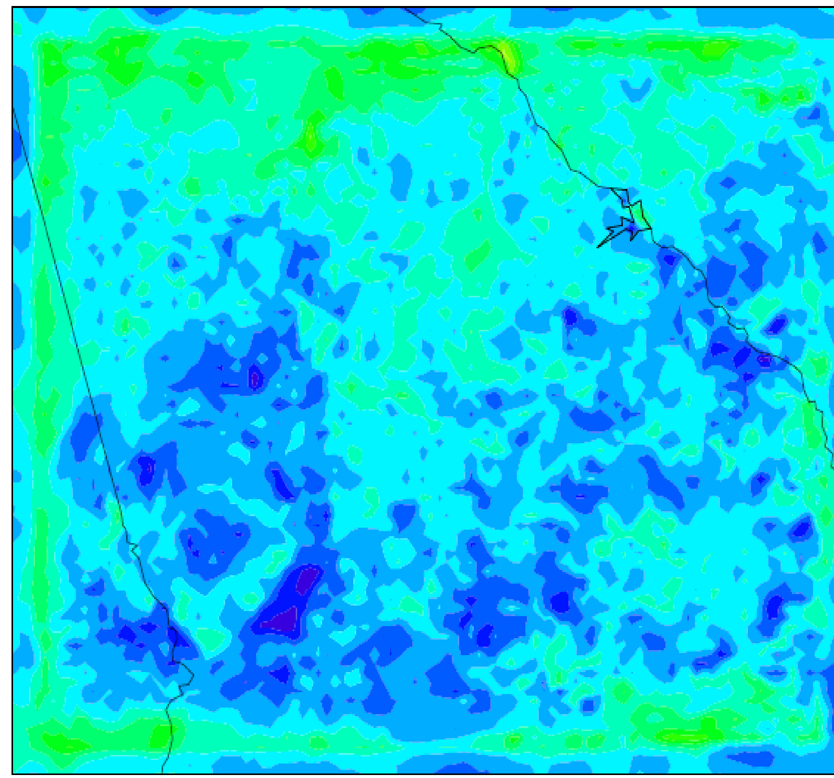
Difference in wind speed (m/s) loop minus original Noah

(UTC 00/local 19:00)



Difference in wind speed (m/s) loop minus original Noah

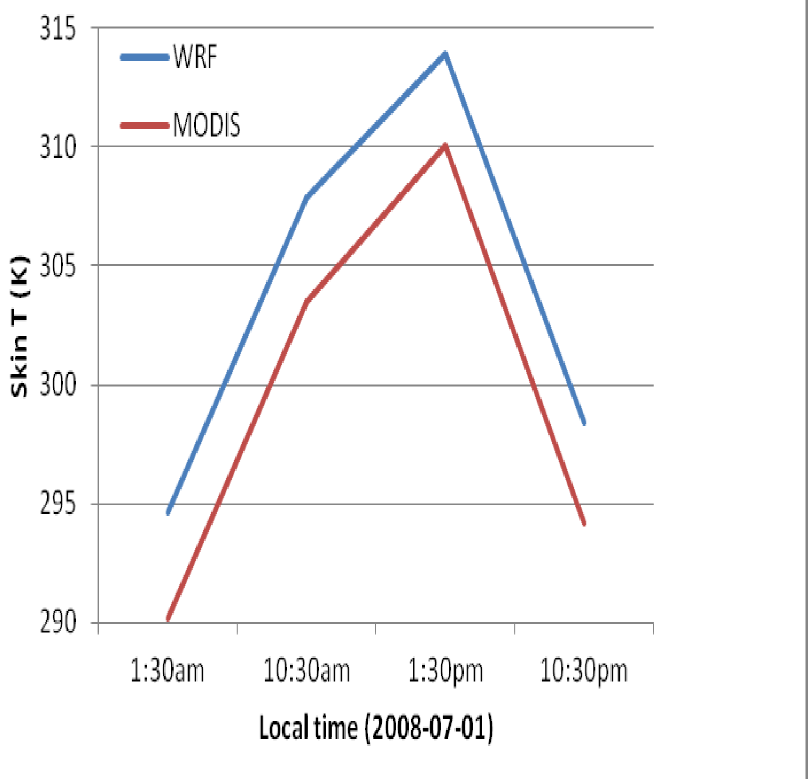
(UTC 16/local 11:00)

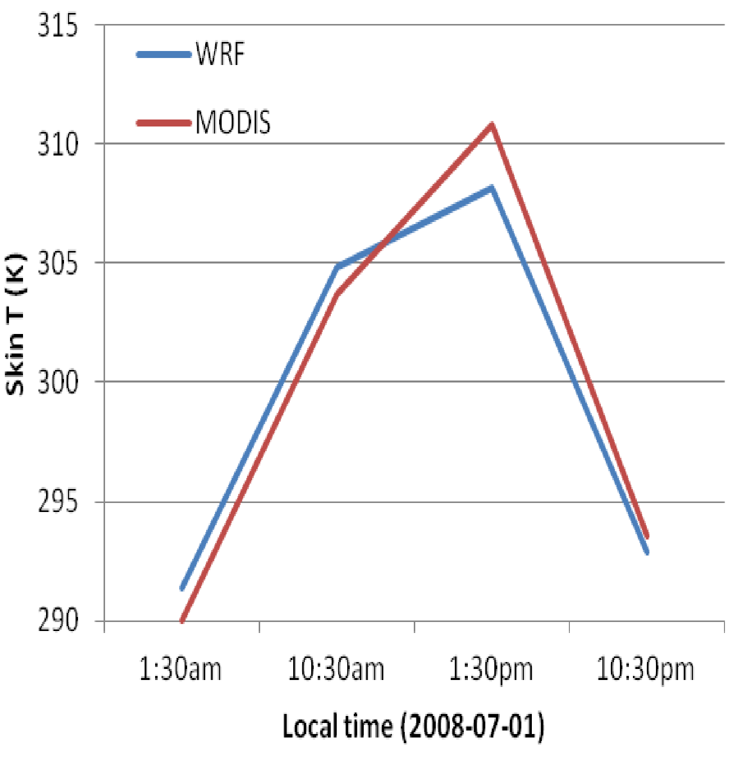


Comparison of sub-grid TSK with MODIS data

Fig.a Comparison b/w 1km resolution MODIS data and averaged sub-grid urban TSK of 4km resolution grids dominated by urban

Fig.b Comparison b/w 1km resolution MODIS data and averaged sub-grid agriculture TSK of 4km resolution grids dominated by urban





Developing Emission Growth Factors: Background

- Emissions growth factors were developed based on the control scenarios modeled in the US9R energy model.
- The growth factors are used as inputs to the air quality modeling being preformed at Georgia Institute of Technology as part of the larger climate and air quality assessment.
- US9R emission growth factors were mapped into SCC based growth factors to accommodate the development of air quality modeling inputs.

NESCAUM

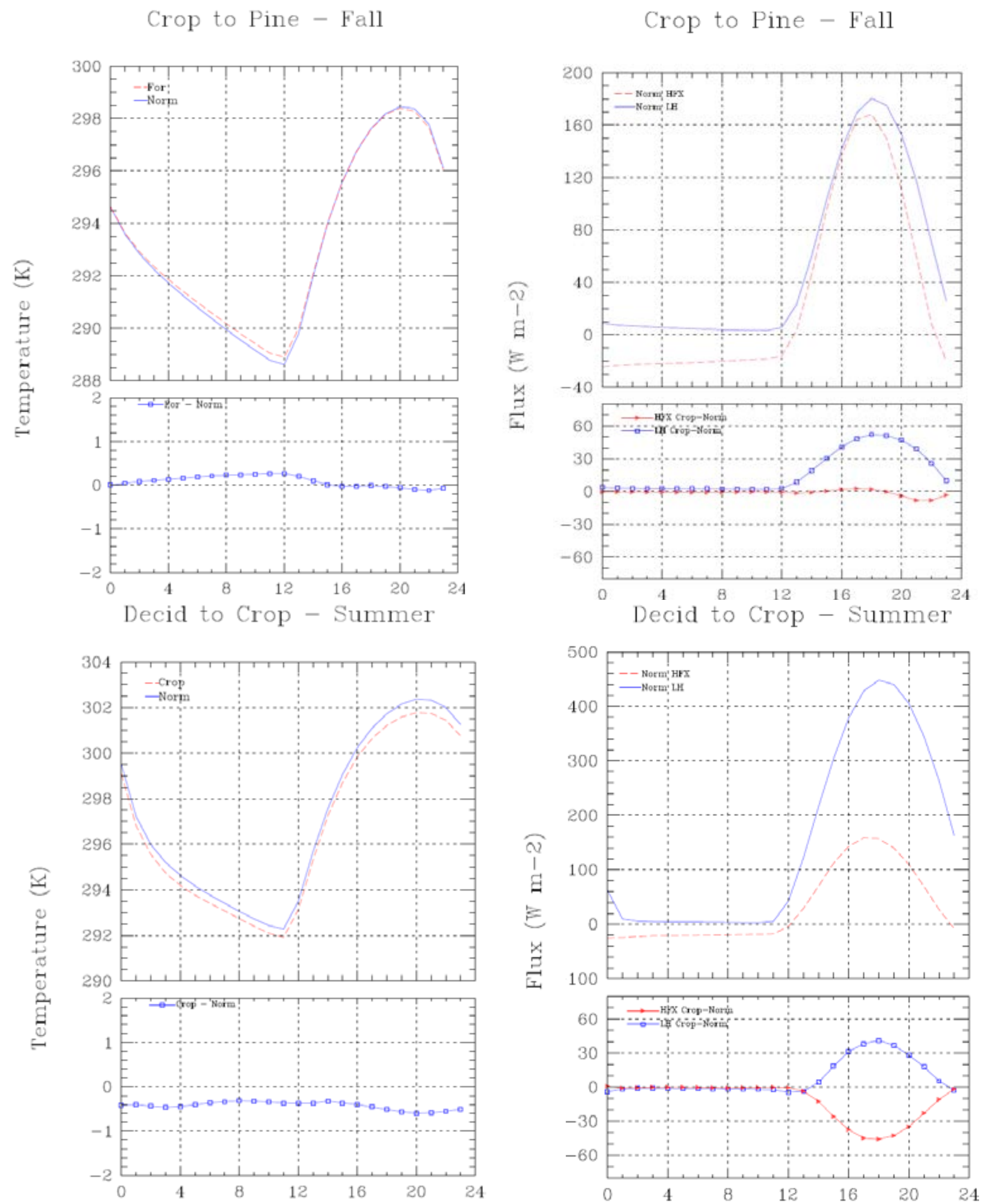
Emission Growth Factor Development Process

1. The US9R model is run to develop a reference scenario and a number of potential “control” (i.e., policy) scenarios.
2. Emissions for each pollutant are summed up for each US9R technology group, region and year.
3. The aggregated US9R emissions are allocated to a number of SCC codes based on a mapping table relating US9R technologies to appropriate SCC codes.
4. Multiplicative emissions growth factors are calculated for each pollutant and SCC code.
5. The growth factors are organized into a file written for standard SMOKE input processing.

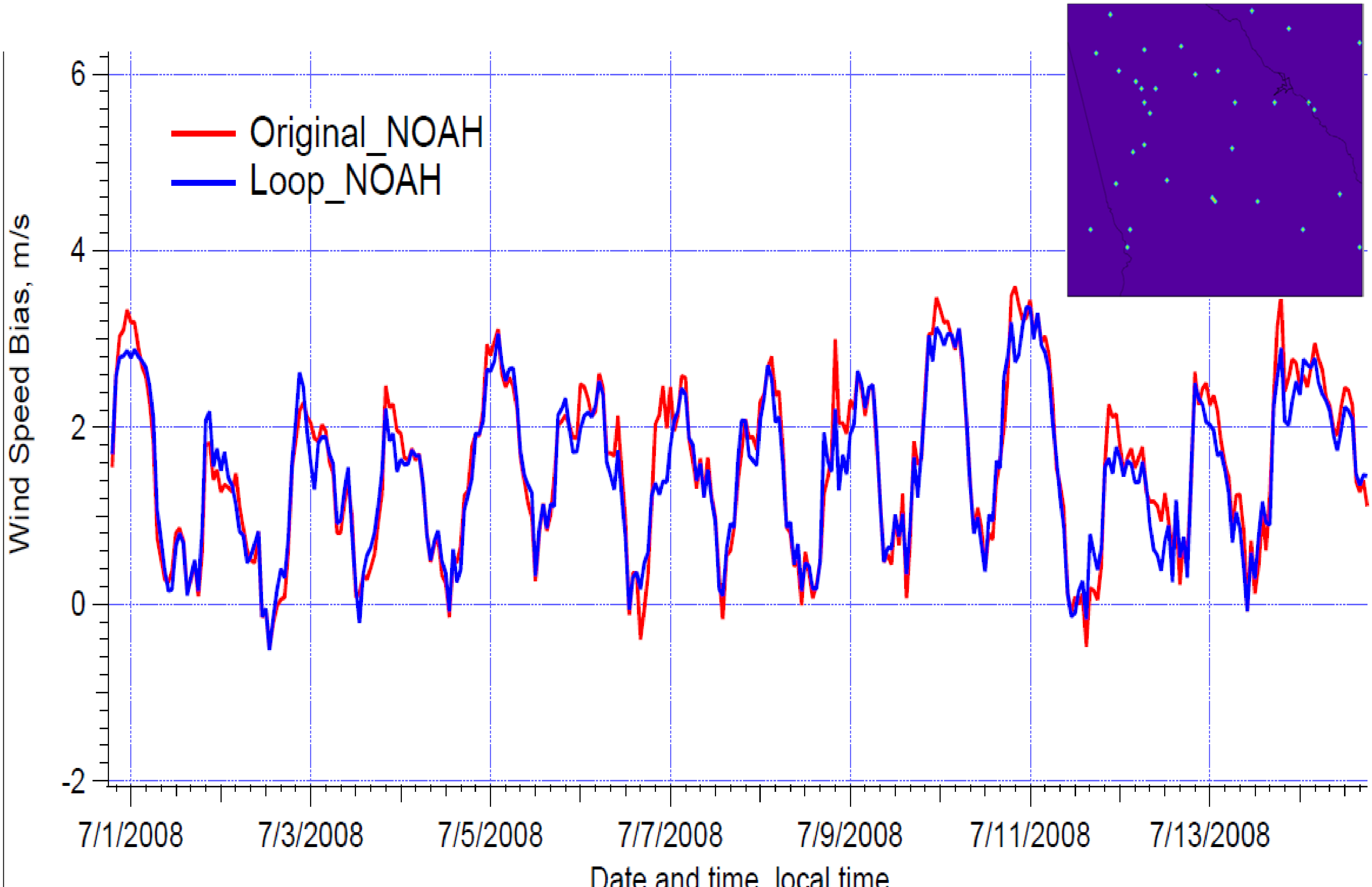
NESCAUM

Preliminary Results: Reforestation

- Average daily Temperature and Heat Flux differences
- Dry cropland converted to Pine forest (top)
  - Not much difference here
  - Vary with location (Carolinas vs. Louisiana)
- Deciduous Forest converted to cropland (bottom)
  - Cooler by almost 1 degree at hottest time of day
  - More latent heat
    - Higher leaf area in the crops
  - Less sensible heat
    - Higher crop albedo



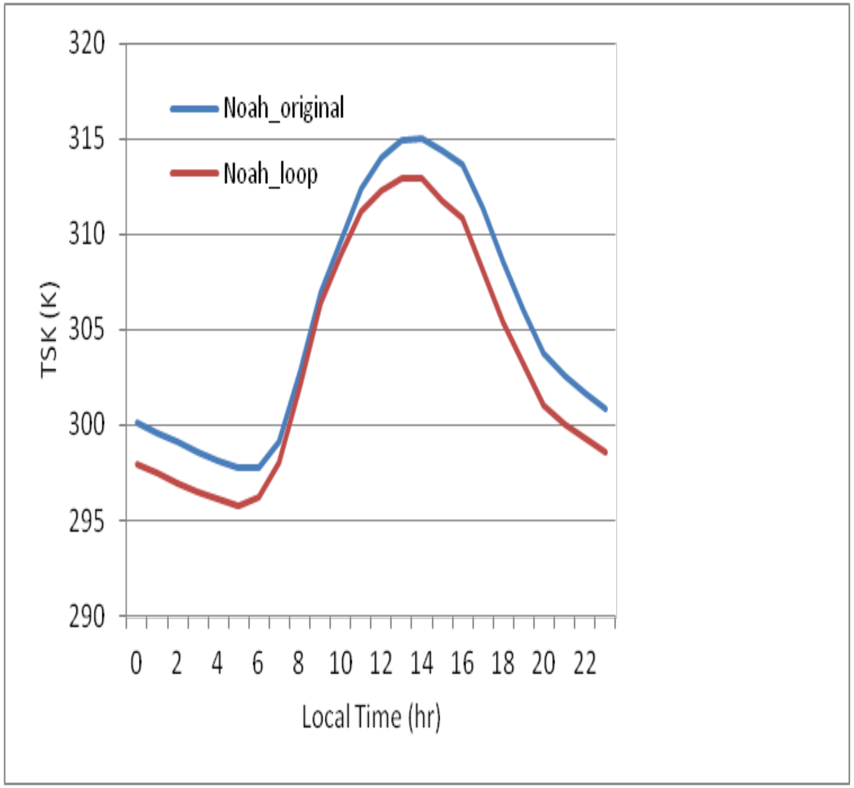
Loop Noah results vs. observation over the Southeast



Station Locations

Difference of Skin Temperature (TSK) b/w original and loop Noah method

Averaged diurnal TSK of grids dominated by urban, but with urban fraction less than 60%



Averaged sub-grid diurnal TSK of different land use types for grids dominated by urban, but with urban fraction less than 60%