Coupling Global and Regional Model Predictions of the Interactions of Aged Aerosols and Mixed-Phase Clouds in the Arctic

Jerome Fast, Po-Lun Ma, Richard Easter, Balwinder Singh, and Phil Rasch
Pacific Northwest National Laboratory, Richland, Washington

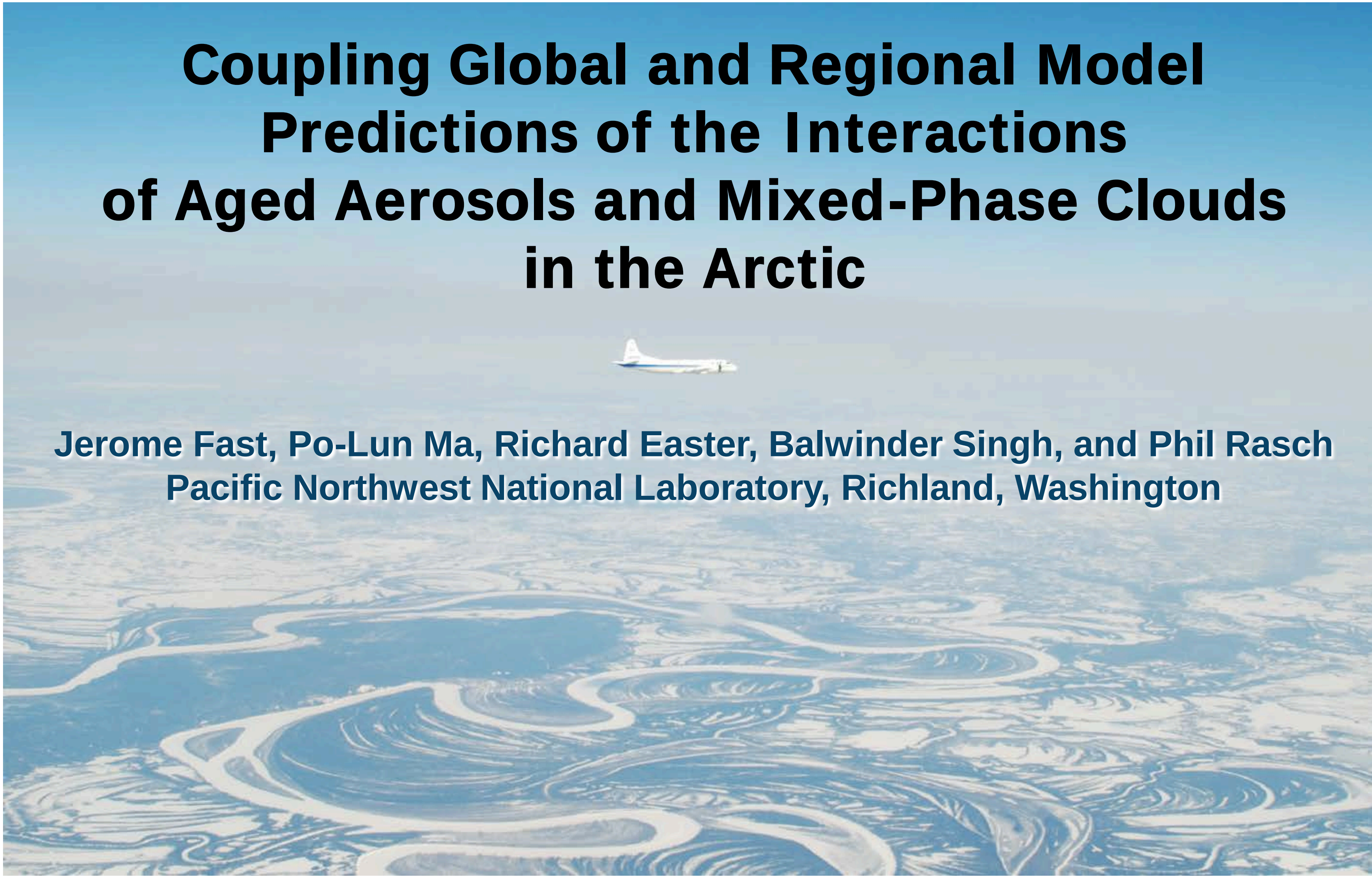


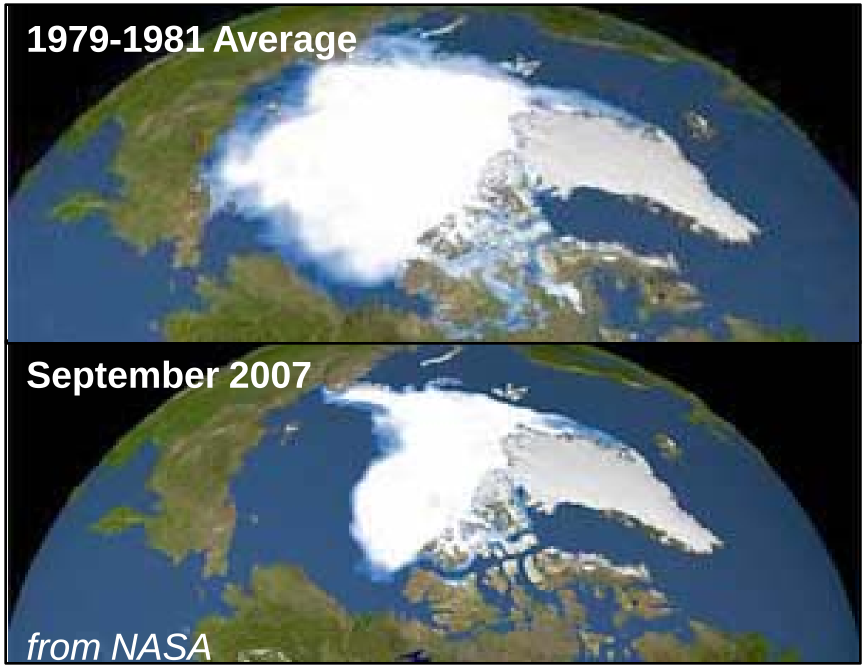
Photo: NASA P3-B

Climate and Earth System Modeling Meeting
September 18 - 22, Washington DC

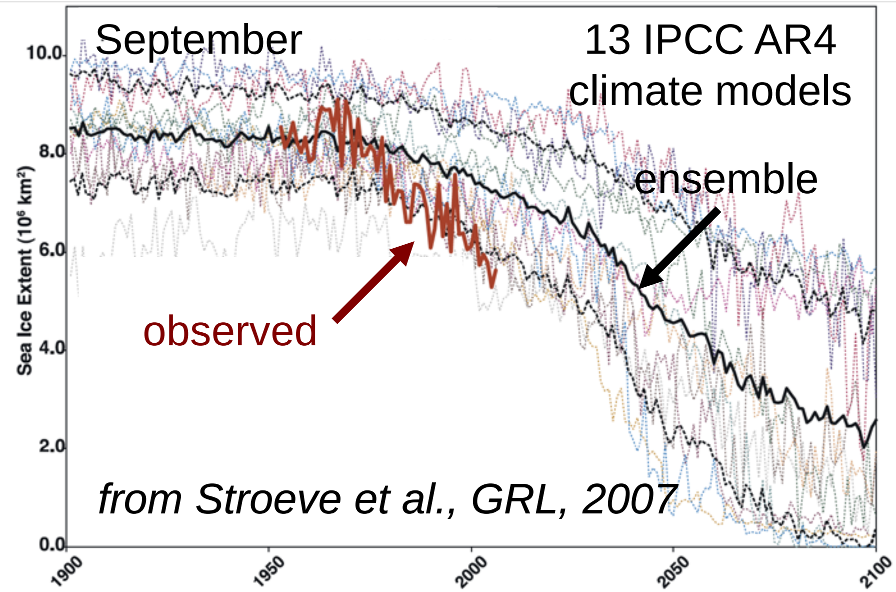
Pacific Northwest
NATIONAL LABORATORY

Science Motivation

Shrinking Arctic Ice Cover



Climate Models Do Not Predict the Rapid Loss of Ice



Sources of Atmospheric Model Uncertainties:

- Estimates of emissions
- Transport of aerosols into Arctic
- Treatment of BC on and in ice/snow
- Cloud-aerosol interactions, scavenging
- Others?

Issues of resolution and parameterizations

Pacific Northwest
NATIONAL LABORATORY

Modeling Approach Motivation

- CAM will be run at higher spatial resolution in the future, but the ***performance of the current suite of physics modules at those scales is not known***

- Rapid development and evaluation of the next generation suite for CAM requires the ability to ***isolate processes*** as well the ability to test parameterizations across a range of scales

- Relatively ***little interaction*** between the cloud-resolving / mesoscale and global scale communities
  - Models optimized for different purposes
  - Lessons learned are not necessarily shared

global models becoming global mesoscale-resolving models

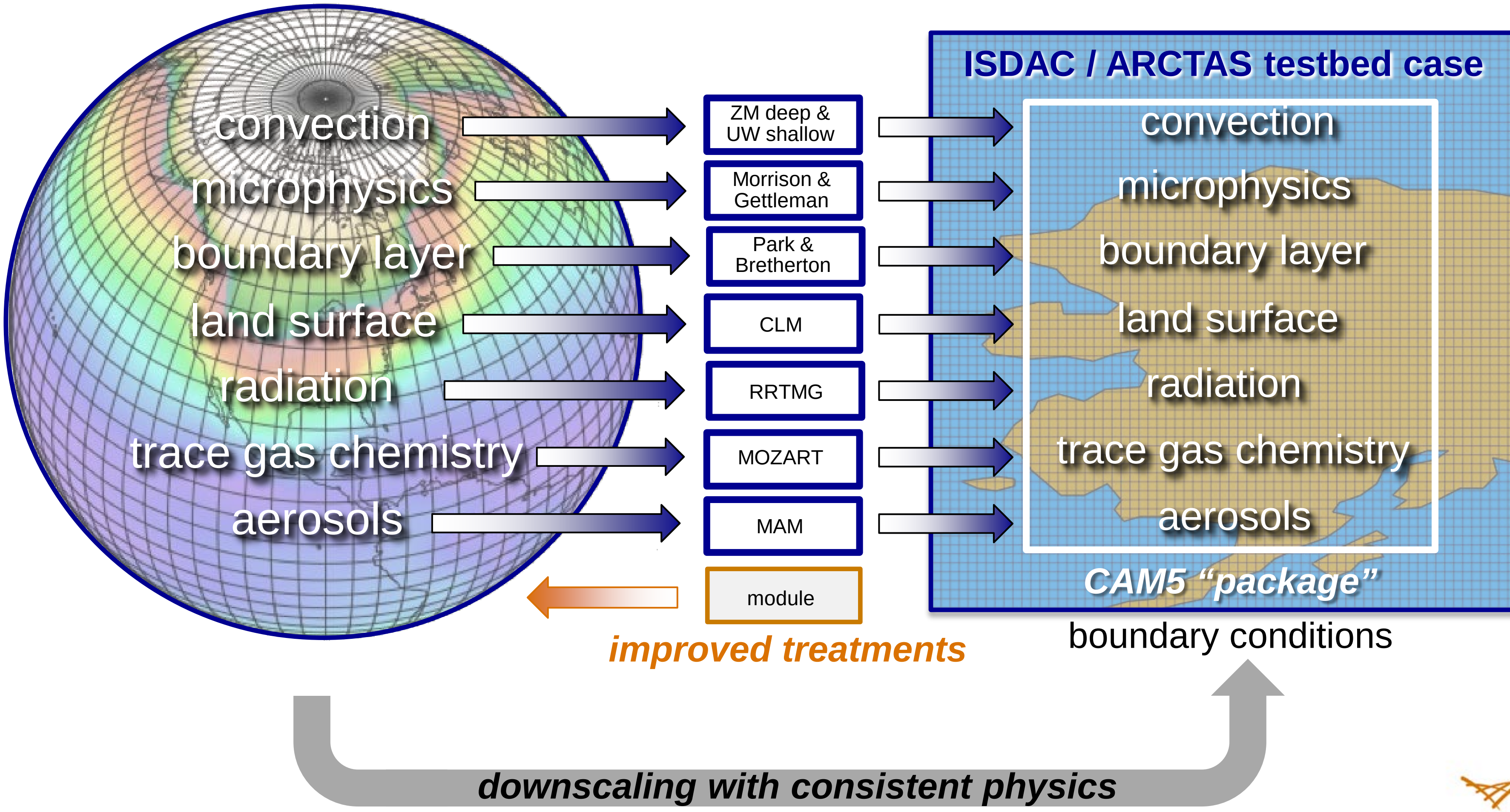
Concept

Community Atmosphere Model (CAM5)

Philosophy: Single parameterization for each atmospheric process for long-term climate simulations using a coarse grid

Weather Research & Forecasting (WRF)

Philosophy: Several parameterizations for each atmospheric process for short-term simulations using range of grid spacings

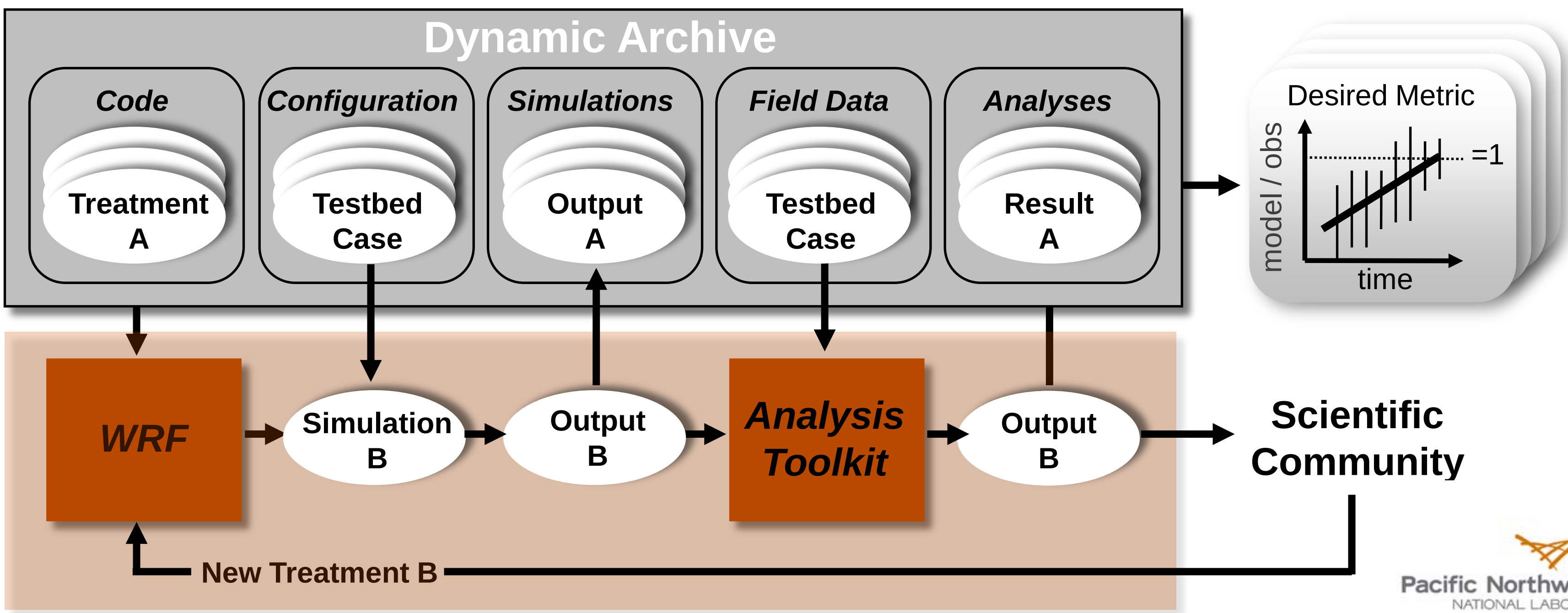


Pacific Northwest NATIONAL LABORATORY

Employ Aerosol Modeling Testbed

A computational framework that systematically and objectively evaluates **aerosol** and **cloud** process modules over a range of spatial scales
see *Fast et al*., BAMS [2011]

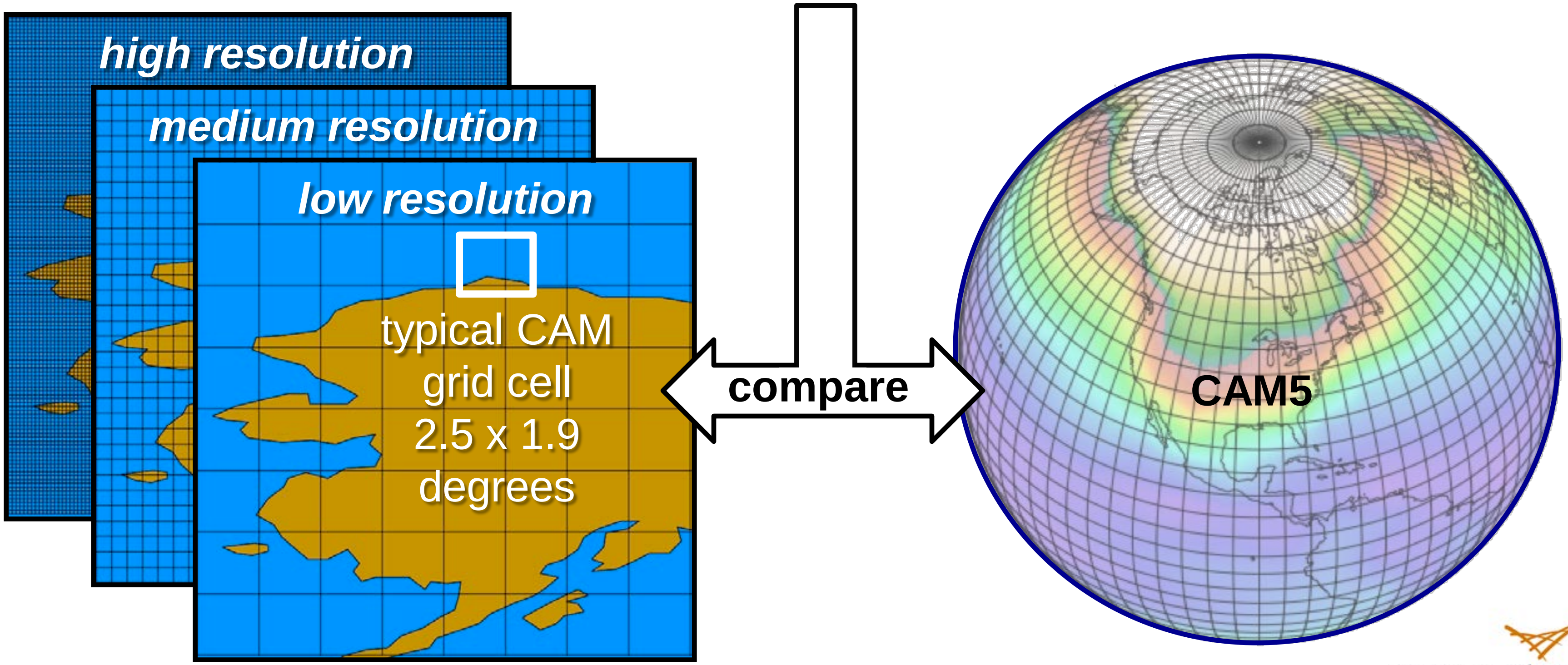
- *Better **quantify uncertainties** by targeting specific processes*
- *Provide tools to **facilitate science** by minimizing redundant tasks*
- ***Document** performance and computational expense*
- *Build **internationally-recognized capability** that fosters collaboration*



Pacific Northwest NATIONAL LABORATORY

Arctic Testbed Case

Use field campaign data in conjunction to evaluate how performance of CAM5 physics varies as a function of resolution and how it differs from more detailed representations of clouds, aerosols and their interactions

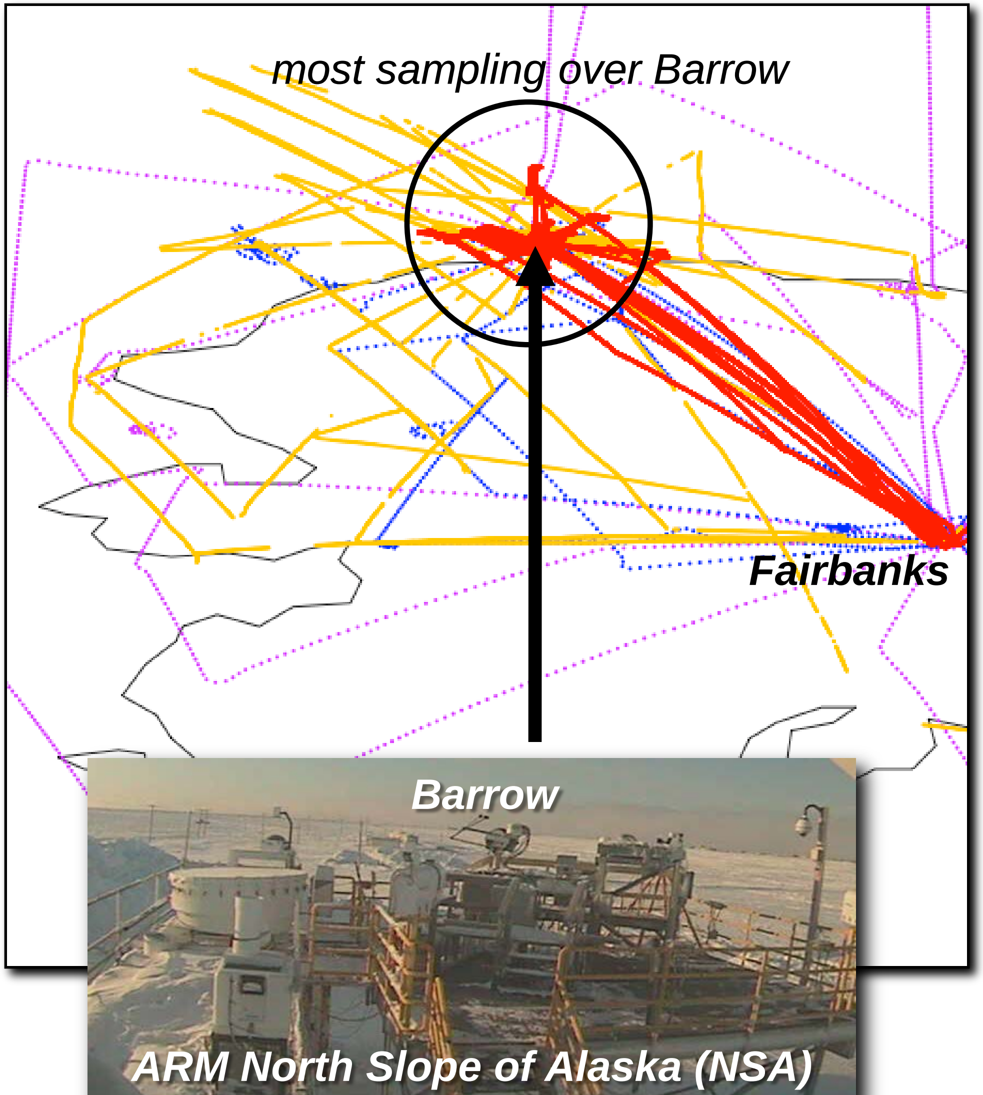


multi-scale WRF simulations

Pacific Northwest
NATIONAL LABORATORY

ISDAC / ARCTAS / ARCPAC Campaigns

Aircraft Flight Paths – April 2008



Convair (DOE), **28** flights
meteorology, cloud properties, aerosol size distribution, single particle instrument, CVI inlet

B-200 (NASA), **27** flights
high-resolution spectral lidar

DC-8 (NASA), **9** flights
meteorology, trace gases, aerosol size and composition

P-3B (NSF), **8** flights
meteorology, trace gases, aerosol size and composition

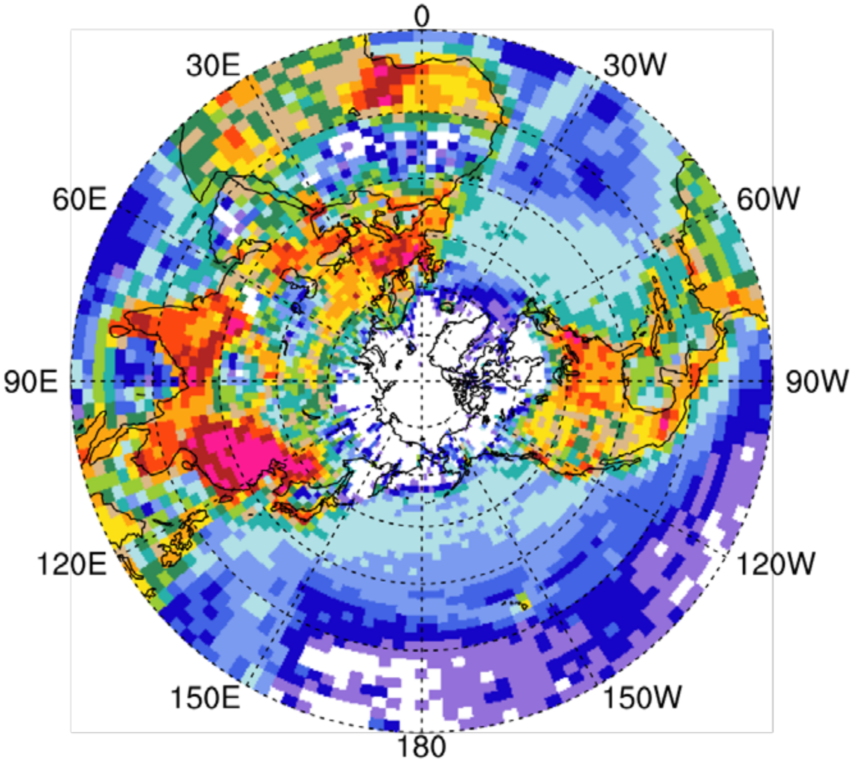
P-3B (NOAA), **8** flights (not shown)
meteorology, trace gases, aerosol size and composition

Type and amount of trace gas and aerosol data not identical

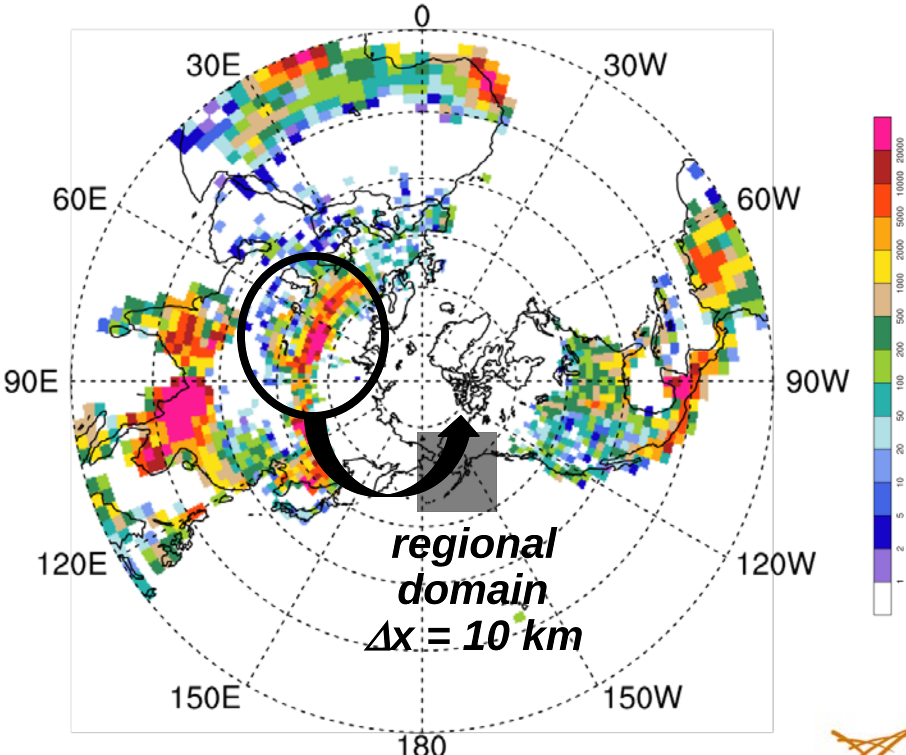
Pacific Northwest
NATIONAL LABORATORY

Model Configuration

- **CAM5:** Offline version driven by ERA meteorological analyses to simulated observed synoptic systems as close as possible, *MOZART* trace gases and *MAM* aerosols
- **Emissions:** Developed specifically for 2008 Arctic simulations by the POLARCAT Modeling Intercomparison Project (POLMIP)



Anthropogenic



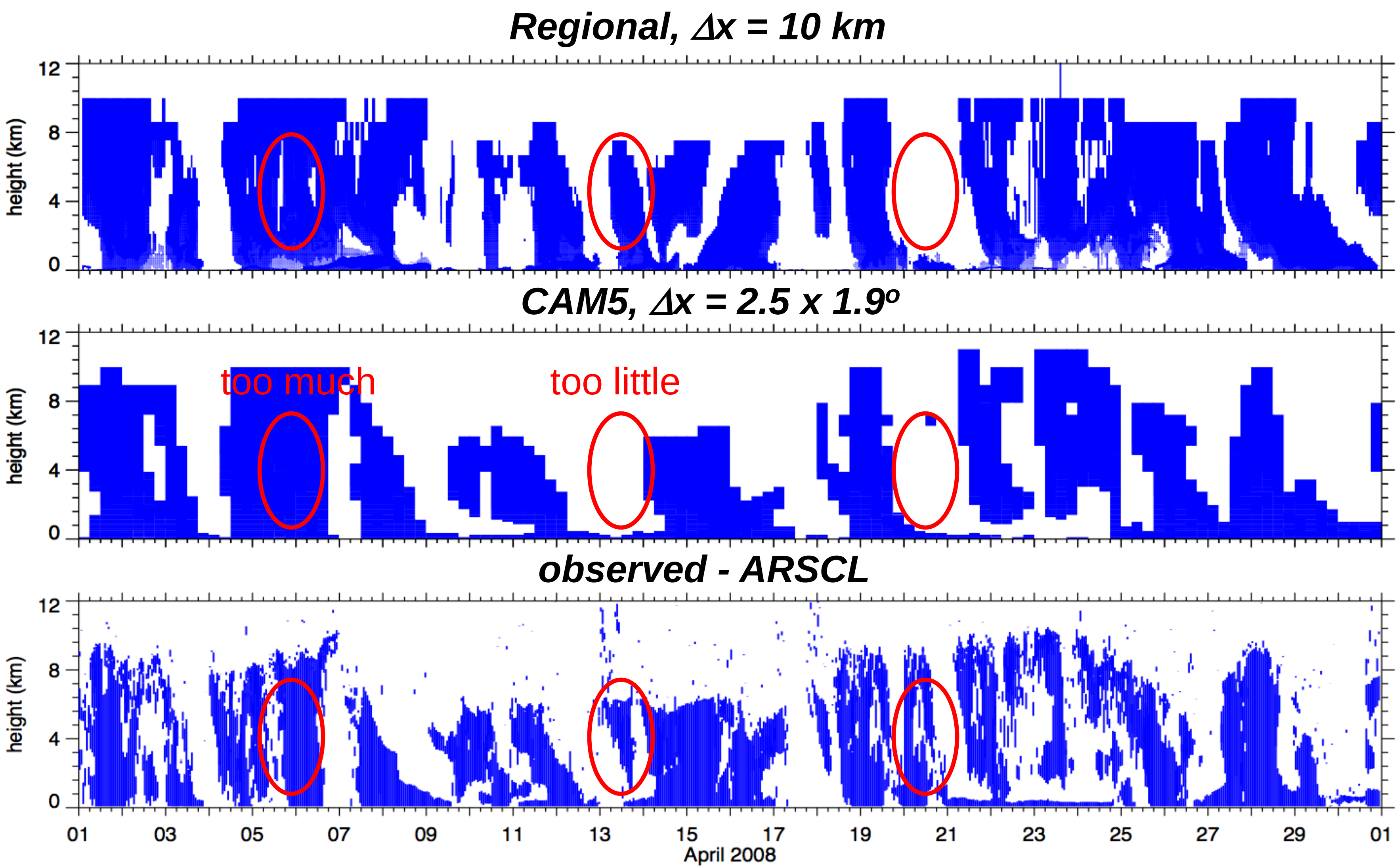
Biomass Burning

Pacific Northwest
NATIONAL LABORATORY

Results

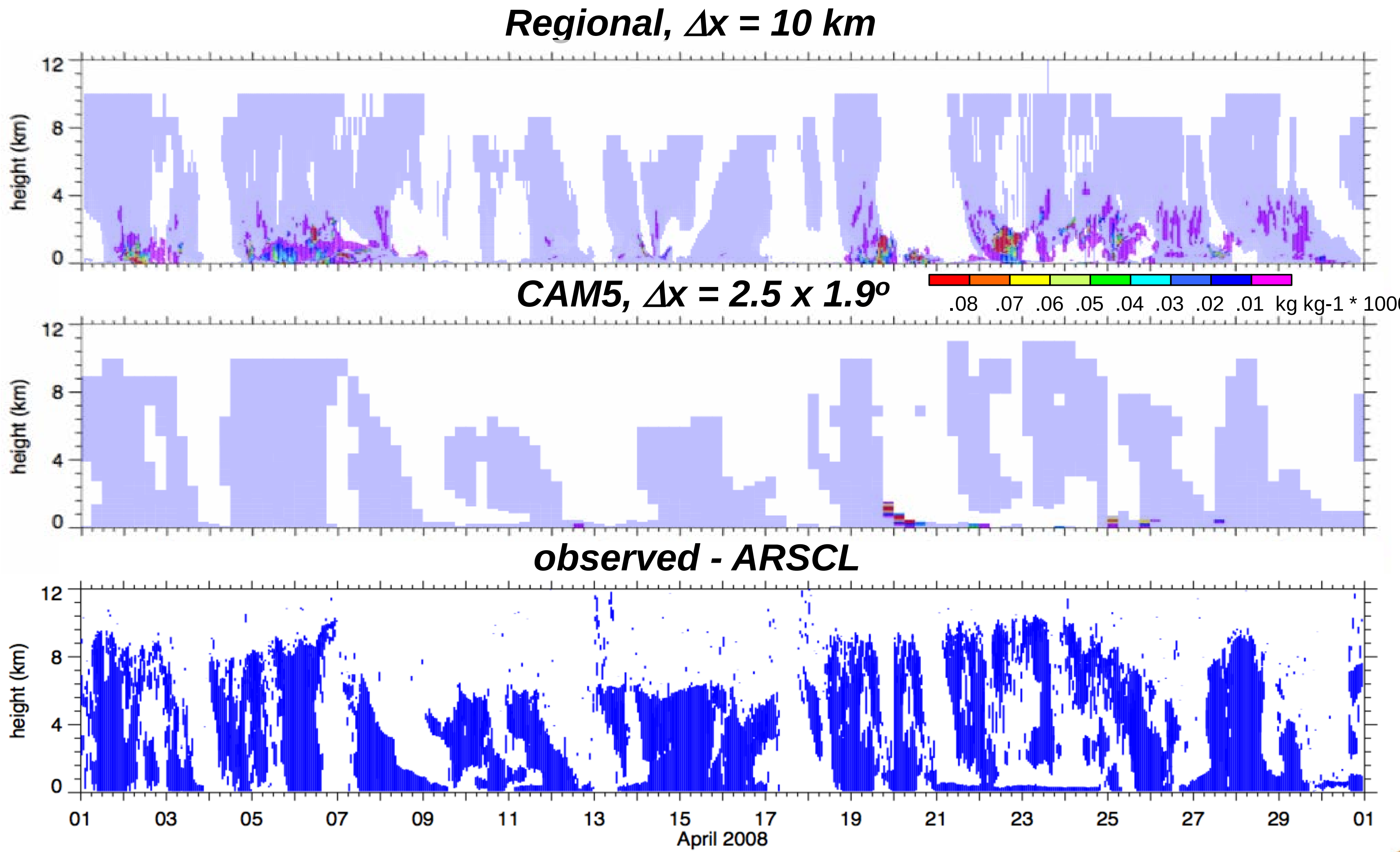
How do CAM5 Physics Perform at Higher Spatial Resolution?

Clouds over Barrow



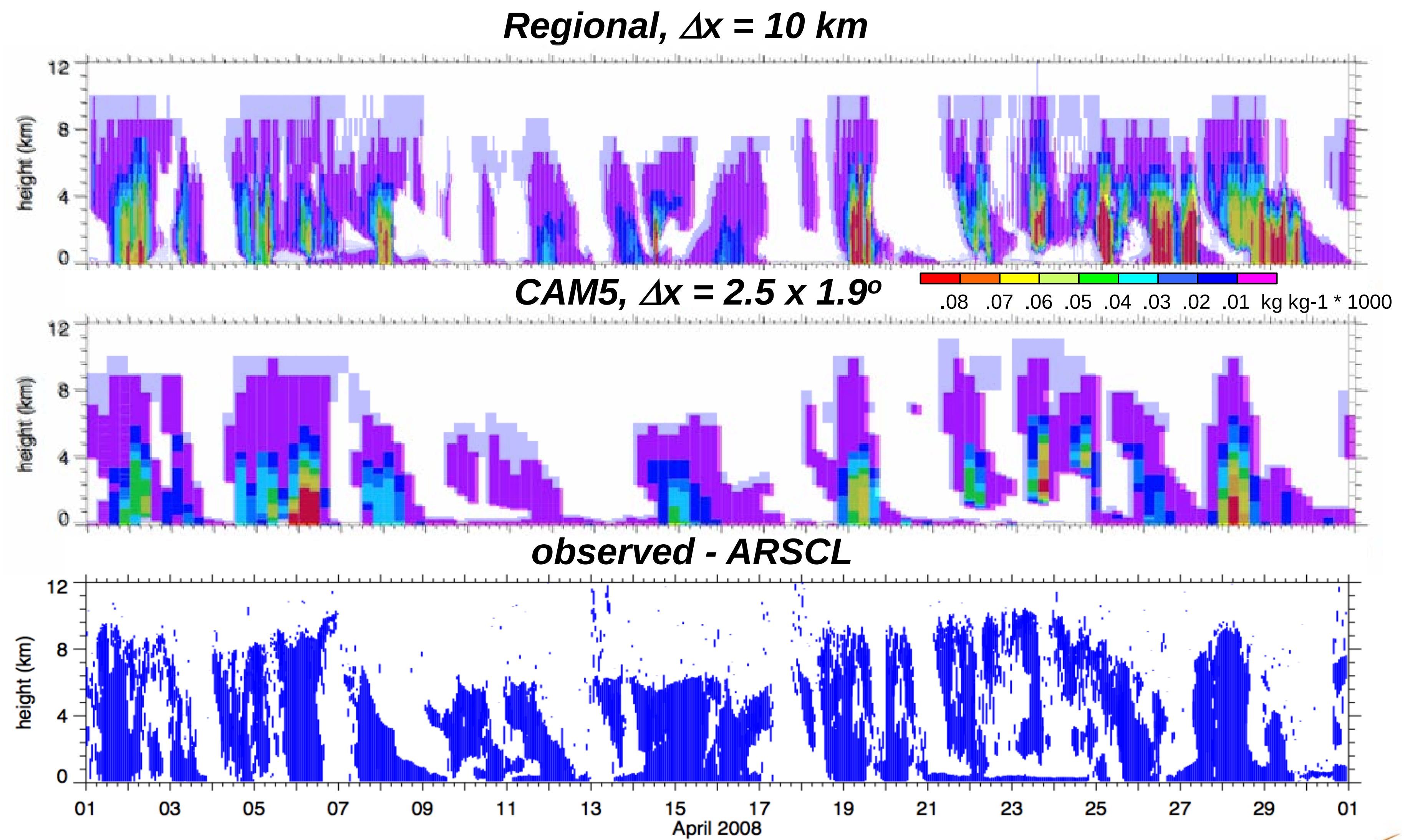
- Resolution may explain some of the missing clouds in CAM5

Clouds (Liquid) over Barrow



- Resolution may explain some of the missing clouds in CAM5

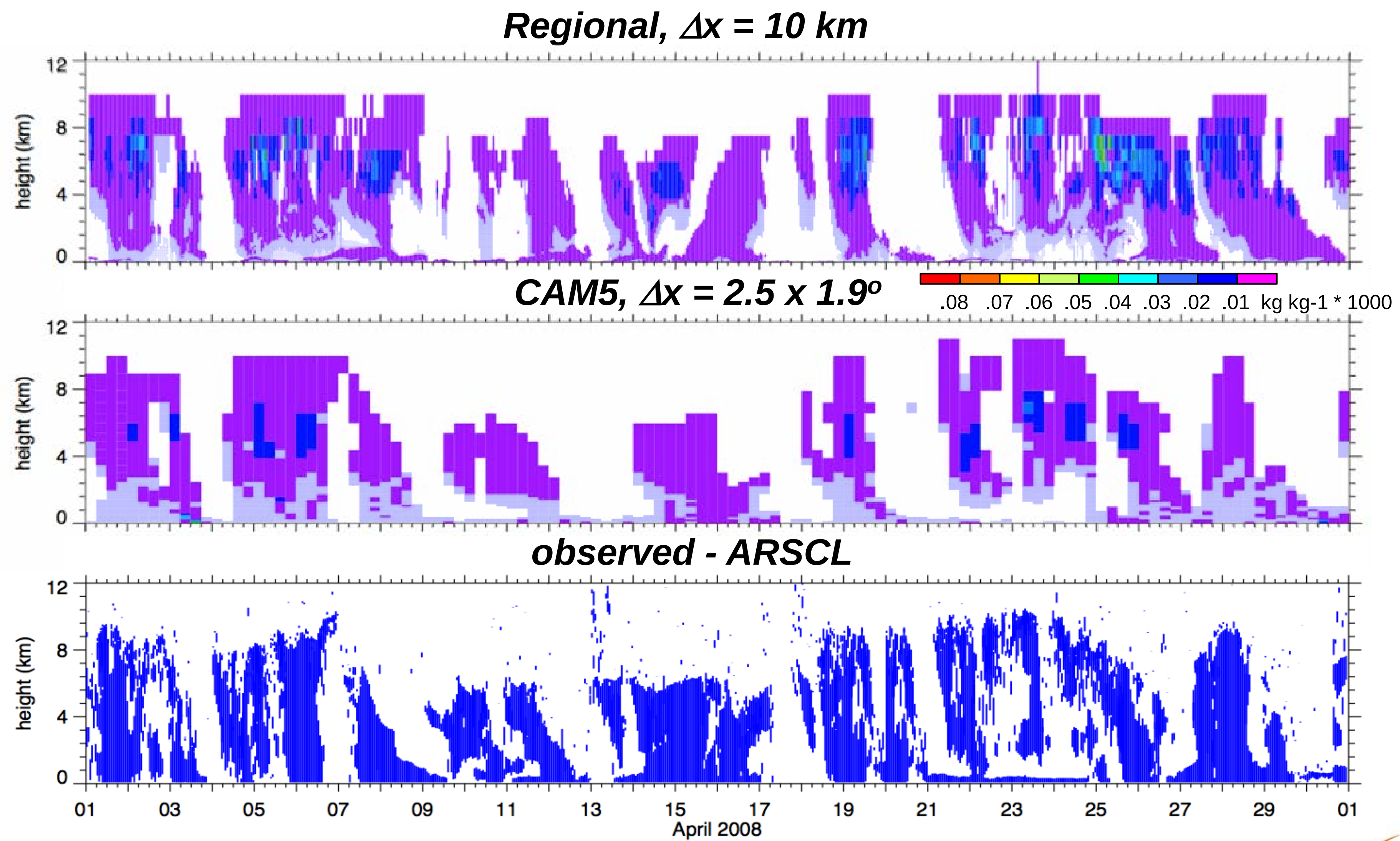
Clouds (Snow) over Barrow



- Resolution may explain some of the missing clouds in CAM5

Pacific Northwest NATIONAL LABORATORY

Clouds (Ice) over Barrow

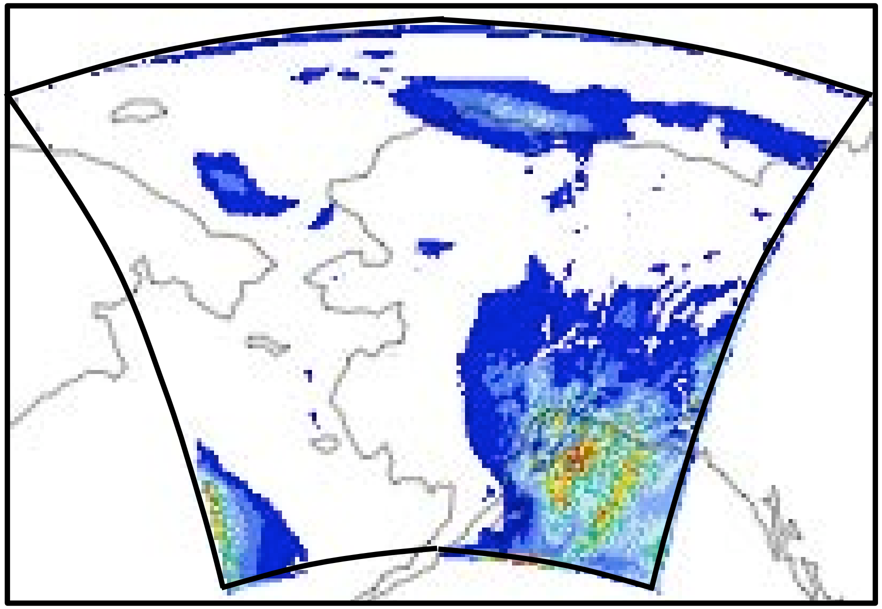


- Resolution may explain some of the missing clouds in CAM5

Regional Variations in Clouds

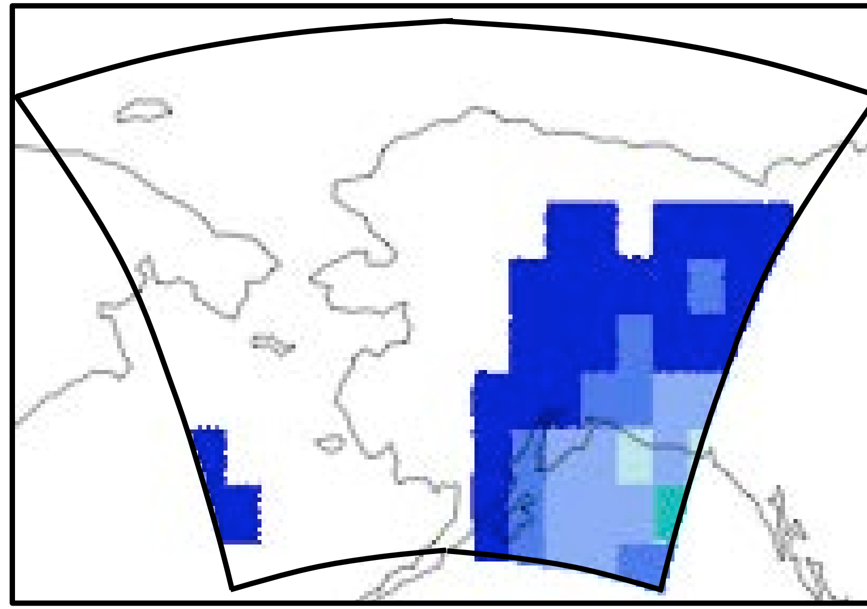
Vertically Integrated Cloud Water, Snow, and Ice, 00 UTC April 27

Regional, Δx = 10 km

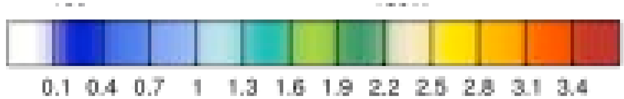


average = 0.25 kg m^{-2}

CAM5, Δx = 2.5 x 1.9°



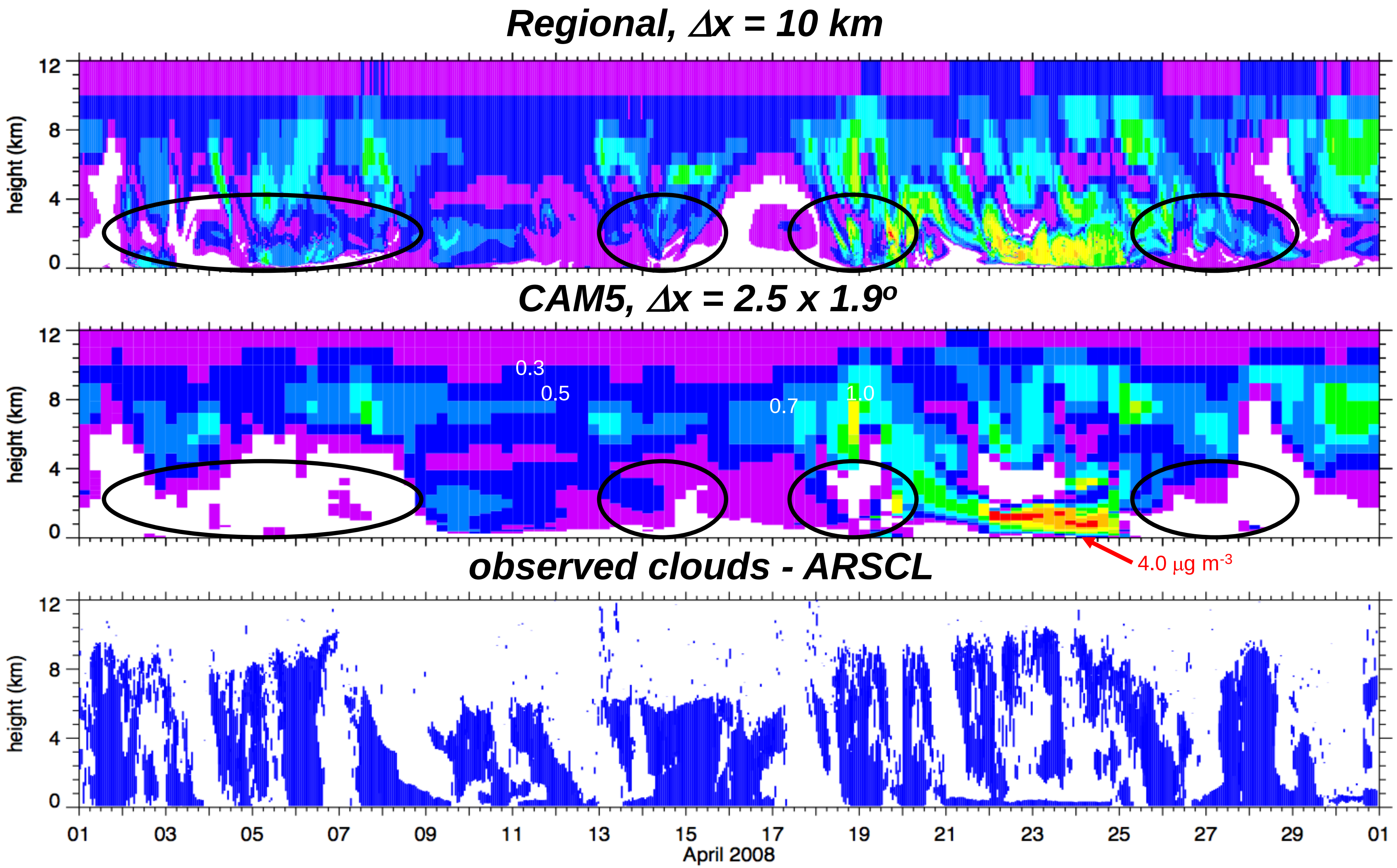
average = 0.16 kg m^{-2}



- Both simulations qualitatively similar, but there are many periods when regional model simulates clouds when and where CAM5 does not

Pacific Northwest
NATIONAL LABORATORY

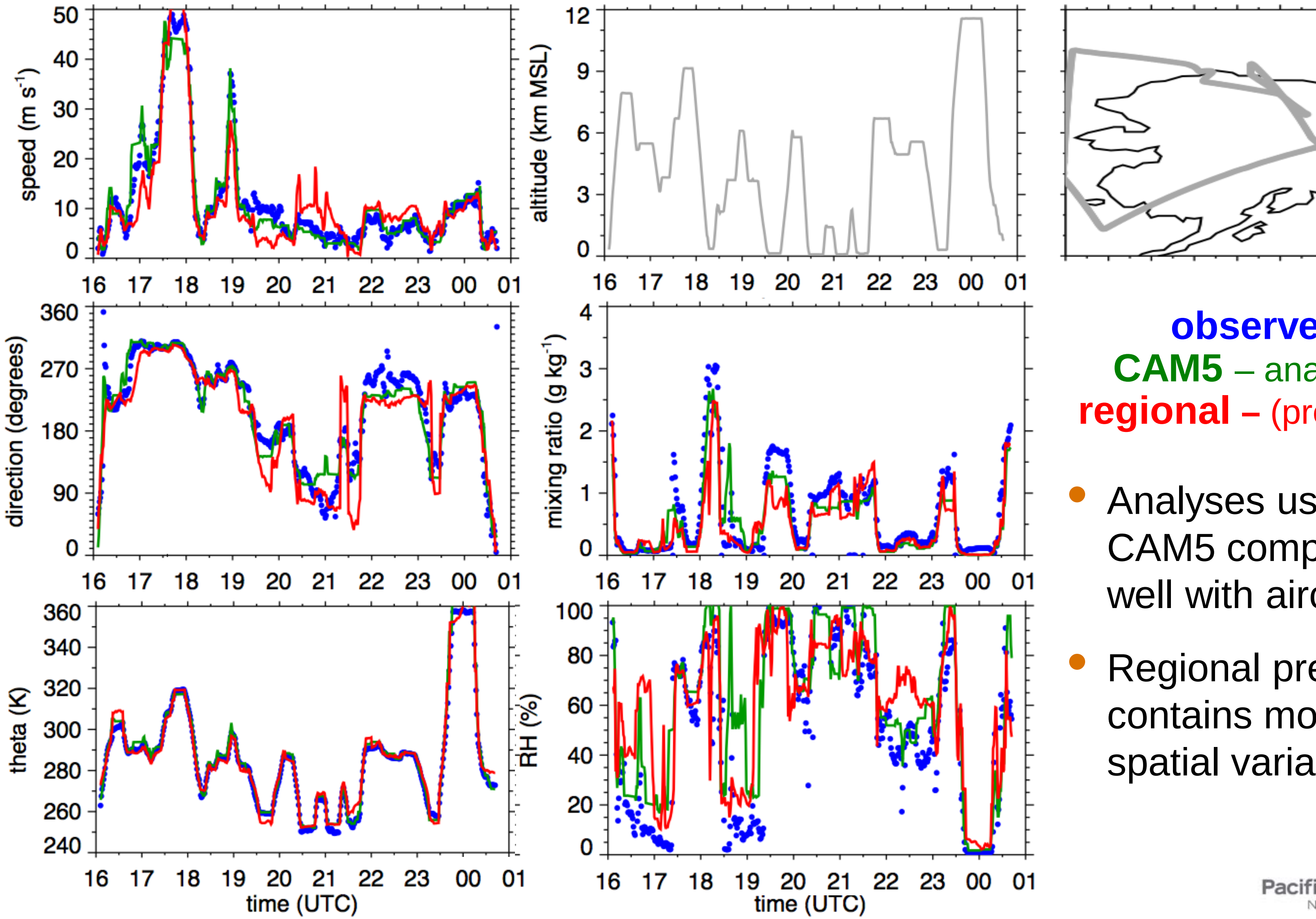
Aerosols ($PM_{2.5}$) over Barrow



- Regional simulation produces higher concentrations < 4 km

Meteorological Evaluation

9-h DC-8 Flight on April 12, 2008

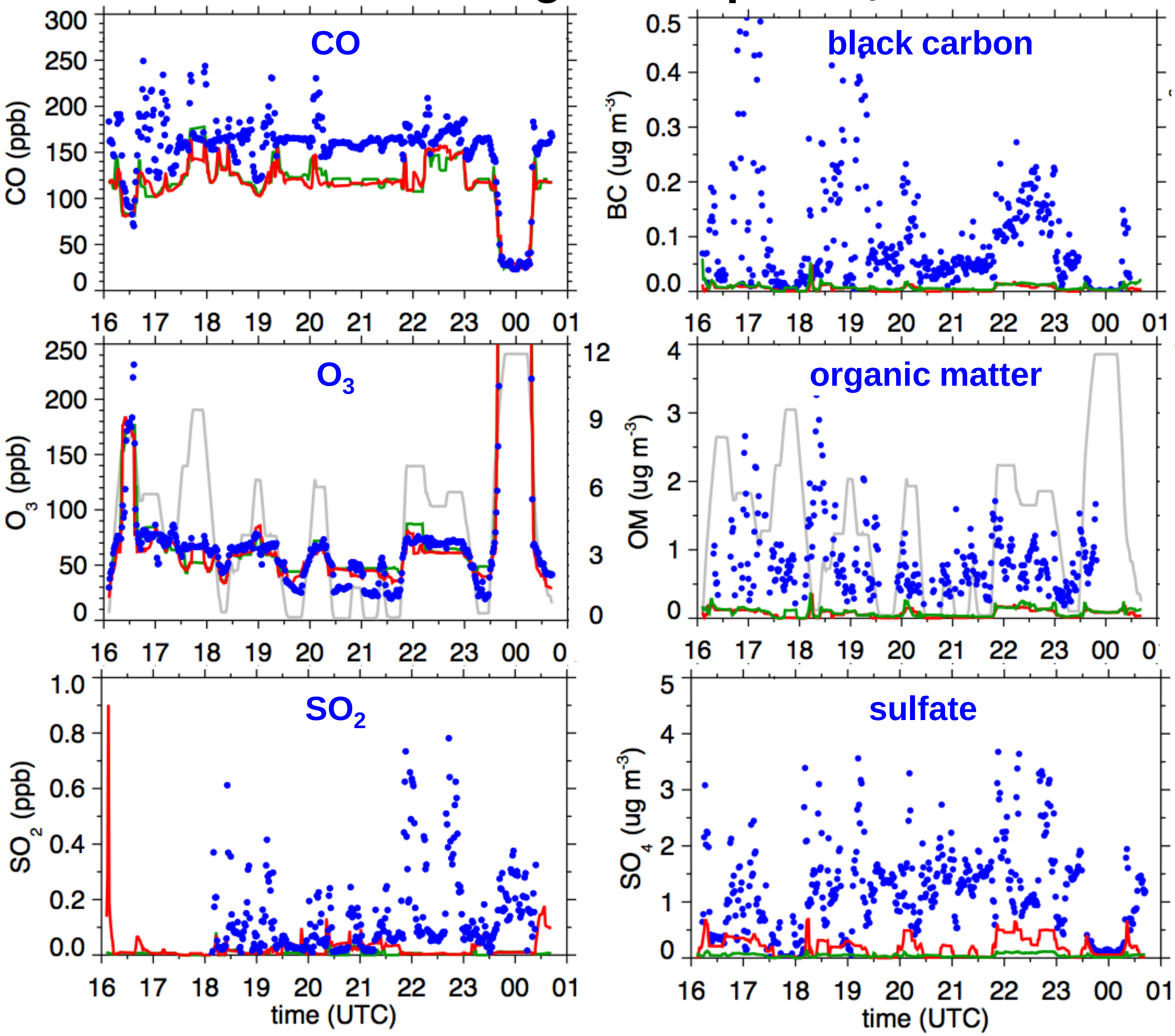


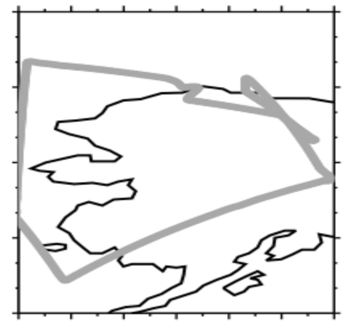
observed
CAM5 – analyses
regional – (predicted)

- Analyses used in CAM5 compare well with aircraft
- Regional prediction contains more spatial variability

Trace Gases and Aerosols

9-h DC-8 Flight on April 12, 2008



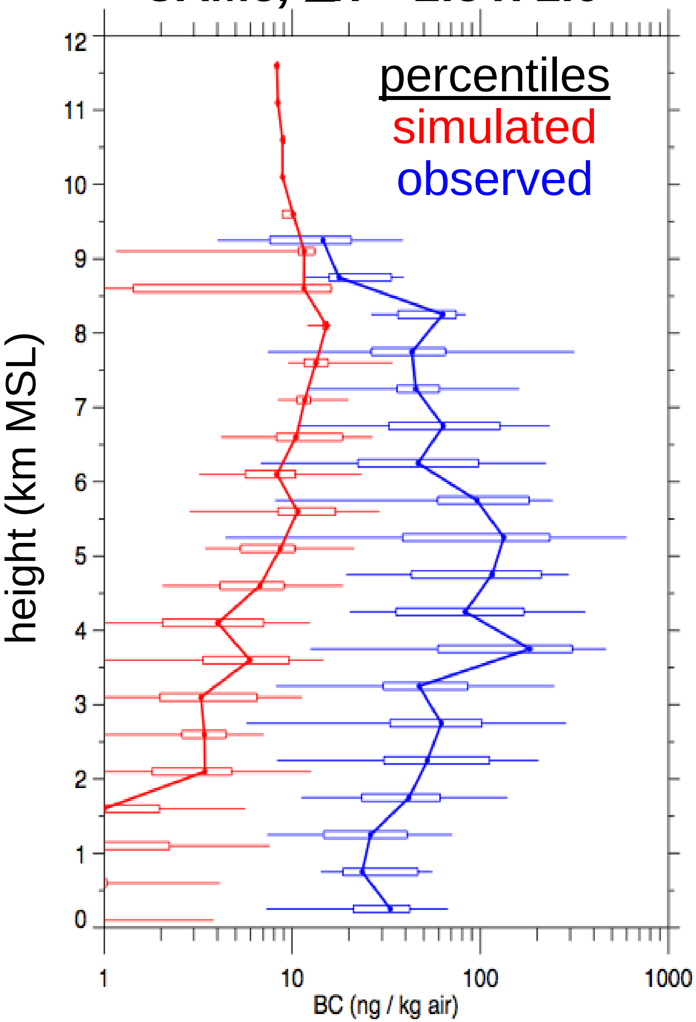


observed
CAM5 – analyses
regional – (predicted)

- Aerosols too low (not surprising)
- Some trace gases such as CO and SO_2 are too low as well

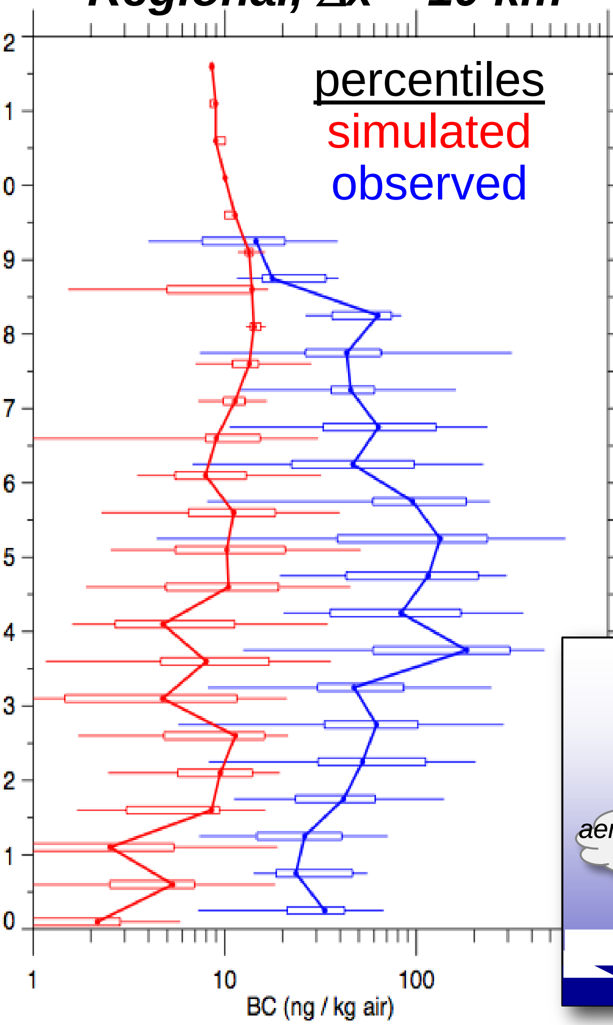
Black Carbon Profiles

CAM5, Δx = 2.5 x 1.9°



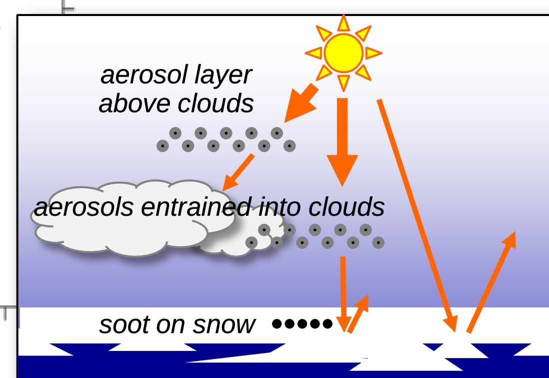
observed from 5 DC-8 and 3 P3-B flights

Regional, Δx = 10 km



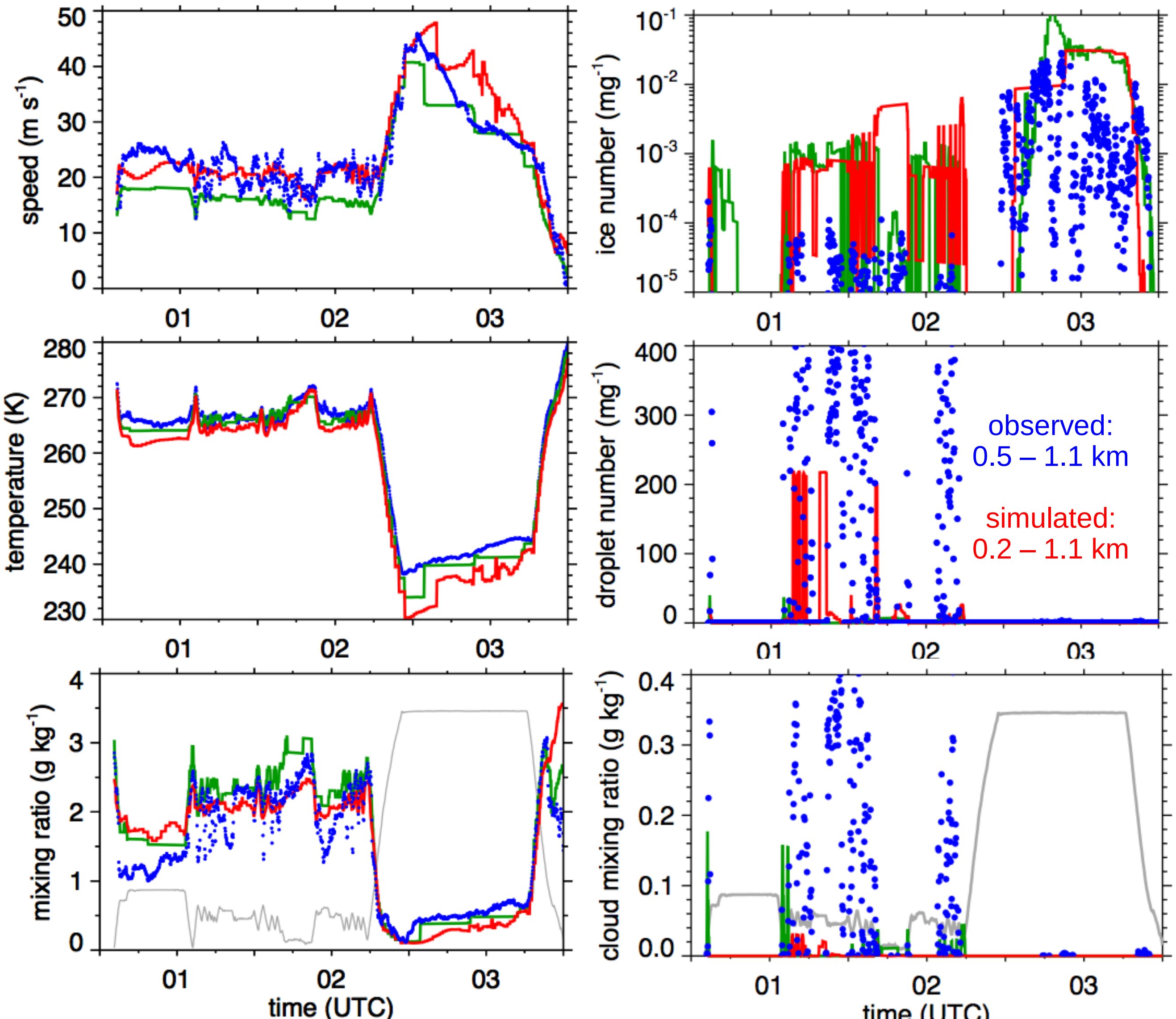
more downward transport or less removal locally ?

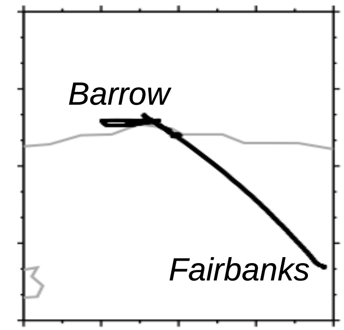
- Most global models under-predict BC in the Arctic
- Regional simulation somewhat higher, despite boundary conditions from CAM5



Pacific Northwest
NATIONAL LABORATORY

Mixed-Phase Clouds





observed

CAM5 – analyses

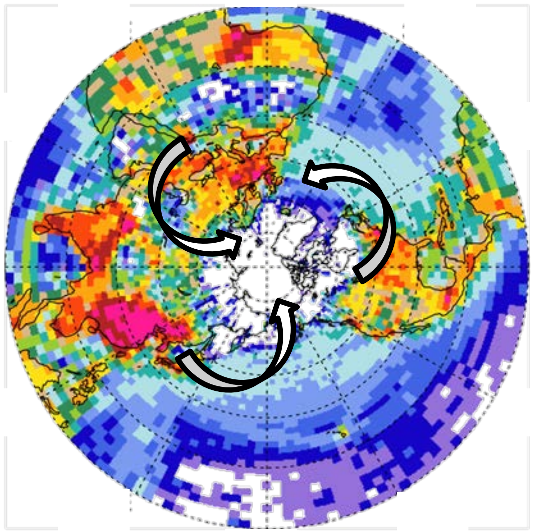
regional – (predicted)

- Simulated ice too high and liquid water too low at this time
- Temperature a few degrees to cold near just above ice pack

Pacific Northwest
NATIONAL LABORATORY

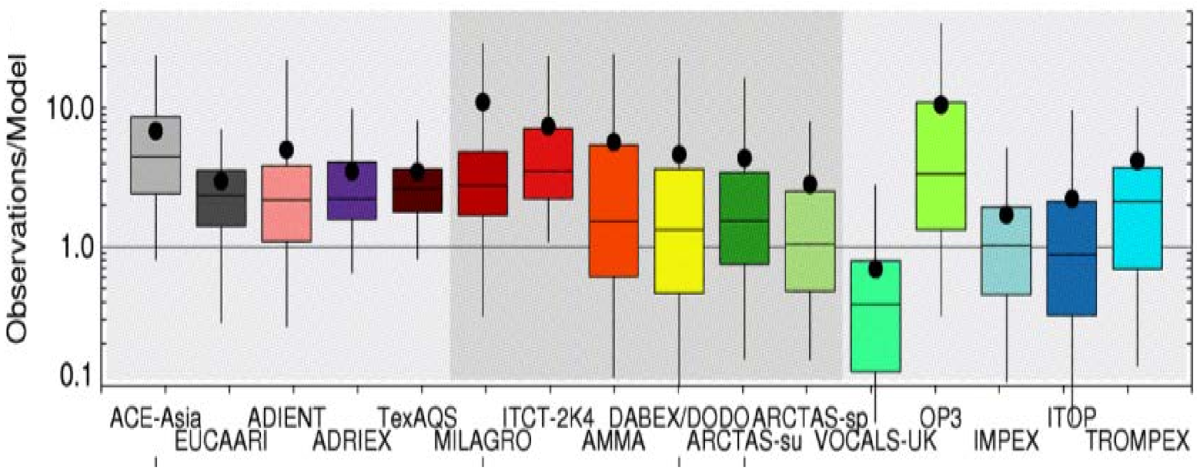
Testing Aerosol Parameterizations

Uncertainties in the formation of secondary organic aerosols (SOA) likely contribute to under-predictions of total particulate matter over the Arctic



SOA Transport to Arctic

Under-prediction of SOA from Global Models



from GEOS-Chem, *Heald et al.*, ACPD, [2011]

Comparing Aerosol Models

- **AMT methodology:** identical emissions, meteorology (aerosol-radiation-cloud feedbacks turned off), chemistry, dry deposition, boundary conditions

MAM (from CAM5)
modal – 3 modes, **18** species

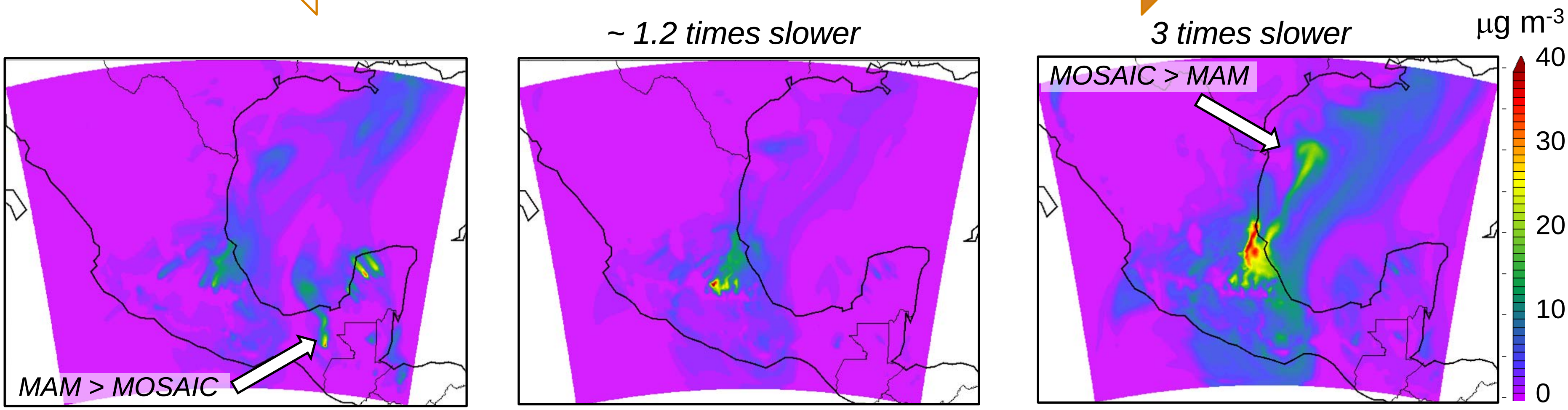
MADE/SORGAM
modal – 3 modes, **38** species

MOSAIC
sectional – 4 bins, **164** species

'simple' ⟷ *9 times more species* ⟷ **'complex'**

~ 1.2 times slower (MADE/SORGAM)

3 times slower (MOSAIC)



fine PM (< 2.5 μm), excluding dust ~1800 m AGL

- Differences due to secondary aerosols (SO_4, NO_3, NH_4, organics)
- Treatment of organics:

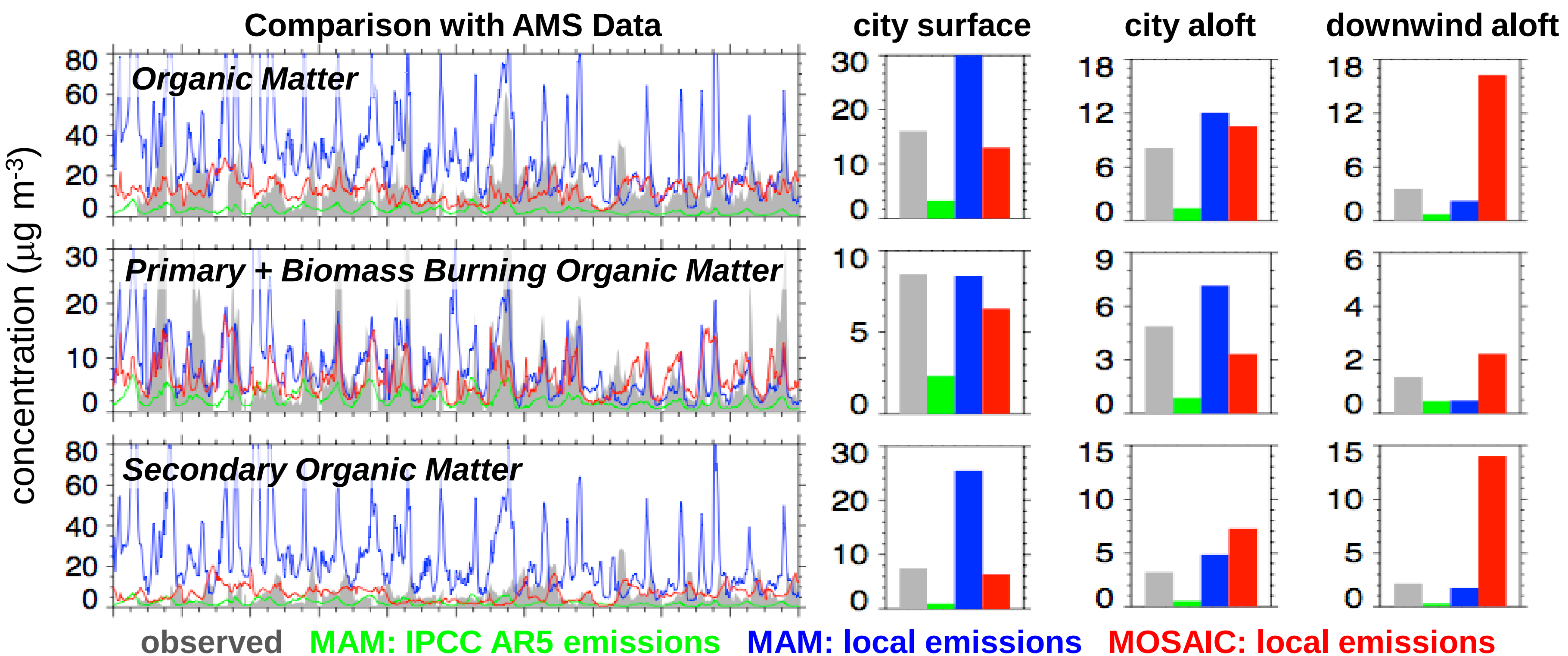
MAM: POA - non-volatile, SOA employs simple yields

MADE/SORGAM: POA - non-volatile, SOA employs traditional 2-product approach

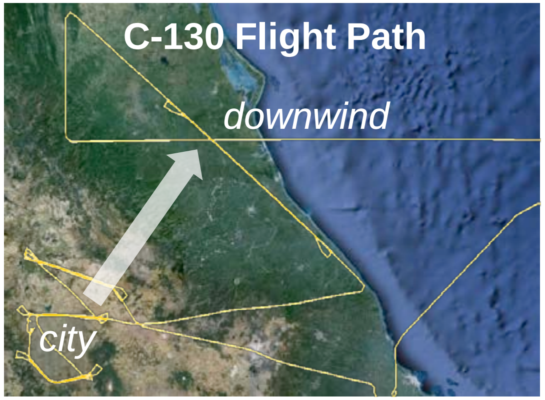
MOSAIC: non-volatile POA & SOA, volatility basis set approach

Pacific Northwest
NATIONAL LABORATORY

Assessing Organic Matter Components



- Primary organic matter from 2 models similar in the city, but SOA from MAM too high
- SOA from MOSAIC too high downwind
- Scale dependence of SOA in MAM needs to be investigated further and for other locales

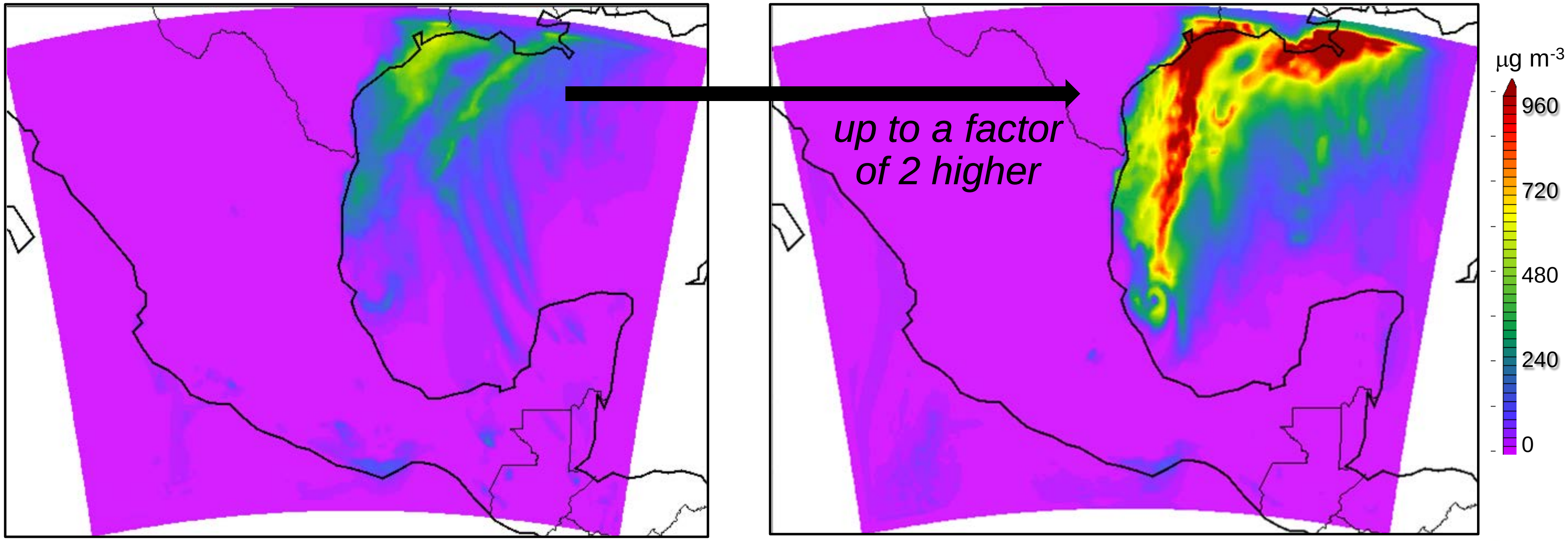


Impact on Aerosol Water

- Treatment of hygroscopic properties as well as predicted mass, composition, and size distribution affects aerosol water, and consequently direct radiative forcing and CCN
- In this case, differences in thermodynamic modules and secondary aerosols leads to large variations in uptake of water on aerosols

MAM (from CAM5)
modal – 3 modes, **18** species
'simple'

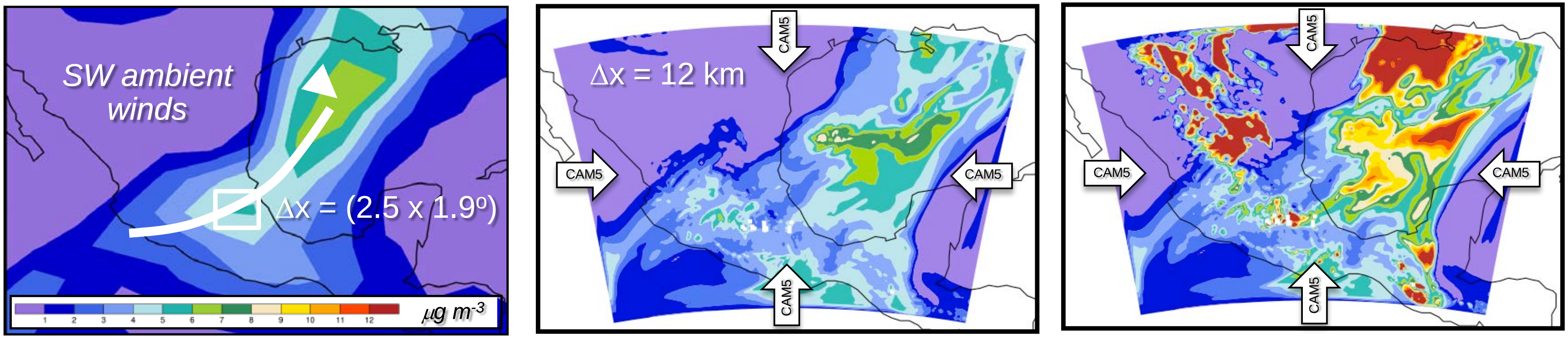
MOSAIC
sectional – 4 bins, **164** species
'complex'



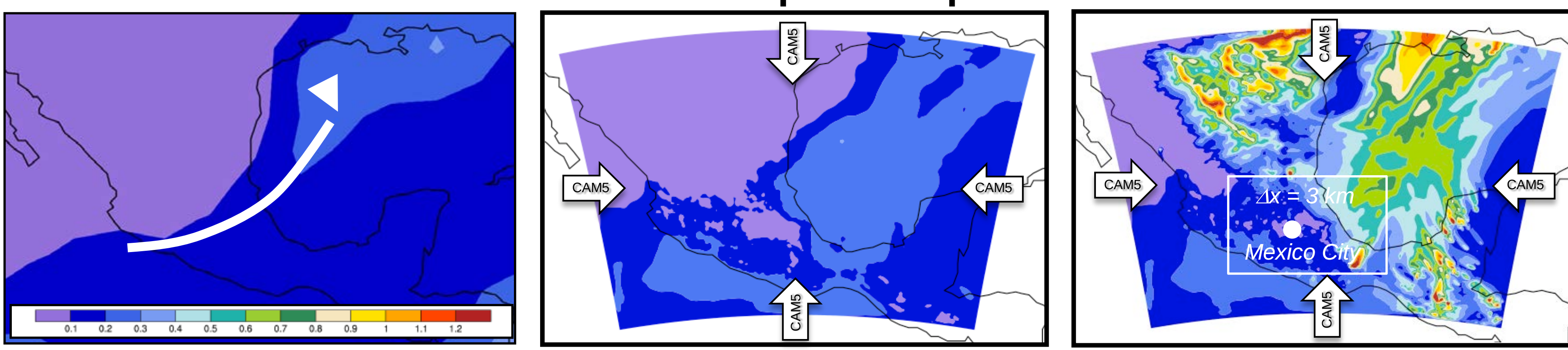
fine aerosol water (< 2.5 μm) ~200 m AGL

Global and Regional Scale Differences

PM2.5 at 700 hPa, 18 UTC 19 March 2006



Aerosol Optical Depth



CAM5 + IPCC AR5 emissions

WRF + CAM5 Physics + (IPCC AR5) emissions

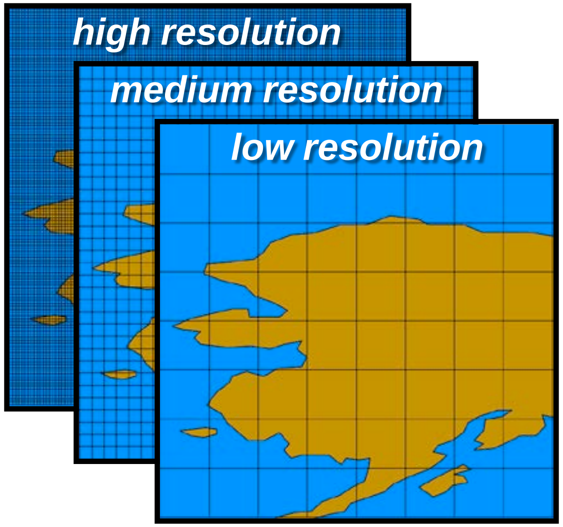
WRF + CAM5 Physics + local emissions

- Magnitude similar, but small grid spacing add details
- Differences mostly due to on-line dust calculations

Pacific Northwest NATIONAL LABORATORY

Summary and Next Steps

- New modeling framework available to test and evaluate CAM5 aerosol and cloud treatments against treatments developed by the mesoscale modeling community
- Examine scale-dependency of current cloud and cloud-aerosol interaction treatments in the Arctic
  - *Will the current suite of physics be suitable for the next generation climate model?*
- Determine whether transport of organic aerosols to the Arctic can be improved by incorporating new knowledge on their formation / evaporation
  - *How can we improve the mass of aerosols in the Arctic for the right reasons?*
  - *How will improving aerosol mass and composition affect both liquid and ice clouds, and consequently the regional radiation budget?*



Office of Science
U.S. DEPARTMENT OF ENERGY

Acknowledgements: This research was supported by DOE's Earth System Modeling Program. Data obtained with from the ARM Climate Research Facility, NSF, NOAA, and NASA.

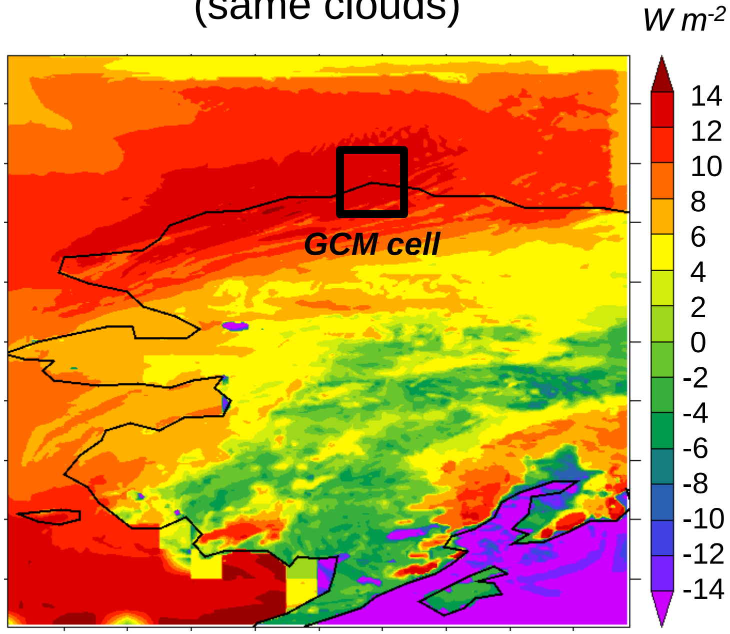
Extra Slides

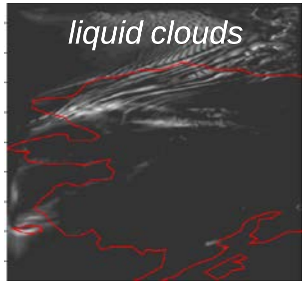
Pacific Northwest
NATIONAL LABORATORY

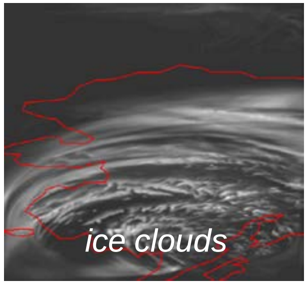
Regional Radiation Variations

Top of the Atmosphere Upward Shortwave Radiation, 00 UTC April 20

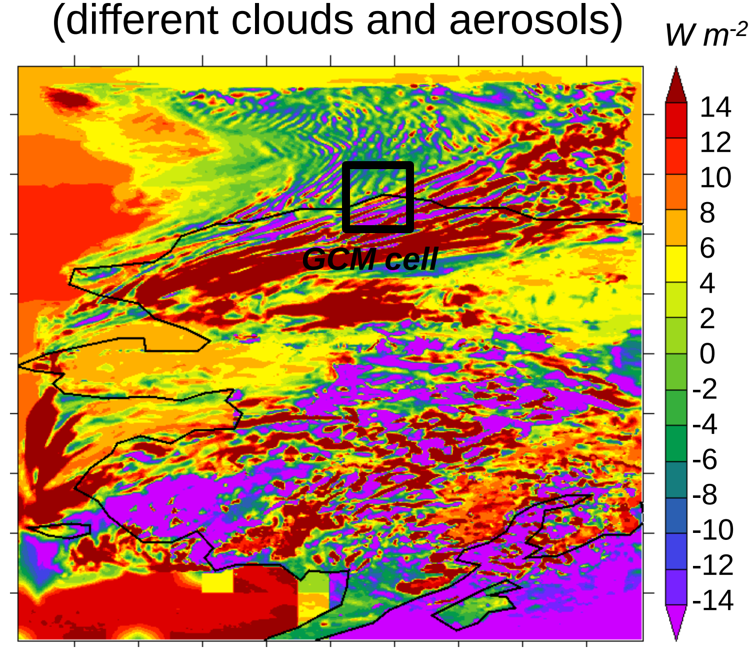
Difference: With – Without Aerosols from Cloud-Aerosol Interaction Simulation
(same clouds)







Difference: Simulation With - Without Cloud-Aerosol Interactions
(different clouds and aerosols)



Domain average
with aerosols = -408 W m^{-2}
without aerosols = -413 W m^{-2}
~ 1.2% difference

Domain average
with interactions = -408 W m^{-2}
without interactions = -410 W m^{-2}
~ 0.5% difference

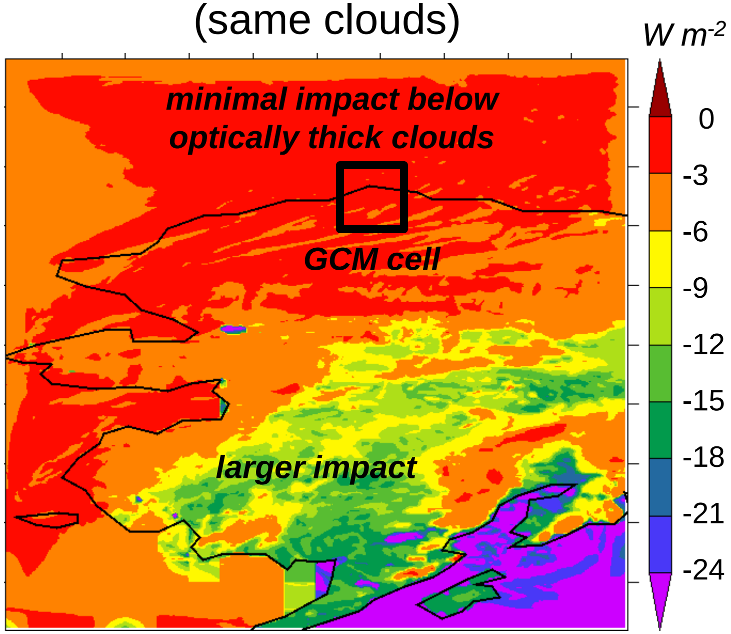
Despite brighter clouds because cloud-aerosol interaction simulation has less cloudiness

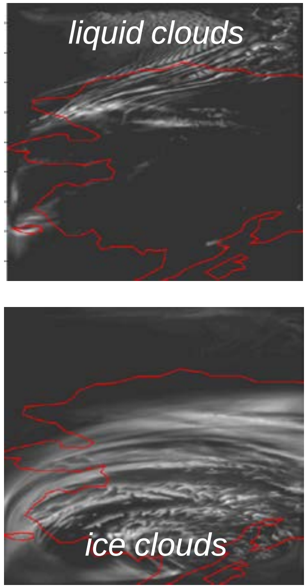
Pacific Northwest
NATIONAL LABORATORY

Regional Radiation Variations

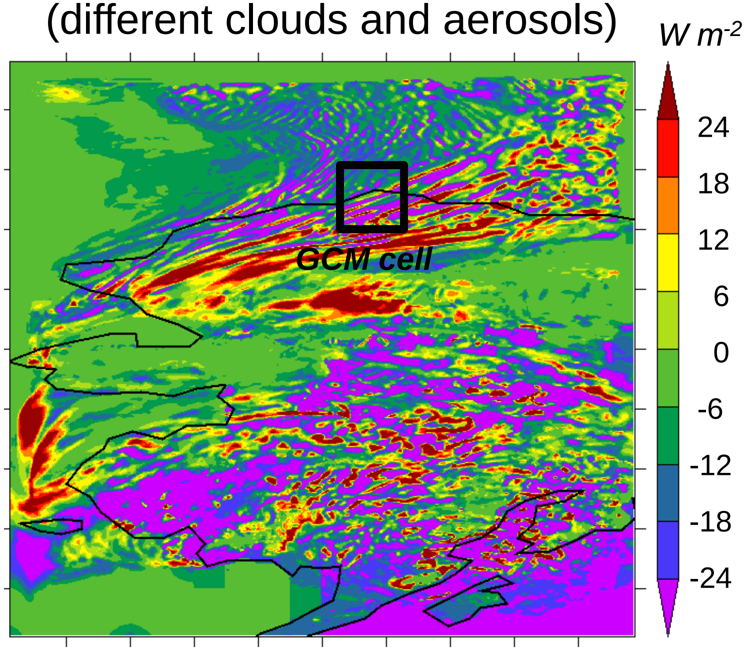
Surface Incoming Shortwave, 00 UTC April 20

Difference: With – Without Aerosols from Cloud-Aerosol Interaction Simulation
(same clouds)





Difference: Simulation With - Without Cloud-Aerosol Interactions
(different clouds and aerosols)



Domain average
with aerosols = 174 W m^{-2}
without aerosols = 180 W m^{-2}
~ 3.4 % difference

Domain average
with interactions = 174 W m^{-2}
without interactions = 182 W m^{-2}
~ 4.6% difference

Pacific Northwest
NATIONAL LABORATORY