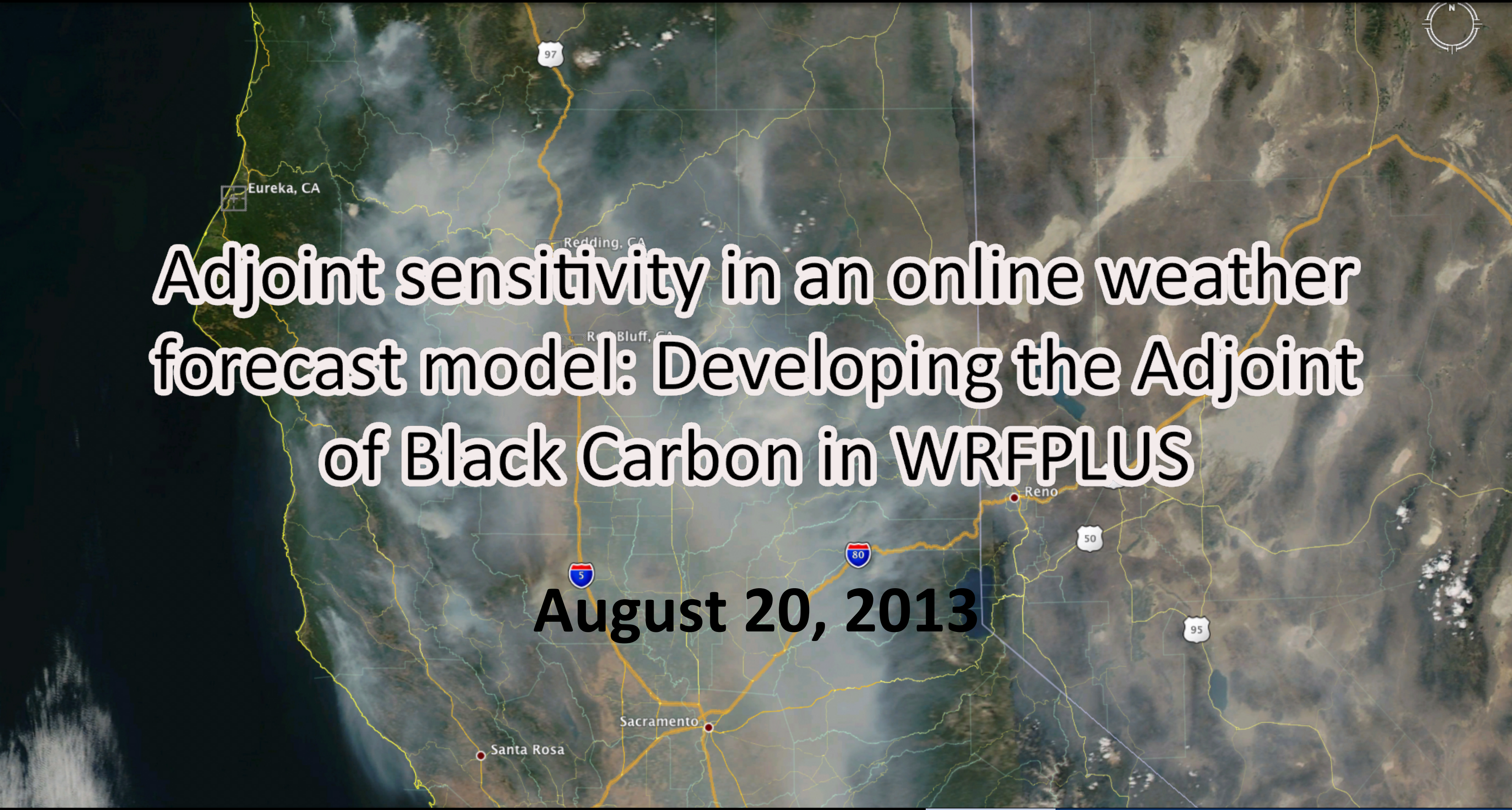

Adjoint sensitivity in an online weather forecast model: Developing the Adjoint of Black Carbon in WRFPLUS

August 20, 2013

Jonathan Guerrette (CU Boulder)

Daven Henze (CU Boulder)

Gregory Carmichael (University of Iowa)

Image: MODIS true color image on June 24, 2008 (http://cimss.ssec.wisc.edu/)

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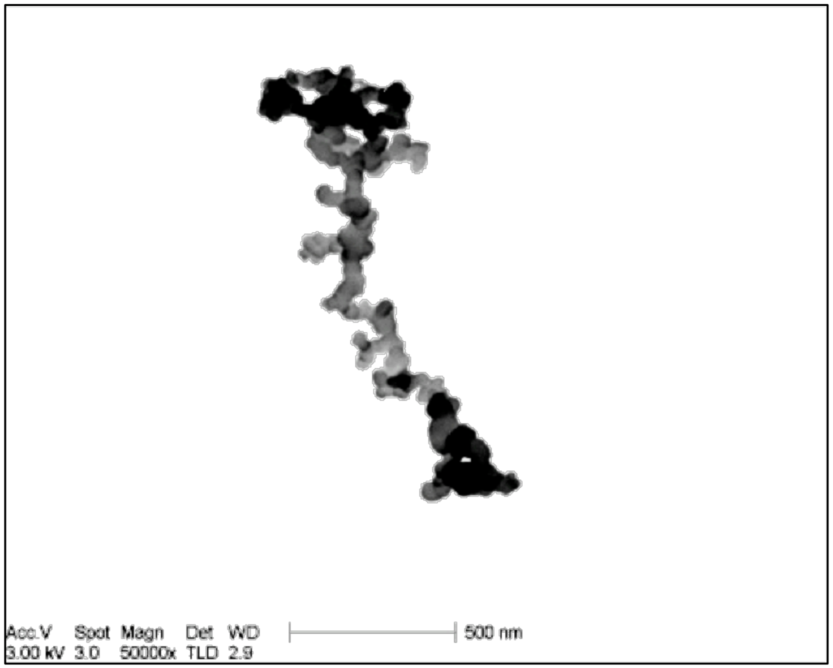
U.S. EPA - Science To Achieve Results (STAR) Program

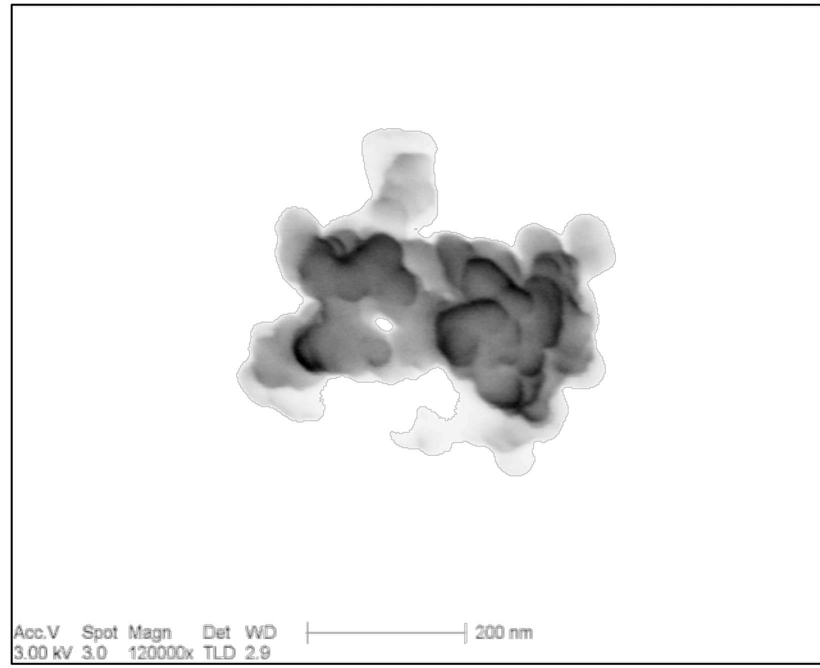
Grant # EPA-G2010-STAR-L1

Black Carbon

Hydrophobic



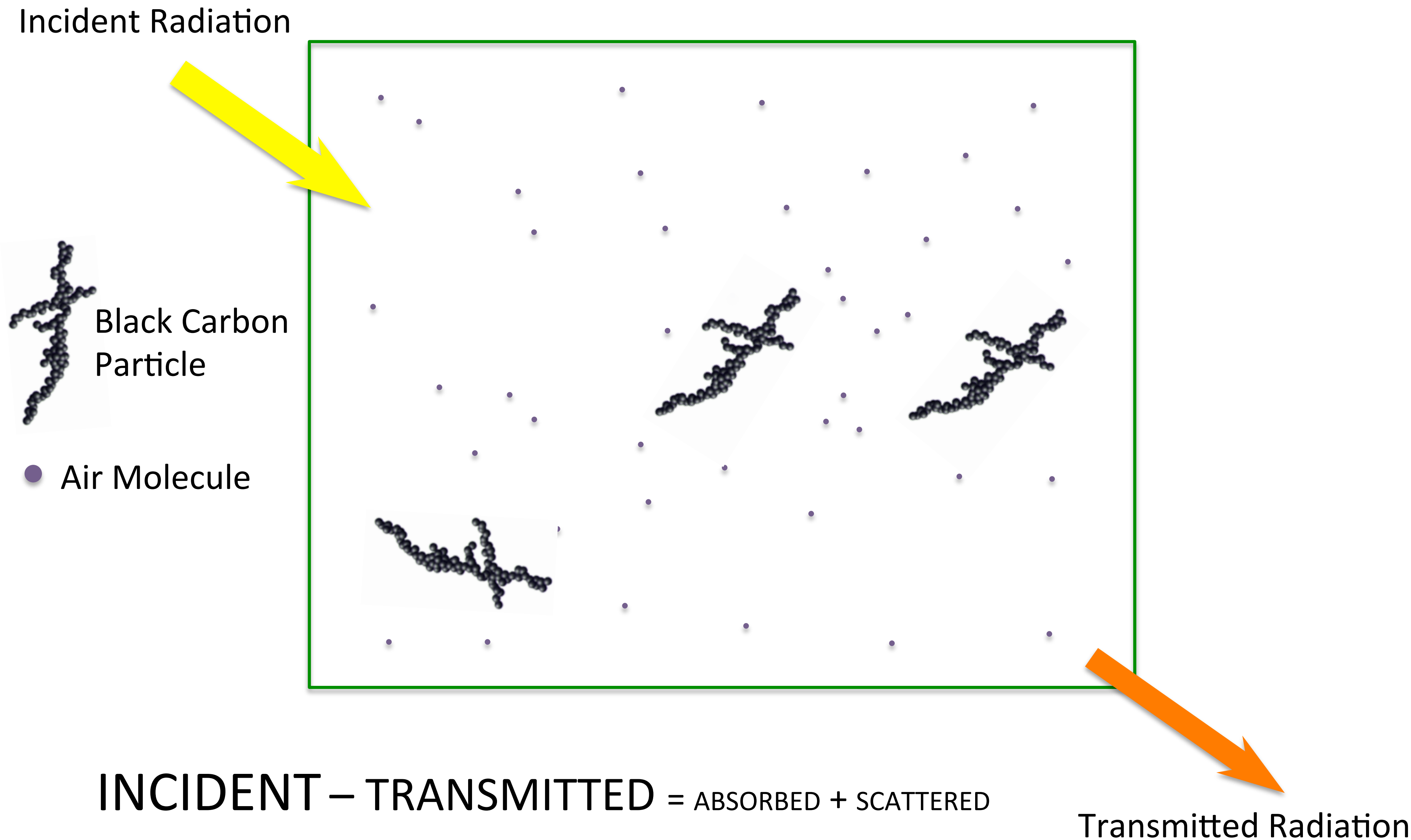
Hydrophilic



D ≈ 200-800nm (Encompasses wavelength of visible light)

http://cires.colorado.edu/jimenez-group/wiki/index.php/DAURE_Microscopy
Esther Coz of CIEMAT/IDAEA-CSIC at RJ Lee Group, Inc. facilities

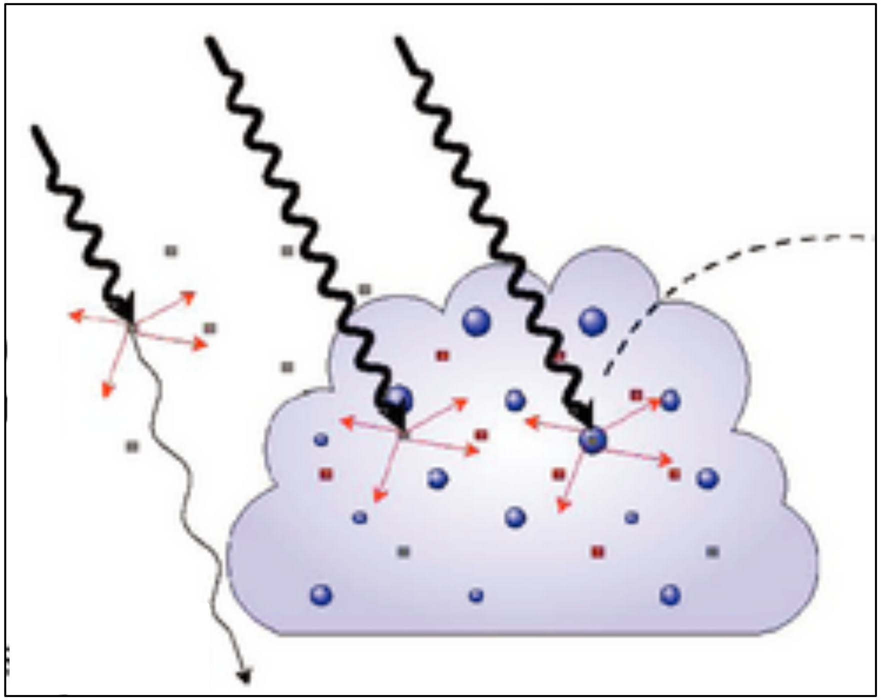
Black Carbon



INCIDENT – TRANSMITTED = ABSORBED + SCATTERED

Radiative Forcing Phenomena

- Direct radiative forcing
  - Local temp. change
- Semi-direct effect
  - Increased static stability below BC (warming or cooling)
  - Cloud evaporation

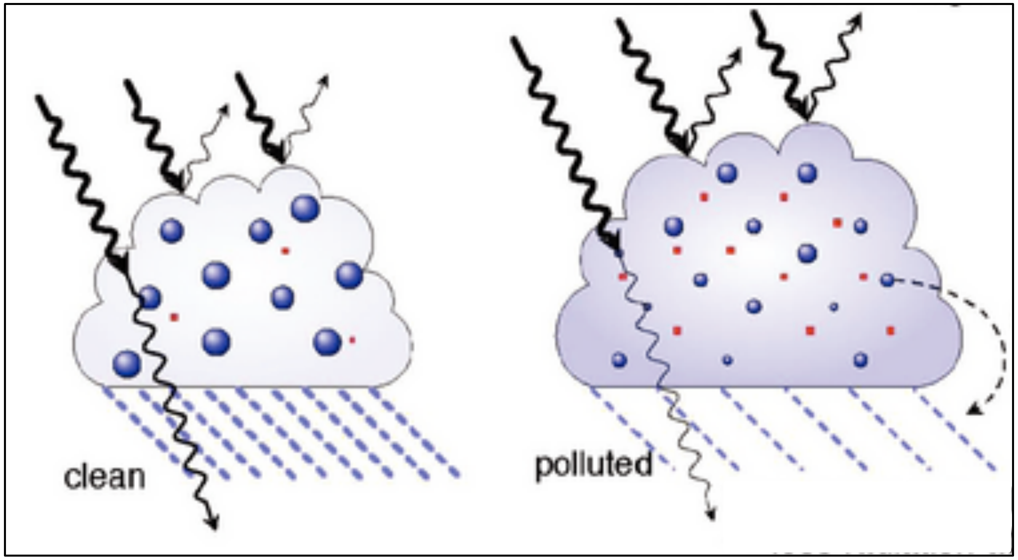


[Source: IPCC AR4, Chapter 7. 2007]

Radiative Forcing Phenomena

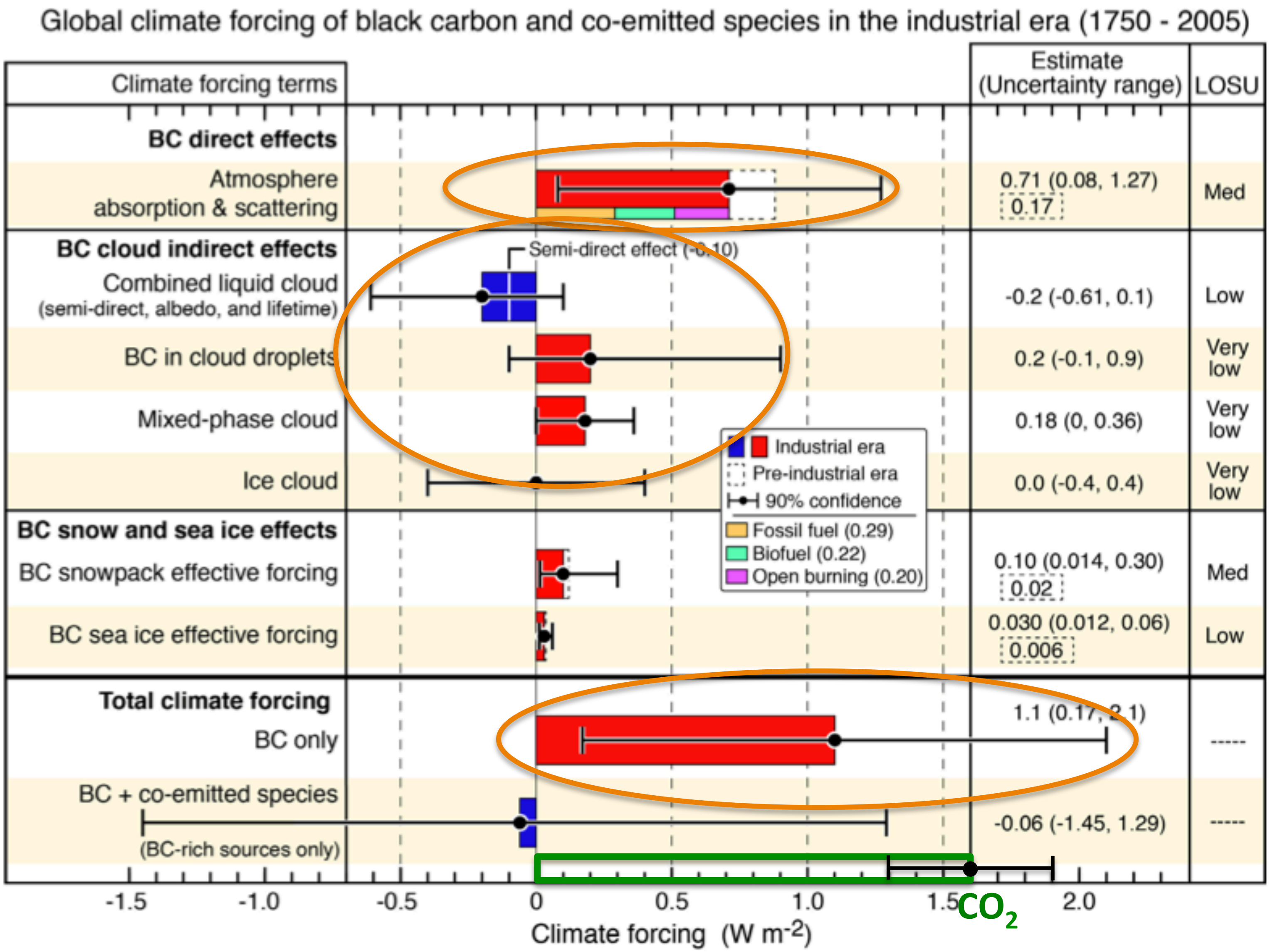
- Aerosol Indirect Effect

  Increase in cloud albedo and lifetime due to increased cloud condensation nuclei



[Source: IPCC AR4, Chapter 7. 2007]

Anthropogenic BC Climate Forcing



Bond et al. (2013)

Global BC Surface Concentration (model year 2000)

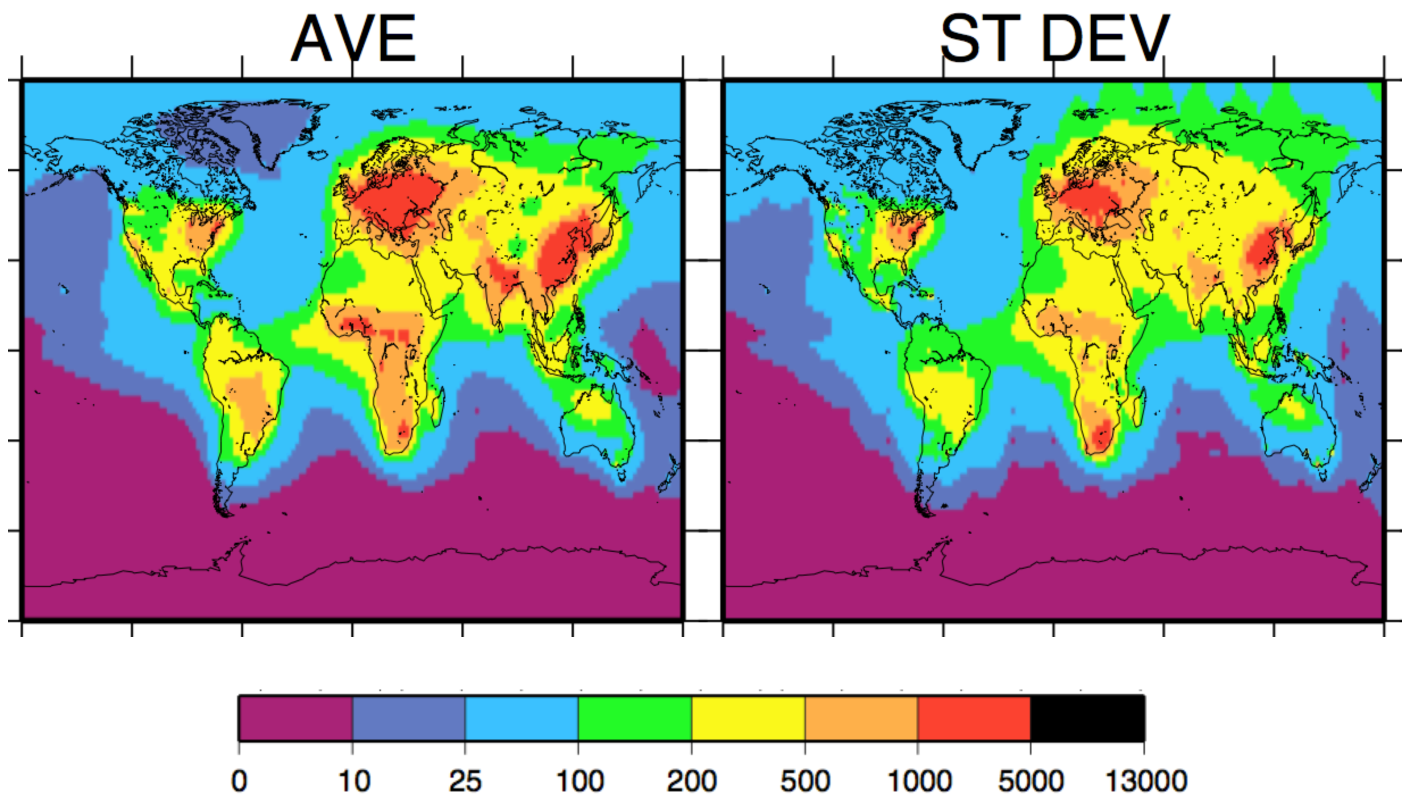


Fig. 2. AeroCom models annual mean BC surface concentrations (ngm^{-3}).

Koch et al. (2009)

Concentration Uncertainty Attribution

- Boundary Conditions: upstream chemical boundary should be well-characterized or based on global model results
- **Emissions Inventories**
  - **Anthropogenic (e.g. diesel, industrial coal, biofuel cooking/heating) [1,220 to 15,000 Gg yr^{-1}]**
  - **Open Biomass Burning [2,000 to 11,000 Gg yr^{-1}]**
- Vertical Mixing/Transport (future work)
- Wet/dry Deposition Losses (future work)

How to determine error sources?

- Sensitivity Studies
  - Perturb model inputs
    - Non-exact derivatives, low detail information
    - Expensive for thorough study of all inputs

      N+1 model runs for N finite difference sensitivities (see below)
  - **Adjoint**
    - **Exact sensitivities**
    - **Single model run for sensitivity of single output to all inputs**

      u, v, w, T, q_v, [BC] and E_{BC} at all input locations/times

      Example model run: 192,000 locations, 24 hourly times.

- Data Assimilation: Assess error sources and reduce model bias by perturbing inputs (future work)

Offline vs. Online Meteorology

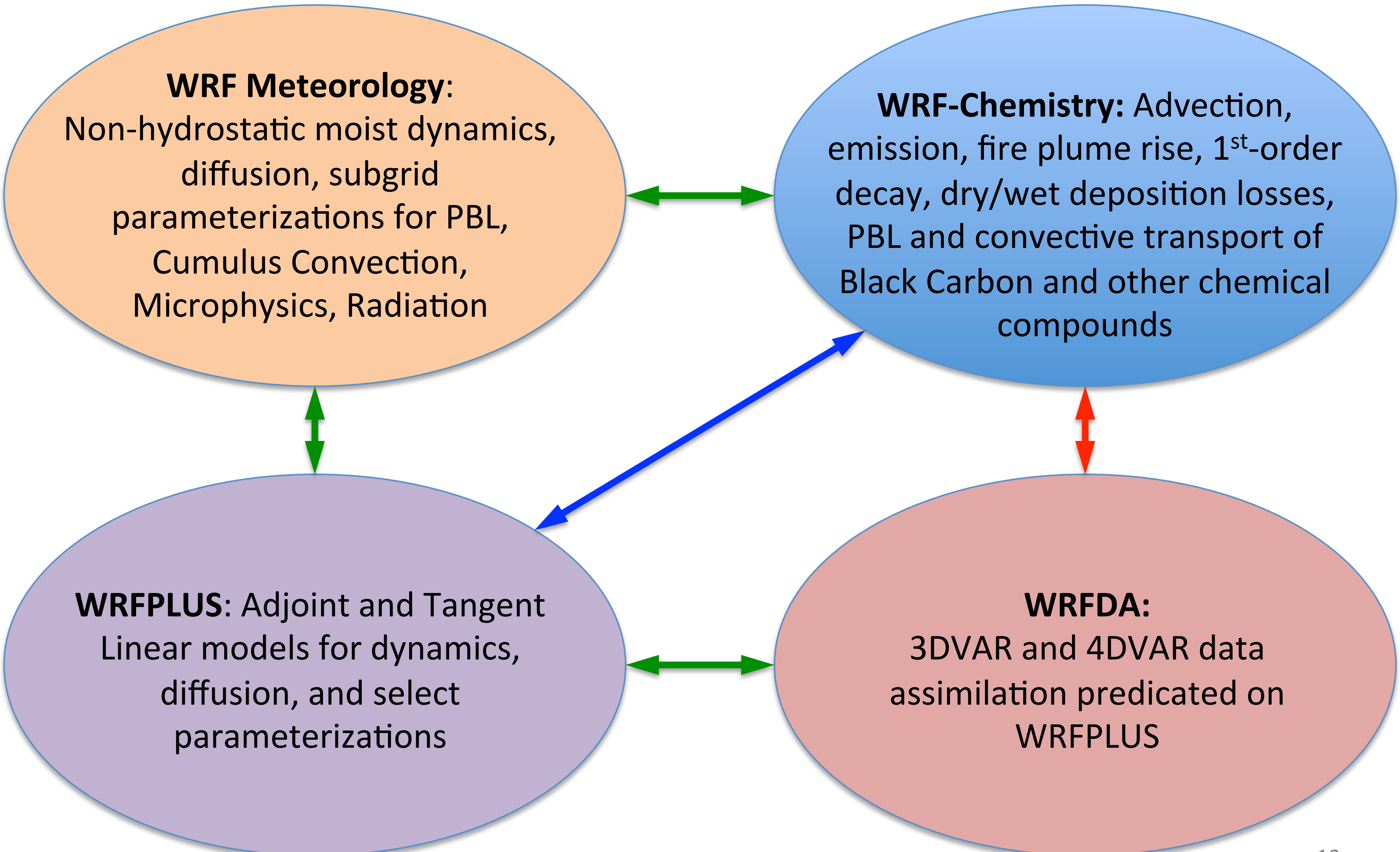
- Chemical Transport Model (CTM)
  - Offline physics state variables from reanalysis data
  - dt = 1-6 hr, with interpolation
  - Direct radiative forcing only
- **MET-Chem model**
  - **Online dynamics solved every time step**
  - **Feedbacks between BC absorption and meteorology**
  - **Direct and cloud radiative forcing**

Previous CTM Adjoint Studies

- "Adjoint inverse modeling of BC during the Asian Pacific Regional Aerosol Characterization Experiment"
  - Hakami et al. (2005)
  - Recovered spatially resolved anthropogenic and biomass-burning emissions using 4DVar Data Assimilation

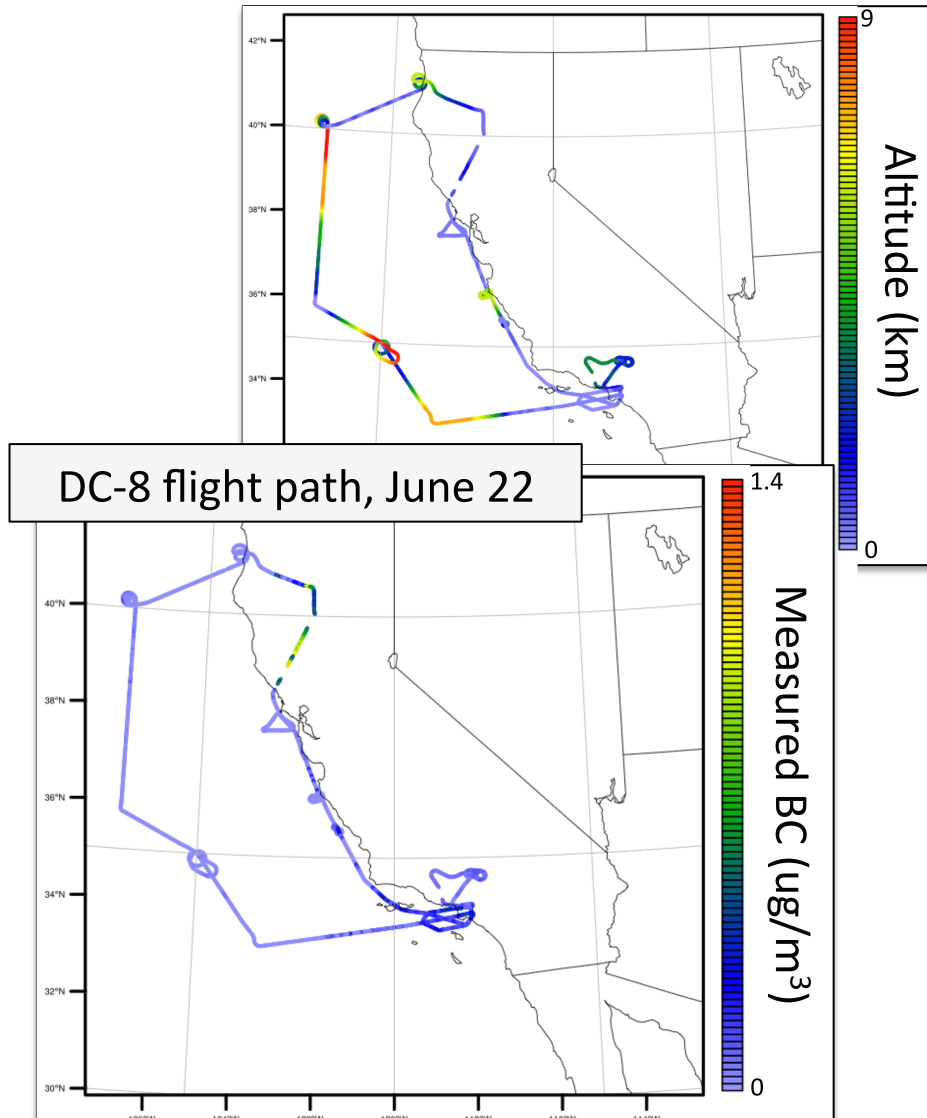
- "Origin and radiative forcing of black carbon transported to the Himalayas and Tibetan Plateau"
  - Kopacz et al. (2010)

WRF Model Capabilities



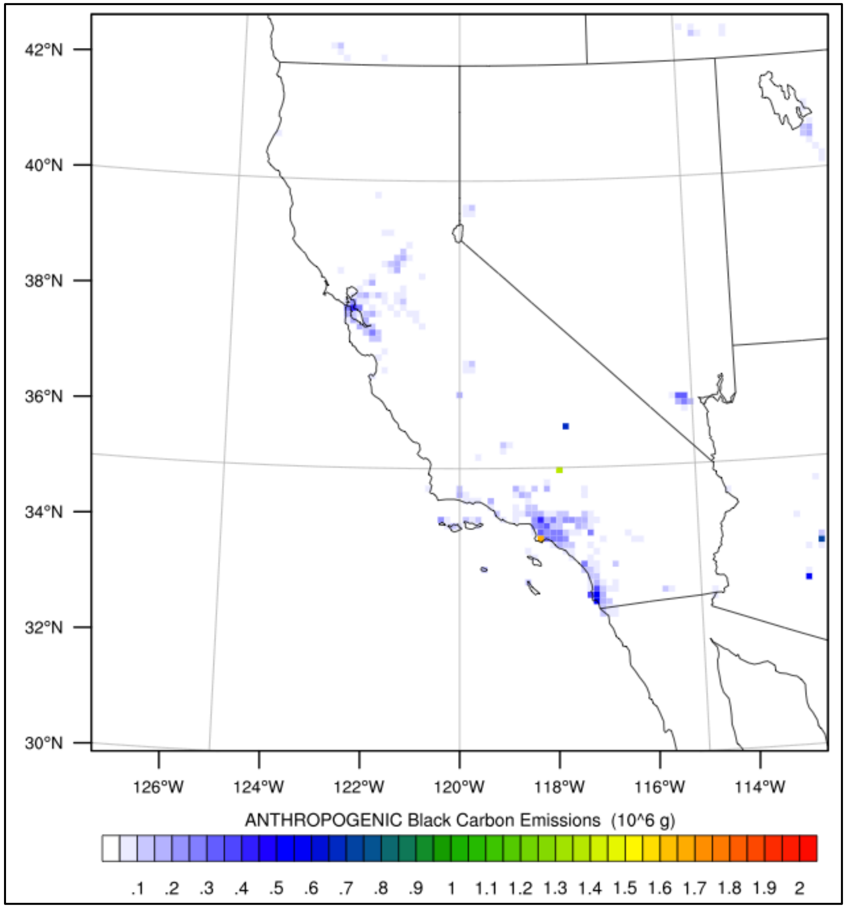
2008 ARCTAS-CARB Case Study

- Aircraft retrievals Jun 20, 22, 24, 26 over CA
- BC measured from SP2 device on board DC-8
- Fires in Northern California
- Clear skies (no cumulus clouds)

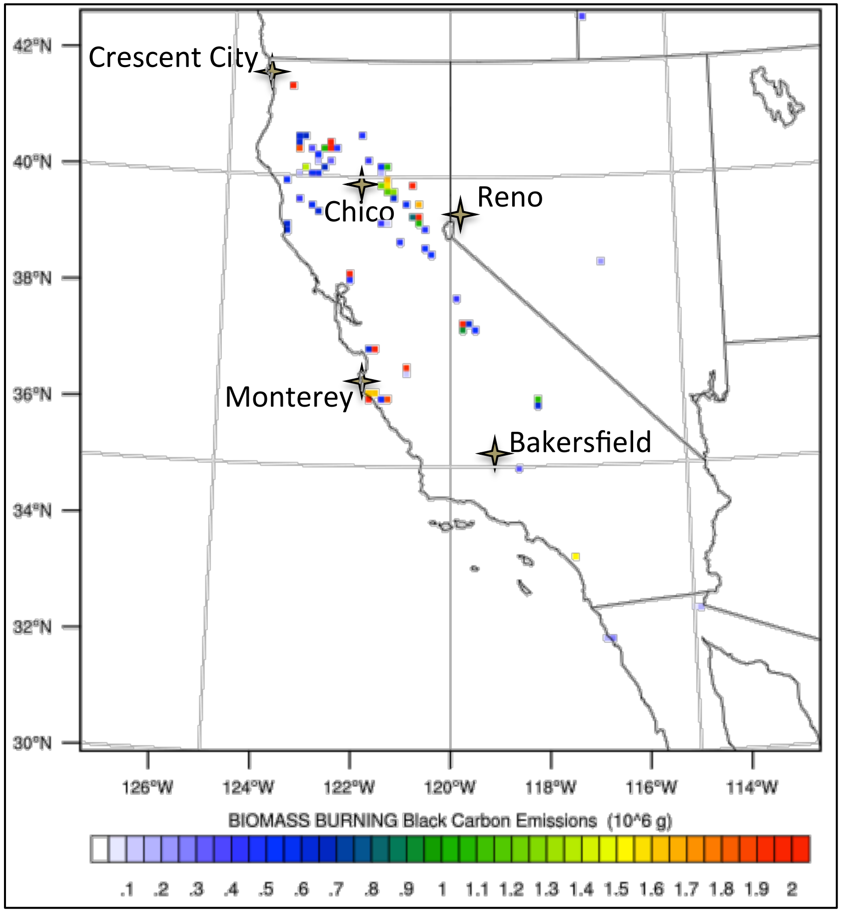


Jun 22, 2008 Emissions

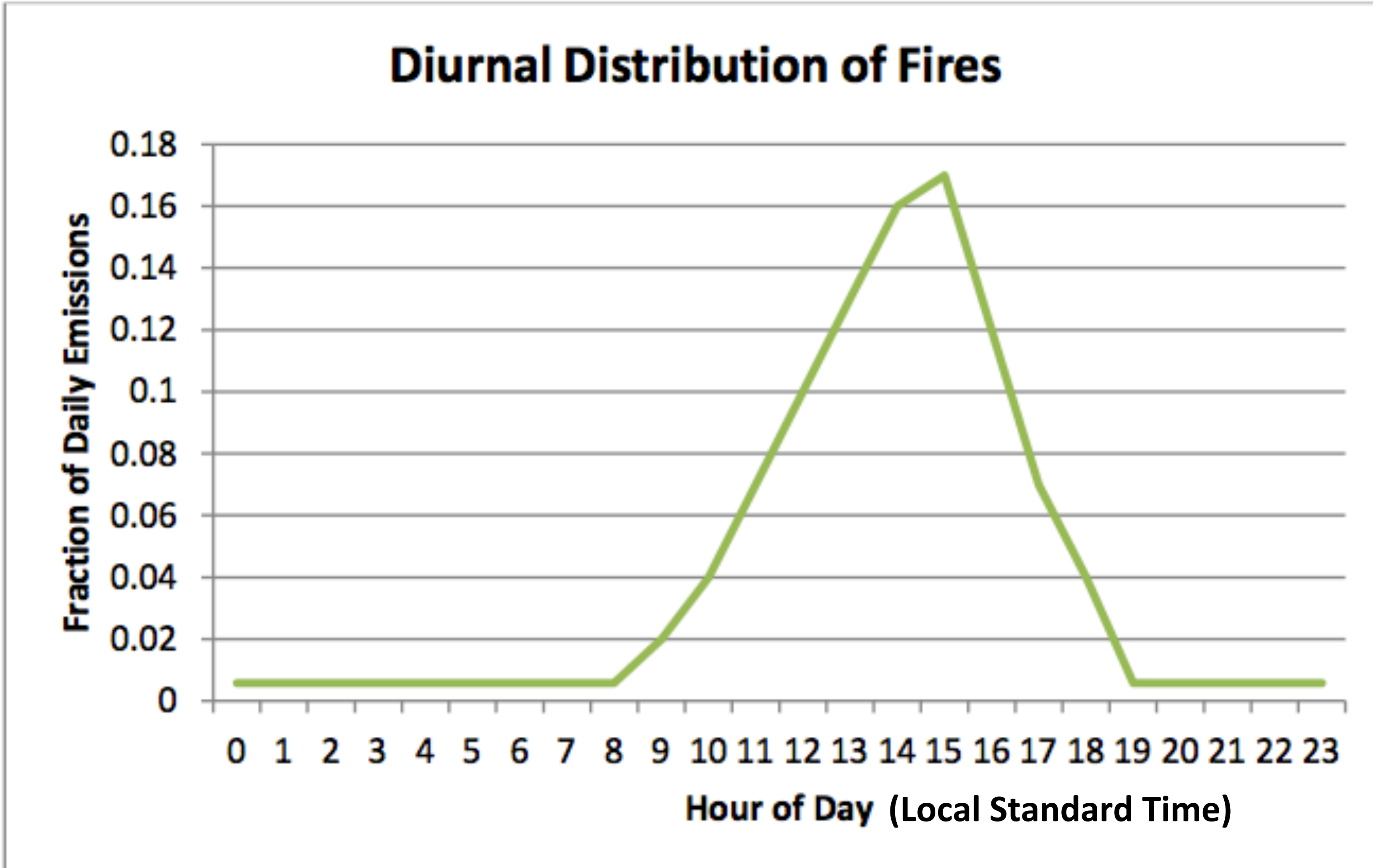
NEI2005 Anthropogenic Emissions



FINN Biomass Burning Emissions



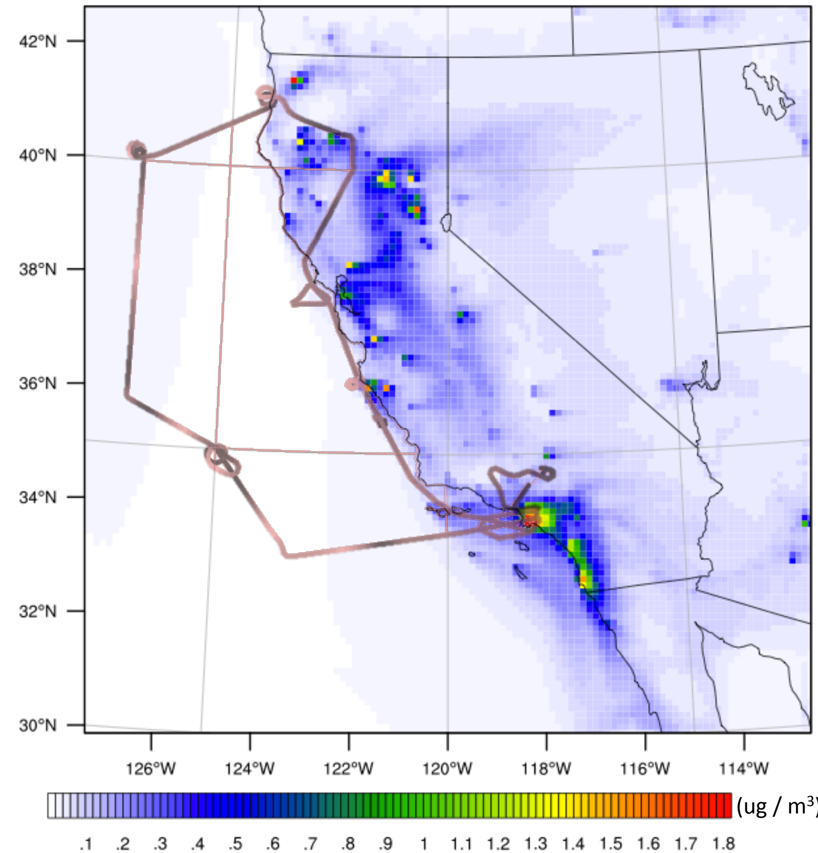
BC Biomass Emissions Diurnal Cycle

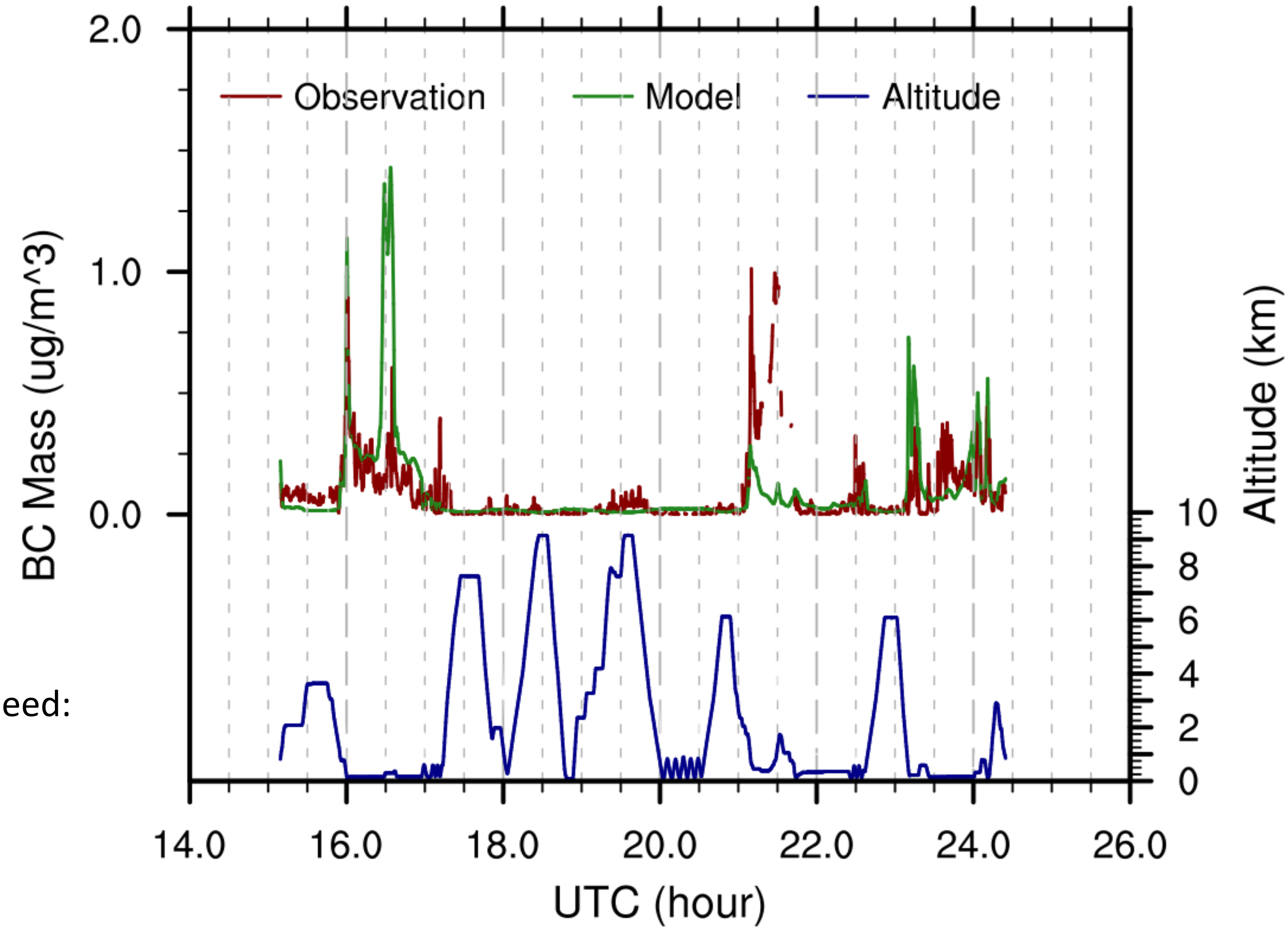


WRF-Chem Model Setup

- dx = 12 km
  (120 x 120 x 30 levels)
- dt = 60 seconds
- Initial Conditions:
  Spin-up from Jun 15
- Boundary:
  [BC] = 0.01ug/m^3
- Anthropogenic: NEI2005
- Biomass Burning: FINN

Jun 22 Average WRF-Chem Surface BC



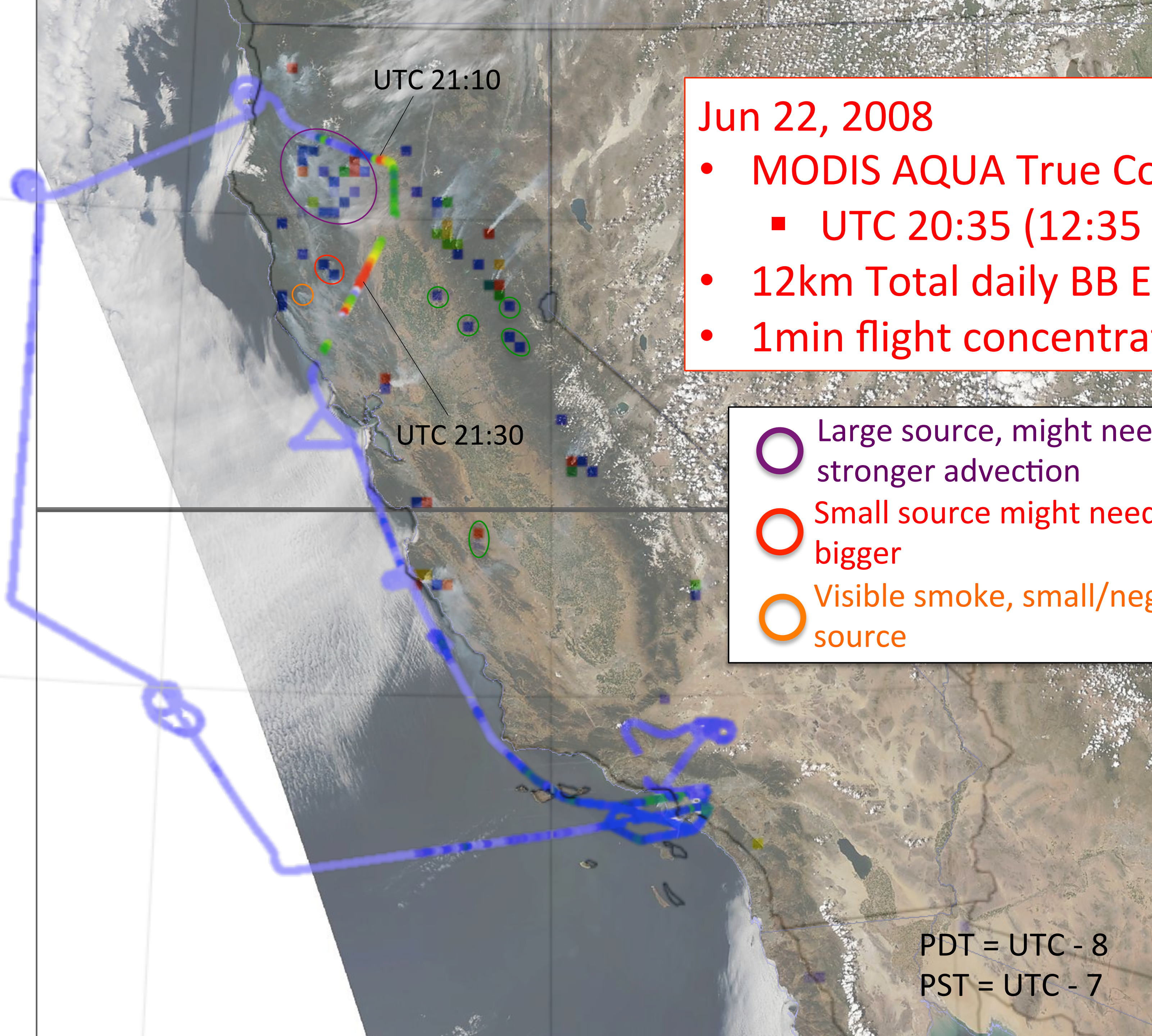


Typical air speed:
8-12 km/min

- 2 minute average observation (10 sec from instrument)
- 1 hour model interpolated to 10 sec measurement locations, then averaged every 2 minutes

Jun 22, 2008

- MODIS AQUA True Color
  - UTC 20:35 (12:35 PST)
- 12km Total daily BB Emissions
- 1min flight concentration

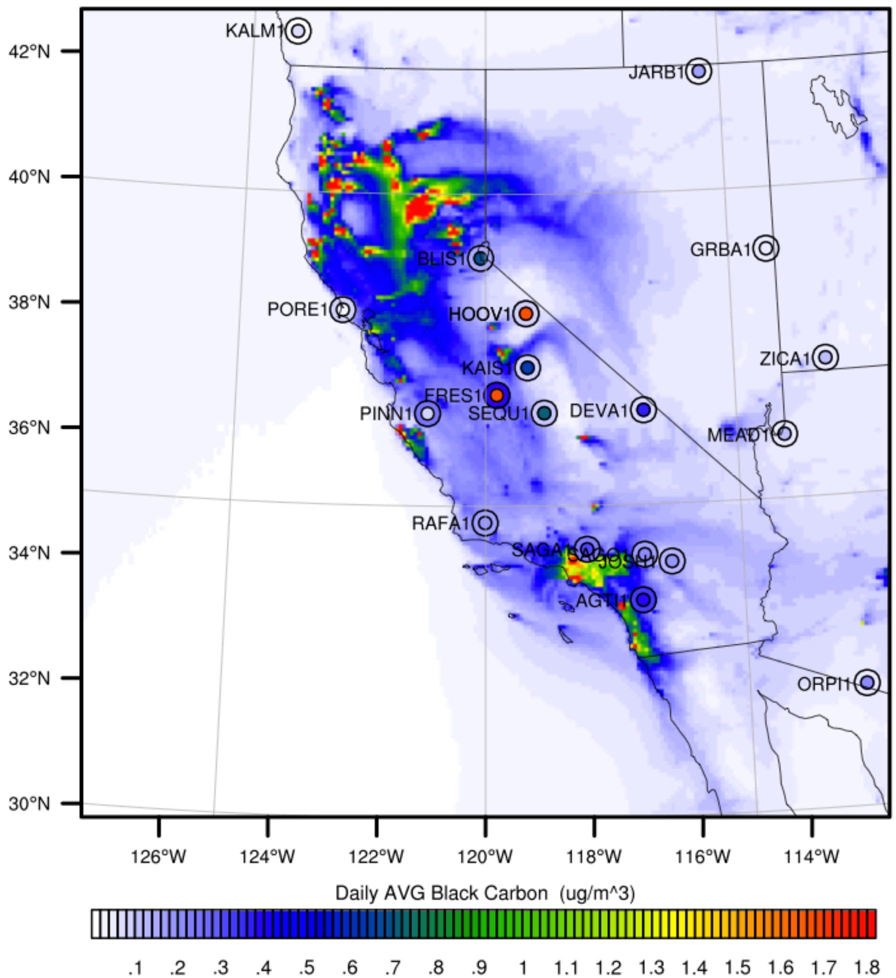


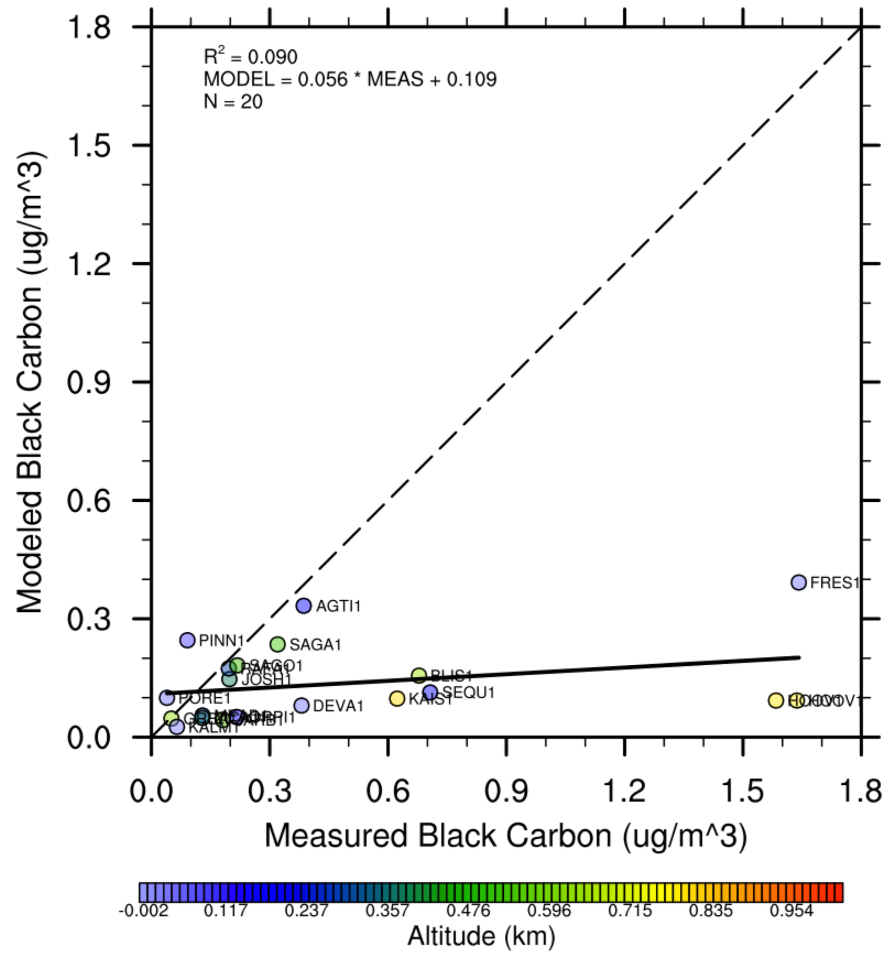
Large source, might need stronger advection

Small source might need to be bigger

Visible smoke, small/negligible source

June 23 Average Surface BC (IMPROVE network)





Adjoint Modeling

- OUTPUTS: Sensitivity of a single scalar output to model inputs
- INPUTS: Adjoint forcing
- Adjoint variables are gradients of original model state variables, linearized at a chosen model configuration
- Integrates backwards from final to initial time

- Requires TRAJECTORY of nonlinear model state variables at every time step – memory intensive

Adjoint Forcing

- Choose the cost function

$$J = \sum_k \sum_j \sum_i [BC]_{i,j,k}$$

$$i = [i_0, i_f], j = [j_0, j_f], k = [k_0, k_f]$$

- Take derivative w.r.t. state variables

$$\lambda_{BC,i,j,k} = \left.\frac{\partial J}{\partial [BC]}\right|_{i,j,k} = \left[\begin{array}{ll} & i_0 < i < i_f, \\ 1.0 & j_0 < j < j_f, \\ & k_0 < k < k_f \\ 0.0 & otherwise \end{array} \right.$$

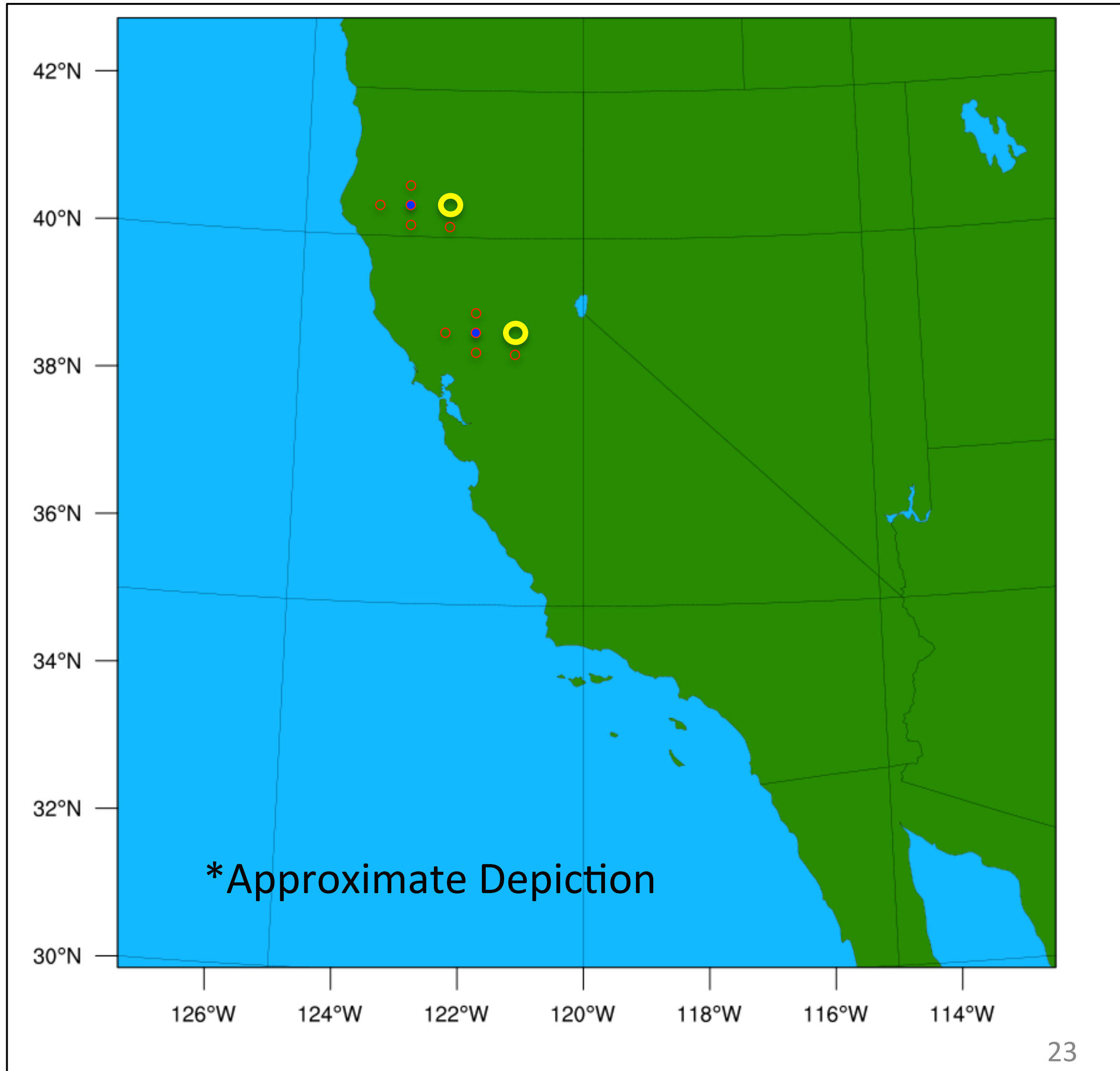
New Adjoint Capabilities

- **Anthropogenic and Biomass Burning Emissions for BC and sulfate precursors**
- **BC aging**
- **Sulfate aerosol chemistry (TESTING)**
- PBL transport of chem species (DEVELOPING)
- Deep cumulus convective transport of chem species (DEVELOPING)
- Dust aerosols (FUTURE WORK)

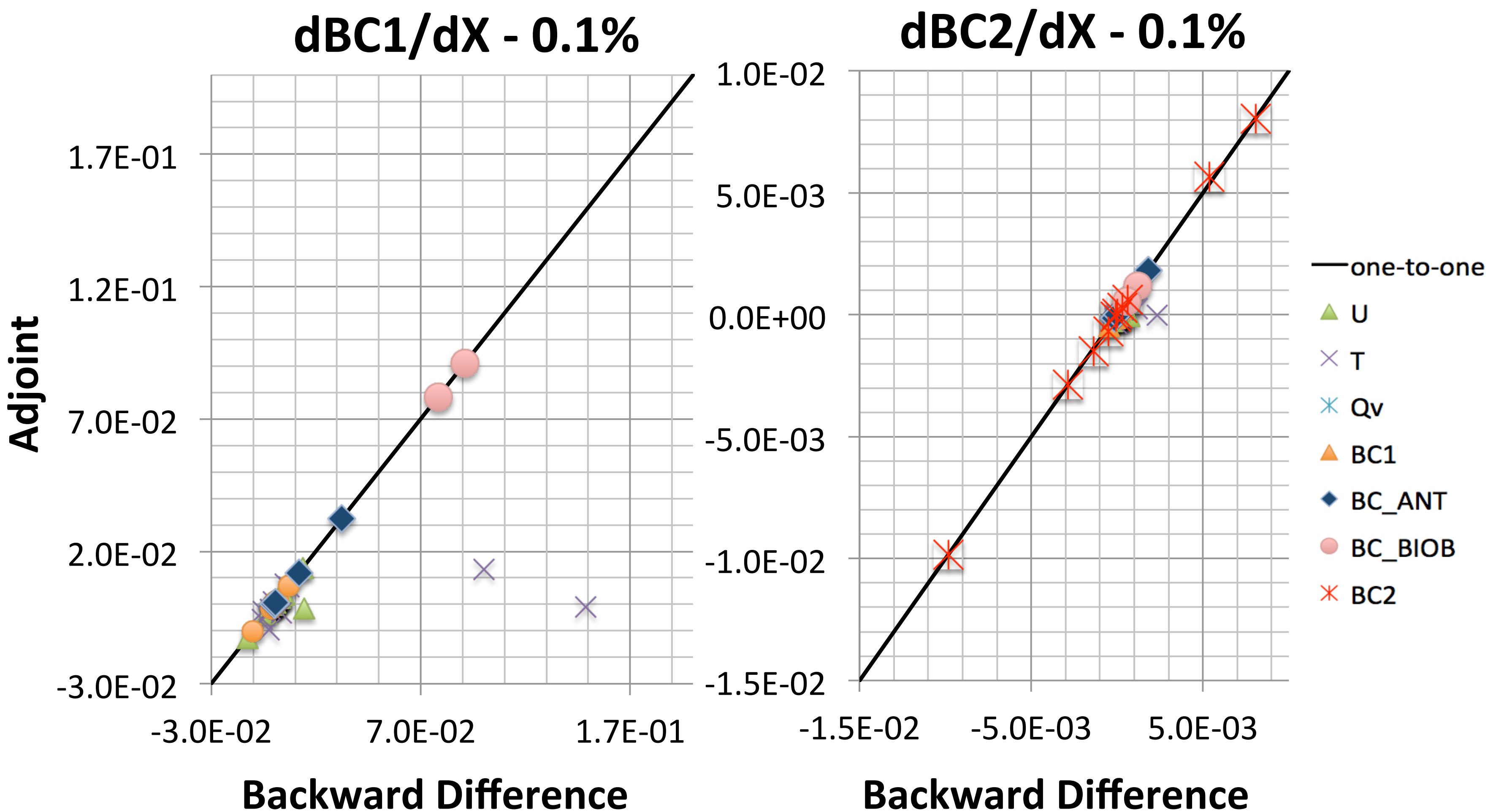
Finite Difference Test

Locations:

Final i	Final j	Final k	Initial i	Initial j	Initial k
28	64	1	24	64	1
28	64	1	28	63	1
28	64	1	26	63	1
28	64	1	26	65	1
28	64	1	26	64	2
35	53	1	31	53	1
35	53	1	35	52	1
35	53	1	33	52	1
35	53	1	33	54	1
35	53	1	33	53	2

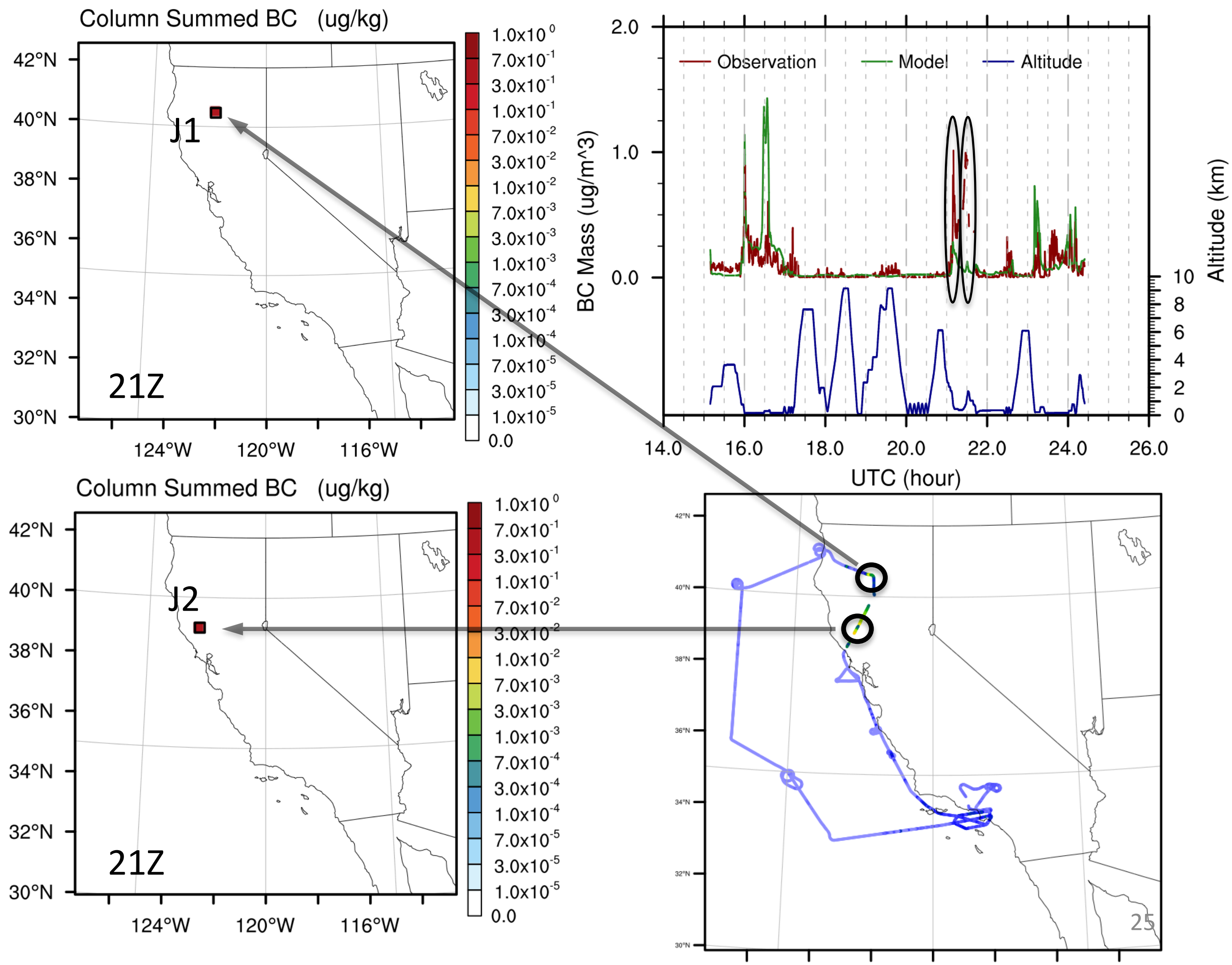


Model Verification: Results

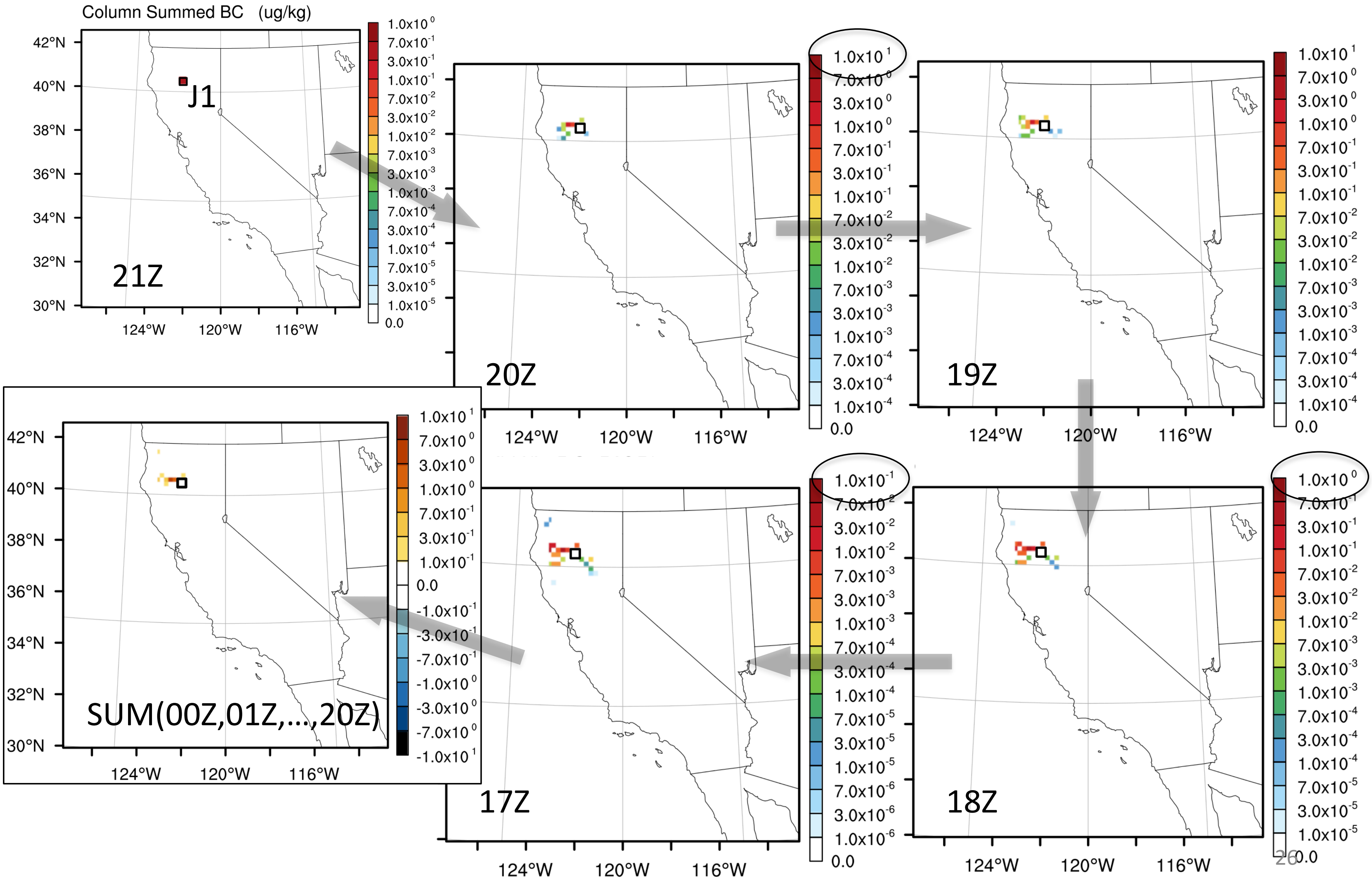


ARCTAS-CARB Sensitivity Study

dx = 18km
dt = 90 seconds



Sensitivity of Column BC to Emissions(x,t)



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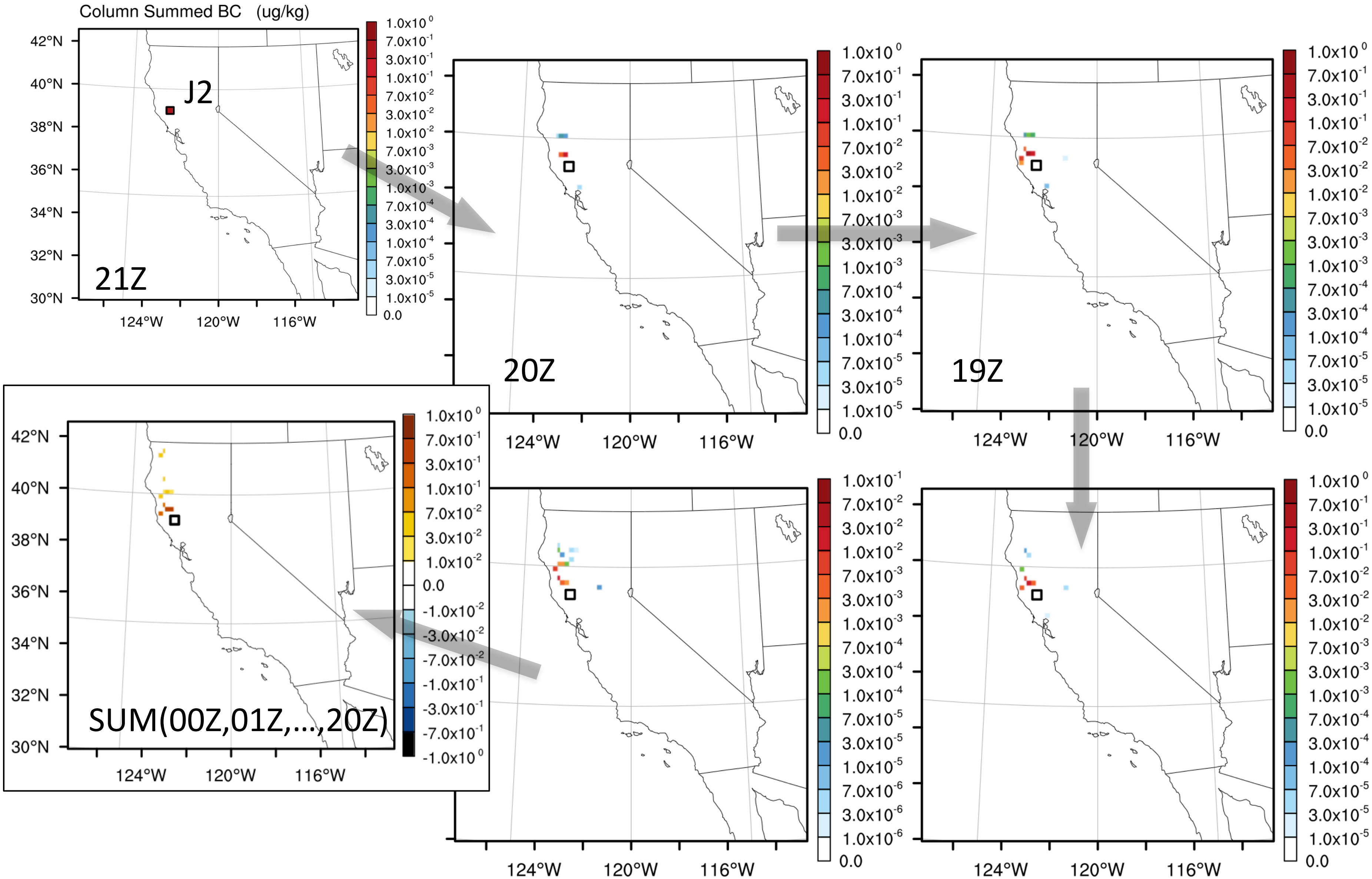
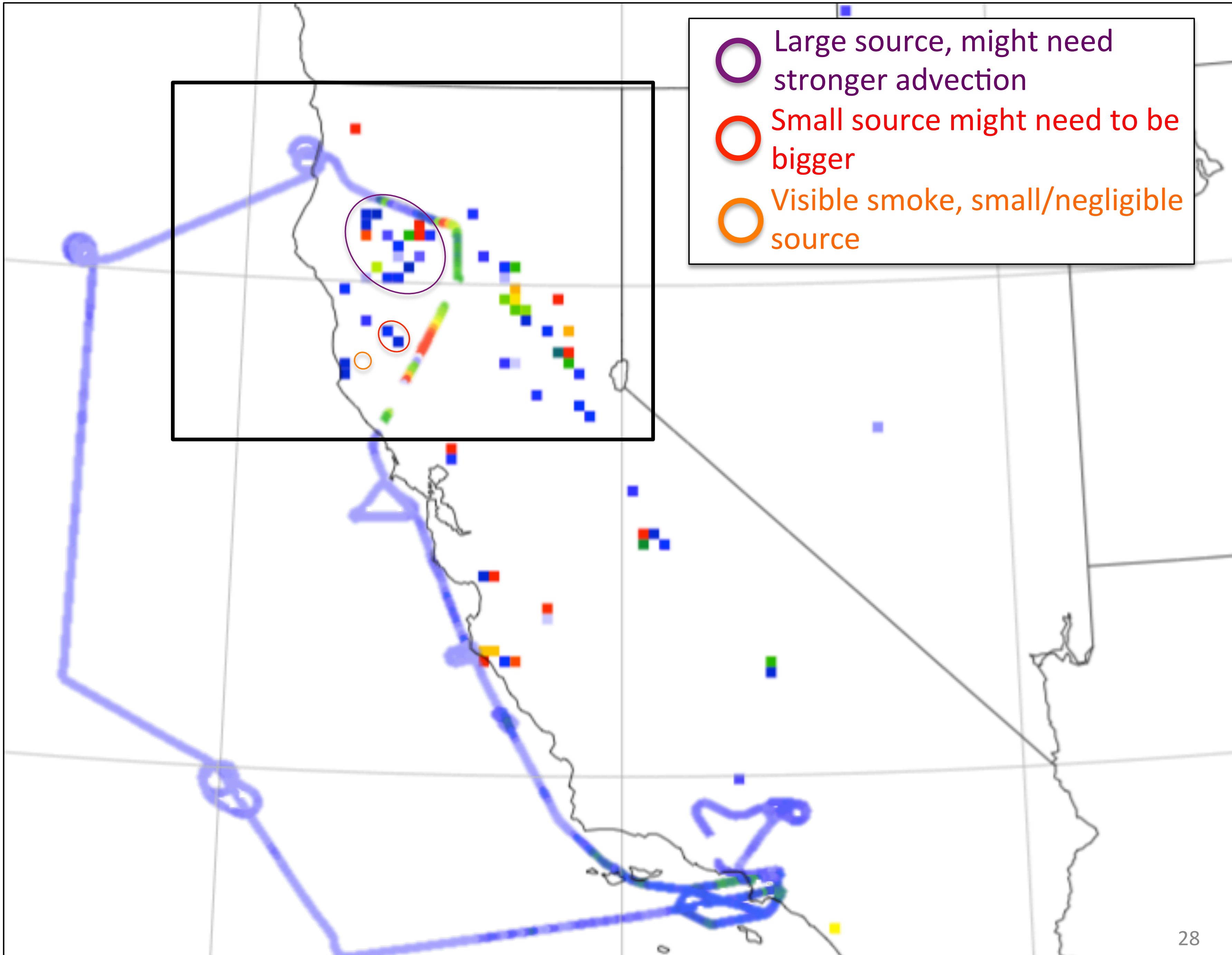
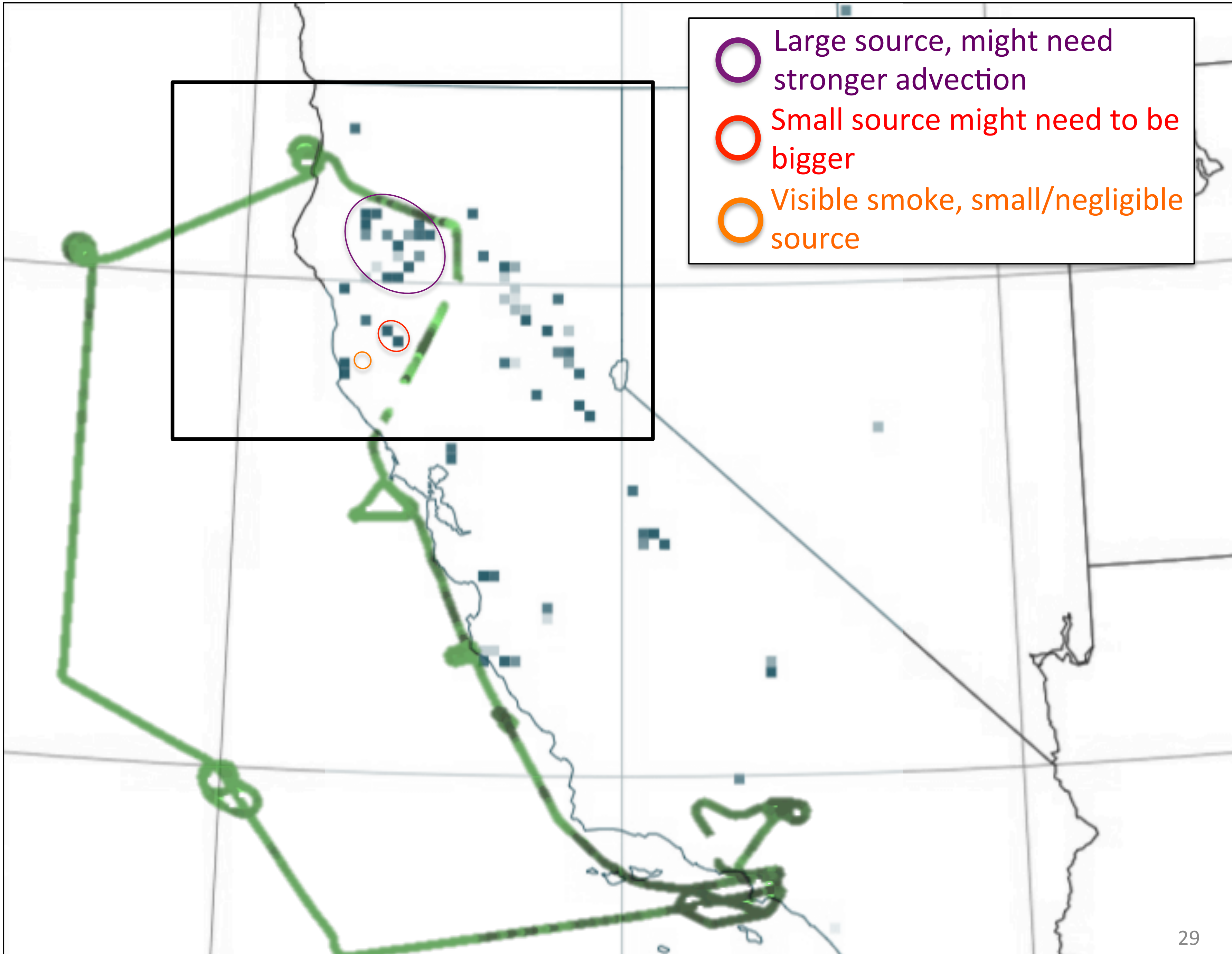



Large source, might need stronger advection
Small source might need to be bigger
Visible smoke, small/negligible source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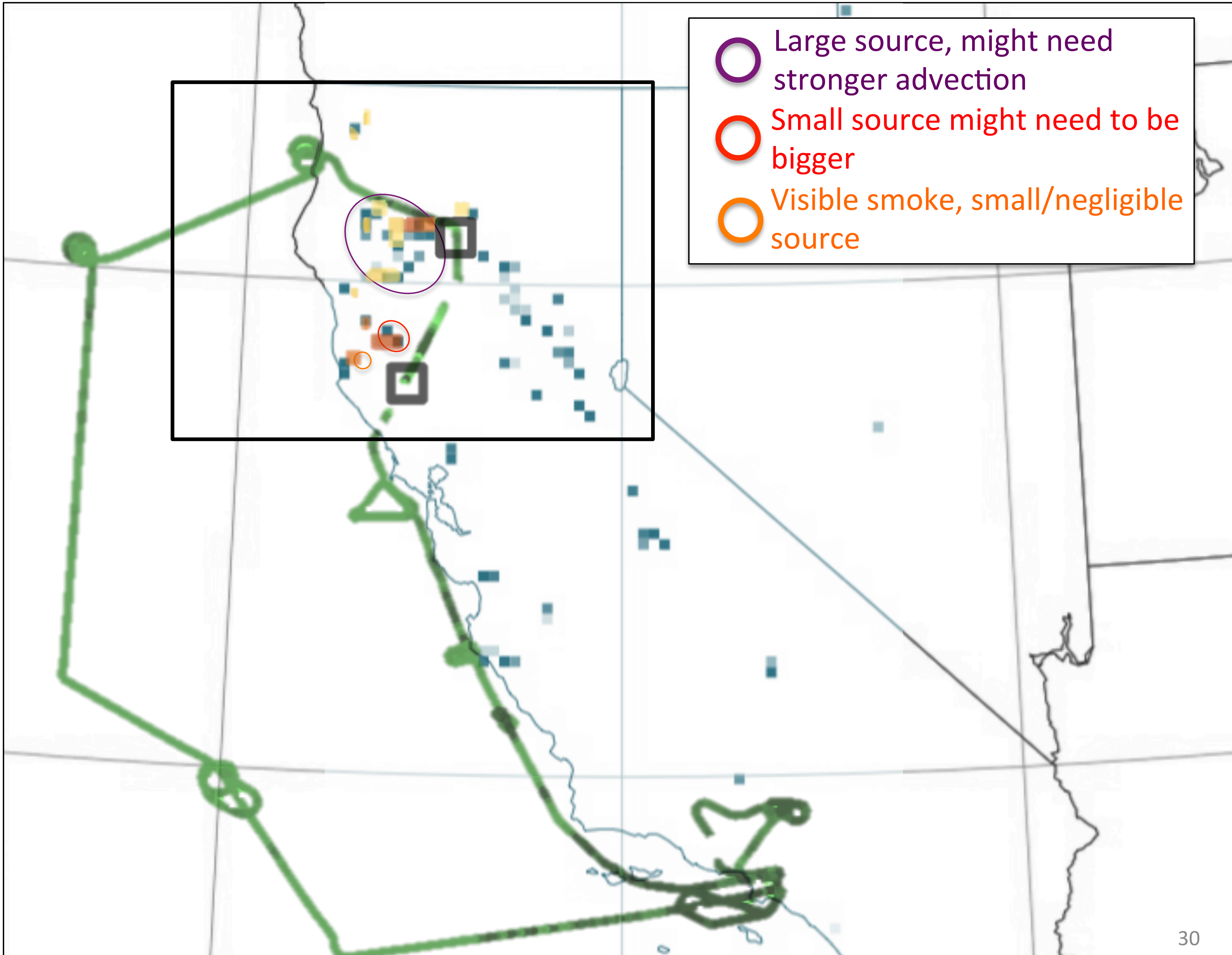

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Visible smoke, small/negligible source

Next Steps

- Increase Adjoint resolution to 12km (3.375x memory and time requirements)
- Add PBL and Cumulus Convection adjoints to trace back vertical transport
- Include multiple obs. and multiple obs. types in a single adjoint simulation

- Long Term: 4DVar Data Assimilation

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Bottom-up Emission Inventories

- Anthropogenic

$$E_{ANT,i} = A_i EF_i (1 - eff_i)$$

A = activity
EF = emission factor
eff = abatement efficiency

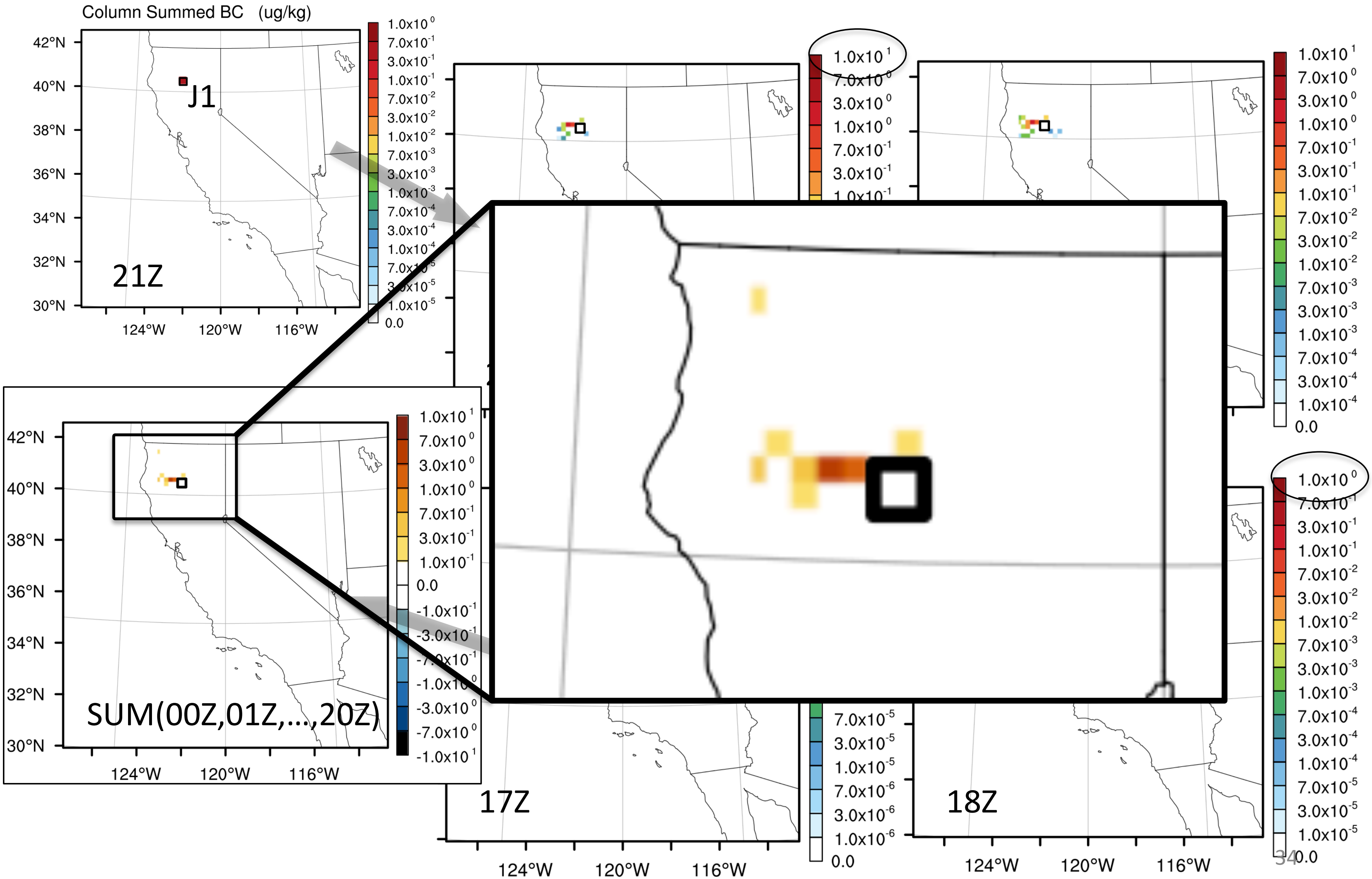
- Biomass Burning (0.29-5.0x uncertainty bands)

$$E_{BB,i} = BA_i FL_i CC_i EF_i$$

BA = burned area
FL = fuel load
CC = combustion completeness
EF = emission factor

Bond et al. (2013)

Sensitivity of Column BC to Emissions(x,t)



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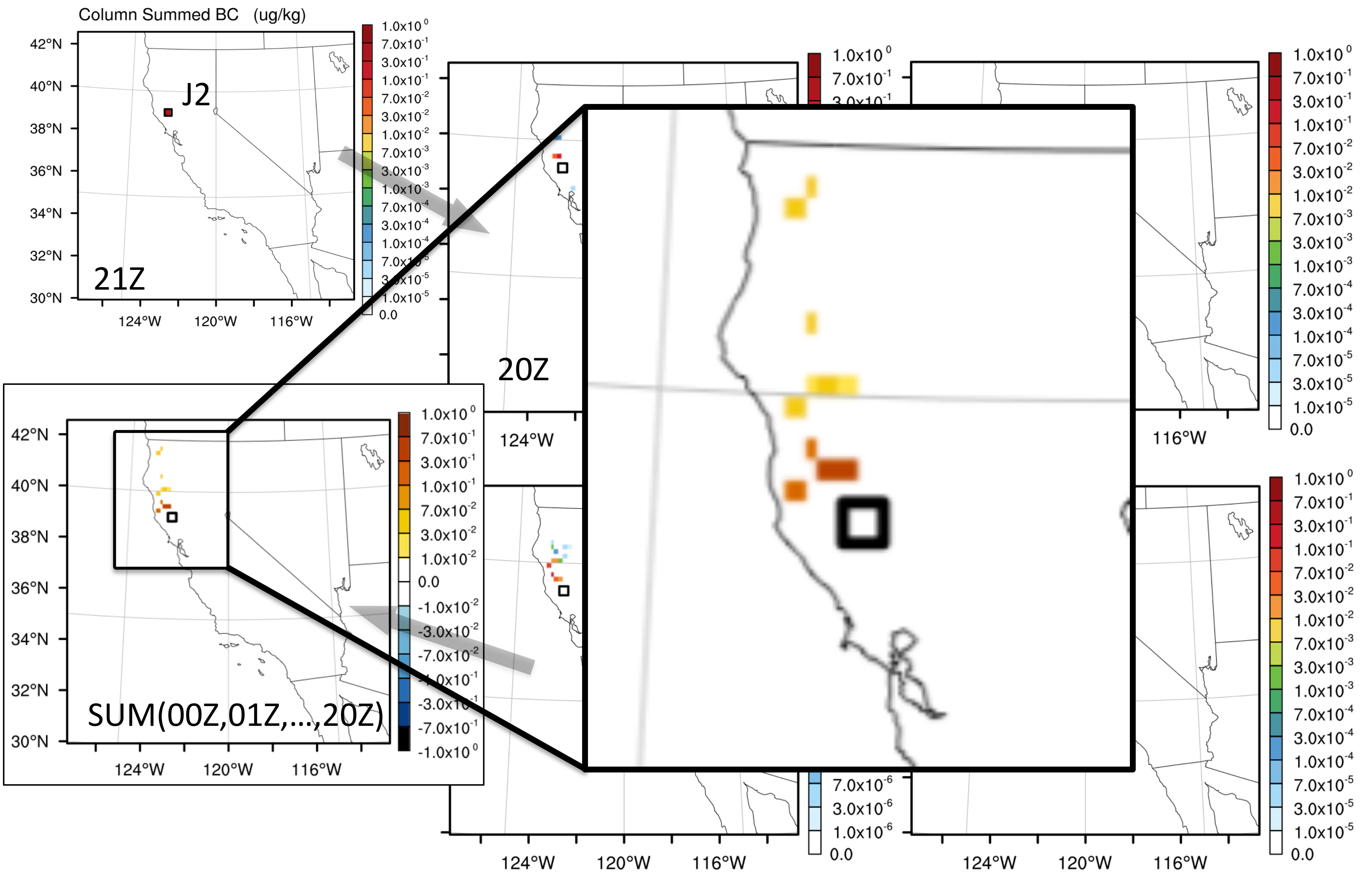

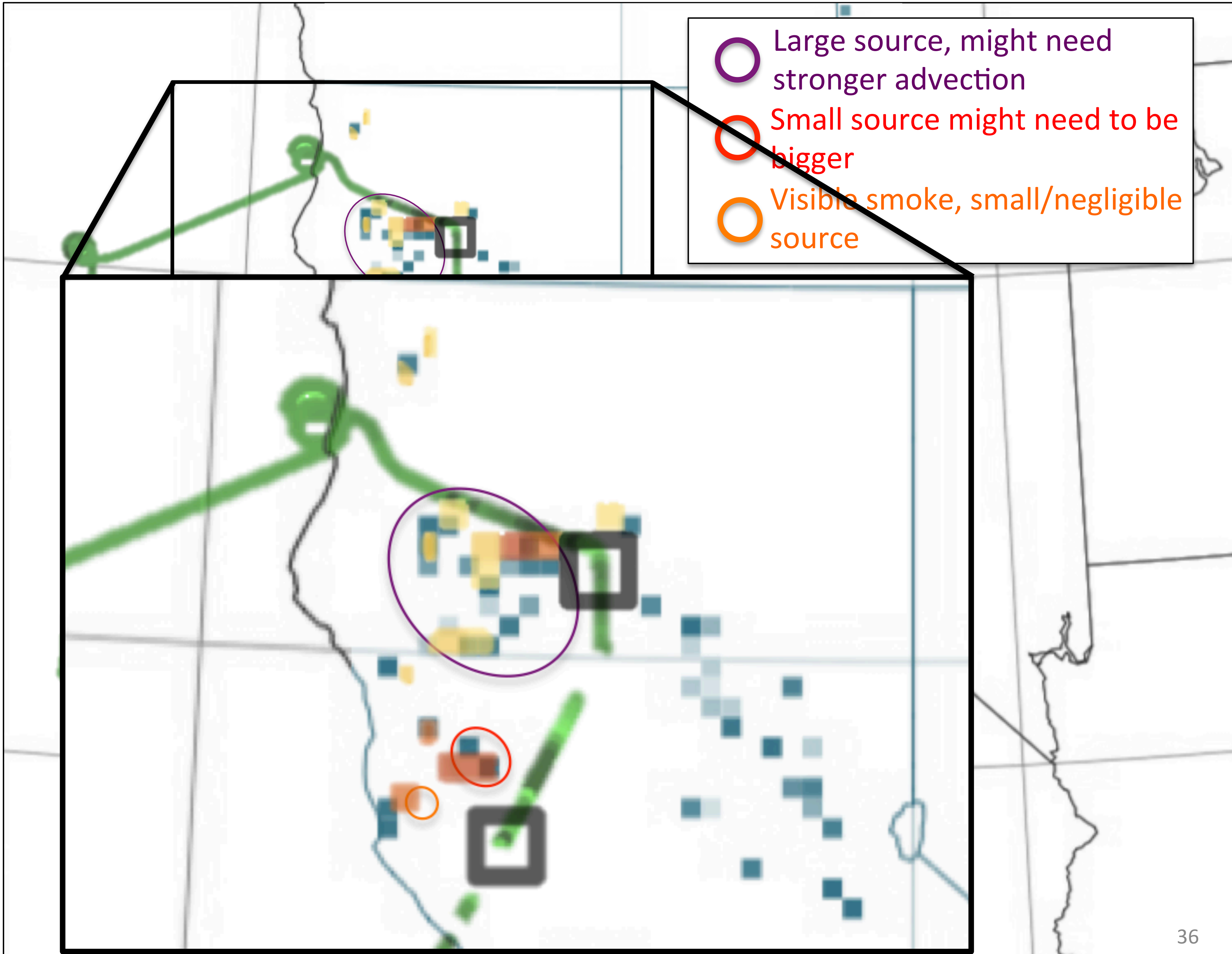
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