WRF-STILT Transport Modeling: An Introduction to the ASC Source-Receptor ("footprint") Library

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4th ABoVE Science Team Meeting
23 January 2018
Seattle, WA

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Purpose of Talk

- **Advertise existing footprint and WRF libraries to broader ABoVE community**

- **Describe how to read and apply footprints to your research**

- **Receive feedback from ABoVE science team members**
  - **Audience is encouraged to think about how these products can help with your current and future research**

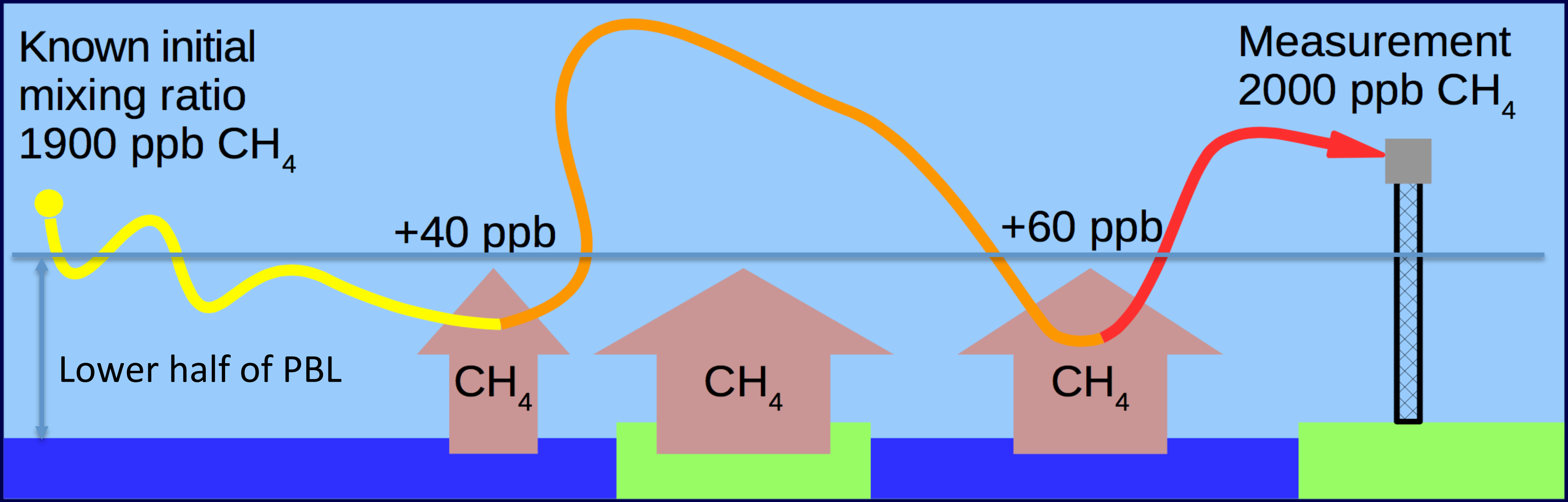
- **Framework for testing models (flux estimates) being put in place**
  - **Help us tailor the scripts to your needs**

- Outline of talk:
  - Introduction to footprints; how they are generated; their availability and application
  - Less focus on theoretical concepts and details of WRF-STILT model
  - Provide sample high-resolution WRF fields

Footprints – basic concept

Inferring fluxes from atmospheric data

- Path and CH_4 mixing ratio of an air parcel:

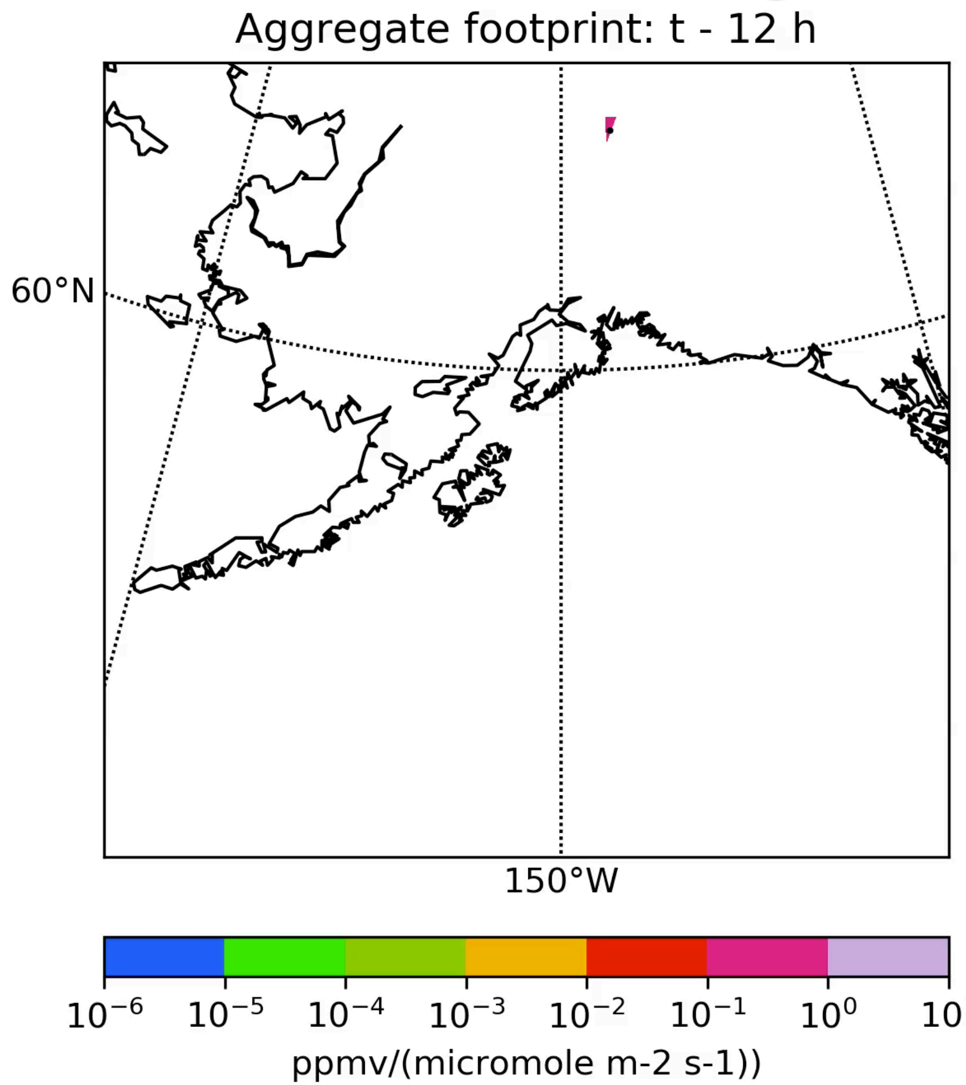


Footprints - basics

- Footprints describe “source-receptor” relationship
  - Often used to identify biogenic/biomass burning contributions
  - Receptor=observed concentration of GHG at x, y, z and t
  - Source=upstream location on Earth’s surface that may have contributed GHG fluxes
- Time-dependent, two-dimensional grid on Earth’s Surface
  - Typically 0.5x0.5-deg grid, but can be finer
- Effective adjoint of the transport model
- Computed using STILT Lagrangian Particle Dispersion Model
  - follow 500 tracer particles backward in time for each receptor
- Often applied to observations obtained from aircraft and towers
  - need x,y,z and t only -> species independent

STILT Transport Model: Standard footprint

- Footprints equivalent to adjoint of transport field of NWP model
- Species independent source-receptor relationship
- Release 500 particles at each receptor location
- Movement dictated by mean wind and turbulent motions
- Footprints are function of residence time of those trajectories in lower part of PBL and are inversely proportional to mixing height
- Continental-scale 0.5 deg x 0.5 deg footprint+0.1 deg nearfield
- **Units: ppm/(umol/m²s)**



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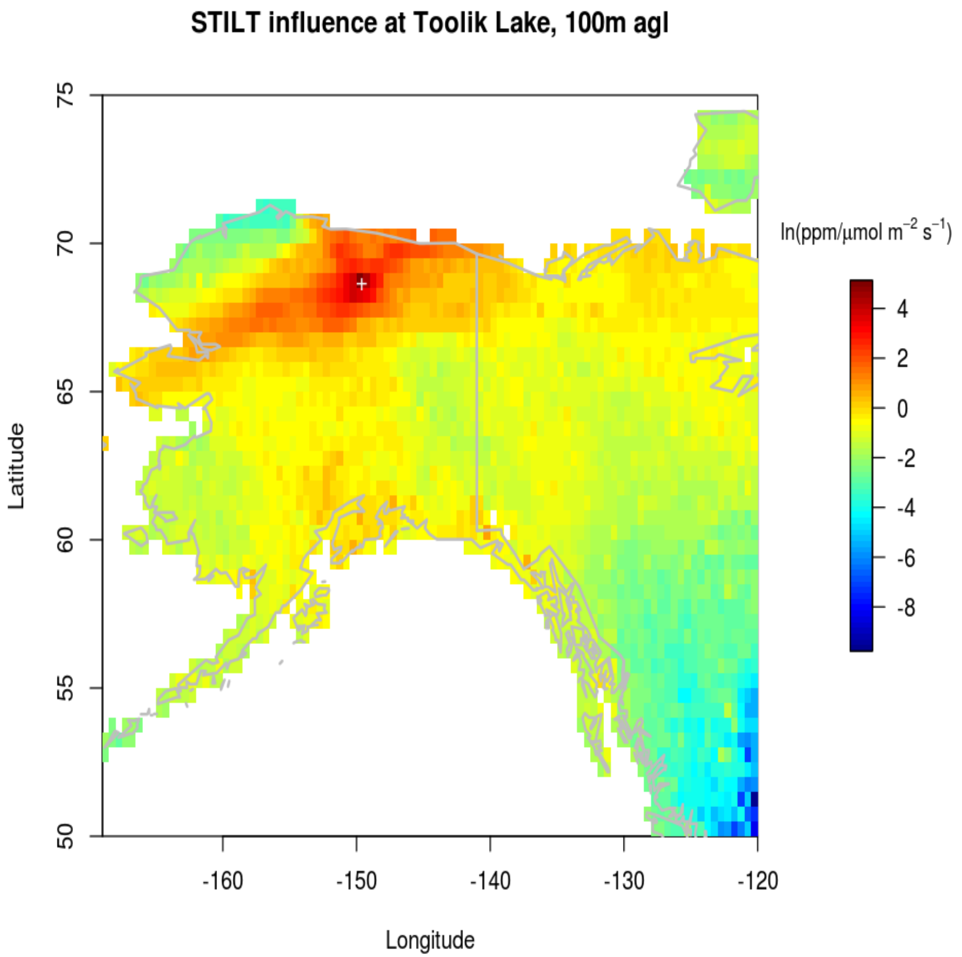

0.5-deg lat-lon grid for multiple receptors at Toolik Lake

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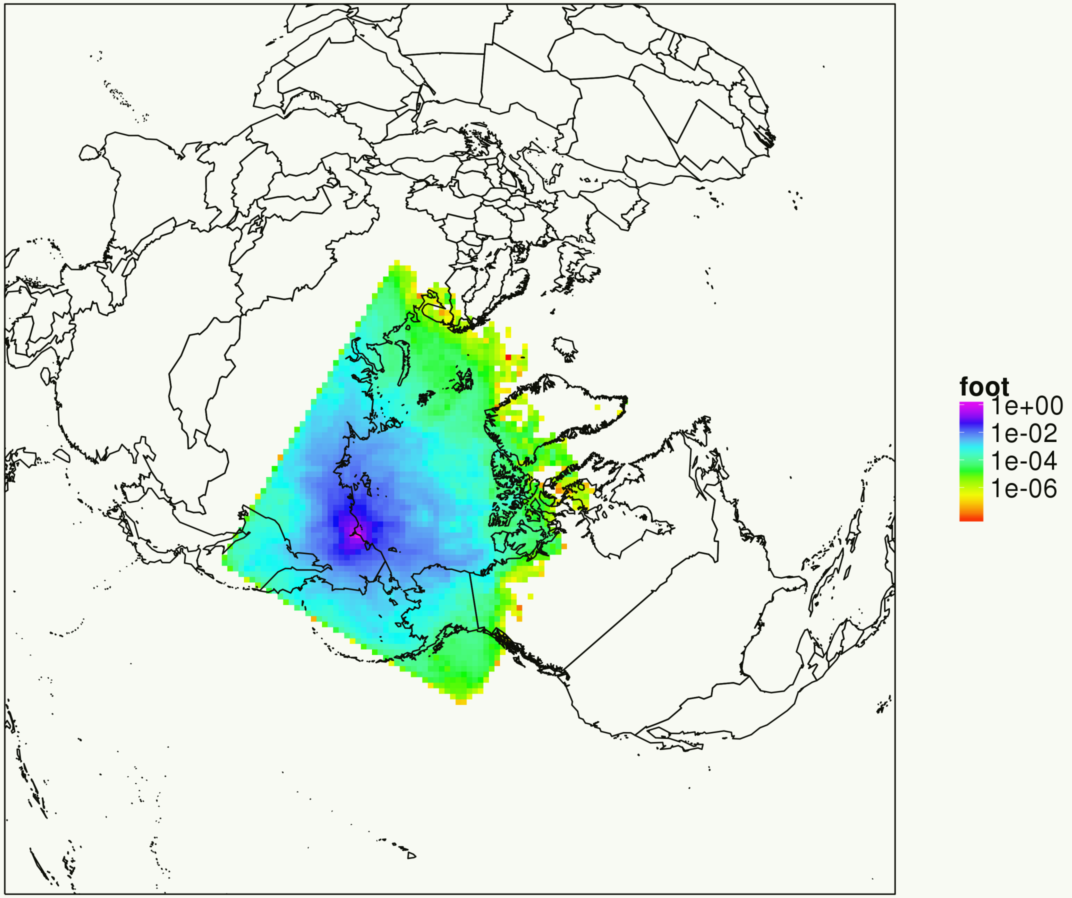
Comparison with flux footprint

- STILT concentration footprint:
  - Appropriate for regional and larger studies
  - Cumulative effect of multiple upstream surface contributions
  - Strongly influenced by regional-scale advection, plus stochastic component

- Flux footprint:
  - Eddy covariance: high-frequency vertical wind and gas concentration measurements
  - Source is immediately upstream (meters)
  - Scale of turbulent eddies; sub-grid scale wrt WRF grid; requires LES



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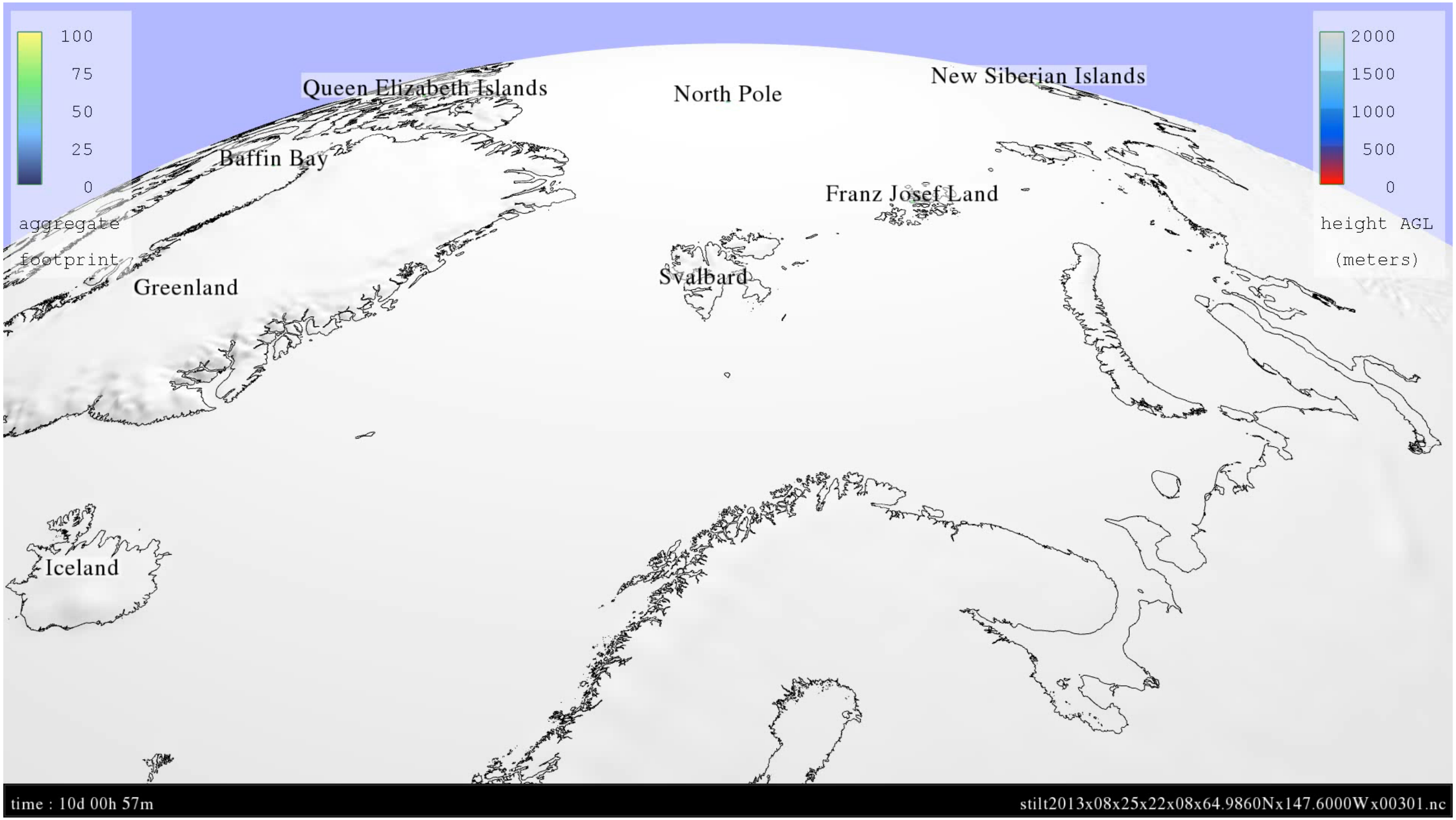
Reconstruction of flow toward obs location



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Footprints – How they are generated

- Two-step process using WRF-STILT:
  - Step 1): Simulate high-resolution meteorological fields using WRF (numerical weather prediction model)
  - Step 2) Apply WRF fields to Stochastic Time-Inverted Lagrangian Transport (STILT) dispersion model

Step 1 - CARVE WRF domain placement

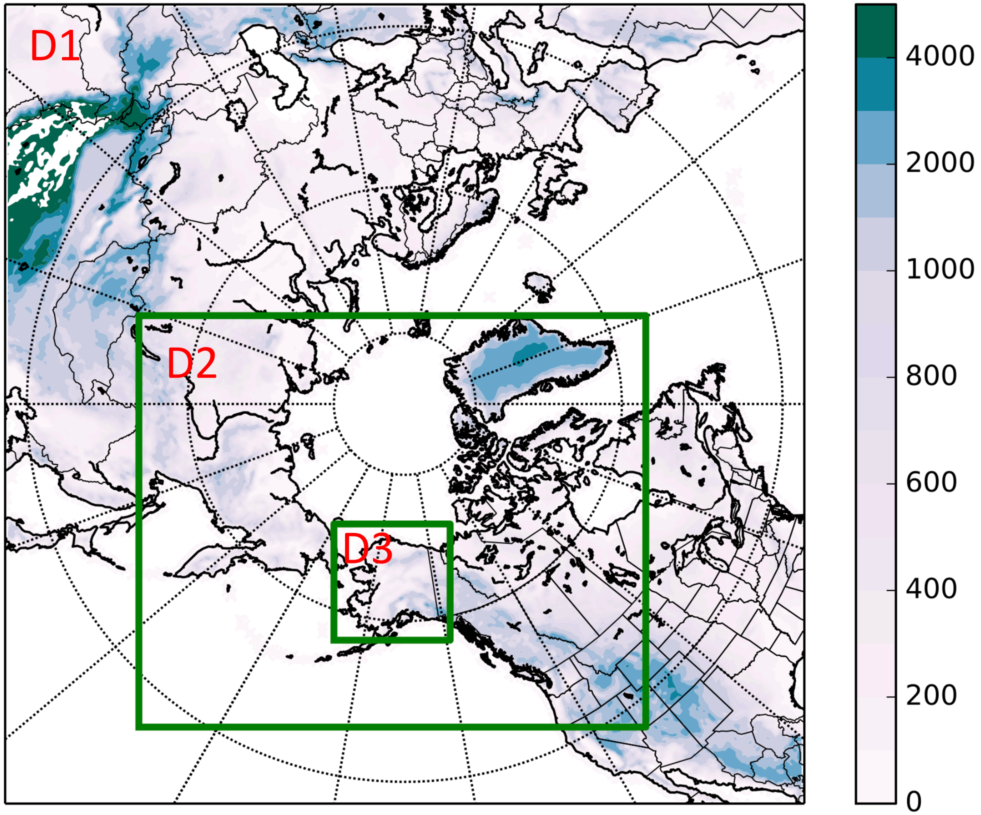
Polar stereographic grid

D1: 30-km 418x418

D2: 10-km 799x649

D3: 3.3-km 550x550

41 vertical levels



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Step 1 - CARVE-CAN domain placement

Polar stereographic grid

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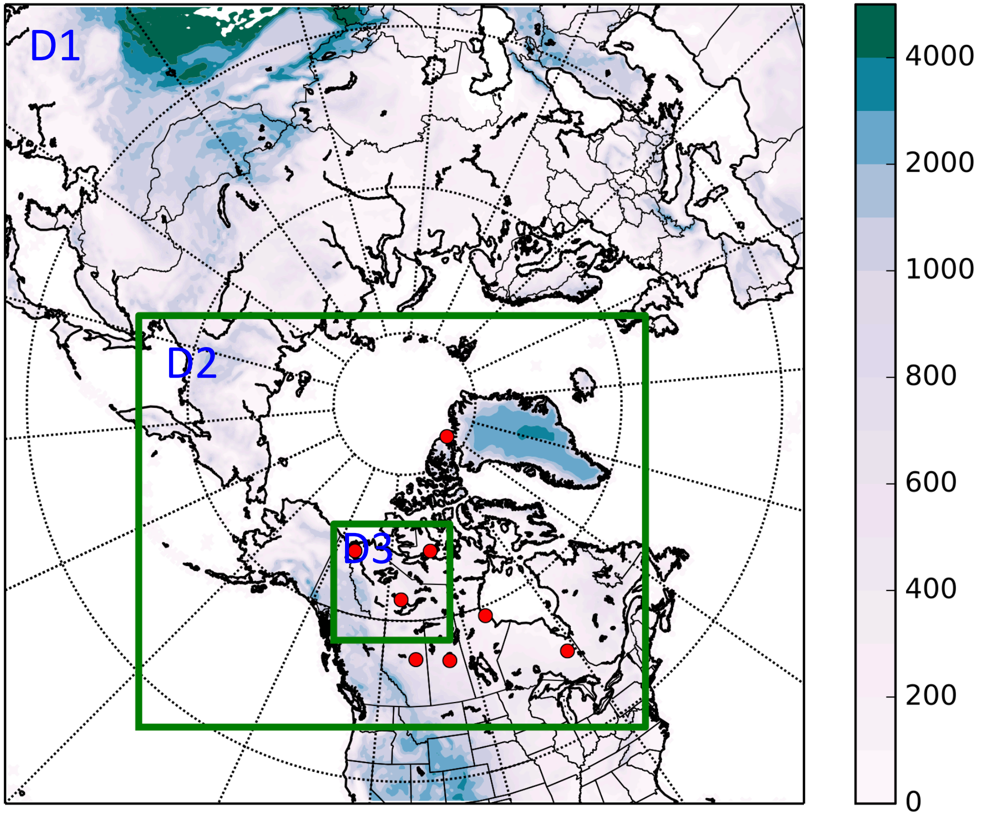
41 vertical levels



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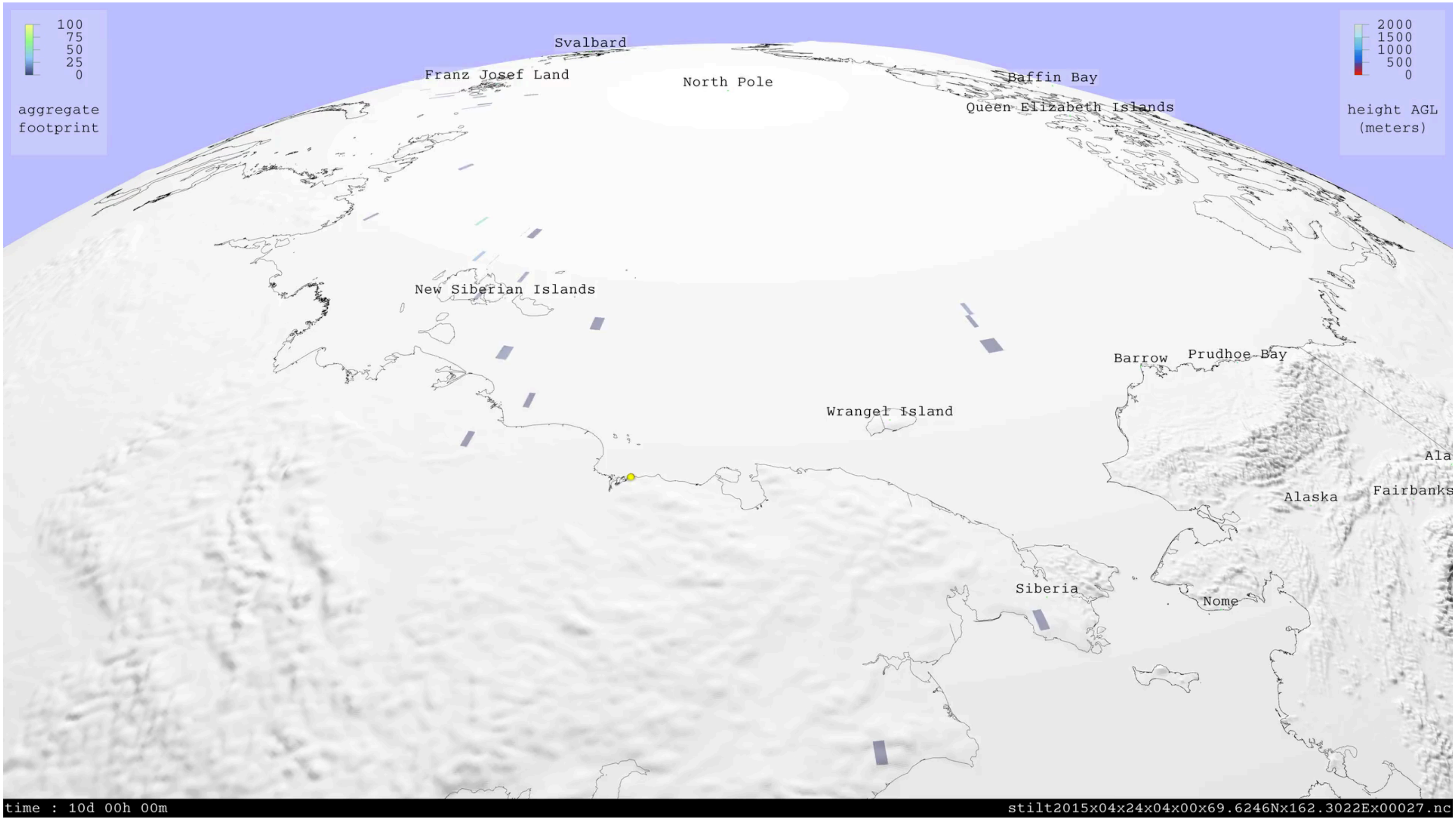
Particles move with WRF winds and terrain



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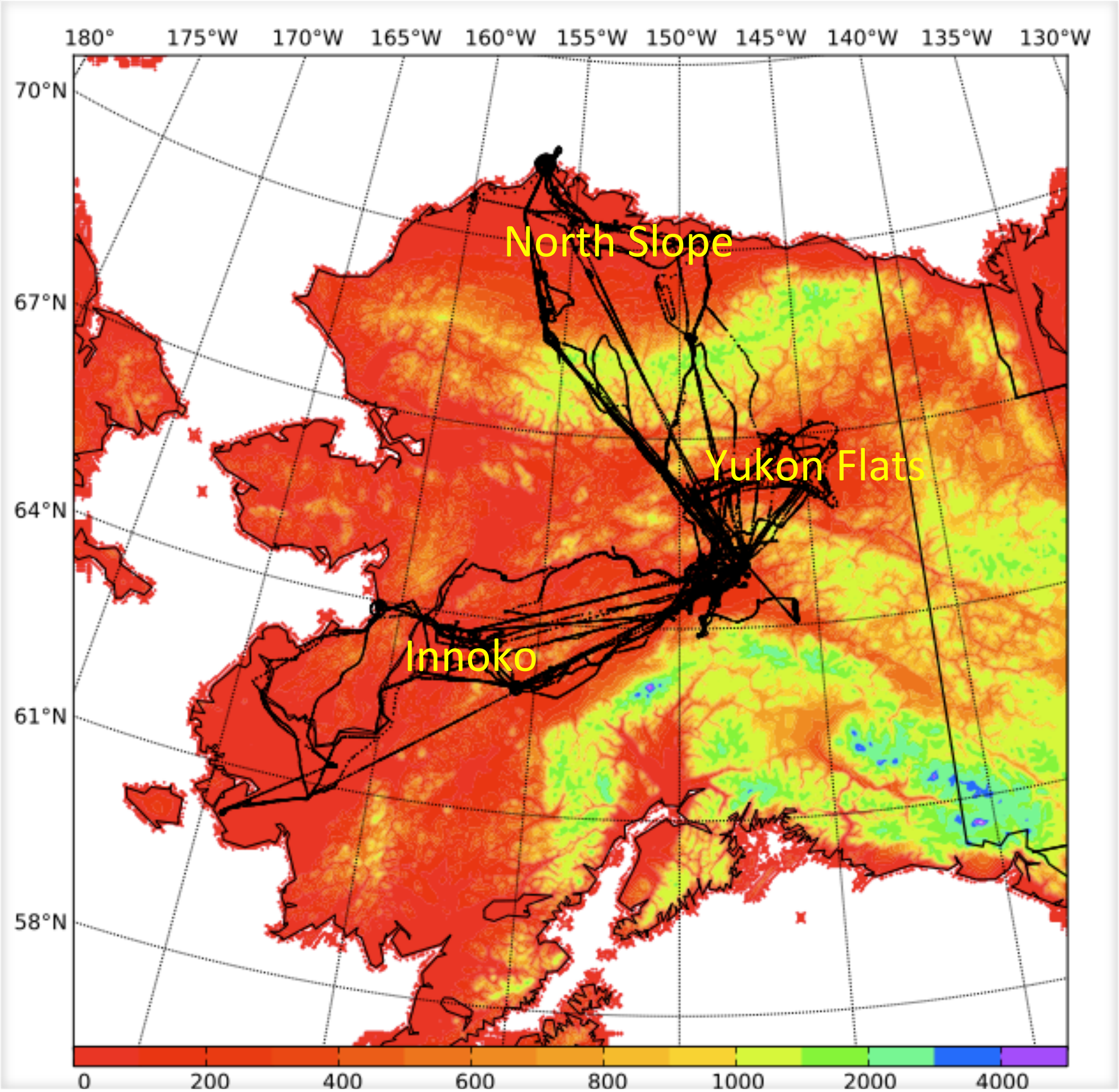
2012 flight tracks on domain 3 of WRF

Terrain height shaded (m)

Tens of thousands of receptor locations



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Step 2- STILT overview

- Based on NOAA/ARL HYSPLIT code

- Lagrangian Particle Dispersion Model coupled offline with WRF
  - WRF 3D fields advect particles backward in time in STILT
  - Turbulence and dispersion represented as stochastic technique
  - AER enhancements for WRF: customized time-averaged mass, and convective mass, flux mass fields for mass conservation, a critical consideration for inversion work.

- Optimized implementation on HPC for 100,000+ receptors

- Major STILT features not currently in HYSPLIT:
  - Mass conservation
  - Convection scheme that utilizes WRF convective fluxes (Grell-Devenyi; see AER for Grell-Freitas support in v38)
  - More complex turbulence module with reflection/transmission scheme for Gaussian turbulence. This preserves well-mixed distributions of particles moving across interfaces between step changes in turbulence parameters.
  - Account for transport errors by incorporating uncertainties in winds into the motion of air parcels

(Chris Loughner NOAA : CO_2-Urban Synthesis and Analysis ("CO_2-USA") Workshop, NIST, 6-7 Nov 2017)

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Footprint Library

- Location: NASA Ames Lou and ORNL DAAC; **ASC in near future**

- Period of record:
  - CARVE domains (mainland Alaska): 20120101 to 20160830
  - CARVE-CAN domains (Mackenzie river delta, NWT): 20140501 to 20170330

- Two products in netcdf4 format for each receptor:
  - **footprint files (prefix: foot)**
    - **0.5-deg north of 30N and receptor-centered nearfield 0.1-deg grid 3x5 deg in size**

  - transport files (prefix: stilt)
    - "thinned" particle file – describes location of particles as they move backward in time
    - times and locations where contribution to footprint is zero have been removed
    - Also contains footprint field

- Footprint library and processing code will be made available on ASC
  - Transport files available upon request

- ABoVE email subgroup will enable communication

Footprint file

- Nomenclature for one footprint file:

netcdf4 format

foot2013x12x10x16x00x64.9863Nx147.5980Wx00300.nc

footprint file yyyy mm dd hh min lat lon to 4 digits height AGL (m)

- File sizes for 10-day back trajectory:

foot2013x07x15x00x21x71.2602Nx156.7502Wx00415.nc	**280K**
foot2013x07x15x00x21x71.2602Nx156.7502Wx00415.nc.gz	**68K**
CARVE-AIRMETH-2013-convect-footprints.tar (4322 f*nc)	**1.3GB**
CARVE-AIRMETH-2013-convect-particle-files.tar (4322 s*nc)	**9.6GB**

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Footprint file – Most important contents

ncdump –h **foot2013x07x15x00x21x71.2602Nx156.7502Wx00415.nc:**

dimensions:

foot1lon=720, **foot1lat**=120, **foot1date**=240

footnearfield1lon=50, **footnearfield1lat**=30 **footnearfield1date**=24

variables:

float **origagl** [m AGL], float **origlat,** float **origlon,** **char origutctime**

float **foot1(foot1date, foot1lat, foot1lon)** [ppm per (micromol m-2 s-1)]

double **foot1lon(foot1lon),** double **foot1lat(foot1lat)**

double **foot1date(foot1date)** [days since 2000-01-01 00:00:00 UTC]

float **foot1hr(foot1date)** [stilt footprint hours back from stilt start time]

float **footnearfield1(footnearfield1date, footnearfield1lat, footnearfield1lon)**

[ppm per (micromol m-2 s-1)]

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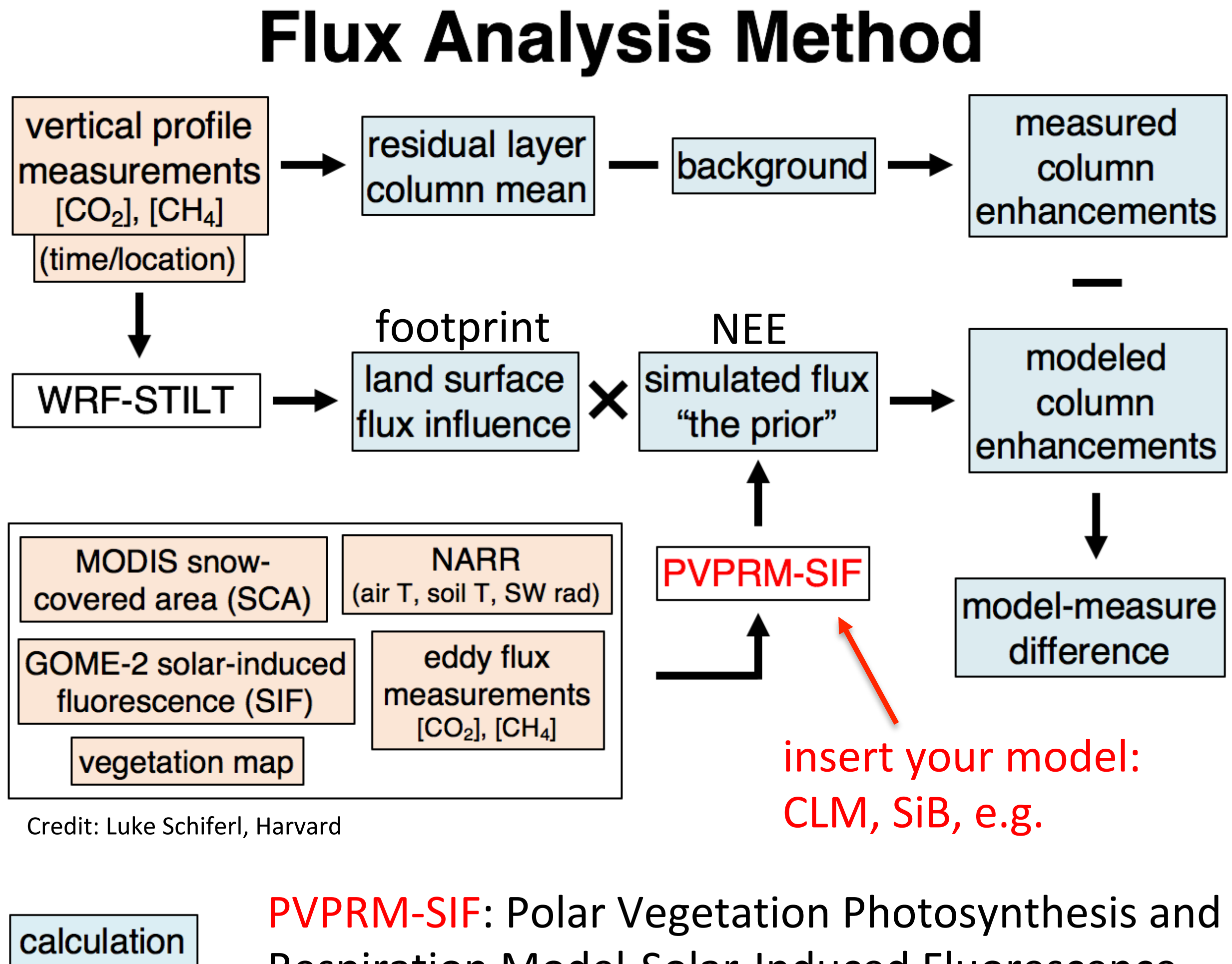
Footprint applications - Validation

- Validate estimates of flux field from a model (empirical or process-based)
- Evaluate different assumptions and datasets that are input to the flux model



Credit: Luke Schiferl, Harvard

PVPRM-SIF: Polar Vegetation Photosynthesis and Respiration Model-Solar-Induced Fluorescence

Convolving footprint files – simplified steps

footprint.file='foot2013x05x10x15x00x64.9863Nx147.5980Wx00300.nc'   #only one footprint file in this example

```
#outline of script 'crv.tower.convolve.src':
fp = nc_open(footprint.file)                                  #open ncdf4 footprint file using library(ncdf4)
m=ncvar_get(fp,"foot1")                                       #read the 0.5x0.5-deg STILT footprint
flat=ncvar_get(fp,"foot1lat");  flon=ncvar_get(fp,"foot1lon") #read lat/lon of footprint grid
fp.time = ncvar_get(fp,"foot1date")                           #read dates of footprint grids; 5-day footprints= 120 h
```

```
name=load("nee.pvprm.sif.2013.RData")
nee=get(name)                                                 #load process model NEE; assume times match
```

```
lat.extent = c(50,75); lon.extent = c(-169,-120)              #define spatial extent of grid for convolution
flat.index = flat>=lat.extent[1] & flat< lat.extent[2]        #create mask for lat/lon extent
flon.index = flon>=lon.extent[1] & flon< lon.extent[2]        #can also use land mask
```

```
conv.tower = matrix(NA,nrow = 1,ncol=7)                                          #define output matrix
colnames(conv.tower)=c("JD","Lat","Lon","Alt","Time","STILT","STILTxPVPRMSIF")   #output matrix column names

conv.tower[1,"STILT"] = sum(apply(m[flon.index,flat.index,1:120],c(1,2),sum,na.rm=T))   #write out cumulative footprint field

#convolve footprints with fluxes: multiply time-dependent 2D matrices:
mm = m[flon.index,flat.index,]*nee                            #apply spatial mask to NEE input from PVPRM

#write out footprints convolved with model fluxes
conv.tower[1,paste("STILTxPVPRMSIF")] = sum(apply(mm[,,1:120],c(1,2),sum,na.rm=T))
```

```
#Write out R data object:
save(conv.tower,file="carve.tower..convolved.pvprm.sif.Data")
```

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Convolving footprint files – simplified steps

```
#Run script:
source('crv.tower.convolve.r')
#creates: carve.tower.convolved.pvprm.sif.Data
```

```
##Read in R data object:
convolved.data.name <- load('carve.tower.convolved.pvprm.sif.Data')
#returns 'conv.tower' string
convolved.data <- get(convolved.data.name')
```

#display output matrix of STILT footprint and footprint convolved with flux estimate from physical model:
convolved.data:

						[ppm/(umol/m^{2}s)]	**[ppm]**
rec	JD	Lat	Lon	Alt	Time	STILT	STILTxPVPRMSIF
1	129.625	64.986	-147.6	301	2013-05-10T15:00:00	6.993728	3.916888

#convolved field represents change in concentration due to the influence of upstream fluxes

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Footprint applications - Inversions

- Top-down estimate studies (Inversions)
  - Refine regional estimates of GHG surface fluxes
  - Can involve complex variational data assimilation

- Example: NOAA/GMD CarbonTracker-Lagrange
  - Minimize: $\hat{s} = s_p + (HQ)^T * (HQH^T + R)^{-1} * (z - H s_p)$
  - **Python code at: https://www.esrl.noaa.gov/gmd/ccgg/carbontracker-lagrange/doc/index.html**

Papers using CARVE footprints

- Chang, R. Y.-W., et al., 2014: Methane emissions from Alaska in 2012 from CARVE airborne observations. *Proceed. National Academy Sci*., doi:10.1073/pnas.1412953111.

- Henderson, J. M., et al., 2015: Atmospheric transport simulations in support of the Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE). *Atmos. Chem. Phys*., 15, 4093-4116, doi:10.5194/acp-15-4093-2015.

- Zona, D., B. et al., 2016: Cold season emissions dominate the Arctic tundra methane budget. *Proceed. National Academy Sci*., doi:10.1073/pnas.1516017113.

- Miller, S. M. et al., 2016: A multiyear estimate of methane fluxes in Alaska from CARVE atmospheric observations. *Global Biogeochem. Cycles*, 30, doi:10.1002/2016GB005419.

- Xu, et al. 2016: A multi-scale comparison of modeled and observed seasonal methane emissions in northern wetlands. *Bio. Geo. Sc*.,13, 5043–5056, doi: 10.5194/bg-13-5043-2016.

- Luus, K. A., et al., 2017: Tundra photosynthesis captured by satellite-observed solar-induced chlorophyll fluorescence, *Geophys. Res. Lett*., *44*, doi:10.1002/2016GL070842.

- Commane, R. et al., 2017: Carbon dioxide sources from Alaska driven by increasing early winter respiration from Arctic tundra budget. *Proceed. National Academy Sci*., doi: 10.1073/pnas.1618567114.

- Hartery, S. et al., 2018: Estimating regional-scale methane flux and budgets using CARVE aircraft measurements over Alaska, Atmos. Chem. Phys., 18, 185-202, doi: 10.5194/acp-18-185-2018.

Stepping back: WRF High-Resolution meteorological fields

- **High-resolution meteorological fields used to drive STILT are available**
  - **Fields: http://www2.mmm.ucar.edu/wrf/users/docs/user_guide_V3.9/users_guide_chap5.htm#fields**

- Period of record (same as footprints):
  - CARVE WRF domains (mainland Alaska): 20120101 to 20160830
  - CARVE-CAN WRF domains (Mackenzie river delta): 20140501 to 20170330

- **Spatial grid: 30, 10 and 3.3 km, 41 vertical levels**

- **Temporal availability: d01 and d02: hourly; d03: 30 minutes**

- Reanalysis products (e.g., NARR, MERRA(2), ERA-5) are on ~30-km grid at best

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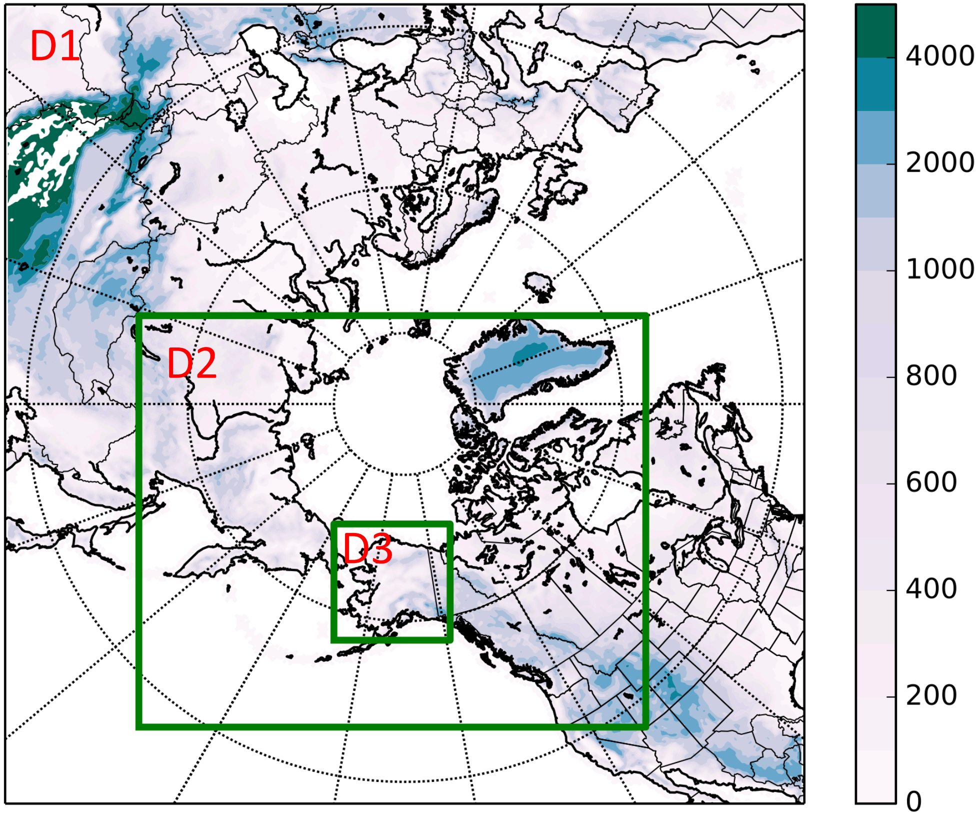
41 vertical levels



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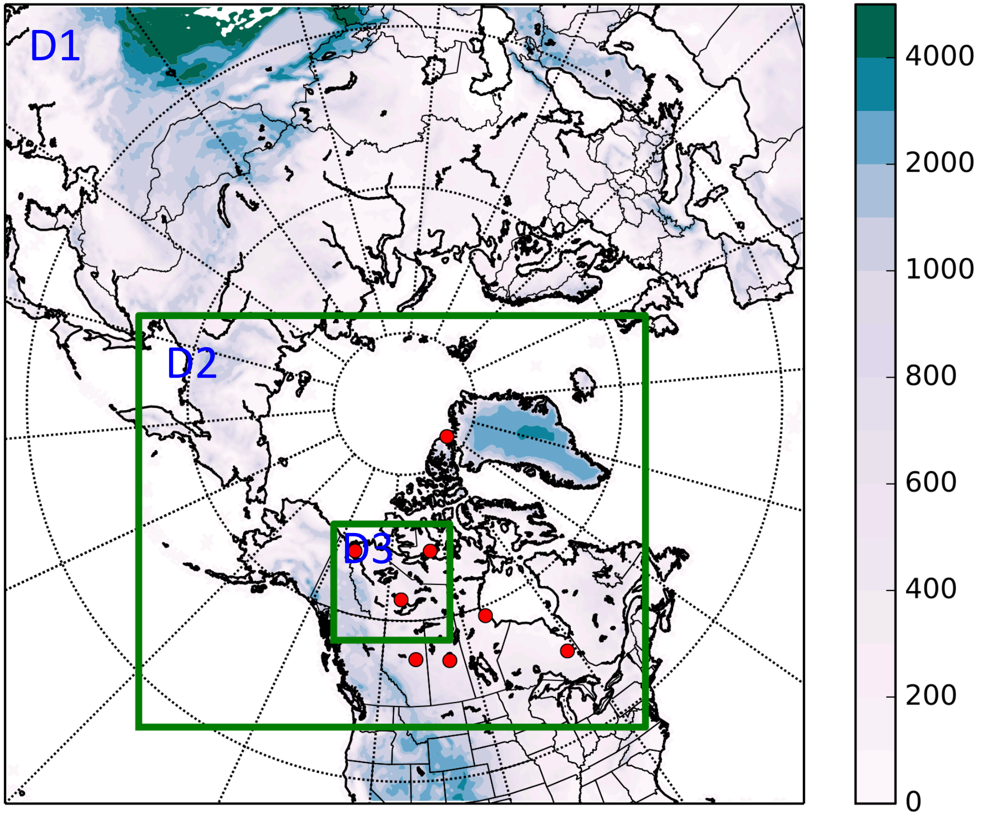
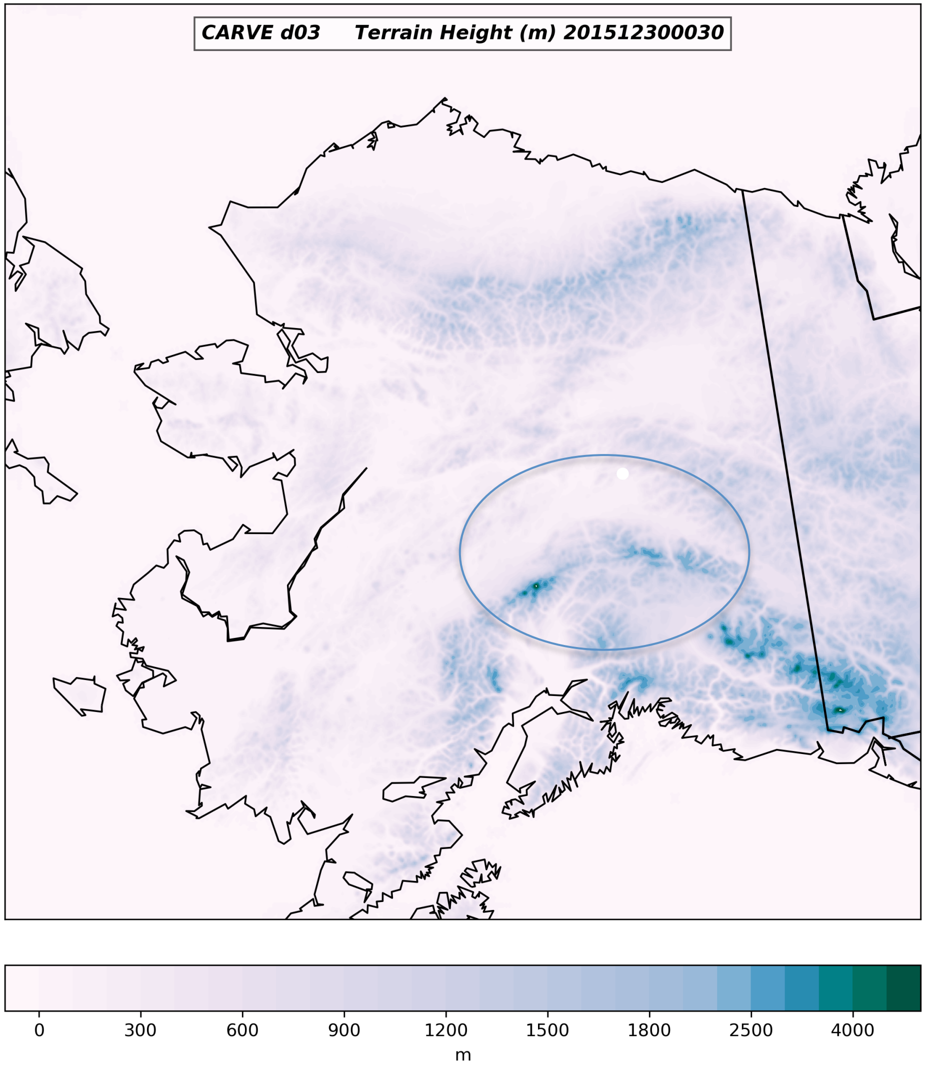


Sample WRF fields – terrain height



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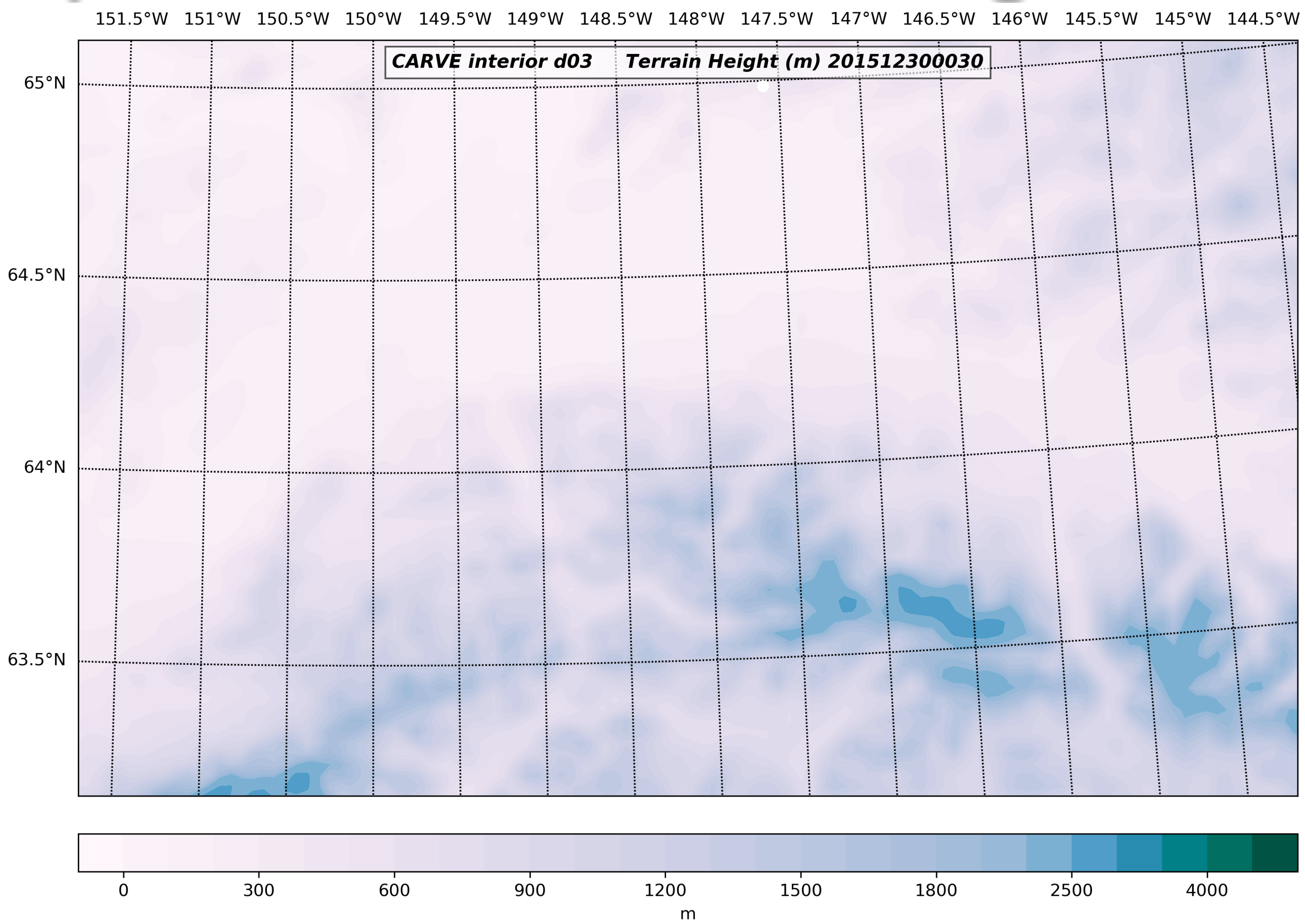

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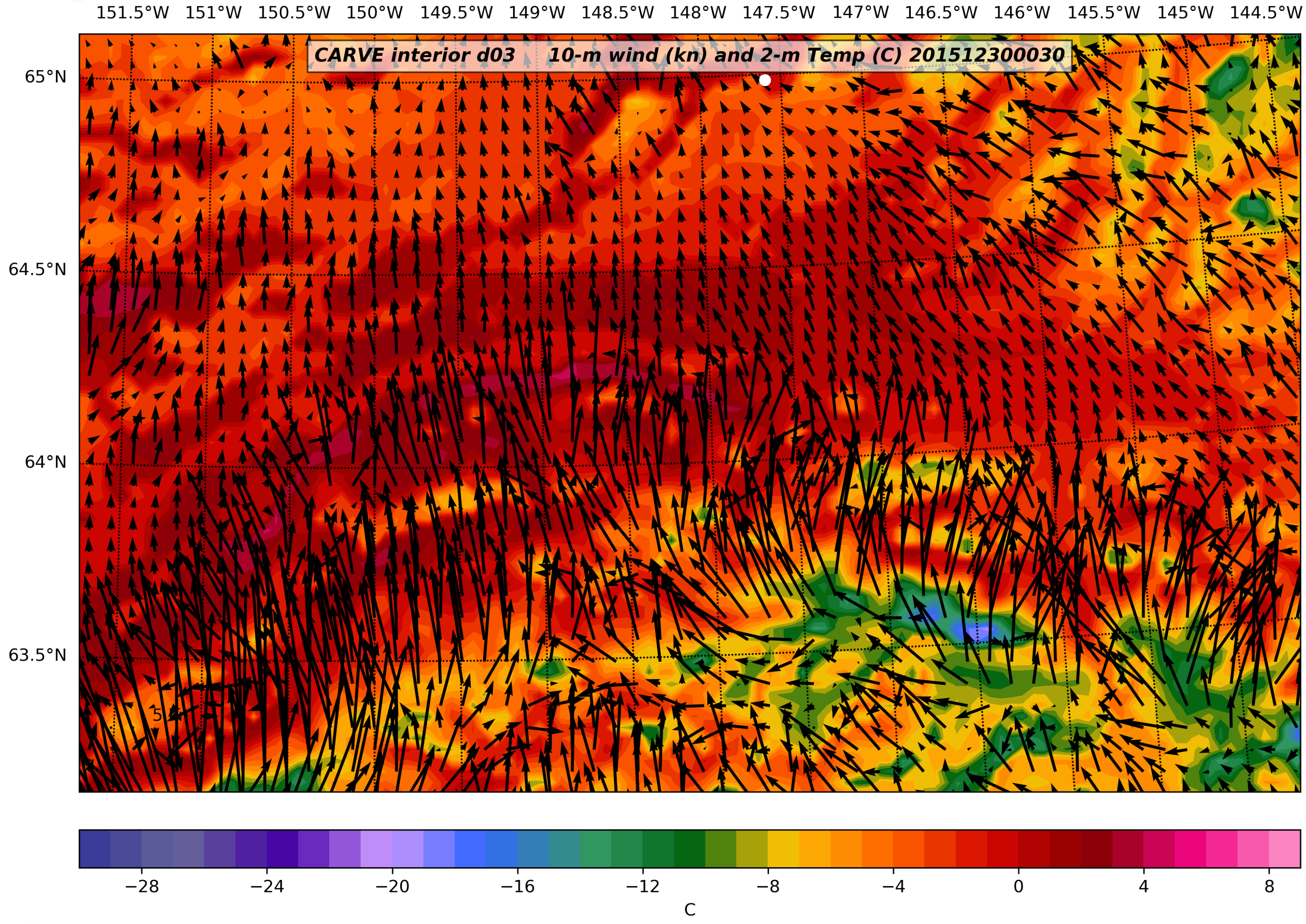
Sample WRF fields – surface T and wind



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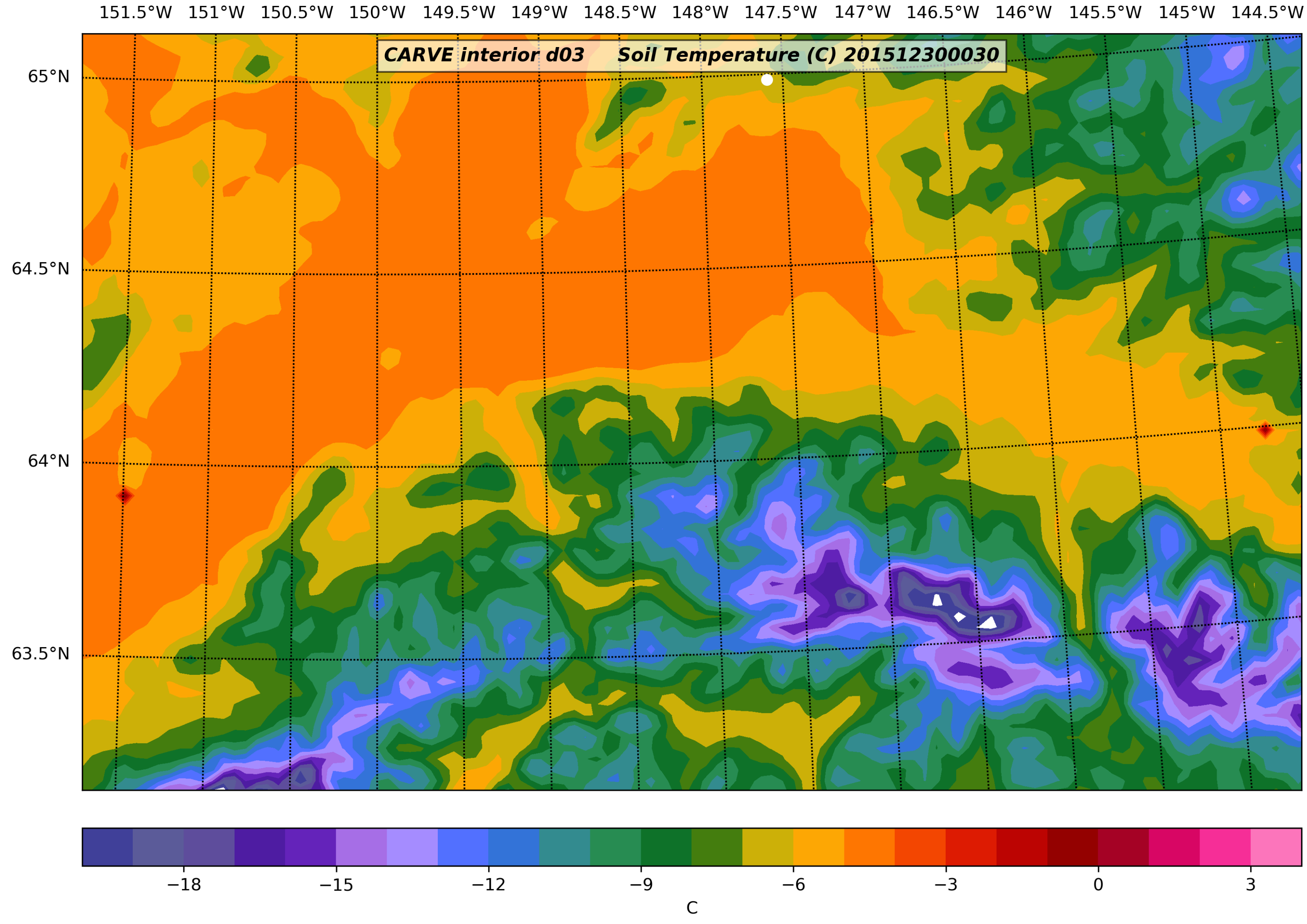
Sample WRF fields – Soil temperature



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Sample WRF fields - SWDOWN

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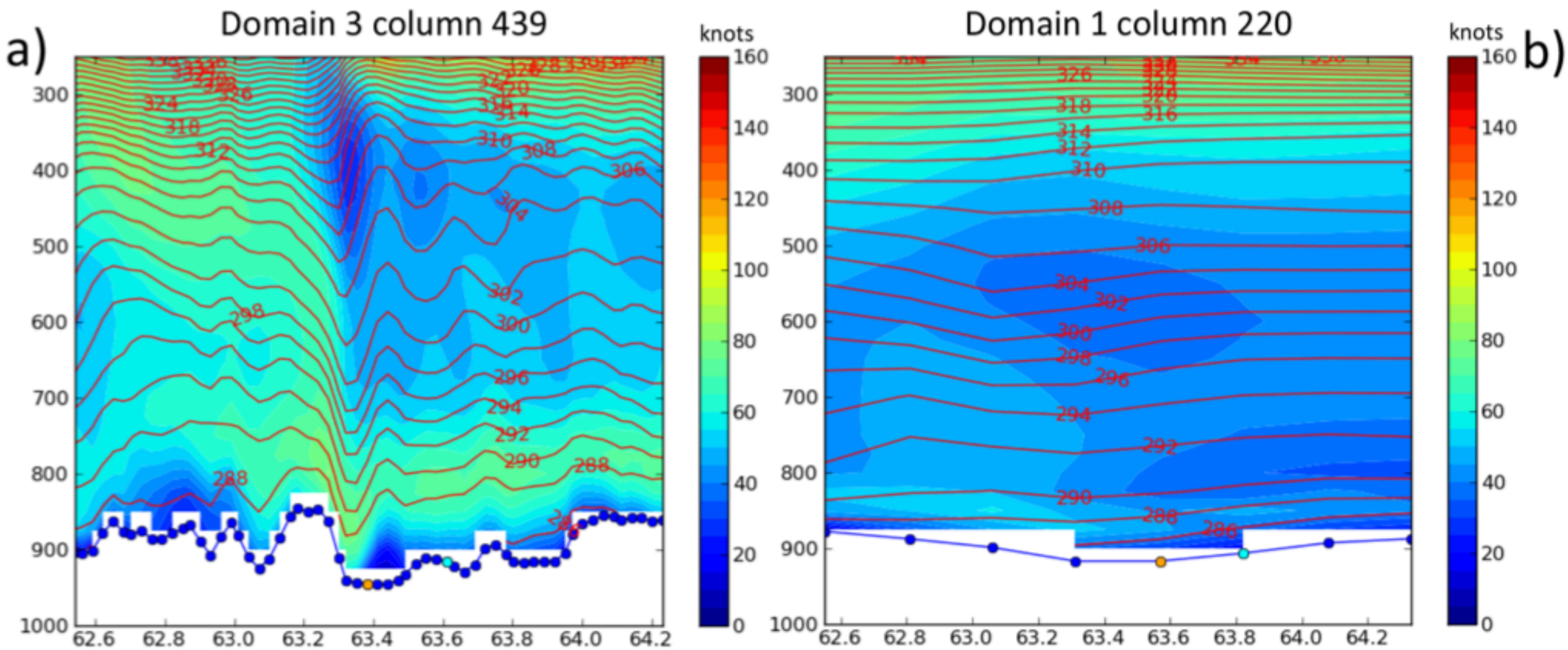
Value of high-res WRF over reanalyses



- Tanacross, AK, windstorm event of 17 September 2012
- Domain 1 30-km grid spacing (panel b) does not support downslope windstorm that is present in innermost domain 3 (3.3-km grid; panel a)

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Bias during 2012 aircraft campaign

Surface Variable	May	June	July	August	September	2012 Campaign
2-m Temperature (K)	-2.24	-1.81	-1.60	-1.08	-0.70	-1.44
2-m Dewpoint temperature (K)	1.11	0.11	-0.74	-0.63	-0.04	-0.10
10-m Wind speed (m s^{-1})	-0.67	-0.47	-0.30	-0.32	0.25	-0.29
10-m Wind direction (deg)	4.7	3.3	1.6	4.6	4.1	3.7

- Trends in surface temperature and moisture evident
- Overall error values compare well with literature

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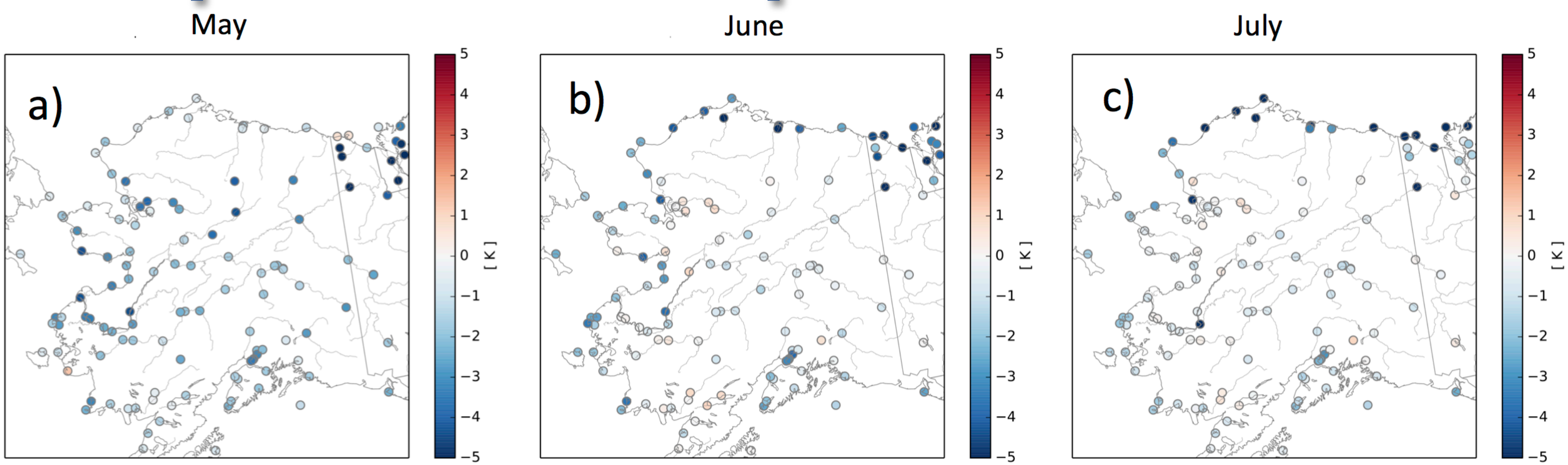
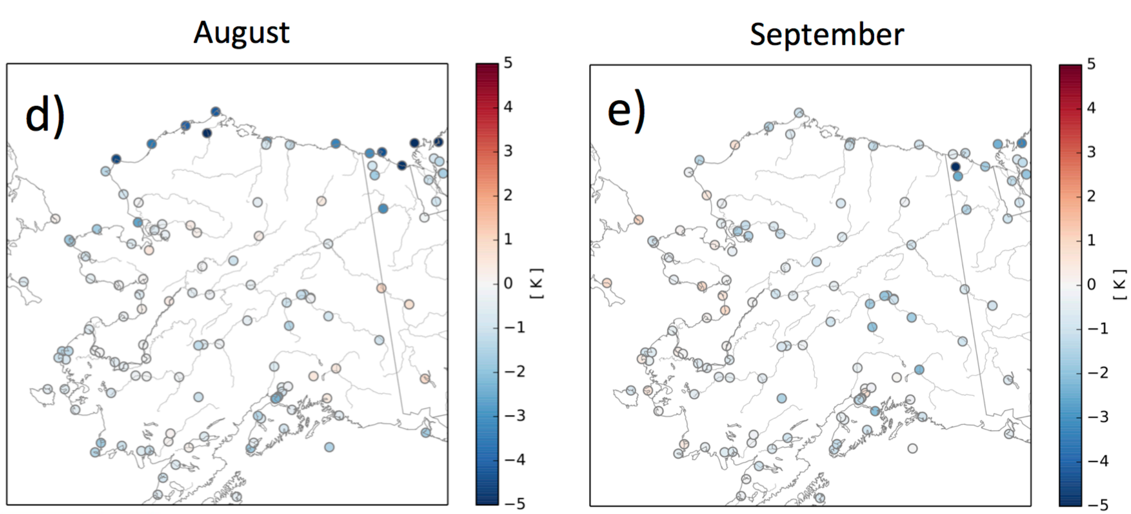
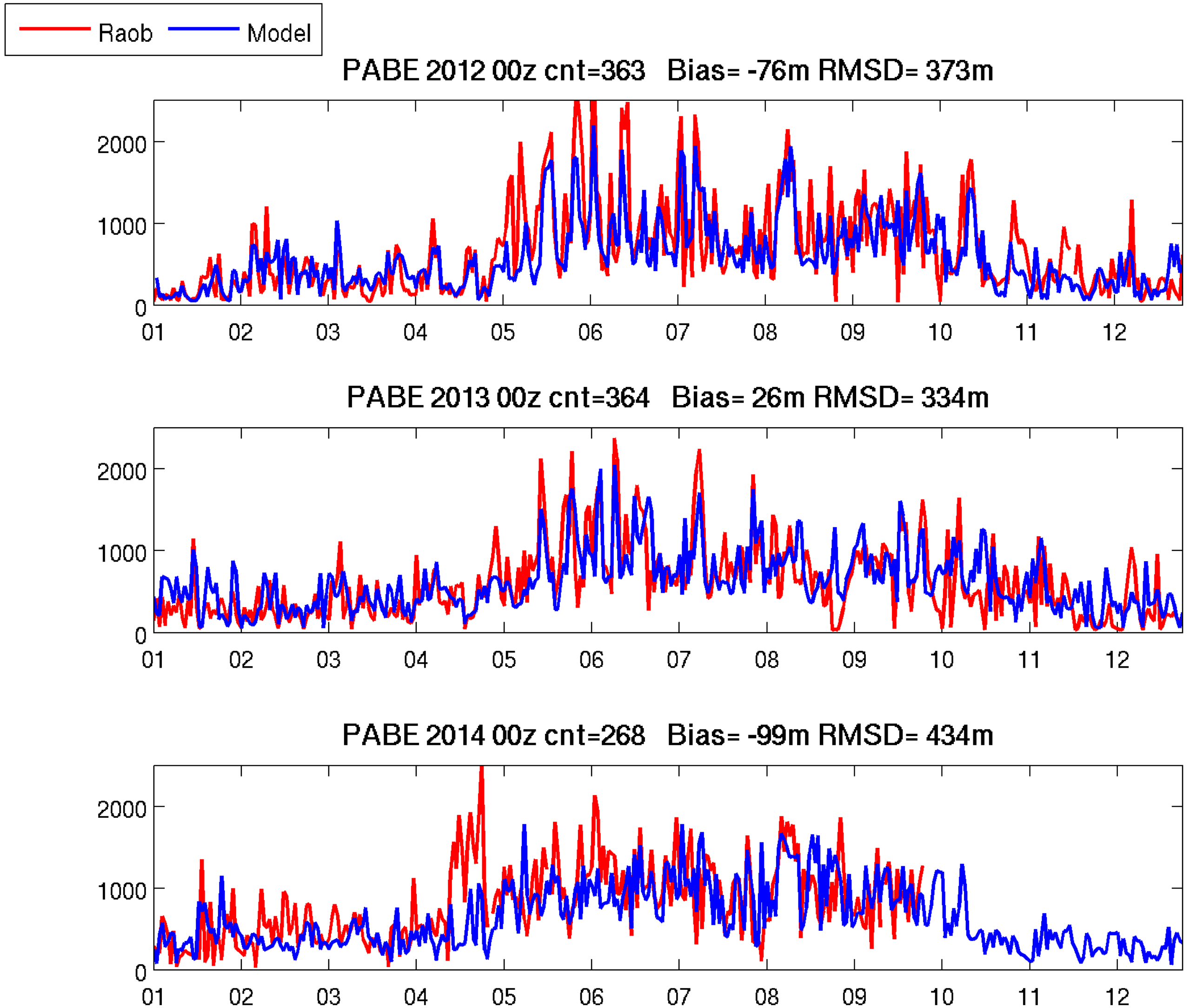
Temperature bias plots for 2012





- Location of largest negative temperature bias mirrors northward progression of thaw
- Potentially related to inadequate representation of soil moisture/state

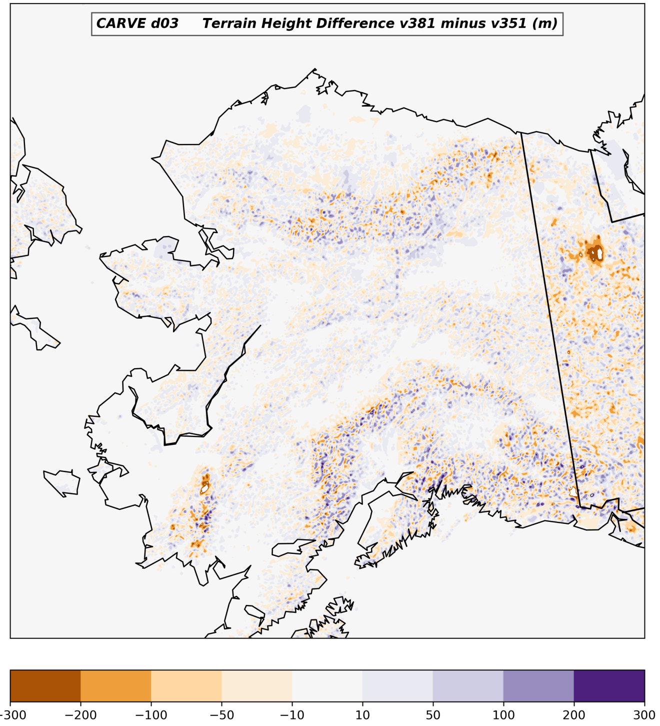
PBL Height Validation: Daily 0000 UTC



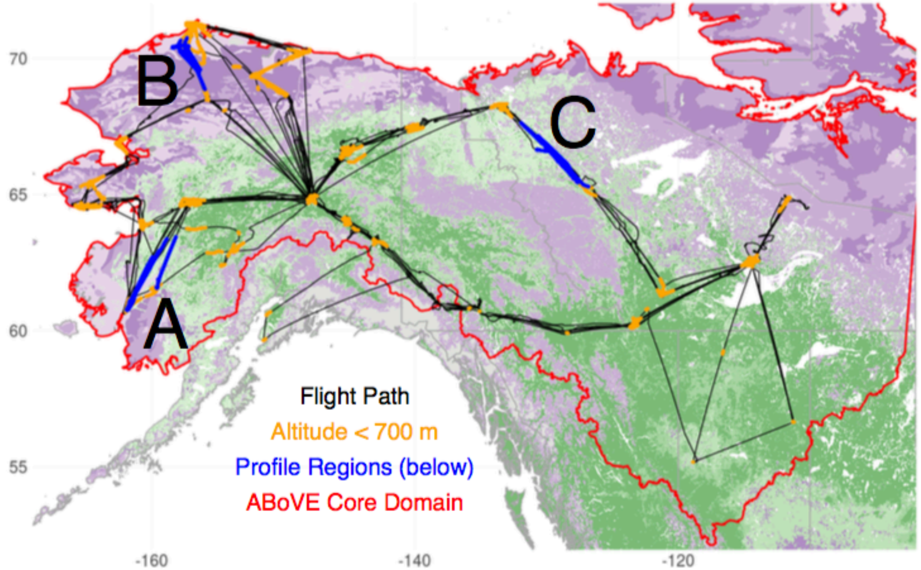
Future Work

- Update WRF-STILT to Polar WRF v3.9: Improved land use (21-cat IGBP MODIS) and terrain height (30-arc-second USGS GMTED2010) datasets

- Design new unified WRF domain for ABoVE and its aircraft campaigns



ArctiCAP Airborne Measurements



- Generate footprints for 2017 Arctic Carbon Atmospheric Profiles (ArctiCAP) campaign and NOAA/ECCC towers

- Rerun CARVE-era receptors using WRF v3.9

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Summary

- Multi-year library of footprints on ASC
- Simple netcdf format enables use by all ABoVE community
- Code/scripts available for processing:
  - reading/writing, convolving, inclusion in formal inversions
- High-spatial and temporal WRF fields can be requested
- We are here to help apply these datasets to your current and future research:
  - Mailing list will soon be available
  - Biophysical model experts are part of ABoVE
  - AER: transport modeling for ABoVE (jhenders@aer.com)