The critical role of fine-grained atmospheric data in determining the rates of transport, sources, and sinks of greenhouse gases across the globe.

Steven C. Wofsy
Harvard University

Keck Institute for Space Studies

Pasadena, CA 03 March 2010

HIAPER Pole-to-Pole Observations 2009 (“HIPPO”)

Brooks Range, AK

Part I: Global Science Objectives:

Use observed distributions of major greenhouse gases to help determine the continental-scale sources and sinks of major greenhouse gases.

Motivation:

Computer models are the basic tool for this application.

Models obtain the global distributions of surface fluxes for GHGs by optimizing *a priori* emission rates to match time series observations at surface stations.

Approach:

Challenge models with fine-grained data of global scale: HIAPER Pole-to-Pole Observation program (HIPPO).

"HIPPO" is designed to confront models with a new type of data.

We wish to uncover and eliminate sources of bias and error that limit the application of models to assessment of source trends and distributions: to distinguish to model-data differences that tell us about sources and sinks from those arising due to deficiencies of transport, model aggregation, etc

Fine-grained data for multiple species of different source/sink distributions, at he surface and in profile should provide critical tests of models**.**

Part II: Verification Science Objectives:

Use observed time series of CO_2 and other greenhouse gases in major source locales to help track trends in emission sources.

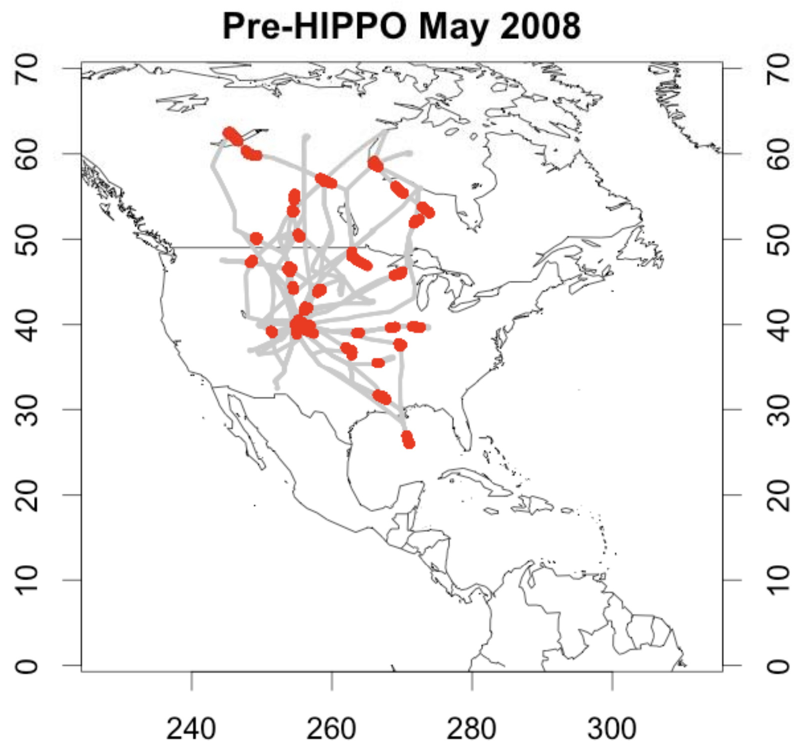
Motivation:

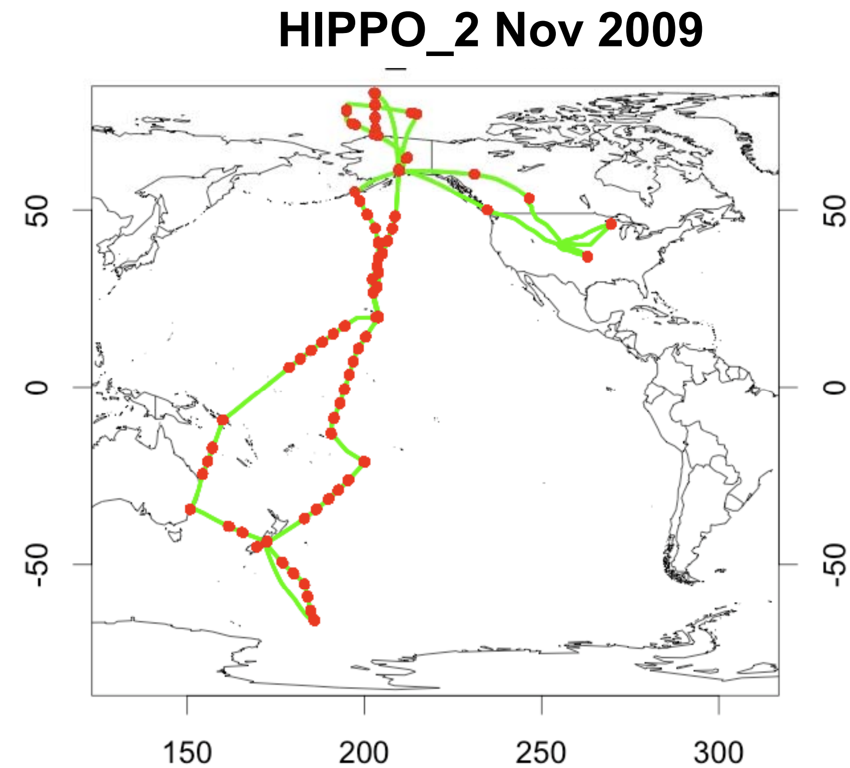
The largest emissions sources reveal the largest signals of human-caused emissions. Compliance with treaty provisions will translate into measurable changes in emission rates from major emitting regions.

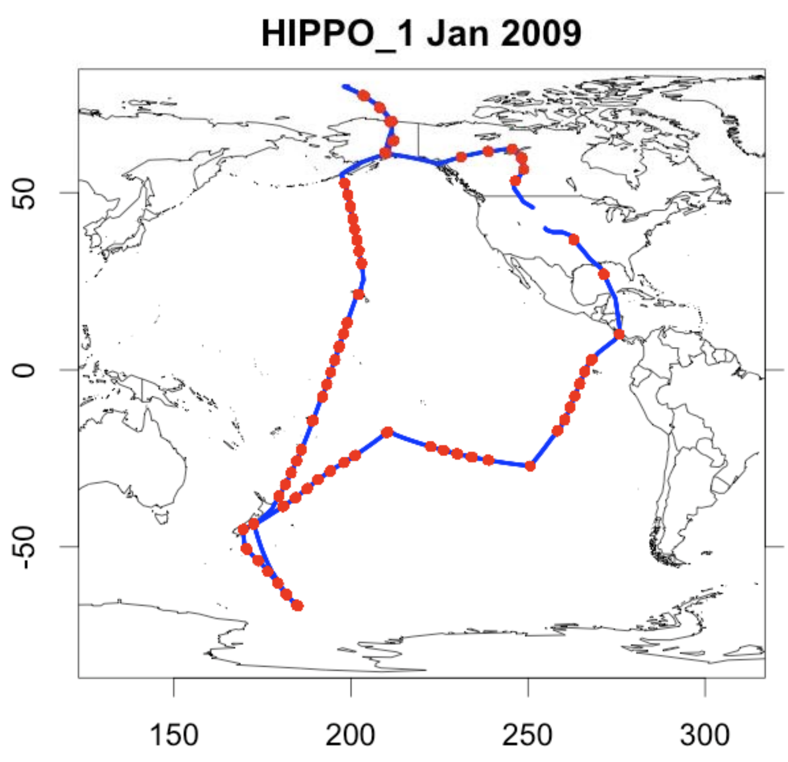
Approach:

Modeling of highly resolved concentration data from a highly resolved inventory and fine-resolution model. Use of multiple tracers (^{222}Rn, $^{14}CO_2$, CO, ...).


N677F
National Center for Atmospheric Research
National Science Foundation





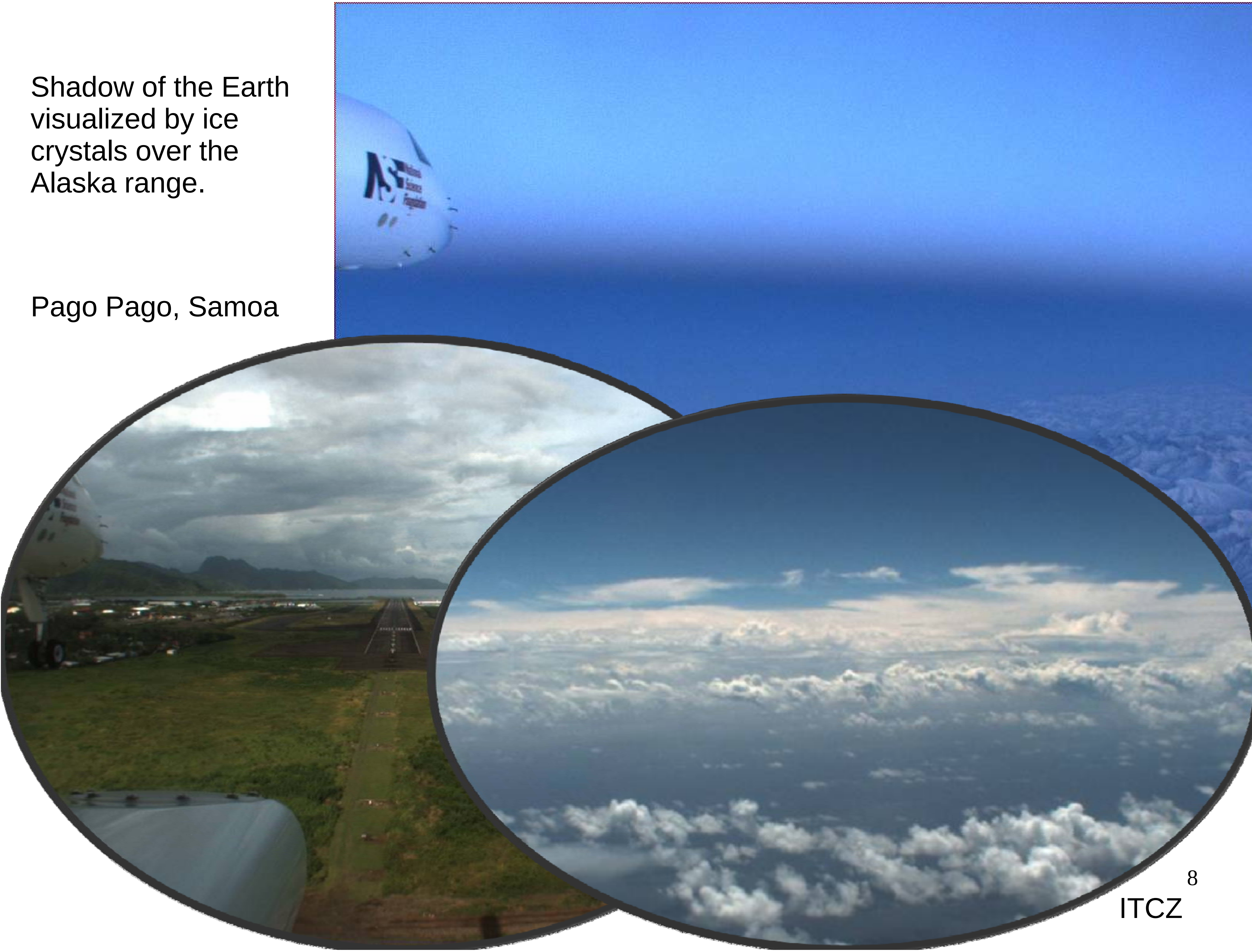


- ~400 vertical profiles in 3 of 6 missions.

- 3 missions yet to go; nearly 1000 at HIPPO's conclusion.

Shadow of the Earth visualized by ice crystals over the Alaska range.

Pago Pago, Samoa

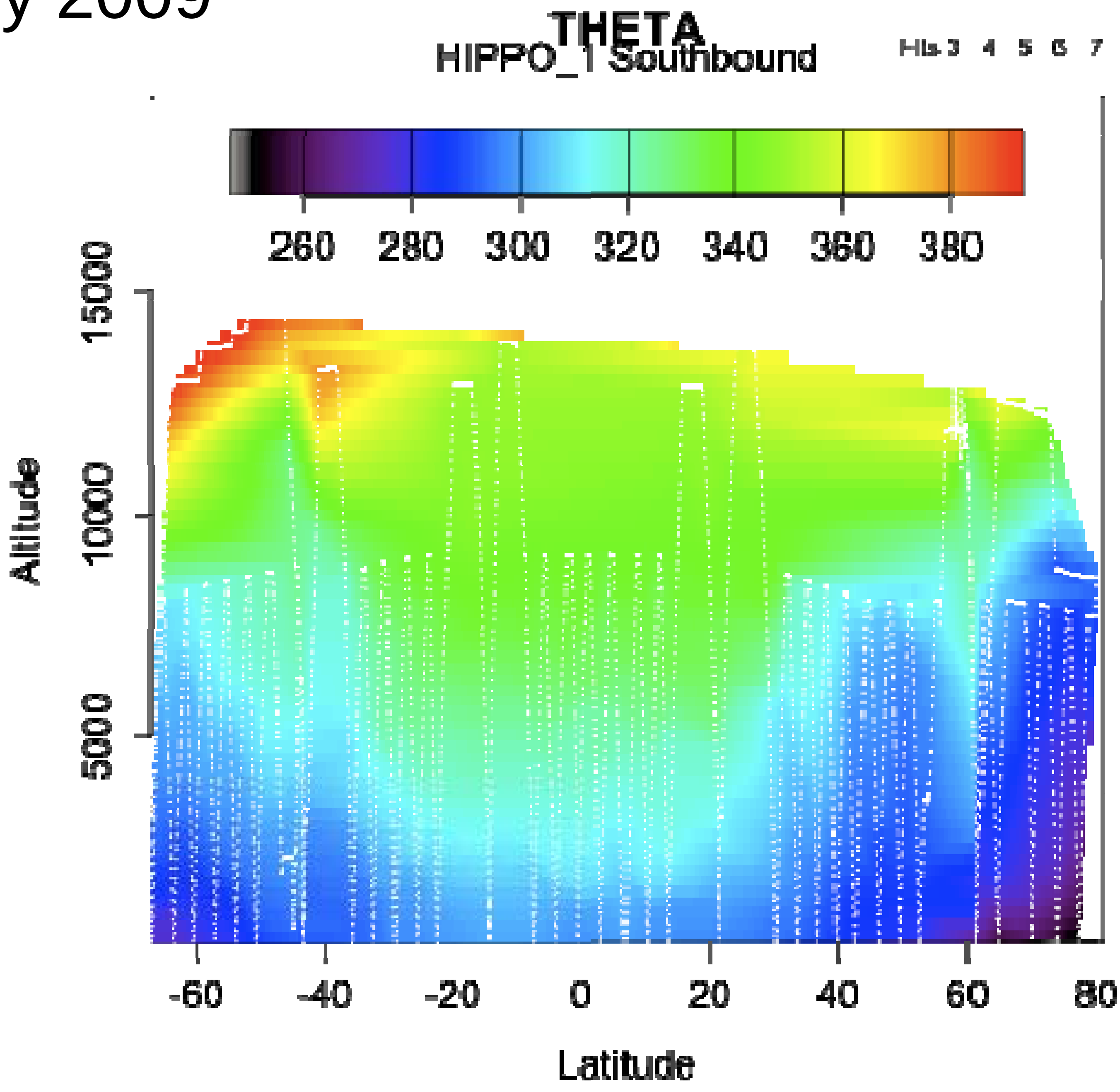


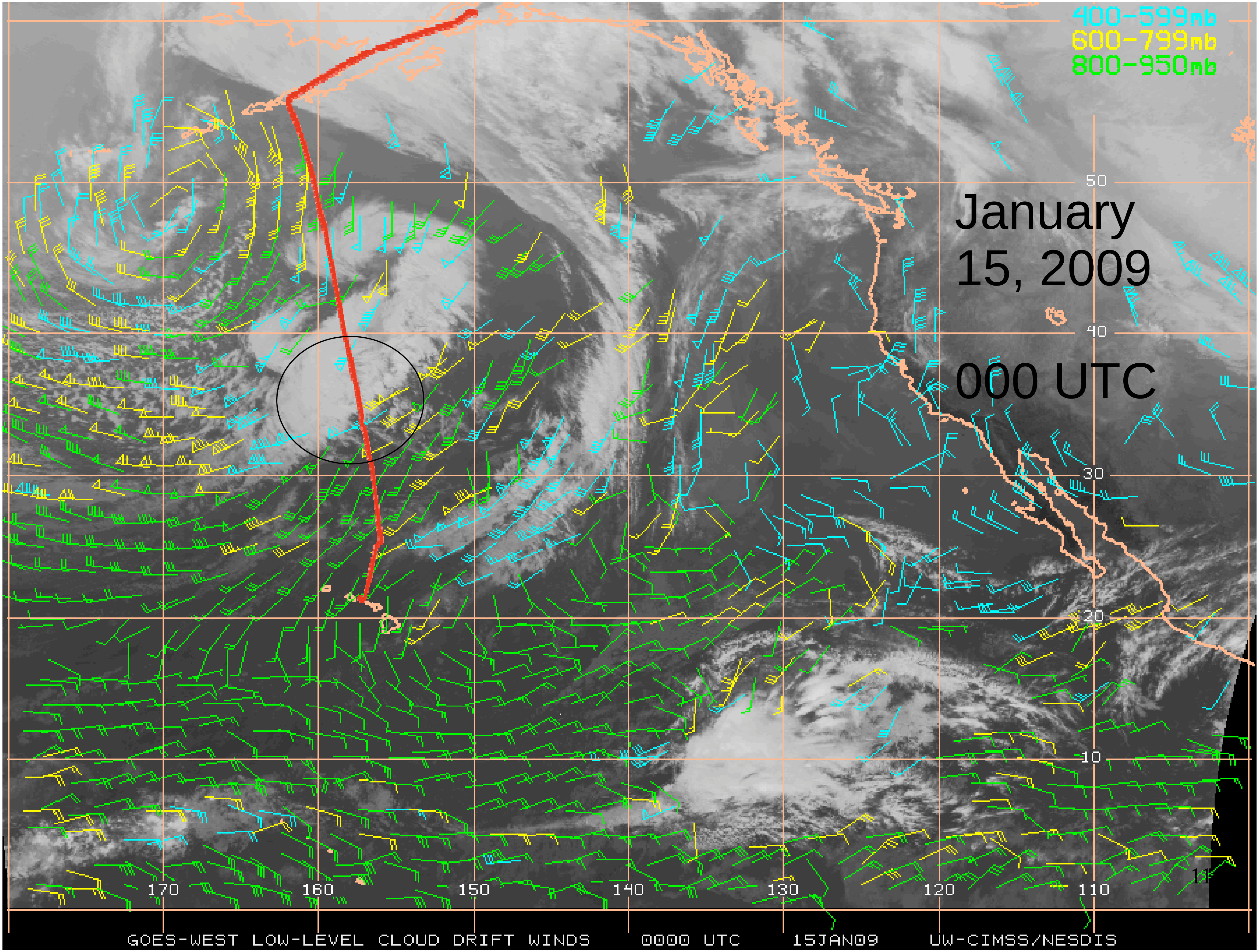
ITCZ

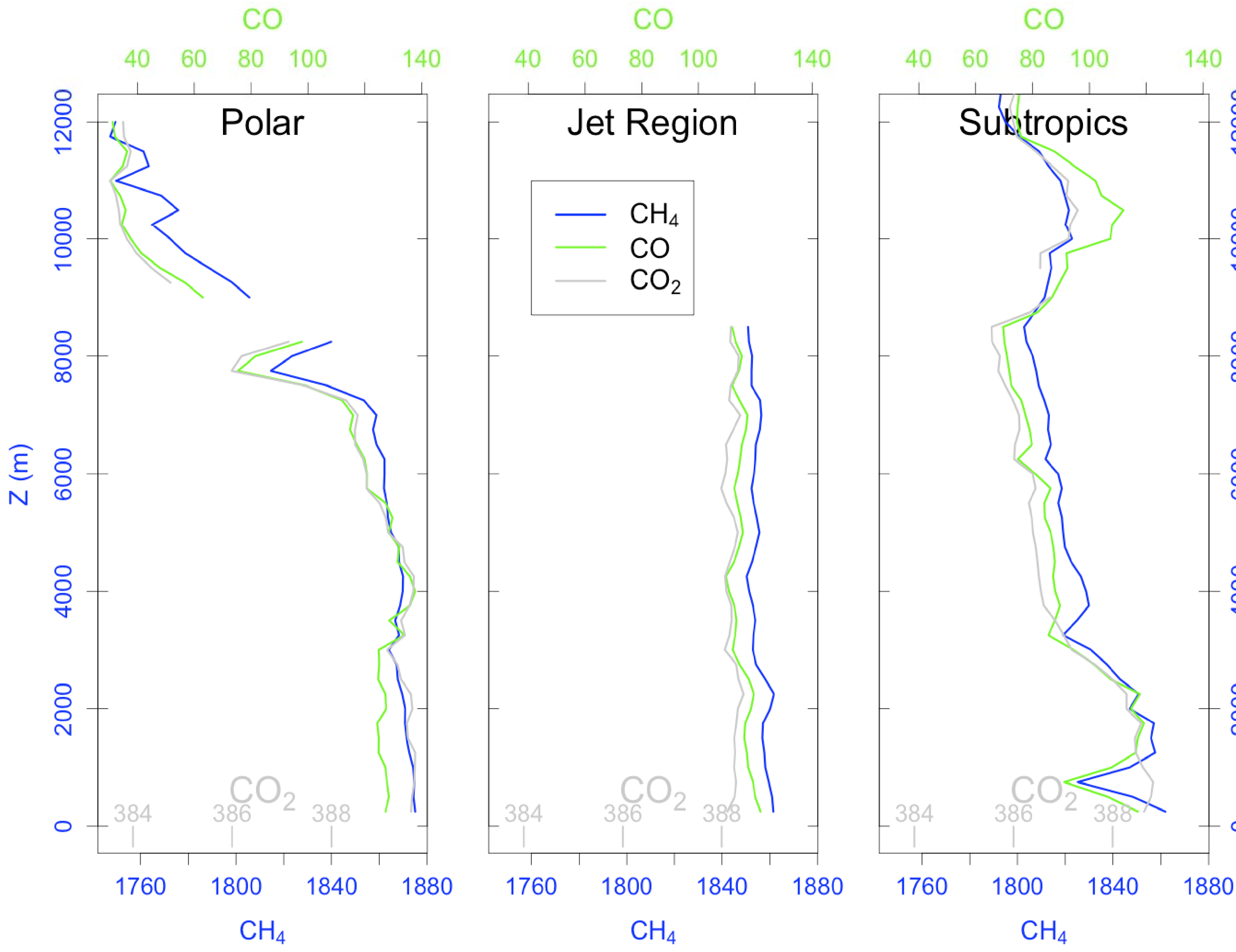
HIPPO Aircraft Instrumentation

Harvard/Aerodyne—HAIS QCLS	**CO_2**, **CH_4**, **CO**, **N_2O** (*1 Hz*)
NCAR AO2	O_2:N_2 , **CO_2** (*1 Hz*)
Harvard OMS CO_2	**CO_2** (*1 Hz*)
NOAA CSD O_3	O_3 (*1 Hz*)
NOAA GMD O_3	O_3 (*1 Hz*)
NCAR RAF CO	**CO** (*1 Hz*)
NOAA- UCATS, PANTHER GCs (1 per 70 – 200 s)	CO, **CH_4**, **N_2O**, CFCs, HCFCs, **SF_6**, CH_3Br, CH_3Cl, H_2, H_2O
Whole air sampling: NWAS (NOAA), AWAS (Miami), MEDUSA (NCAR/Scripps)	O_2:N_2, **CO_2**, **CH_4**, **CO**, **N_2O** , other GHGs, **COS**, halocarbons, solvent gases, marine emission species, many more
Princeton/SWS VCSEL	H_2O (*1 Hz*)
NOAA SP2	Black Carbon (*1 Hz*)
MTP, wing stores, etc	T, P, winds, aerosols, cloud water

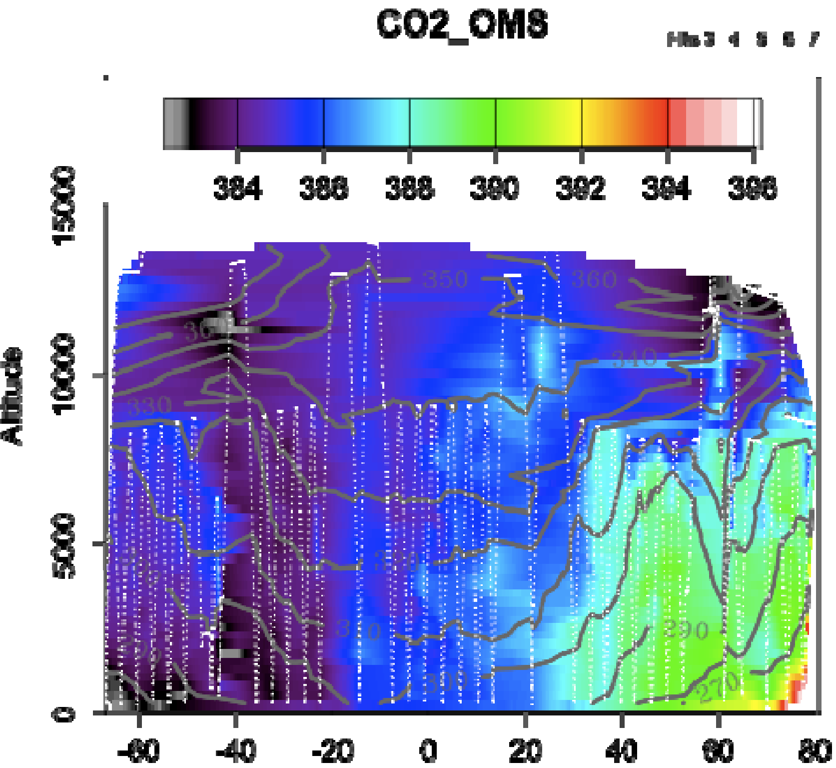
Global distribution of potential temperature – January 2009

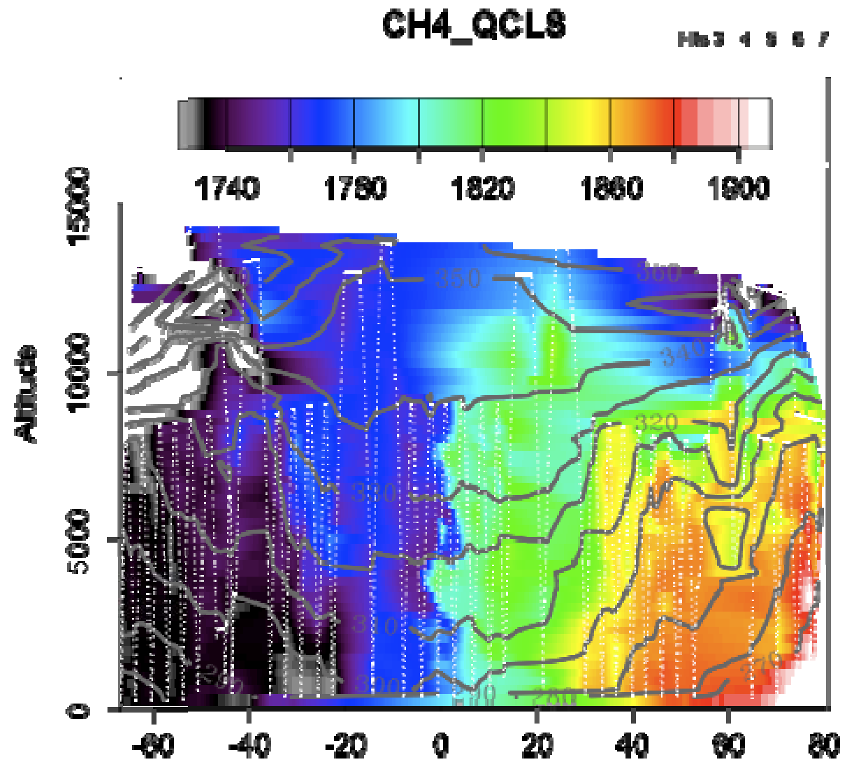



400-599mb
600-799mb
800-950mb
January 15, 2009
000 UTC
50
40
30
20
10
170
160
150
140
130
120
110
GOES-WEST LOW-LEVEL CLOUD DRIFT WINDS 0000 UTC 15JAN09 UW-CIMSS/NESDIS



CO
40
60
80
100
140
Polar
Jet Region
Subtropics
CH4
CO
CO2
Z (m)
0
2000
4000
6000
8000
10000
12000
CO2
384
386
388
1760
1800
1840
1880
CH4

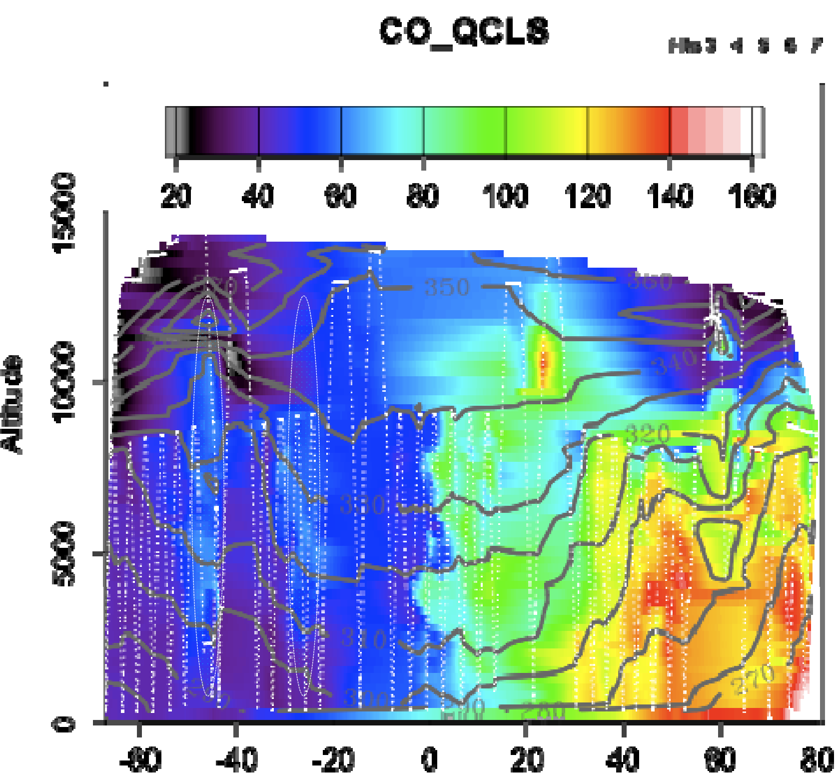


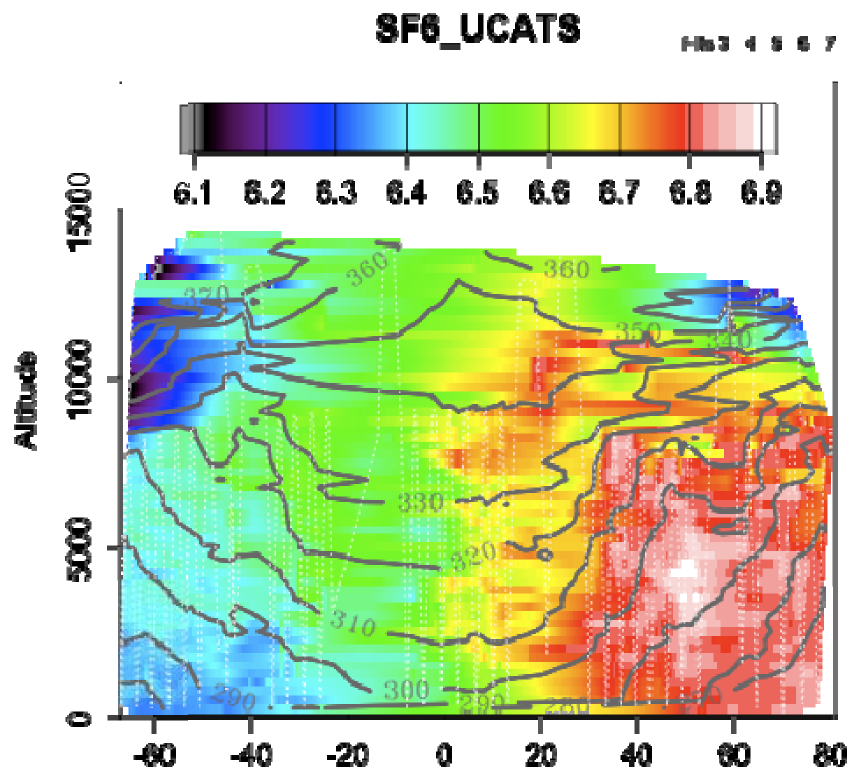


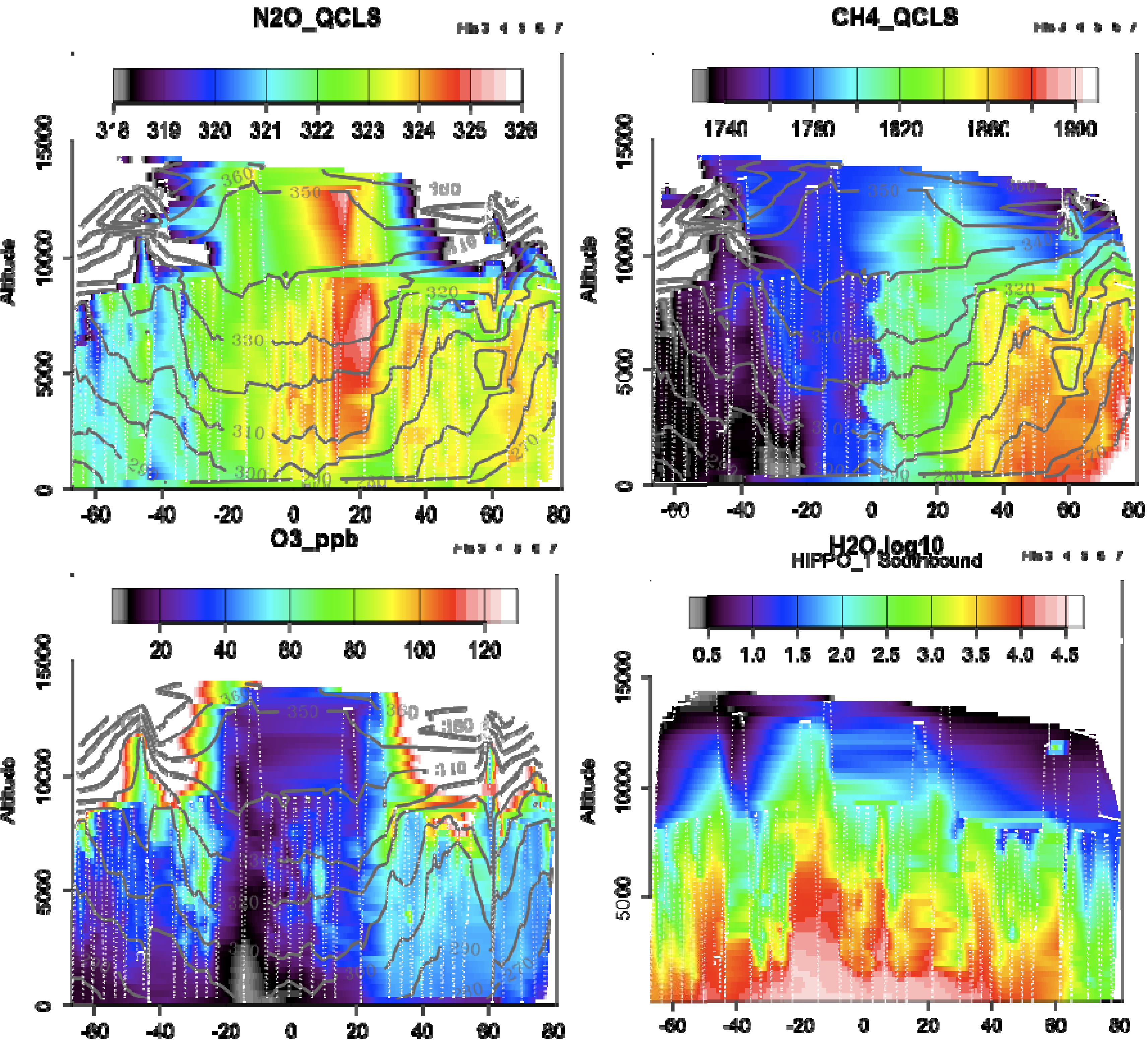
HIPPO_1

Xsects along the Dateline

Jan 2009



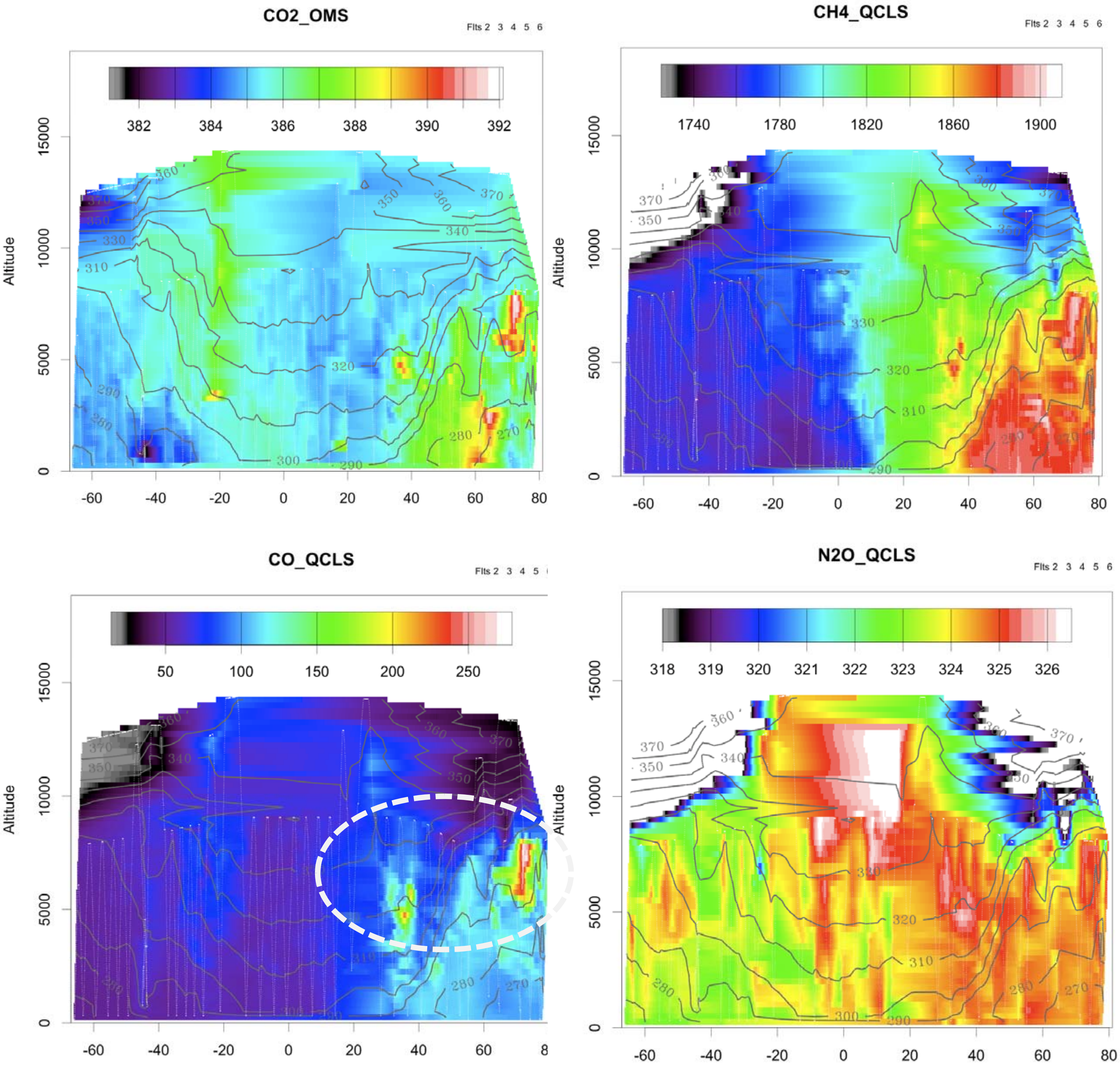




HIPPO_1

Xsects along the Dateline

Jan 2009



HIPPO_2

Xsects along the Dateline

Nov 2009

N_2O is upside down

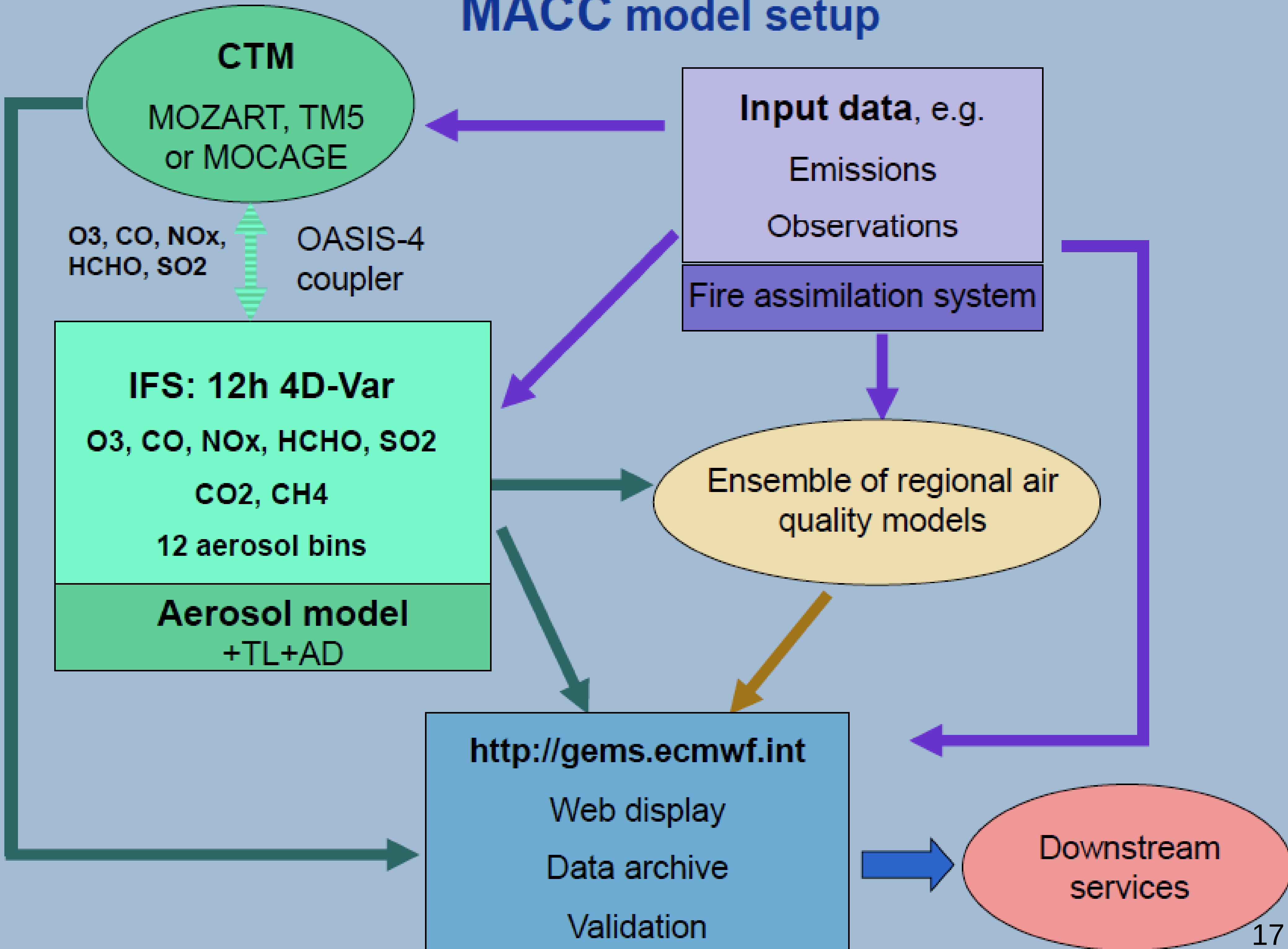
Models with detailed simulations of HIPPO_1 or Pre-HIPPO Data

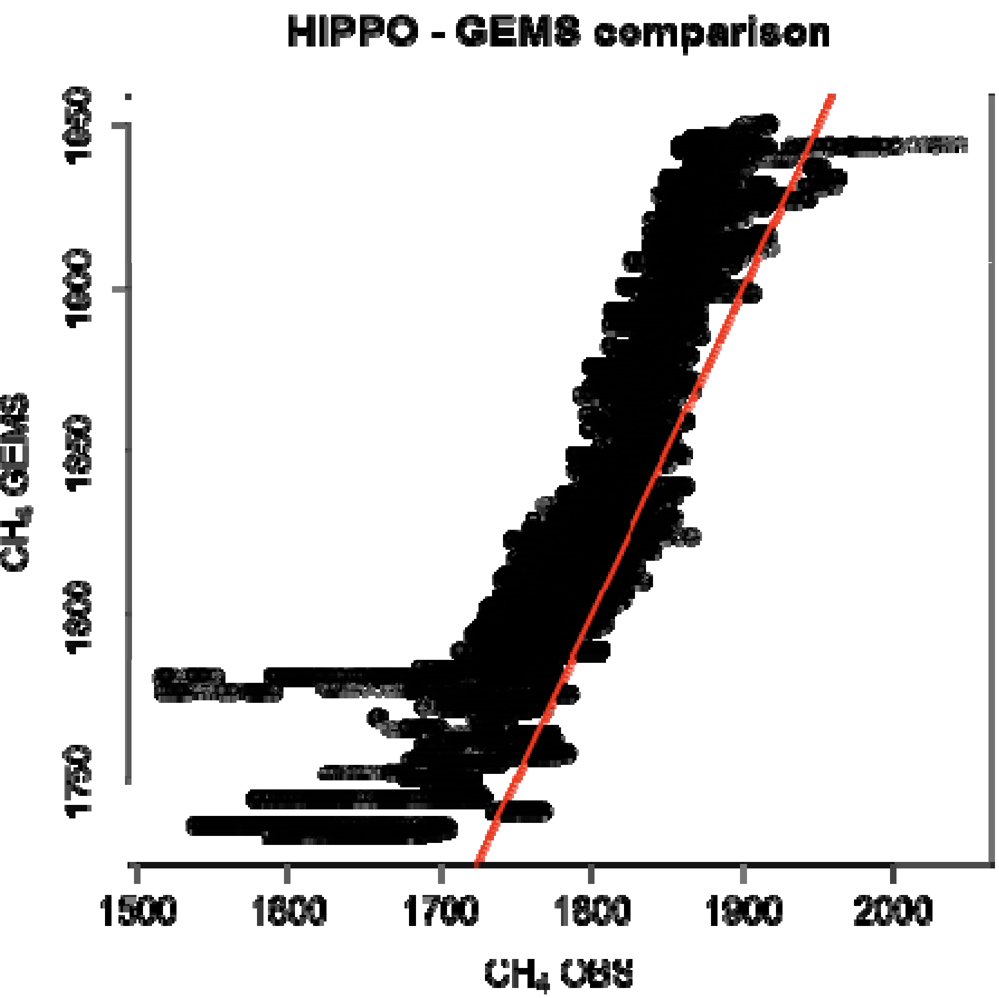
- **Earth Simulator – ACTM** CCSR/NIES/FRCGC AGCM
- **GEOS-CHEM (NASA DAO)** Harvard
- **MACC-GEMS ECMWF** Air Quality and Air Chemistry model

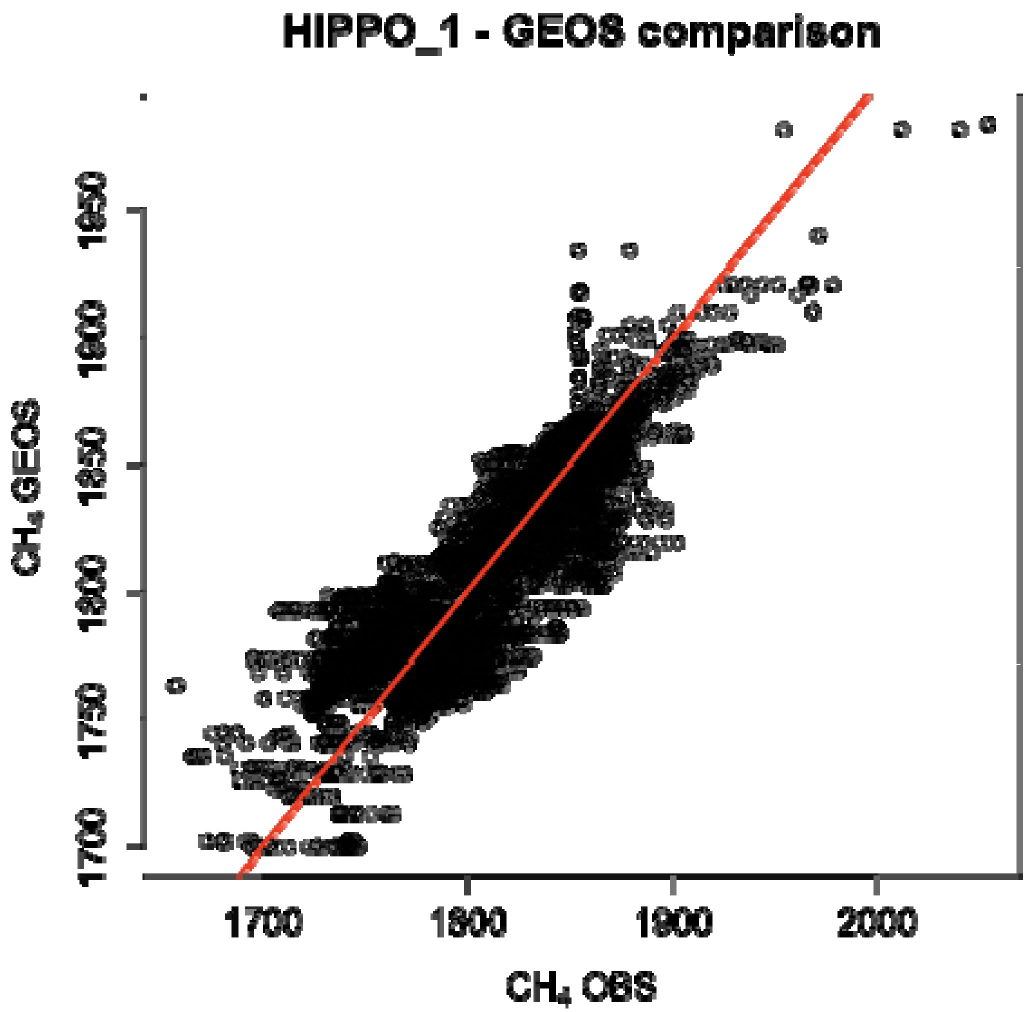
Detailed Model results for HIPPO_1:

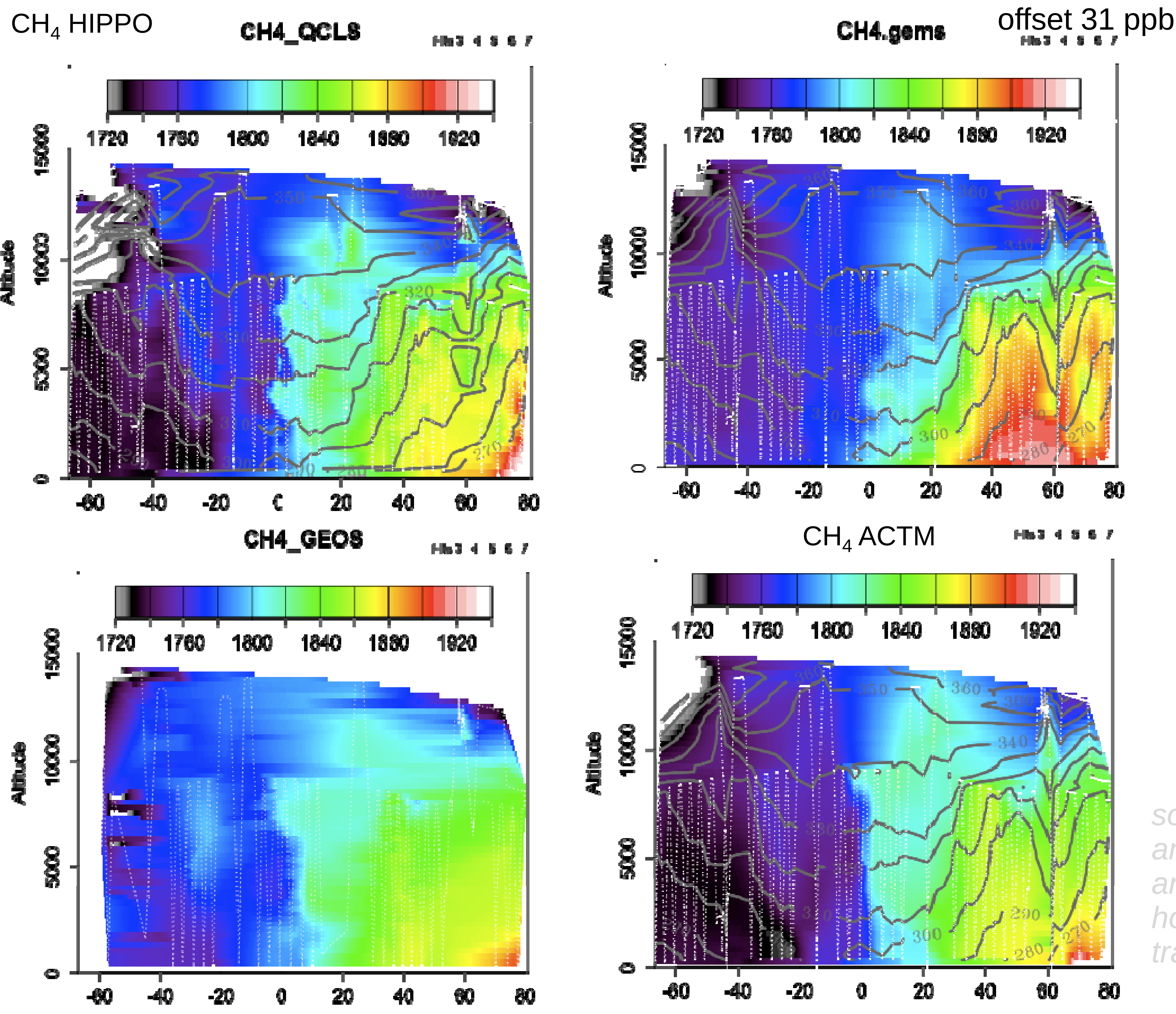
	CO_2	SF_6	C_2H_6	CO	N_2O	CH_4	O_3	PAN	NO_x	HCHO	BlkC
GEOS_C	1	1	1	1	0	1	0	0	0	0	*
ACTM	1	1	0	0	1	1	0	0	0	0	
MACC	0	0	1	1, **Fcst**	0	1	1	1	1	1	
TOTALS	2	2	2	2, **Fcst**	1	3	1	1	1	1	

MACC model setup

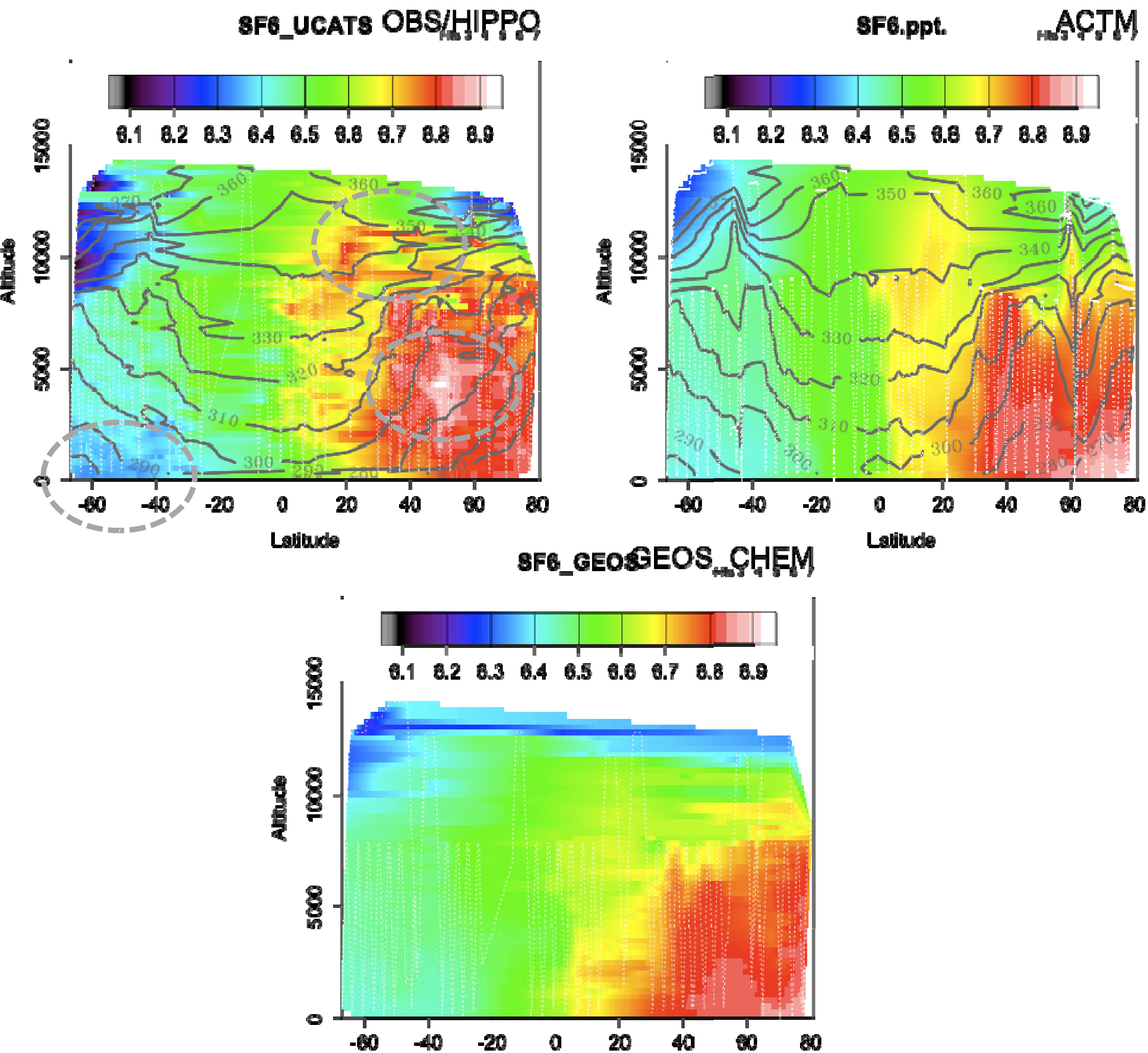



HIPPO - GEMS comparison
CH4 GEMS
CH4 OBS
1500
1600
1700
1800
1900
2000


HIPPO_1 - GEOS comparison
CH4 GEOS
CH4 OBS
1700
1800
1900
2000



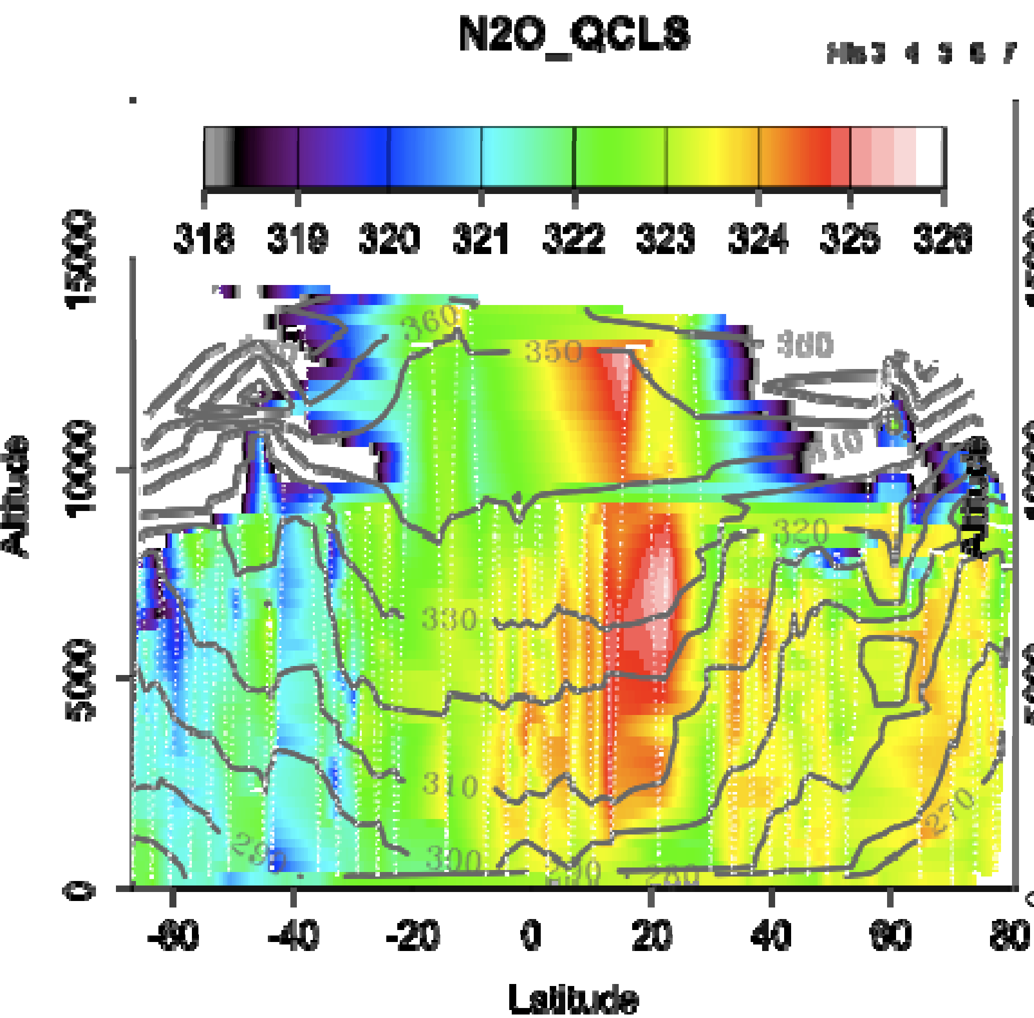
sources and vertical and horizontal transport

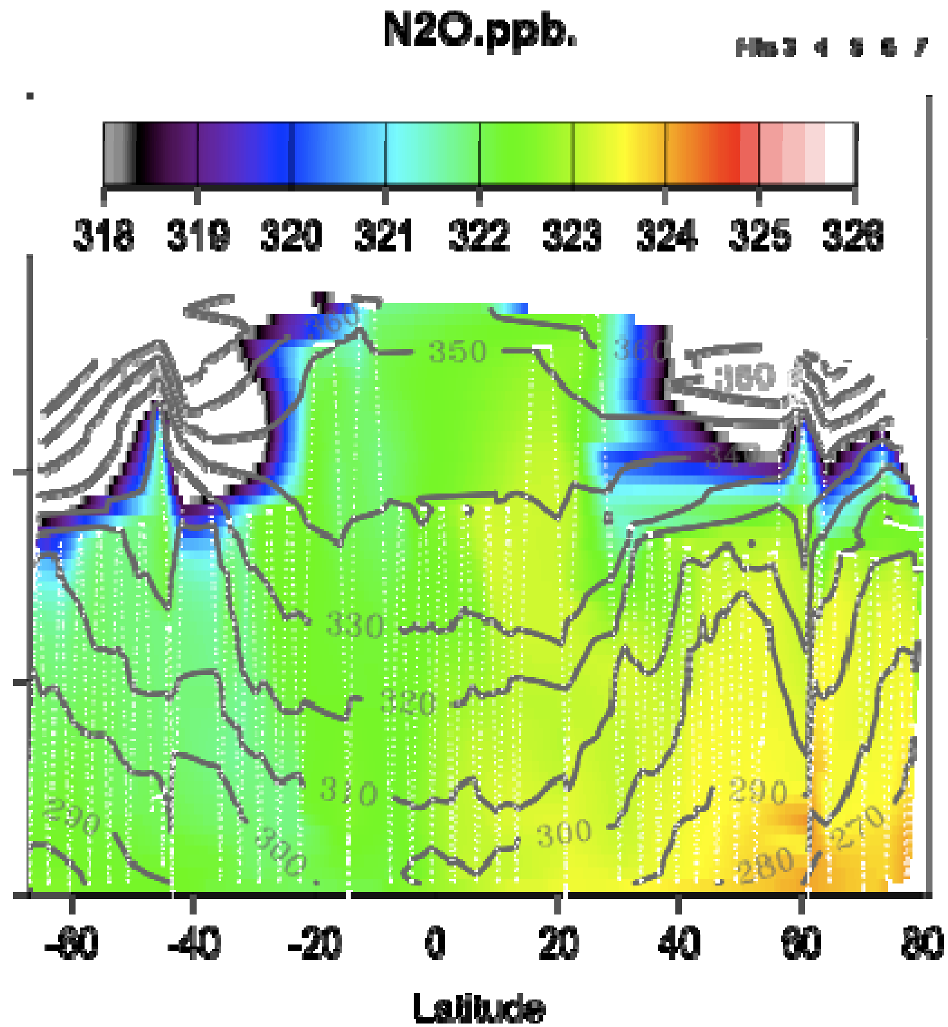


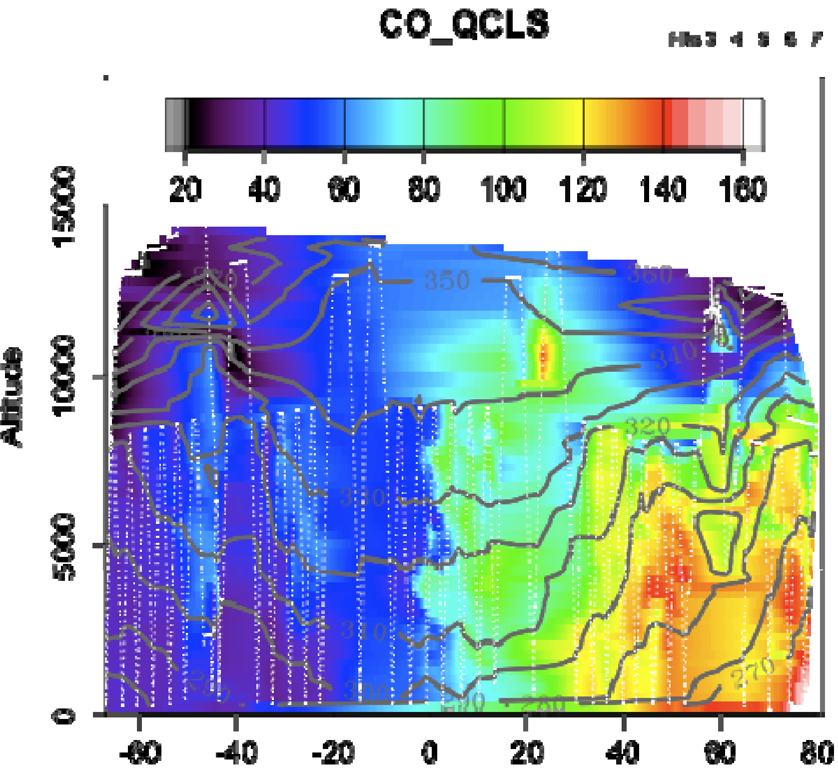
sources
and vertical
and
horizontal
transport

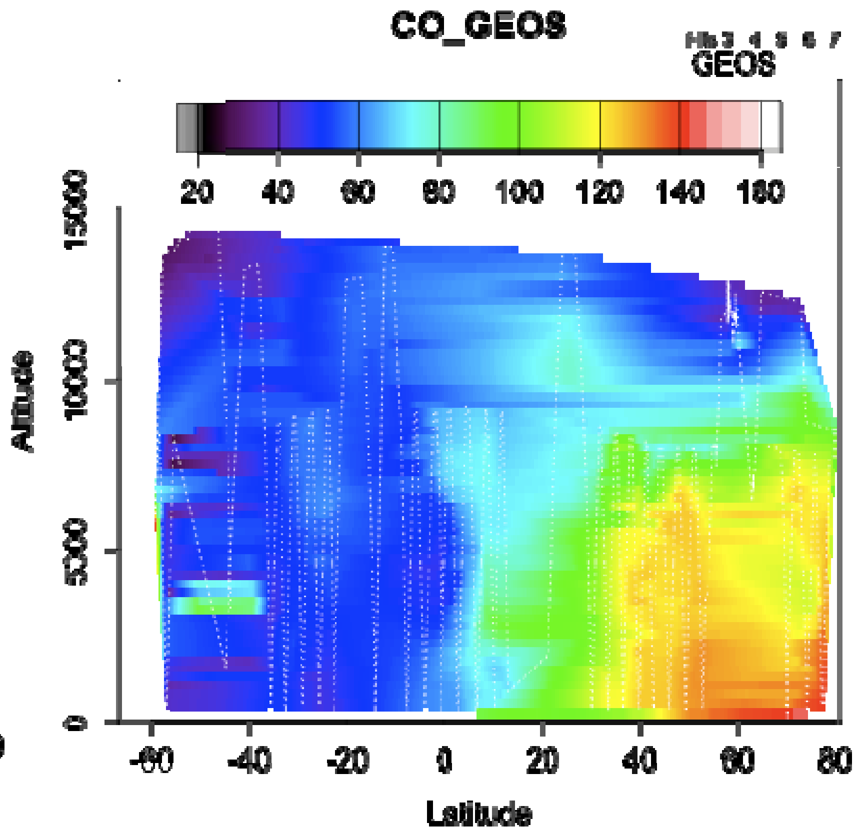
Jan 2009 Observed

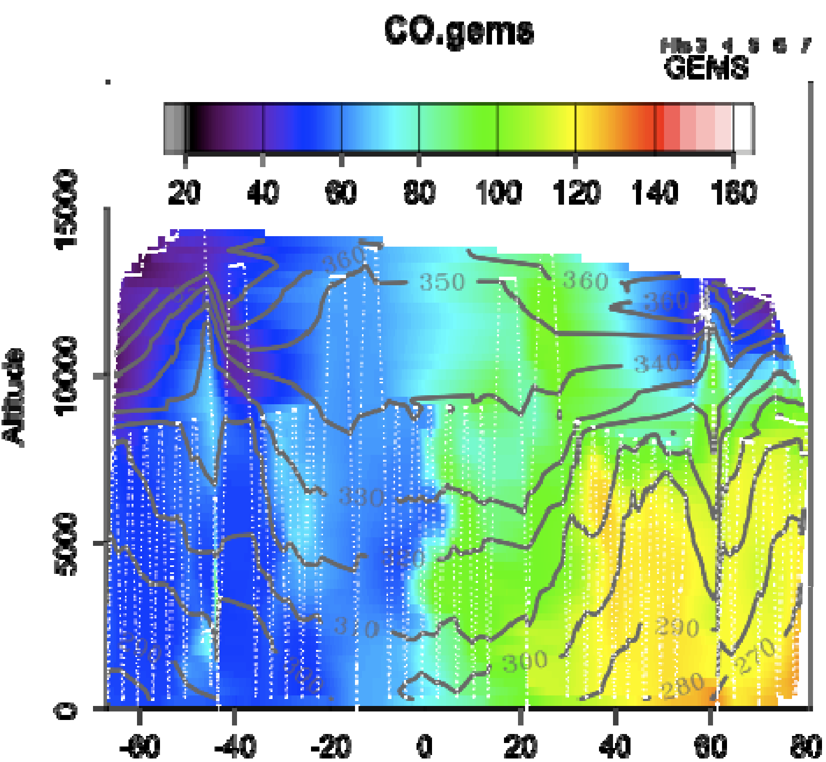
ACTM (GEIA)

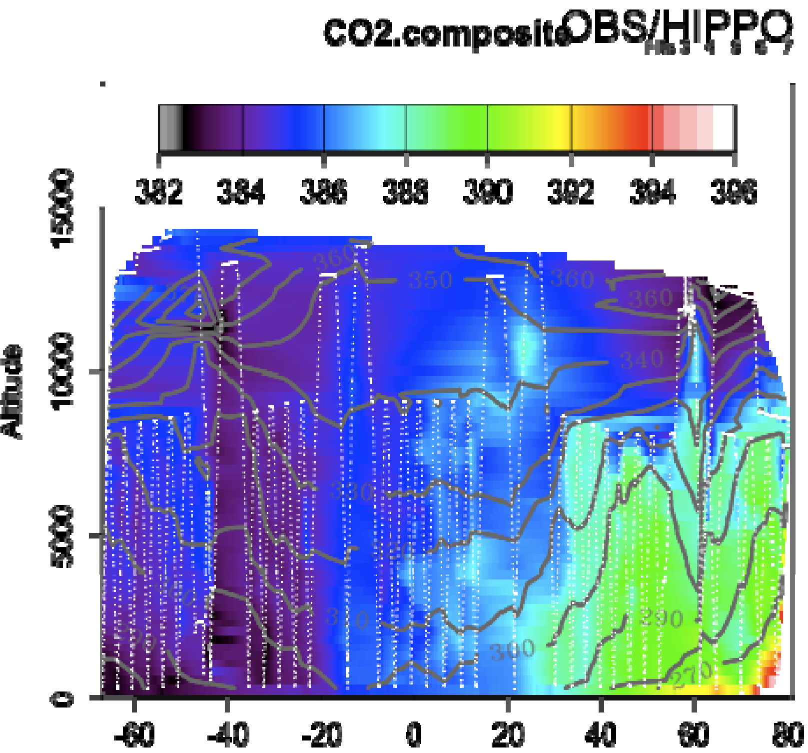


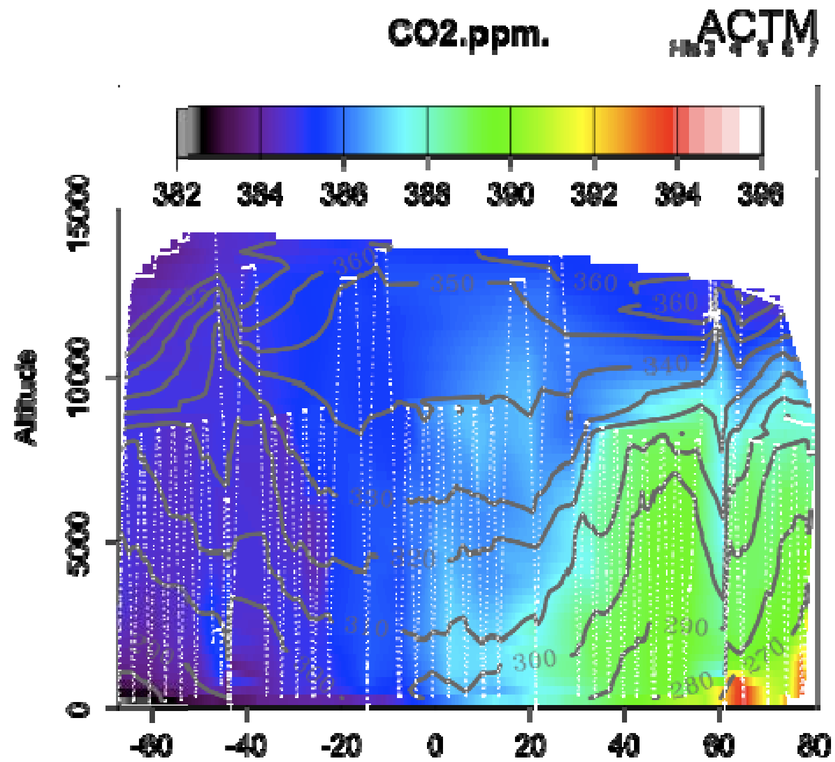


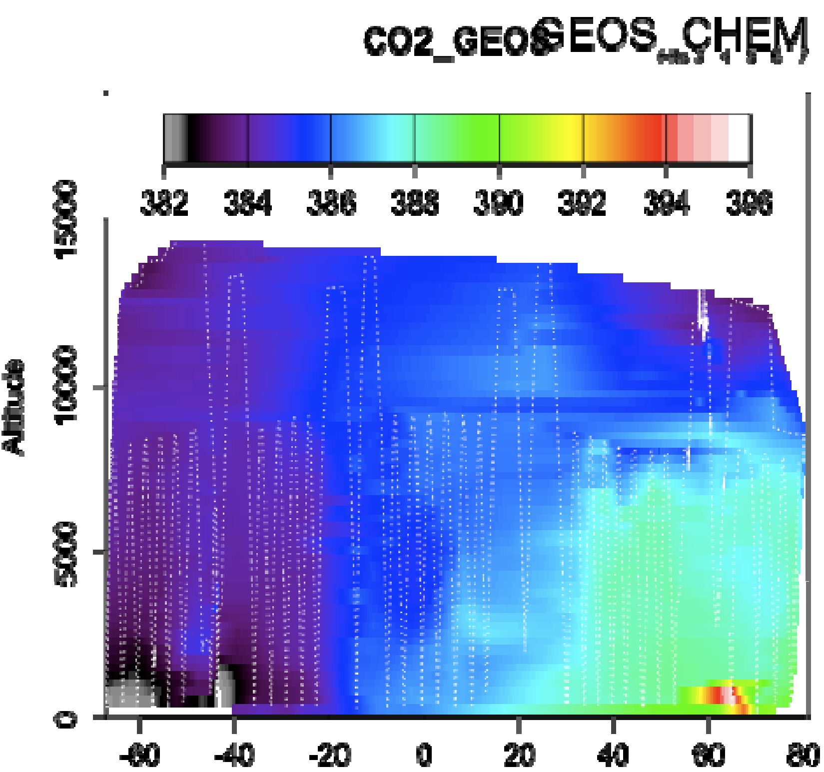

CO_QCLS
20 40 60 80 100 120 140 160
Altitude
0 5000 10000 15000
-60 -40 -20 0 20 40 60 80
350
340
320
330
310
300
290
280
270

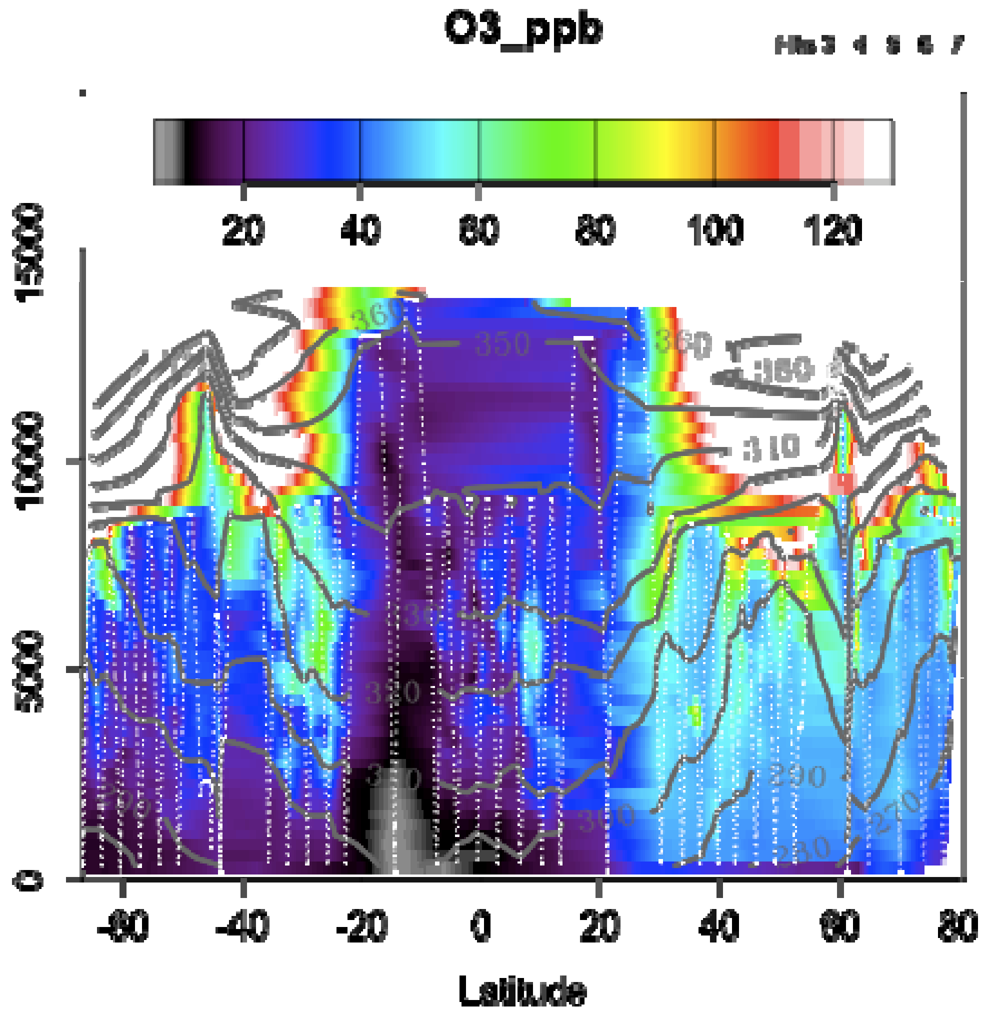

CO_GEOS
GEOS
20 40 60 80 100 120 140 160
Altitude
0 5000 10000 15000
-60 -40 -20 0 20 40 60 80
Latitude


CO.gems
GEMS
20 40 60 80 100 120 140 160
Altitude
0 5000 10000 15000
-60 -40 -20 0 20 40 60 80
360
350
340
330
310
300
290
280
270

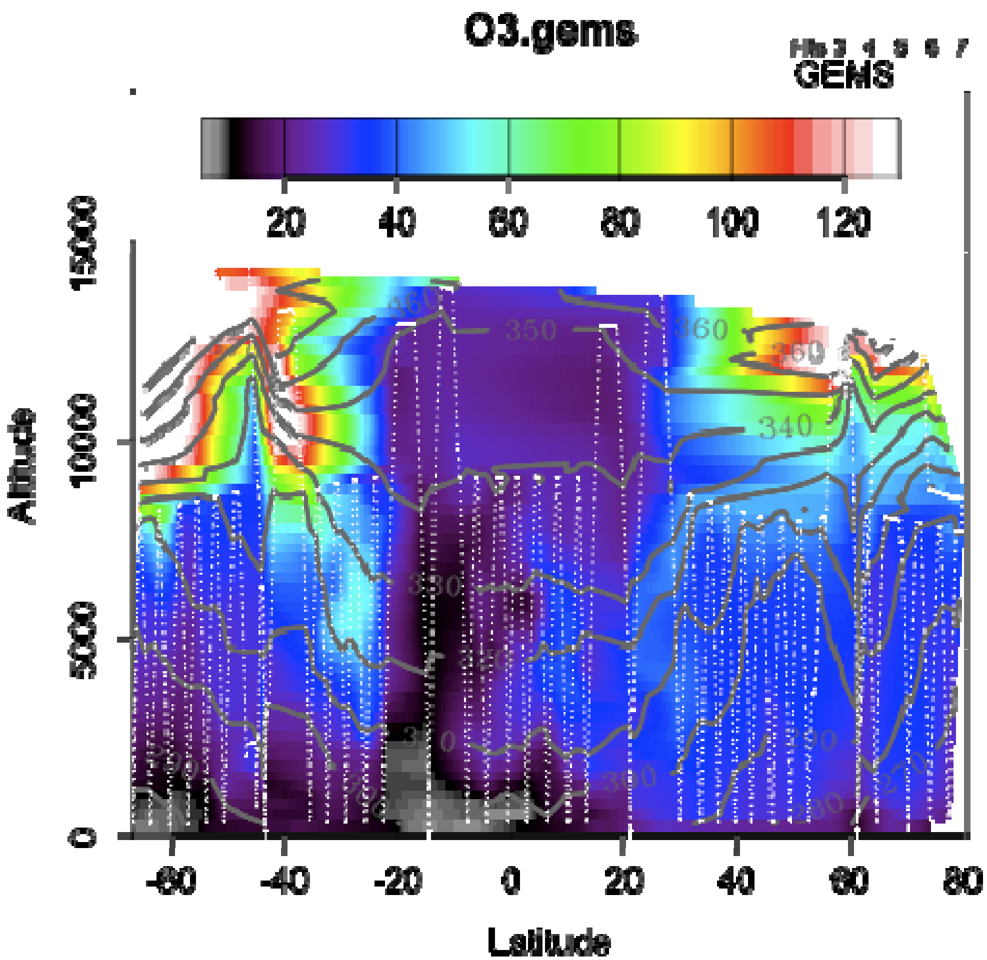

CO2.composite
OBS/HIPPO
382 384 386 388 390 392 394 396
Altitude
0 5000 10000 15000
-60 -40 -20 0 20 40 60 80


CO2.ppm.
ACTM
382 384 386 388 390 392 394 396
Altitude
0 5000 10000 15000
-60 -40 -20 0 20 40 60 80


CO2_GEOS
GEOS_CHEM
382 384 386 388 390 392 394 396
Altitude
0 5000 10000 15000
-60 -40 -20 0 20 40 60 80



O3_ppb
Altitude
Latitude

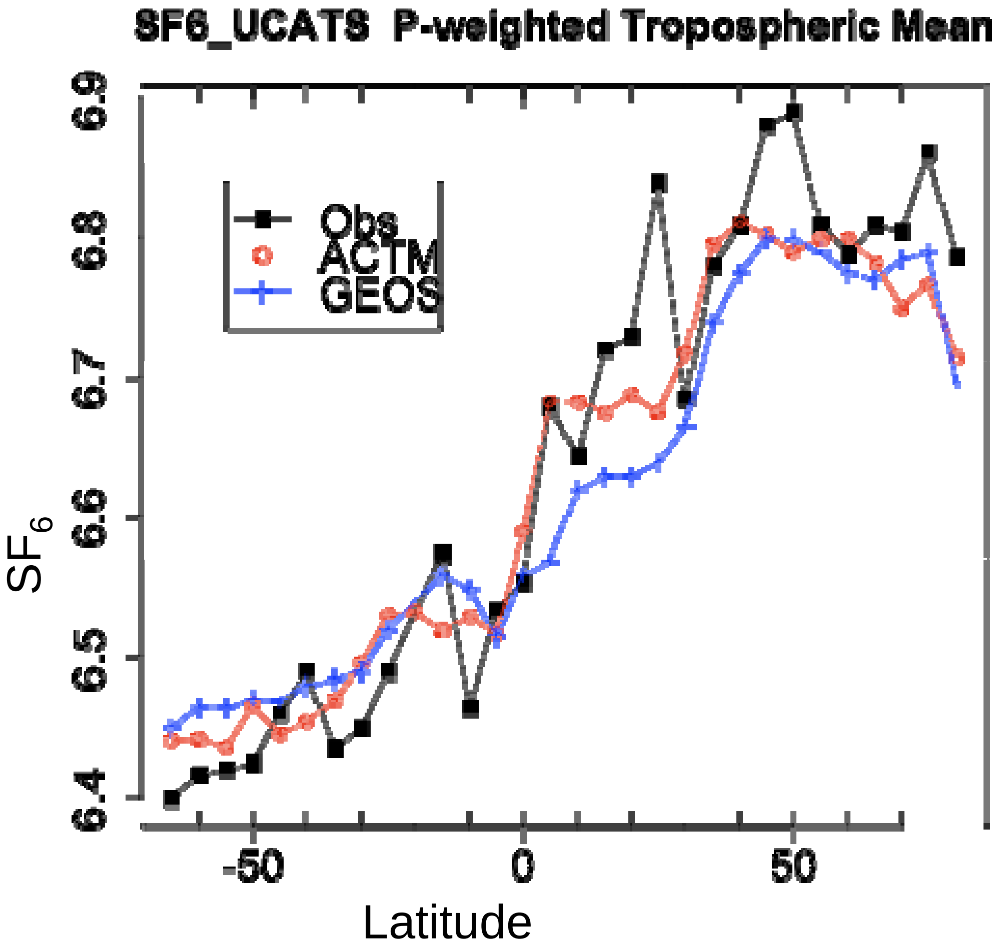


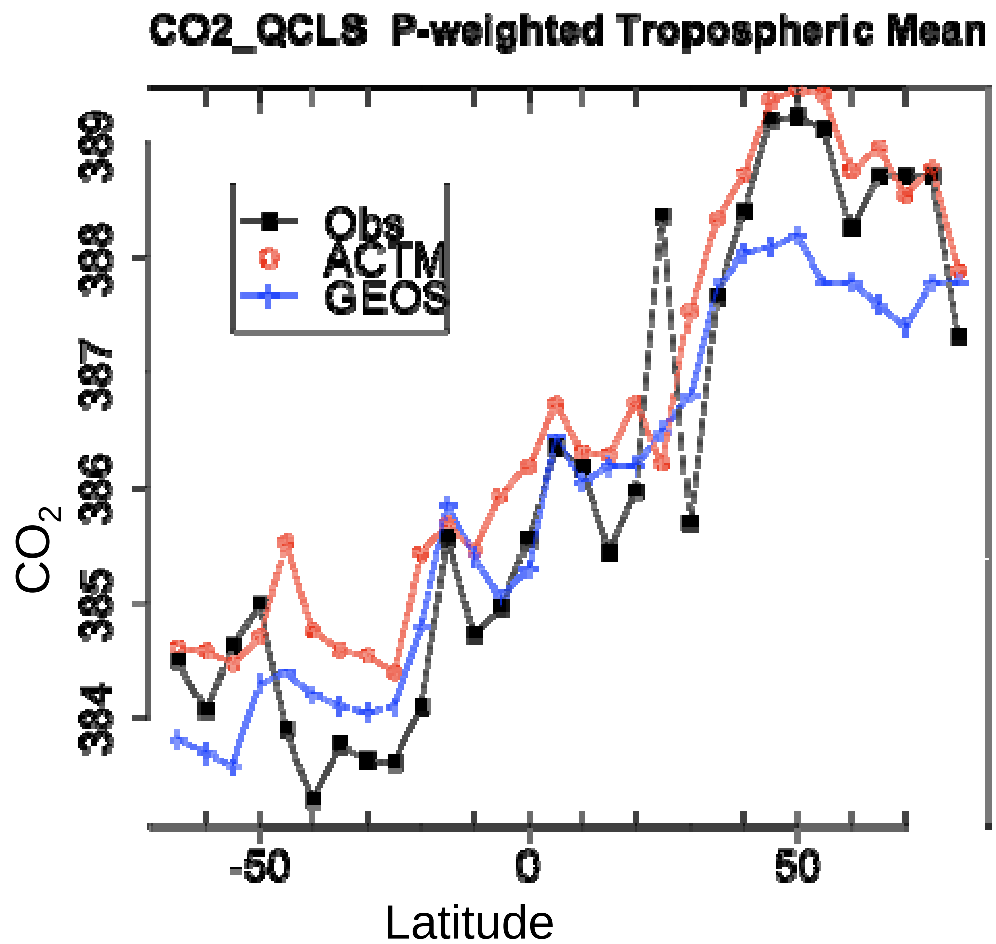
O3.gems
GEMS
Altitude
Latitude

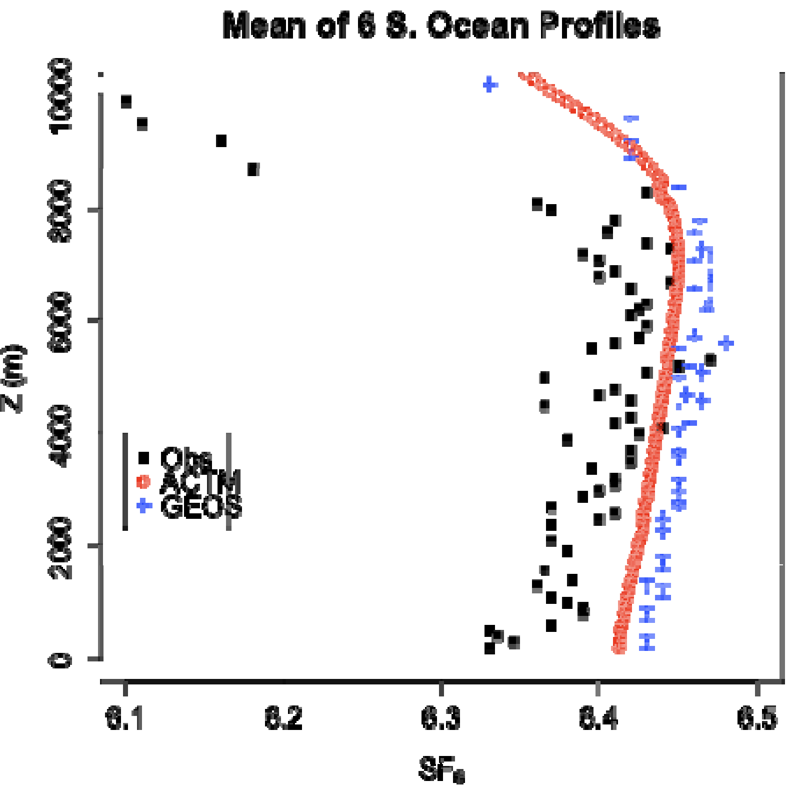
Using multiple tracers to help solve the model-measurement conundrum

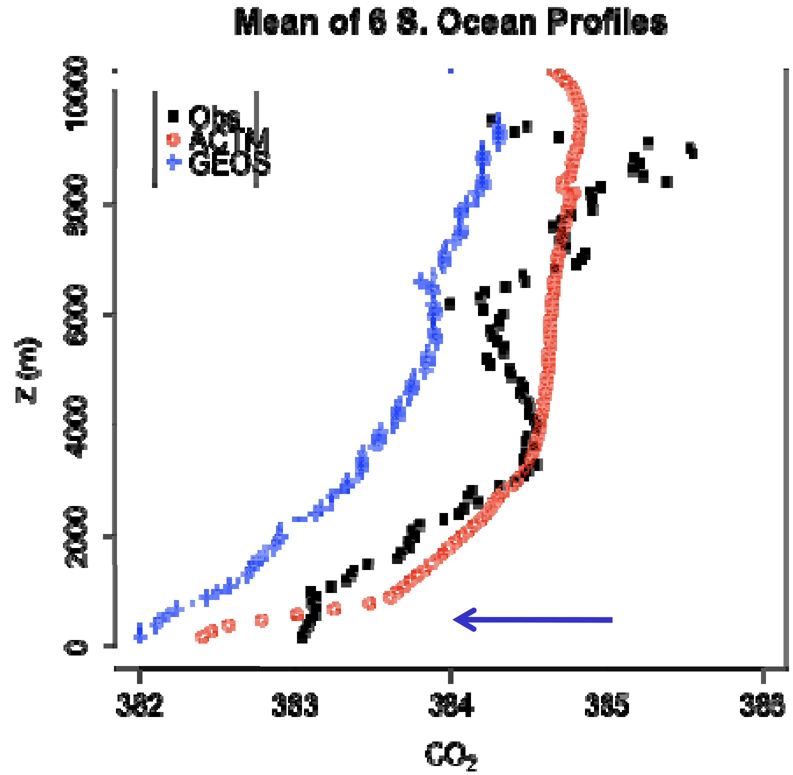
- The stratosphere has a major influence on the concentrations of tracers distributed through the troposphere. How well is this feature captured by models ?

- What do we learn about sources, versus transport, from latitude and altitude profiles ?

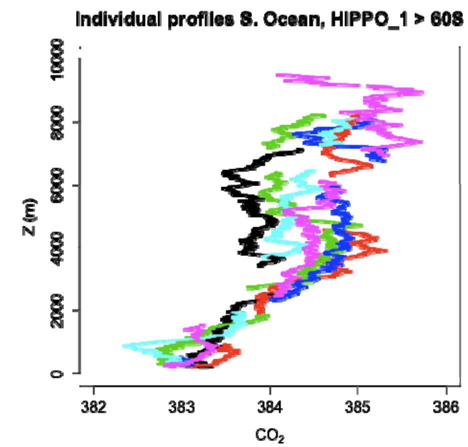

SF6_UCATS P-weighted Tropospheric Mean
Obs
ACTM
GEOS
SF_6
6.4
6.5
6.6
6.7
6.8
6.9
-50
0
50
Latitude

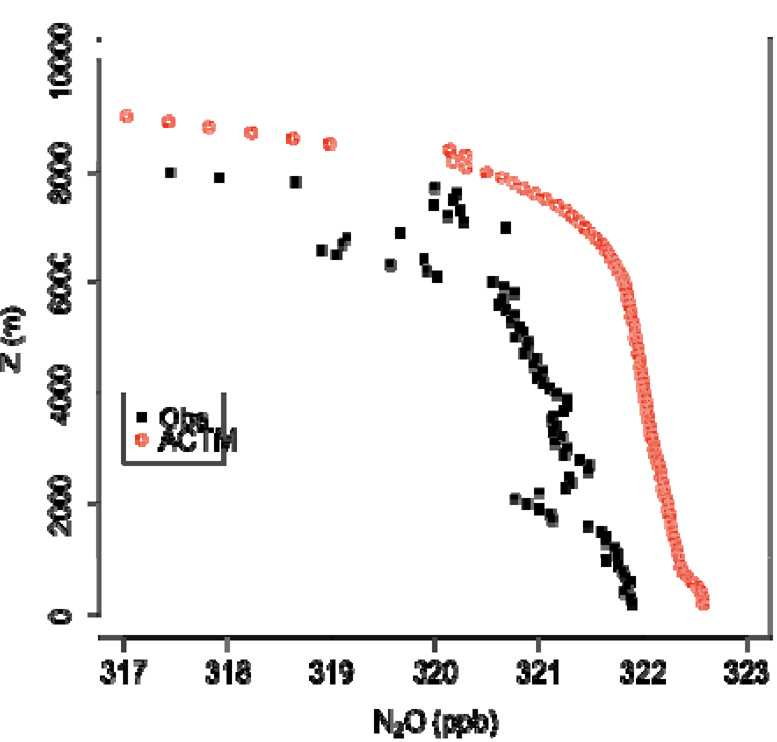

CO2_QCLS P-weighted Tropospheric Mean
Obs
ACTM
GEOS
CO_2
384
385
386
387
388
389
-50
0
50
Latitude

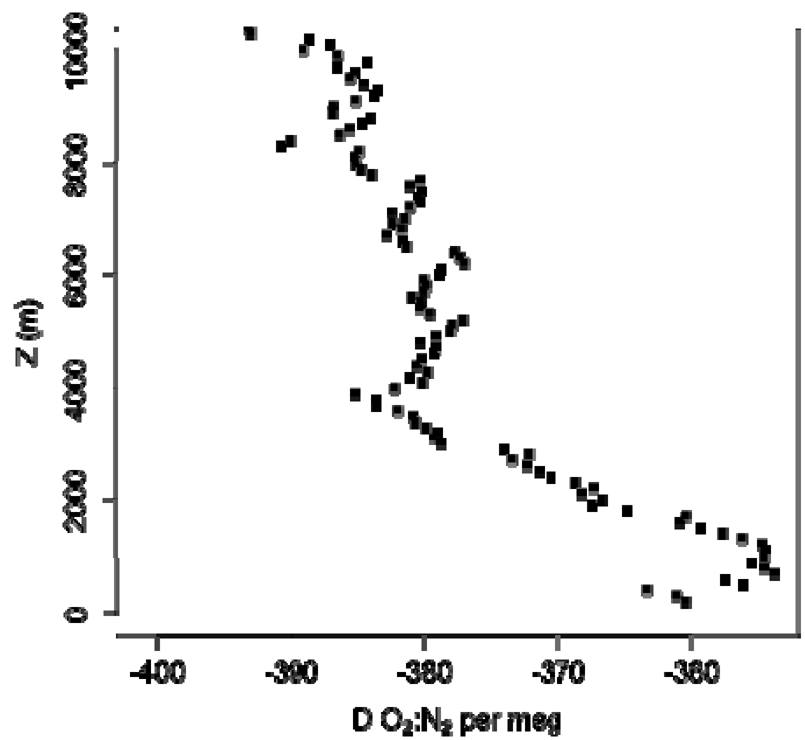




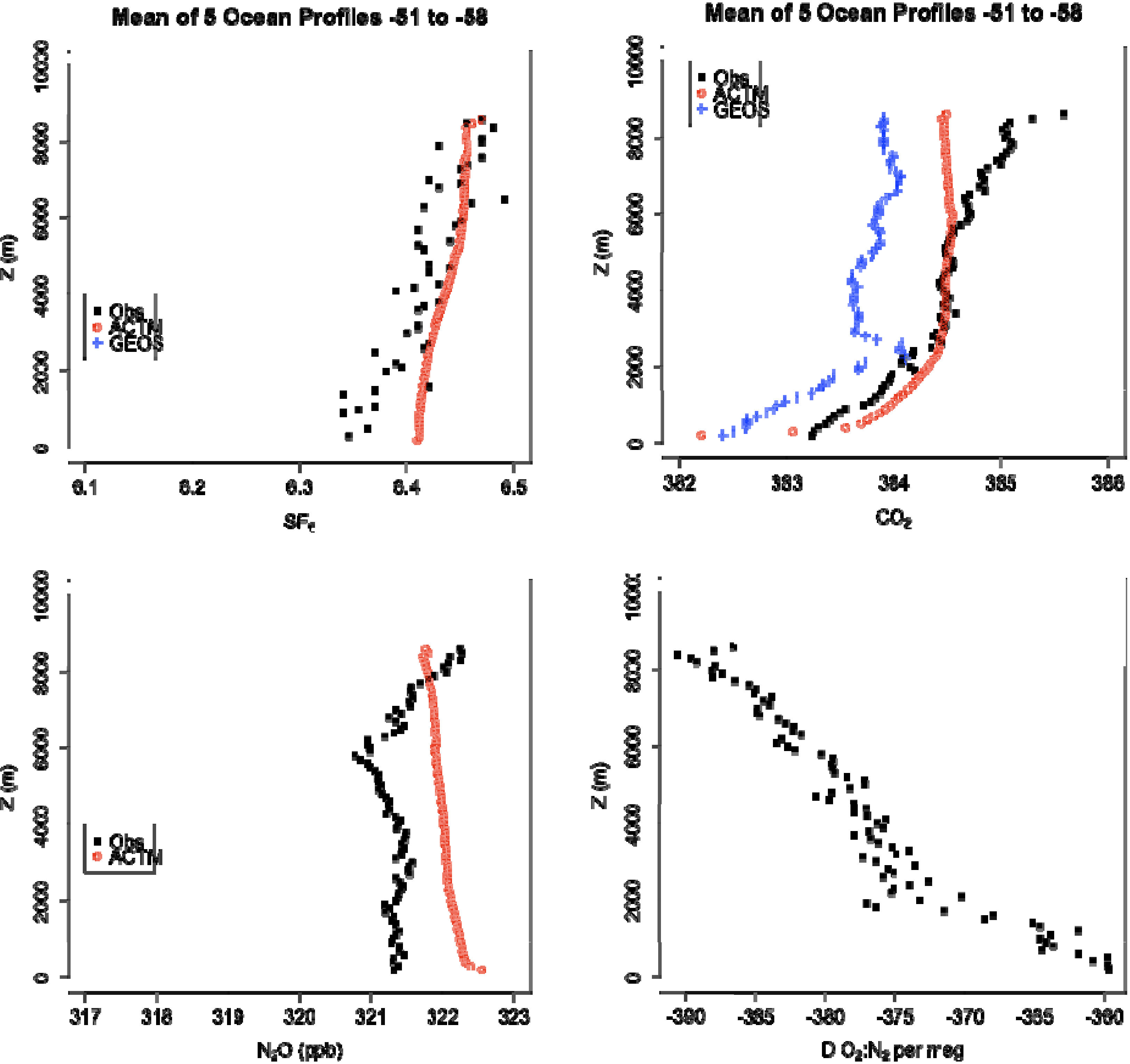
lat -60 to -70





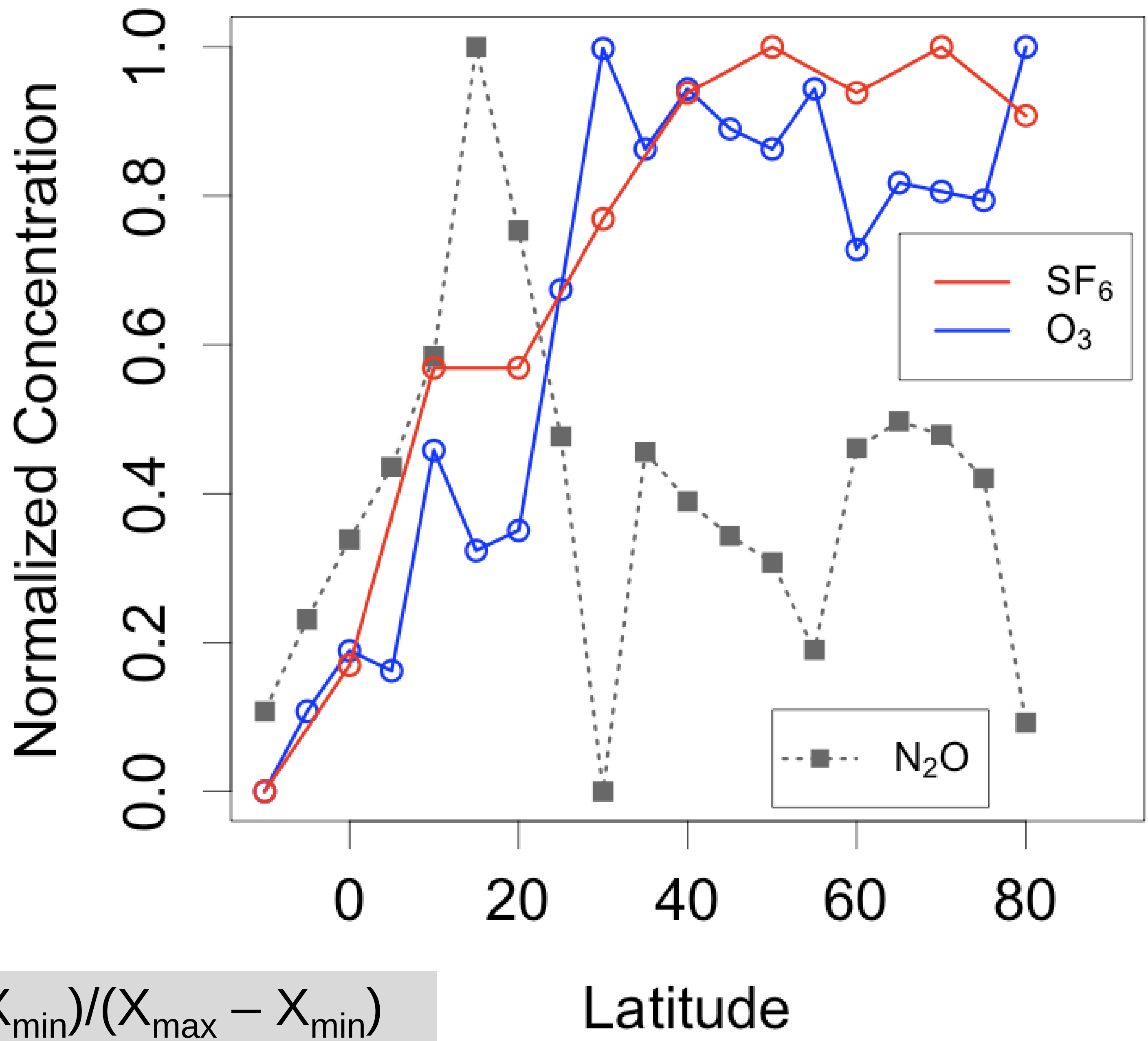


CO_2 and other gases in S. Polar regions

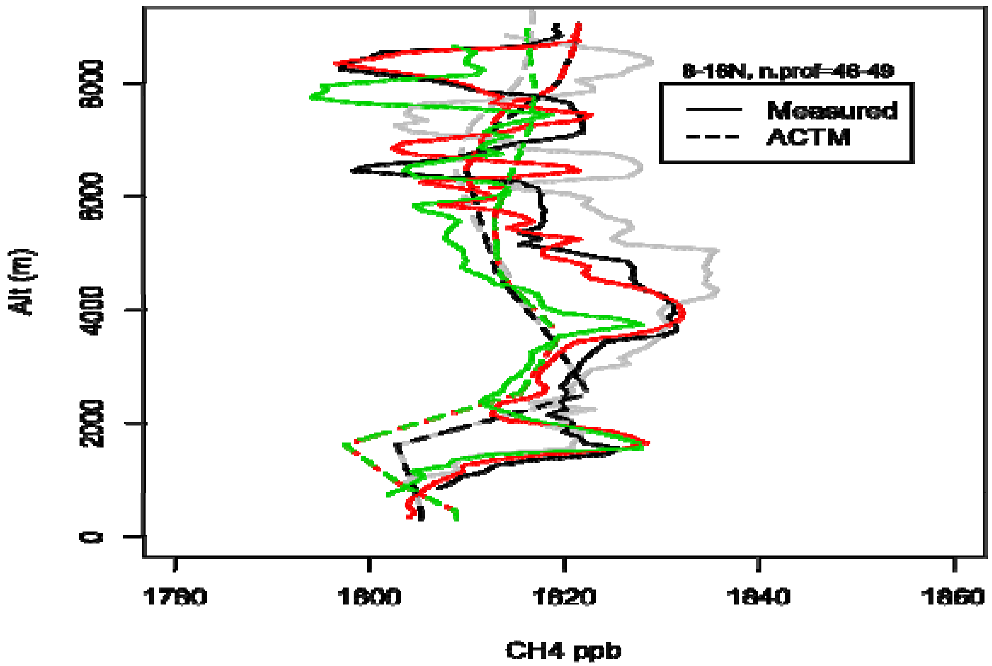


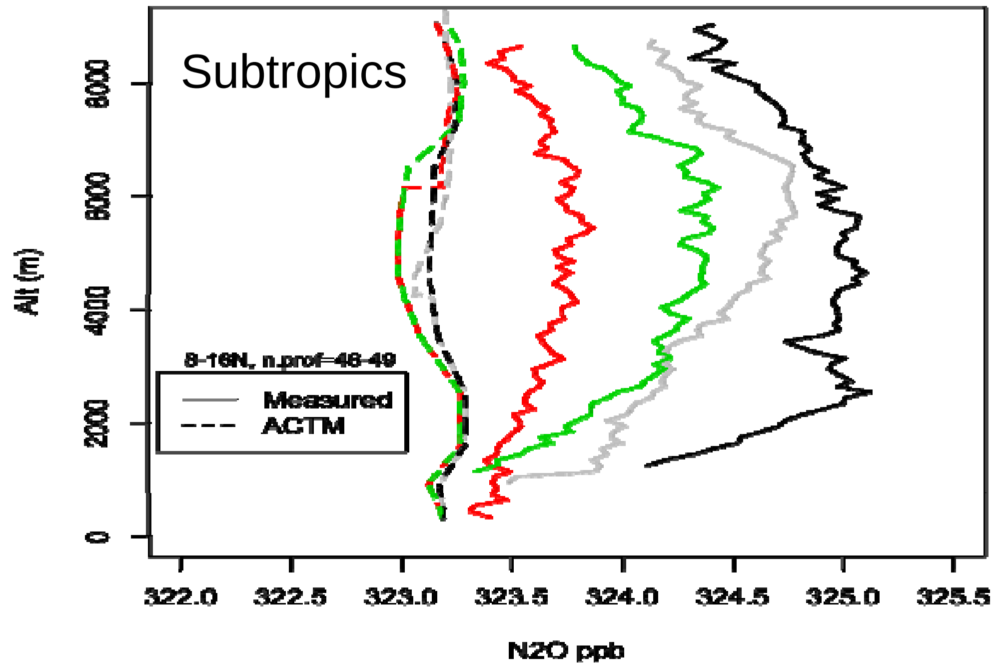
CO_2 and other gases in Southern Ocean area

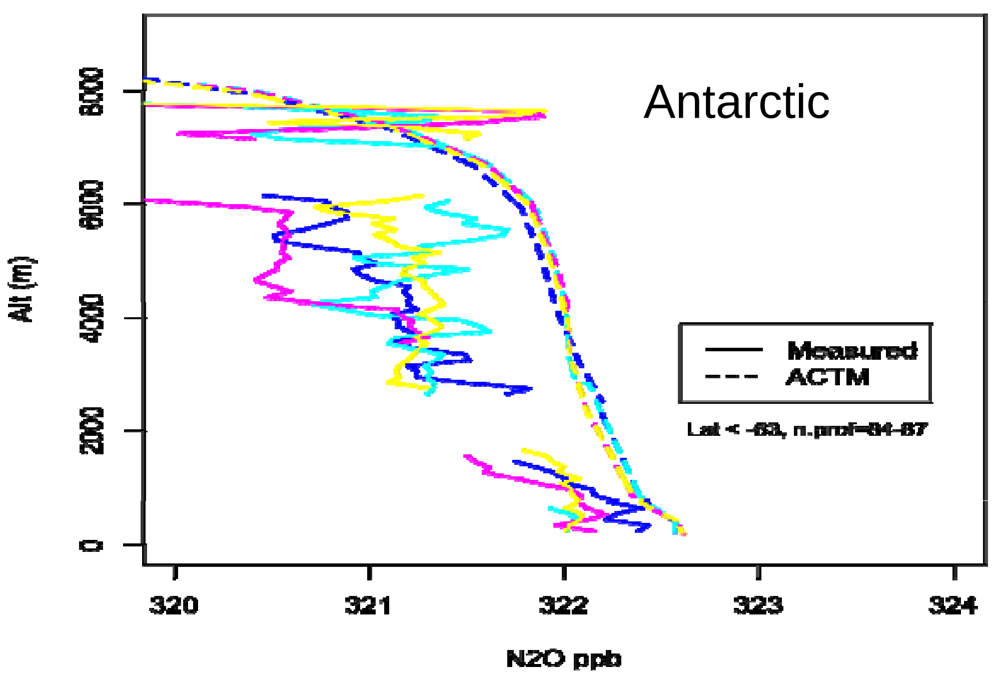
Northern Hemisphere Tropospheric Tracers of Strat/Trop Exchange

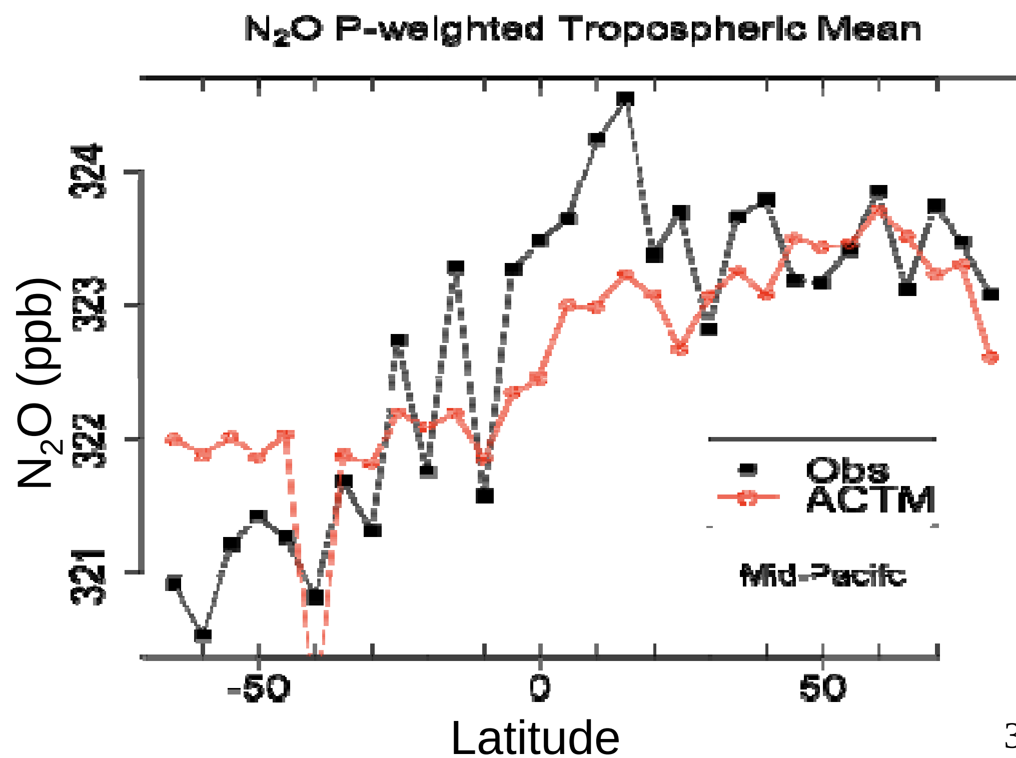


$(X - X_{min})/(X_{max} - X_{min})$

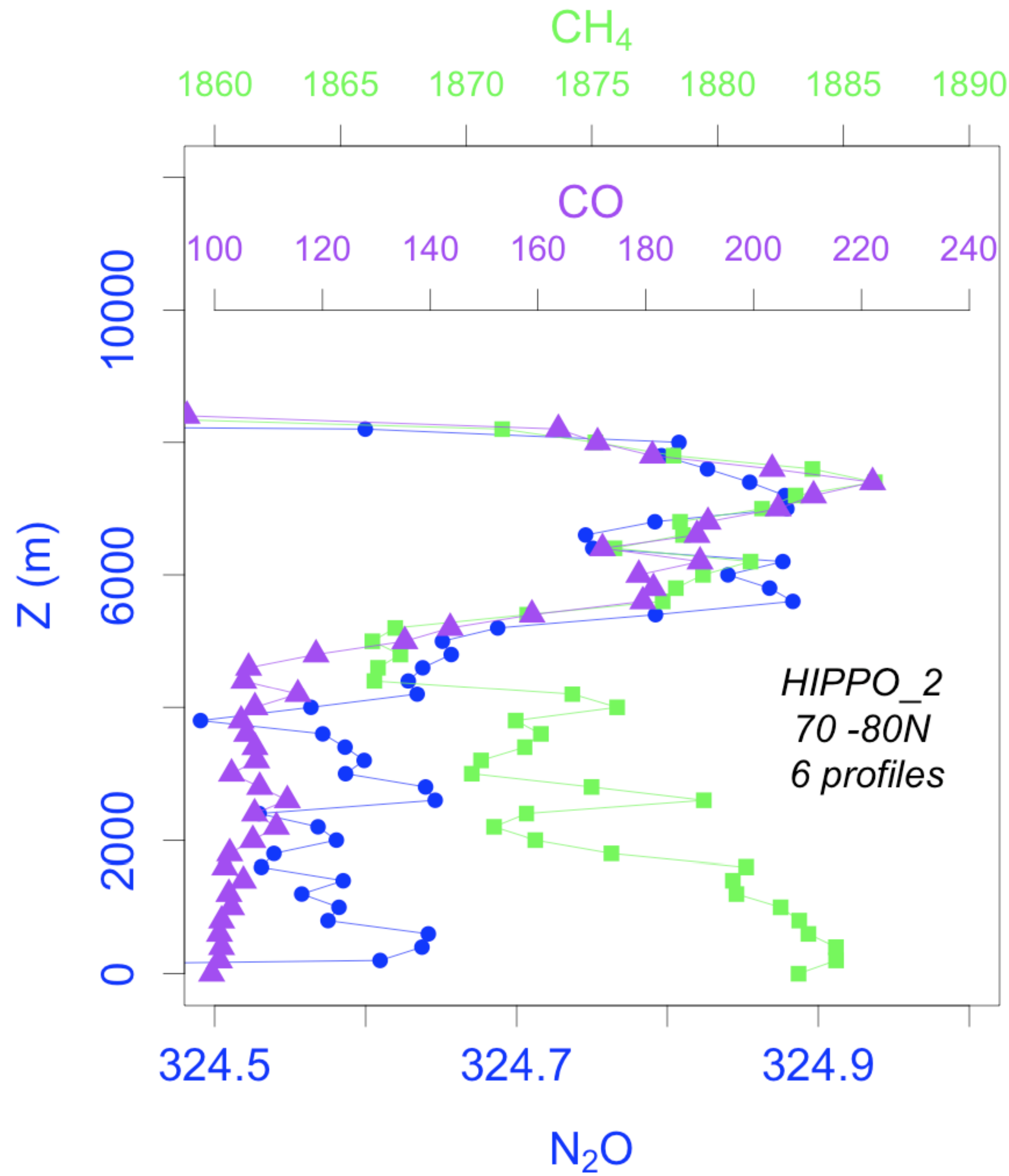

8-16N, n.prof=46-49
Measured
ACTM
Alt (m)
CH4 ppb
1780
1800
1820
1840
1860
0
2000
4000
6000
8000


Subtropics
8-16N, n.prof=46-49
Measured
ACTM
Alt (m)
N2O ppb
322.0
322.5
323.0
323.5
324.0
324.5
325.0
325.5
0
2000
4000
6000
8000

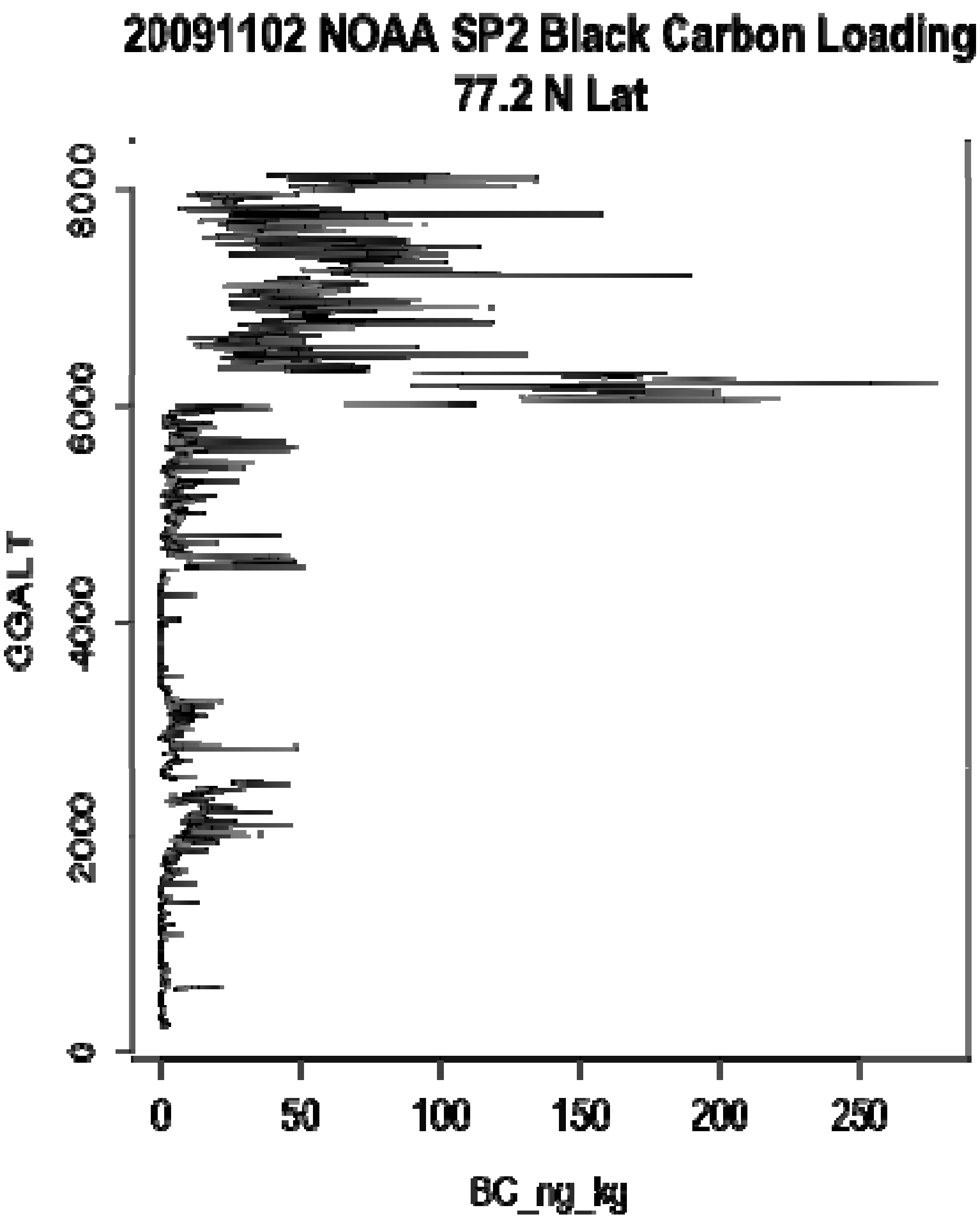

Antarctic
Measured
ACTM
Lat < -63, n.prof=64-67
Alt (m)
N2O ppb
320
321
322
323
324
0
2000
4000
6000
8000

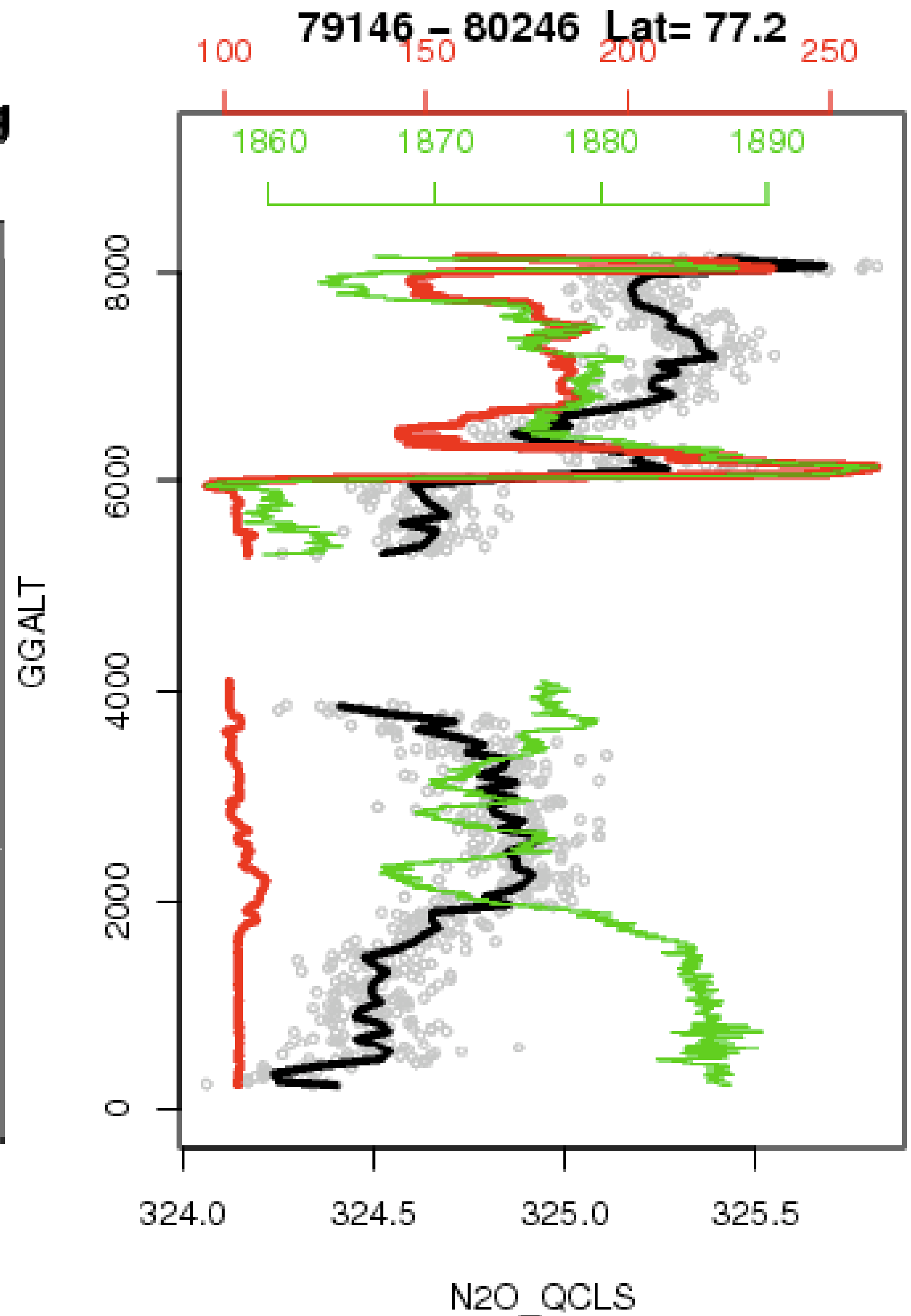

N2O P-weighted Tropospheric Mean
N2O (ppb)
Latitude
Obs
ACTM
Mid-Pacific
321
322
323
324
-50
0
50

HIPPO_2: High-altitude pollution phenomena in the Arctic

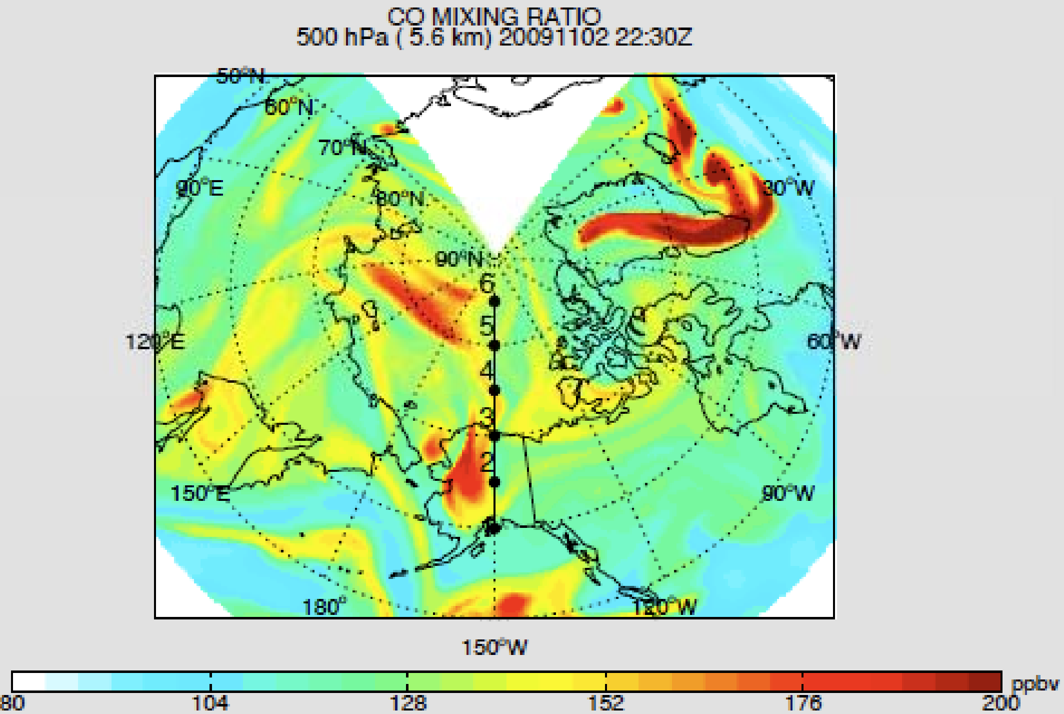



78N latitude, 160W (north of Barrow) 04 Nov 2009
moonrise, haze, black carbon



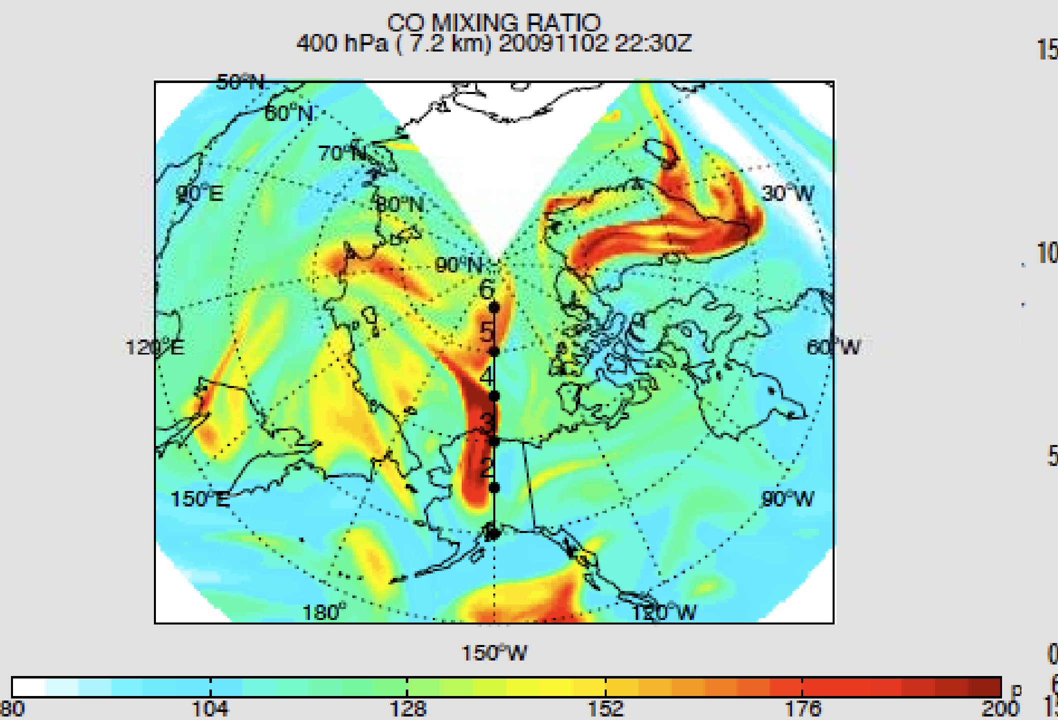


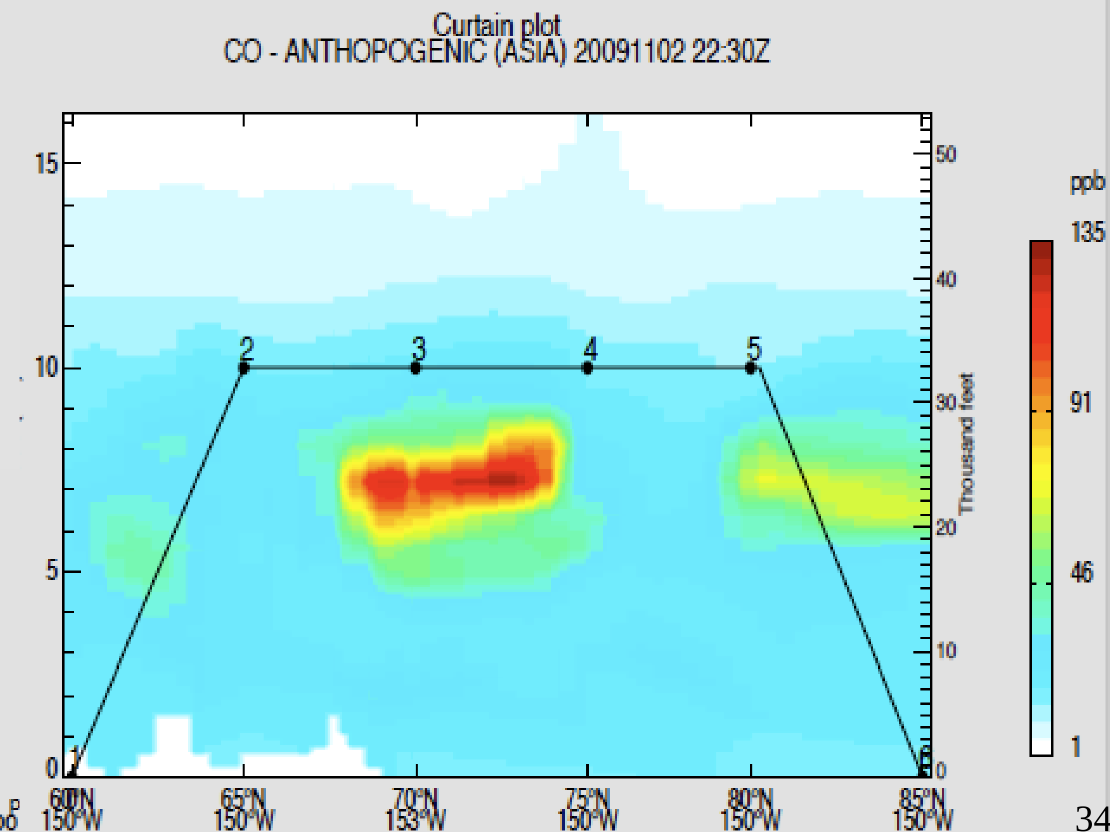
Urban plumes (Dallas, Houston): 500-600 ng/kg
Texas non-urban: 50-100 (USA) (*Schwartz et al., 2008*)



HIPPO_2:

Pollution from Asia covered a vast area of the Arctic on 02 Nov 2009

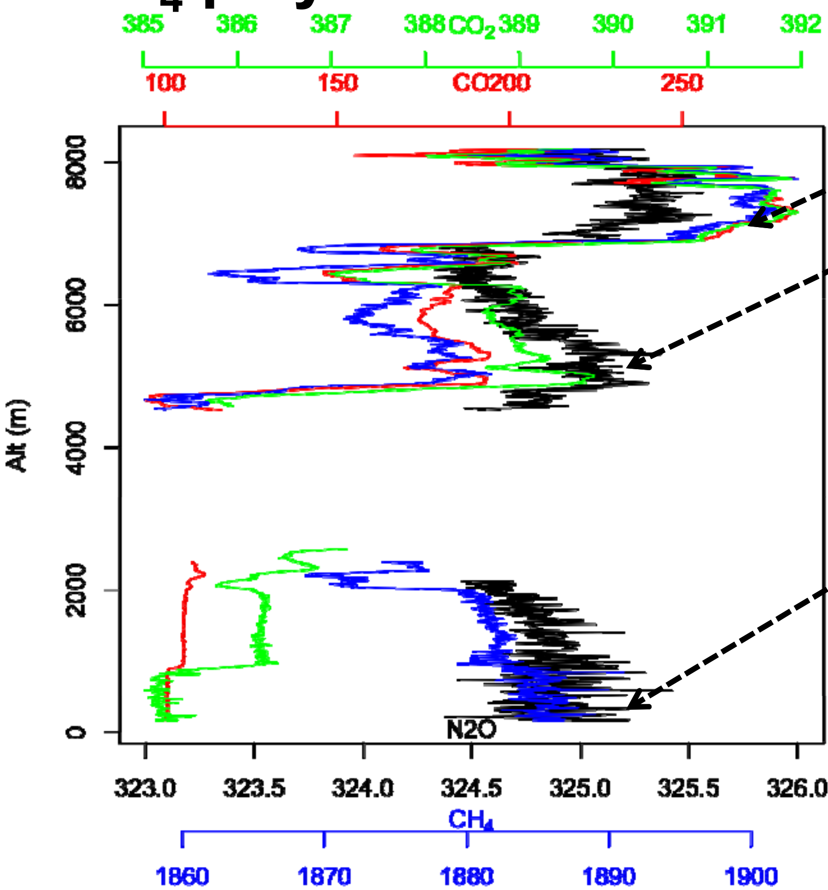


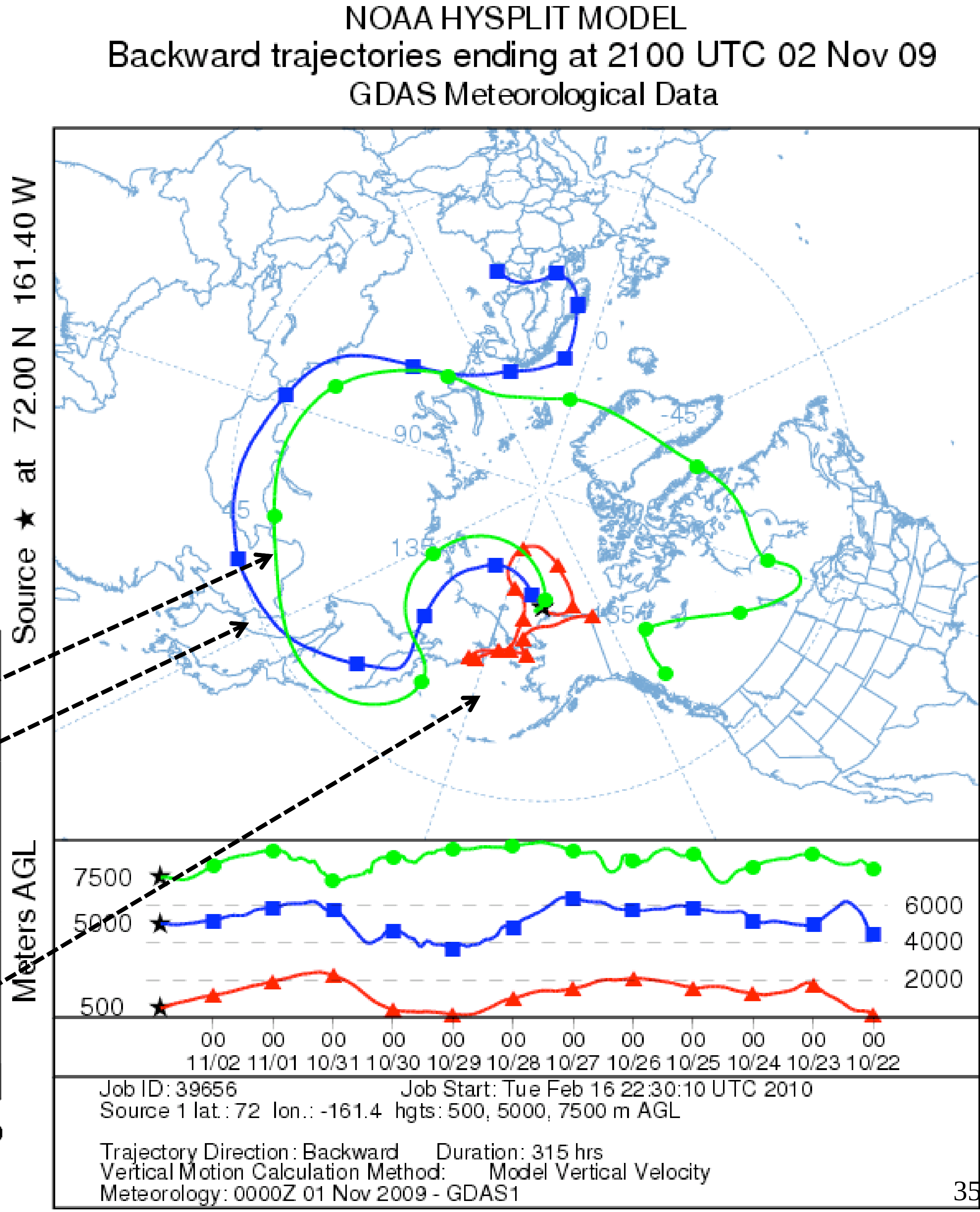


H2 Profile 19

How do anomalies arise? How is a profile composed?

Arctic, very dense high-altitude pollution juxtaposed with "a pure CH_4 play"

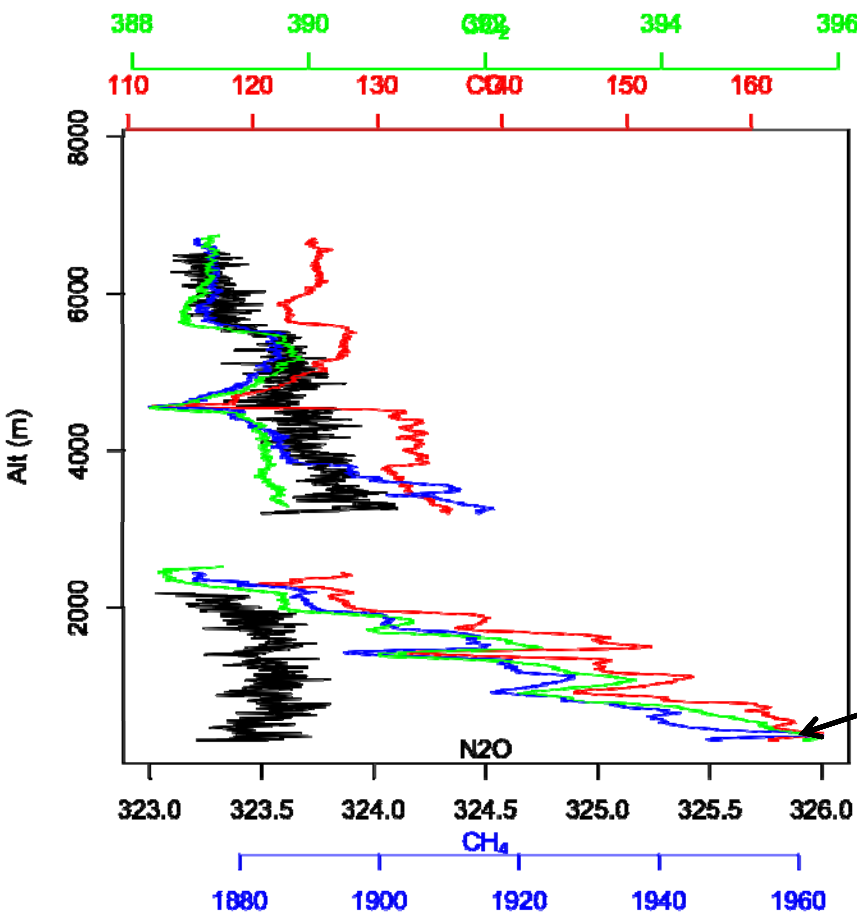


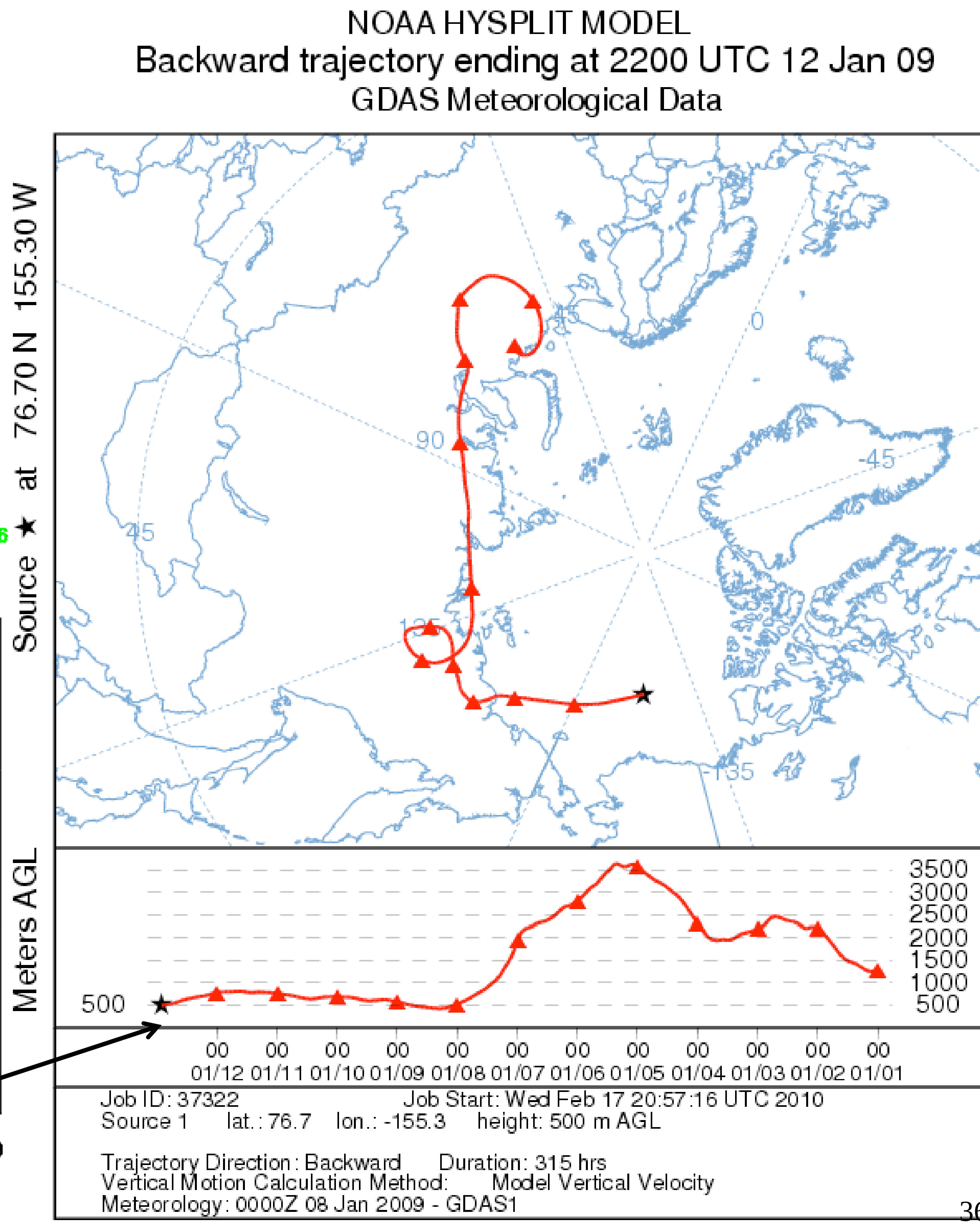


H1 Profile 24

How do anomalies arise? How is a profile composed?

Arctic low altitude pollution

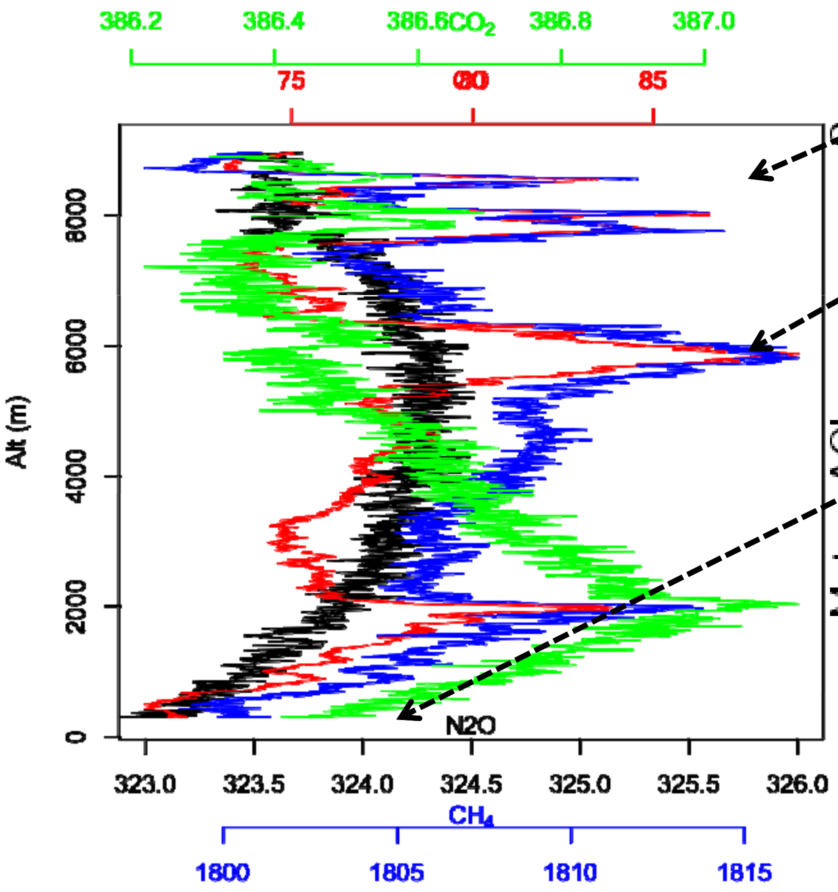


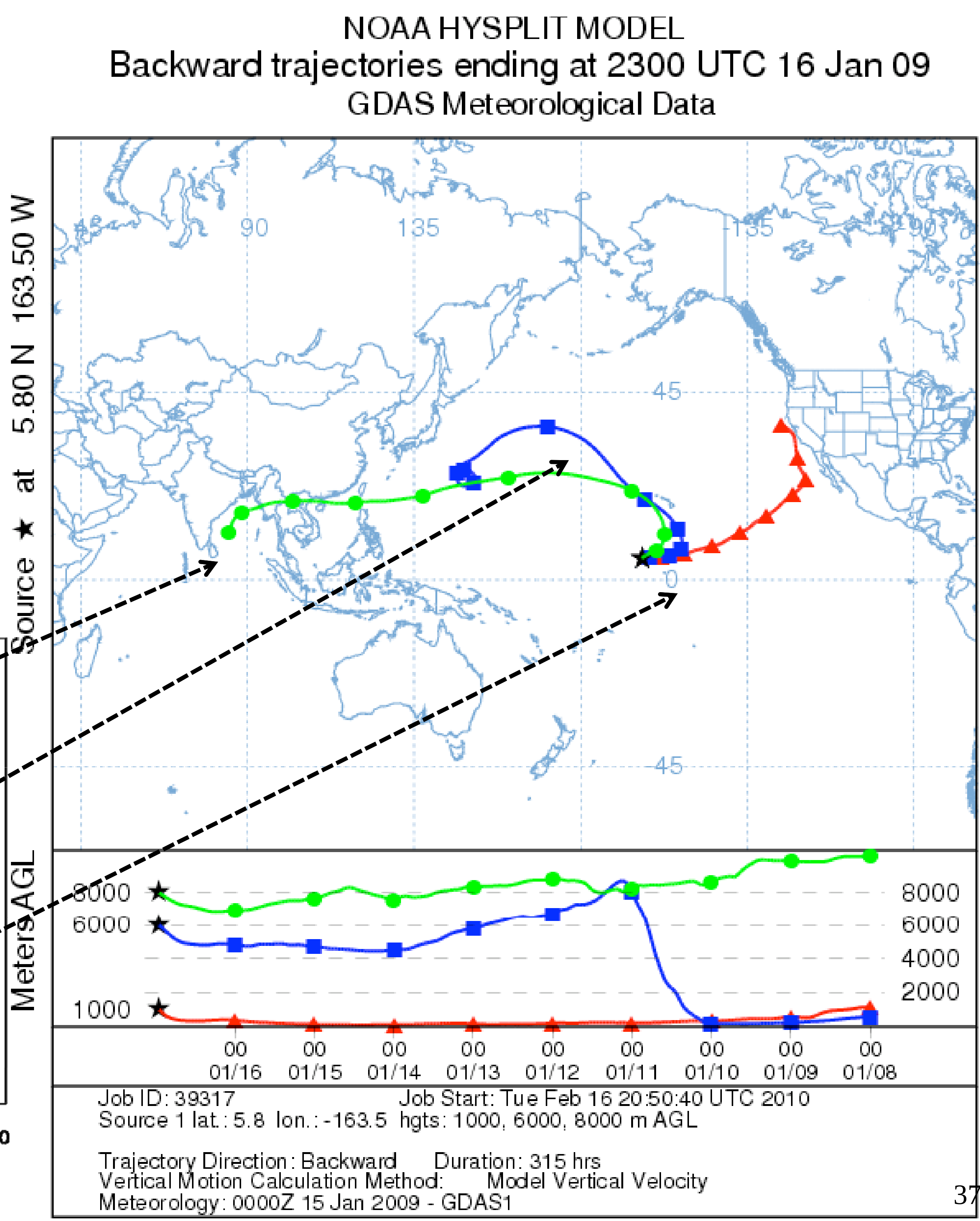


H1 Profile 51

How do anomalies arise? How is a profile composed?

Central Pacific





Summary/ conclusions: Part 1 – Global fine-grained data

- **HIPPO provides a new type of data for CO_2 and GHG studies: global, extremely fine grained, many tracers. Data of this type should be part of a global observing strategy for GHG treaties.**
- Major transport processes are elucidated: Stratosphere [sets the stage; Pre-HIPPO connection]; ***warm conveyor belt*** (intense, persistent, ensemble of small scale processes)—**mixes the whole atmosphere [CO_2, CH_4, CO: QCLS, RAF;** *all models***];** ***Arctic Cold Dome***—**brings strong pollution to high altitudes in pivotal season [BC, CH_4, N_2O: QCLS, SP2;** □*GEMS, ACTM and GEOS***]** and ***Antarctic marine PBL*** –**distortion of surface observations used in models [CO_2, CH_4, O_2, SF_6 : QCLS, UCATS;** *all models***].**
- Source/sink regions are revealed and impacts quantified: ***N_2O in the tropics*** **and** ***Antarctic***—**a major finding [N_2O: QCLS;** *ACTM***]**□**;** ***marine reactive species***—**obvious implications for source regions [COS, CS2, DMS; ALLWAS]**; ***O_2 and CO_2 Antarctic and S. Ocean***.—source strength, relate to PBL **[CO_2, O_2: QCLS, AO2;** *GEOS-CHEM***].**

* HIPPO and Pre-HIPPO Teams *

<u>Harvard</u>: *PI*: S. Wofsy; *Measurement, data team*: R. Jimenez, S. Park, B. Daube, E. Gottlieb, E. Kort, J. Pittman, R. Commane, Bin Xiang, G. Santoni; *GEOS-CHEM team*: D. Jacob, J. Fisher, C. Pickett-Heaps, H. Wang, J. V. Pittman, K. Wecht, Q.-Q. Wang

<u>NCAR and NCAR-RAF</u>: B. Stephens, P. Romanshkin, T. Campos, Laura Pan, J. Haggerty, S. Schertz, GV Crew (*Henry Boynton, Ed Ringleman, pilots*)

<u>NOAA ESRL and CIRES</u>: J. W. Elkins, D. Fahey, R. Gao, F. Moore, S. A. Montzka, J. P. Schwartz, D. Hurst, B. Miller, J. B. Miller, S. Oltmans, D. Nance, E. Hintsa, G. Dutton, L. A. Watts, R. Spackman, K. Rosenlof, E. Ray; CCG (*E. Dlugokencky, T. Conway, P. Novelli, A. Andrews, C. Sweeney…*)

<u>Princeton</u>: M. Zondlo <u>JPL</u>: *M. J. Mahoney*

<u>UCSD/Scripps</u>: R. Keeling, J. Bent

<u>U. Miami</u>: E. A. Atlas, R. Lueb

<u>Cooperating modeling groups</u>: ACTM (Prabir Patra, Kentaro Ishijima), GEMS-MACC (Richard Engelen), …others soon.

Modelling CO_2 in Salt Lake City

March 3, 2010

Steve Wofsy, Kathryn McKain, Harvard University
Atmospheric and Environmental Research, Inc (AER)

Objective

- Develop and test a method for using ground-based CO_2 concentration measurements for estimating the emissions of a city

    - Quantify the relationship between CO_2 measurements and emissions via a modeling framework

$$CO_{2emissions} = a * \Delta CO_{2observation}$$

    - Determine the statistical requirement for detecting a change in emissions from an observed change in CO_2 concentration

$$\delta(CO_{2emissions}) = \varepsilon a * \delta(\Delta CO_{2observation})$$

Methods

- Emissions
  - **Vulcan Inventory** (by Gurney @ Purdue)
    - Hourly
    - 0.1 º x 0.1º (~8.5 x 11 km)
    - 8 categories
    - 2002

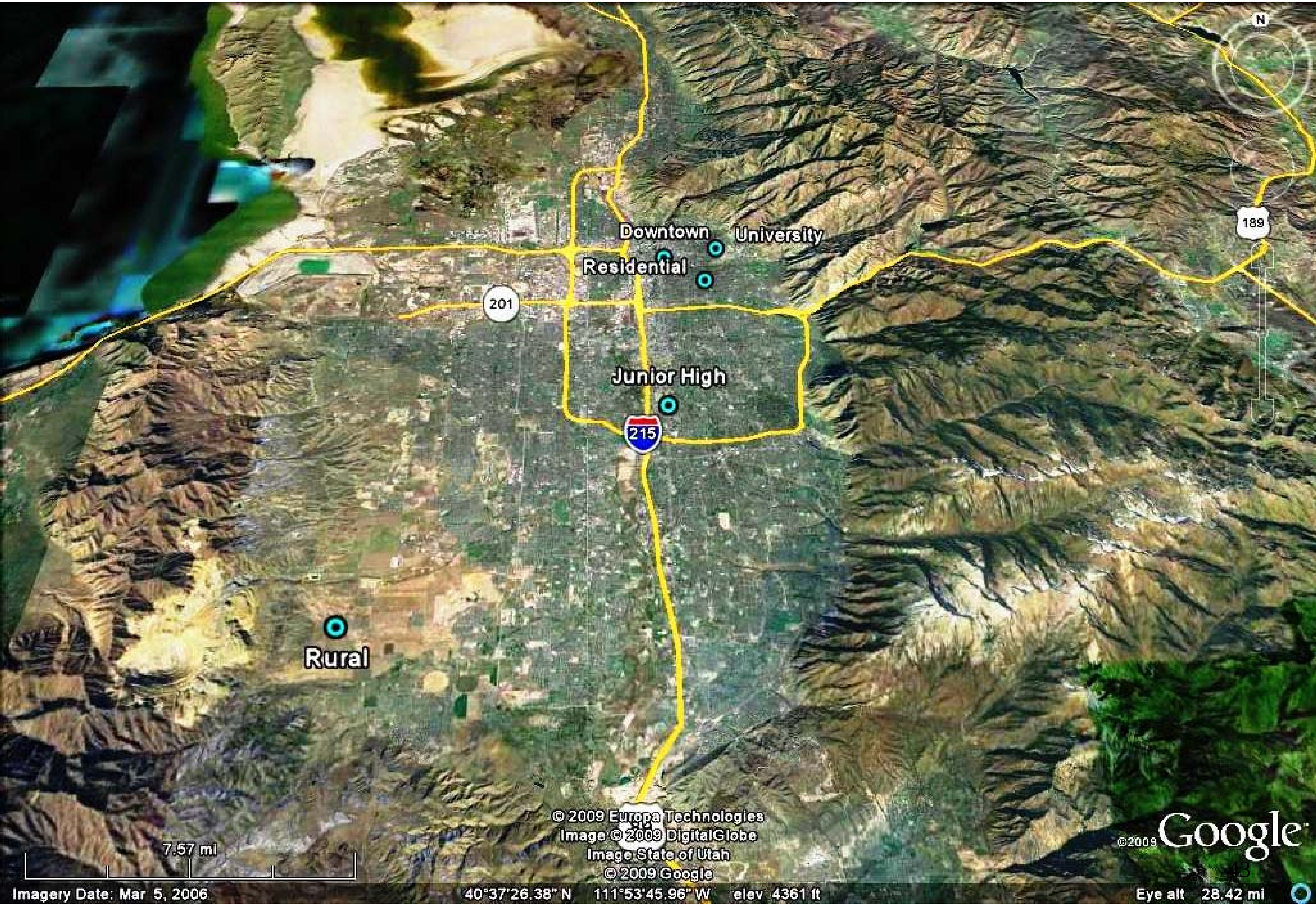
- Observations
  - **Salt Lake City** (by Ehleringer & Pataki @ U of Utah)
    - 5 sites
    - 2001-present
    - 5-minute collection interval

-Model (LPDM)

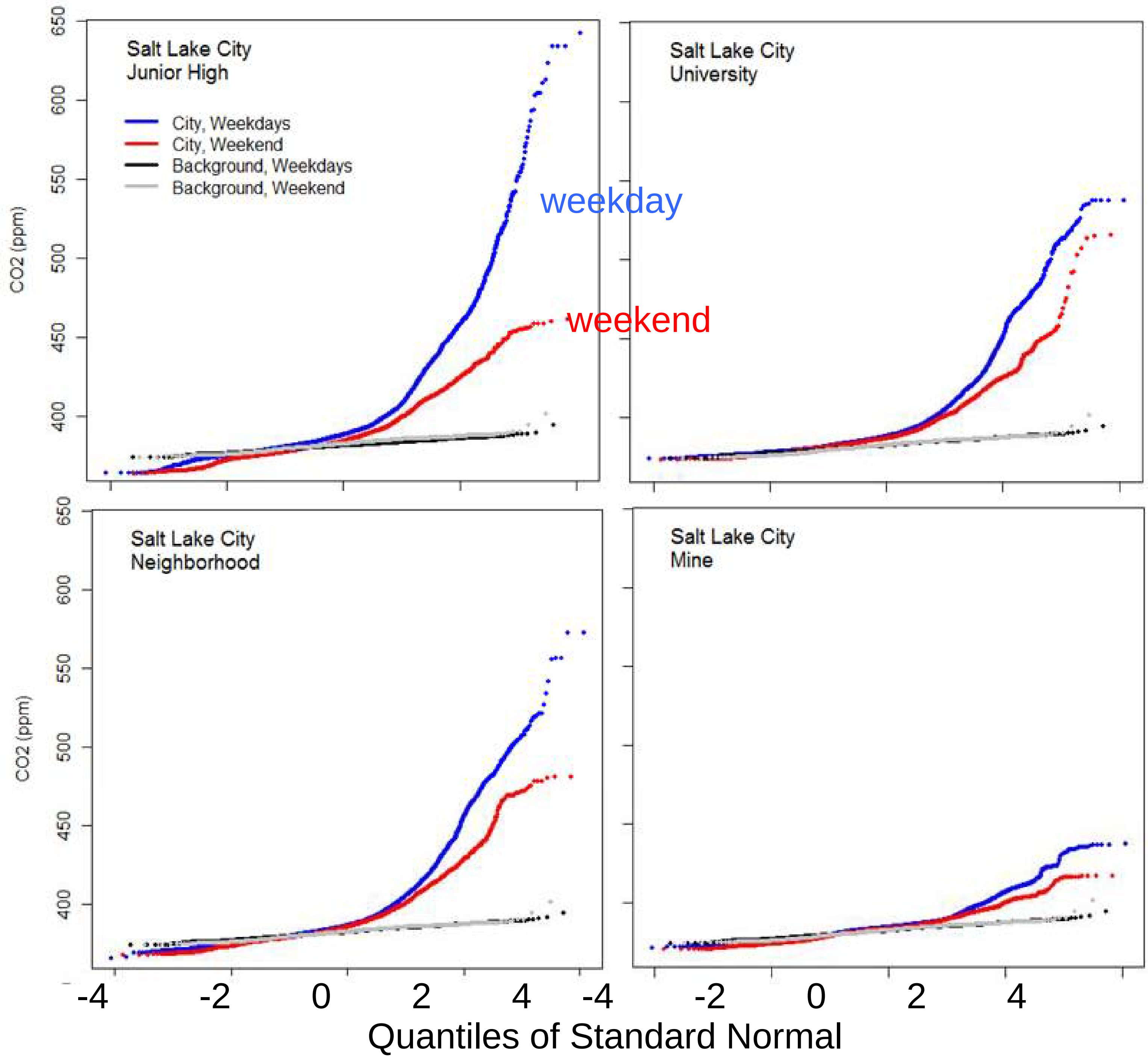
-**Stochastic Time Inverterted Lagrangian Transport** (**STILT**)

-Driven by Weather Research and Forecasting (**WRF/ 3 km**)

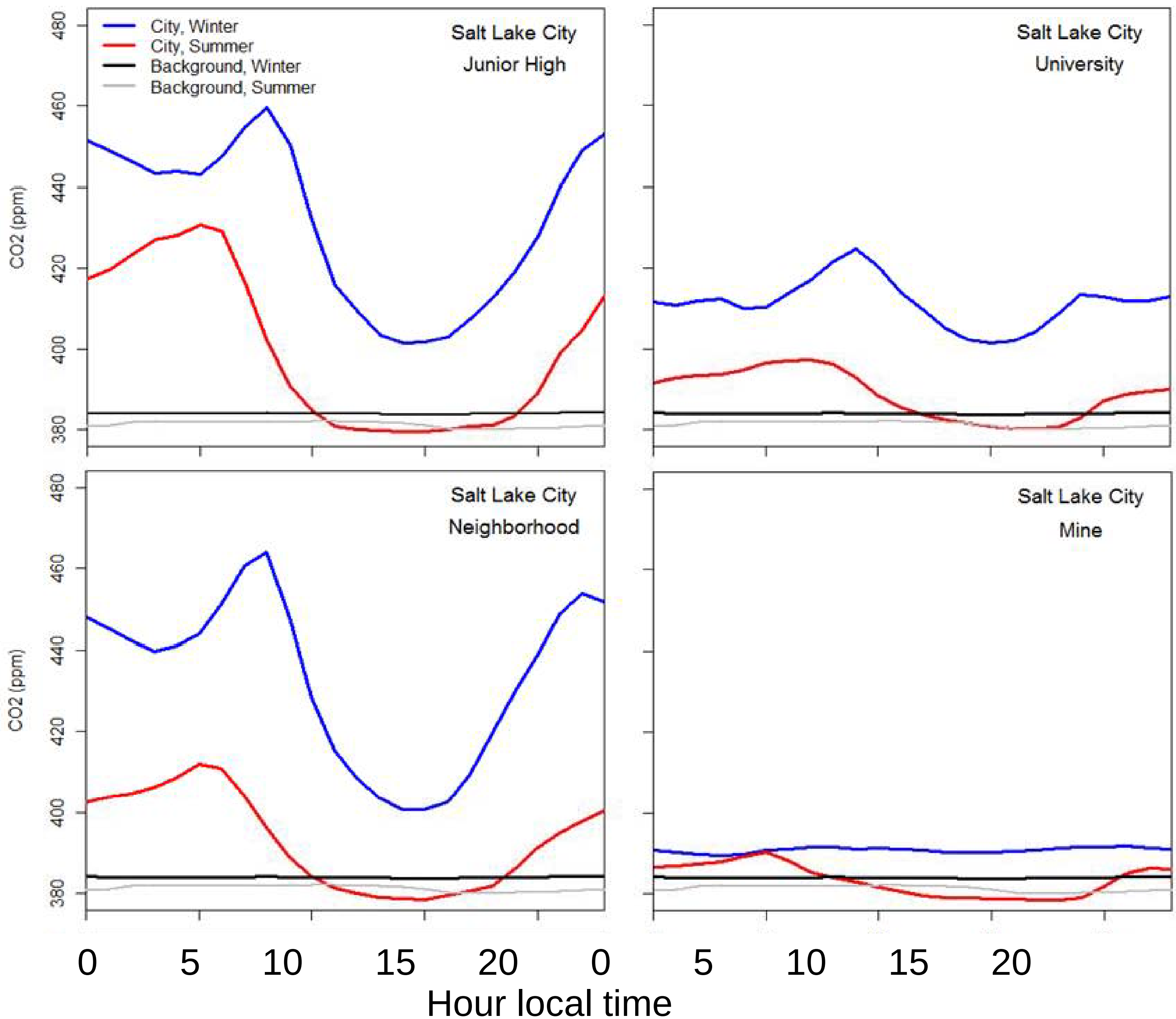
-Generates a footprint (ppm/(µmol/m^2/s)) for each measurement point, which represents the sensitivity of the observed concentration to surface emissions


N
Downtown
University
Residential
201
Junior High
215
189
Rural
© 2009 Europa Technologies
Image © 2009 DigitalGlobe
Image State of Utah
© 2009 Google
7.57 mi
©2009 Google
Imagery Date: Mar 5, 2006
40°37'26.38" N 111°53'45.96" W elev 4361 ft
Eye alt 28.42 mi

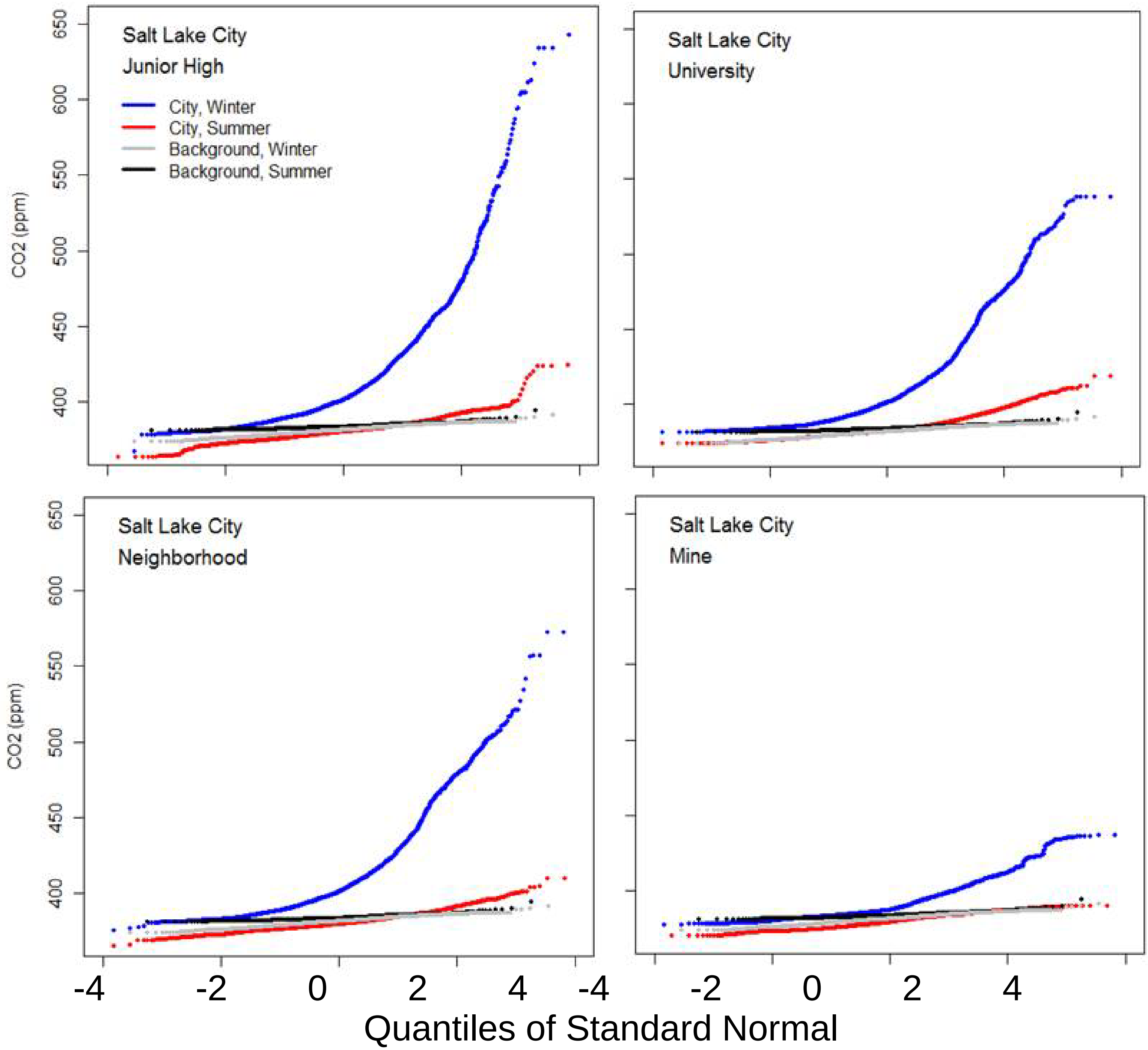
2006 – entire year – Cum PDFs variations by day of the week, 1000 – 1700h local .



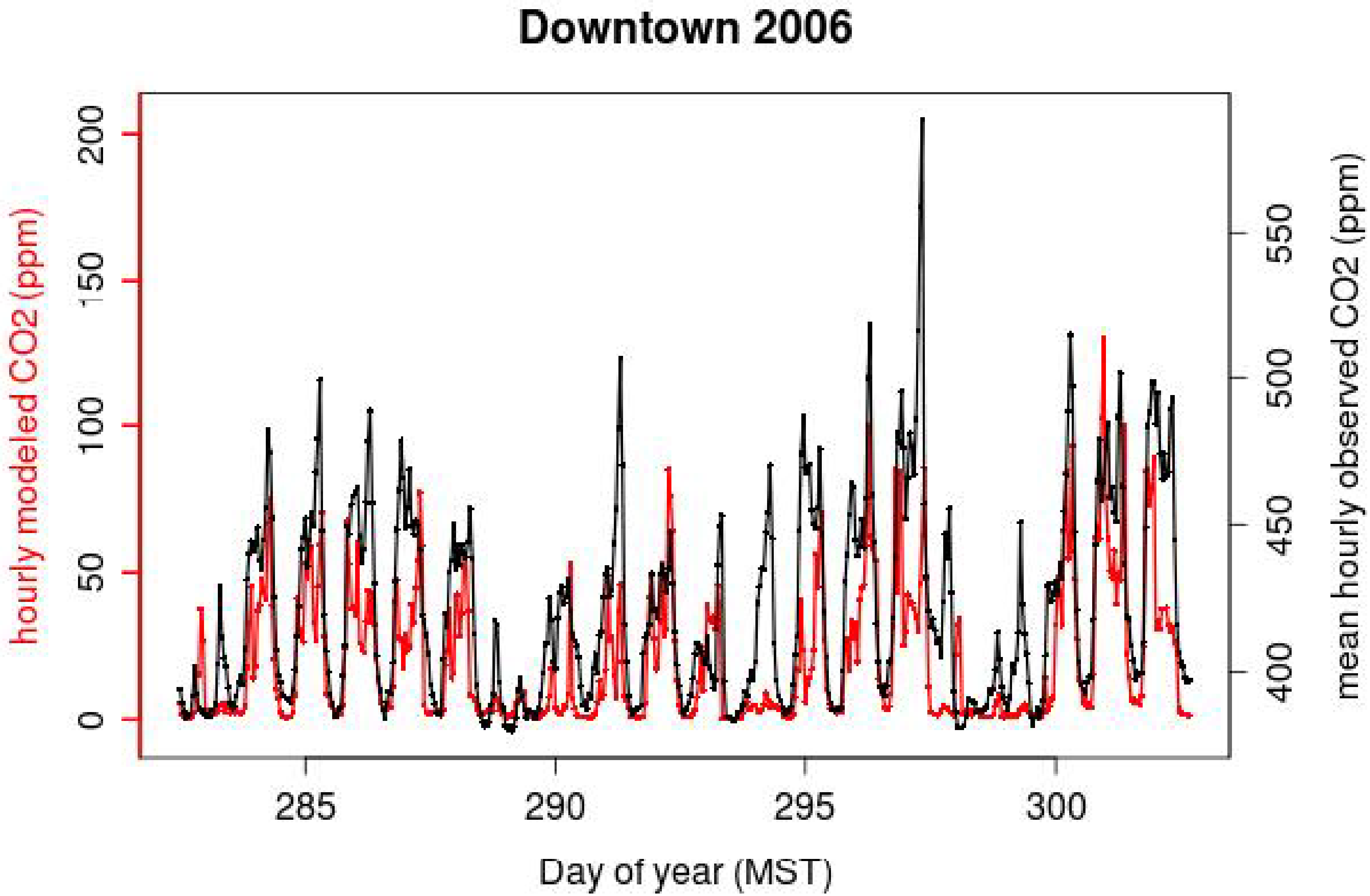
2006 – Time of Day variations: Summer (June – Aug) **Winter (Dec – Feb)**



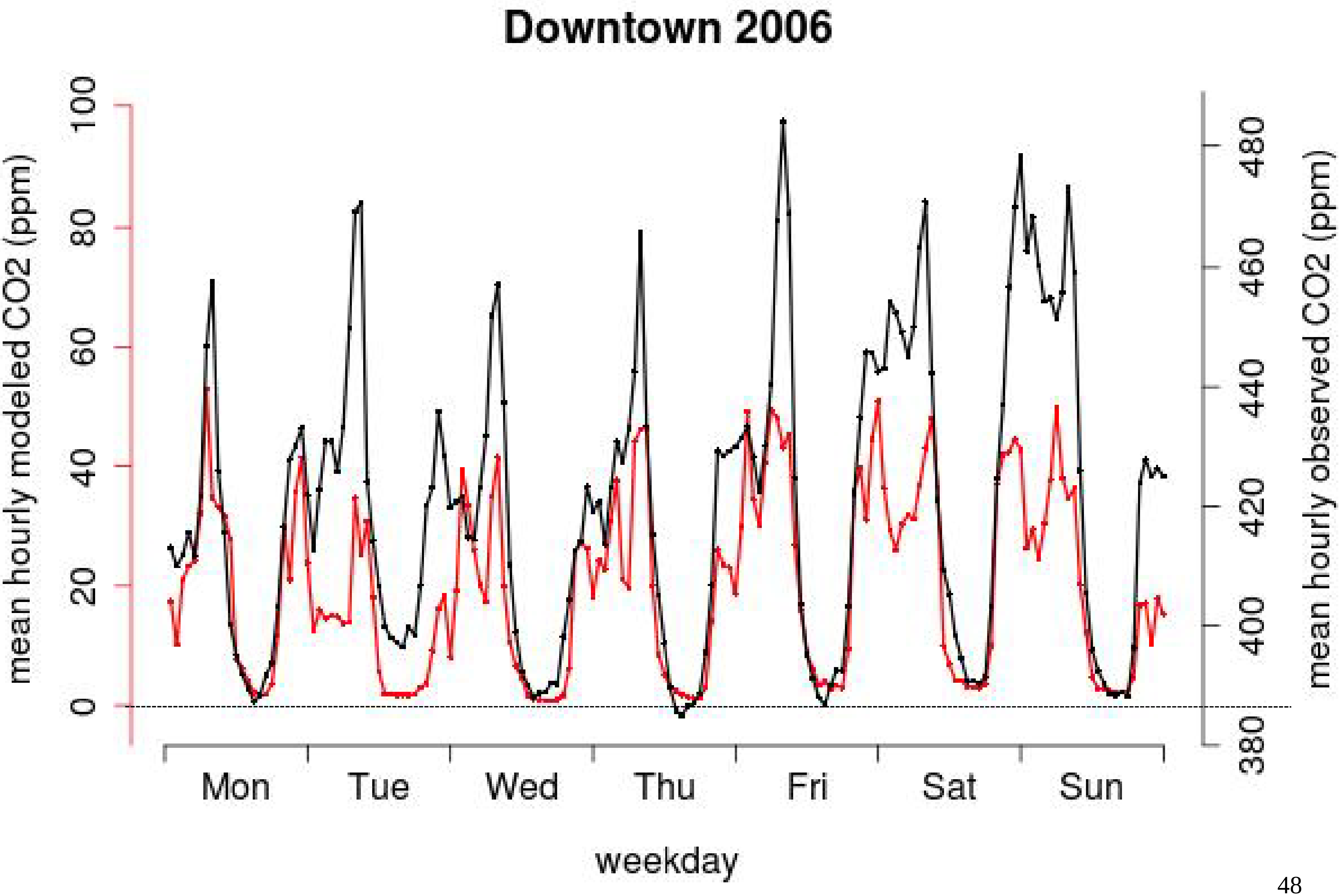
2006, 1000—1700, Cum PDFs: Summer (June – Aug) **Winter (Dec – Feb)**

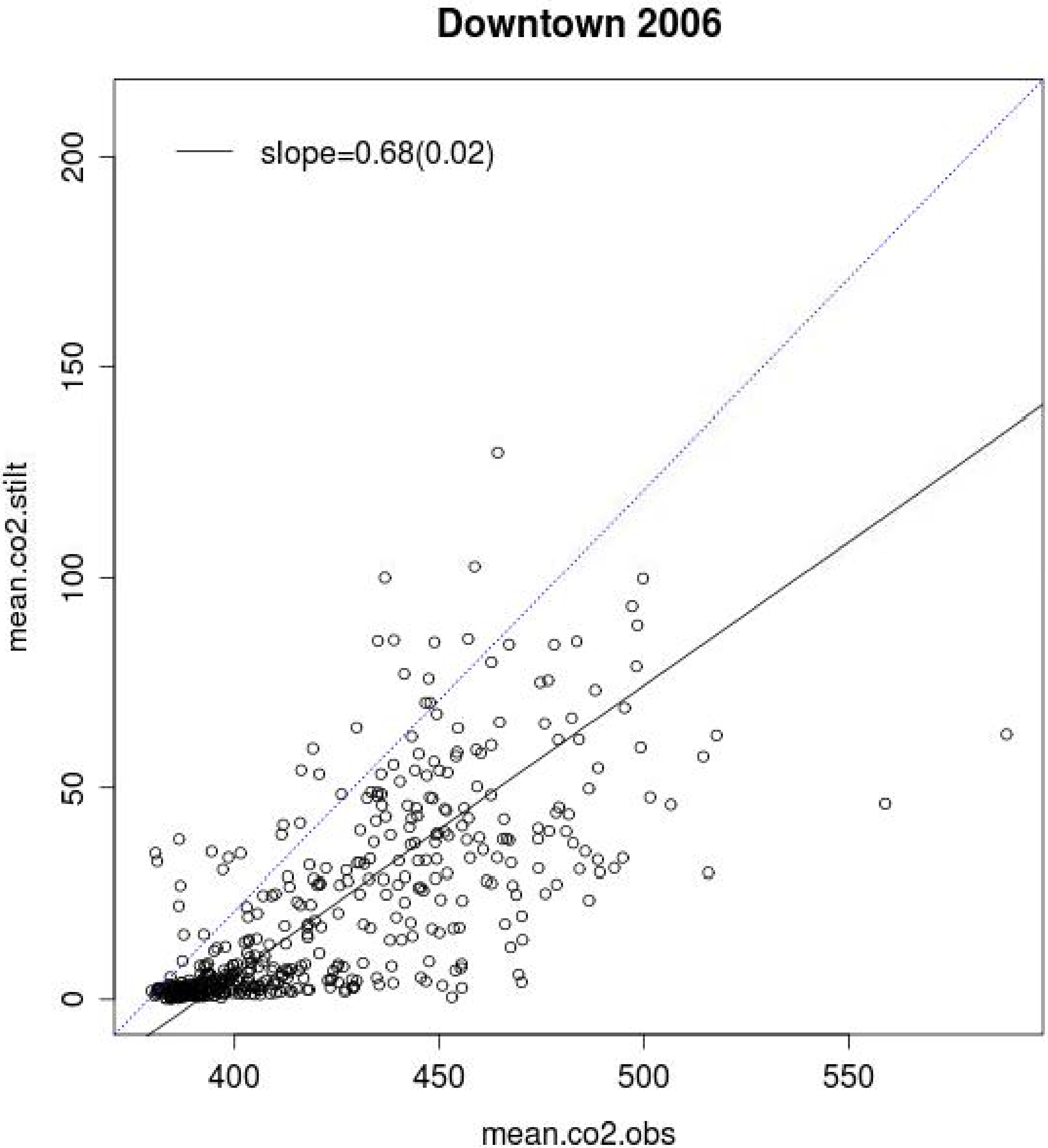


October, Hourly means



October, Daily means by hour




Downtown 2006
slope=0.68(0.02)
mean.co2.stilt
mean.co2.obs
0
50
100
150
200
400
450
500
550

Model – Data Fits – one month (Oct. 2006 or 2009)

site	year	fit	%	slope	S.E. slope
HJH	2006	0	100	0.67	0.02
HJH	2006	1	60	0.74	0.03
HJH	2009	0	100	0.93	0.03
HJH	2009	1	55	1.07	0.05
ASB	2006	0	100	0.99	0.04
ASB	2006	1	65	1.03	0.06
ASB	2009	0	100	0.71	0.03
ASB	2009	1	57	0.78	0.04
AH	2006	0	100	0.79	0.03
AH	2006	1	67	0.87	0.04
AH	2009	0	100	0.95	0.04
AH	2009	1	50	1.09	0.06
SC	2006	0	100	0.68	0.02
SC	2006	1	65	0.74	0.03
SC	2006	2	52	0.71	0.02

Summary and conclusions for Part 2:

High-resolution data at even a single point contain clear signatures of emissions that respond to emission rates.

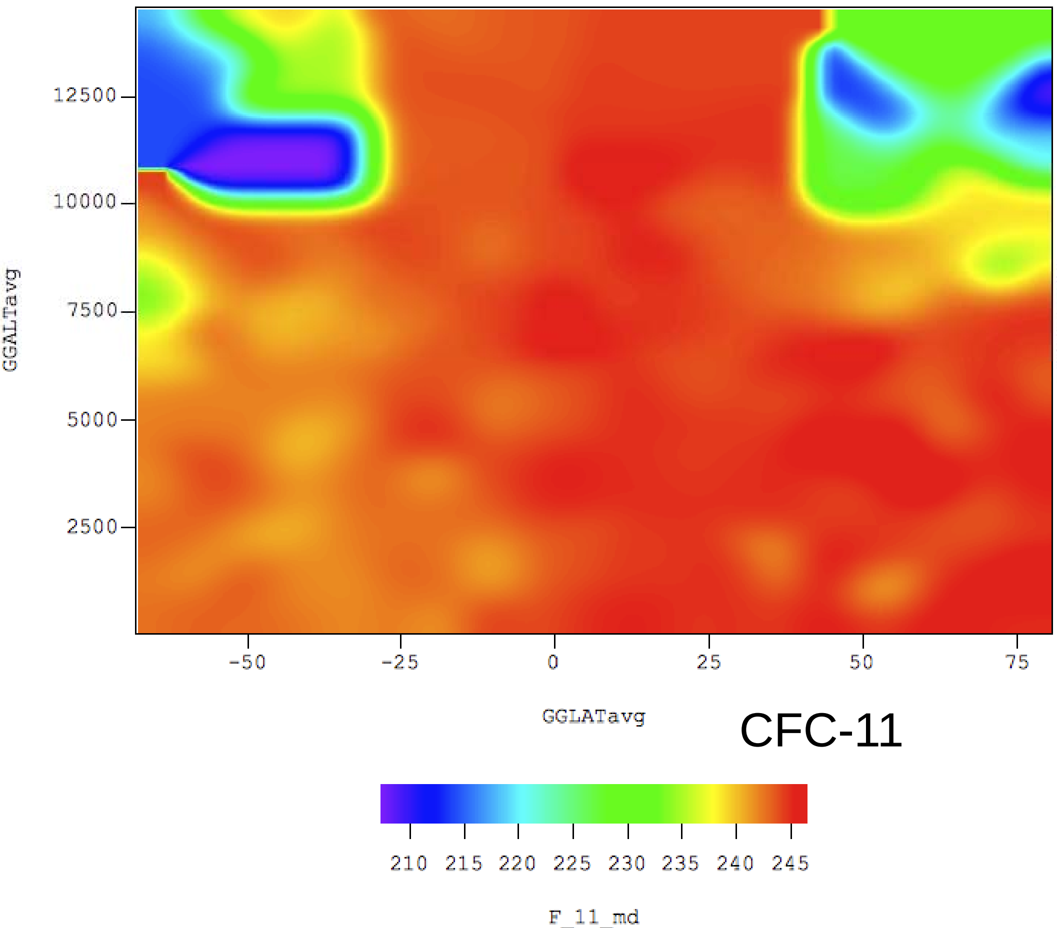
High resolution modeling appears potentially able of providing the metric for determining changes in emission rates for major emitting regions.

Goal of quantifying 5% change over 5 years appears feasible. Shorter times, small changes may not be feasible.

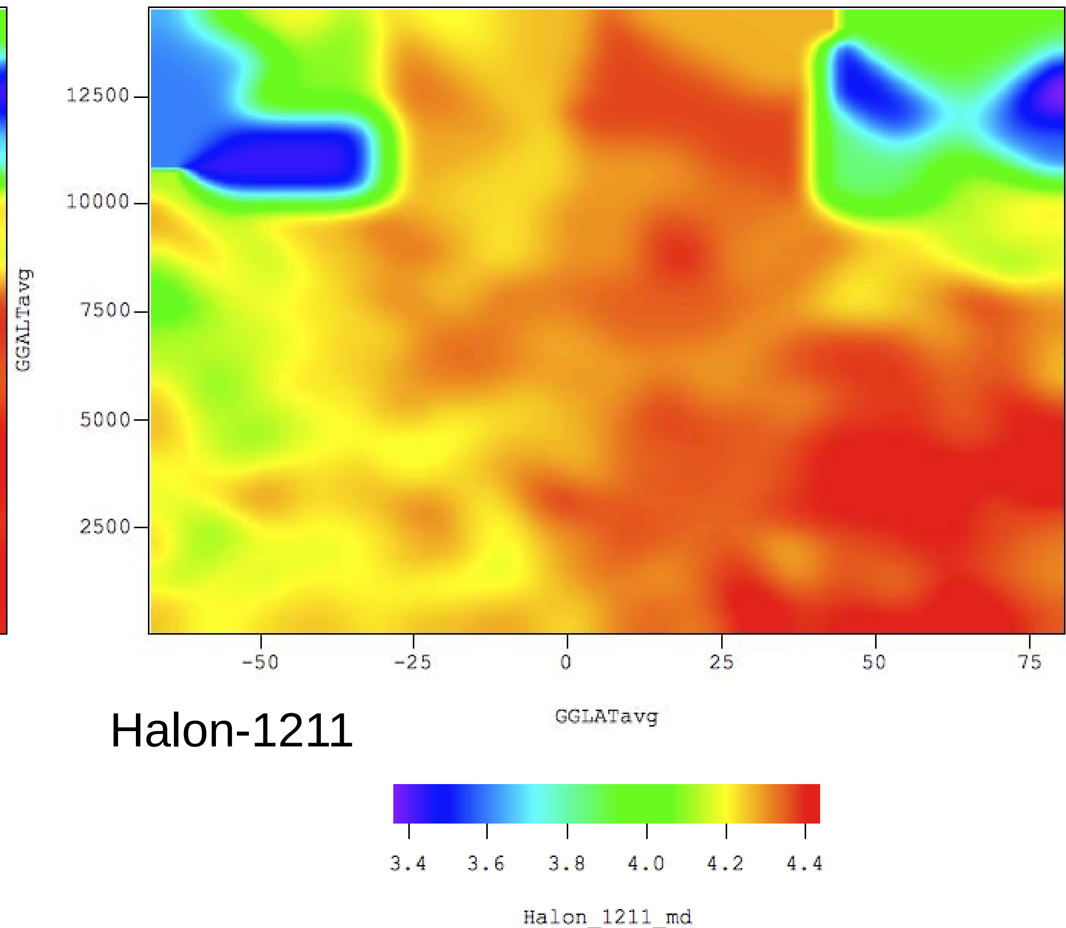
Long time series with unchanging tracers (^{222}Rn) and addition of key covariates ($^{14}CO_2$, CO, …) provide strong validation and high accuracy for change detection (Levine).

Reactive species in the atmosphere:

A movie… (not in 3-D)



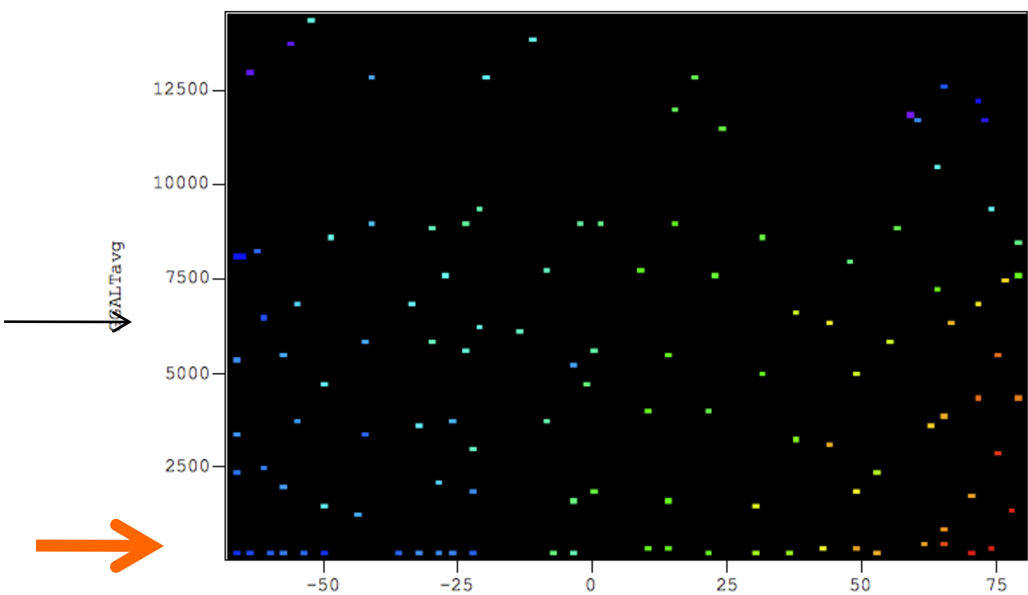
CFC-11



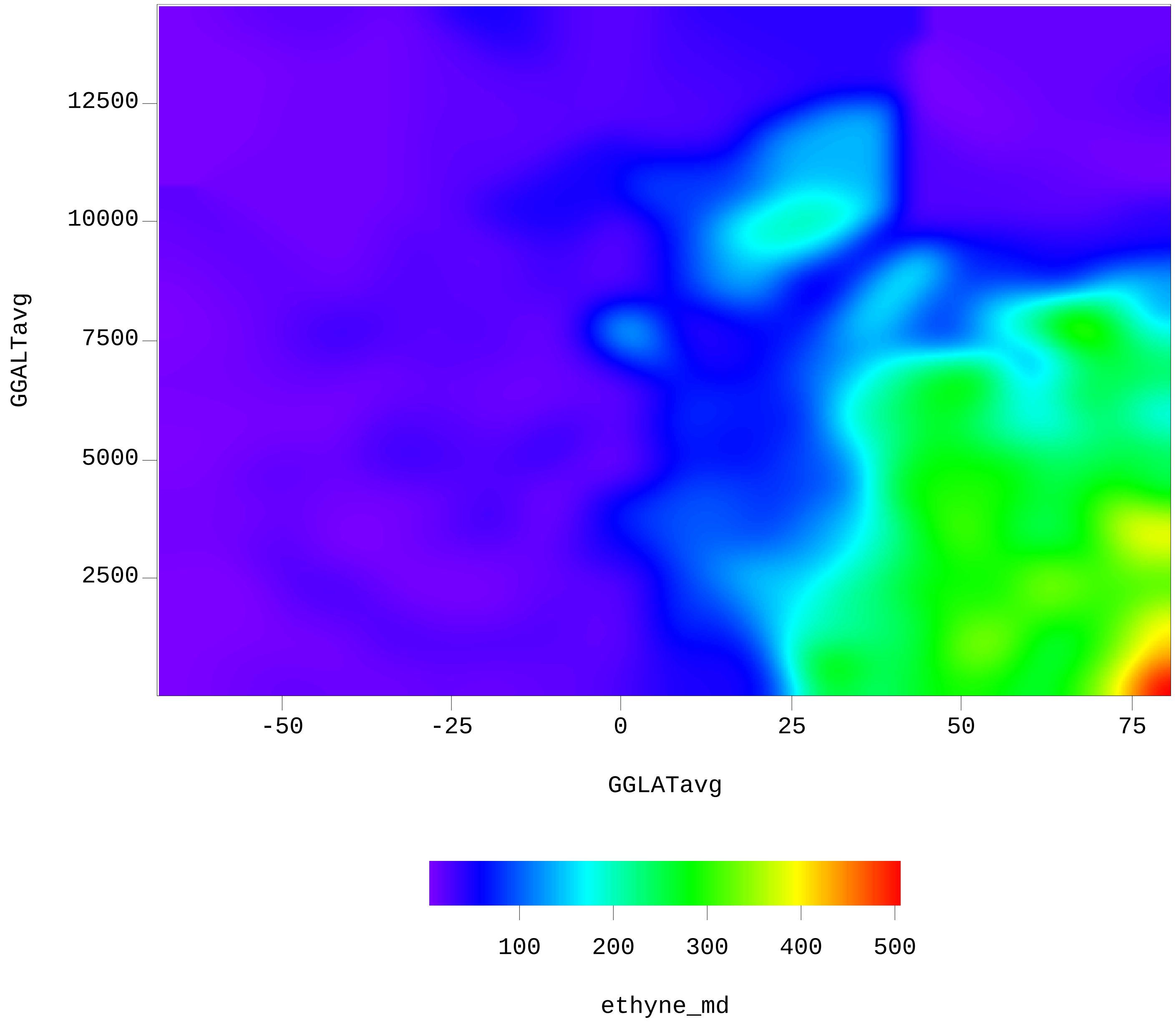
Halon-1211

Whole-Air Sampling NWAS / AWAS (E. Atlas, S. Montzka)

Mid-Pacific Sample coverage

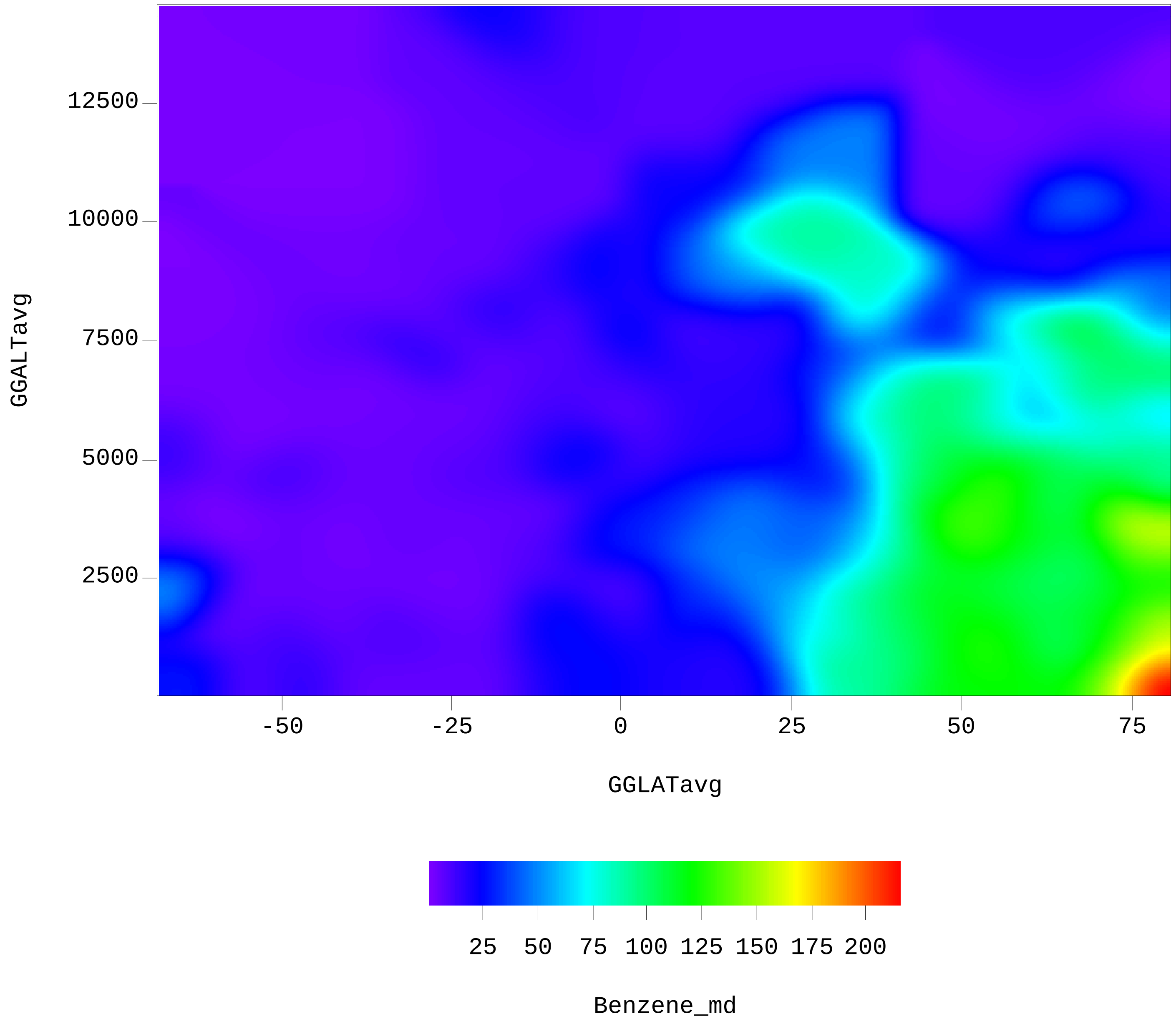


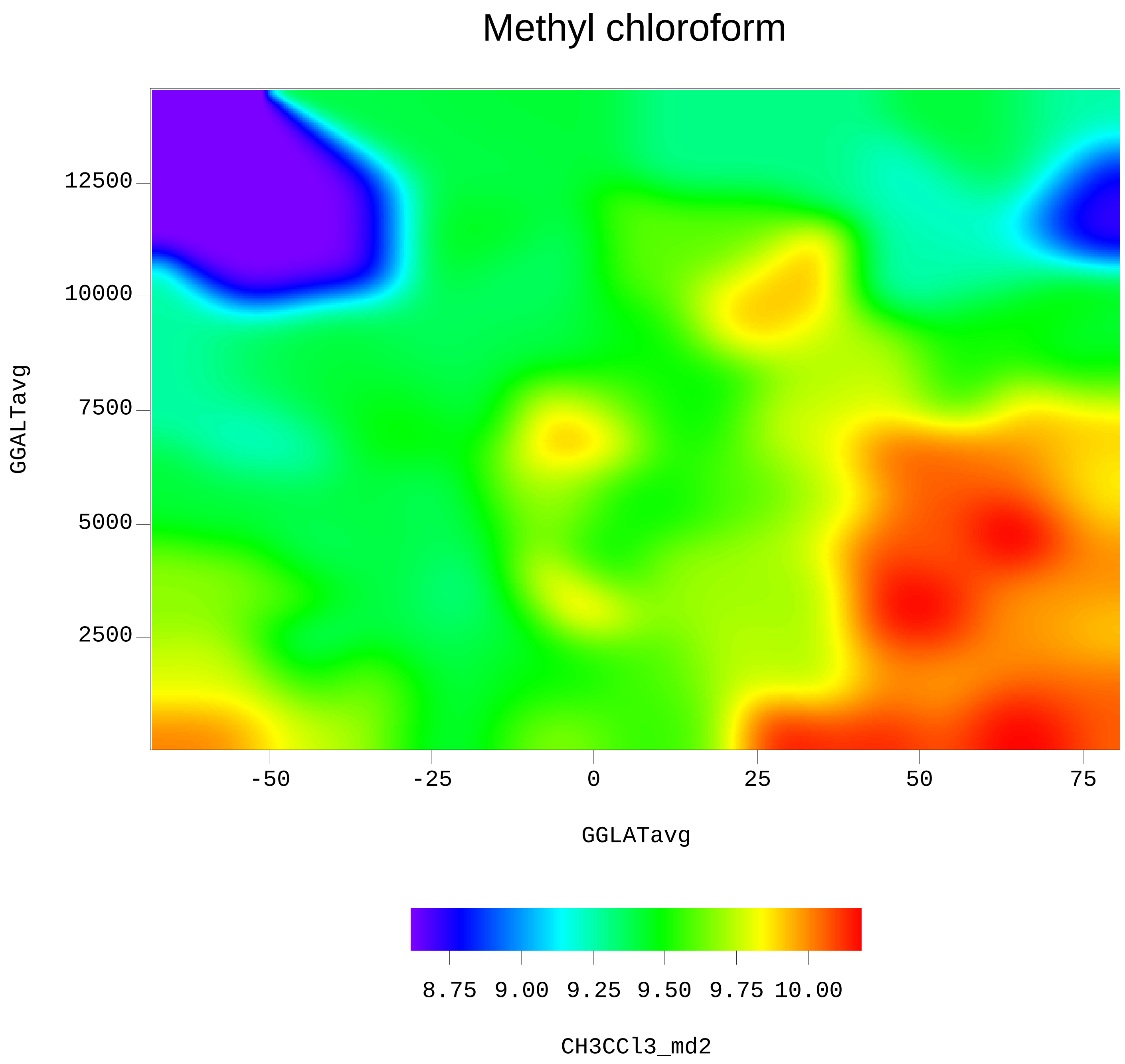
Ethyne



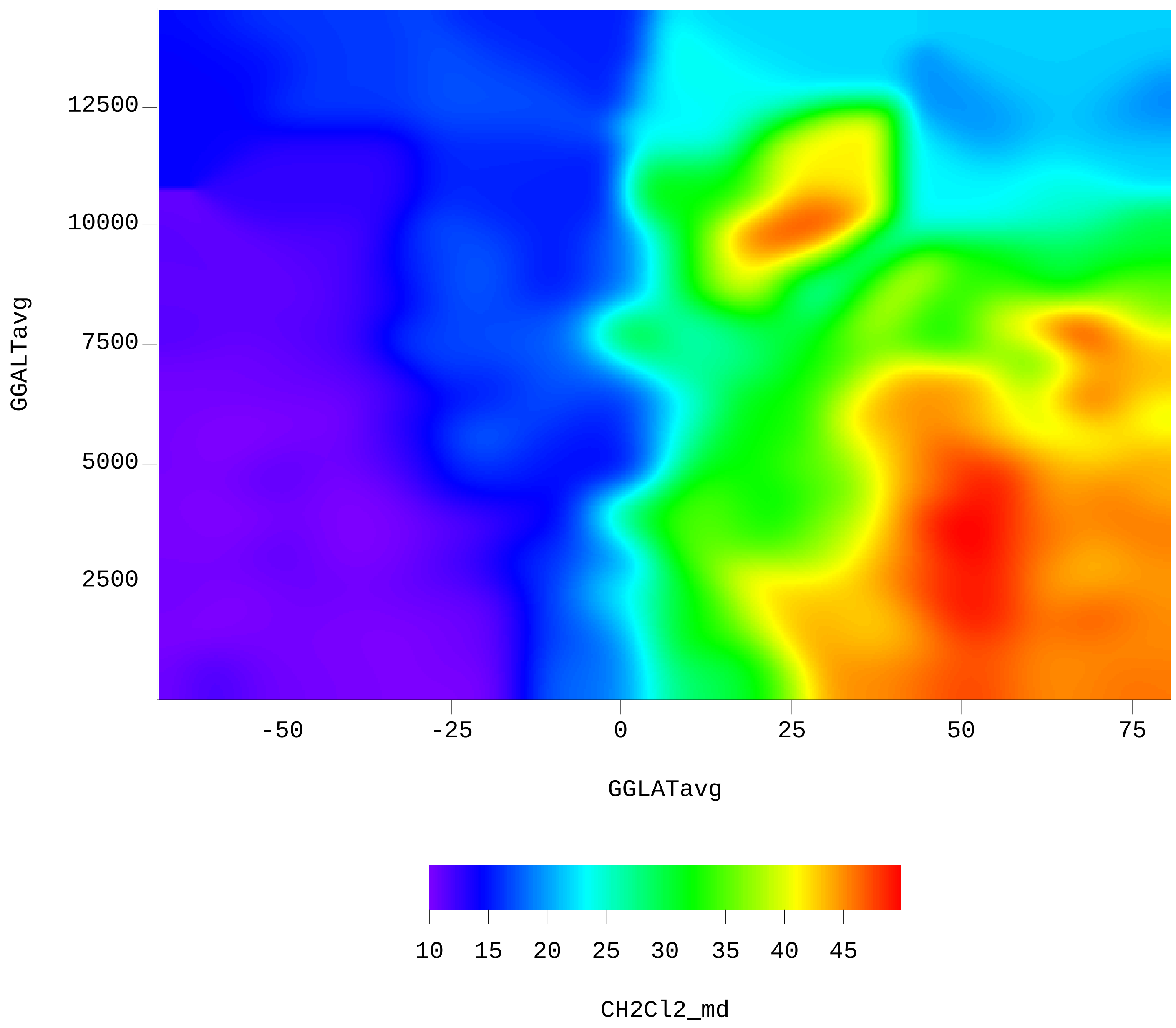
12500
10000
7500
5000
2500
GGALTavg
-50
-25
0
25
50
75
GGLATavg
100
200
300
400
500
ethyne_md

Benzene

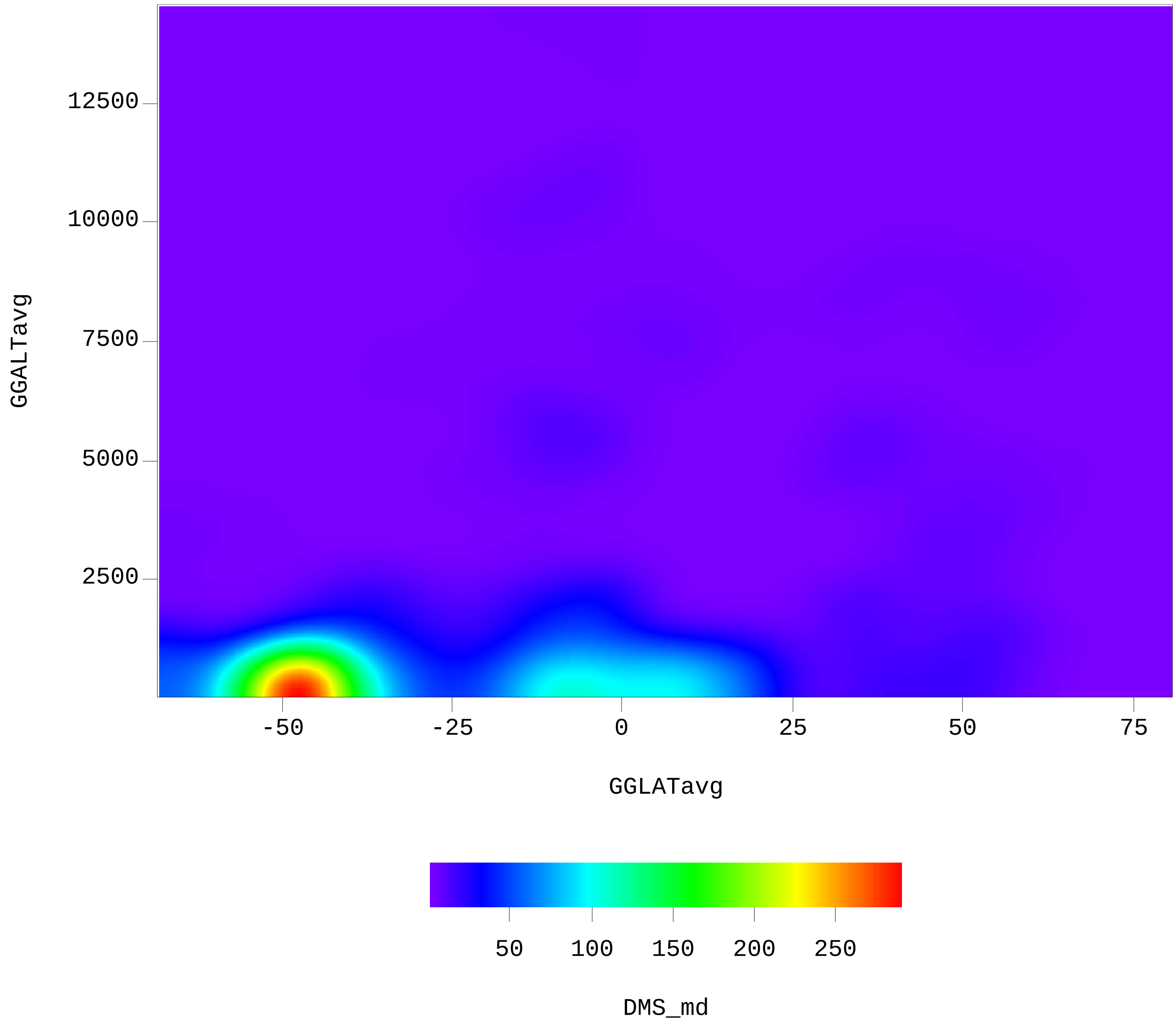

12500
10000
7500
5000
2500
GGALTavg
-50
-25
0
25
50
75
GGLATavg
25
50
75
100
125
150
175
200
Benzene_md


Methyl chloroform
12500
10000
7500
5000
2500
GGALTavg
-50
-25
0
25
50
75
GGLATavg
8.75
9.00
9.25
9.50
9.75
10.00
CH3CCl3_md2

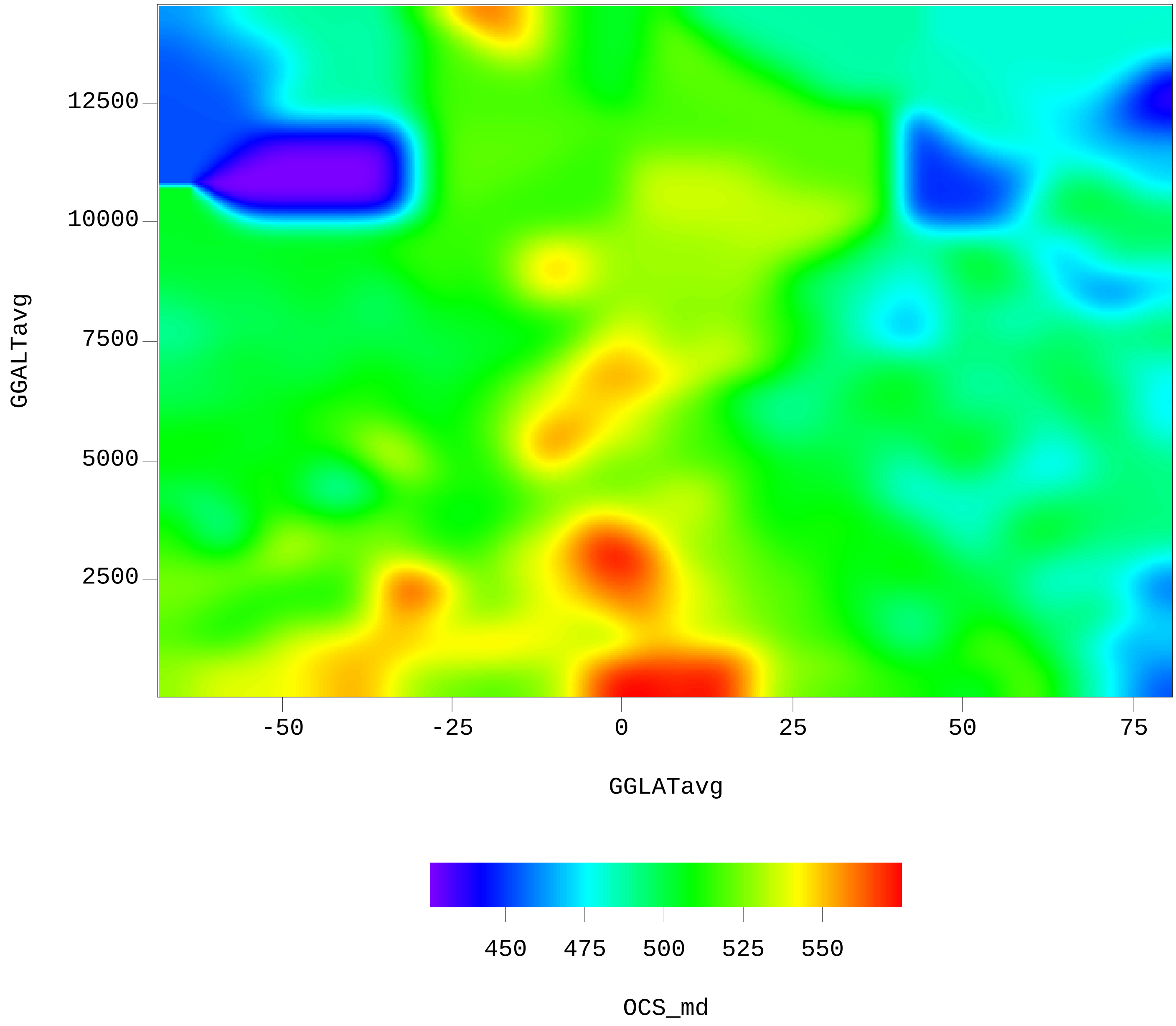
Dichloromethane



Dimethyl Sulfide



Carbonyl Sulfide



Carbon Disulfide