Slicing the atmosphere: global sources of greenhouse gases and pollutants from fine-grained, pole-to-pole observations.

Steven C. Wofsy
and the Science Team of the
HIAPER Pole-to-Pole Observations Program

National Center for Atmospheric Research, March 18 2011.

Brooks Range, AK

•Climate change
•Global environmental pollution

…are driven by changes in atmospheric composition: greenhouse gases, reactive species, aerosols, precipitation – due to human activities and natural processes.

How can we distinguish and quantify the influences, make predictions, craft policy actions?

Measuring these constituents and understanding the sources and sinks, transformations, and transport that underlie the observations, represent one of the major scientific challenges of our time.

Spatial resolution at global scale: observations and models

- Studies of global distributions of Greenhouse Gases typically utilize data from remote stations and/or satellites that measure the time series concentrations of these species. These data sets are global but **vertical structure** is not measured and **horizontal gradients are smoothed/under-sampled**.
- Global models have resolution comparable to the smoothed data.
- Model-data comparisons lose fidelity due to the large spatial scales and long time scales of *both* models and data.
- Model "inversions" (to obtain emission/reaction rates) are under-constrained. Data aggregation can bias or confound interpretation.

HIPPO (HIAPER Pole-to-Pole Observation experiment) was designed to decisively change the predicament due to lack of fine-grained data at global scale.

- **HIPPO has acquired global, fine-grained atmospheric data for multiple species of different source/sink distributions, at the surface, in profiles, and in under-sampled regions of the Southern Ocean and Antarctic.**
- **The HIPPO data set is intended to provide critical tests of global models of atmospheric gases and aerosols, helping to distinguish errors associated with sources and sinks from those due to model simulation transport, model structure, etc.**

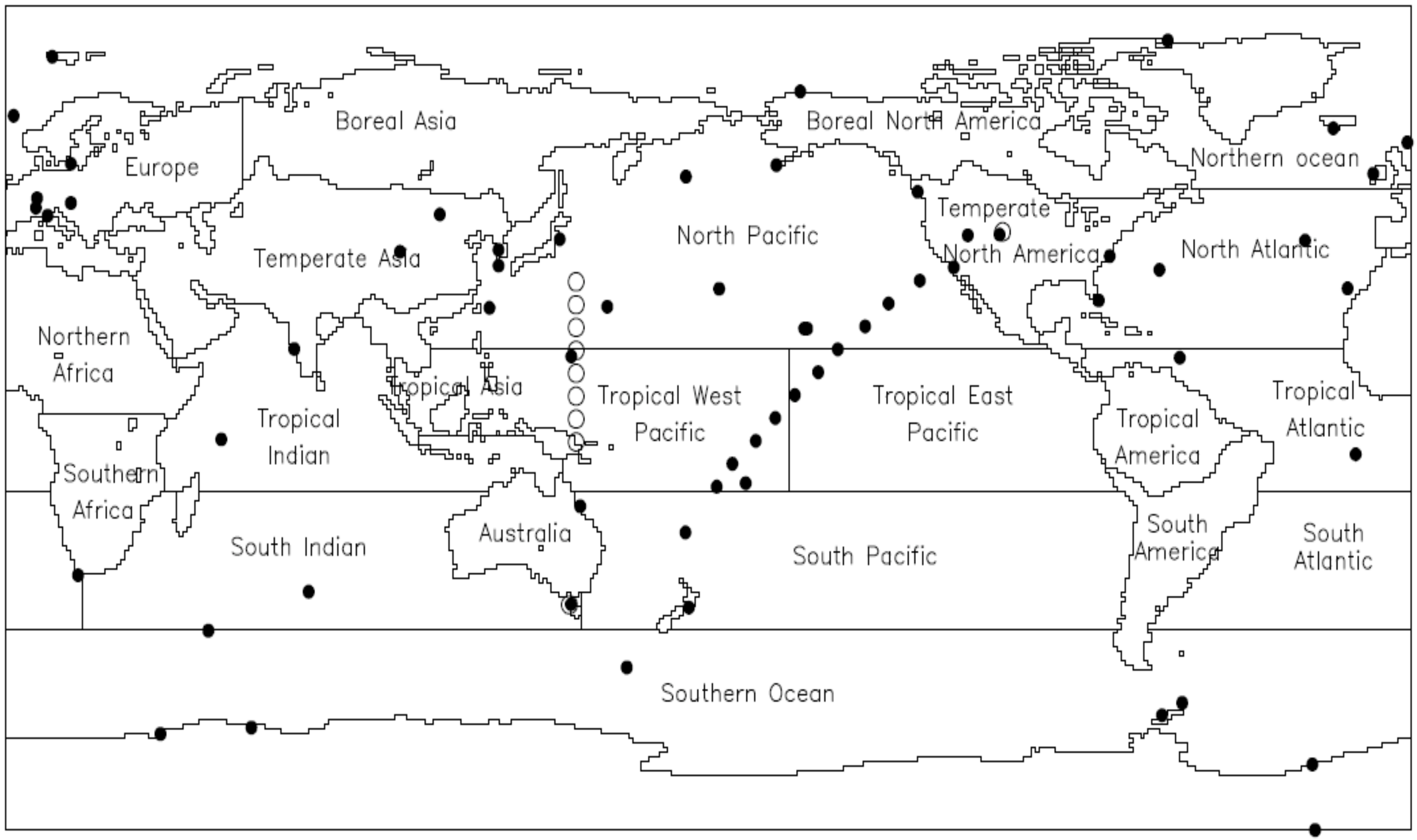


Figure 1. A map of the 22 emission regions and 78 CO_2 measurement locations used in this study. Solid circles indicate surface measurements, open circles, aircraft measurements.

TRANSCOM 3 -- a classic multi-model inverse analysis of CO_2 sources and sinks.

Towards robust regional estimates of CO_2 sources and sinks using atmospheric transport models

Kevin Robert Gurney*, Rachel M. Law†, A. Scott Denning*, Peter J. Rayner†, David Baker‡, Philippe Bousquet§, Lori Bruhwiler||, Yu-Han Chen¶, Philippe Ciais§, Songmiao Fan#, Inez Y. Fung☆, Manuel Gloor**, Martin Heimann**, Kaz Higuchi††, Jasmin John☆, Takashi Maki‡‡, Shamil Maksyutov§§, Ken Masarie||, Philippe Peylin§, Michael Prather||||, Bernard C. Pak||||, James Randerson¶¶, Jorge Sarmiento#, Shoichi Taguchi##, Taro Takahashi☆☆ & Chiu-Wai Yuen**

NATURE | VOL 415 | 7 FEBRUARY 2002 | www.nature.com

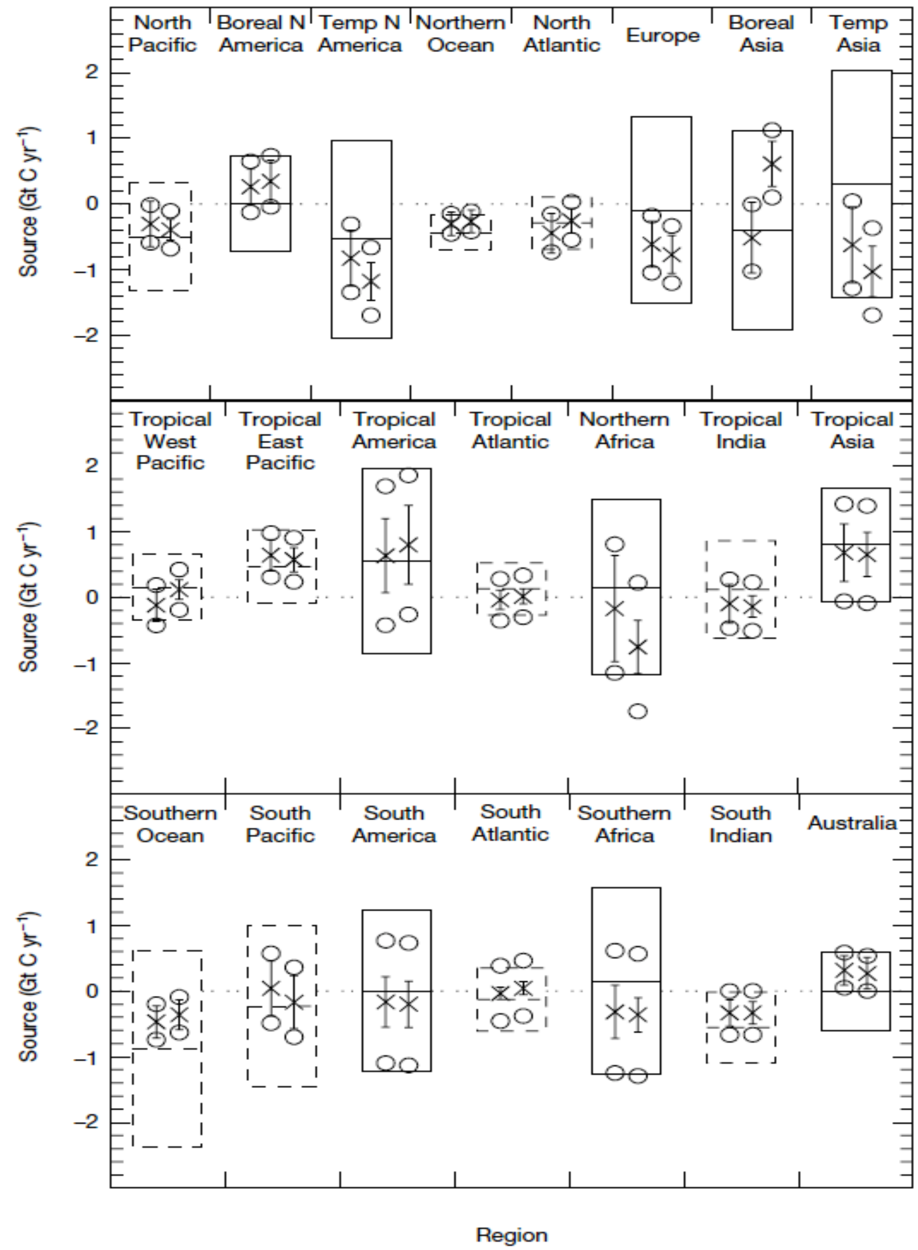
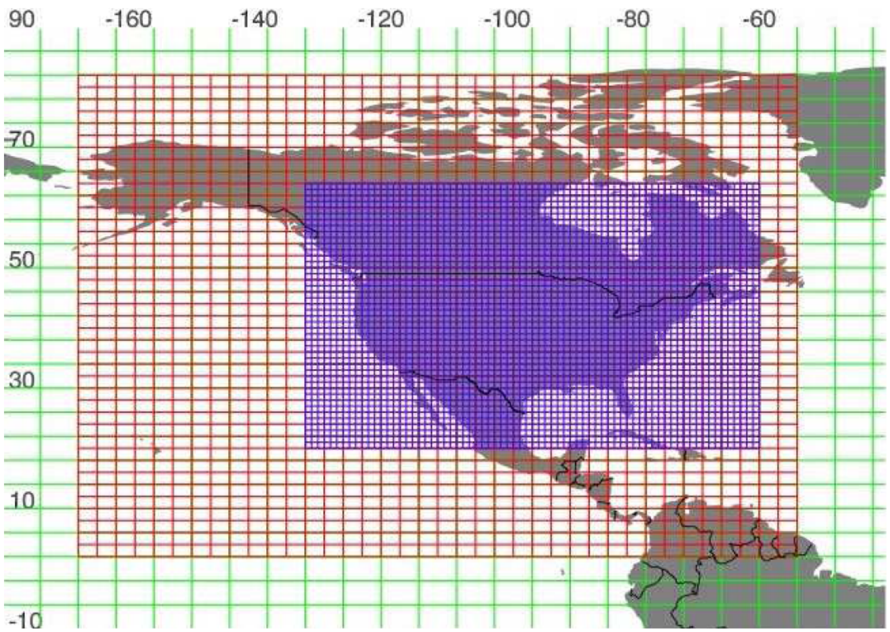
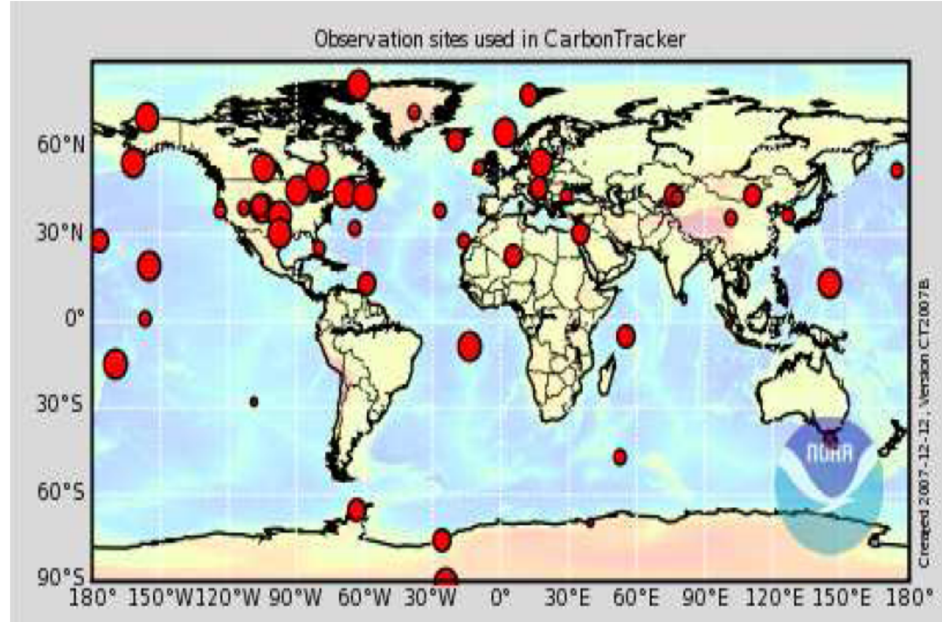


Figure 1 Mean estimated sources and uncertainties for two inversions. Left-hand symbols in each box are for the control inversion, right-hand symbols are for an inversion without the background seasonal biosphere flux. Mean estimated fluxes are shown by crosses, and include all background fluxes except fossil fuel. Positive values indicate a

"Inversion" of time series data from 41 remote stations, 22 regions.
TRANSCOM-3



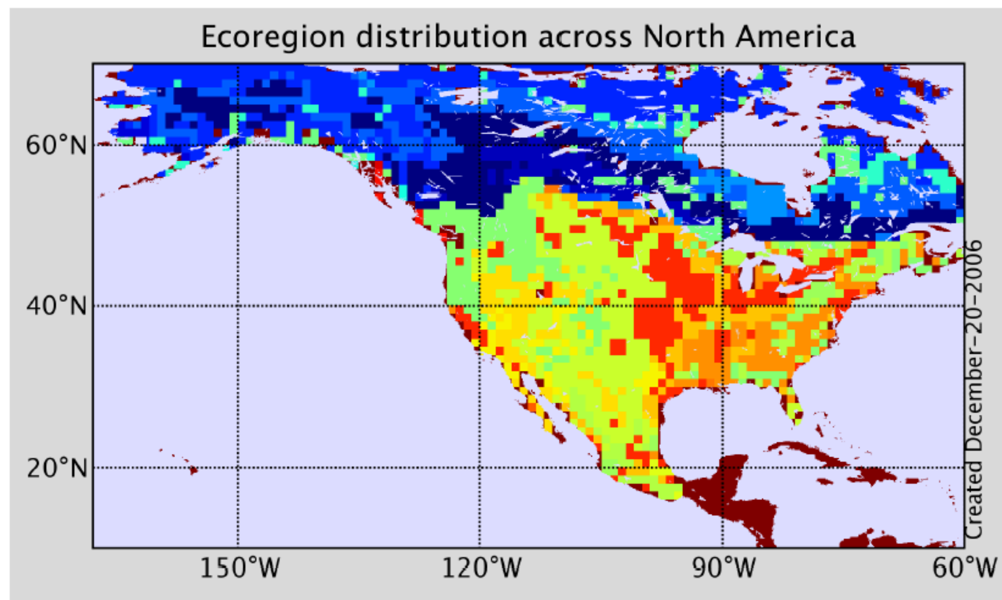
Meteorological Module, Global/Nested TM5



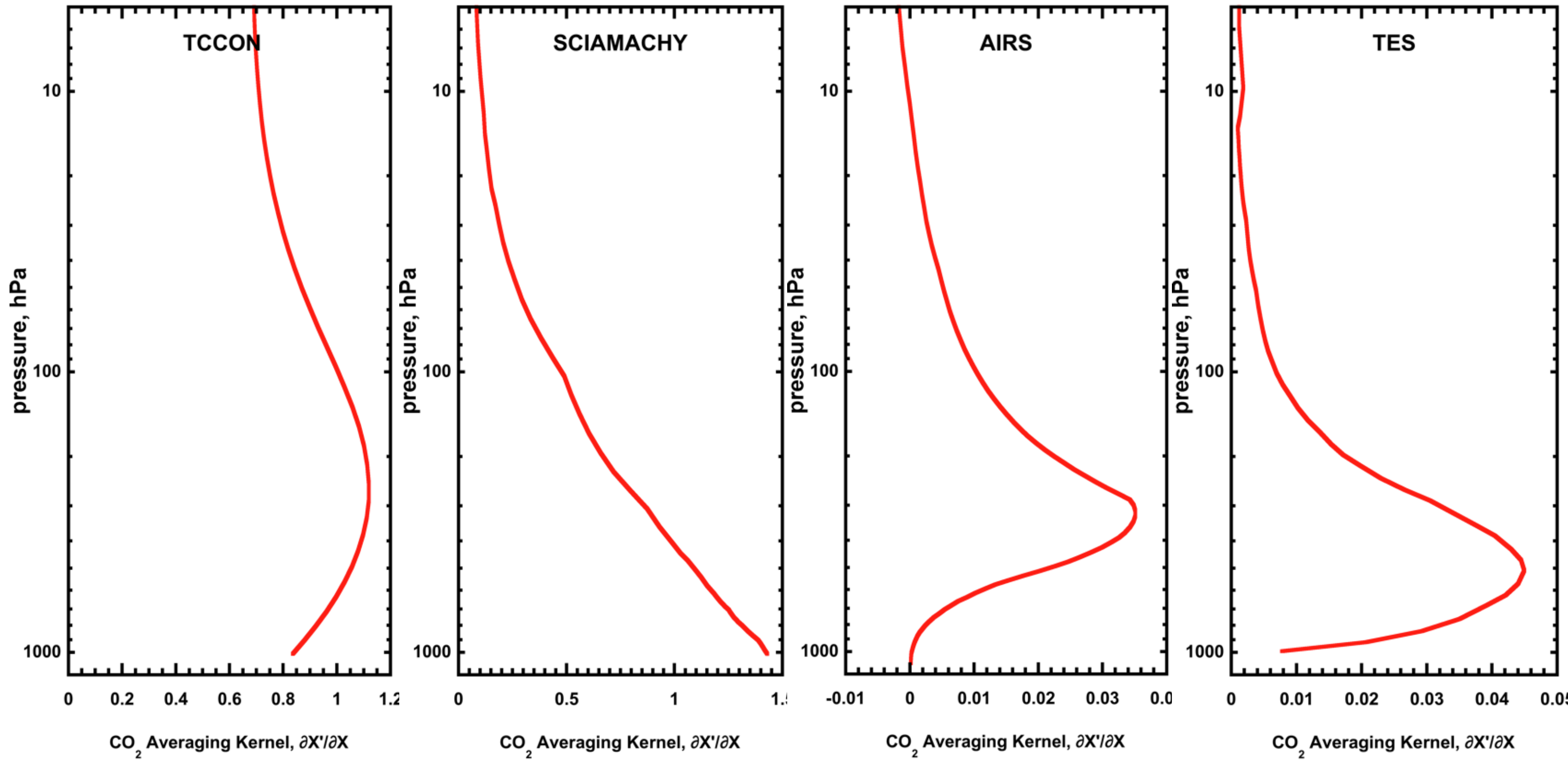
Observation sites (*surface*)

Inverse modeling designed in this century:
CarbonTracker

*same observational locations as TRANSCOM with **addition of land sites, assimilated meteorology**, time frame (2000-2006…) and **model parameter fitting (Kalman filter, not flux regions). Surface data only.***



Vegetation/Soil module, driven by TM5



Averaging Kernels for Remote Sensing Measurements of CO_2 in the atmosphere.

OCO is similar to TCCON (total column average CO_2 retrieved and ratio taken to column O_2. Others don't have a ratio like O_2.)

slide courtesy S. Kulawik

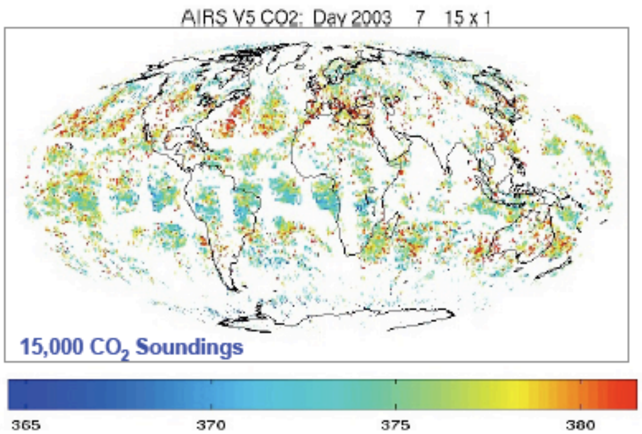
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

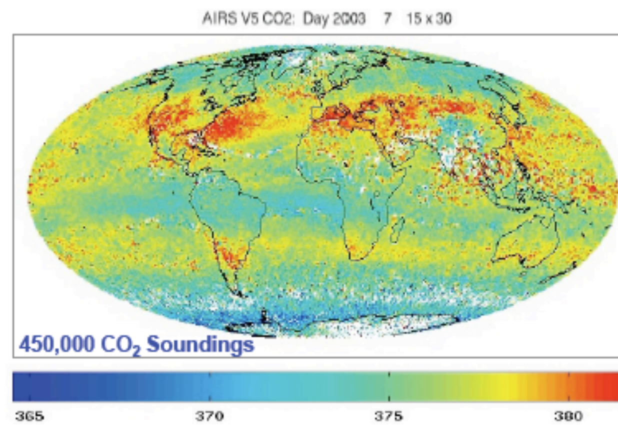
Atmospheric Infrared Sounder

Global Yield of AIRS Level 2 Mid-Tropospheric CO_2

AIRS Daily CO_2 Yield
1°x1° Spatial Resolution



AIRS Monthly CO_2 Yield
1°x1° Spatial Resolution

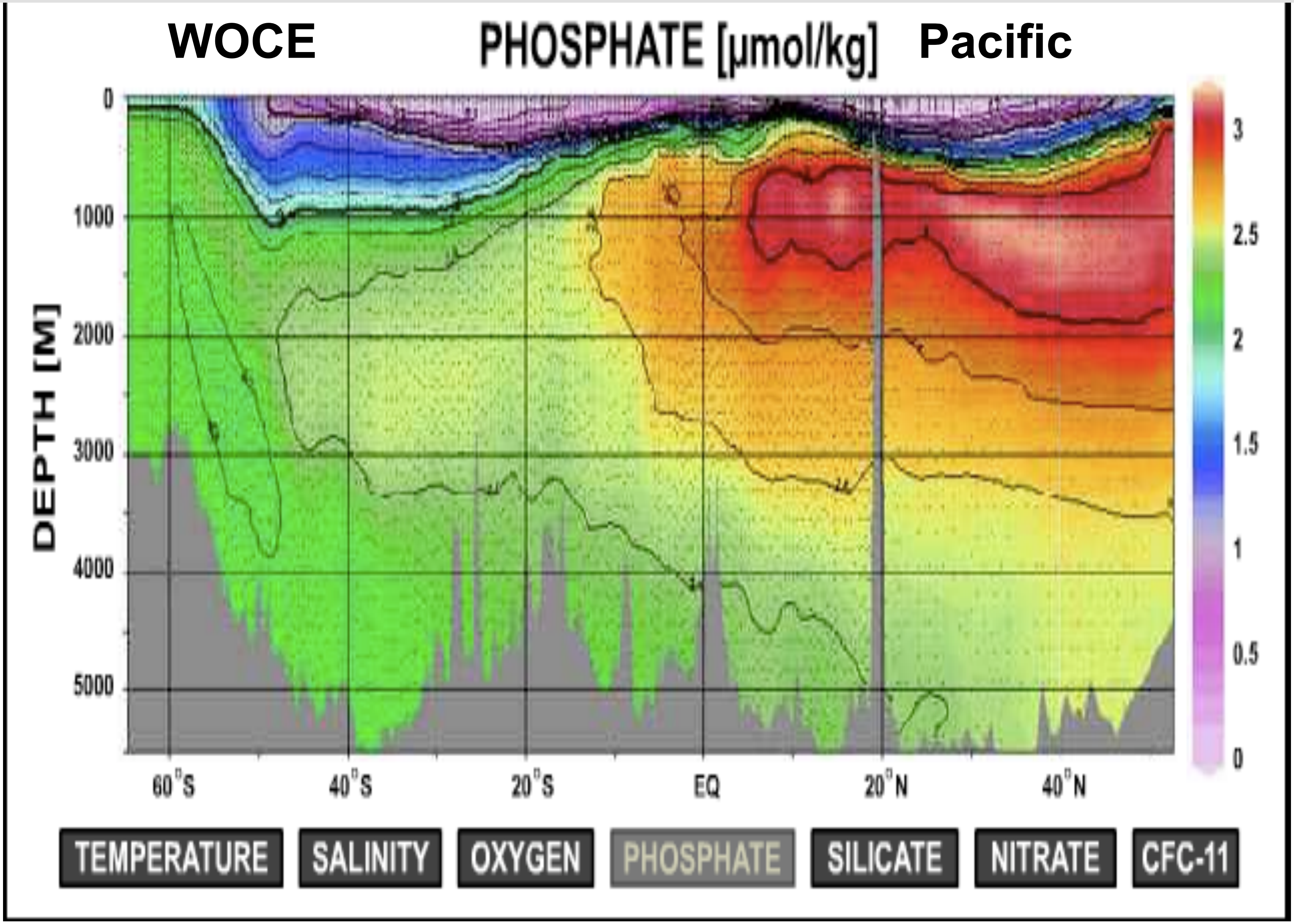


AIRS Level 2 Mid-Tropospheric CO_2 retrieval yield is controlled by requirement for highest quality temperature and water vapor AIRS Level 2 products in 2x2 array of adjacent FOVs

Day/Night, Pole-to-Pole, Land/Ocean/Ice, Cloudy/Clear

slide: E. Olsen

HIPPO aspriation: be like GEOSECS and WOCE, for the atmosphere…



HIPPO boat: NCAR Gulfstream V "HIAPER"

GV launch in the rain, Anchorage, January, 2009 (HIPPO-1)

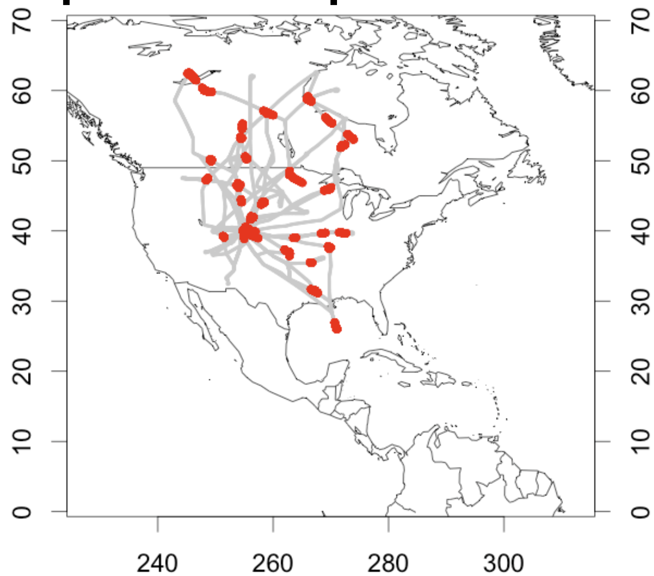
HIPPO Instrumentation

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, H_2O	O_3, H_2O (1 Hz)
NCAR RAF CO	CO (1 Hz)
NOAA-GMD UCATS and PANTHER GCs	CO, CH_4, N_2O, CFCs. HCFCs, SF_6, CH_3Br, CH_3Cl, H_2 (70 – 200 s)
Whole Air Samples: NWAS (NOAA-GMD), AWAS (Miami), MEDUSA (NCAR/Scripps)	O_2/N_2, N_2/Ar, CO_2, CH_4, CO, N_2O, SF_6, H_2, COS, CS_2, halocarbons, solvents, reactive HCs, marine species, ...
VCSEL Princeton/SWS	H_2O (1 Hz)
NOAA SP2	Black Carbon mass (1 Hz)
MTP, wing stores	T, P, winds, aerosols, cloud water

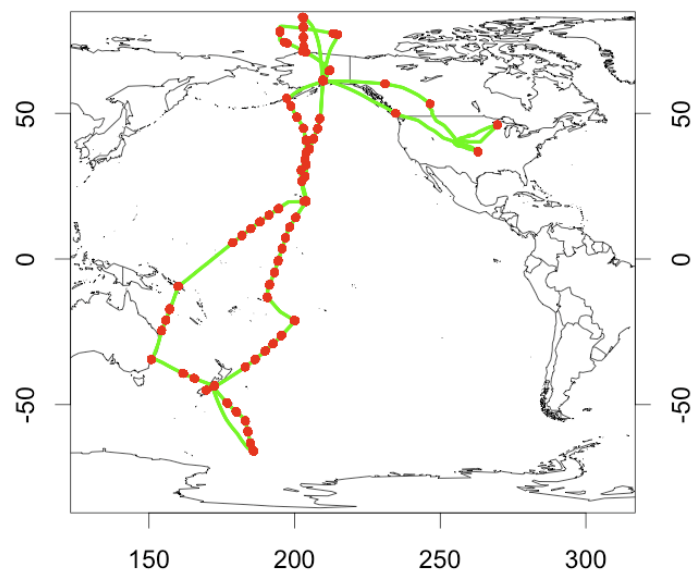
Multiple measurements: ***Red symbols*** *≥ 3,* ***Blue*** *= 2; sampling rates in ().*

HIPPO itinerary

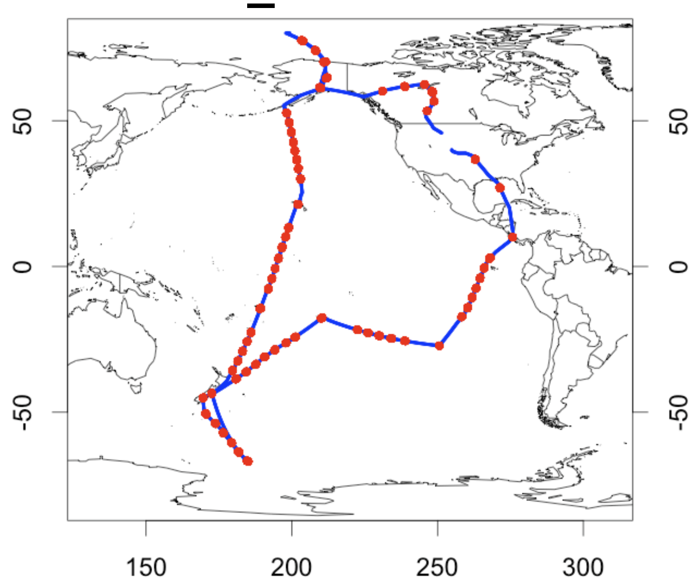
preHIPPO Apr-Jun 2008



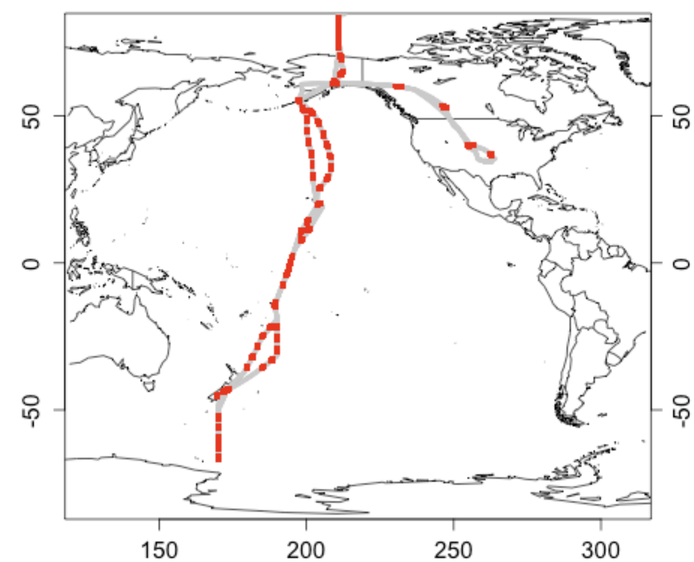
HIPPO_2 Nov 2009



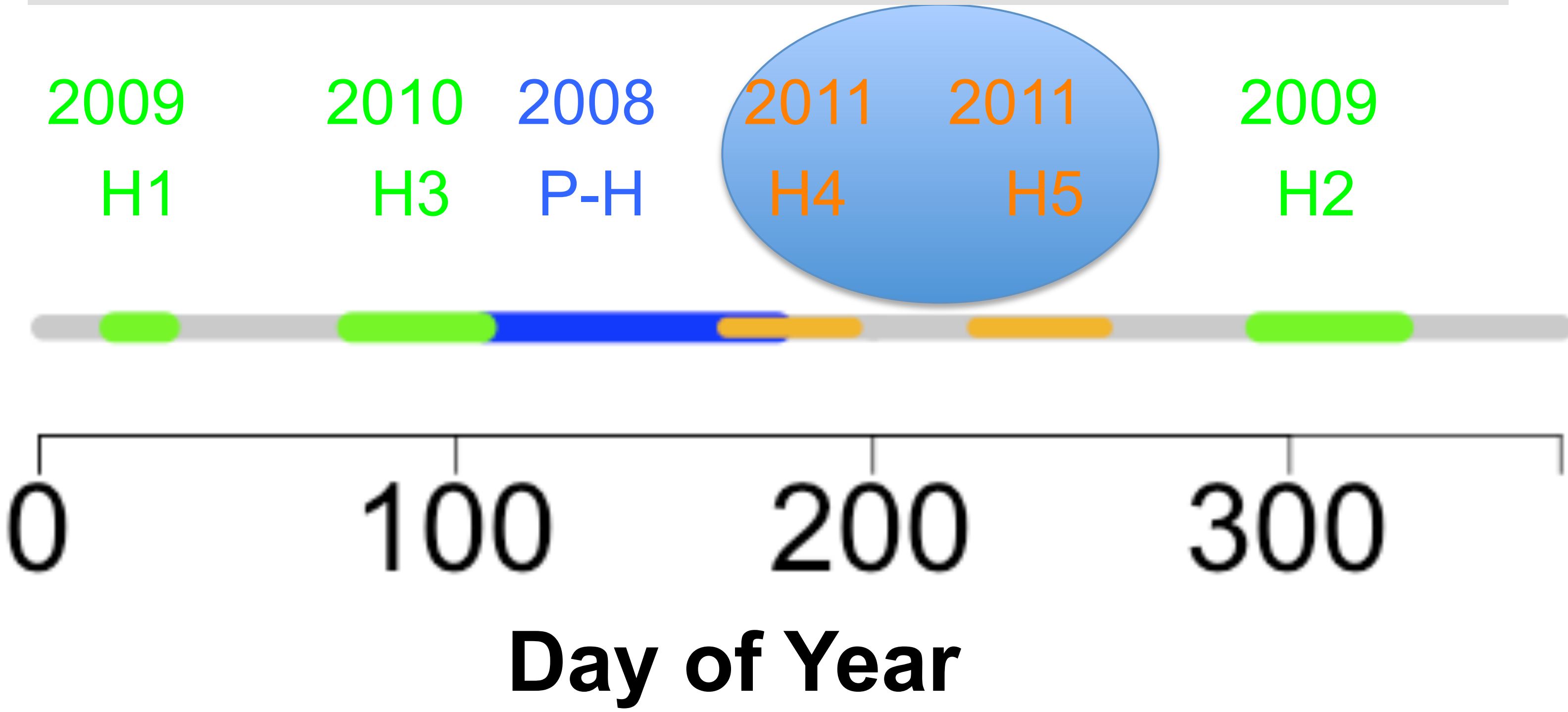
HIPPO_1 Jan 2009



HIPPO_3 Apr 2010



HIPPO Statistics

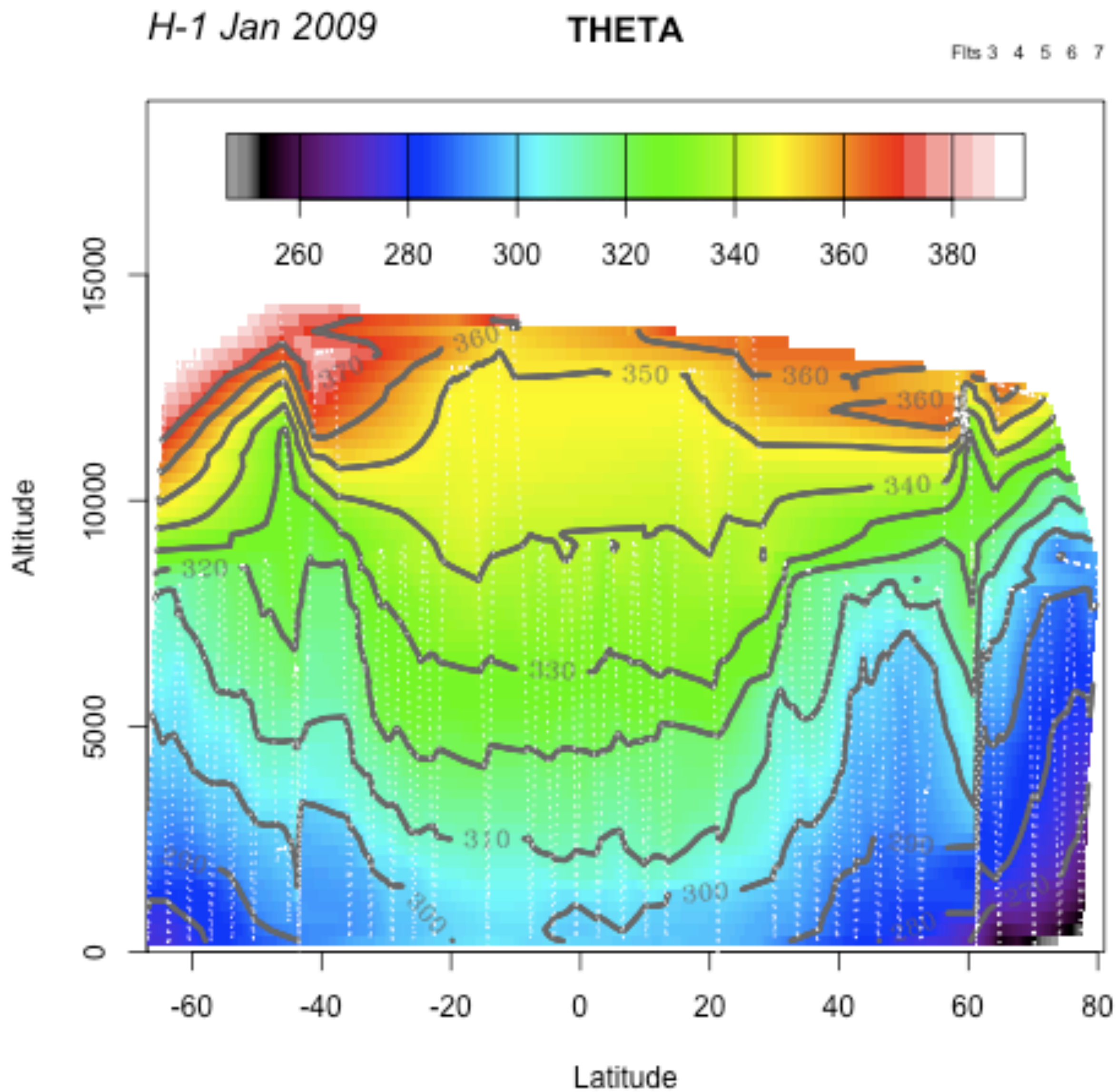


To Date: *156 days of field measurements, 524 profiles*

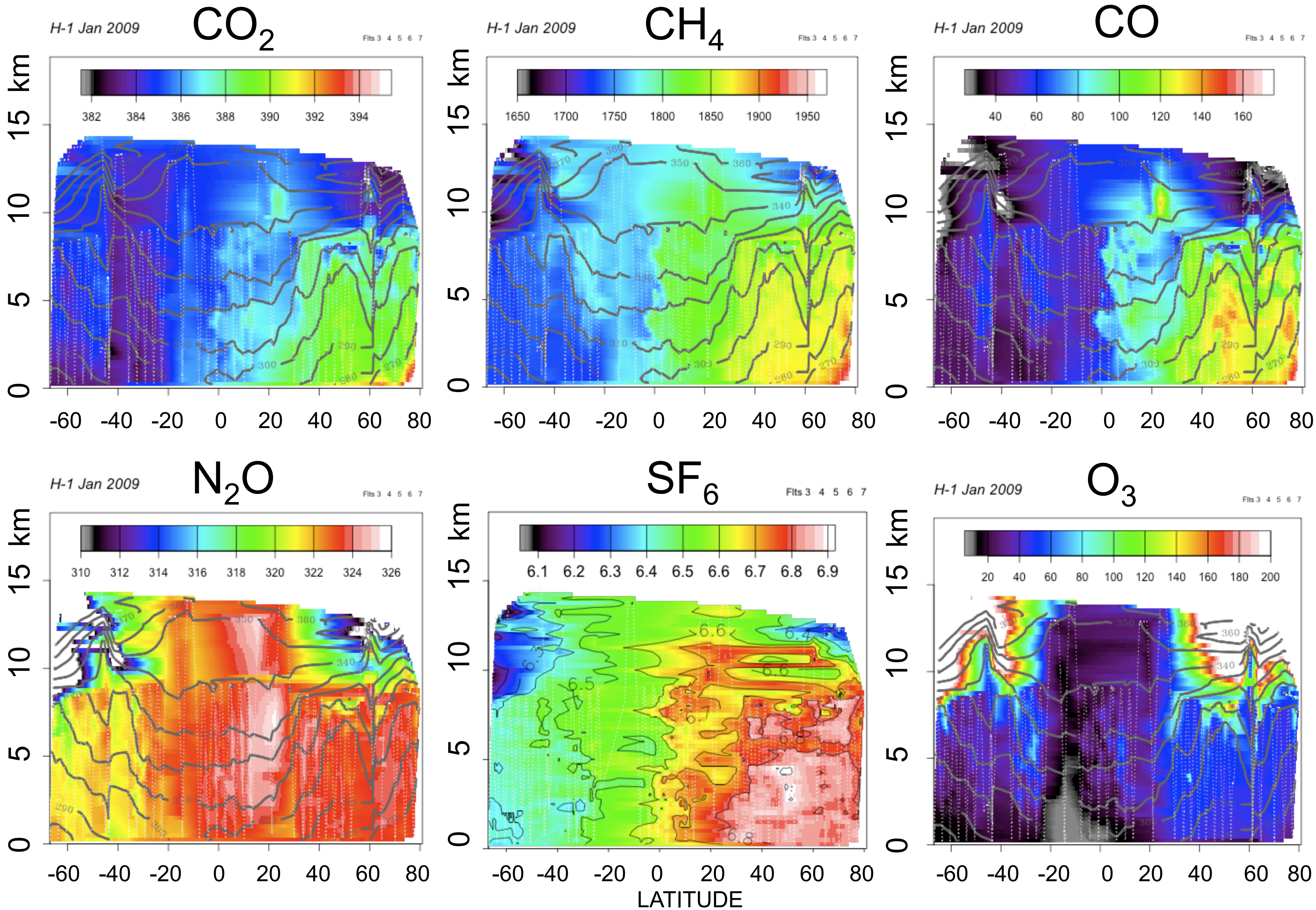
HIPPO Sponsors

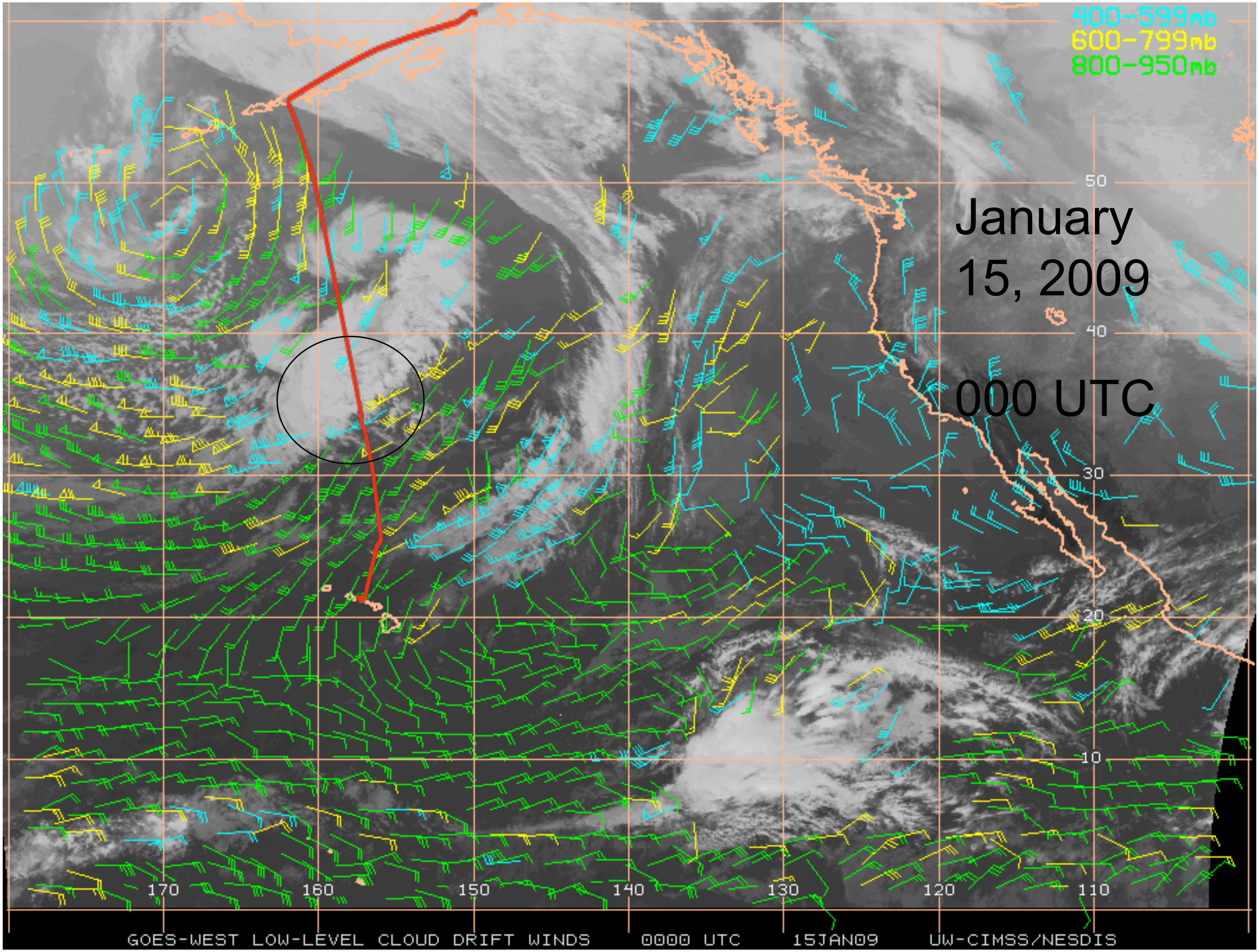
- **National Science Foundation**
- **National Oceanic and Atmospheric Administration**
- **G-V "HIAPER": National Center for Atmospheric Research**

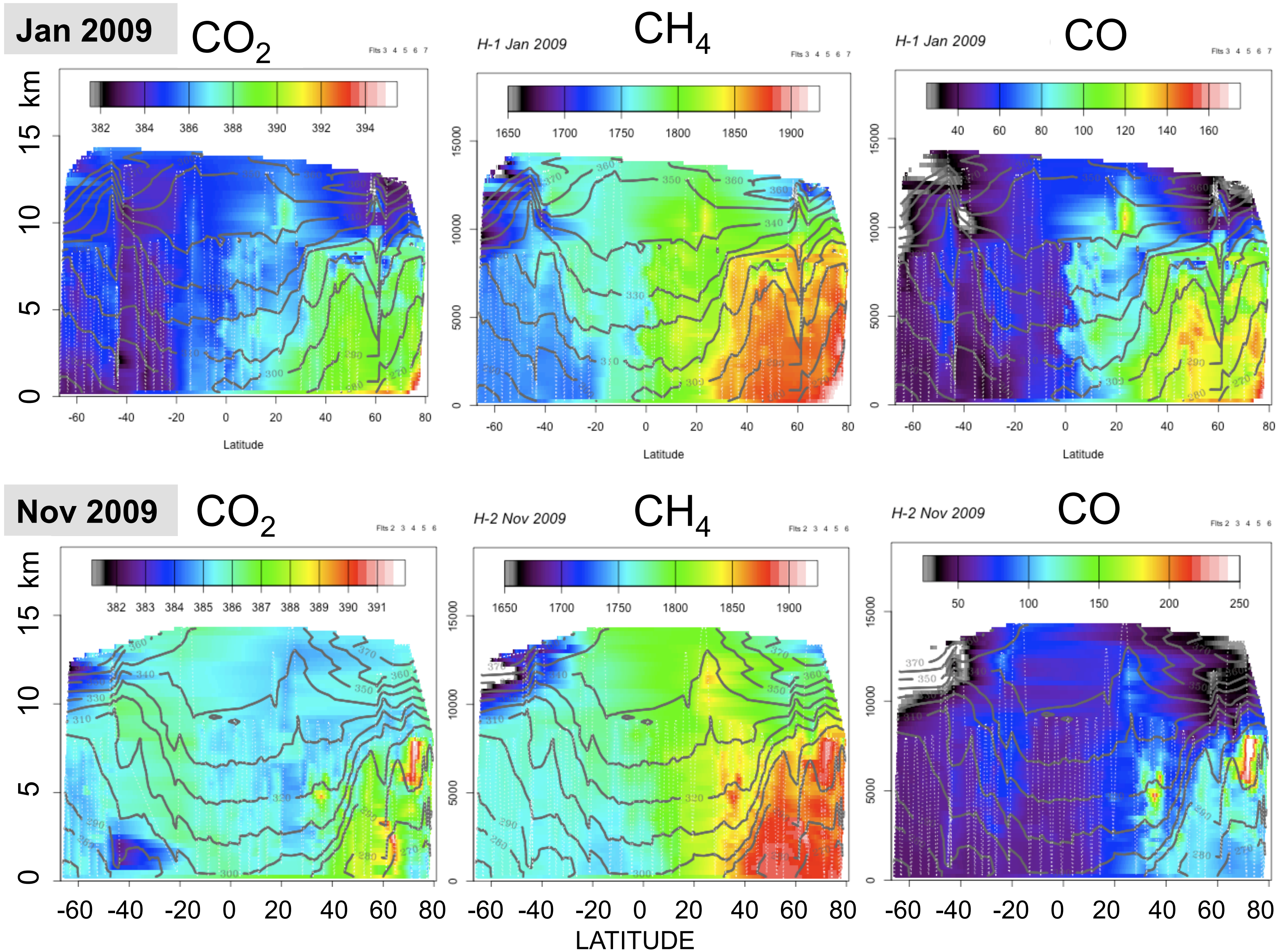
HIPPO-1 Atmospheric Structure (Pot'l T K):
January, 2009, Mid-Pacific (Dateline) Cross section



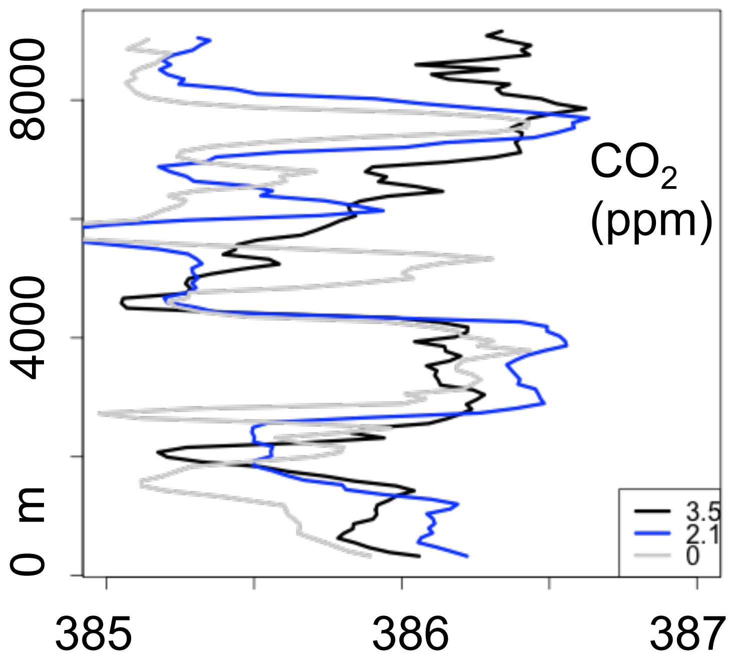
HIPPO sections, January 2009

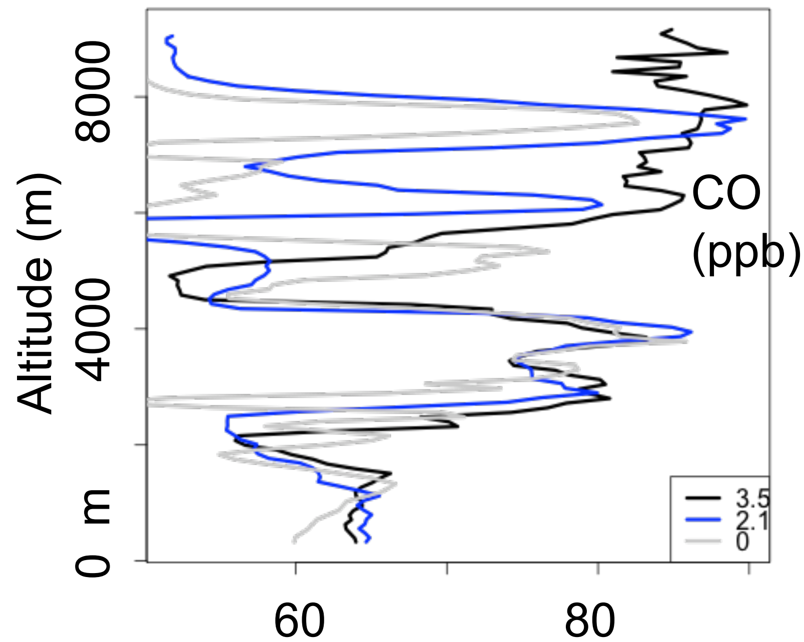



400-599mb
600-799mb
800-950mb
January 15, 2009
000 UTC
50
40
30
20
10
170
160
150
140
130
120
110
GOES-WEST LOW-LEVEL CLOUD DRIFT WINDS 0000 UTC 15JAN09 UW-CIMSS/NESDIS



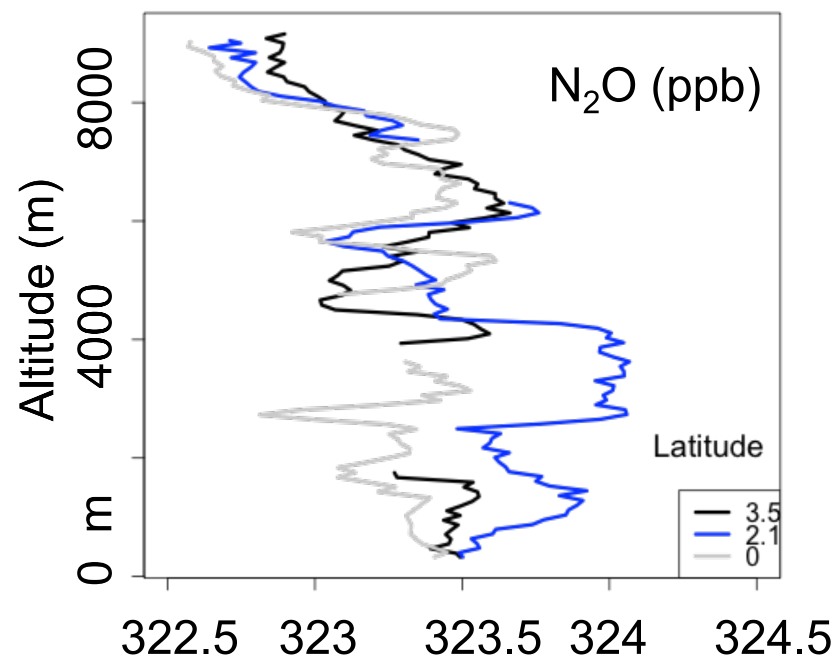
Jan 2009
CO2
CH4
CO
H-1 Jan 2009
H-1 Jan 2009
km
382 384 386 388 390 392 394
1650 1700 1750 1800 1850 1900
40 60 80 100 120 140 160
Latitude
Latitude
Latitude
Nov 2009
CO2
CH4
CO
H-2 Nov 2009
H-2 Nov 2009
km
382 383 384 385 386 387 388 389 390 391
1650 1700 1750 1800 1850 1900
50 100 150 200 250
-60 -40 -20 0 20 40 60 80
LATITUDE





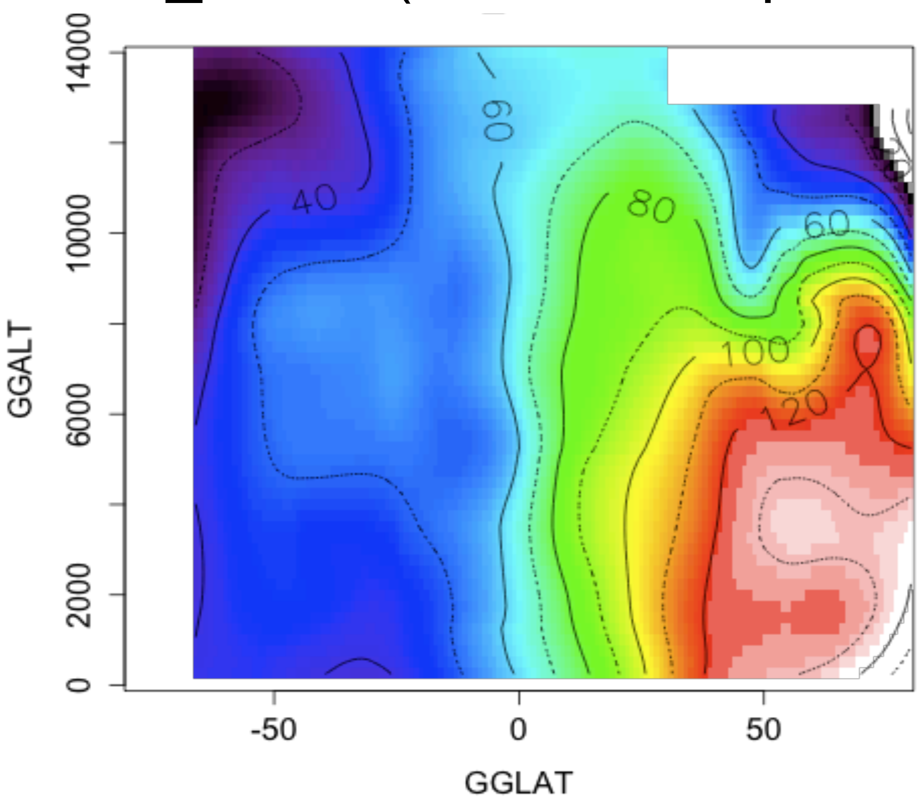
Layering of greenhouse gas concentrations in the tropics

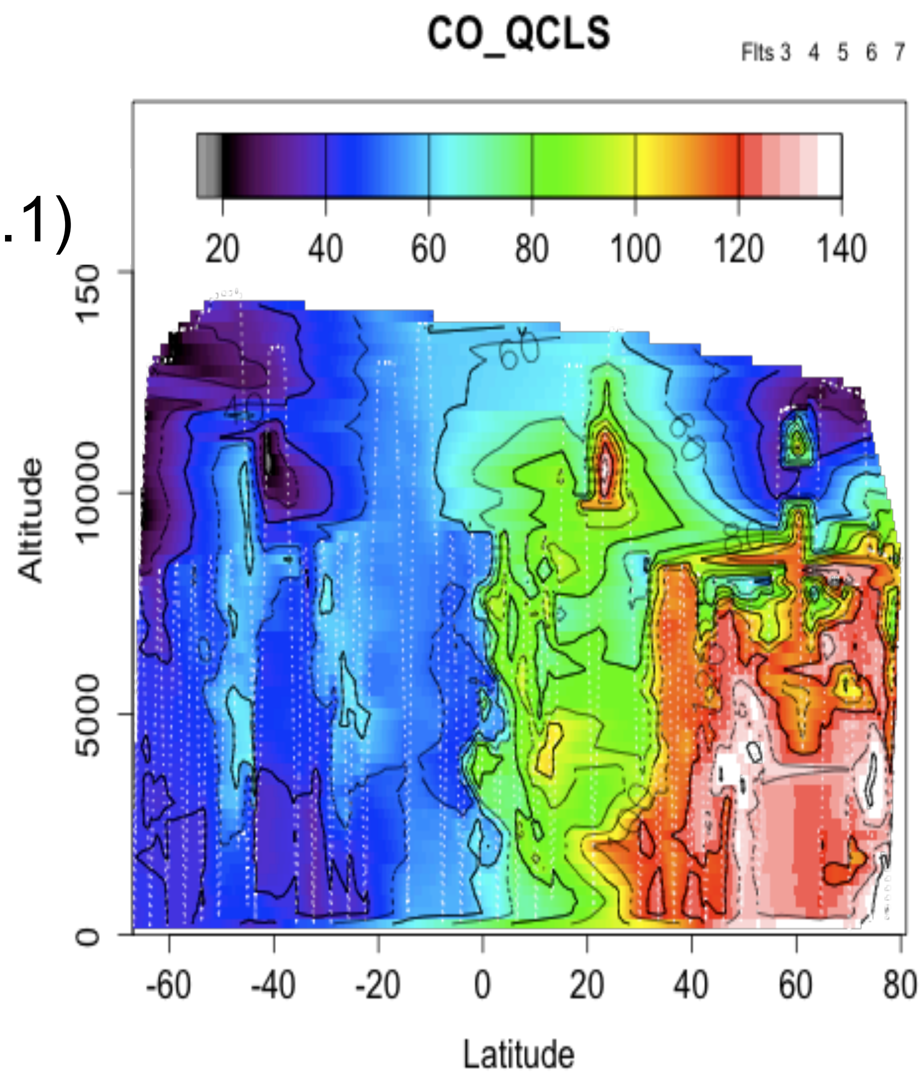
HIPPO-1 Jan 2009

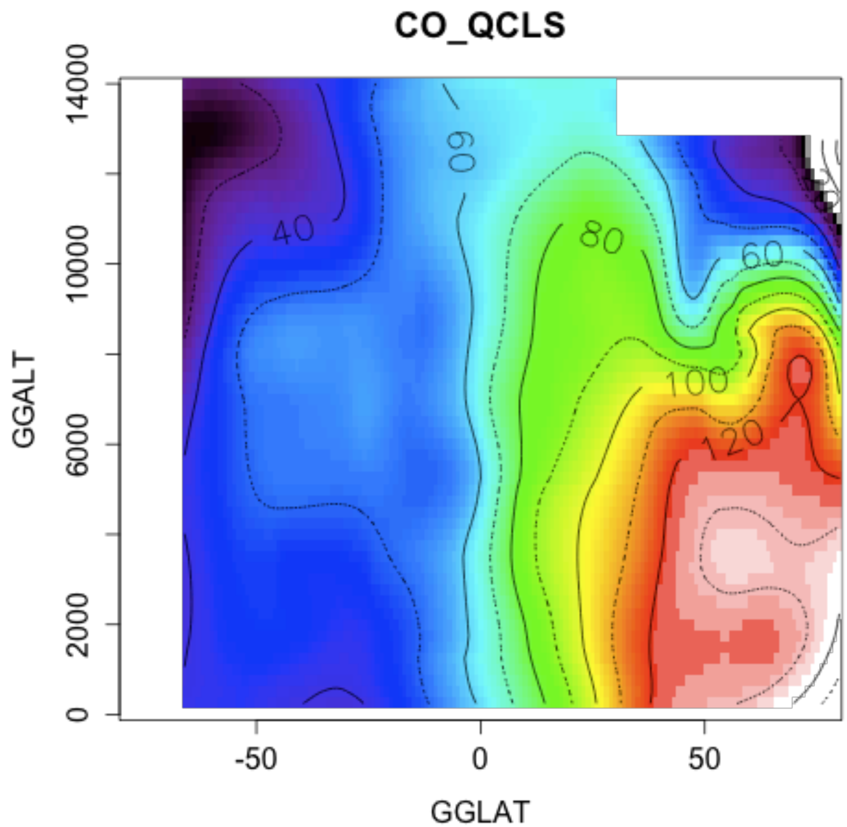


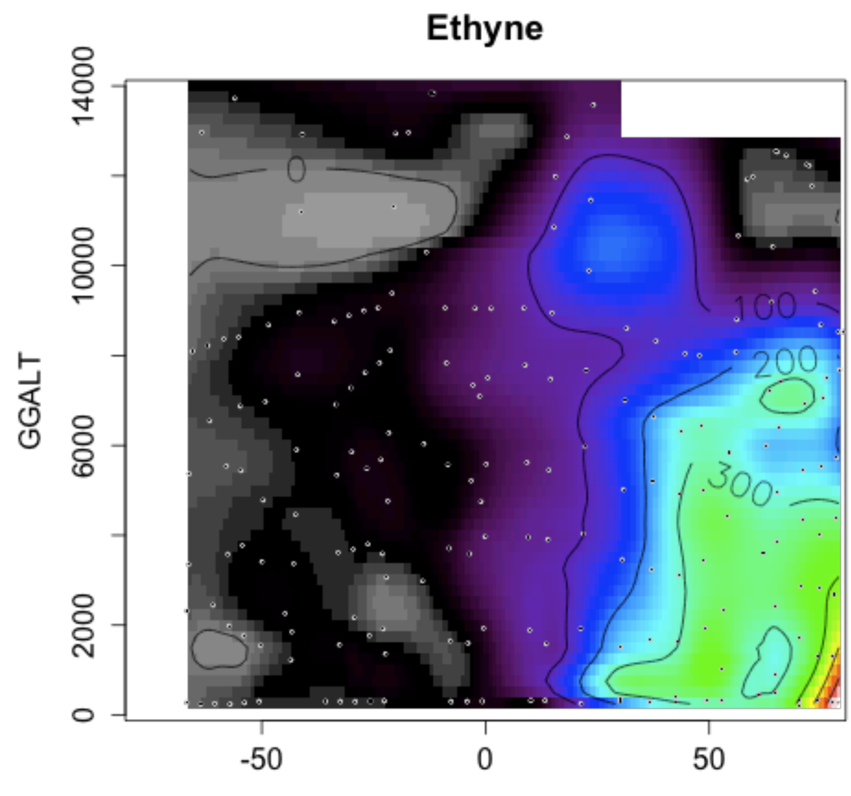
Effect of smoothing and under-sampling on the information content of cross section data

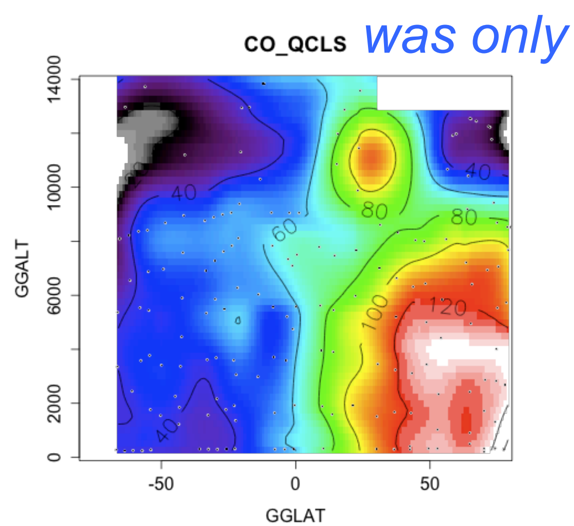
CO_QCLS (loess filter, span=0.1)

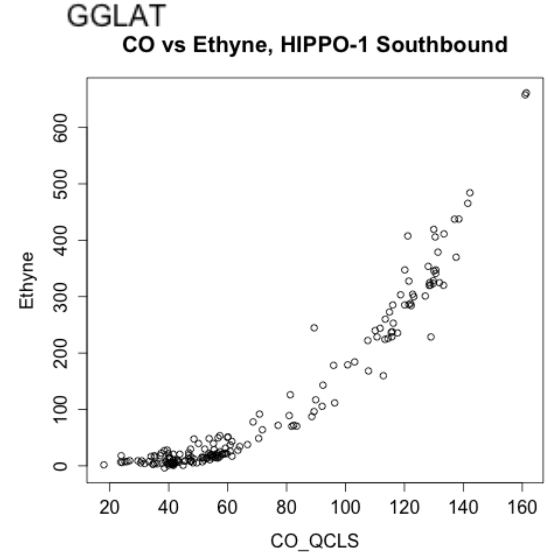






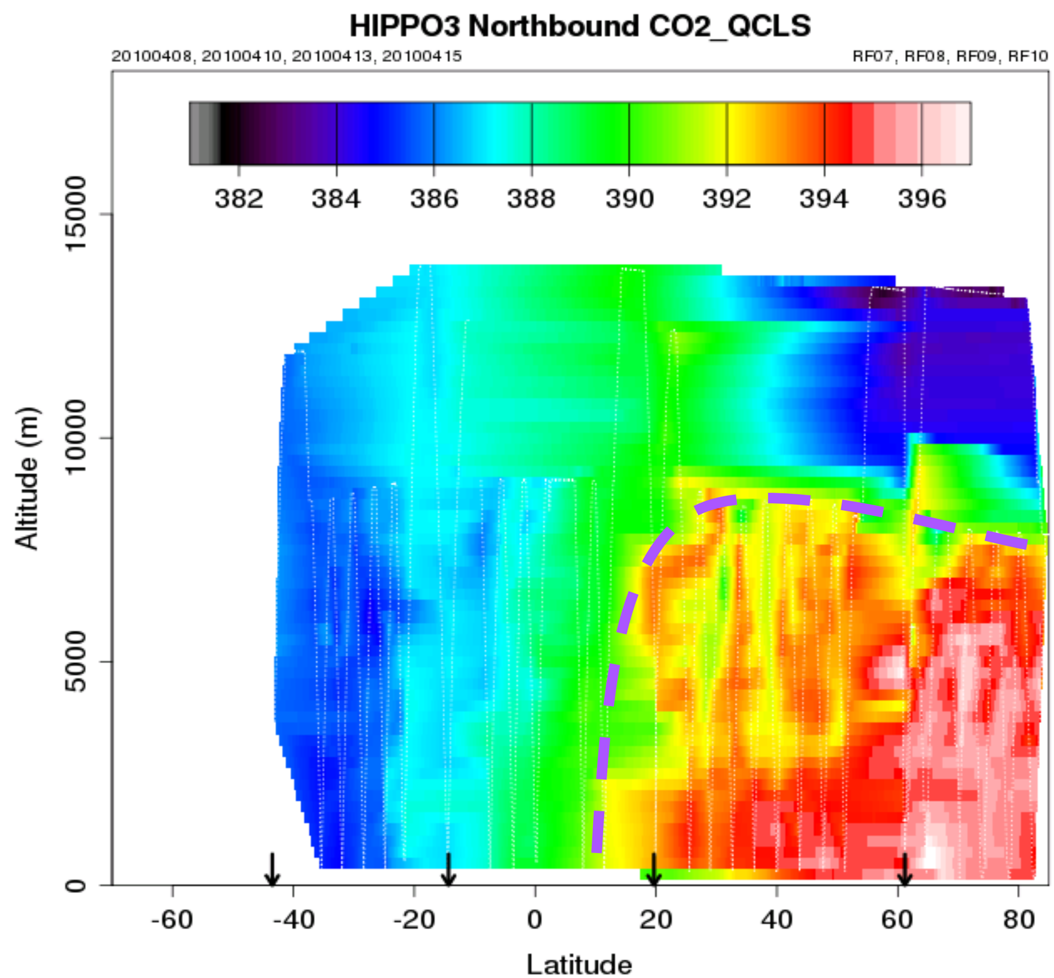




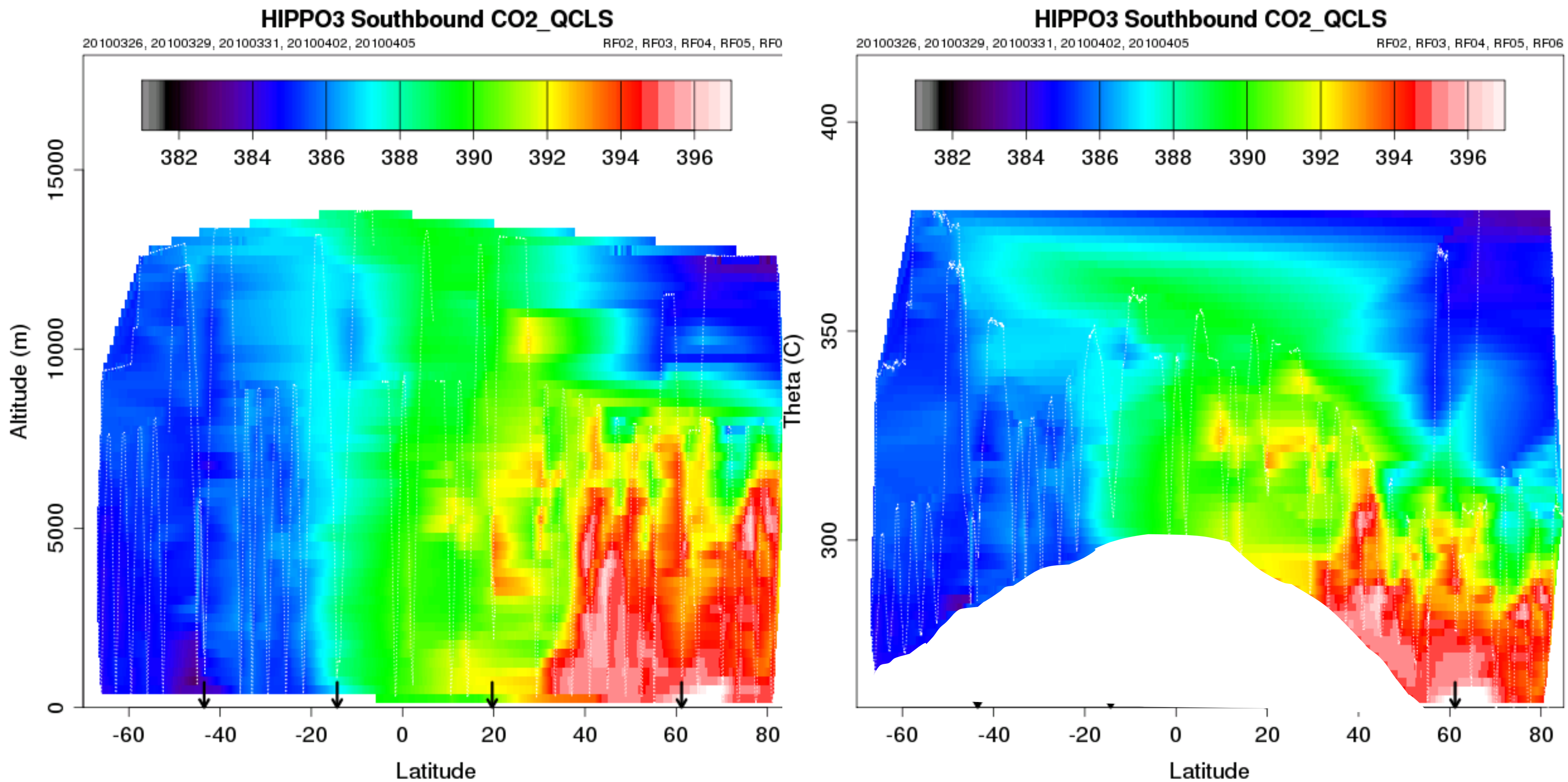


The effect of sampling rate is ameliorated by covariance with 1 Hz tracers

HIPPO defines the boundary between that part of the atmosphere that is directly influenced by the seasonal component of northern CO_2 exchange, and that part which is not.



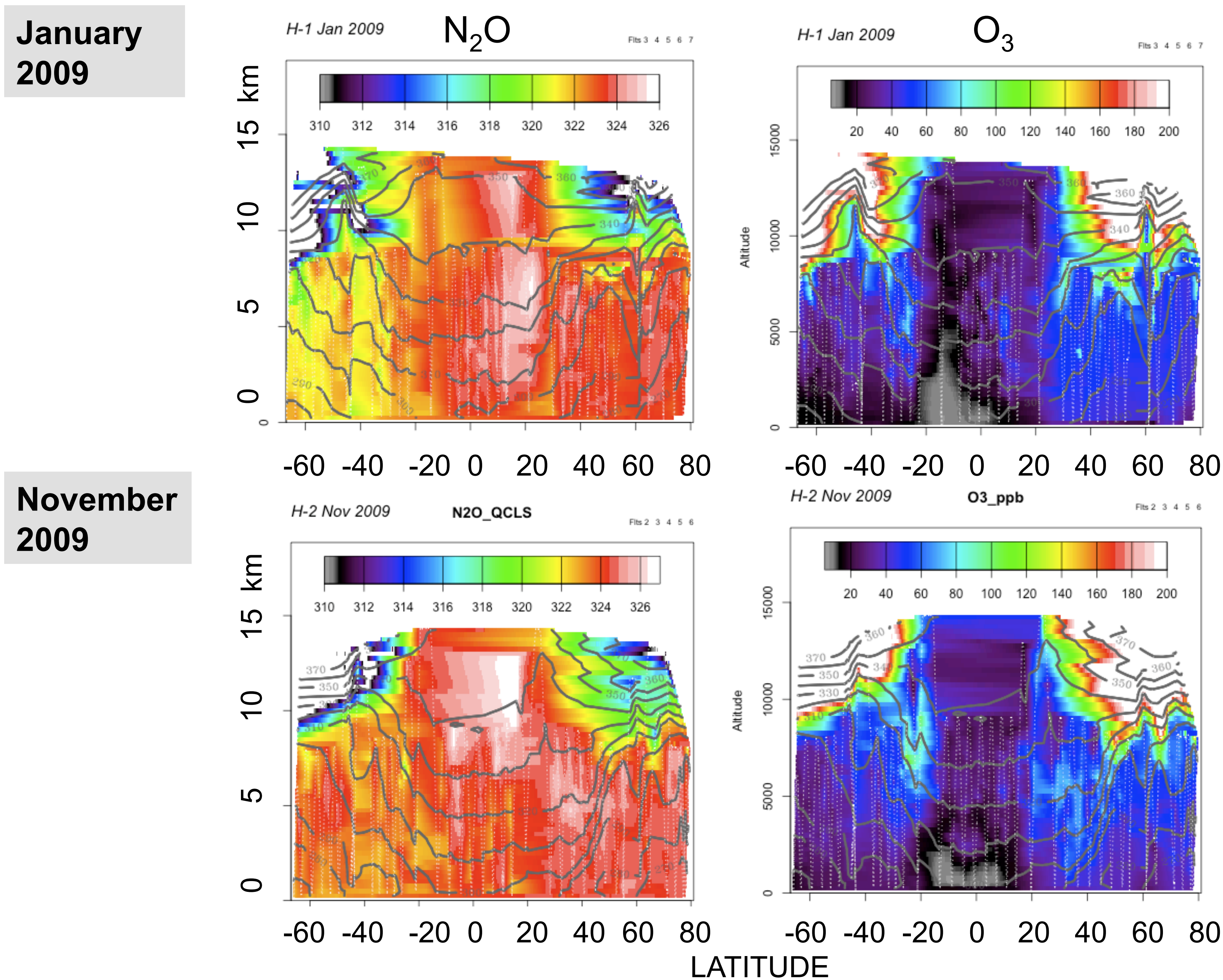
April, 2010



March, 2010

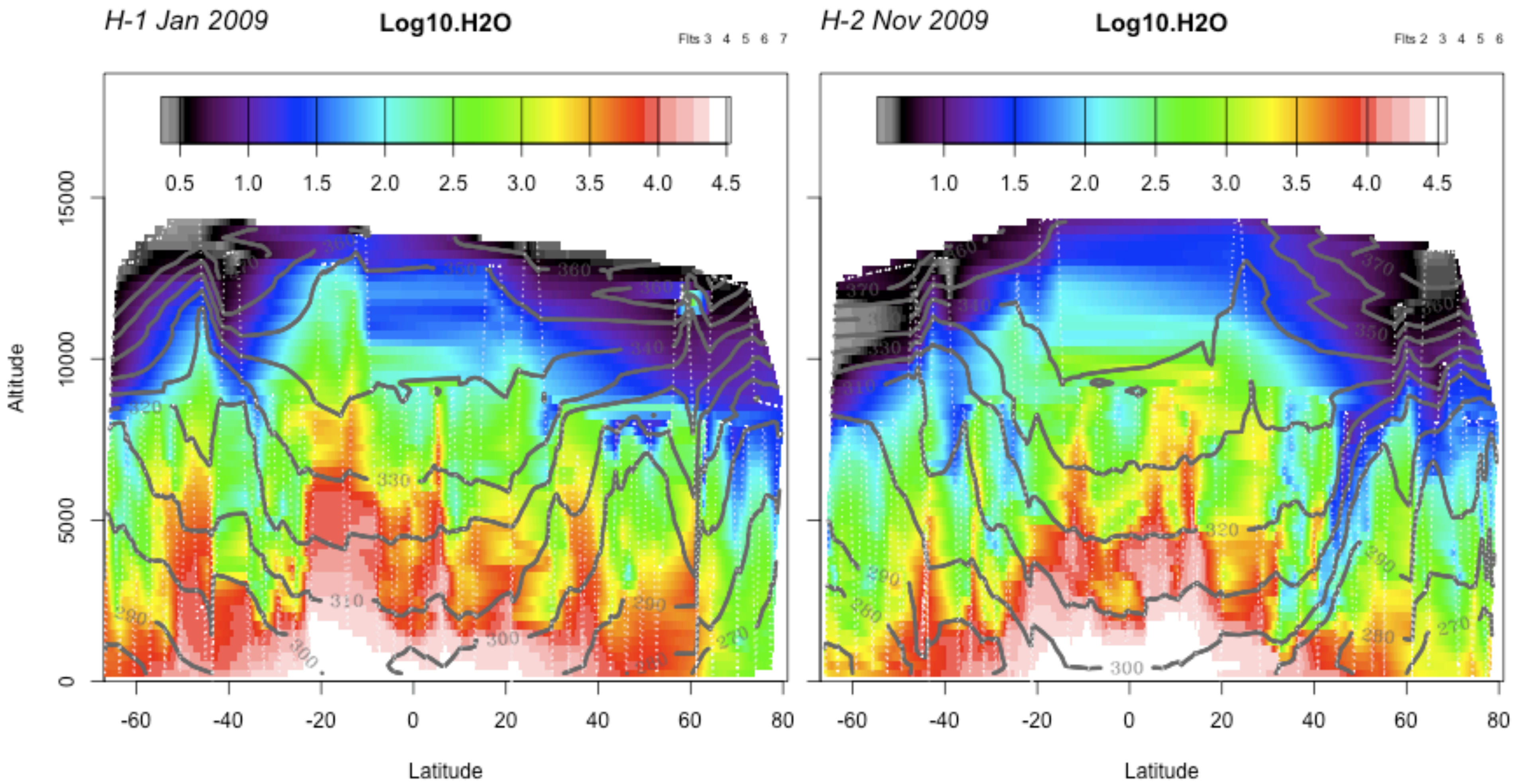
How do CO_2 and pollutants get up to 8 km in the Arctic over the winter?

Slide courtesy Britt Stephens

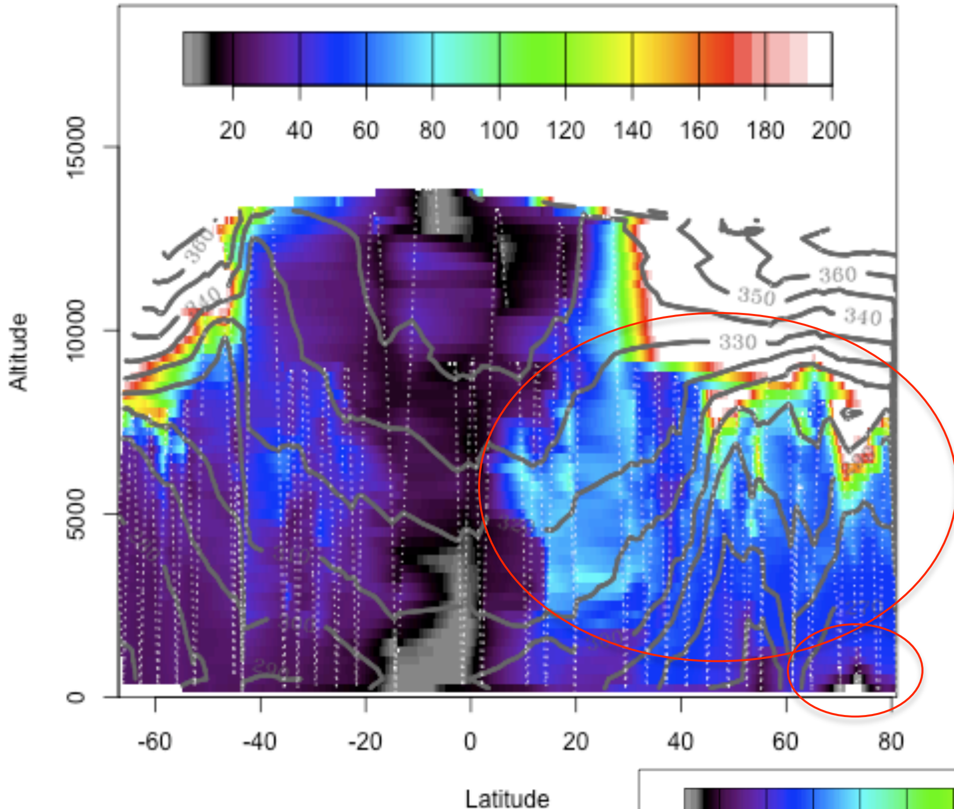


January 2009
November 2009
H-1 Jan 2009
N_2O
O_3
H-2 Nov 2009
N2O_QCLS
O3_ppb
Flts 3 4 5 6 7
Flts 2 3 4 5 6
310 312 314 316 318 320 322 324 326
20 40 60 80 100 120 140 160 180 200
km
0 5 10 15
Altitude
0 5000 10000 15000
-60 -40 -20 0 20 40 60 80
LATITUDE

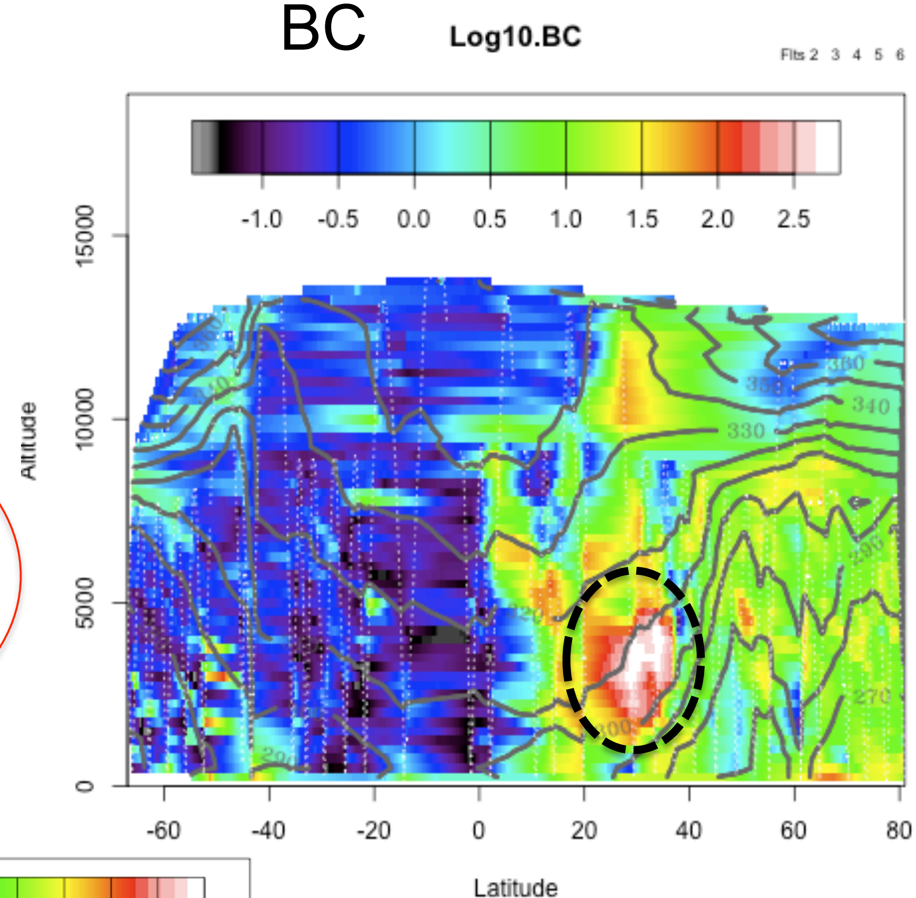
January – November Water Vapor comparison



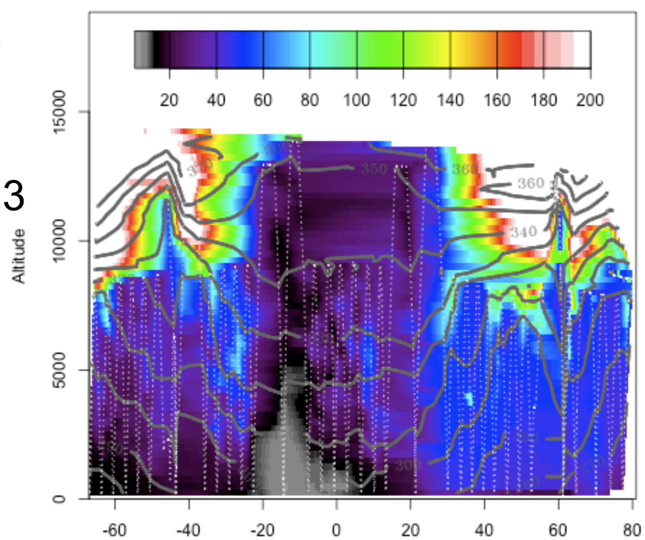
H-3 Mar-Apr 2010 O_3



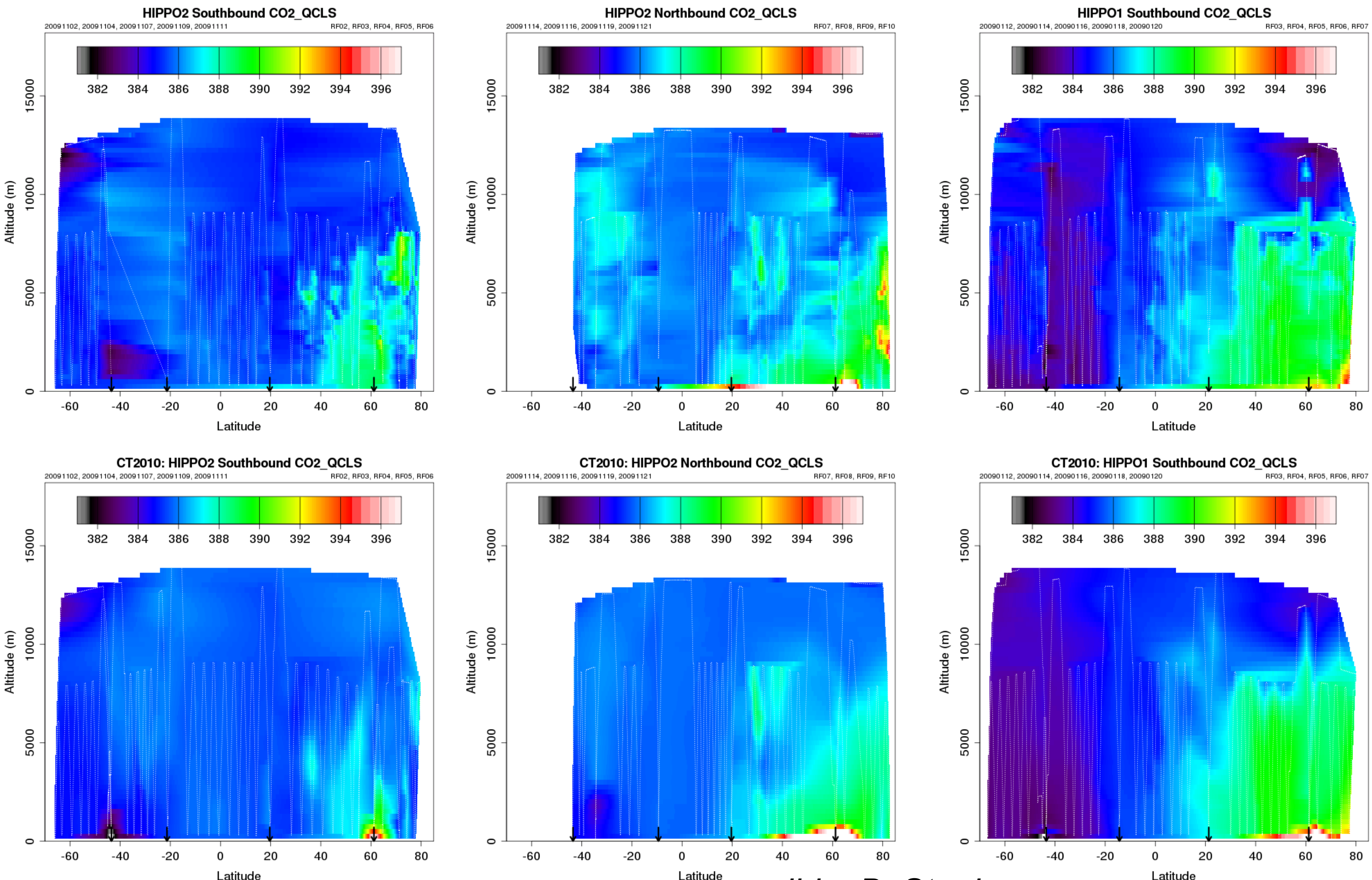
BC



H-1 Jan 2009 O_3

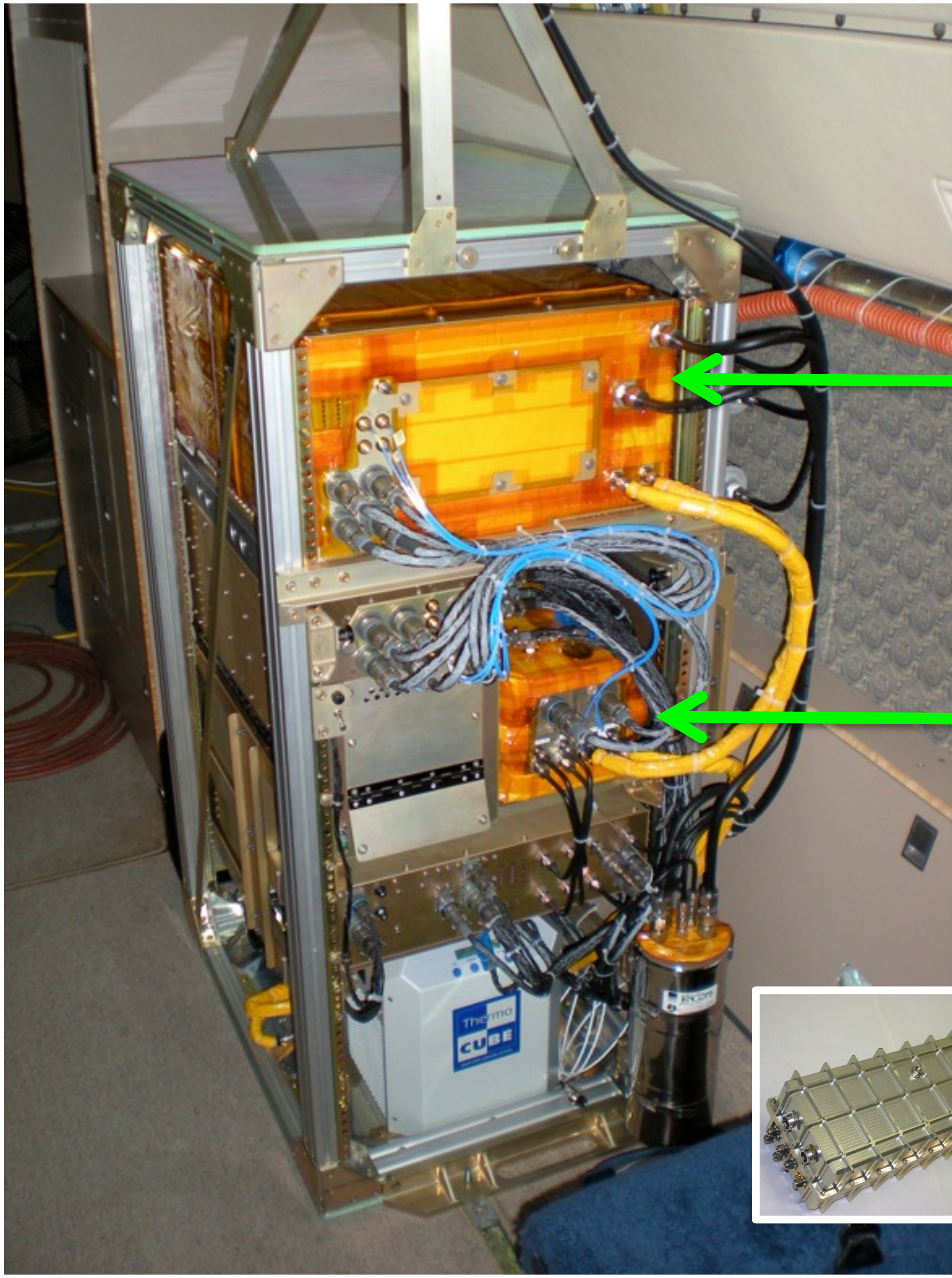


HIPPO 1 and 2 and NOAA CarbonTracker Comparisons



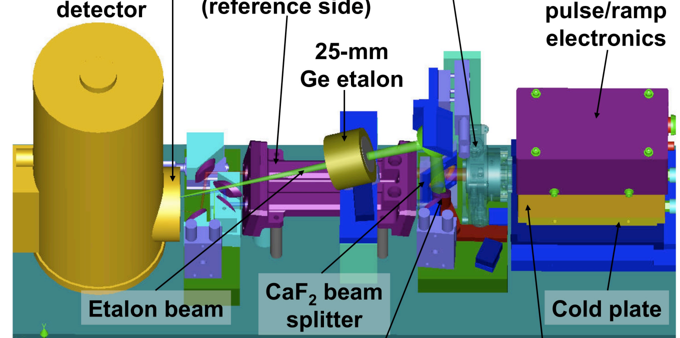
slide: B. Stephens

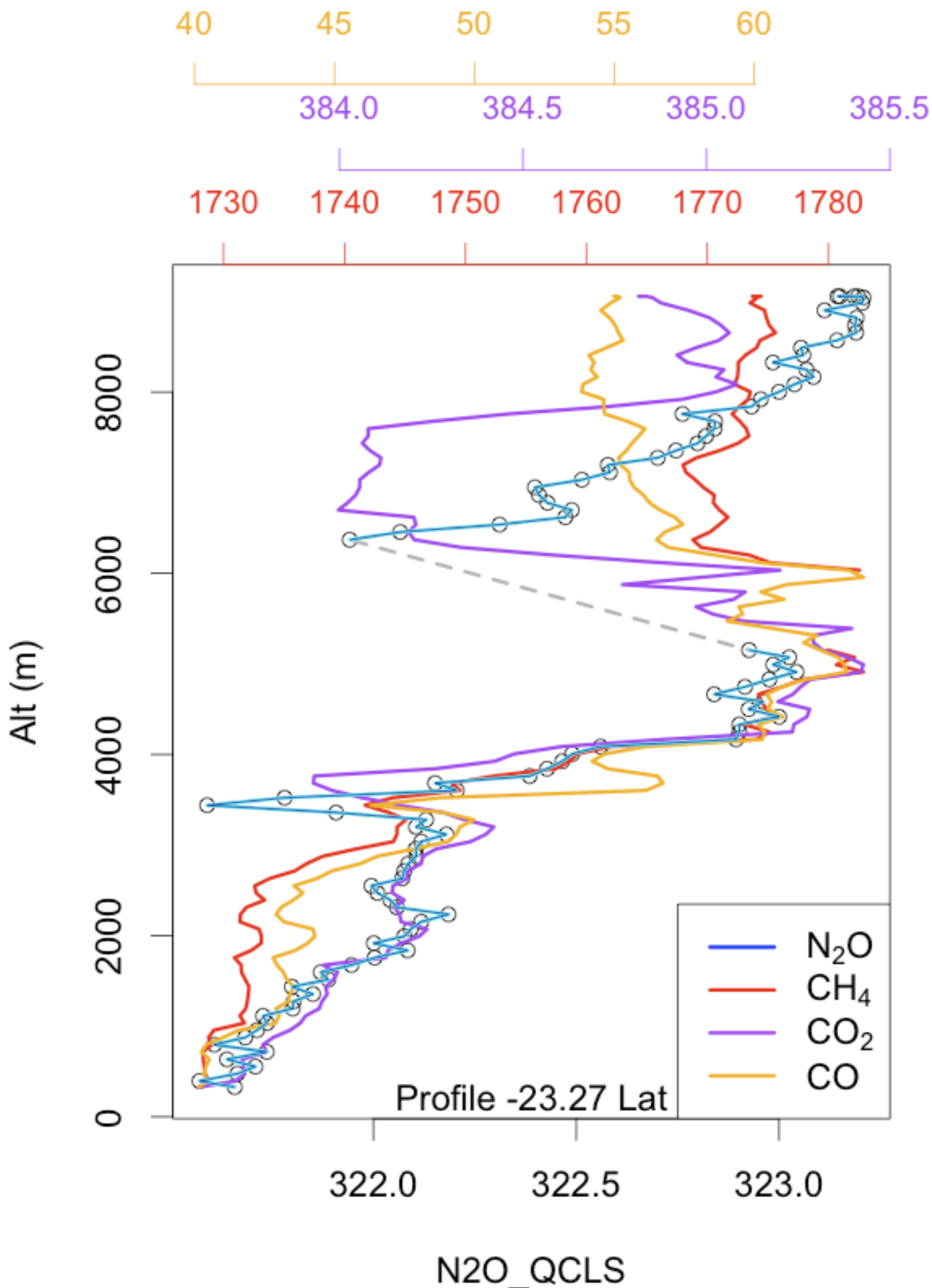
Harvard/Aerodyne Quantum Cascade Laser Spectrometers **(HAIS/NCAR)**



QCLS "DUAL" – 2 lasers
N_2O & CH_4 1275 cm^{-1}
CO 2169 cm^{-1}
76m path, compact cell

QCLS CO_2 2319.18 cm^{-1}
2 10 cm cells (ref, sample)



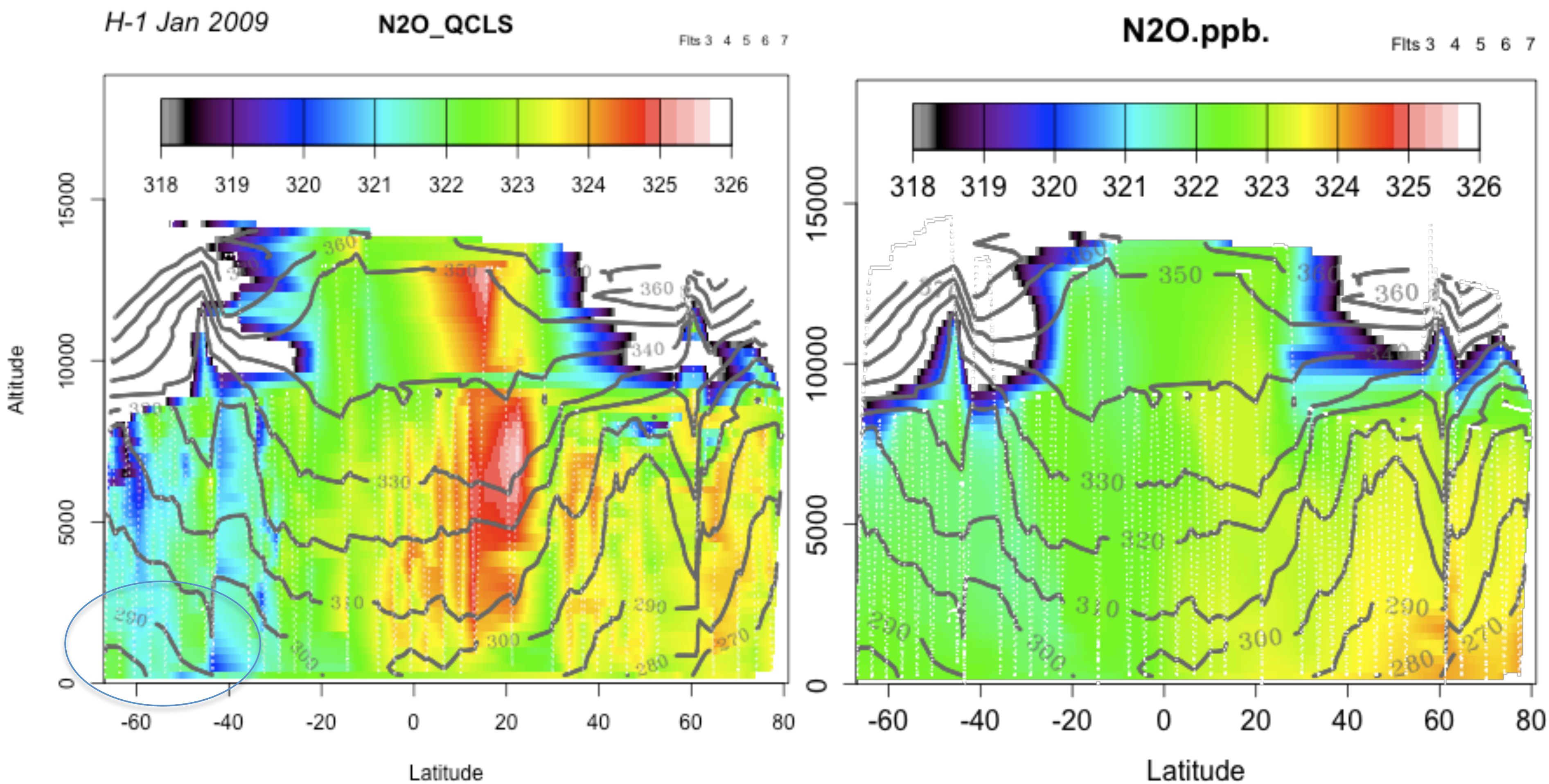


Other tracers confirm N_2O variable layers arise from different air origins

CO_2
CH_4
CO

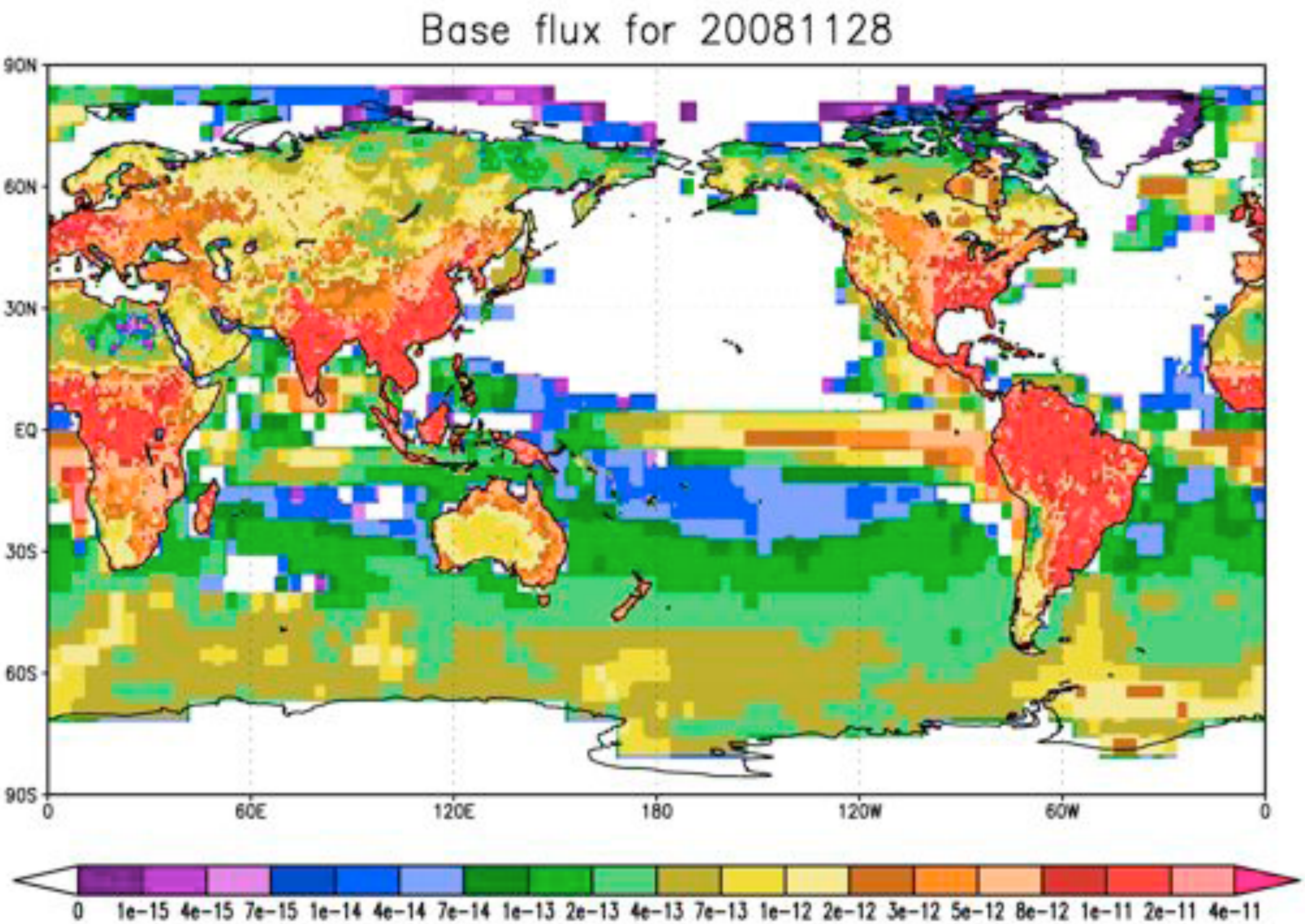
HIPPO Nitrous Oxide (N_2O)

Observed vs Model (ACTM)



HIPPO_1 Jan 2009

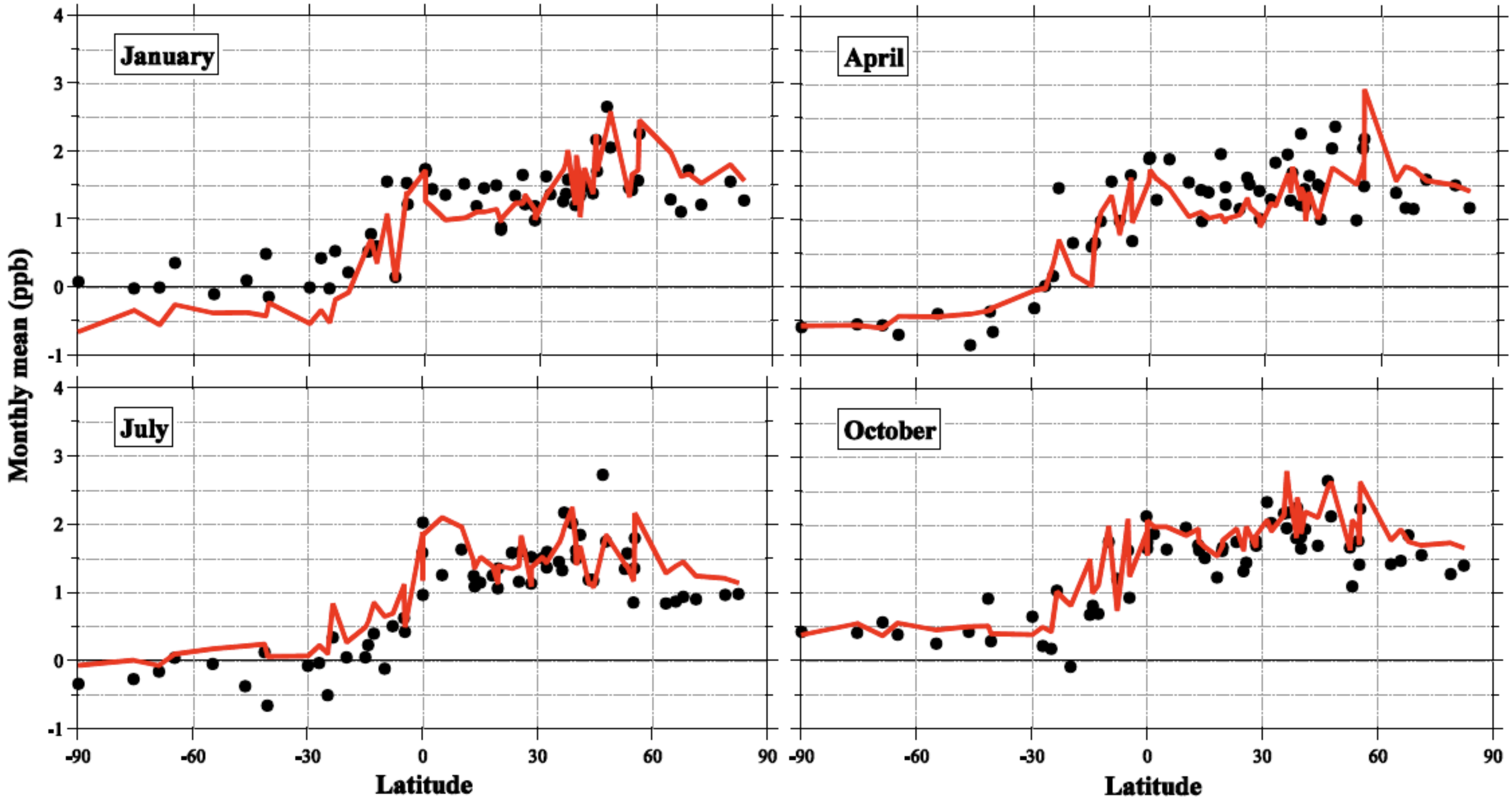
Prabir Patra, Kentaro Ishijima (JAMSTEC)
Eric Kort (Harvard)



ACTM

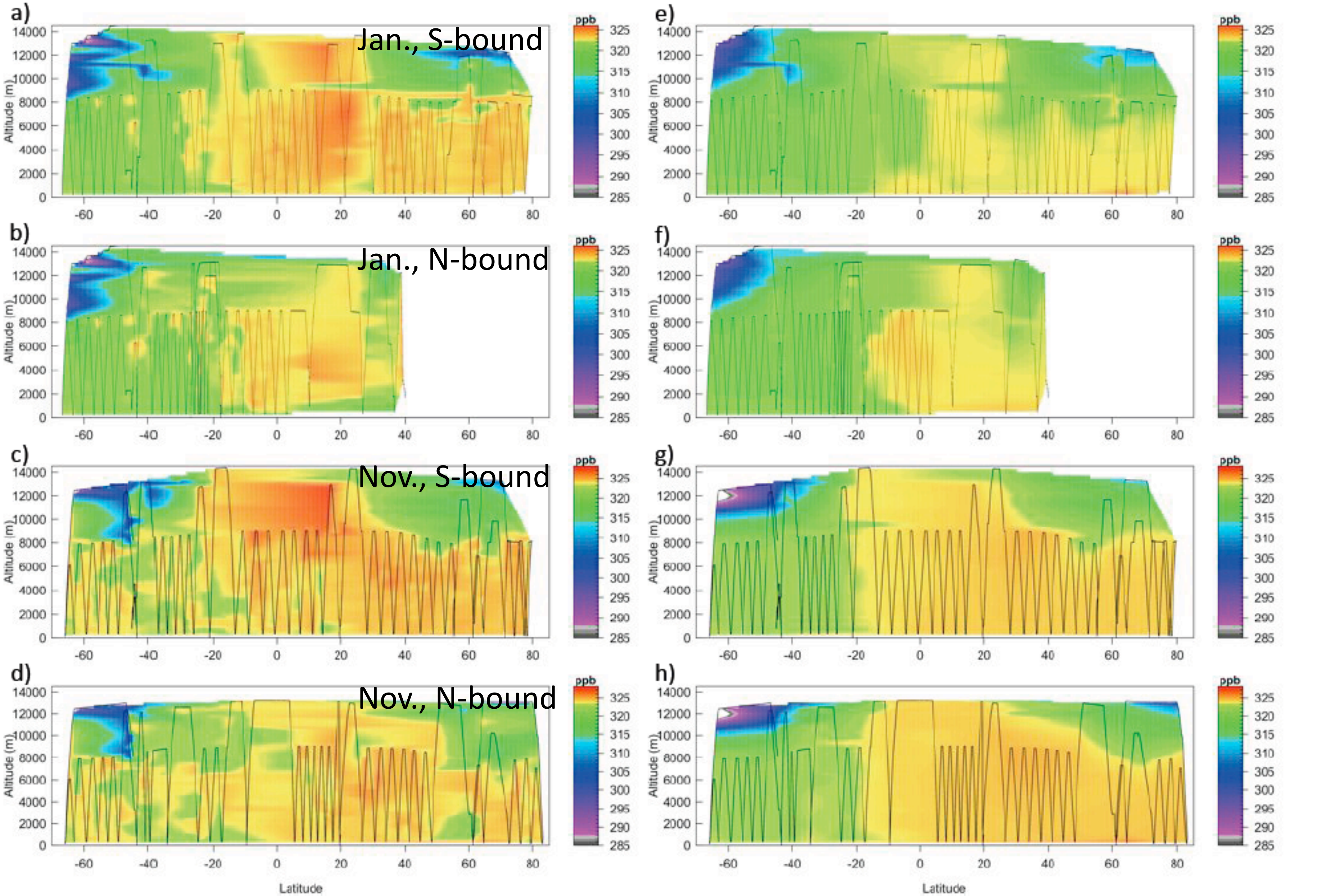
Eric Kort (Harvard); Prabir Patra, Kentaro Ishijima (JAMSTEC)

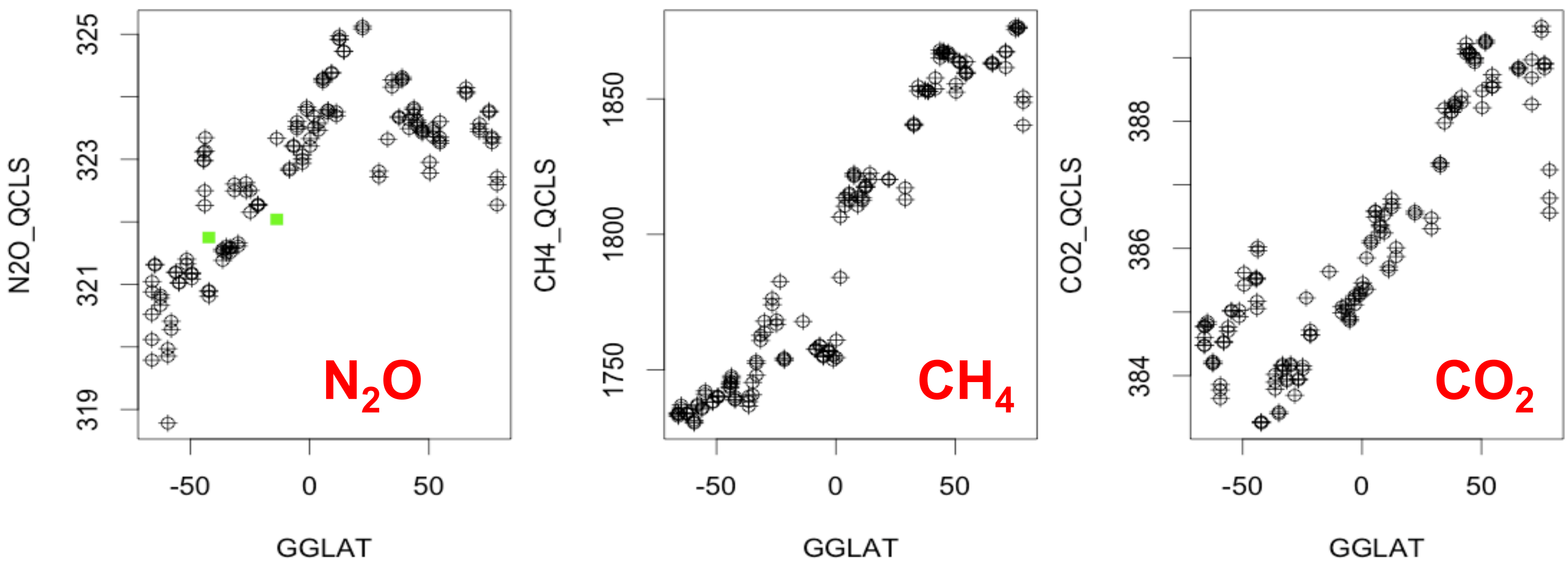
ACTM model (optimized)
Excellent fit to surface observations

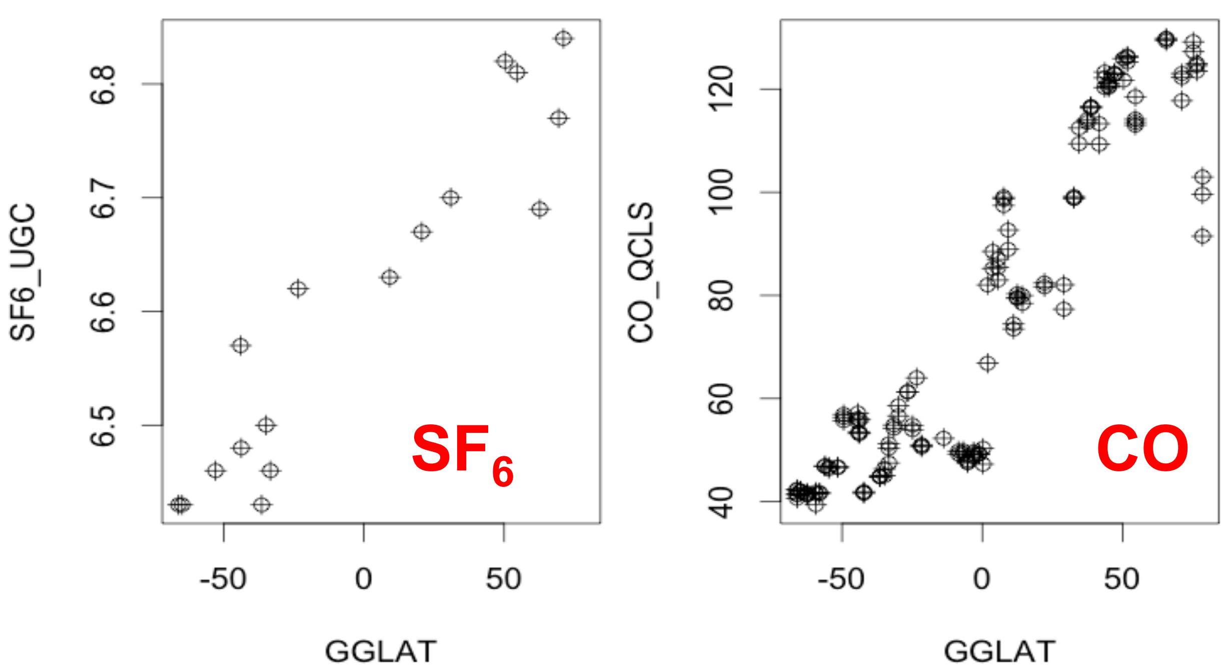


64 surface stations, monthly means (*courtesy K. Ishijima*)

Observed   ACTM Prior





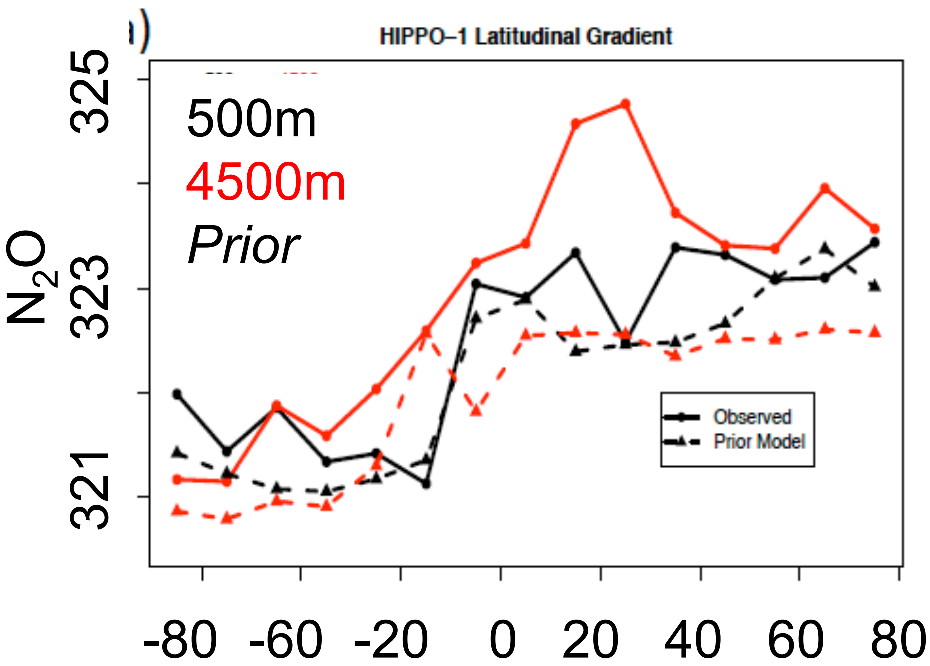


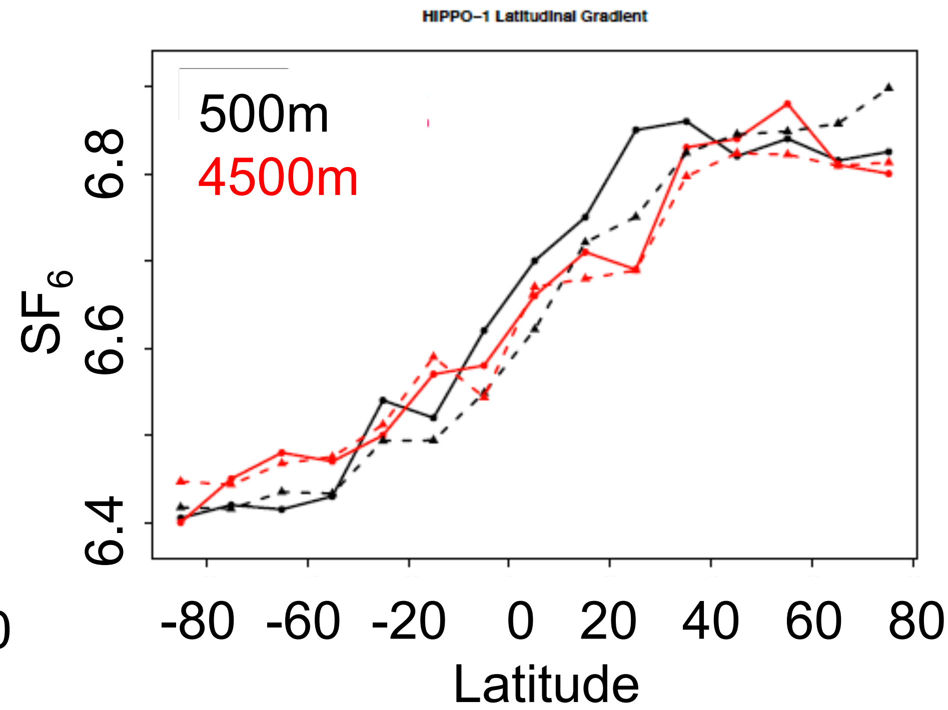
<u>Jan 2009</u>

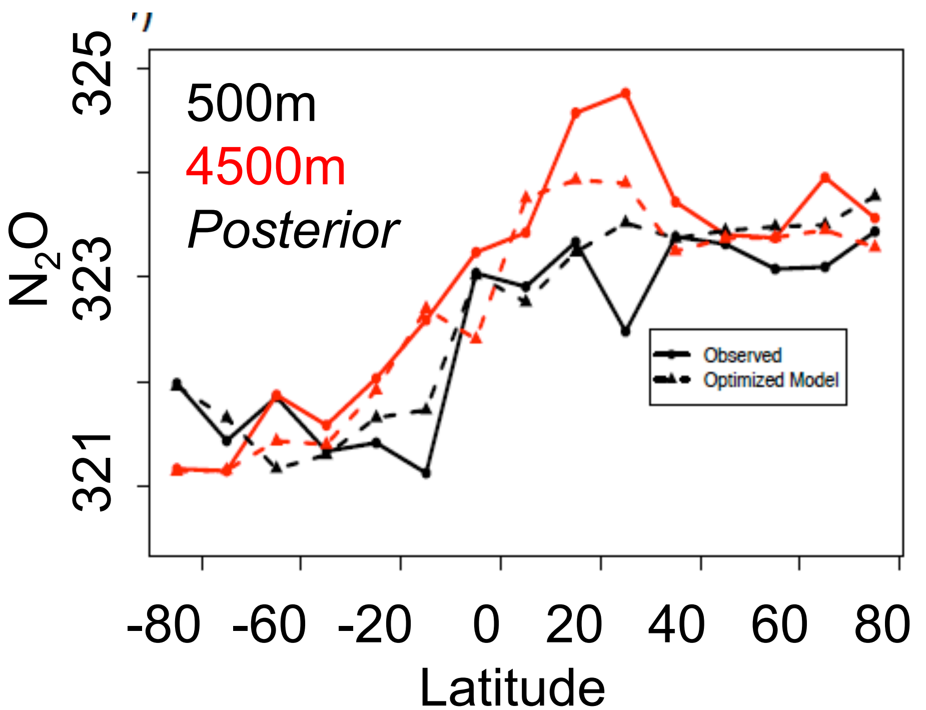
Latitude Gradients of Tracers in H-1 Southbound

@

5900 – 6100 m

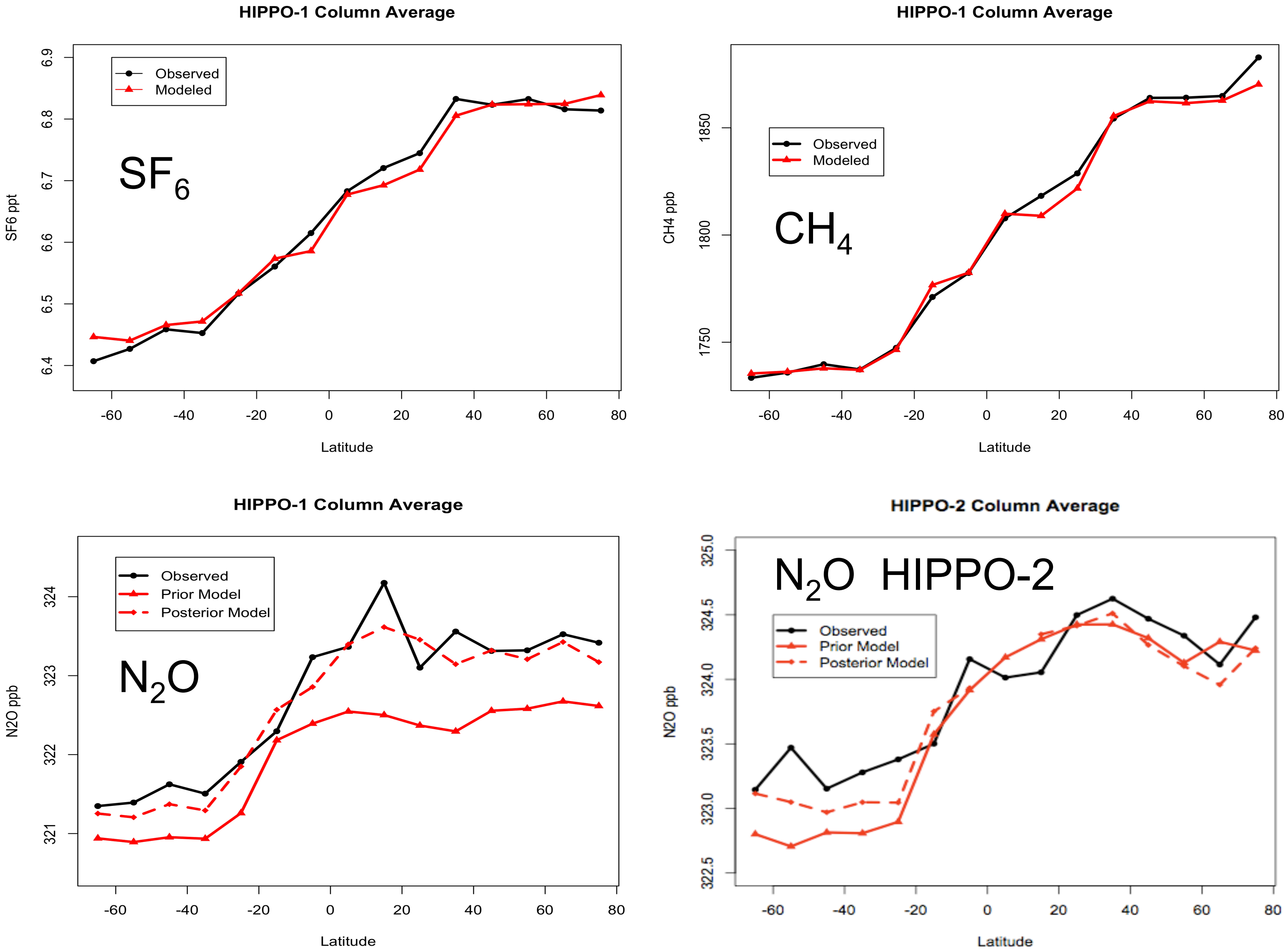




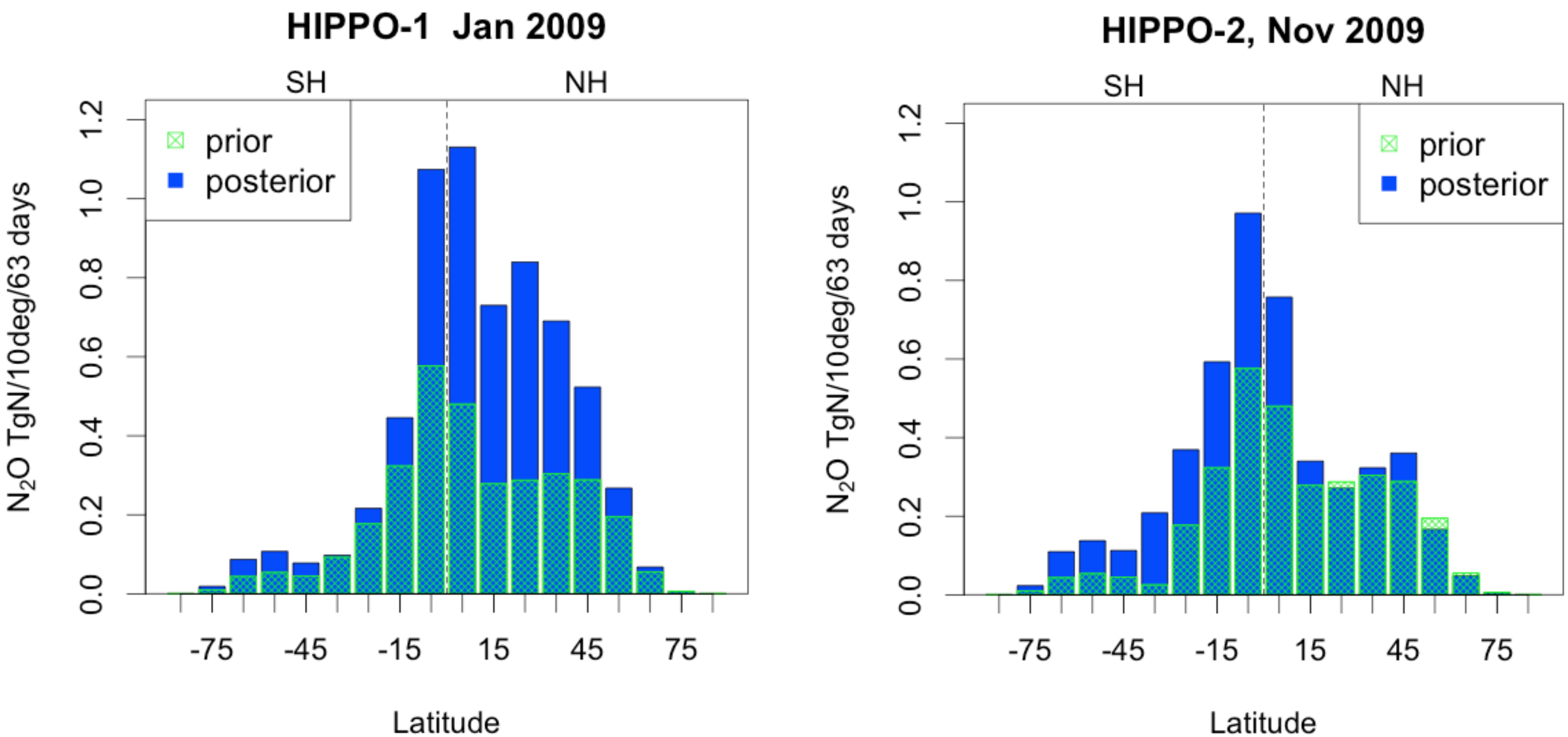


HIPPO_1
N_2O and SF_6

observed vs. ACTM model
(Patra and Ishijima)


HIPPO-1 Column Average
SF6 ppt
SF$_6$
Observed
Modeled
Latitude
HIPPO-1 Column Average
CH4 ppb
CH$_4$
Observed
Modeled
Latitude
HIPPO-1 Column Average
N2O ppb
N$_2$O
Observed
Prior Model
Posterior Model
Latitude
HIPPO-2 Column Average
N$_2$O HIPPO-2
N2O ppb
Observed
Prior Model
Posterior Model
Latitude

Global Distribution of N_2O emissions: HIPPO cross sections, ACTM Model

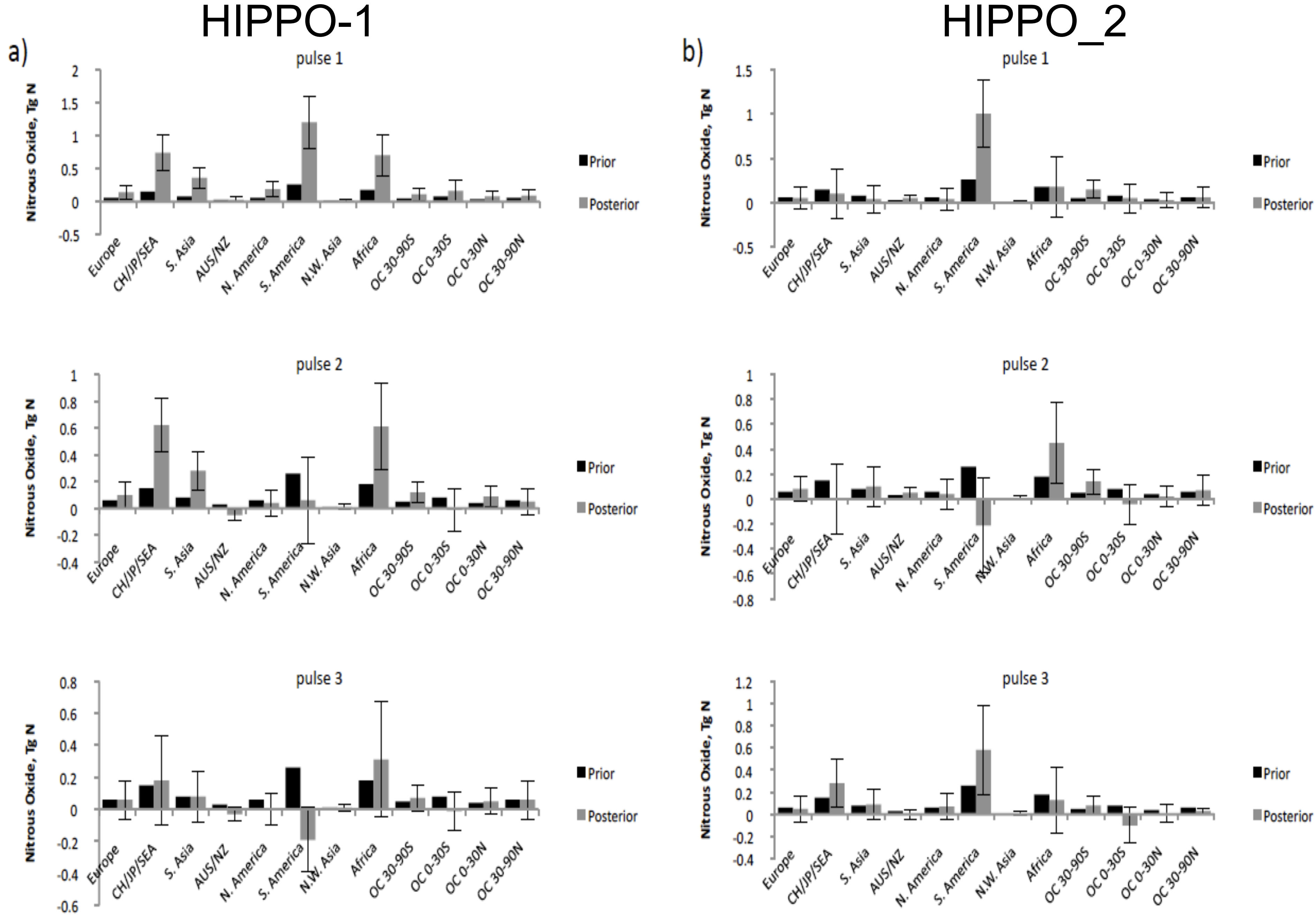


Global Totals (Tg N in N_2O, over 63 days)

6.4	**Posterior**	**4.8**
3.2	*Prior*	*3.15*

Eric Kort (Harvard); Prabir Patra, Kentaro Ishijima (JAMSTEC)

Inversion results by region

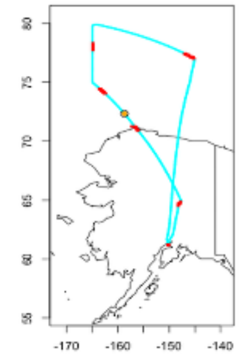


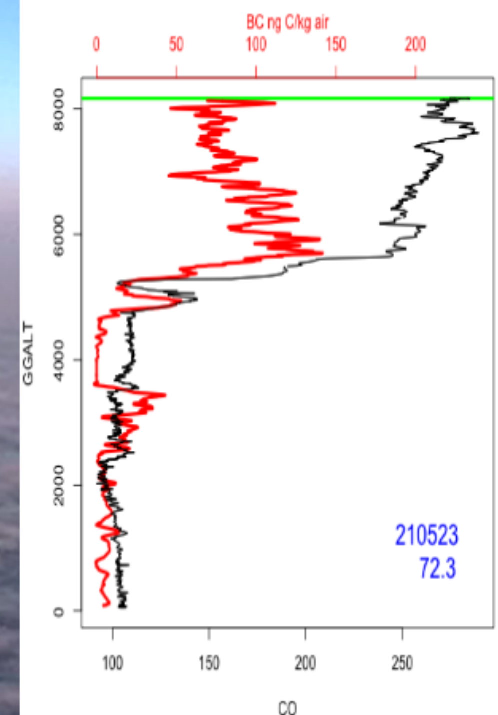
HIPPO Arctic Pollution

Pollution in the upper troposphere of the Arctic

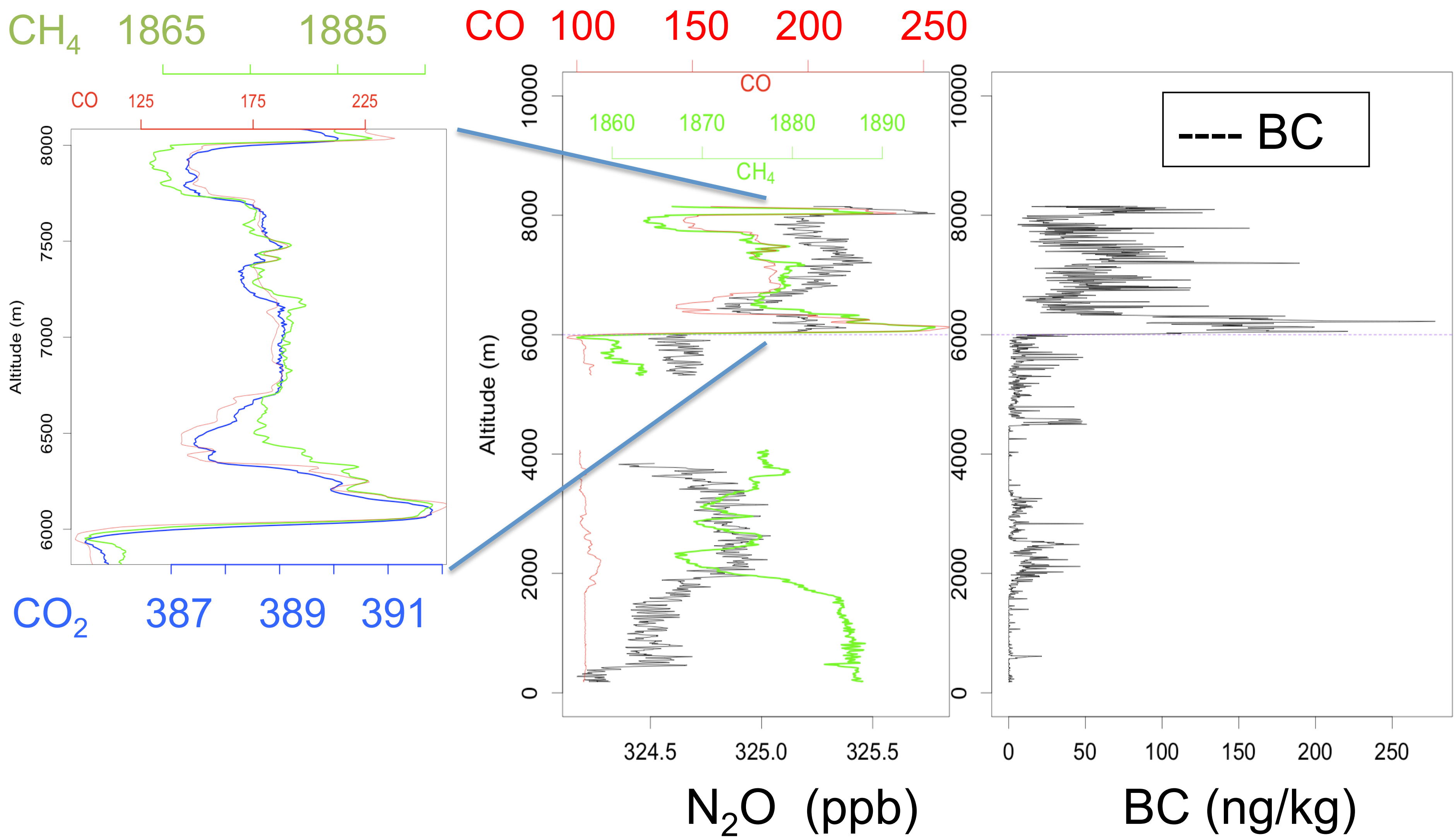
…a fall/winter transition phenomenon


091102-210522

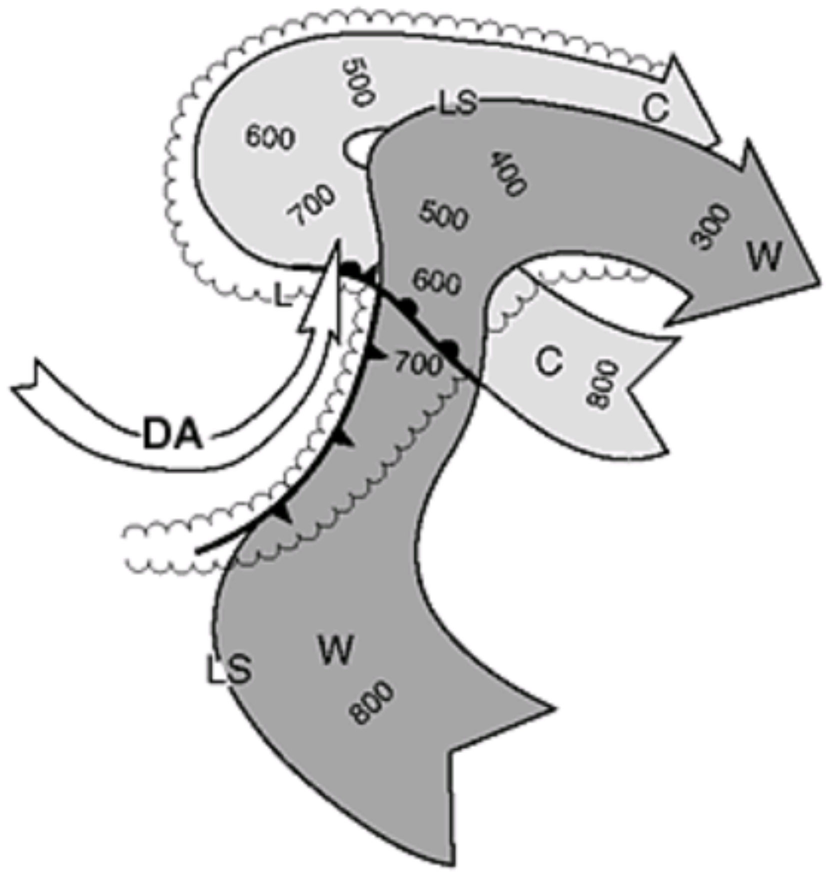

80
75
70
65
60
55
-170
-160
-150
-140


BC ng C/kg air
0
50
100
150
200
8000
6000
4000
2000
0
GGALT
210523
72.3
100
150
200
250
CO

Dense pollution in the Arctic…at very high altitude, Nov. 2009



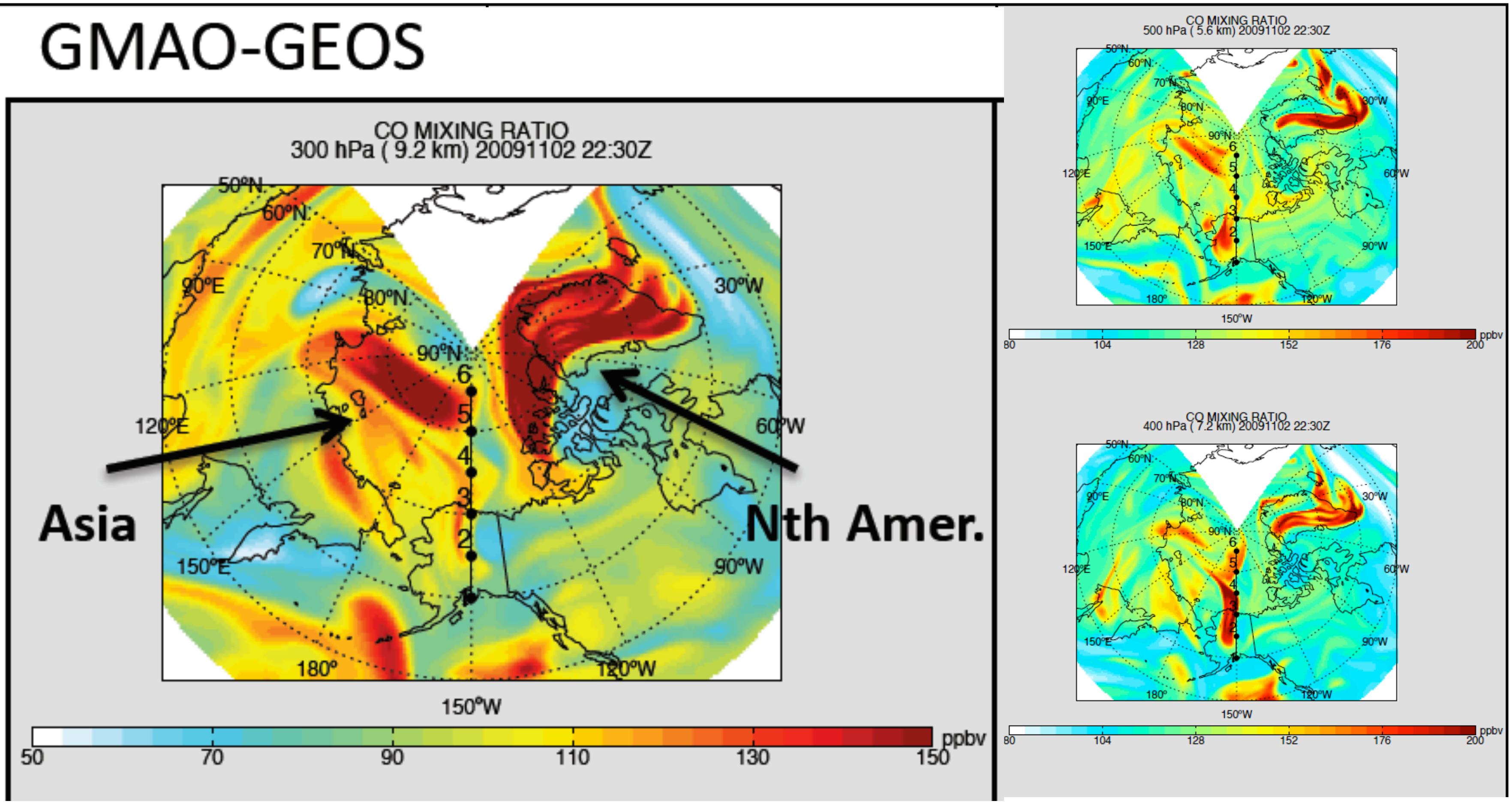
The Warm and Cold Conveyor Belts



[Bader et al 1995, adapted from Carlson, 1980]

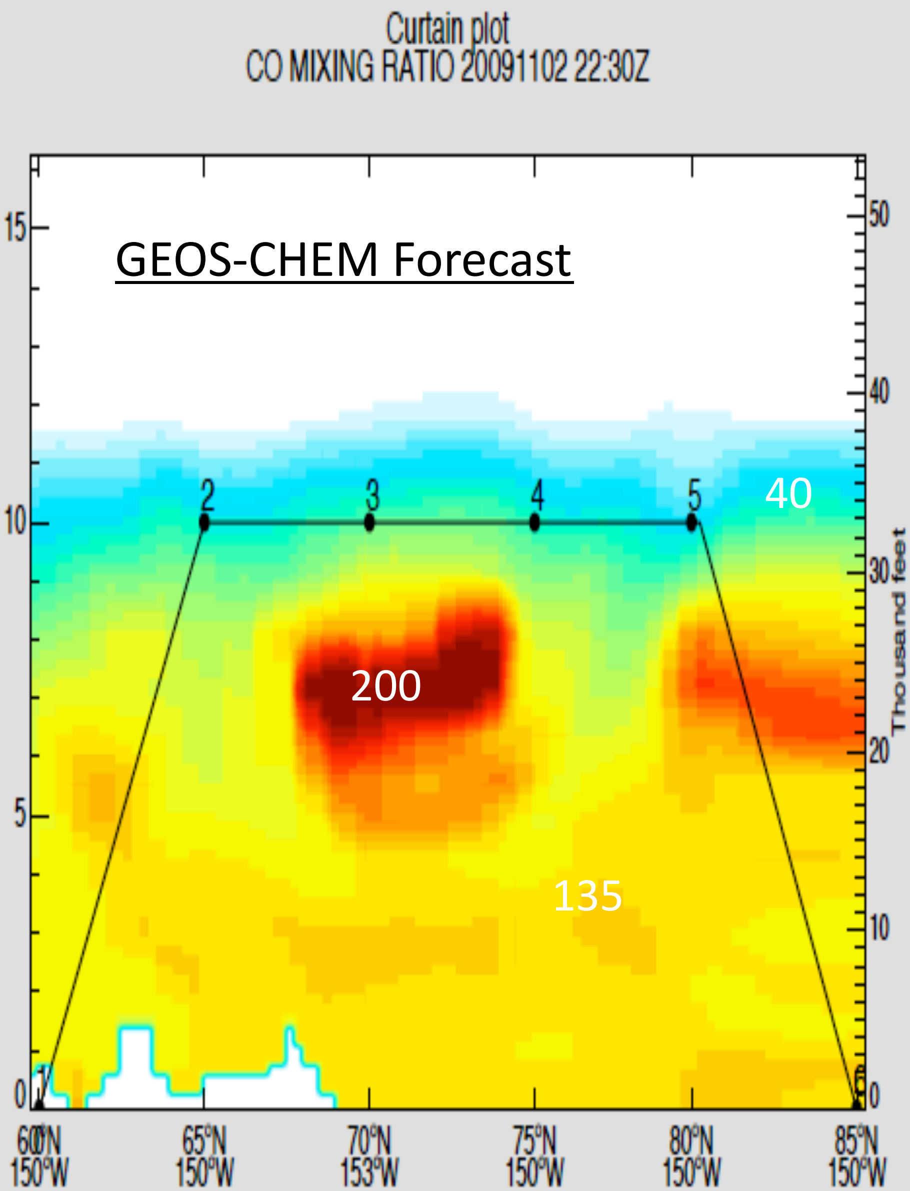
GMAO-GEOS

Forecast: 01-11-2009-00z

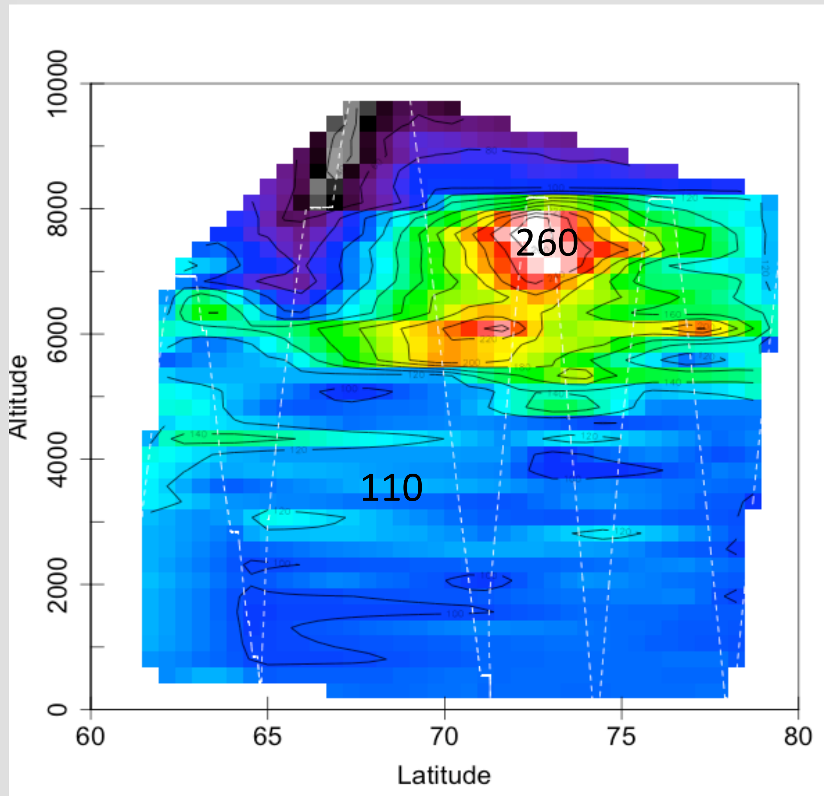


HIPPO-2 Anchorage to 80N /RT
02 November 2009

Altitude



CO Observed

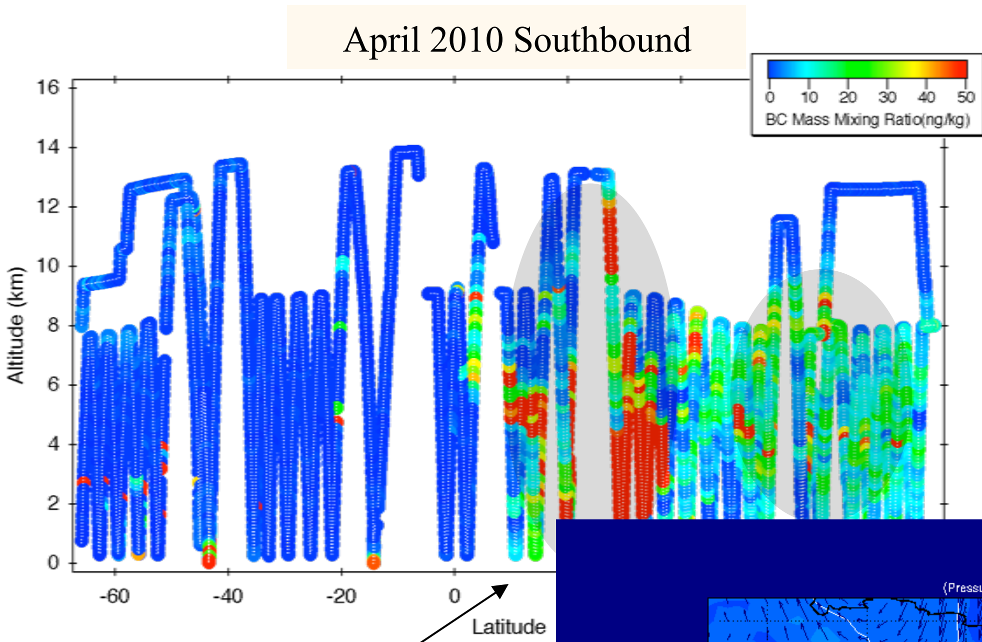


Latitude

80 N 2009 11 02 *Photo E. Kort*

HIPPO-3
April 2010

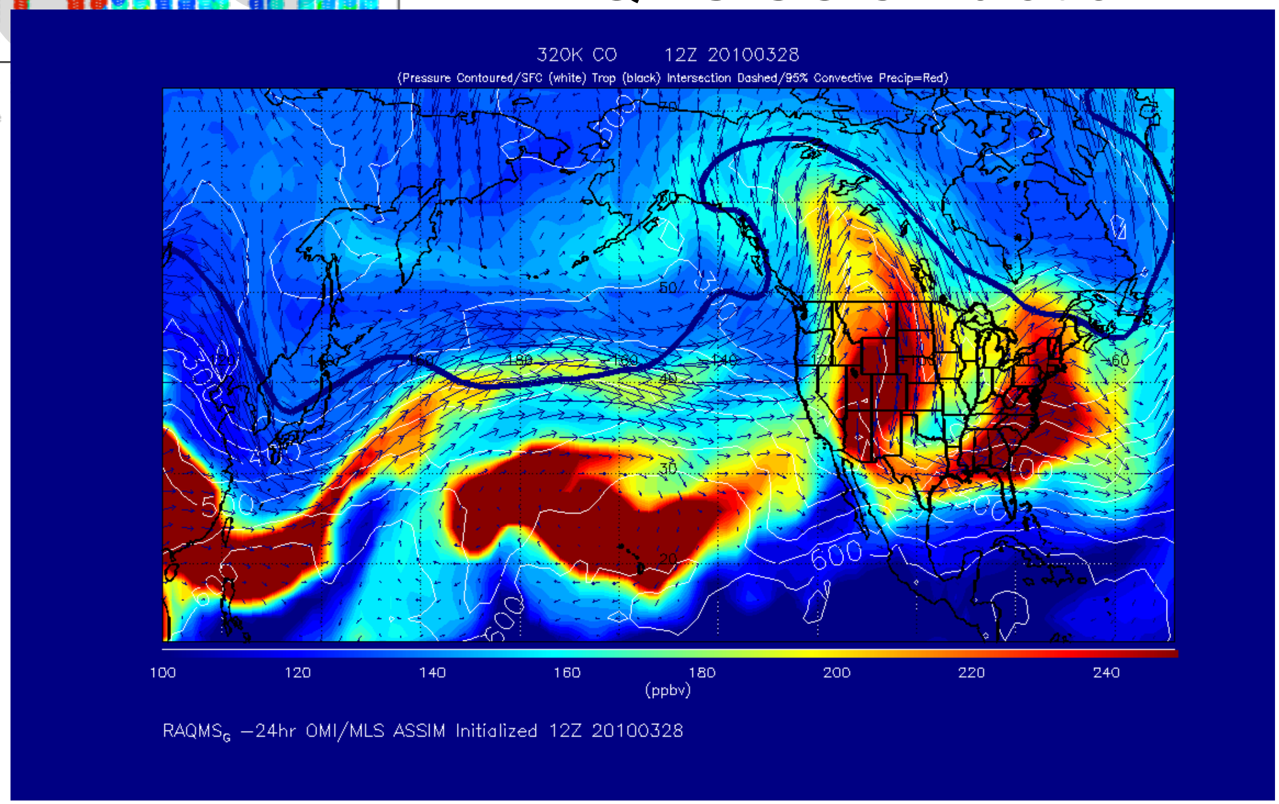
- Asian pollution well stratified in Arctic
- Biomass burning plumes from SE Asia contributed to large BC loadings between ITCZ and ~40°N



Biomass-burning from SE Asia

- Very low BC loadings in southern hemisphere (SH)
- Large BC loadings in northern hemisphere (NH) with loadings comparable to those in urban areas
- Strong interhemispheric gradient at the ITCZ

RAQMS CO simulation



Movie courtesy Brad Pierce, NOAA

HIPPO summary
Bringing the atmosphere into focus

- HIPPO fine-grained data extends to global scale, currently with > 500 vertical profiles in Jan and Nov 2009 and Mar 2010.

- Hundreds of species measured, many on-board, at rates up to 1 Hz.

- First public release in Feb 2011, archived at CDIAC; quicklook data may be requested.

HIPPO summary:
Bringing the atmosphere into focus

The data show:

- Dense pollution at very high altitudes in the Arctic (Nov. 2009).
- Sources of CH_4 in the Arctic from fossil fuel extraction and non-industrial sources (land surface, ocean).
- Large N_2O sources in tropical/subtropical lands; variable inputs on ~week time scales—quantified!*.
- Sinks for CO_2, sources of O_2 at high S. latitudes.
- Unexpected distributions of Black Carbon: radiative forcing?.

The data provide strong tests of satellite retrievals and lead to new *a priori* vertical profiles.

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