The use of airborne and ground based atmospheric observations in carbon cycle research

Christoph Gerbig
Max-Planck-Institute for Biogeochemistry

MPI-BGC
Jena

Presented at the
ECMWF Seminar on
Global Earth-System Monitoring
5-9 September 2005

Overview

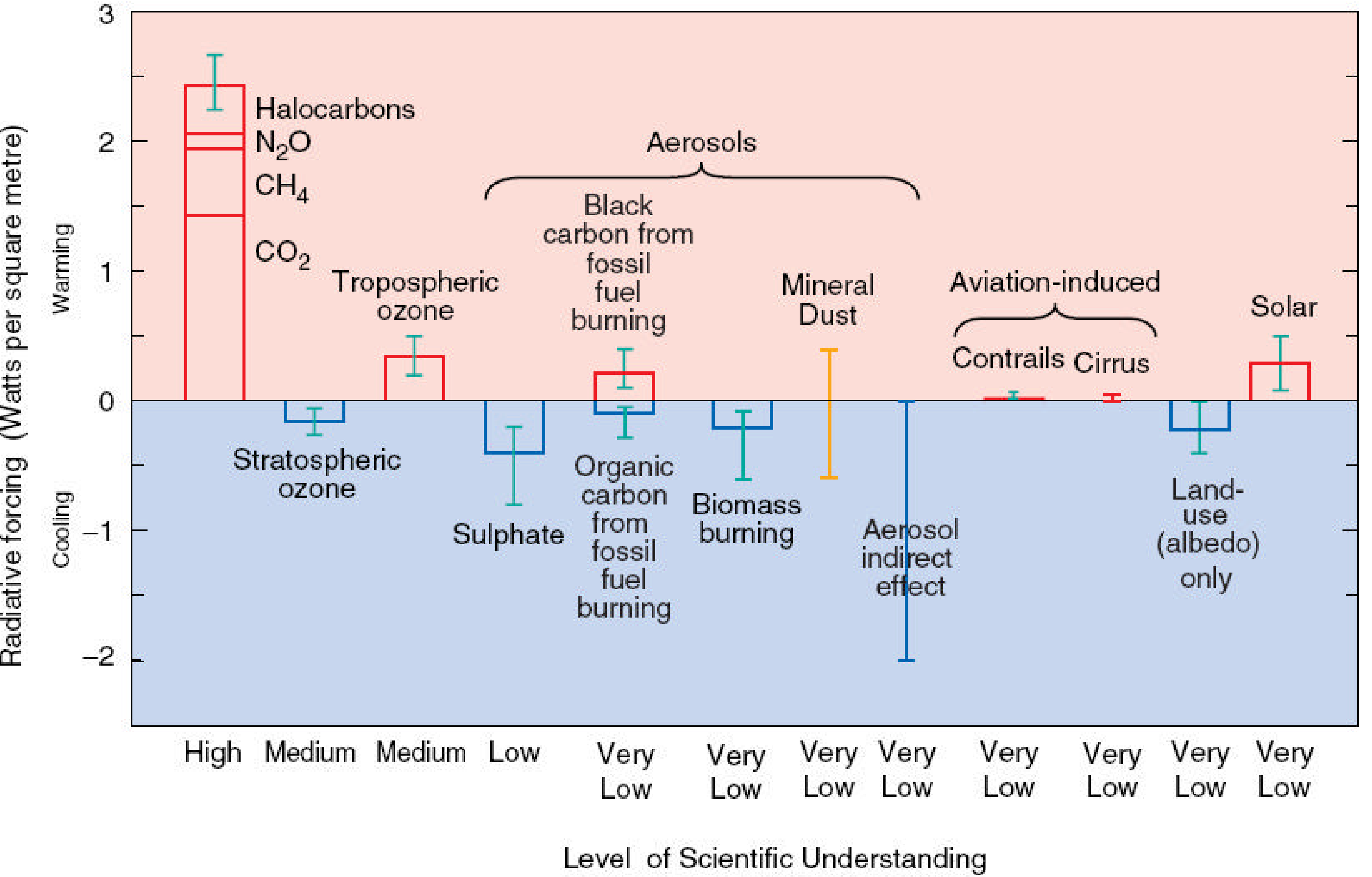
- Introduction: Why Carbon Cycle Research

- Global Observations of atmospheric CO_2:
  from remote islands to places nearby
  from decades to seconds
  Challenge: continental boundary layer, closeness to strong sources & sinks

- Airborne measurements of tracer distributions
  - Surface fluxes on regional scales (biosphere-atmosphere exchange, ...)
  - Transport processes (tropospheric mixing, convection, ...)

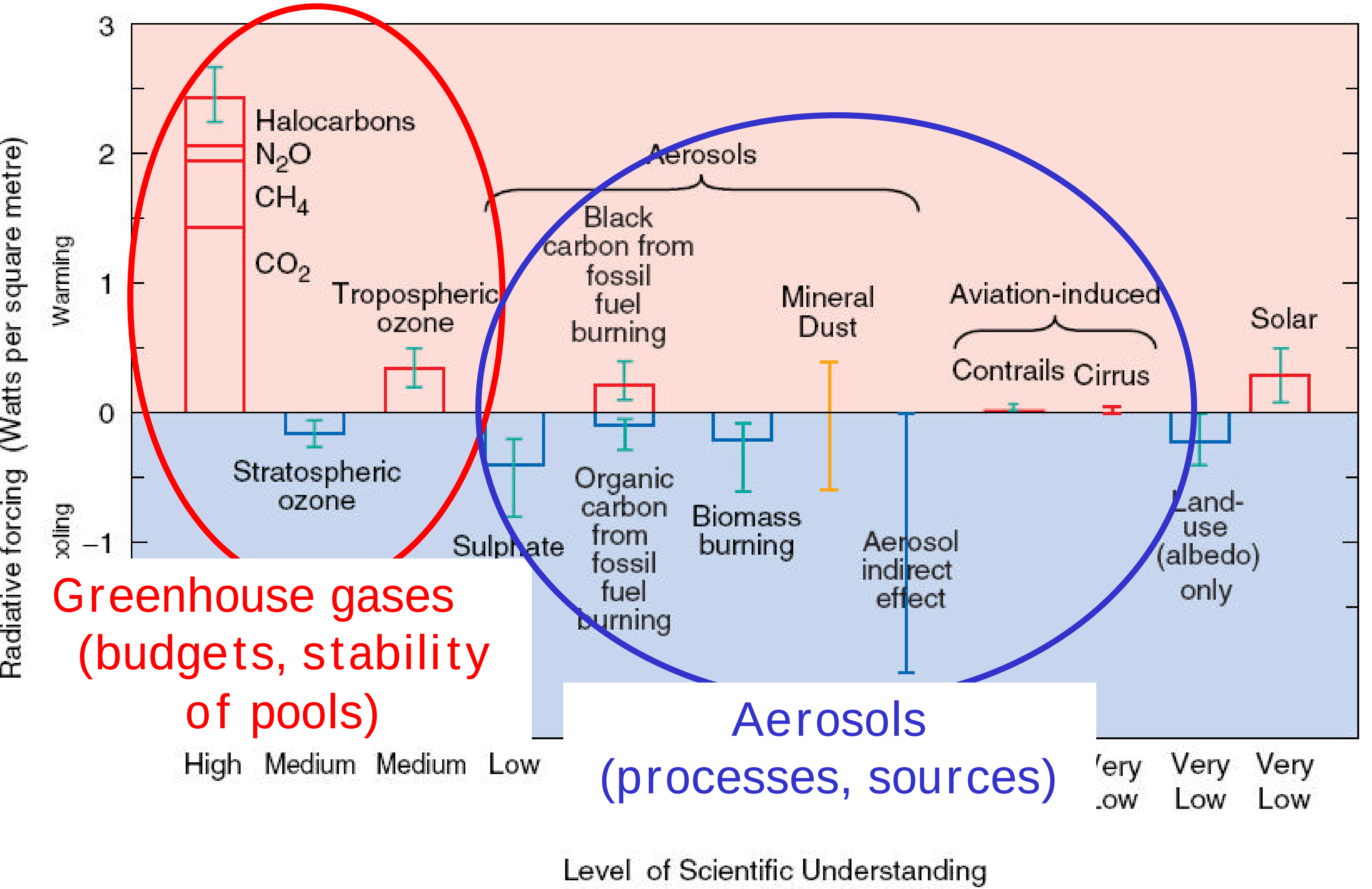
- Hypothesis: Airborne intensives provide paradigm datasets to
  - help design & test (falsify/validate) modeling frameworks
  - help integrate ground based data into data assimilation systems

The global mean radiative forcing of the climate system for the year 2000, relative to 1750



[IPCC Third Assessment Report - Climate Change 2001

The global mean radiative forcing of the climate system for the year 2000, relative to 1750



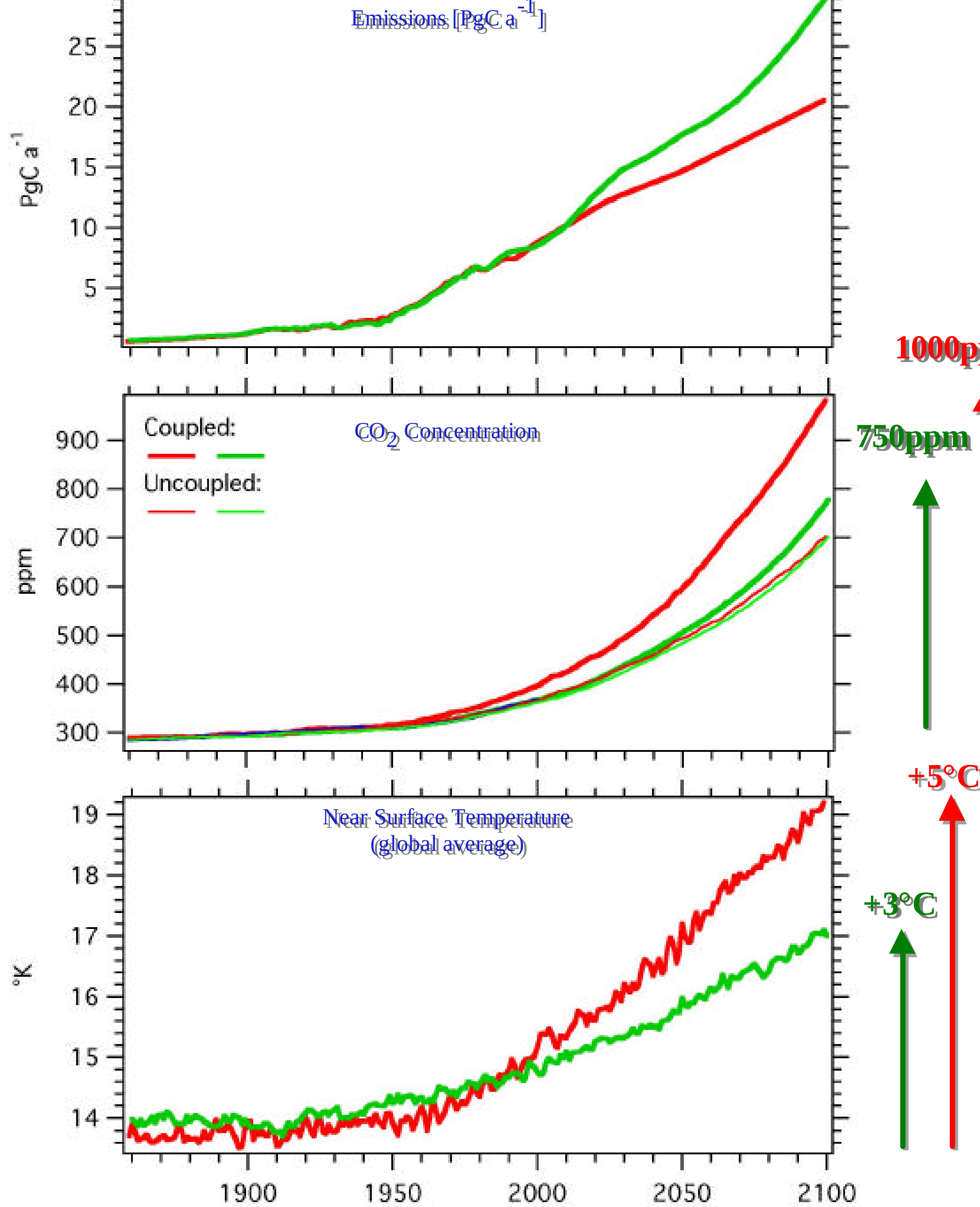
[IPCC Third Assessment Report - Climate Change 2001

Fundamental Carbon Cycle Questions

- Where and through which process is the excess anthropogenic carbon being taken up by land and ocean?
- What and how large are the key feedback links between the carbon cycle and the physical climate system?
- What is the carbon budget of a particular region (continent, country)?

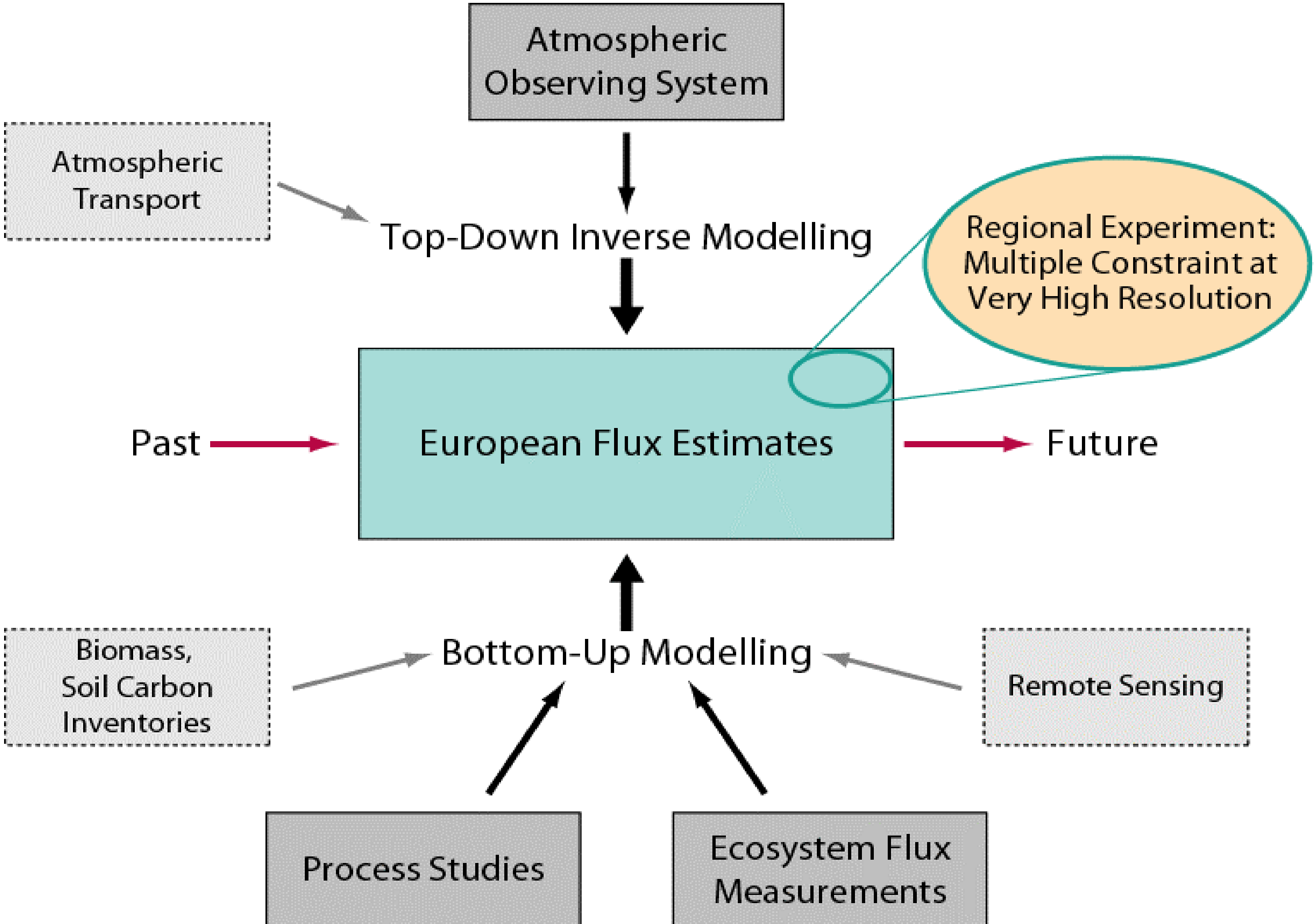
First Scenarios Calculated with Coupled Carbon Cycle - Climate Models

Hadley
IPSL

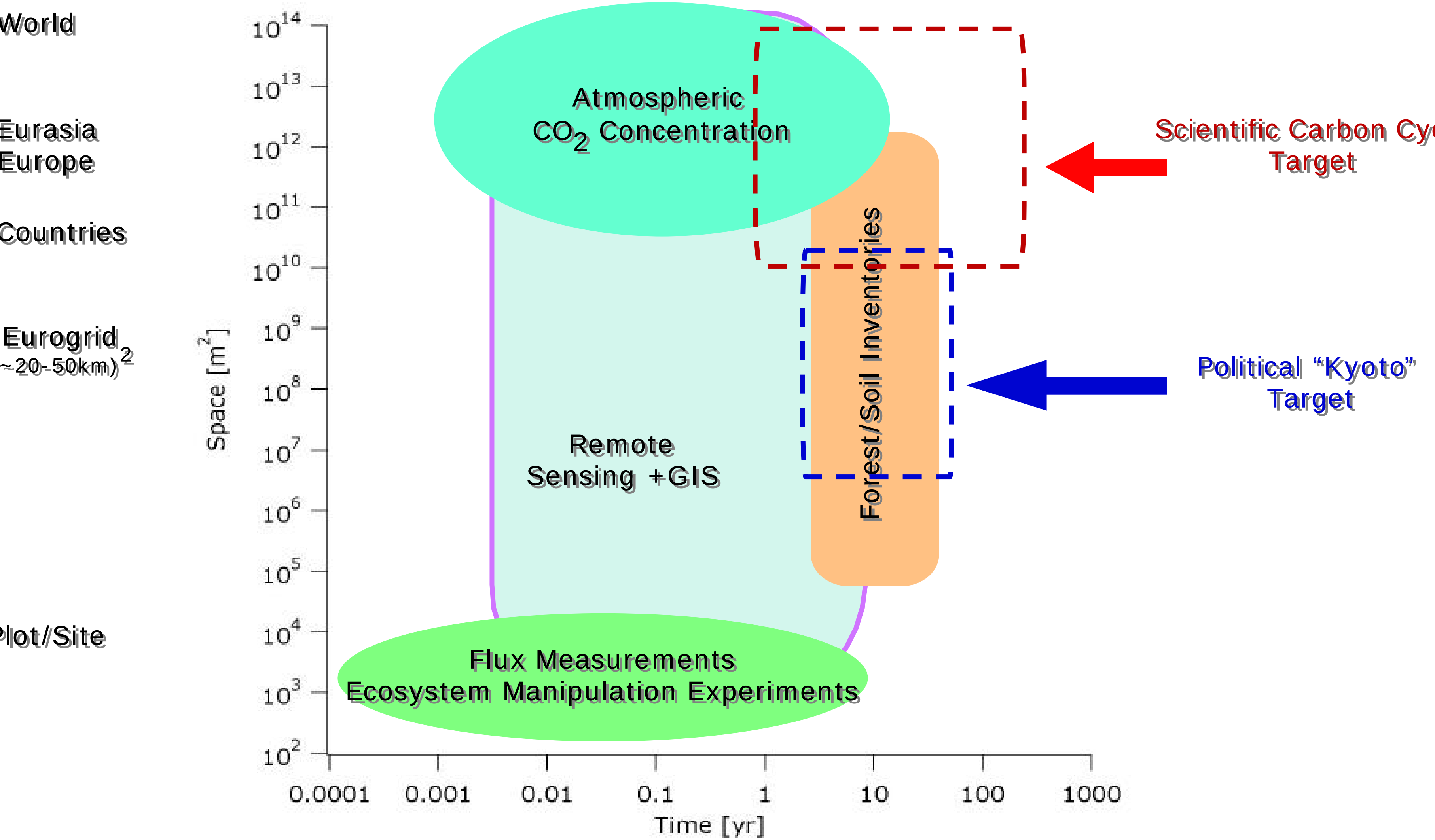


Cox et al. 2001, Dufrene et al., 2001
IPCC 2001

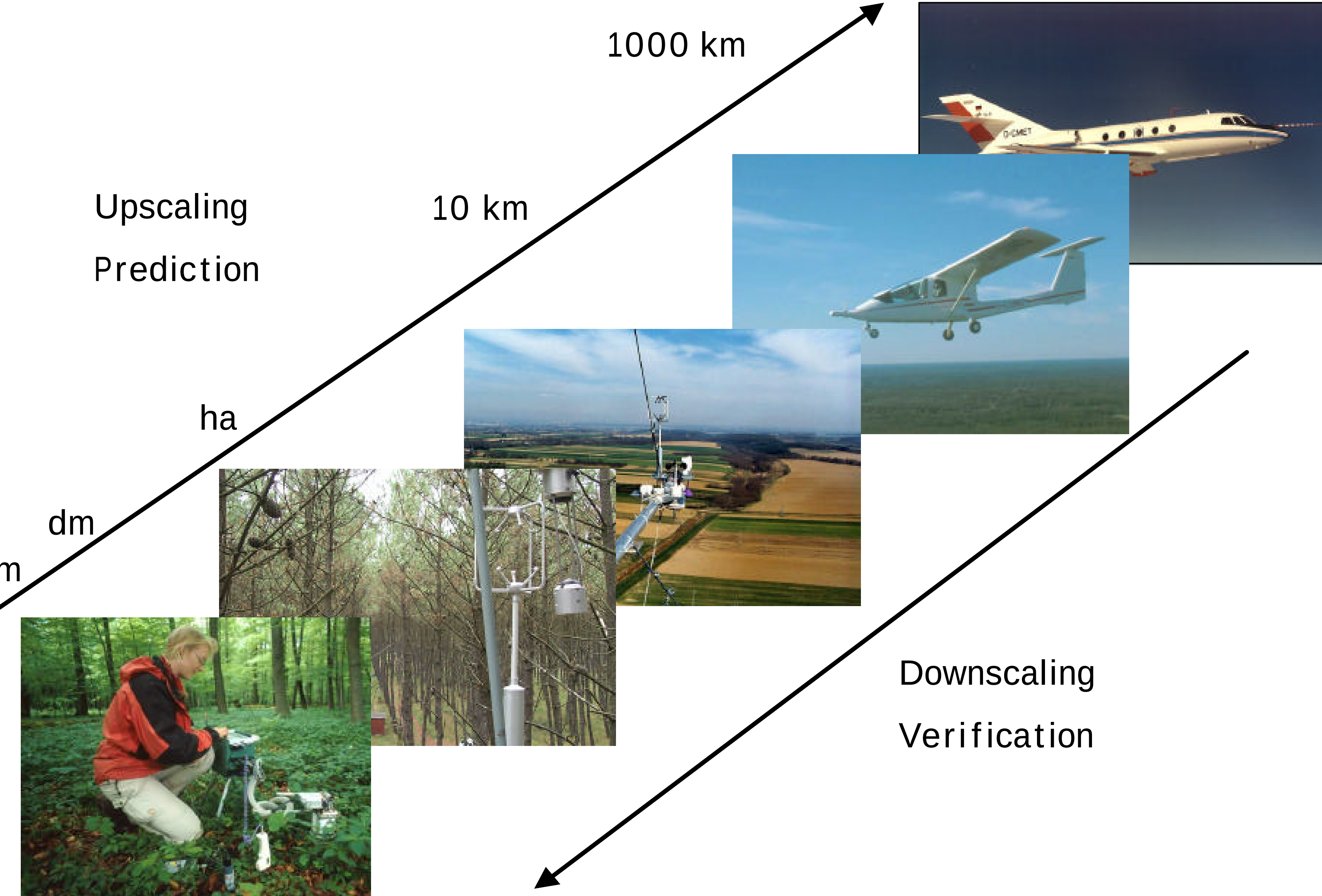
Estimating Reginal Carbon Balances: Top-Down vs. Bottom-Up Approach



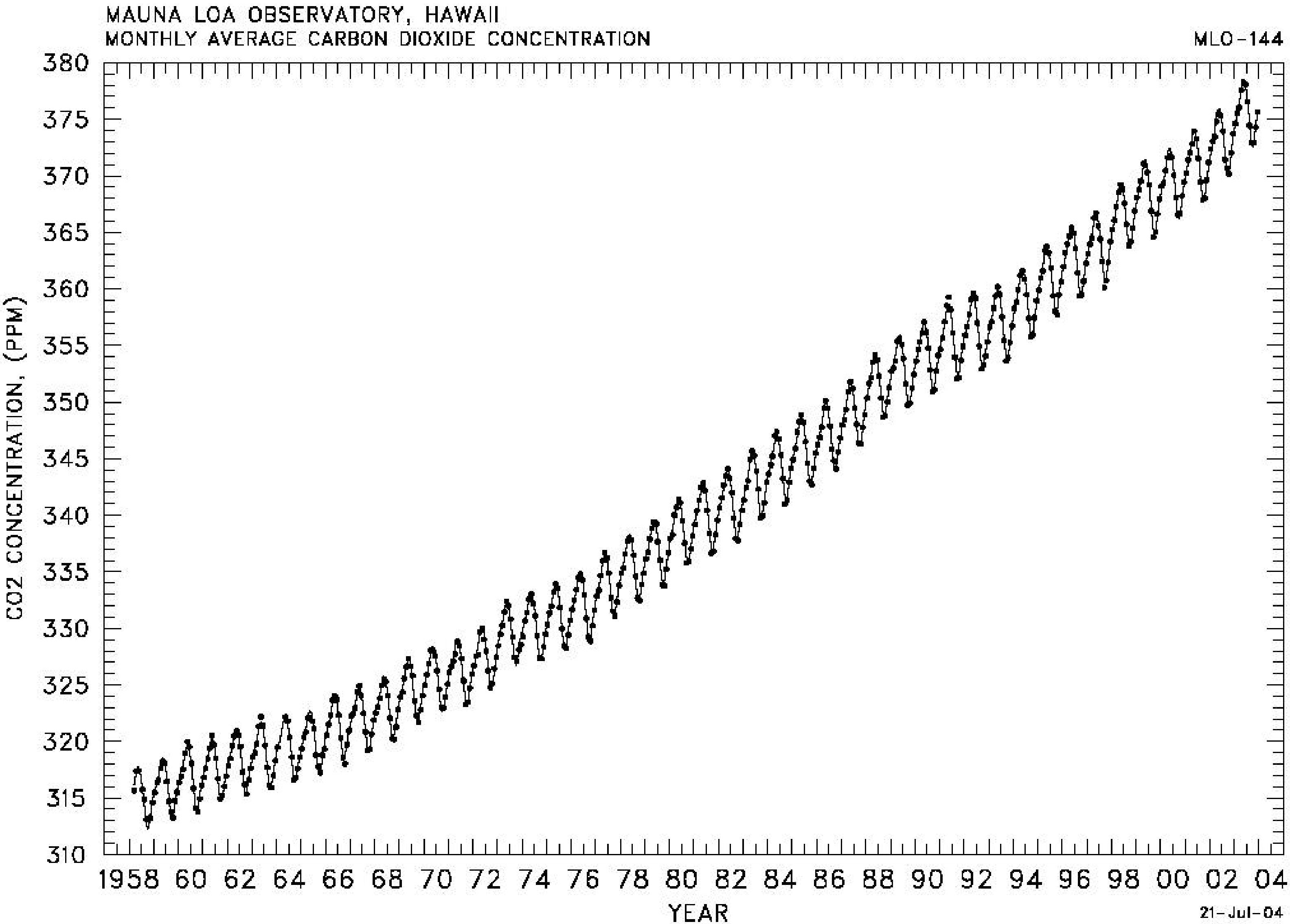
Carbon Cycle Observing Systems



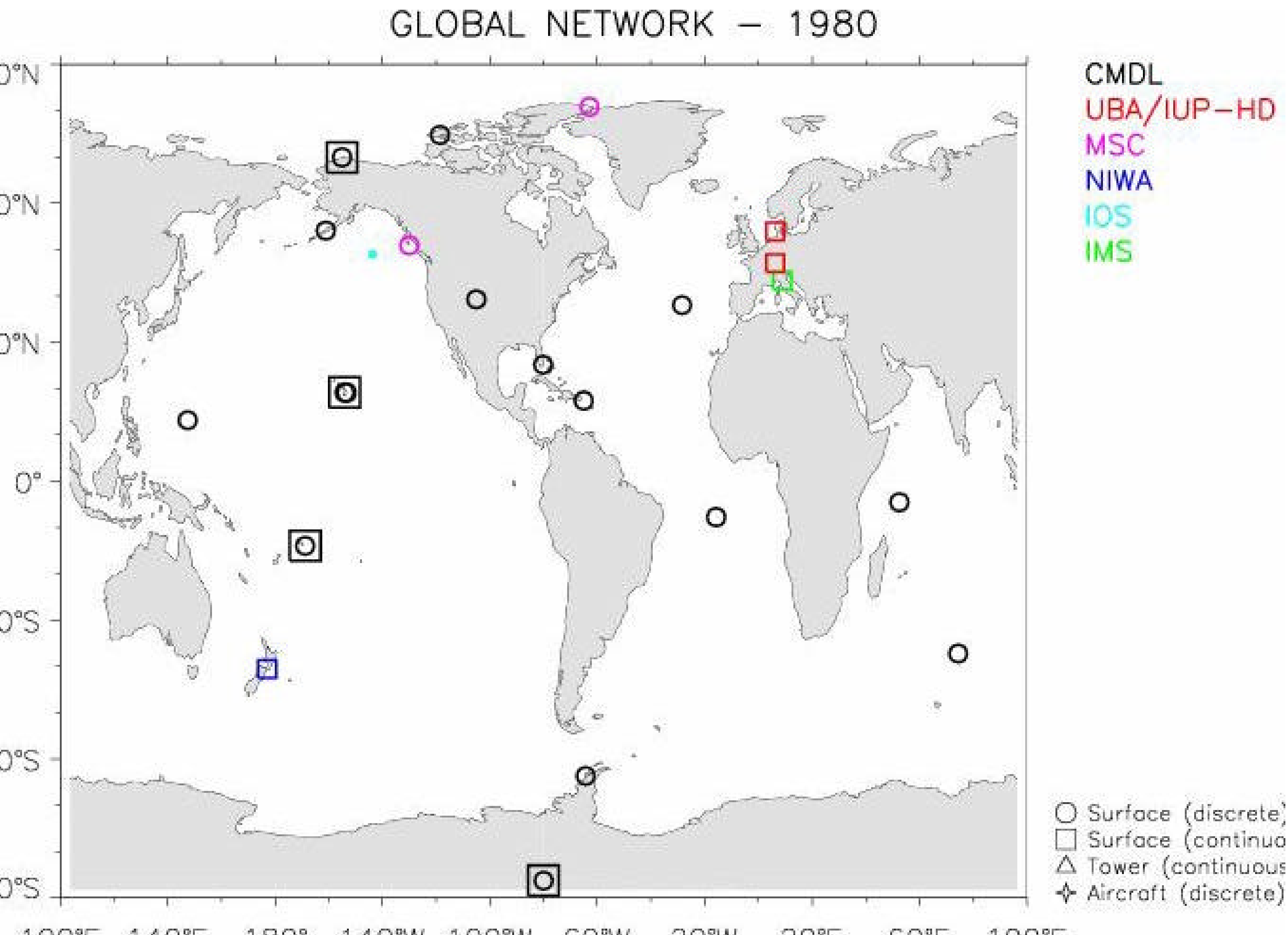
Carboeurope integrated approach to deliver multiple constraints on the C balance



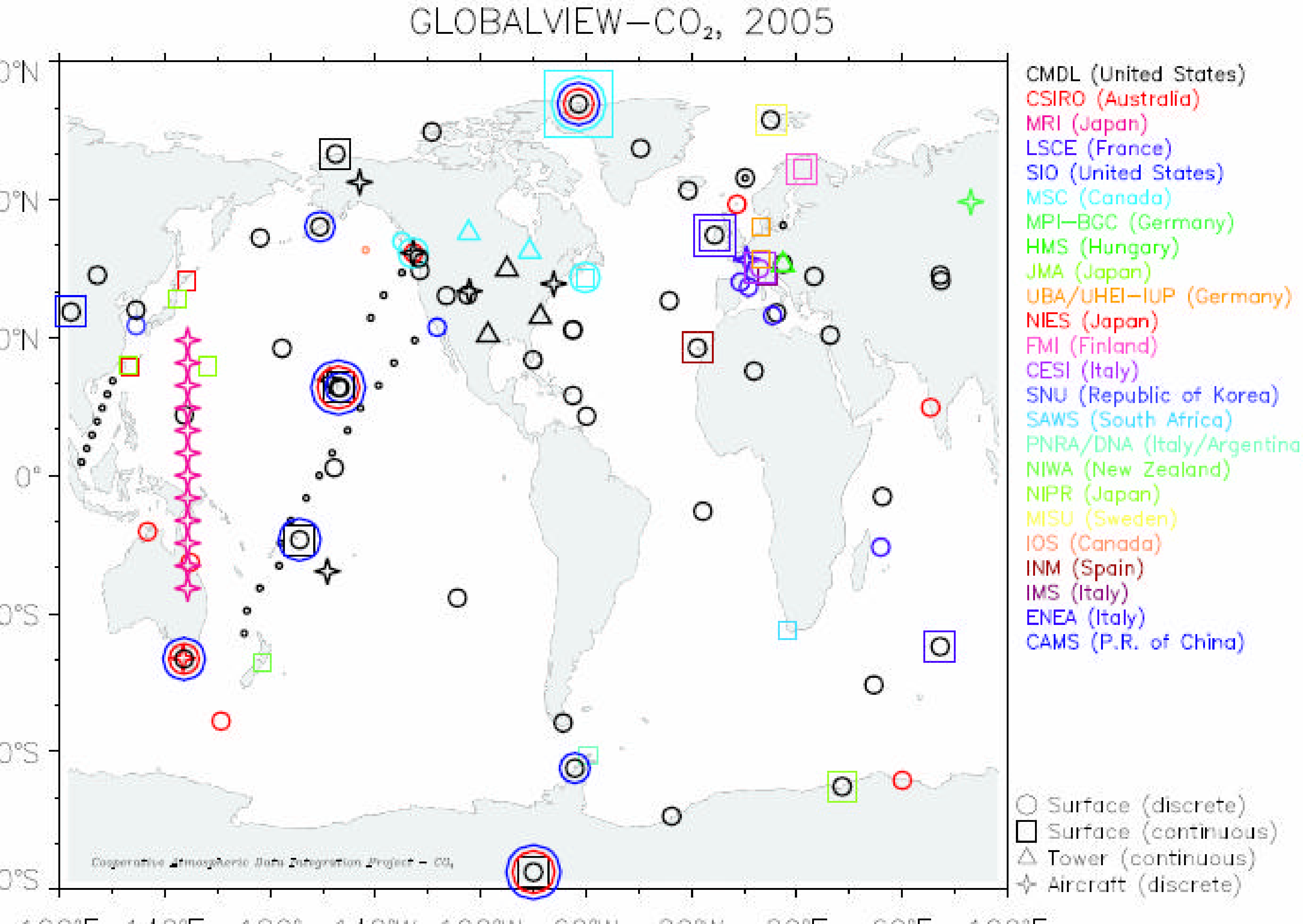
Global network for atmospheric CO_2



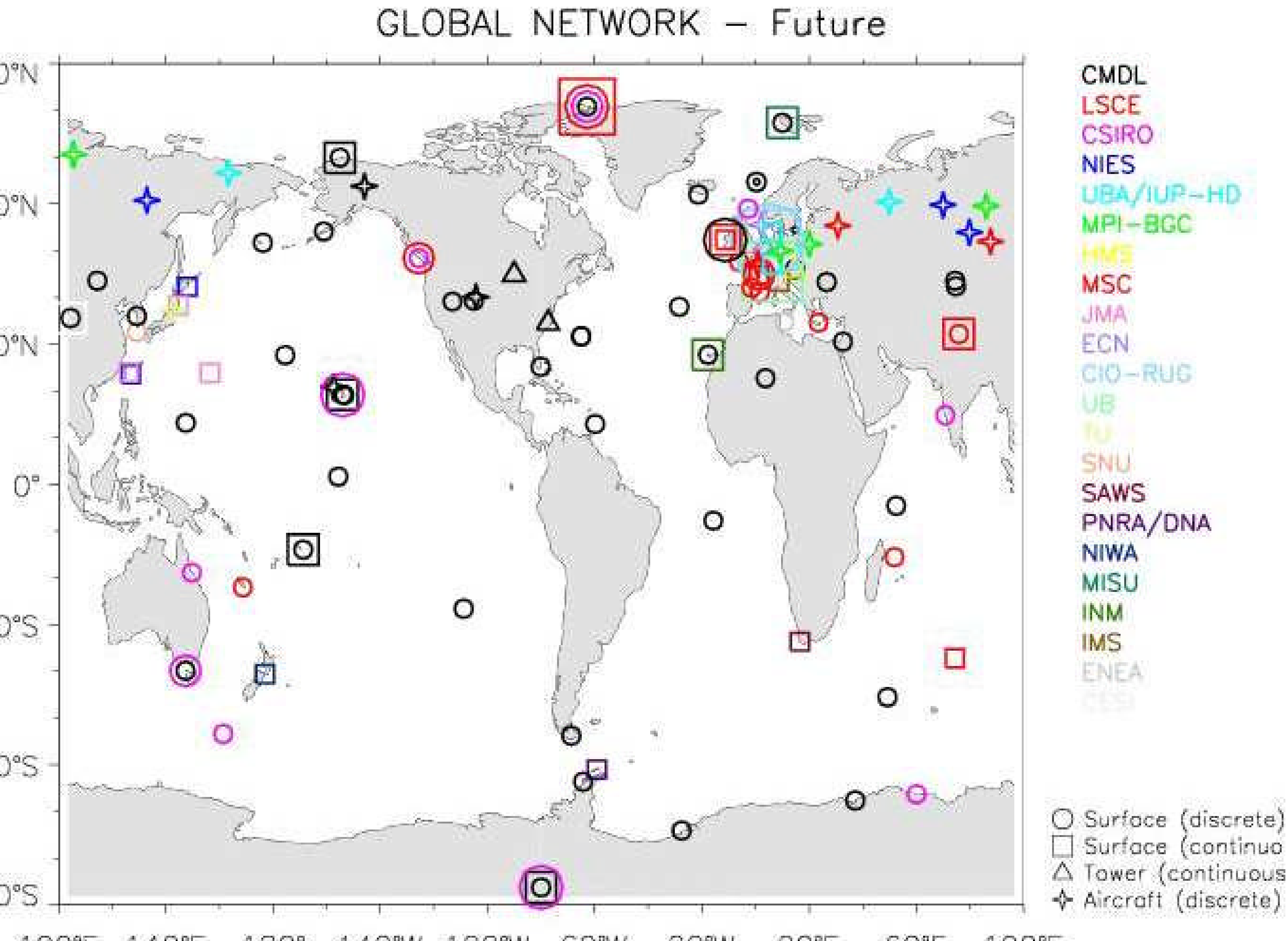
Global network for atmospheric CO_2



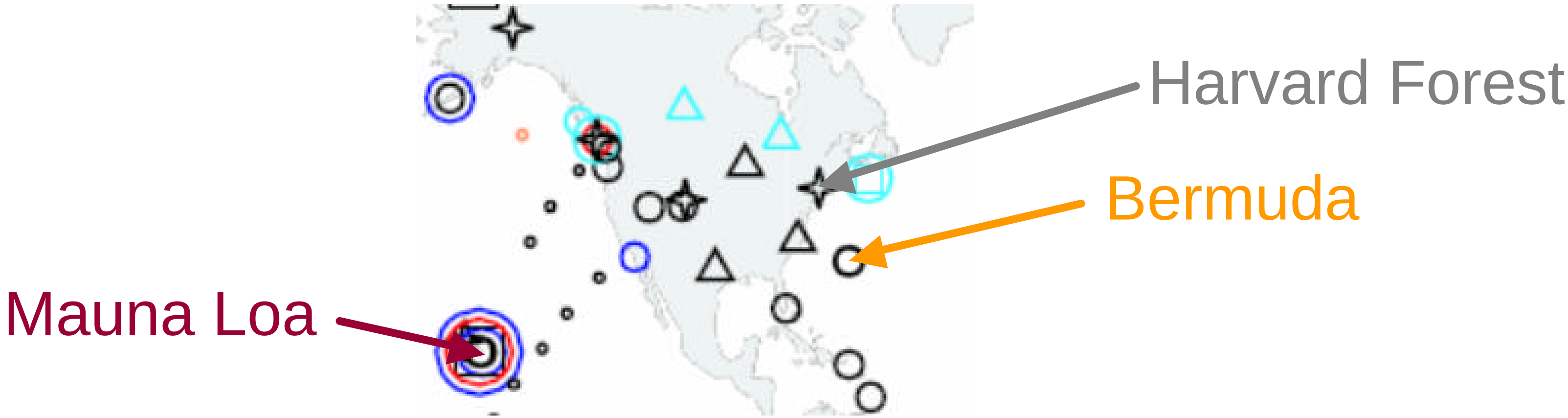
Global network for atmospheric CO_2

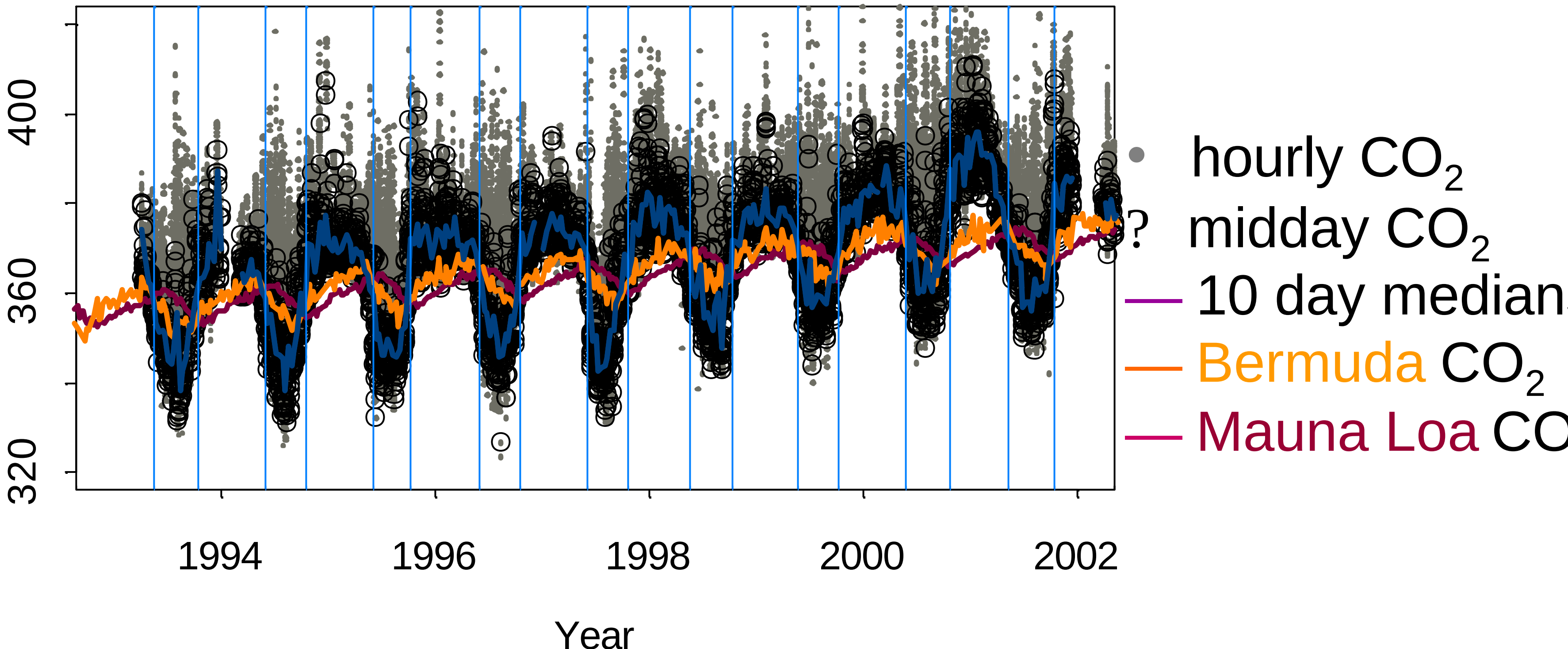


Global network for atmospheric CO_2

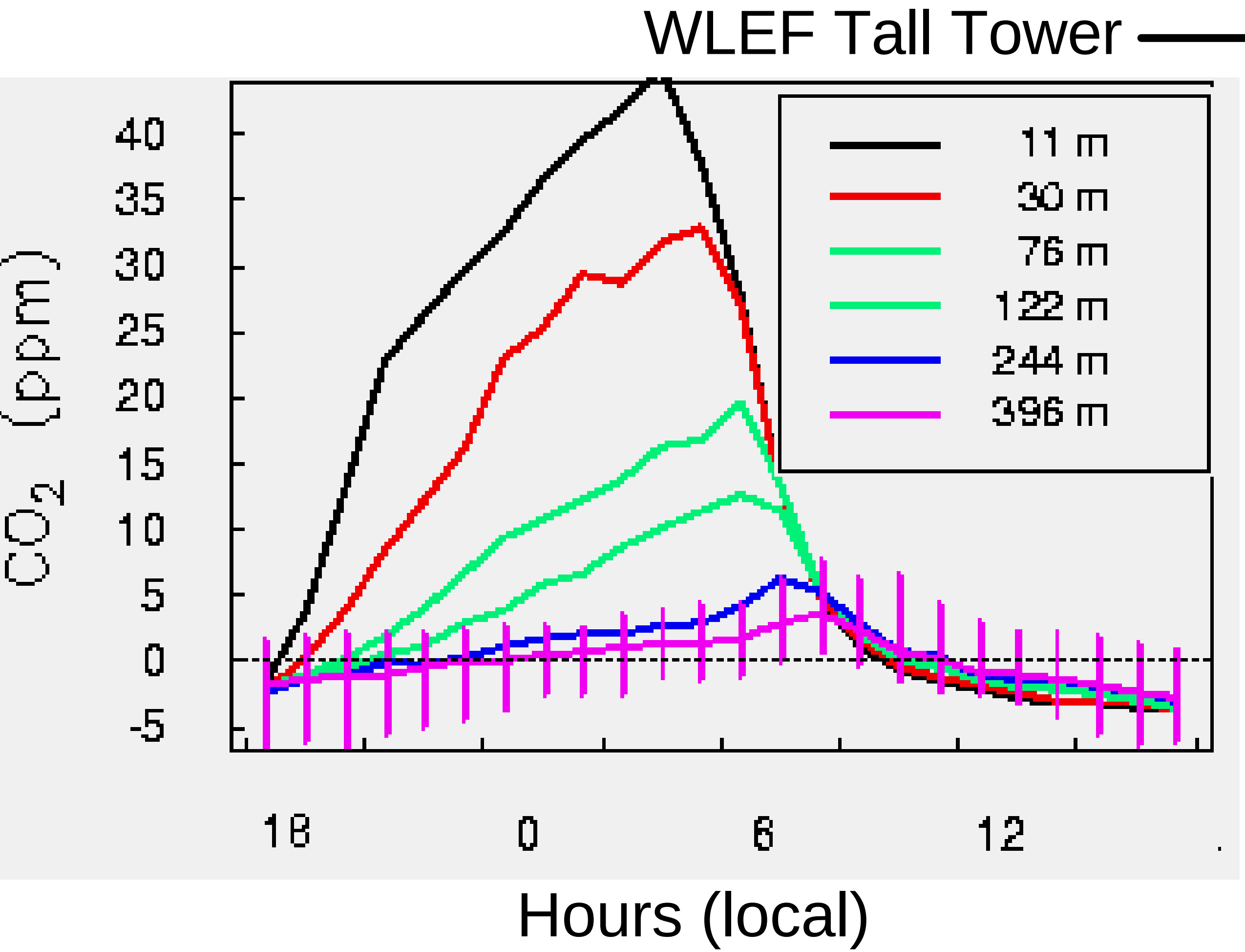


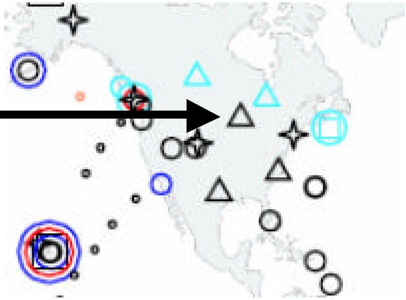
Continental boundary layer:
Harvard Forest Environmental Monitoring Site





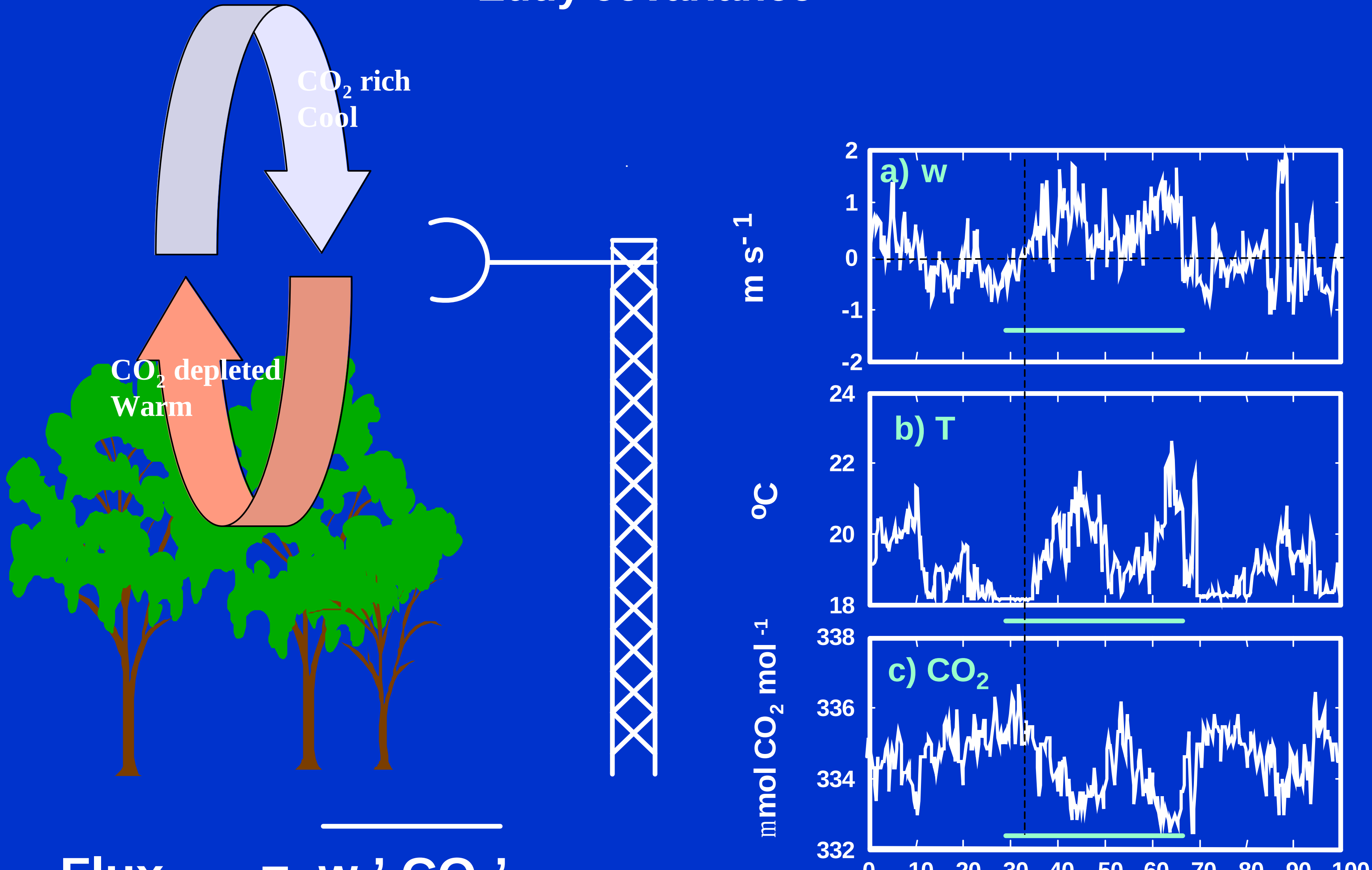
Continental boundary layer:
diurnal cycle for different heights at a tall tower



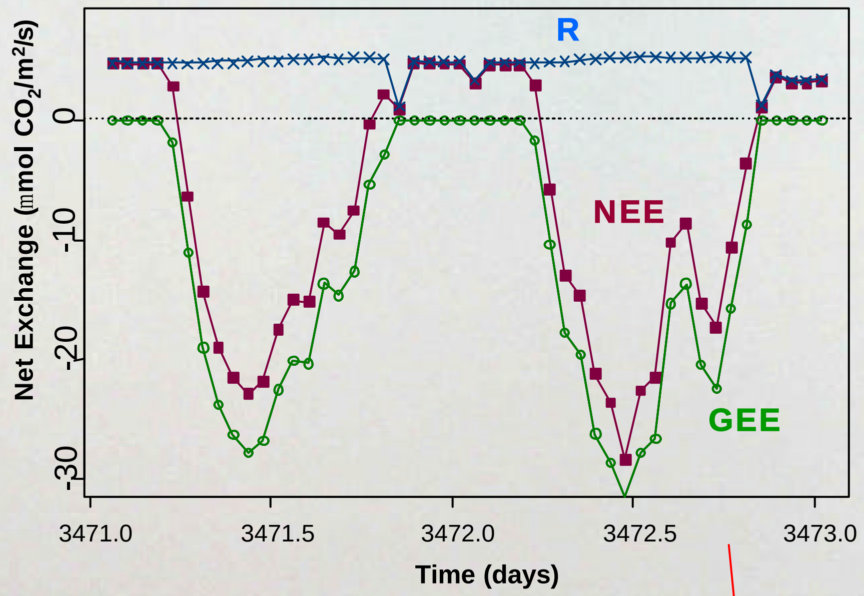


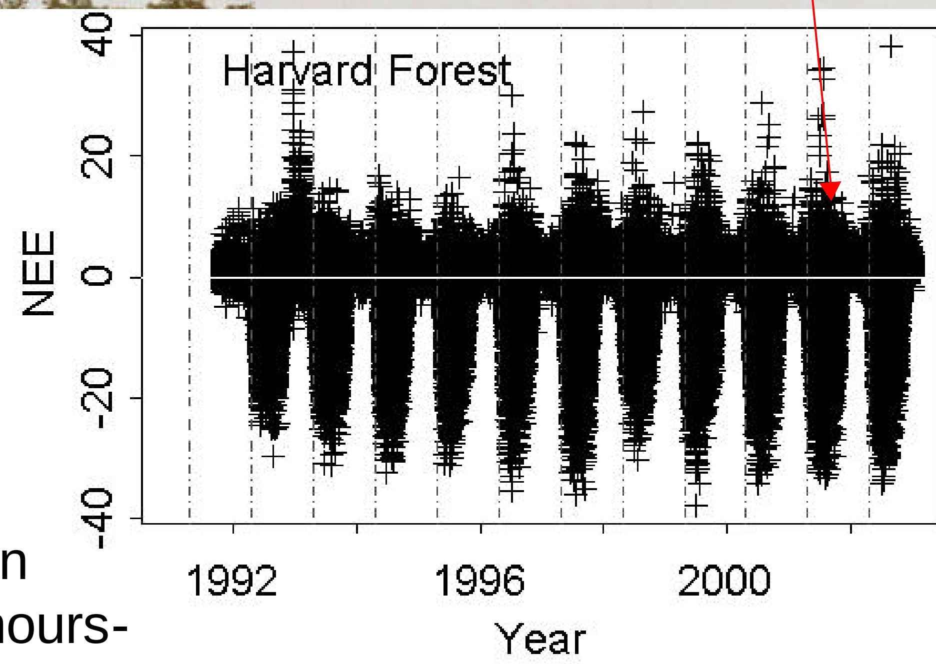
July average diurnal cycle (top level 24h mean substracted)

Eddy covariance

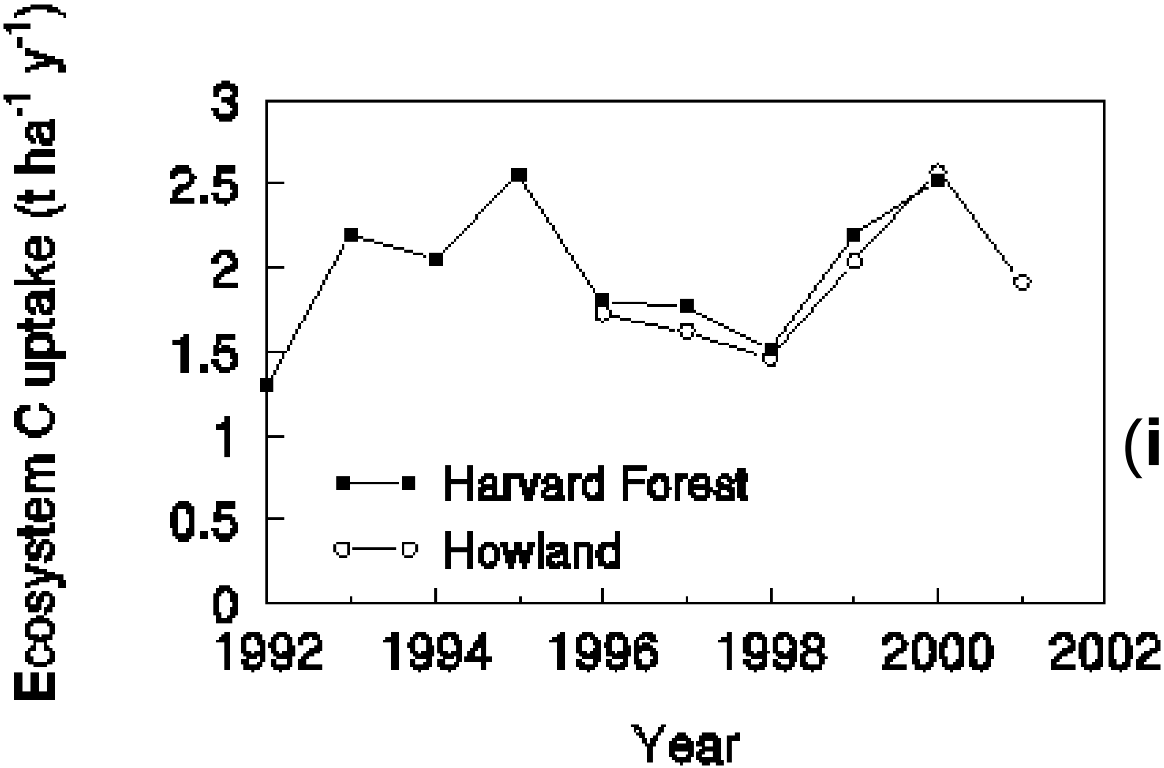


$$\text{Flux}_{CO_2} = \overline{w' \, CO_2'}$$

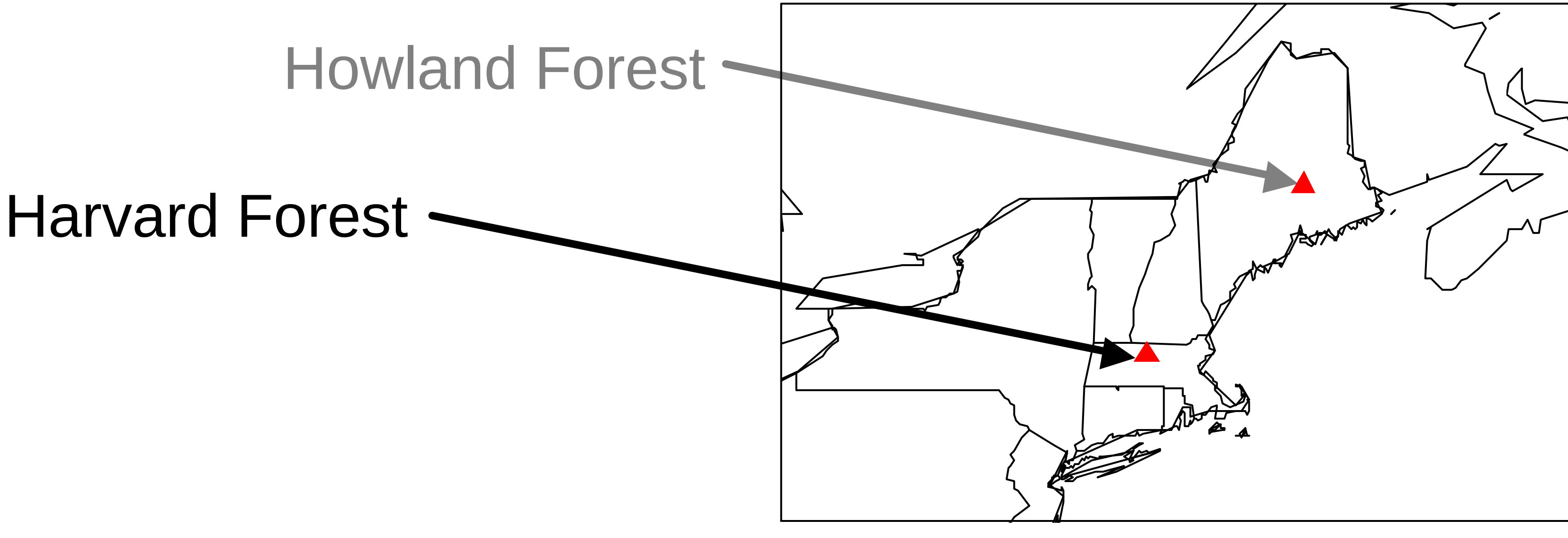


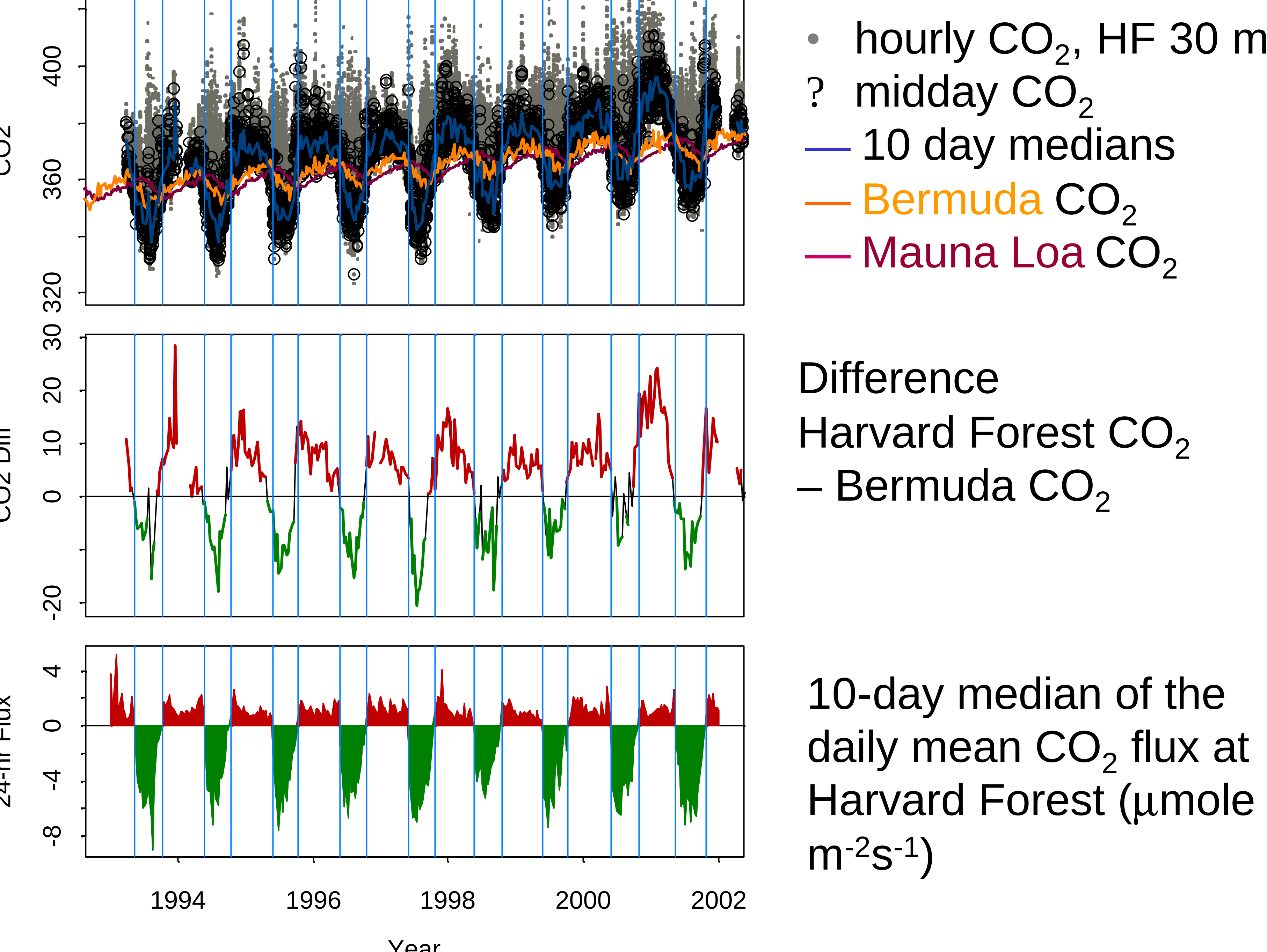


lux towers give detailed information on
tmosphere-biosphere exchange, for hours-
ecade, including annual sums , for ~ 100 ha

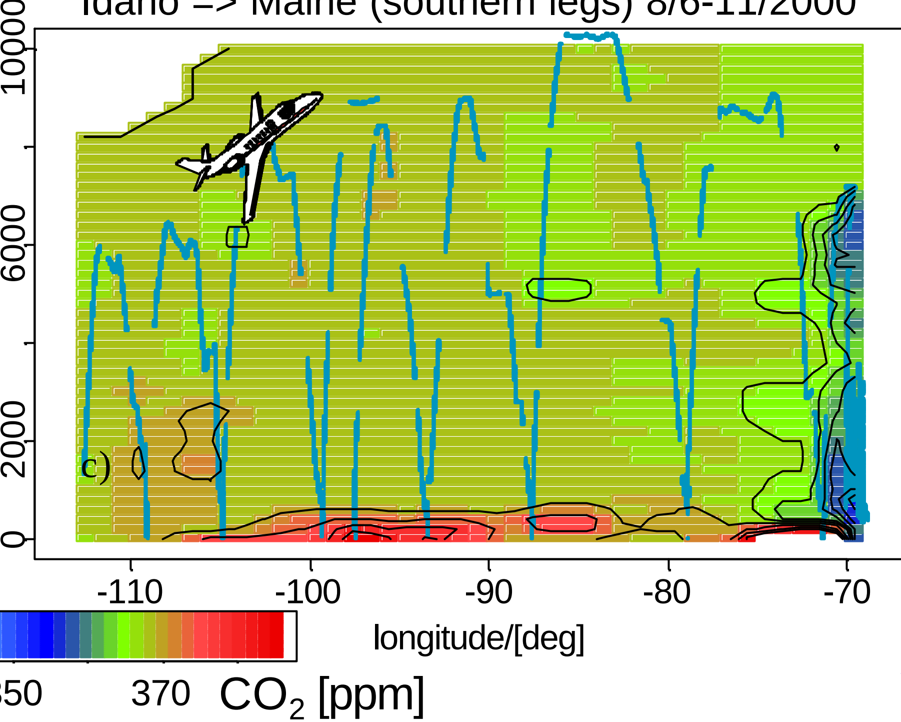


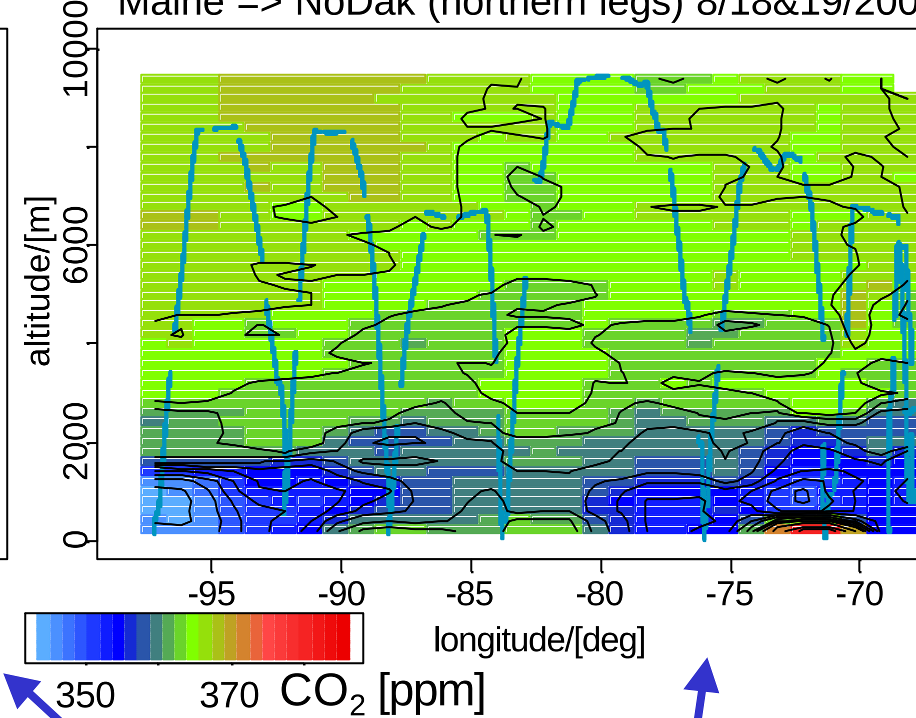
2 AmeriFlux sites
400 km distance
Similar IAVs
(**i**nter**a**nnual **v**ariations)





hourly CO_2, HF 30 m
? midday CO_2
10 day medians
Bermuda CO_2
Mauna Loa CO_2
Difference
Harvard Forest CO_2
– Bermuda CO_2
10-day median of the daily mean CO_2 flux at Harvard Forest (µmole $m^{-2}s^{-1}$)
320
360
400
-20
0
10
20
30
-8
-4
0
4
1994
1996
1998
2000
2002
Year



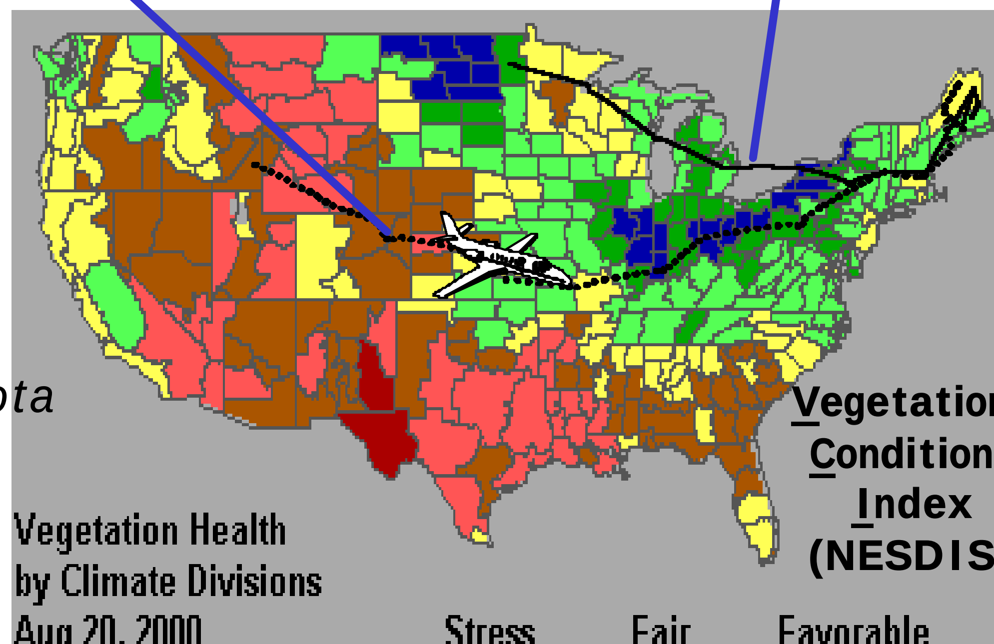


CO_2 Budget and Rectification Airborne Study "COBRA 2000"

Funding: NOAA, NASA, NSF, and DoE

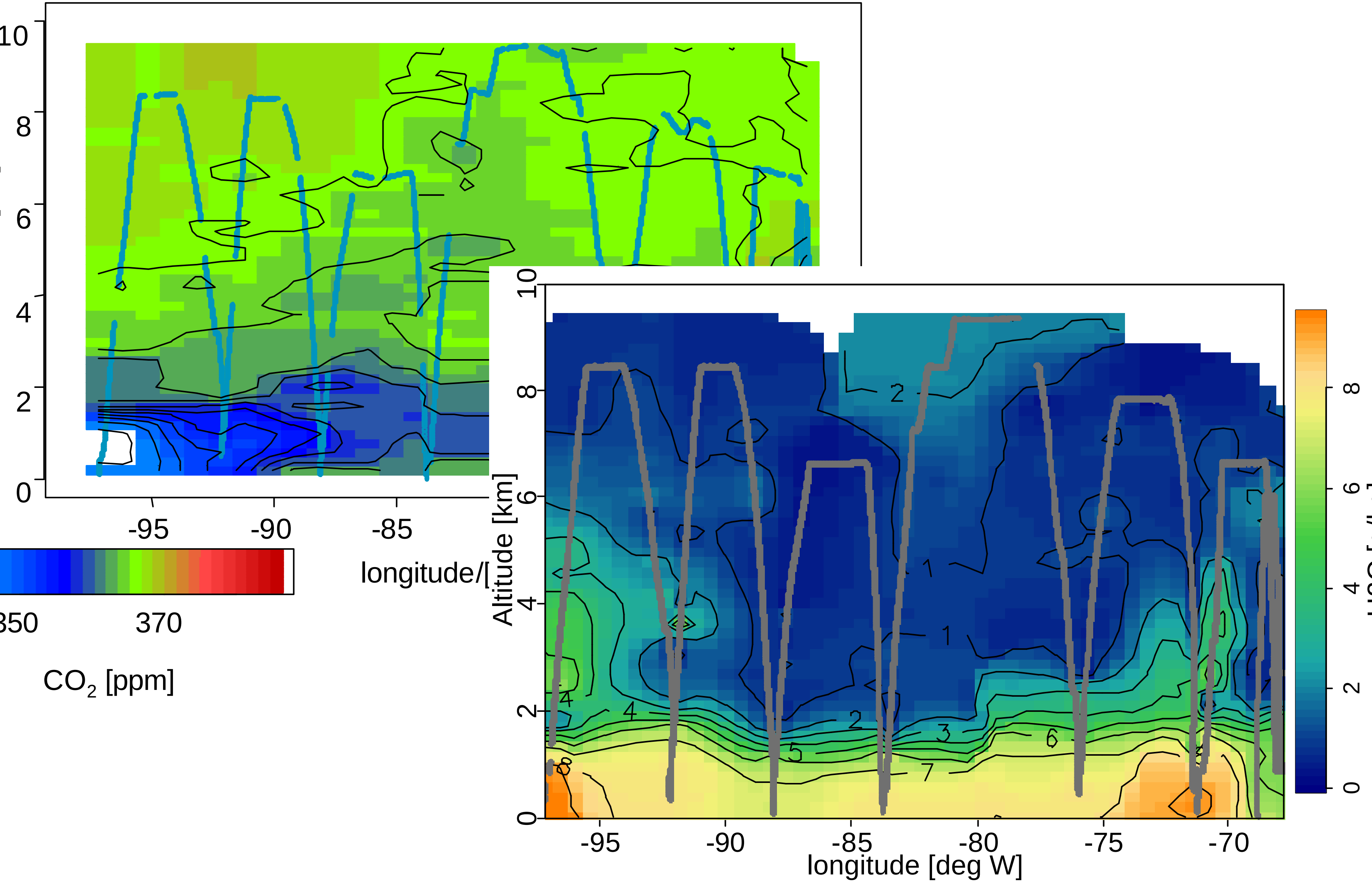
Harvard
U. North Dakota
Scripps
NOAA CMDL
Penn State
CSU

Gerbig et al., 2003a]

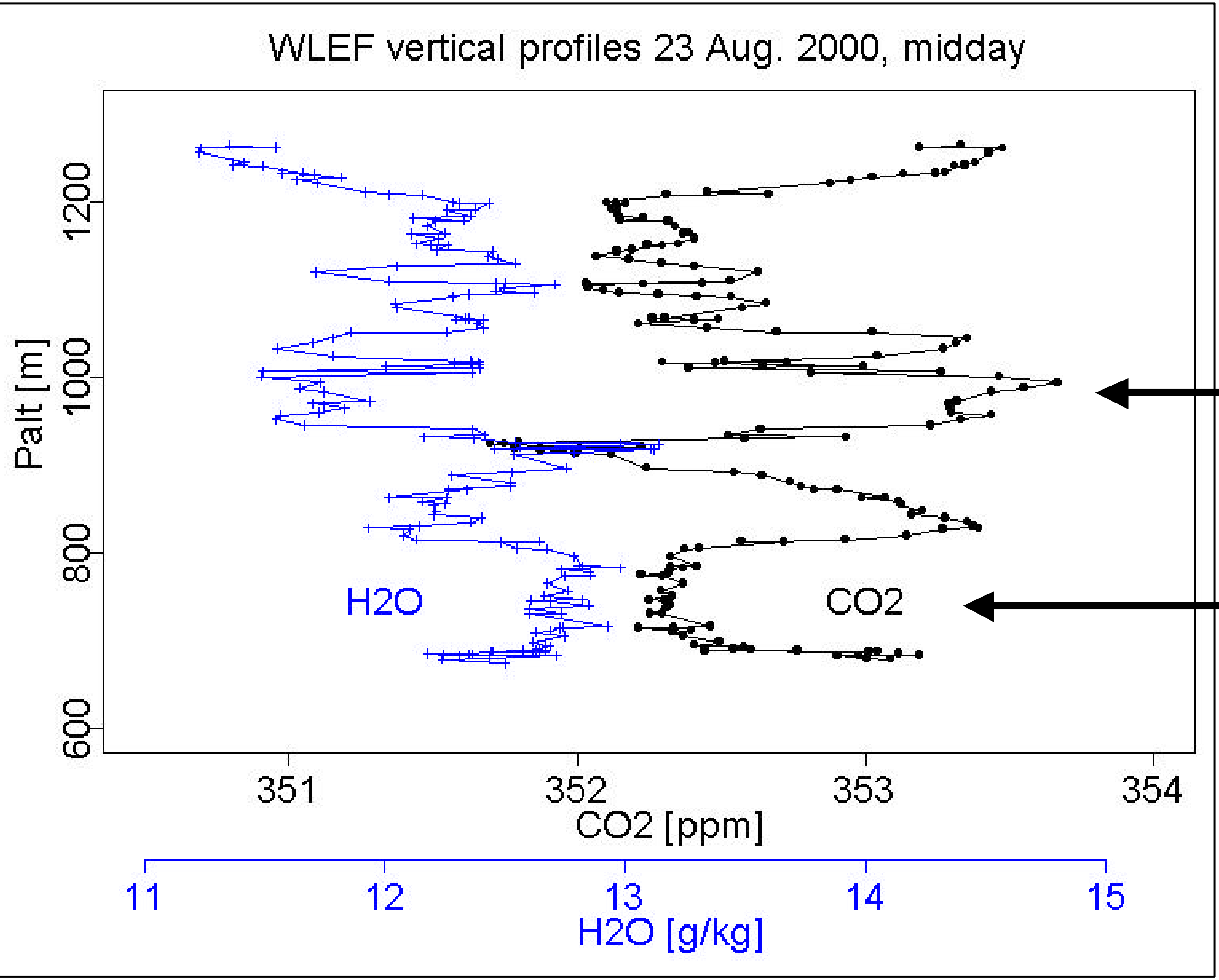


COBRA-2000 Northern Transect

18-19 August 2000



What models don’t need to resolve



Dry layer, high CO2, entrained from above CBL

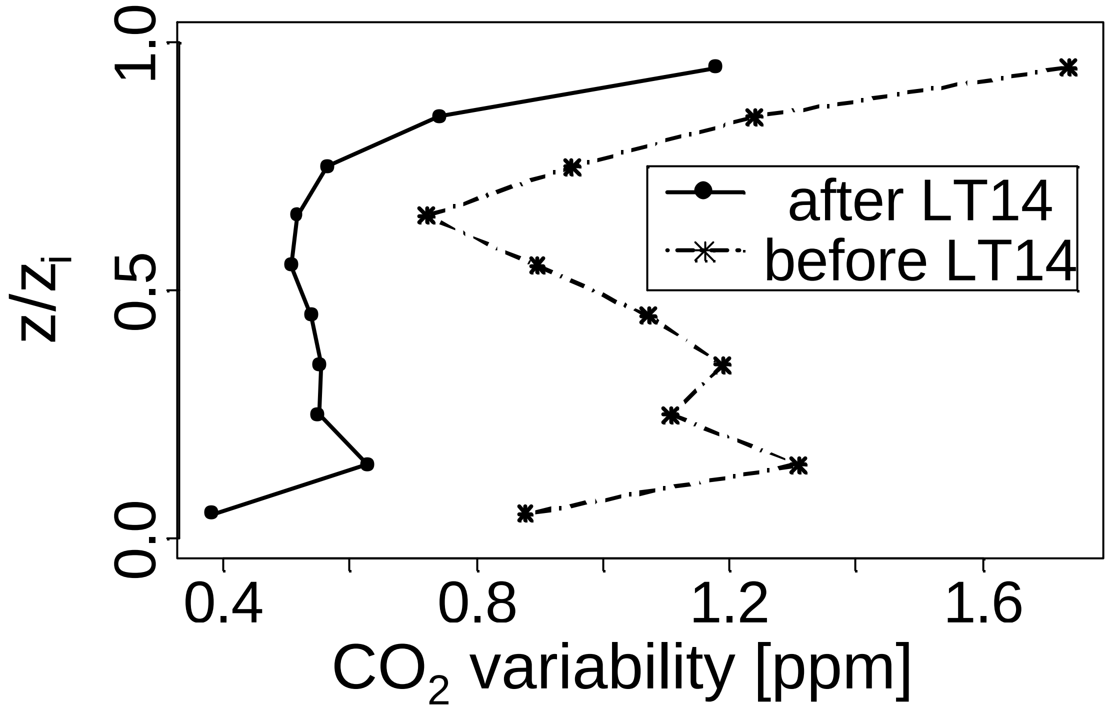
Moist layer, low CO2, from surface

“unresolvable” eddies

⇒ “resolvable” mixed layer mean

What models don't need to resolve

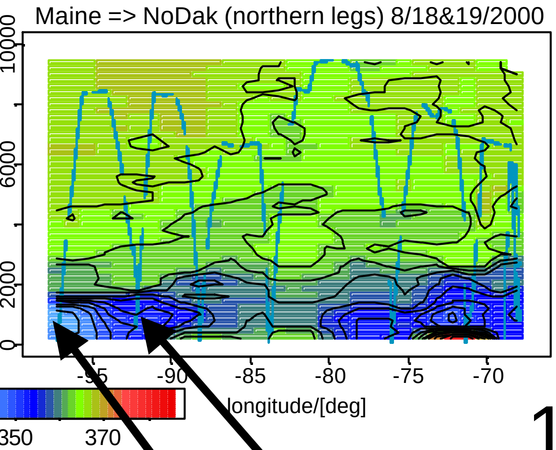
~ 100 profiles
(COBRA,
summer 2000)

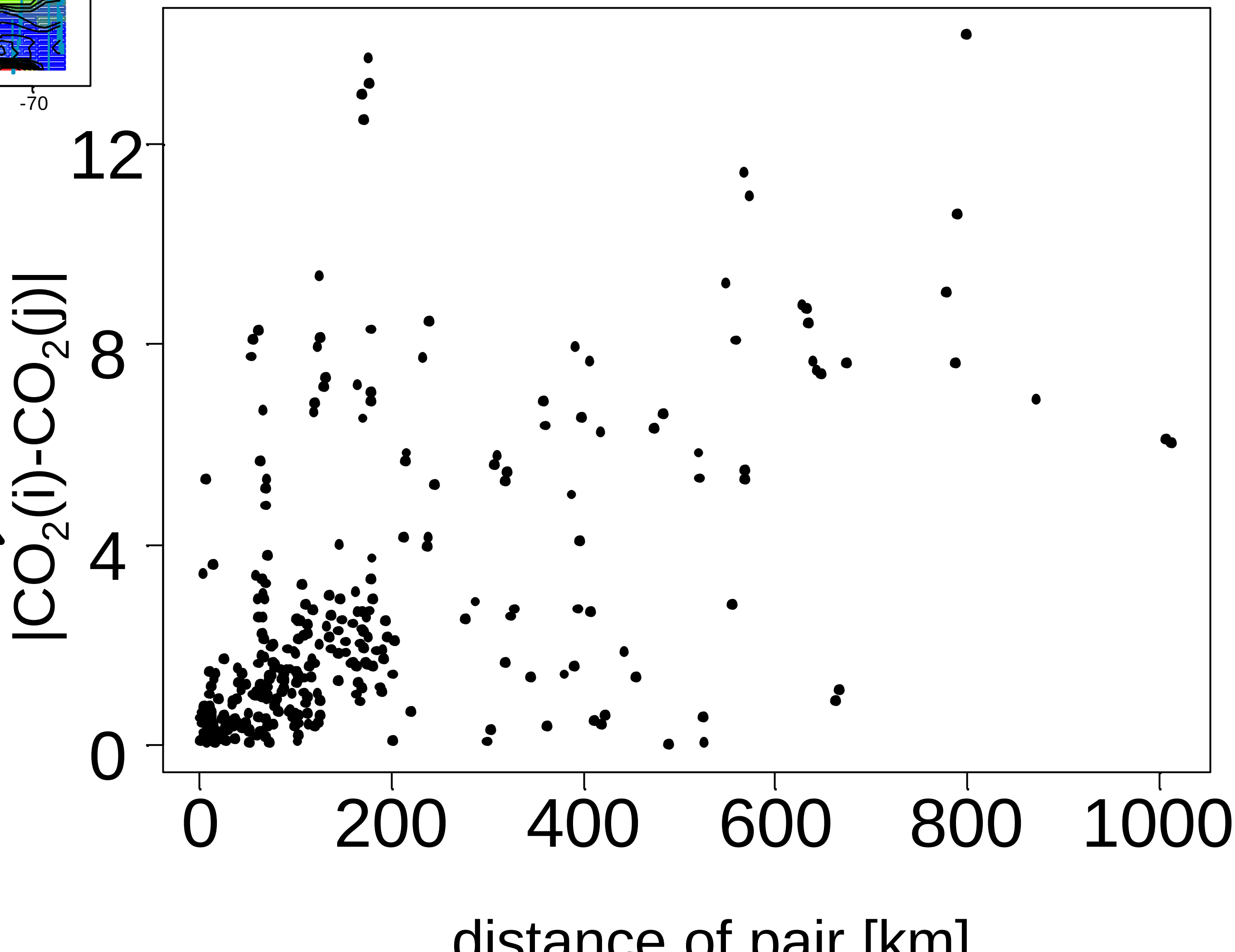


Uncertainty of mixed layer mean
due to eddies:
0.2 ppm
(~ e.g. 25 layers, 1 ppm stdev. each)

[*Gerbig et al.*, 2003a

Grain size
of atmospheric CO_2
or
“how well-mixed is the atmosphere?”





Spatial
ifferences of
airs of mixed
ayer profiles
neasured
vithin 3 hours
f each other

Grain size of atmospheric CO_2: Variogram

Variogram for a given "distance bin" (h=average distance):

$$2g(h) = \mathrm{var}\left(CO_2(s_i) - CO_2(s_j)\right) \text{ with } h = \overline{|s_i - s_j|}$$

classical Variogram:

$$2\hat{g}(h) = \frac{1}{N(h)} \sum_{N(h)} \left(CO_2(s_i) - CO_2(s_j)\right)^2$$

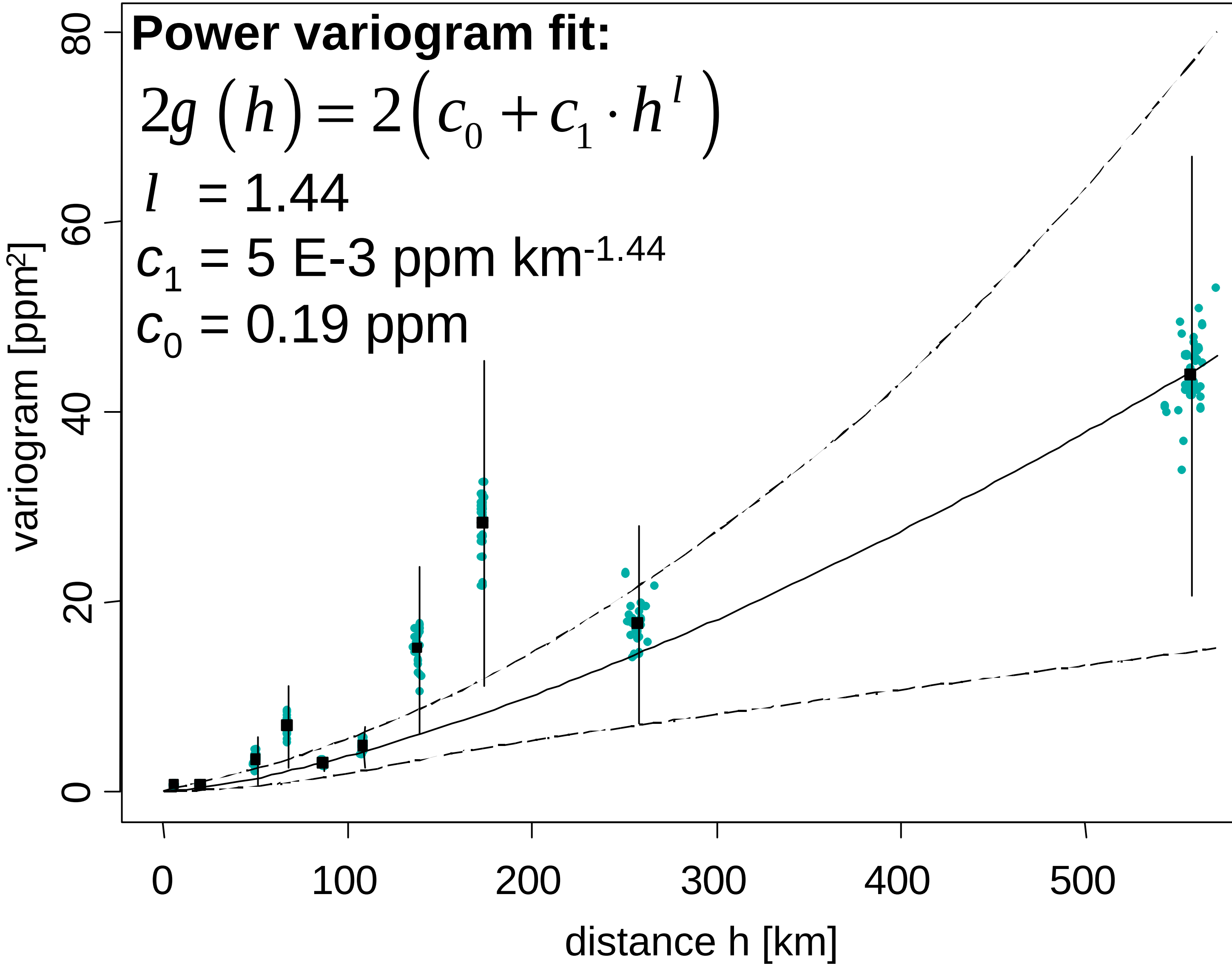
with $N(h)$: Number of pairs

robust Variogram:

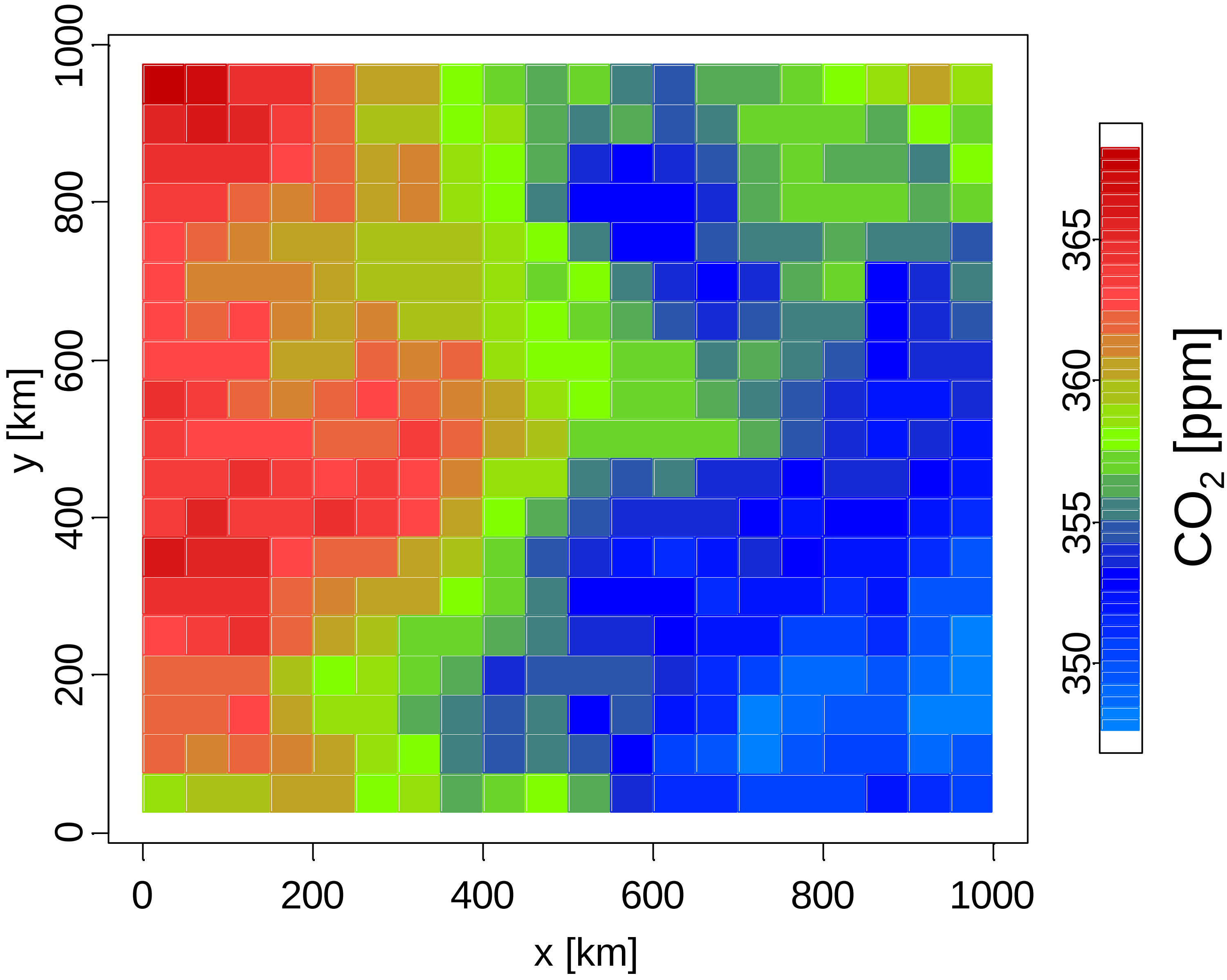
$$2\bar{g}(h) = \frac{\left\{\frac{1}{N(h)} \sum_{N(h)} \left|CO_2(s_i) - CO_2(s_j)\right|^{1/2}\right\}^4}{0.457 + 0.494/N(h)}$$

Fitting of power variogram model

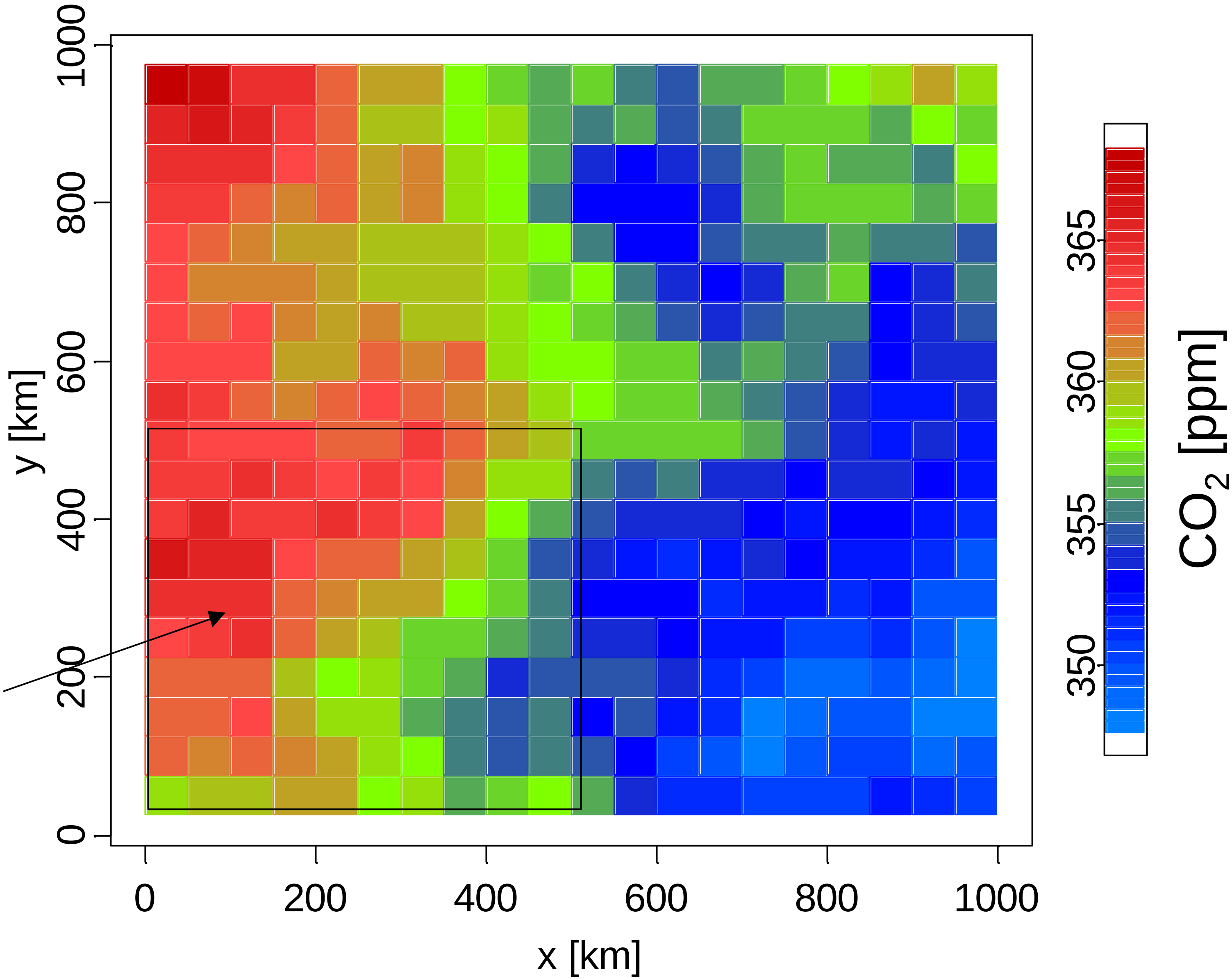
Variogram:
Variance of
differences of
pairs of mixed
layer profiles
measured
within 3 hours
of each other



Spatial simulation for CO_2

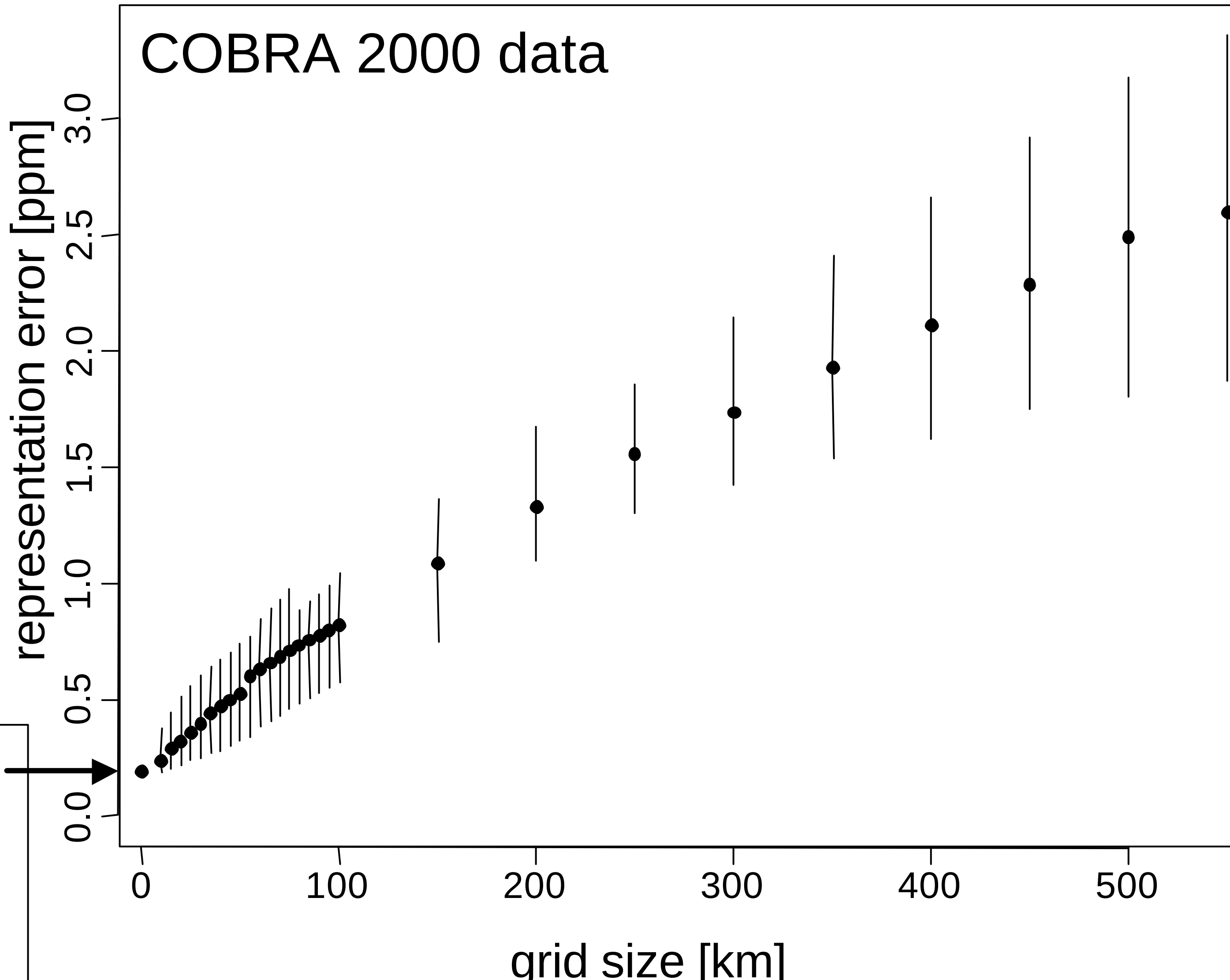


Spatial simulation for CO_2



stdev(CO_2) within each subgrid of size $\Delta x\ \Delta y$

Grain size of atmospheric CO_2: Representation error

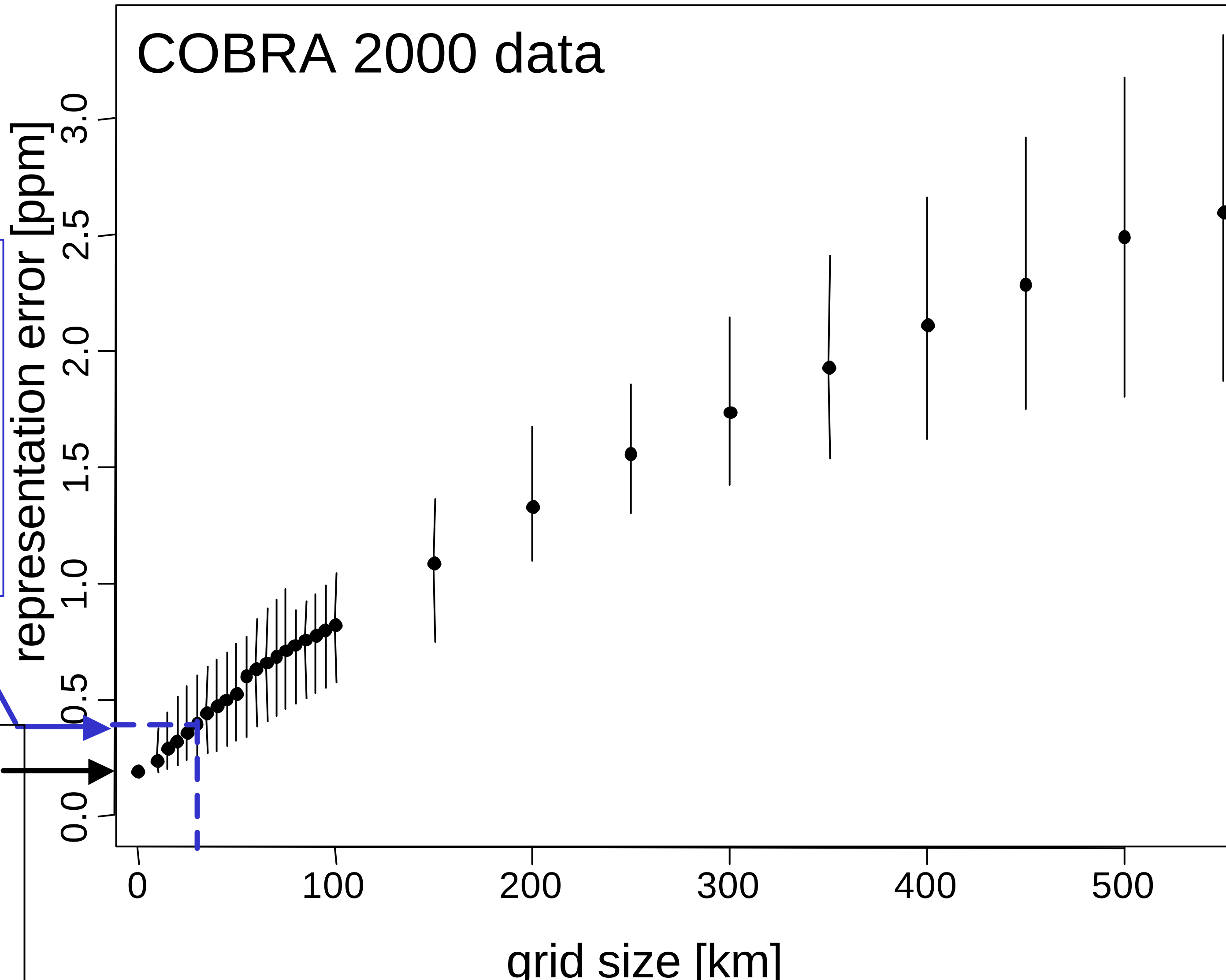


0.2 ppm Precision of mixed layer mean CO_2 (turbulence)

[*Gerbig et al.*, 2003a

Grain size of atmospheric CO_2: Representation error

at 30 km: additional 0.2 ppm representation error

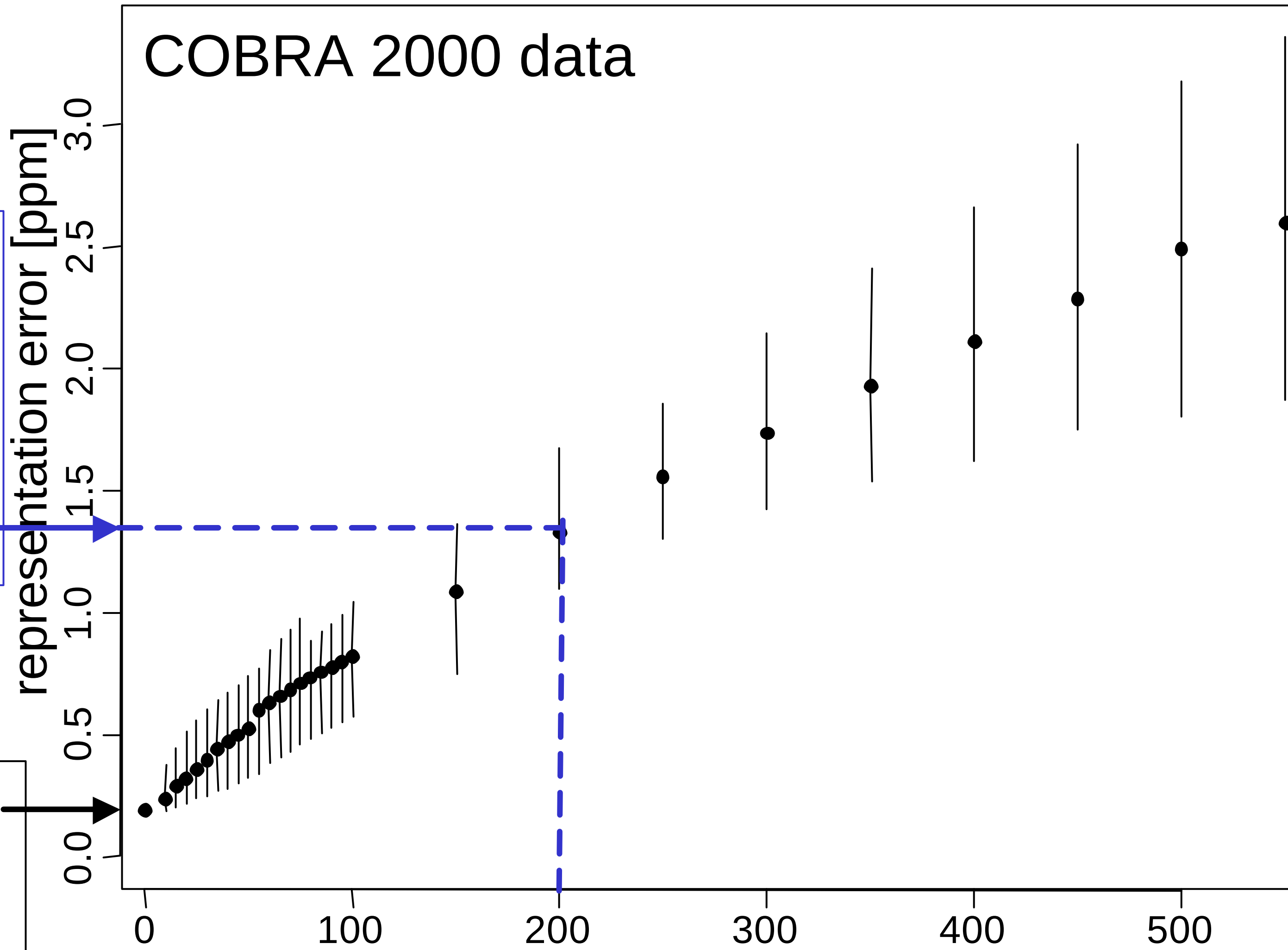


0.2 ppm Precision of mixed layer mean CO_2 (turbulence)

[*Gerbig et al.*, 2003a

Grain size of atmospheric CO_2: Representation error

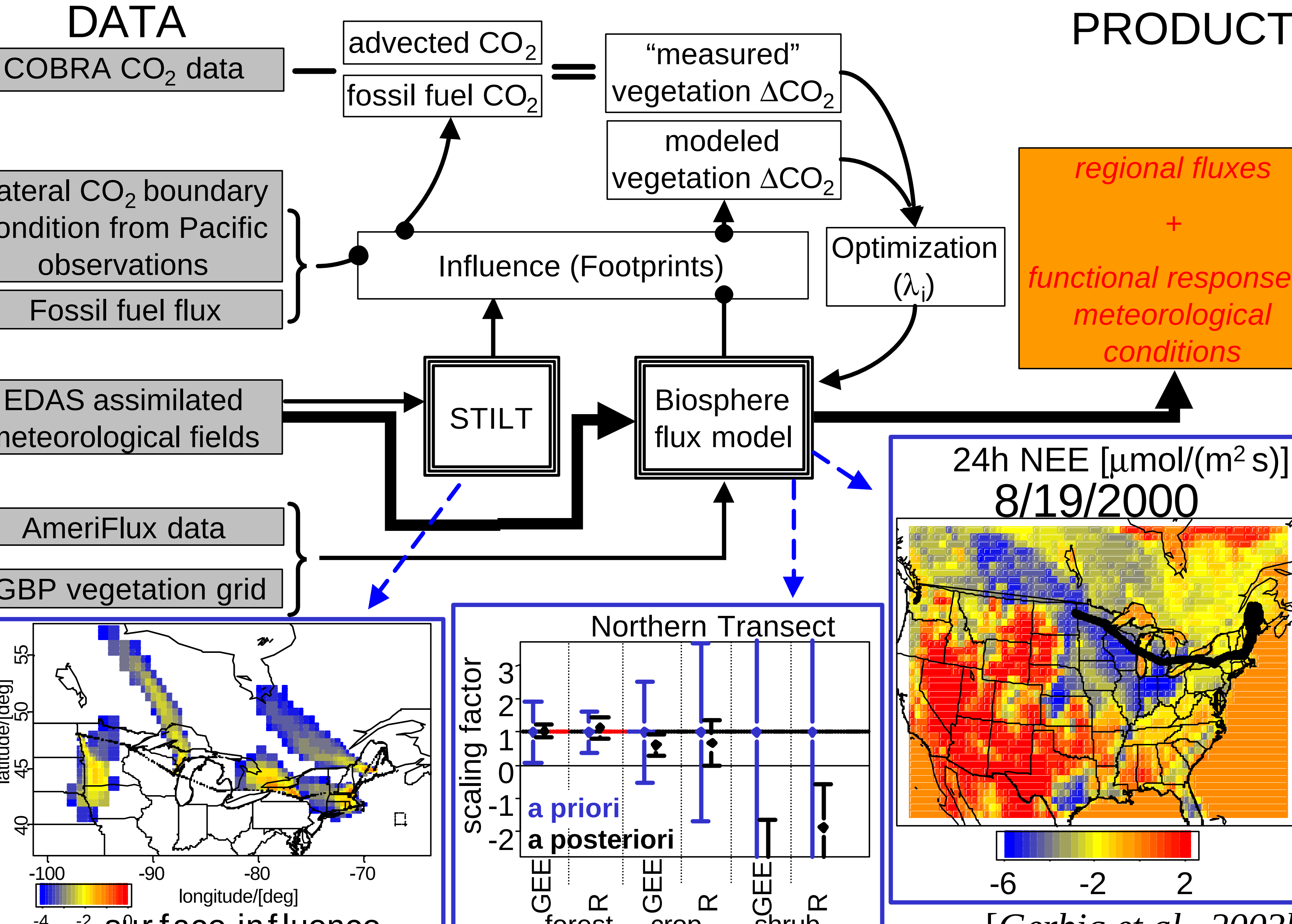
at 200 km: additional 1.1 ppm representation error



0.2 ppm Precision of mixed layer mean CO_2 (turbulence)

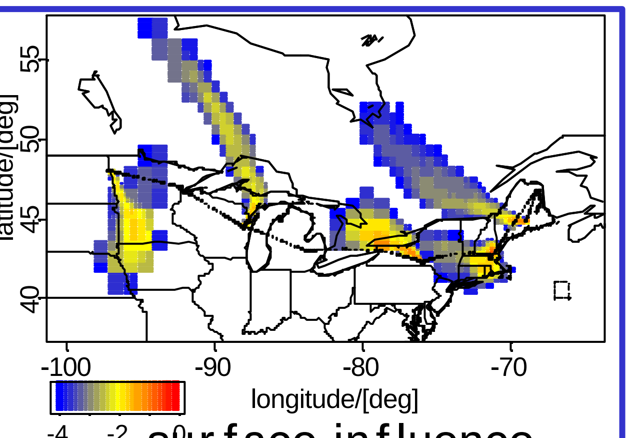
[Gerbig et al., 2003a]

Receptor Oriented Atmospheric Model "ROAM"



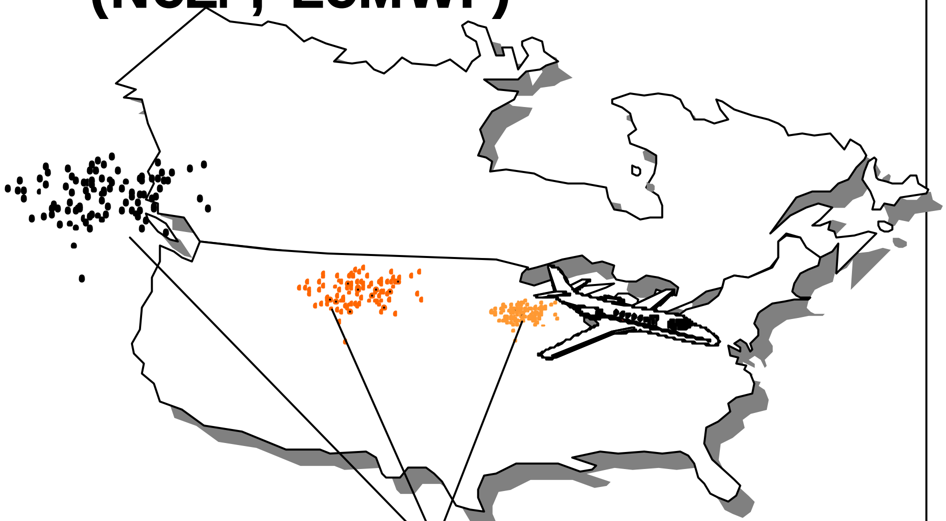
Receptor Oriented Atmospheric Model "ROAM"

EDAS assimilated meteorological fields → STILT



Stochastic Time Inverted Lagrangian Transport Model

- **driven by assimilated or forecasted winds (NCEP, ECMWF)**



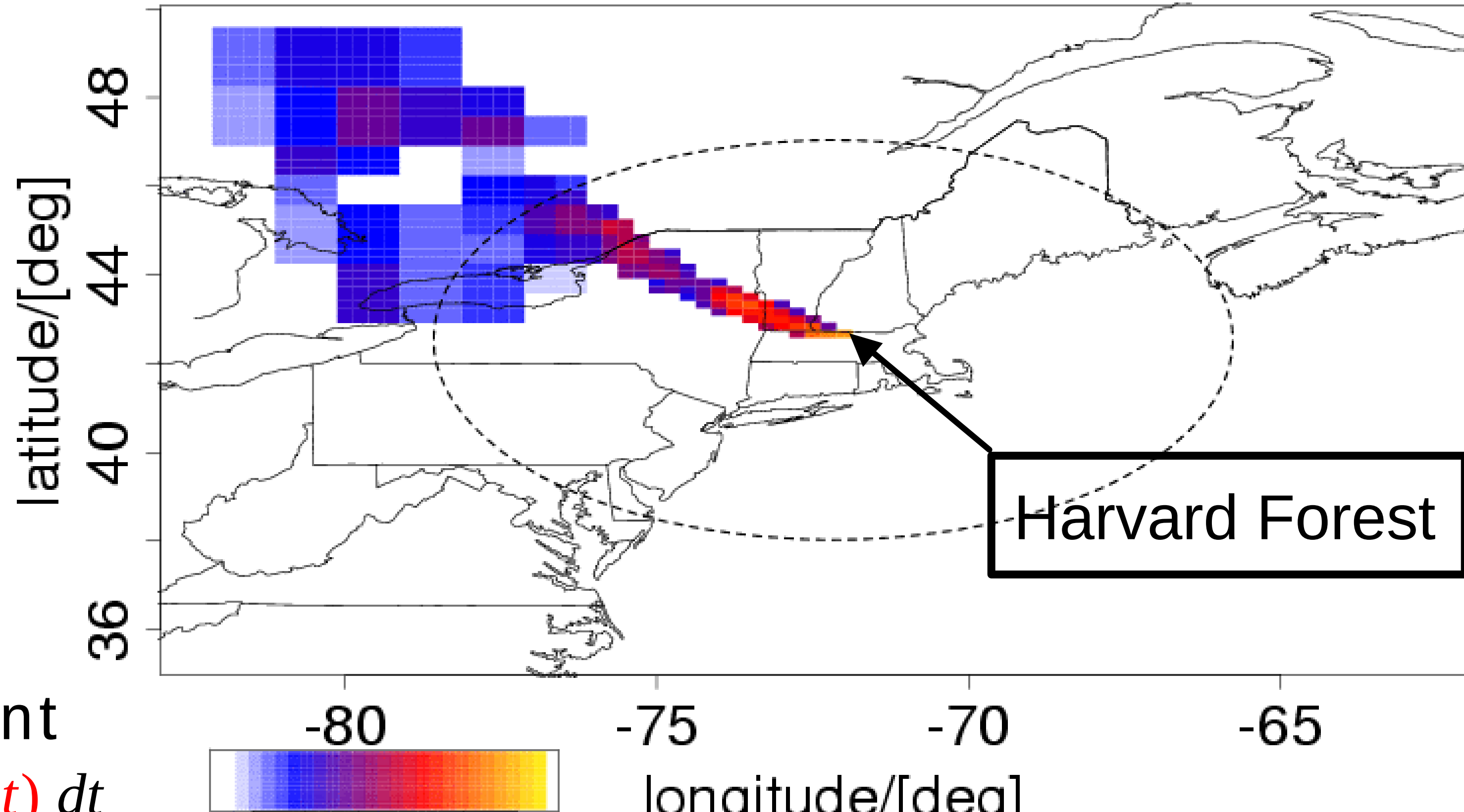
Particle location at different times before arriving at aircraft

[*Lin et al., 2003*], [*Gerbig et al., 2003b*]

What does a (tall) tower "see"?

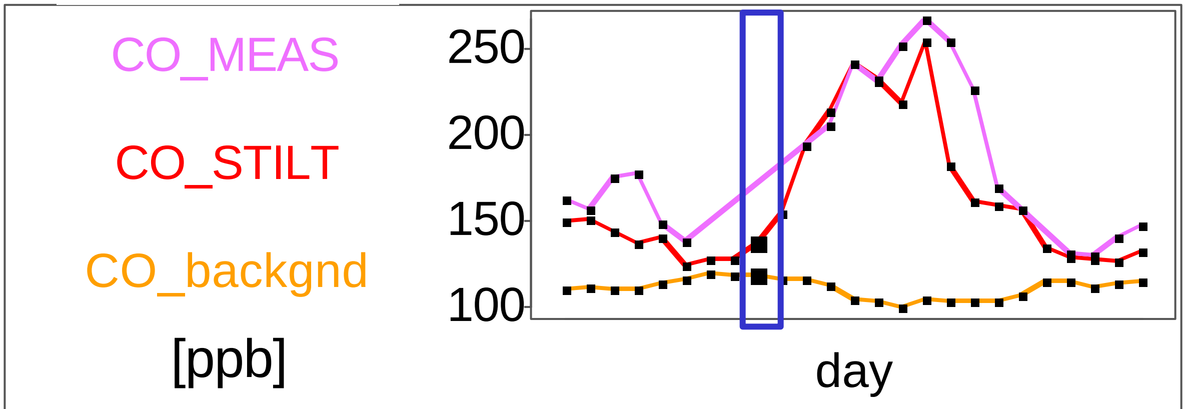
STILT

Stochastic Time
Inverted
Lagrangian
Transport Model
[*Gerbig et al., 2003b*]
[*Lin et al., 2003*]



Footprint

$$\int I(\mathbf{x}_r, t_r \mid \mathbf{x}, t)\, dt$$



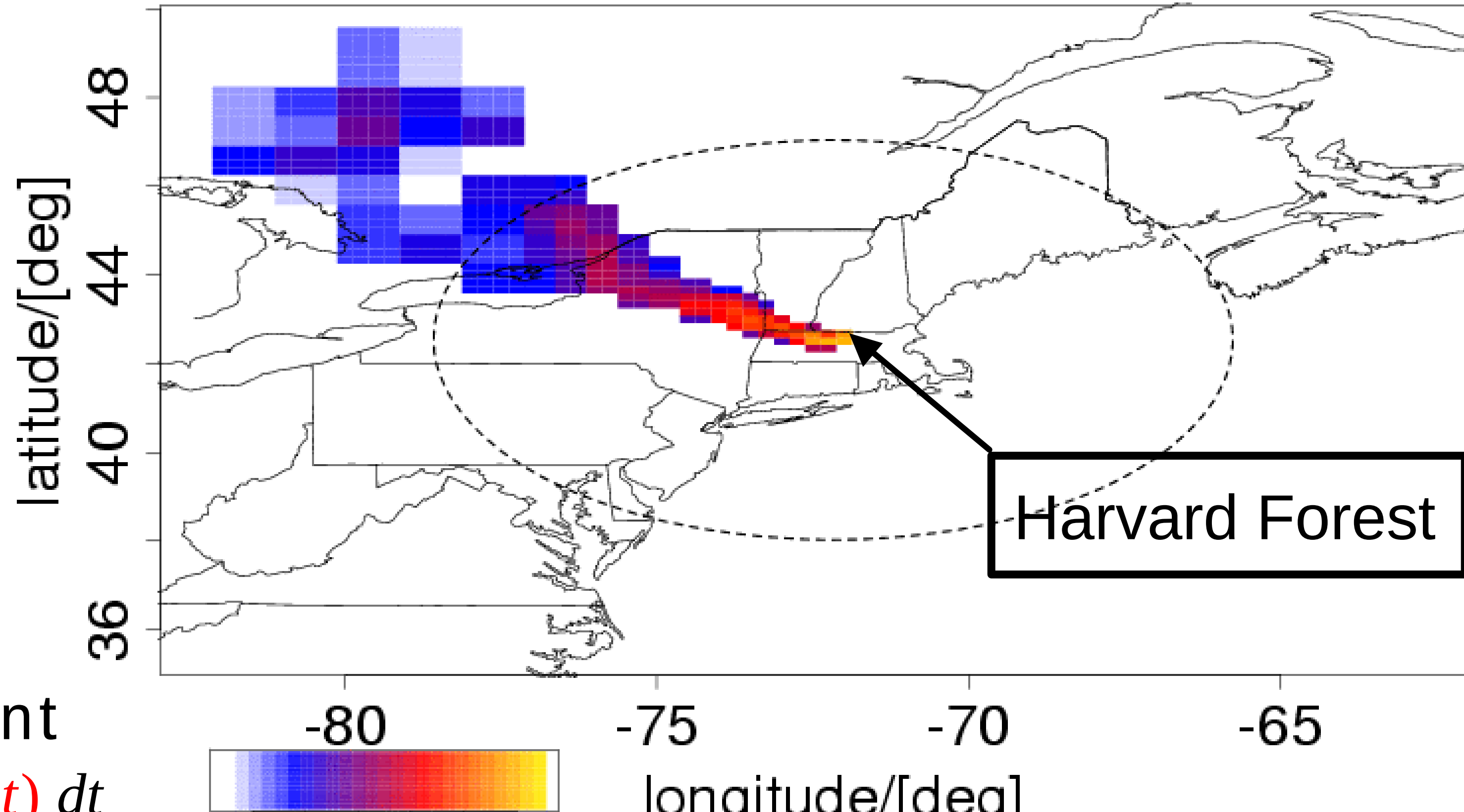
What does a (tall) tower "see"?

STILT

Stochastic Time Inverted Lagrangian Transport Model

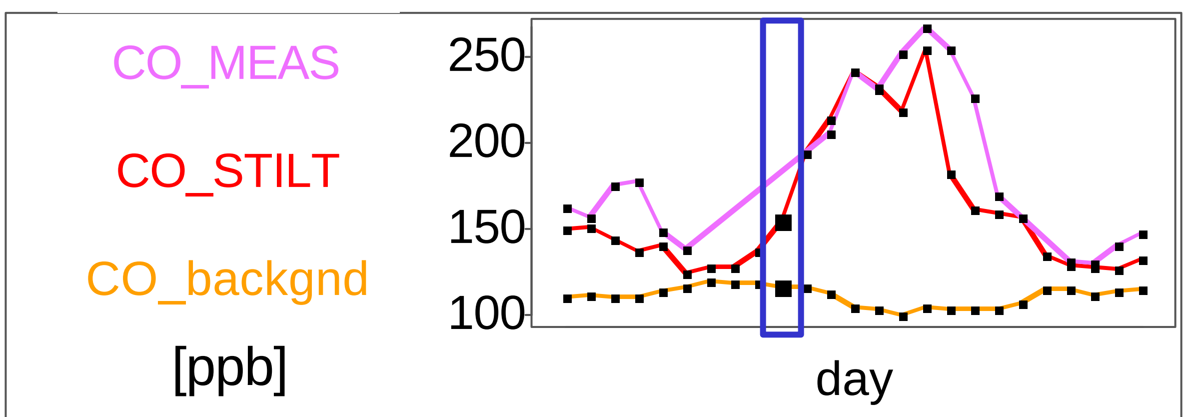
[*Gerbig et al., 2003b*]

[*Lin et al., 2003*]



Footprint

$$\int I(\mathbf{x}_r, t_r \mid \mathbf{x}, t)\, dt$$



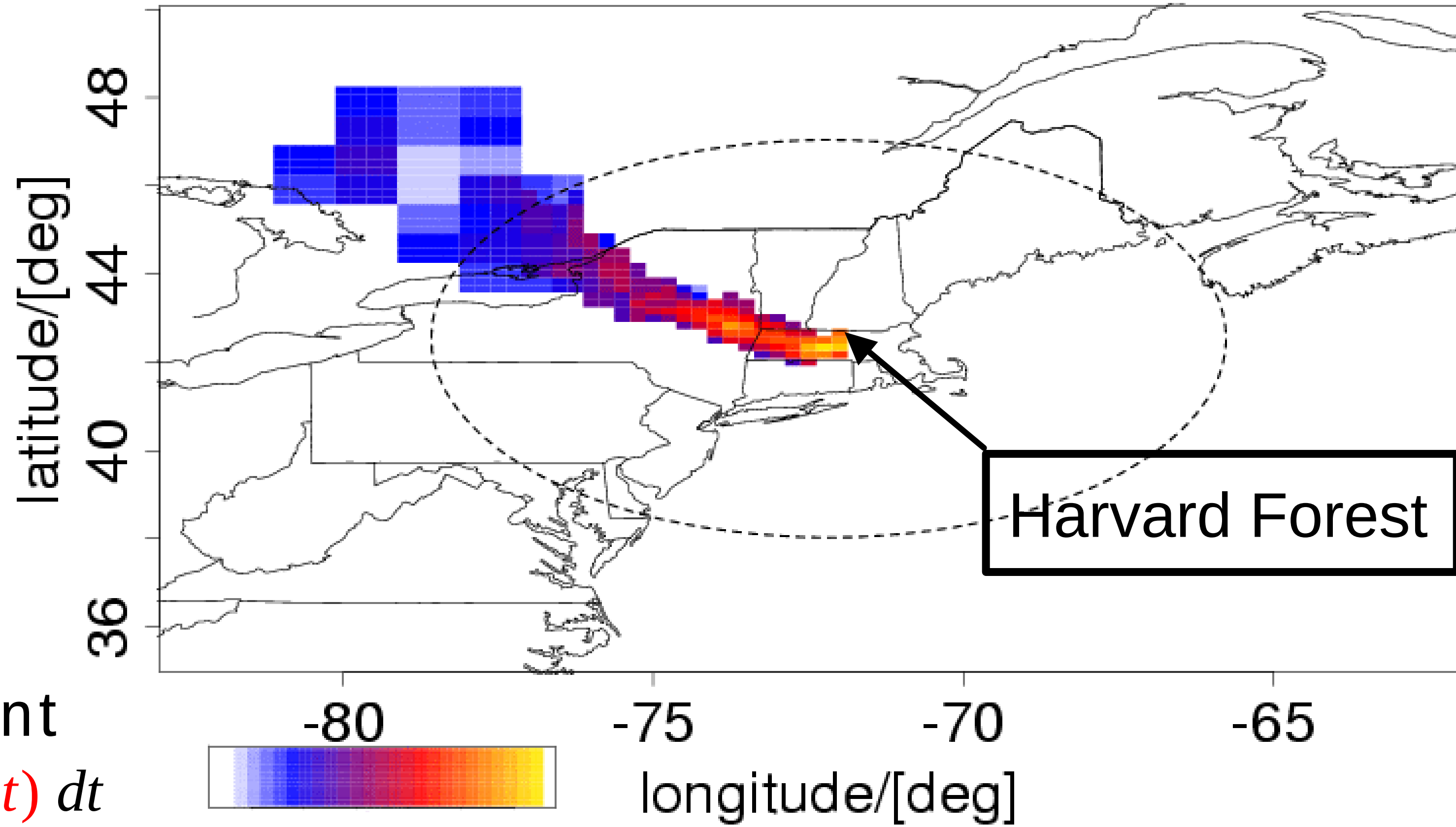
What does a (tall) tower "see"?

STILT

Stochastic Time Inverted Lagrangian Transport Model

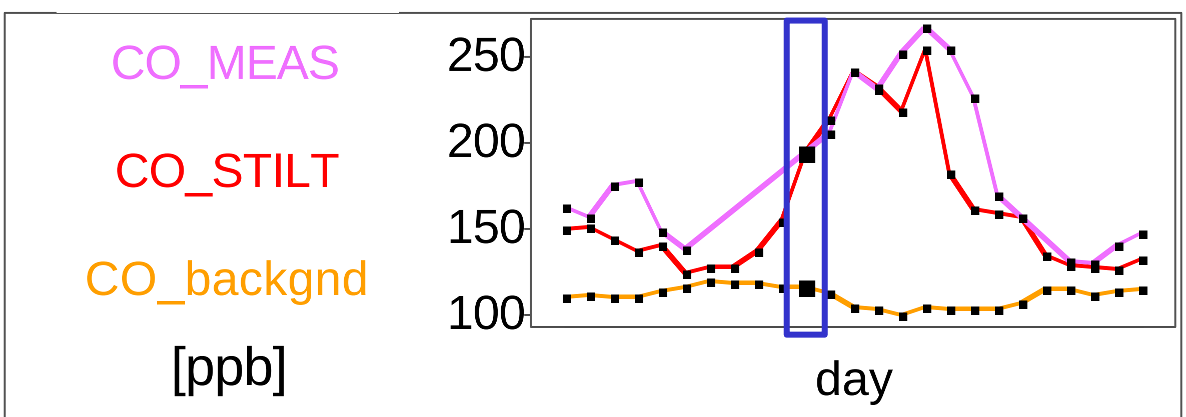
[*Gerbig et al., 2003b*]

[*Lin et al., 2003*]



Footprint

$$\int I(\mathbf{x}_r, t_r \mid \mathbf{x}, t)\, dt$$



What does a (tall) tower "see"?

STILT

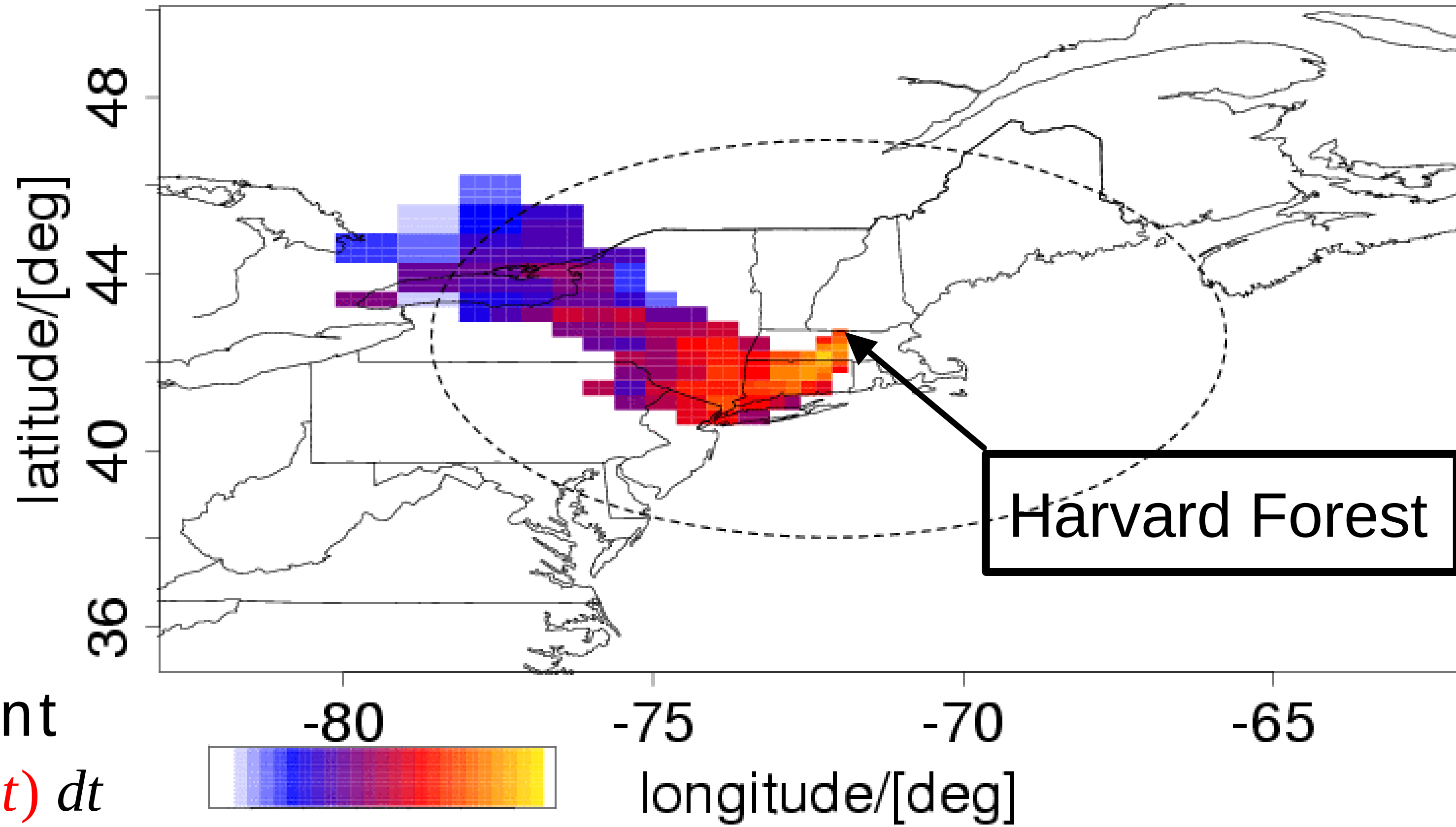
Stochastic Time Inverted Lagrangian Transport Model

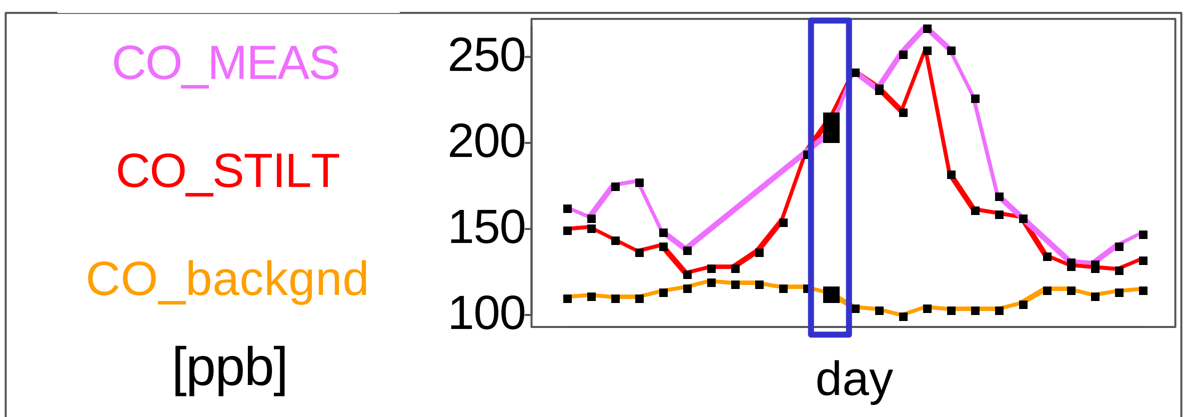
[*Gerbig et al., 2003b*]

[*Lin et al., 2003*]

Footprint

$$\int I(\mathbf{x}_r, t_r \,|\, \mathbf{x}, t)\, dt$$





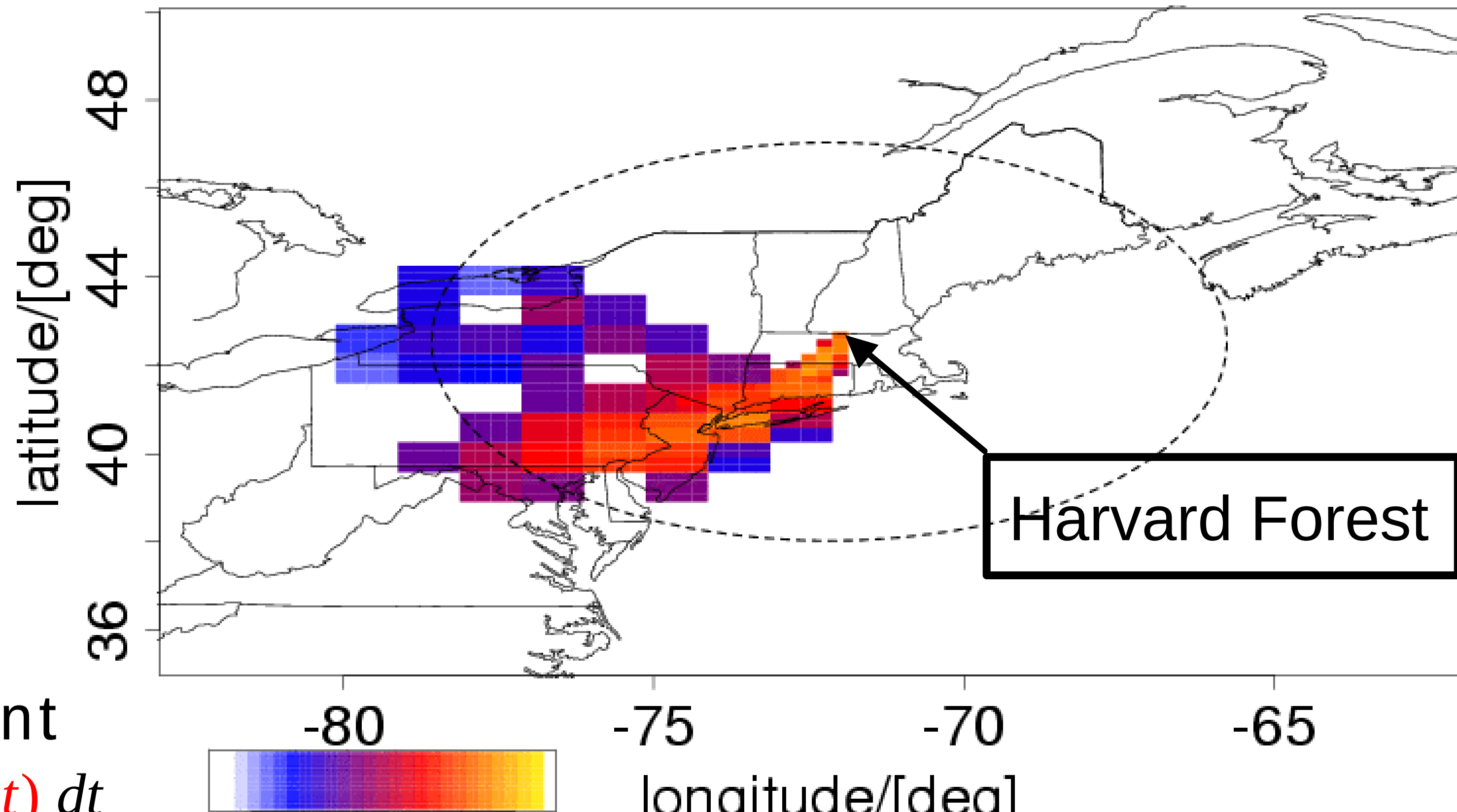
What does a (tall) tower "see"?

STILT

Stochastic Time Inverted Lagrangian Transport Model

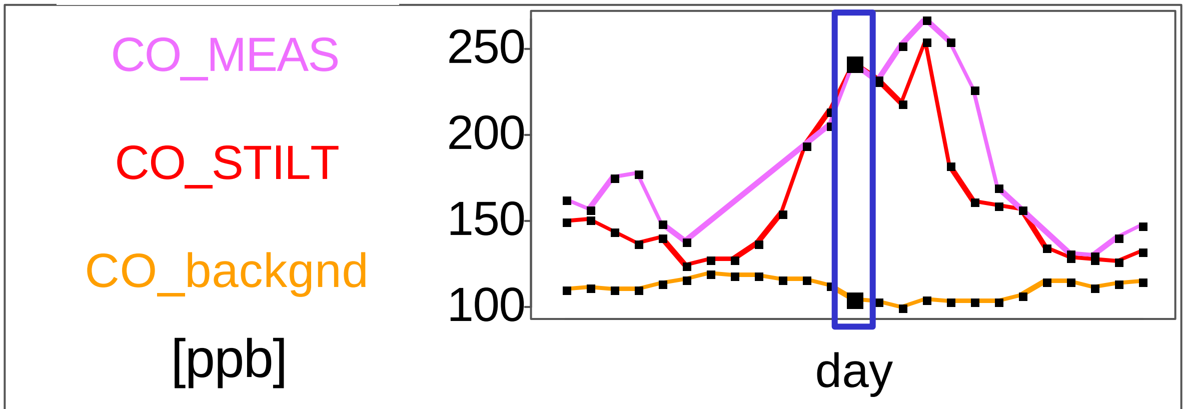
[*Gerbig et al., 2003b*]

[*Lin et al., 2003*]



Footprint

$$\int I(\mathbf{x}_r, t_r \mid \mathbf{x}, t)\, dt$$



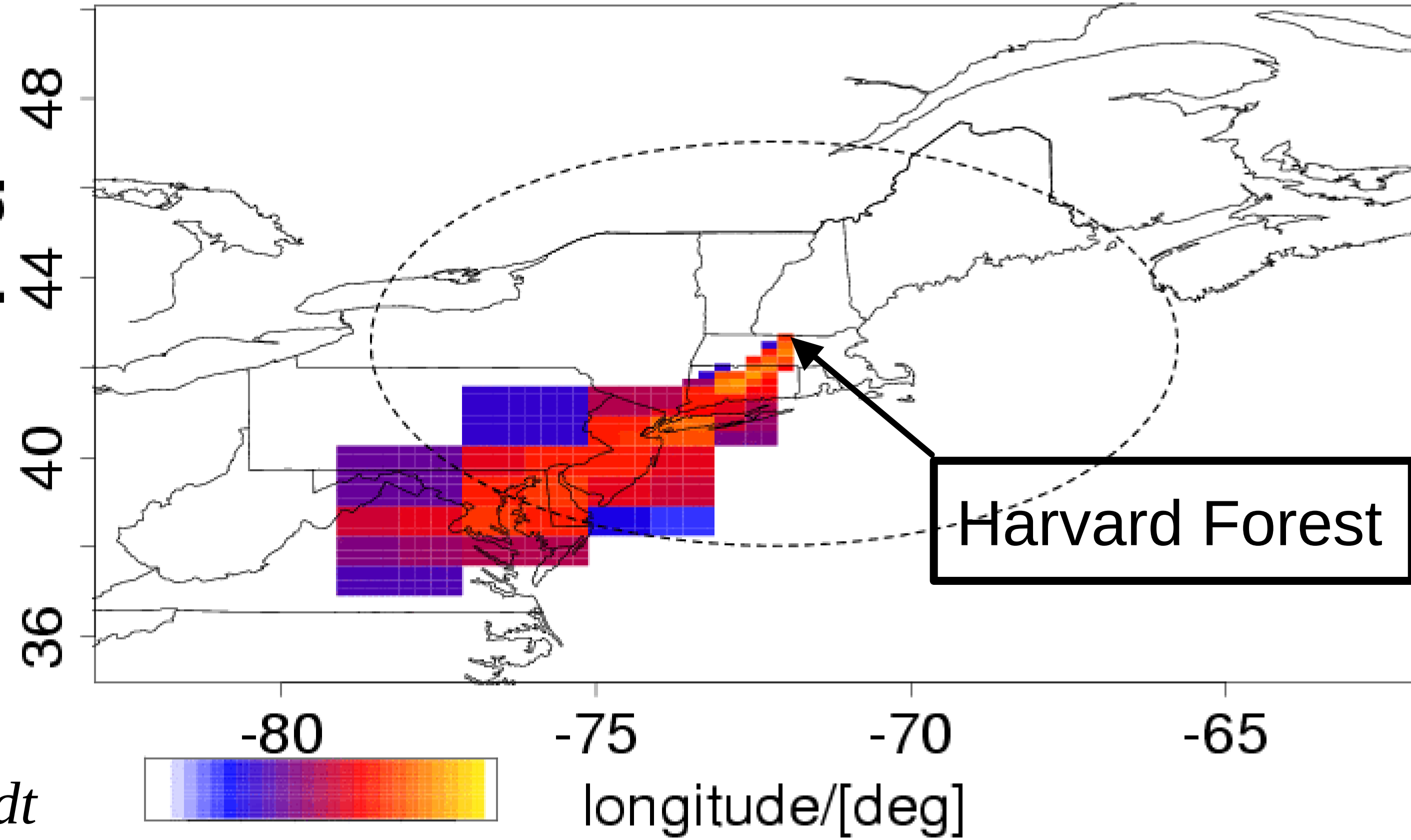
What does a (tall) tower "see"?

STILT

Stochastic Time Inverted Lagrangian Transport Model

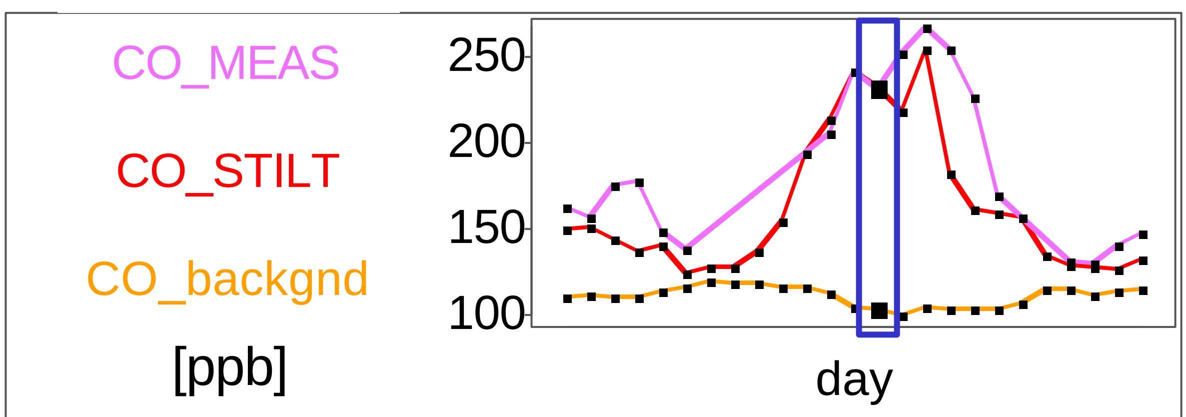
[*Gerbig et al., 2003b*]

[*Lin et al., 2003*]



Footprint

$$\int I(\mathbf{x}_r, t_r \mid \mathbf{x}, t)\, dt$$



What does a (tall) tower "see"?

STILT

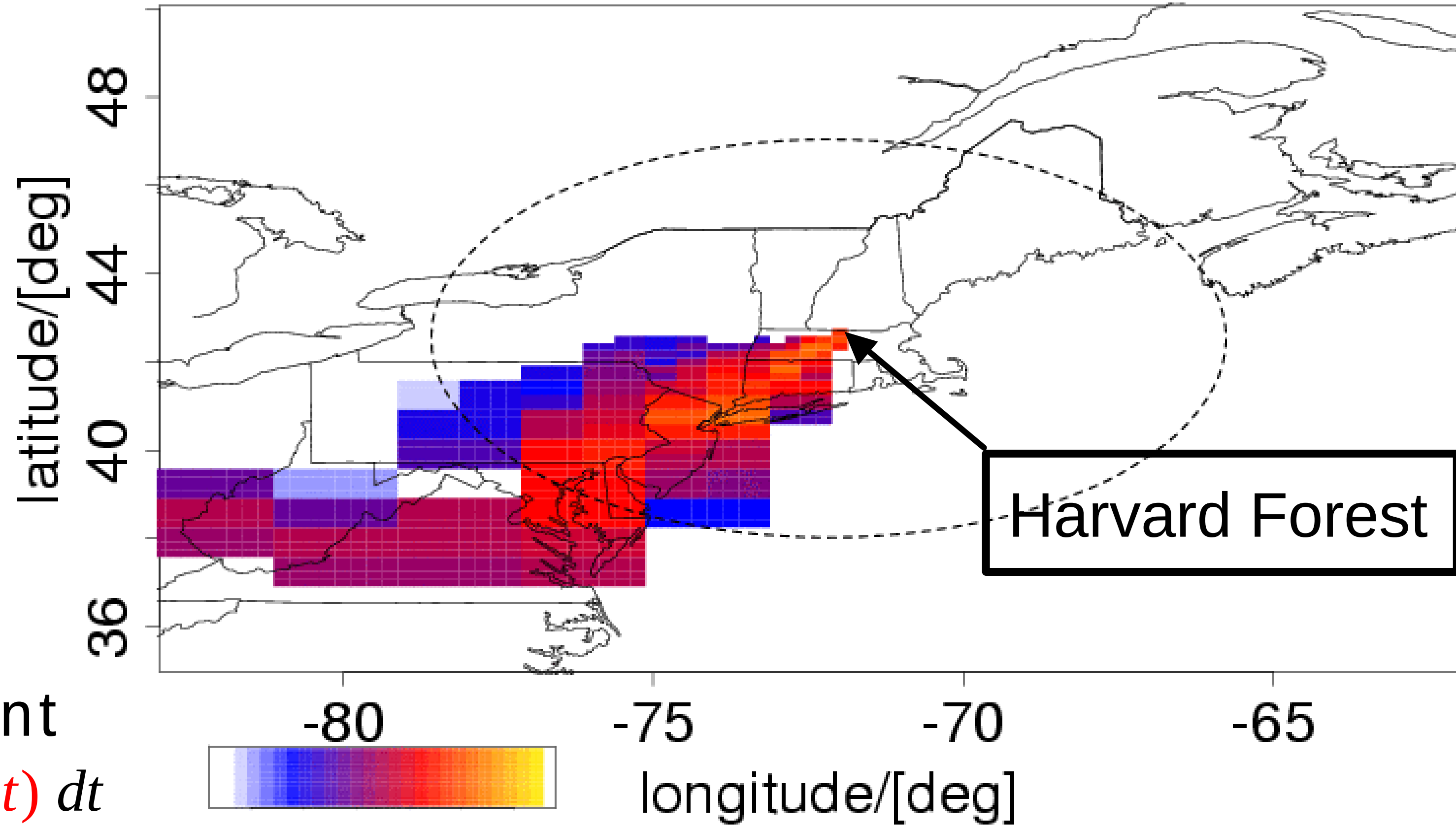
Stochastic Time Inverted Lagrangian Transport Model

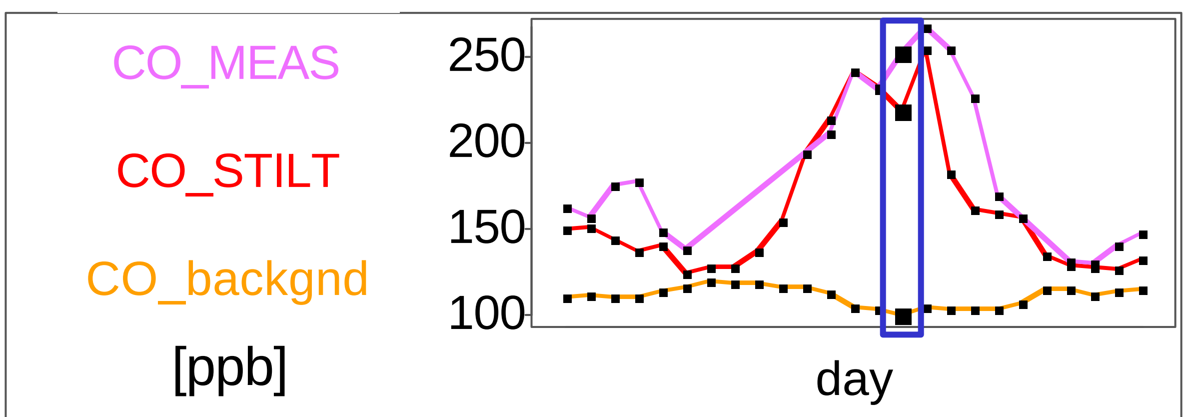
[*Gerbig et al., 2003b*]

[*Lin et al., 2003*]

Footprint

$$\int I(\mathbf{x}_r, t_r \mid \mathbf{x}, t)\, dt$$





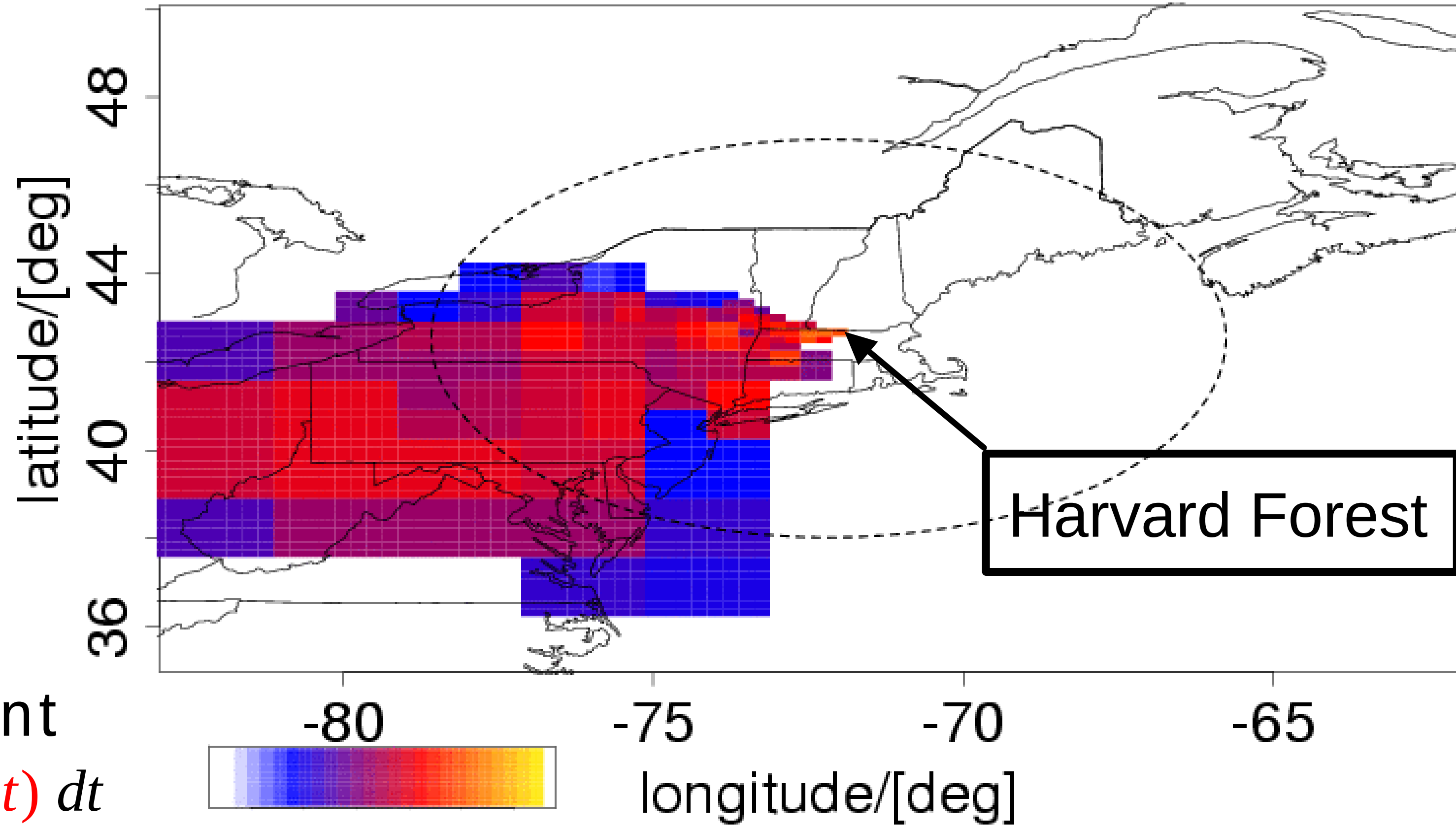
What does a (tall) tower "see"?

STILT

Stochastic Time Inverted Lagrangian Transport Model

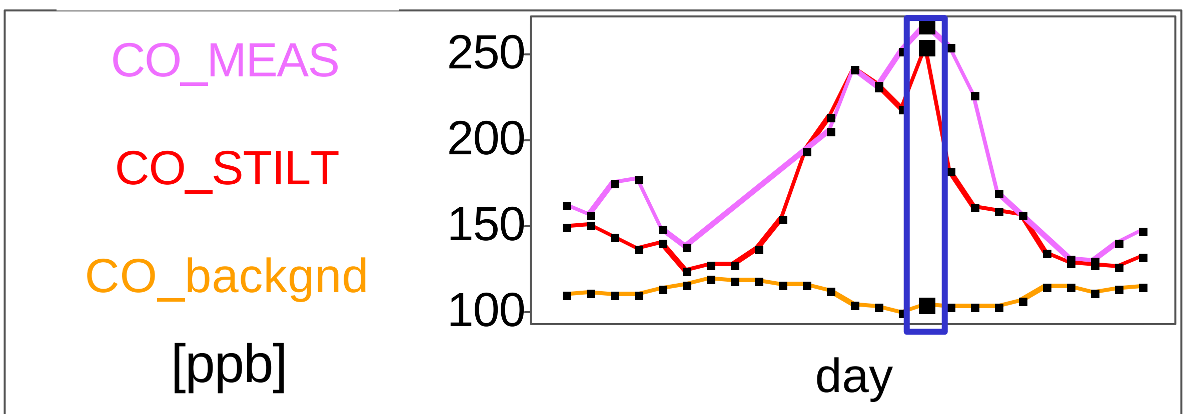
[*Gerbig et al., 2003b*]

[*Lin et al., 2003*]



Footprint

$$\int I(\mathbf{x}_r, t_r \mid \mathbf{x}, t)\, dt$$

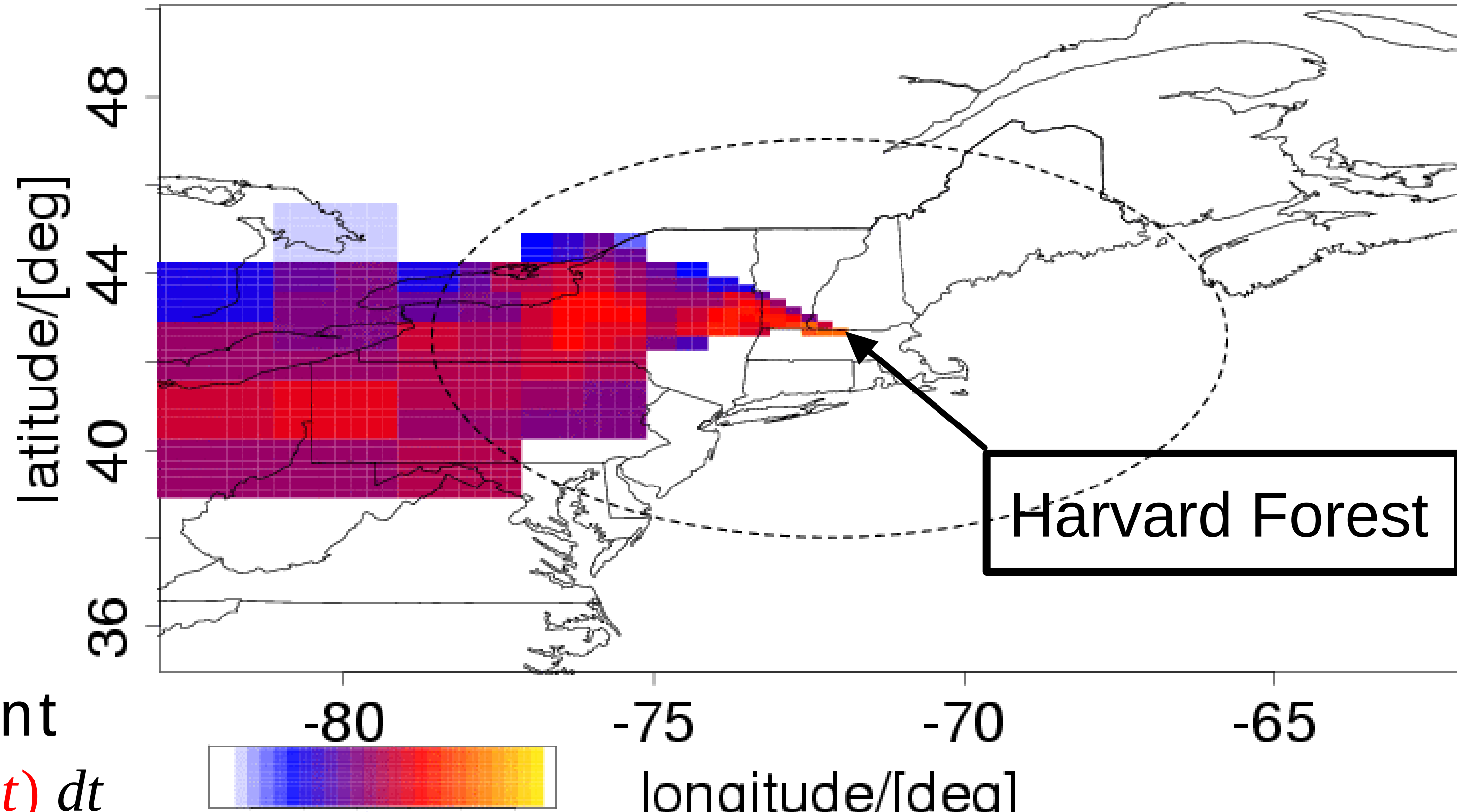


What does a (tall) tower "see"?

STILT

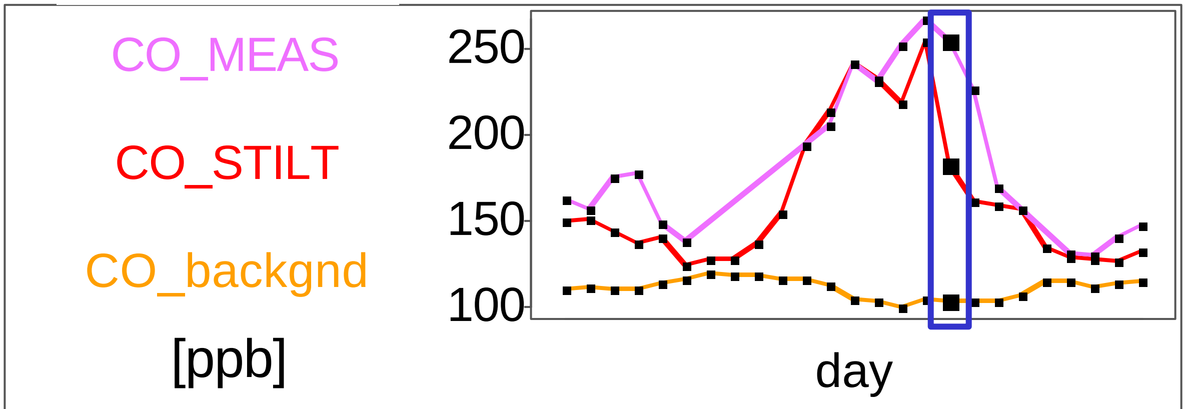
Stochastic Time Inverted Lagrangian Transport Model

[*Gerbig et al., 2003b*]
[*Lin et al., 2003*]



Footprint

$$\int I(\mathbf{x}_r, t_r \mid \mathbf{x}, t)\, dt$$



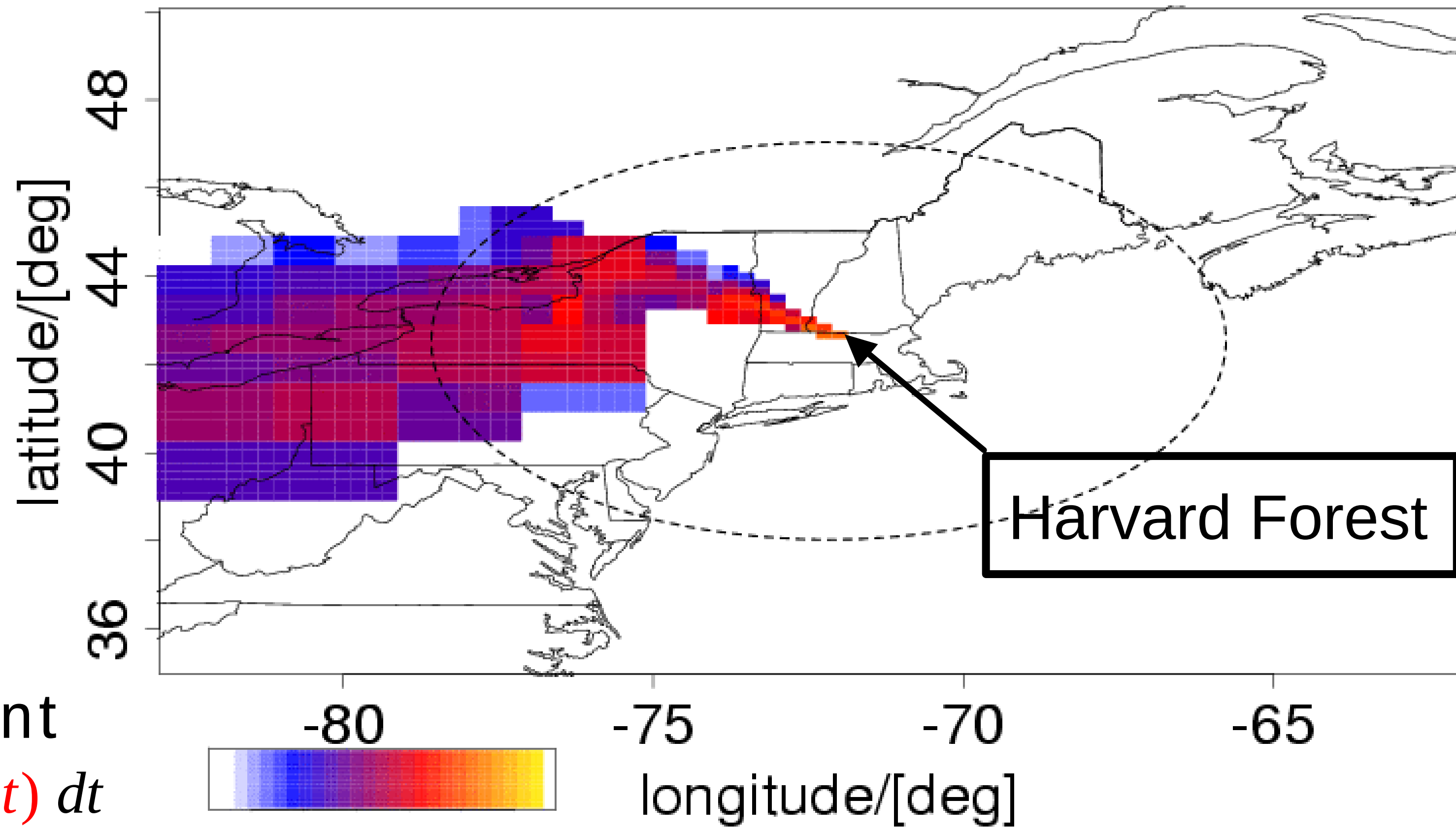
What does a (tall) tower "see"?

STILT

Stochastic Time Inverted Lagrangian Transport Model

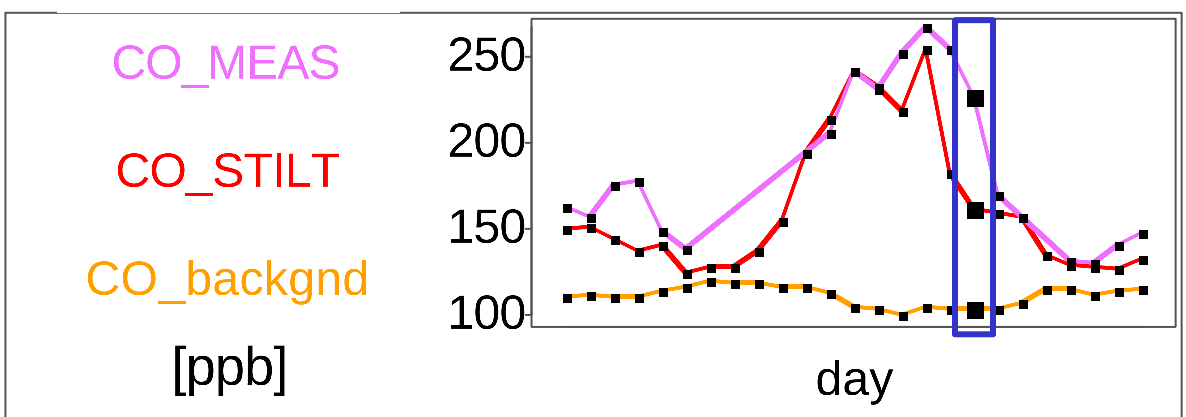
[*Gerbig et al., 2003b*]

[*Lin et al., 2003*]



Footprint

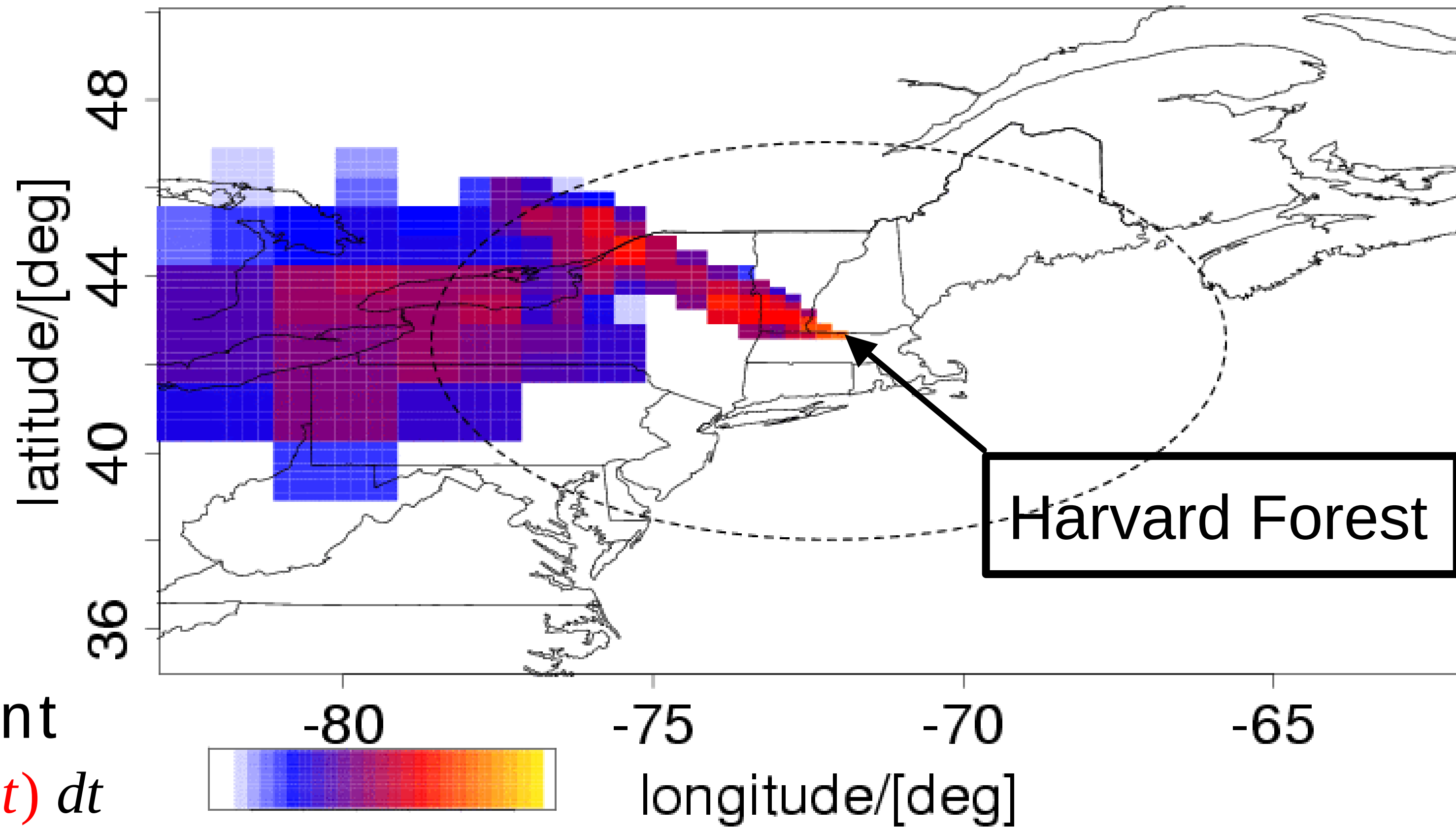
$$\int I(\mathbf{x}_r, t_r \,|\, \mathbf{x}, t)\, dt$$



What does a (tall) tower "see"?

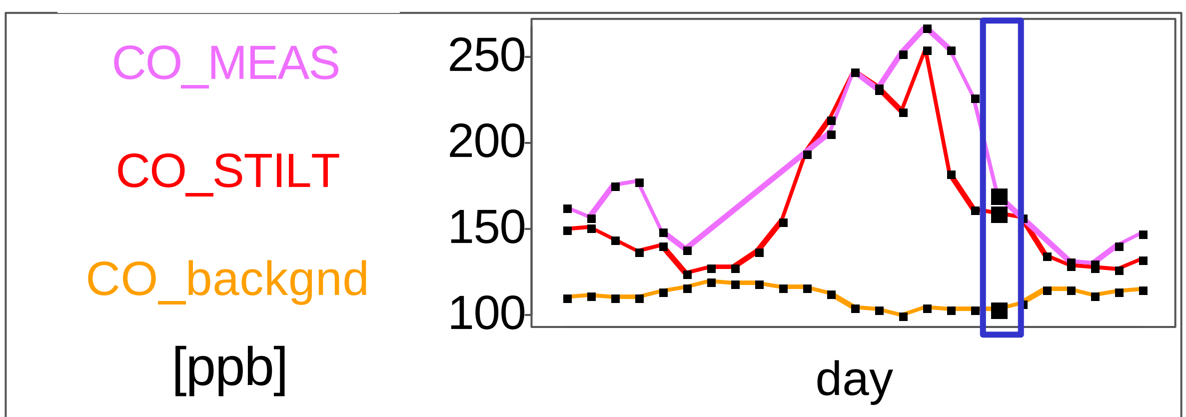
STILT

Stochastic **T**ime
Inverted
Lagrangian
Transport Model
[*Gerbig et al., 2003b*]
[*Lin et al., 2003*]



Footprint

$$\int I(\mathbf{x}_r, t_r \mid \mathbf{x}, t)\, dt$$



What does a (tall) tower "see"?

STILT

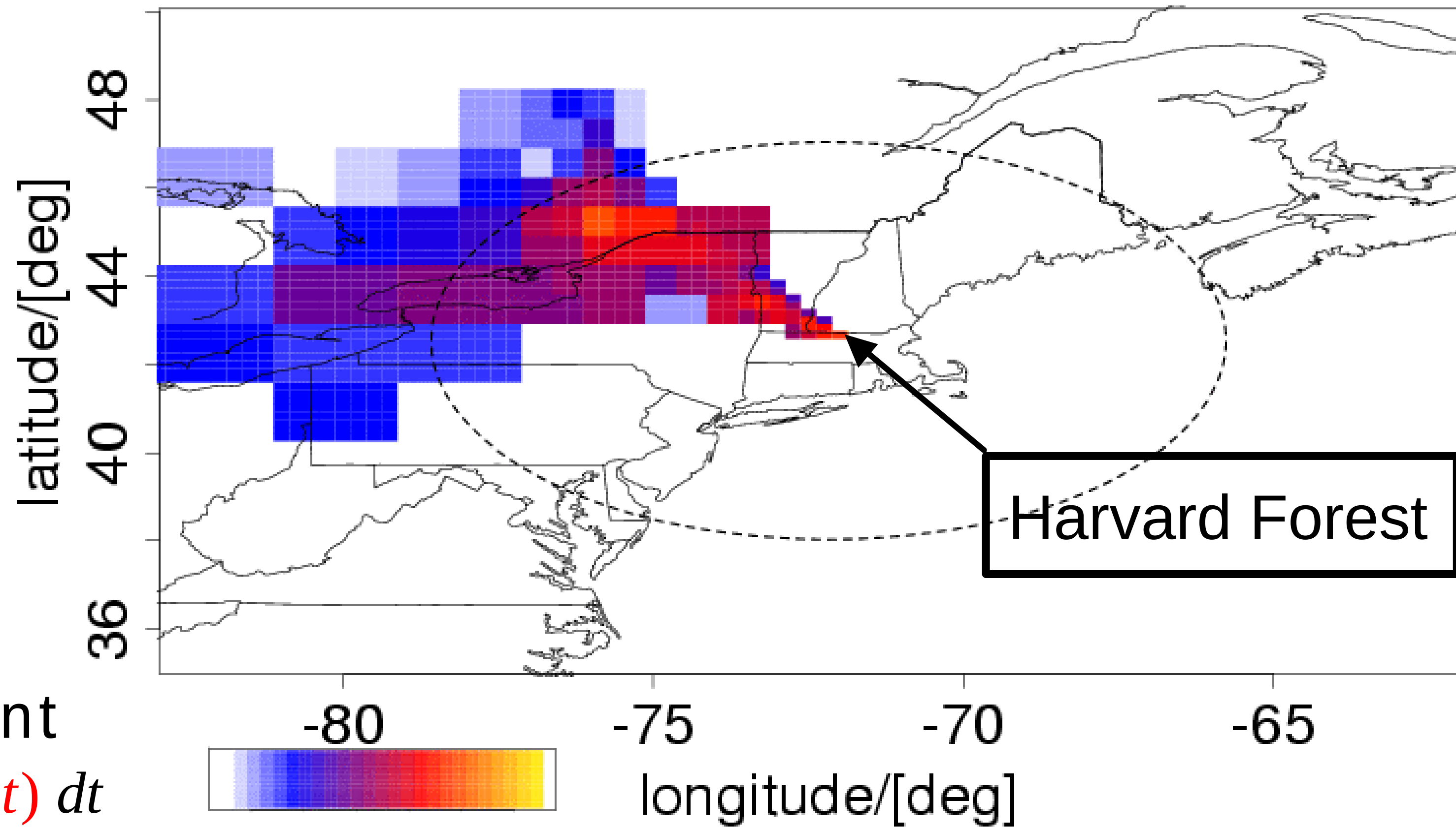
Stochastic Time Inverted Lagrangian Transport Model

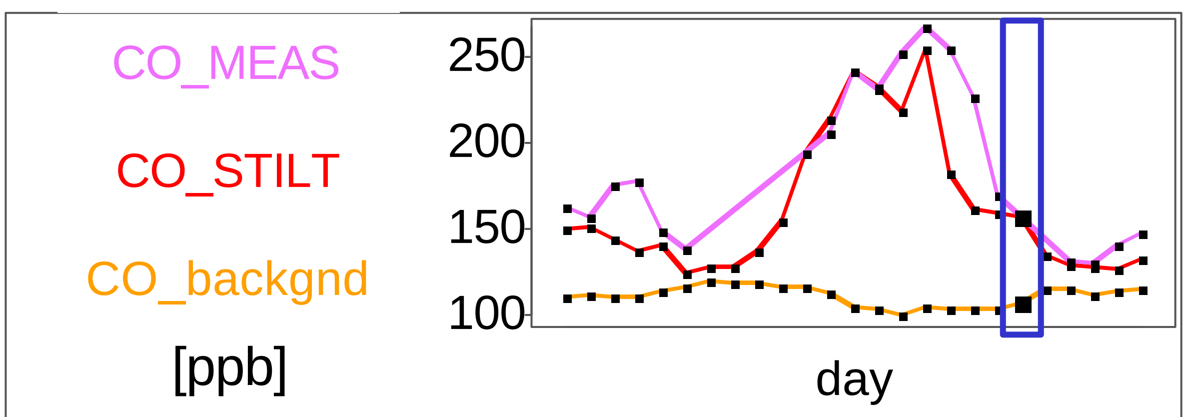
[*Gerbig et al., 2003b*]

[*Lin et al., 2003*]

Footprint

$$\int I(\mathbf{x}_r, t_r \mid \mathbf{x}, t)\, dt$$



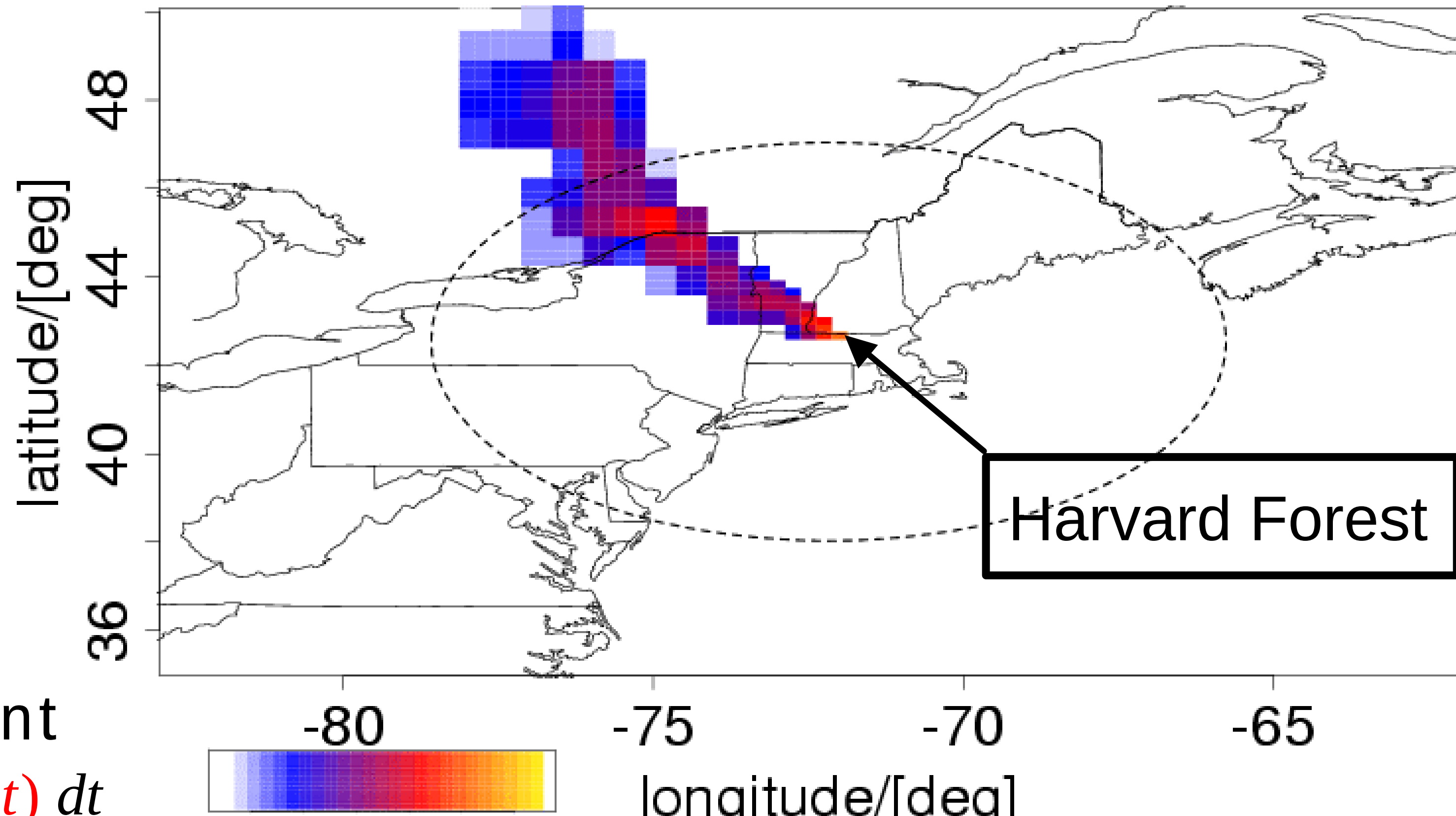


What does a (tall) tower "see"?

STILT

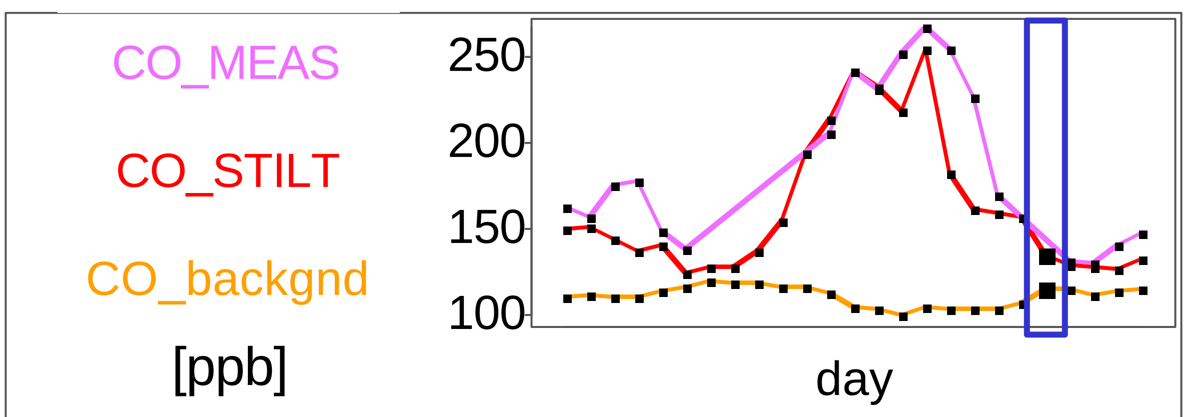
Stochastic Time Inverted Lagrangian Transport Model

[*Gerbig et al., 2003b*]
[*Lin et al., 2003*]



Footprint

$$\int I(\mathbf{x}_r, t_r \mid \mathbf{x}, t)\, dt$$



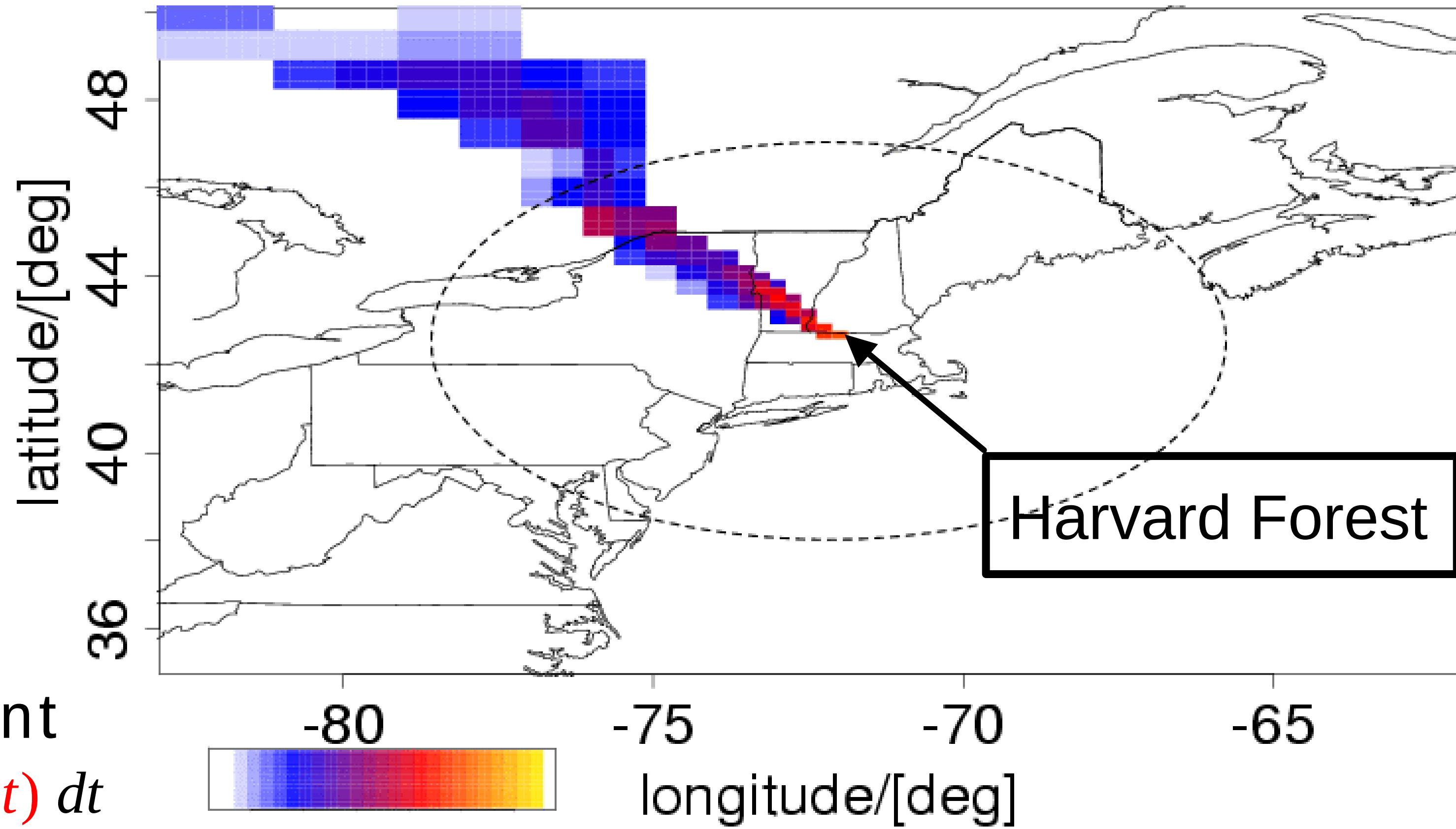
What does a (tall) tower "see"?

STILT

Stochastic **T**ime **I**nverted **L**agrangian **T**ransport Model

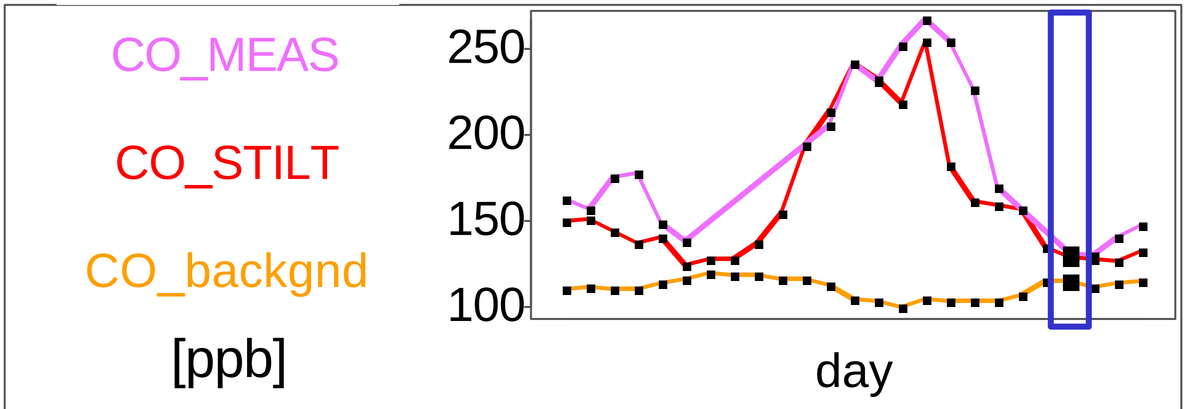
[*Gerbig et al., 2003b*]

[*Lin et al., 2003*]



Footprint

$$\int I(\mathbf{x}_r, t_r \mid \mathbf{x}, t)\, dt$$



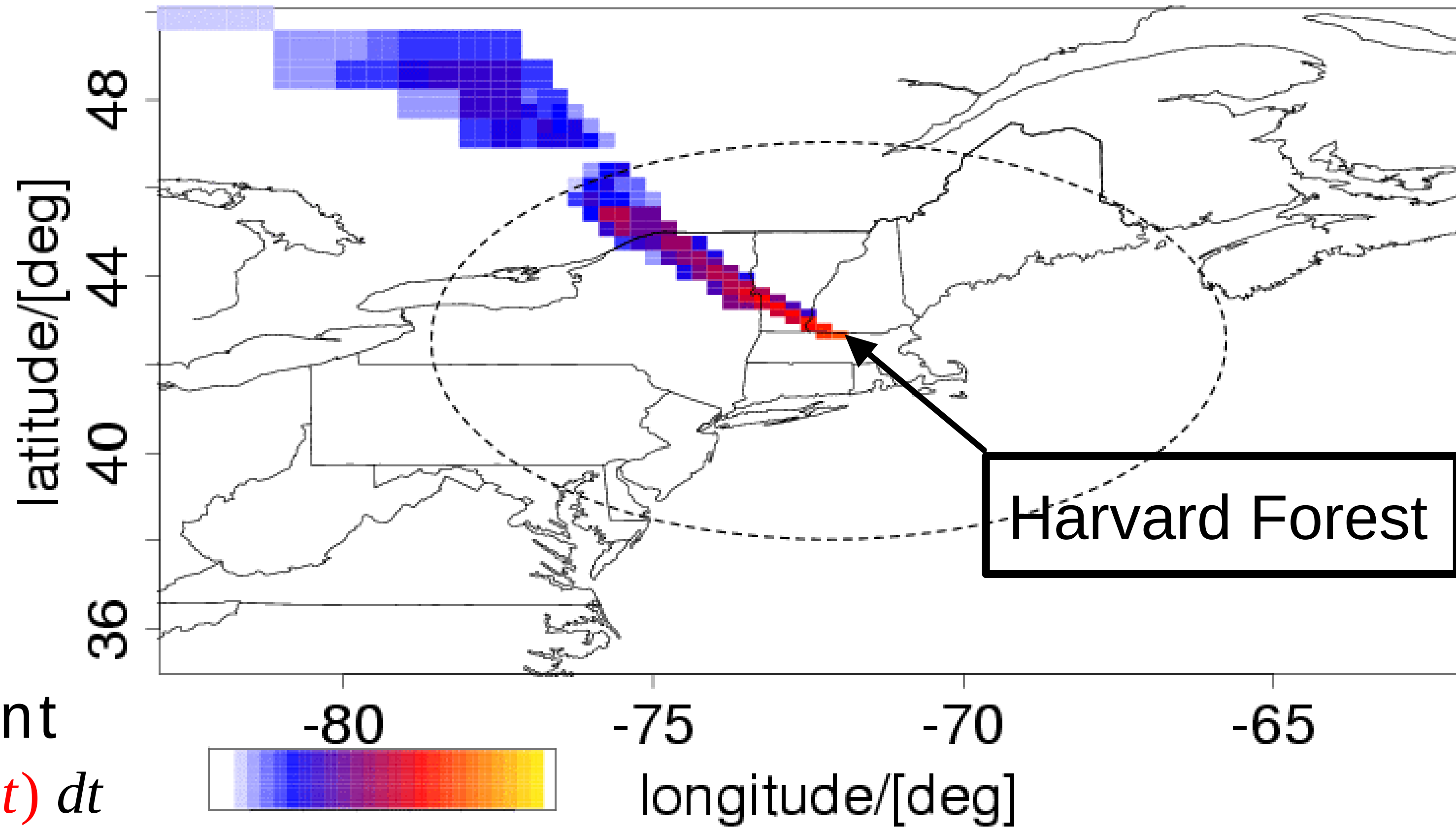
What does a (tall) tower "see"?

STILT

Stochastic Time Inverted Lagrangian Transport Model

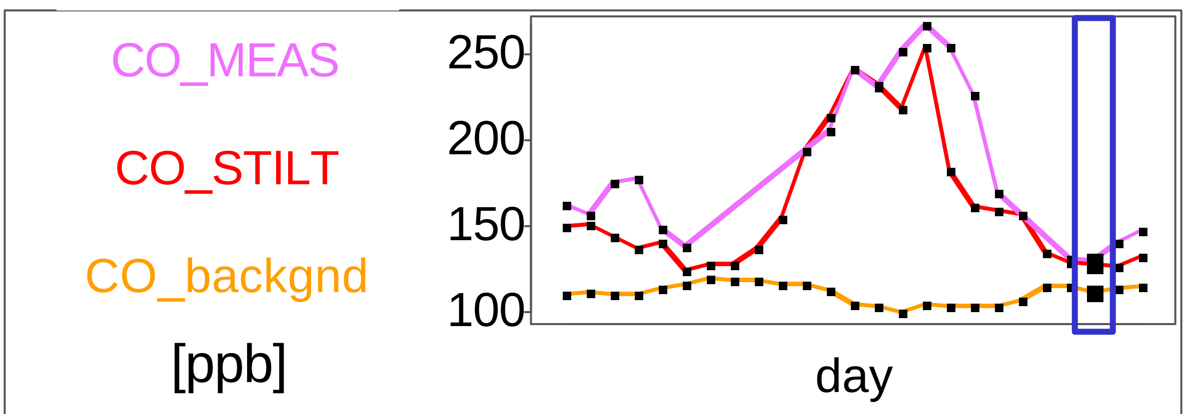
[*Gerbig et al., 2003b*]

[*Lin et al., 2003*]



Footprint

$$\int I(\mathbf{x}_r, t_r \mid \mathbf{x}, t)\, dt$$



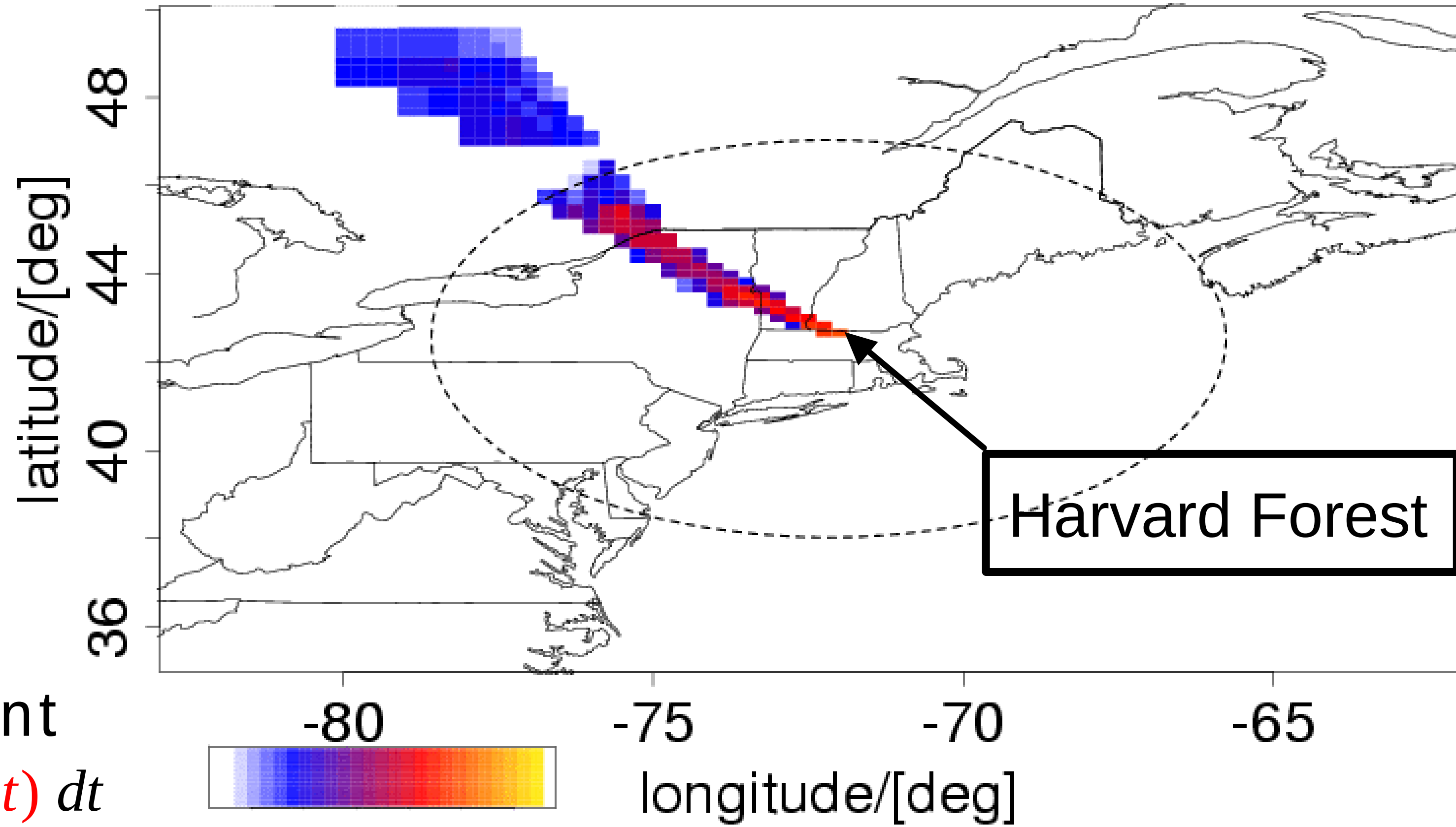
What does a (tall) tower "see"?

STILT

Stochastic Time Inverted Lagrangian Transport Model

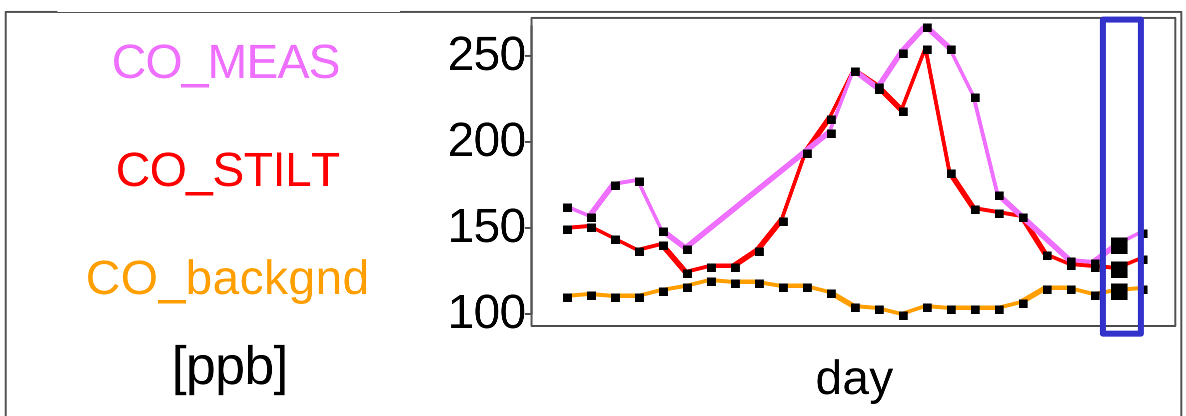
[*Gerbig et al., 2003b*]

[*Lin et al., 2003*]

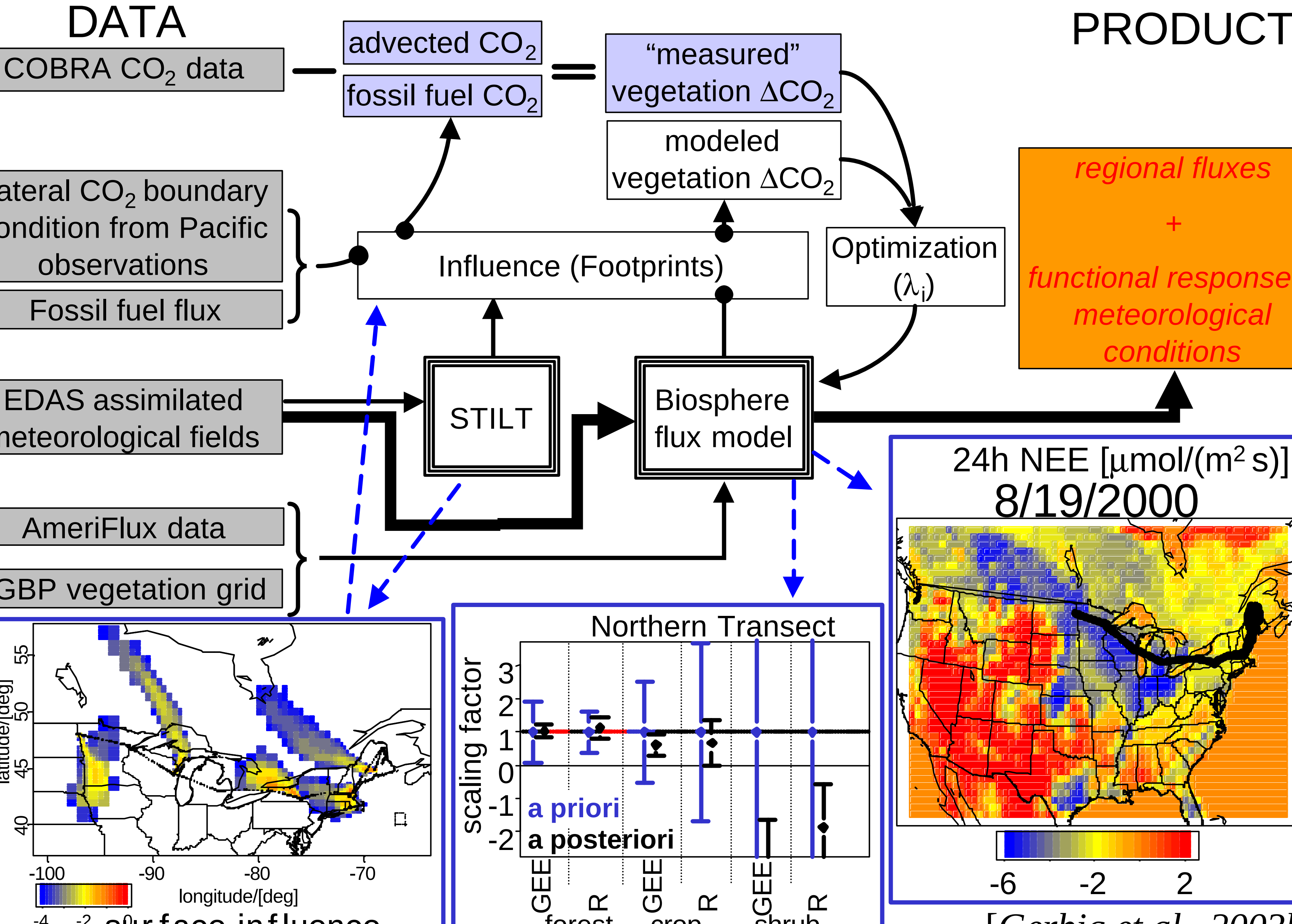


Footprint

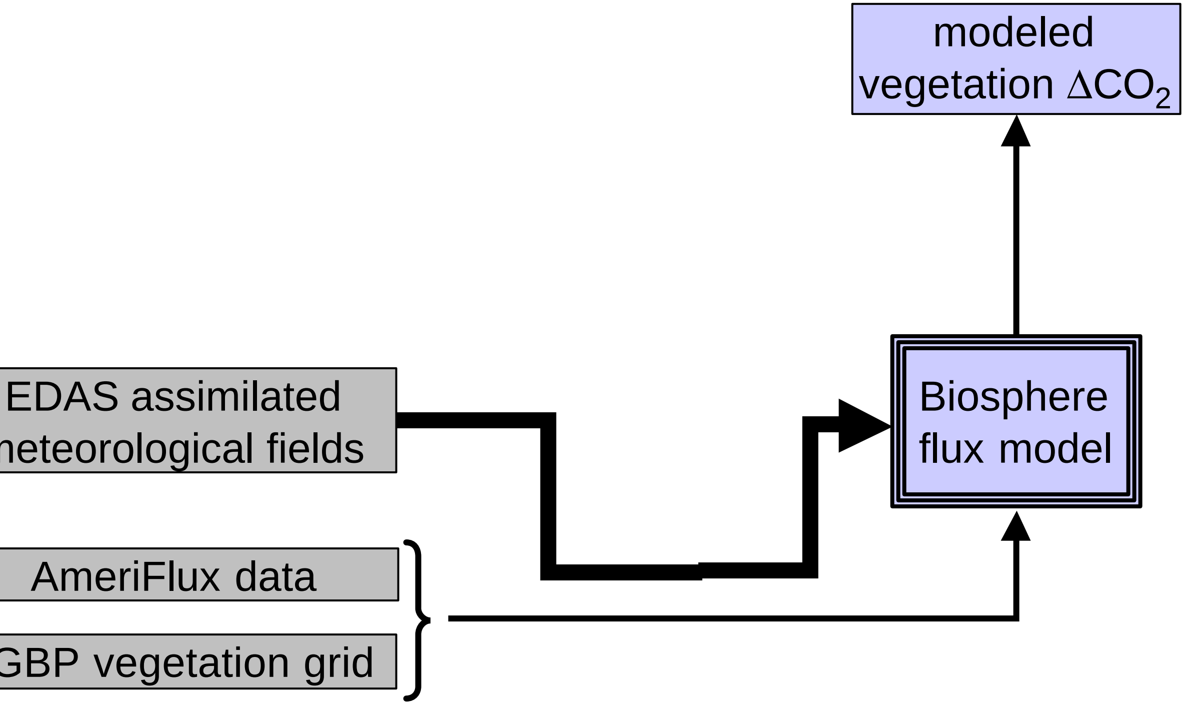
$$\int I(\mathbf{x}_r, t_r \mid \mathbf{x}, t)\, dt$$



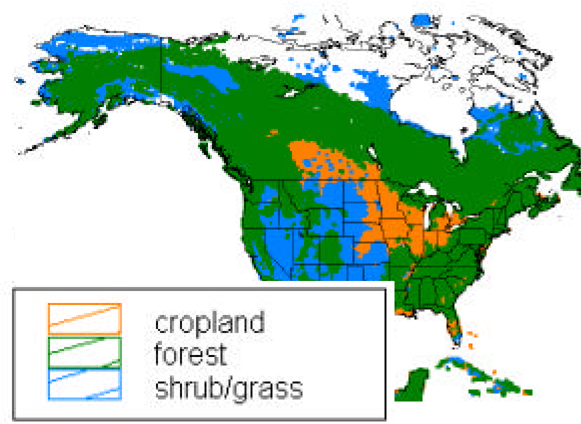
Receptor Oriented Atmospheric Model "ROAM"



Receptor Oriented Atmospheric Model "ROAM"

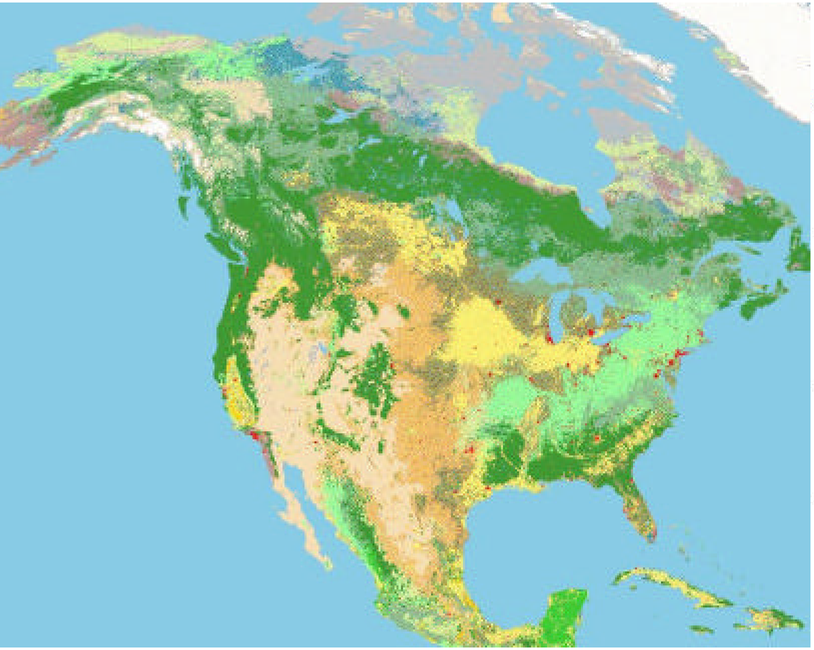


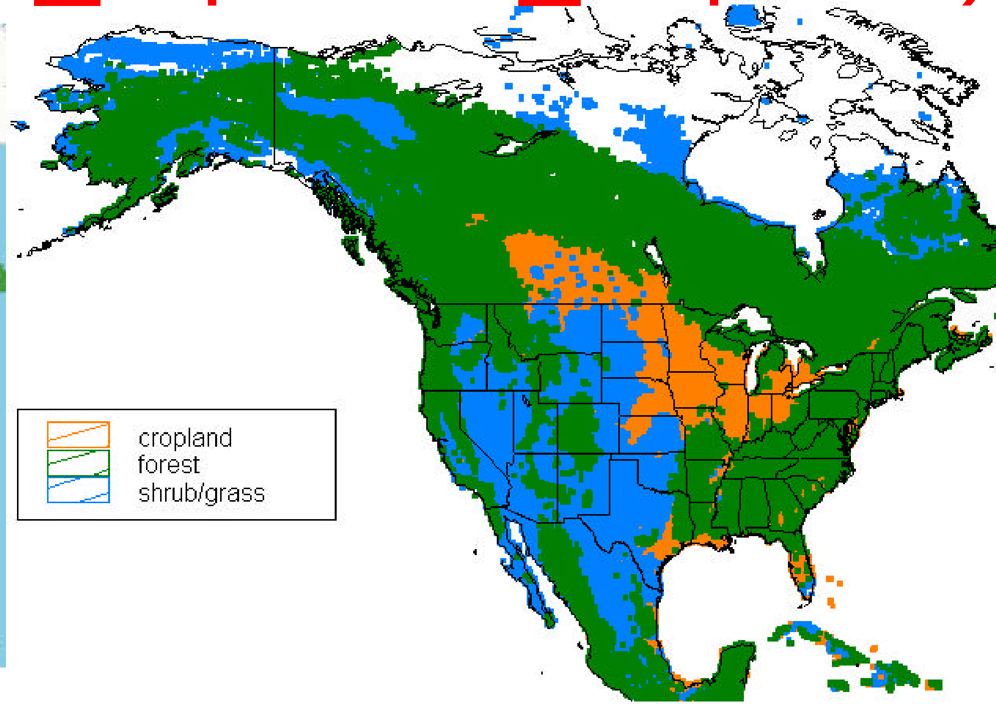
The **GSB** (Greatly Simplified Biosphere)



+ Radiation and Temperature Sensitivity at ~ 15 eddy flux sites (AmeriFlux)

The GSB (Greatly Simplified Biosphere)





GBP Terrestrial Vegetation Map:
17 classes

Minimal Terrestrial Vegetation Map:
3 classes

~10-15 useful eddy flux sites (AmeriFlux)
(mostly NE and SE forests)

$$NEE = \lambda_{ir}\, b_i\, T + \lambda_{ip}\, A_i\, SWR \,/\, (\Gamma_i + SWR)$$

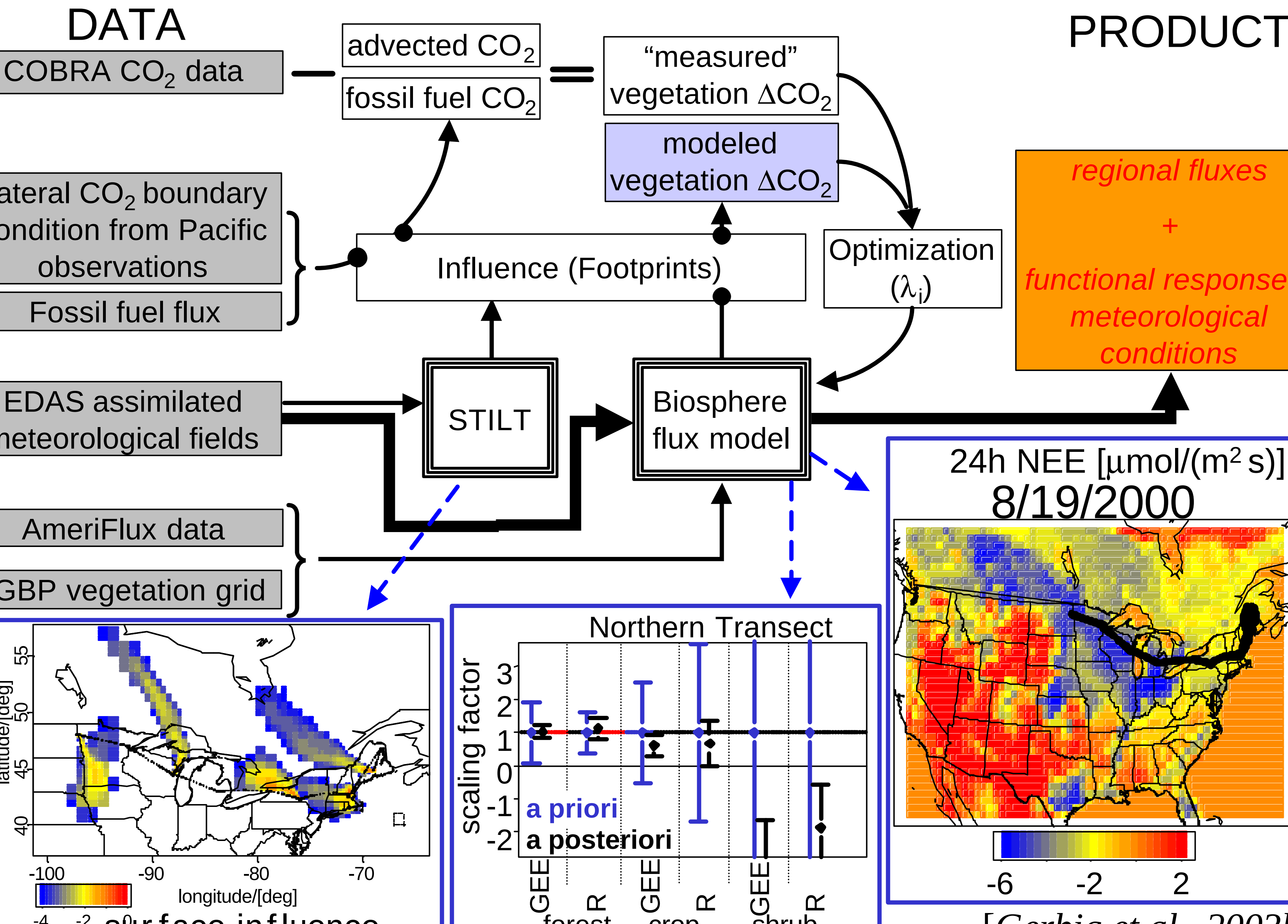
$(b, A, \Gamma)_i$ from eddy flux data, T and SWR from EDAS
λ factors for upscaling, with a priori uncertainty. [Gerbig et al., 2003]

The GSB (Greatly Simplified Biosphere)

\+ captures dominant patterns of variability in space (vegetation cover) and time (light sensitive)

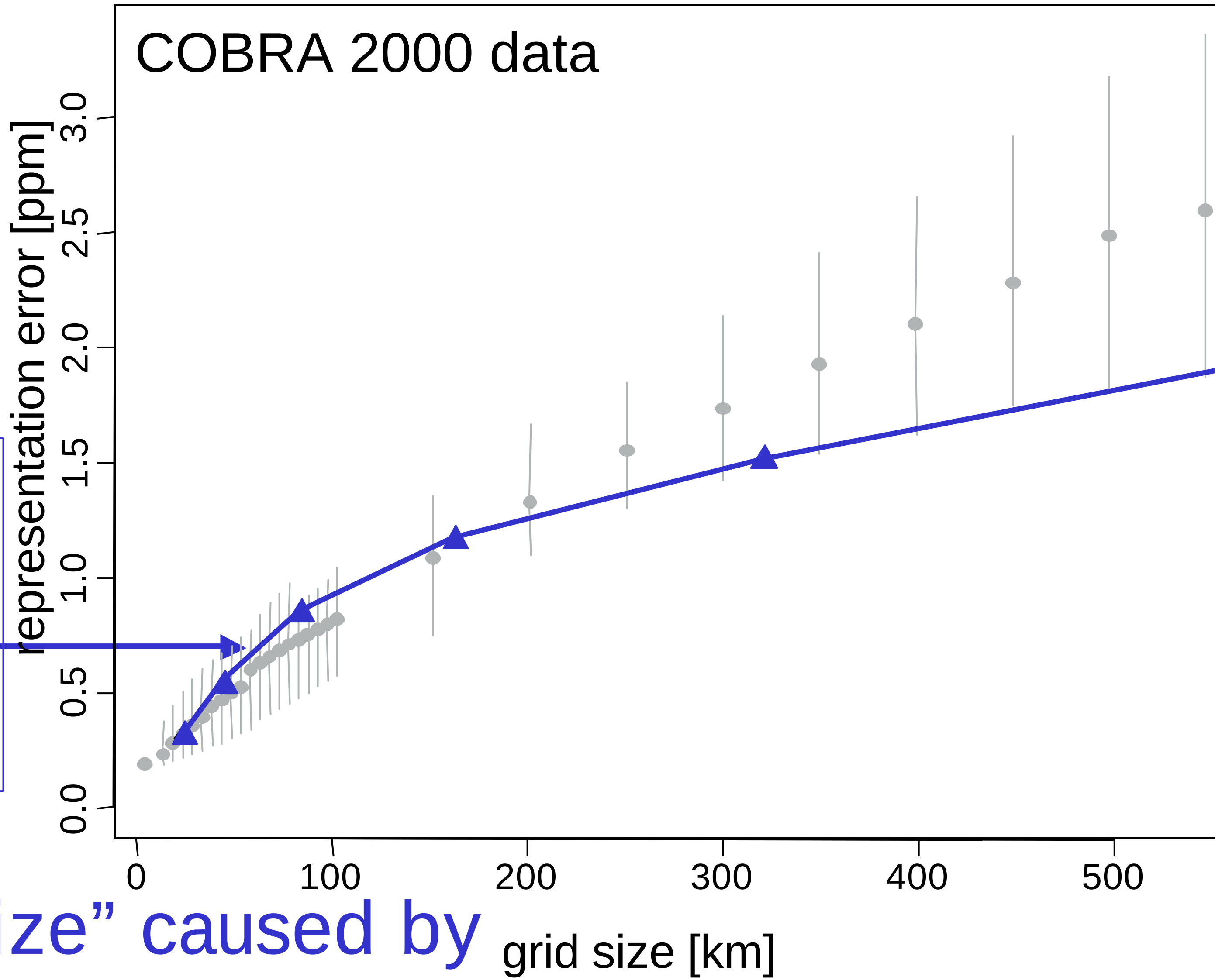
\- Not very detailed, only diagnostic

Receptor Oriented Atmospheric Model "ROAM"



Grain size of atmospheric CO_2: Representation error

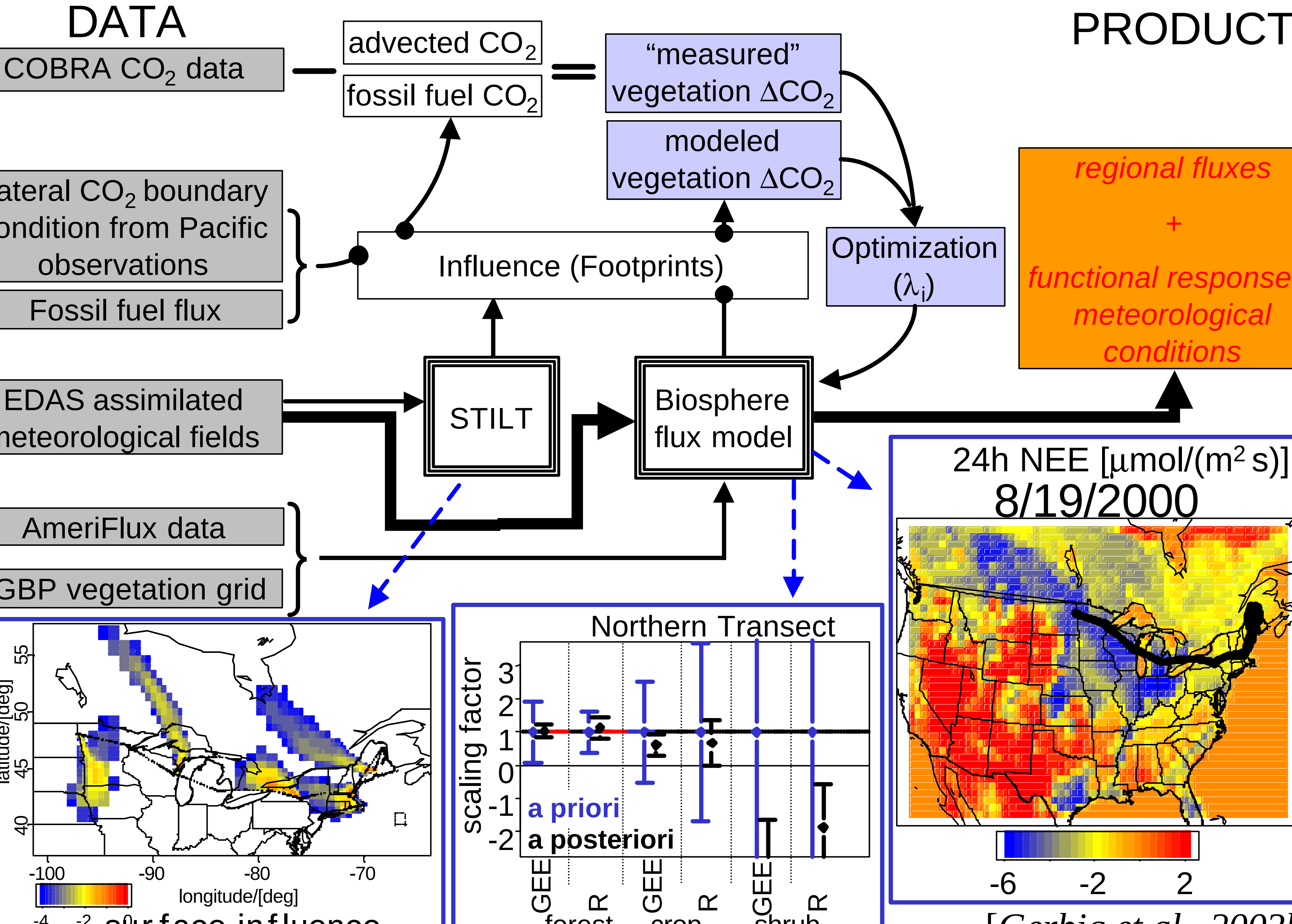
simulated representation error: grid degradation in surface fluxes



⇒"Grain size" caused by patterns in surface flux

[*Gerbig et al., 2003b*]

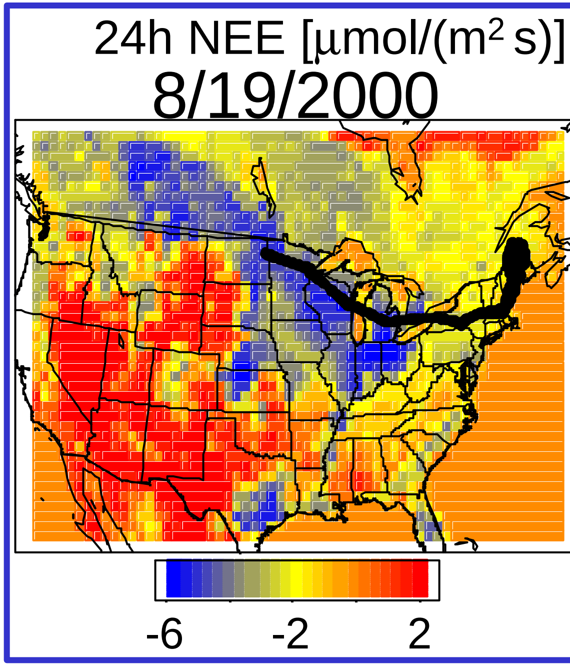
Receptor Oriented Atmospheric Model "ROAM"



Receptor Oriented Atmospheric Model "ROAM"

- Does it work? Is this realistic?

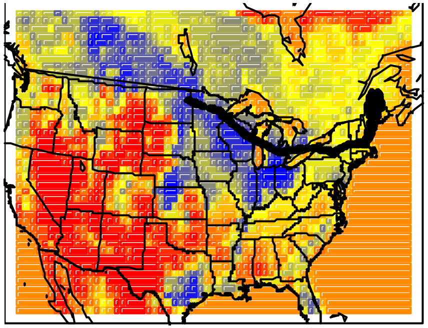
- Compare spatial tracer distribution with observations to validate (or falsify)

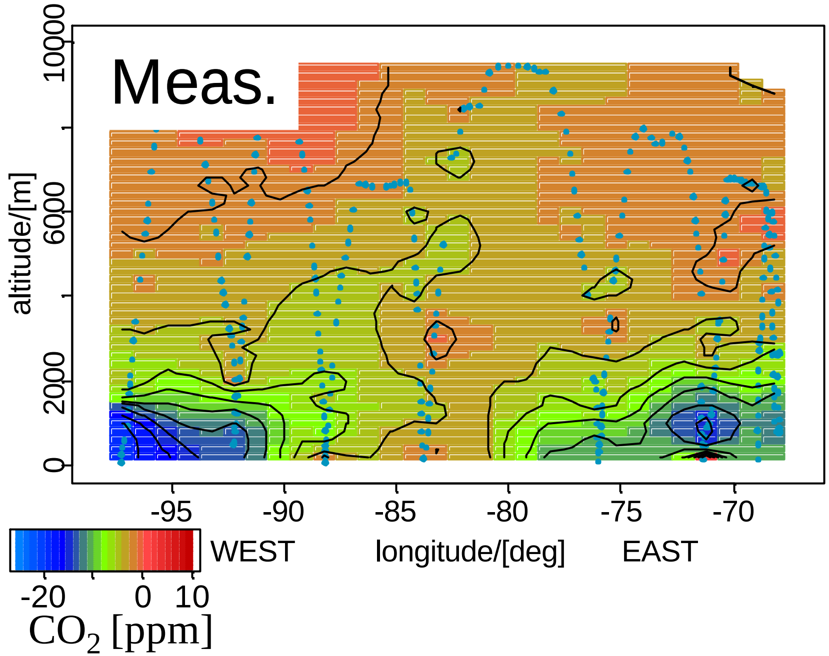


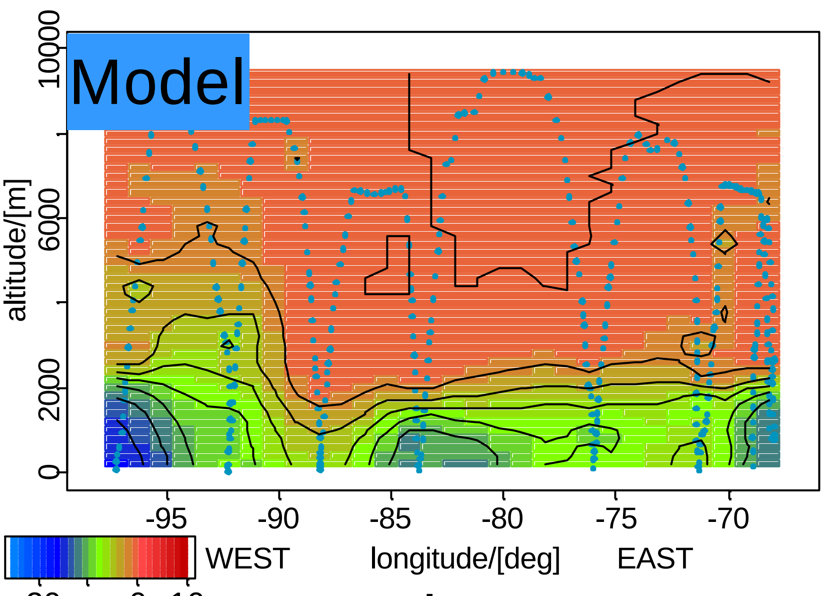
[Gerbig et al., 2003]

Large-scale "biospheric" CO_2 distribution

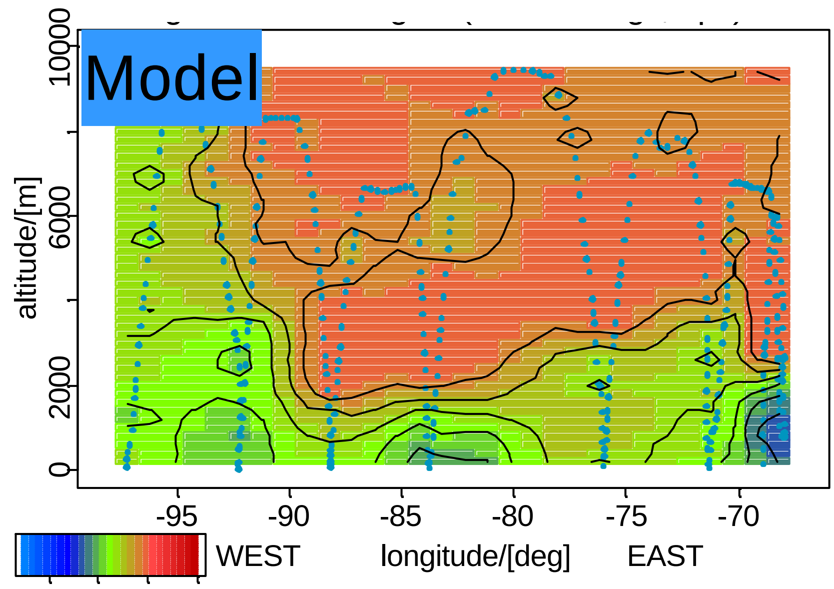
COBRA 2000
northern survey







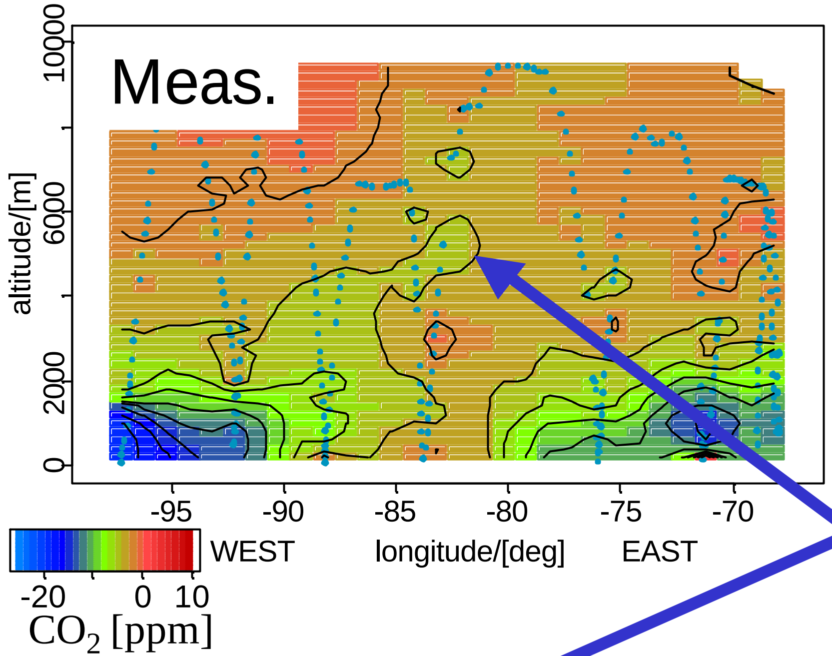
no subgr. conv.



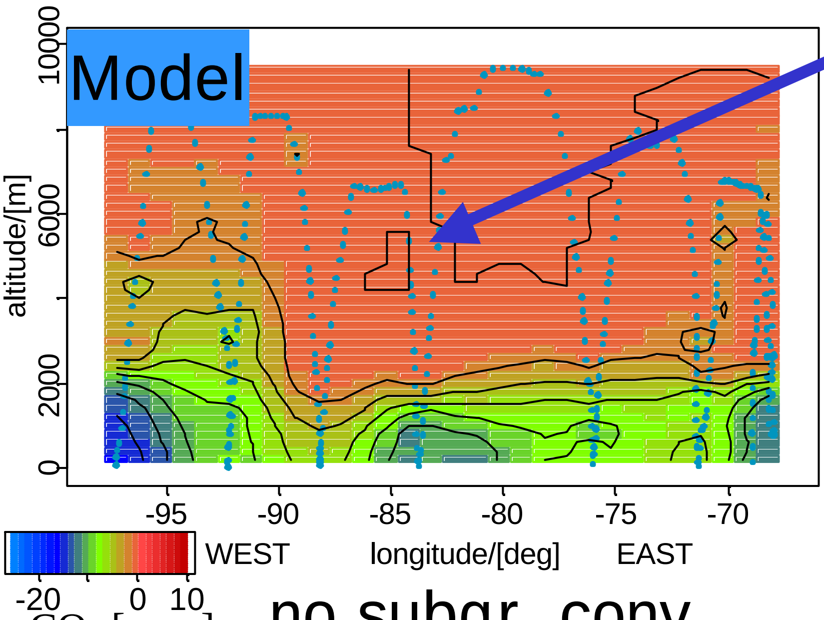
excessive convection

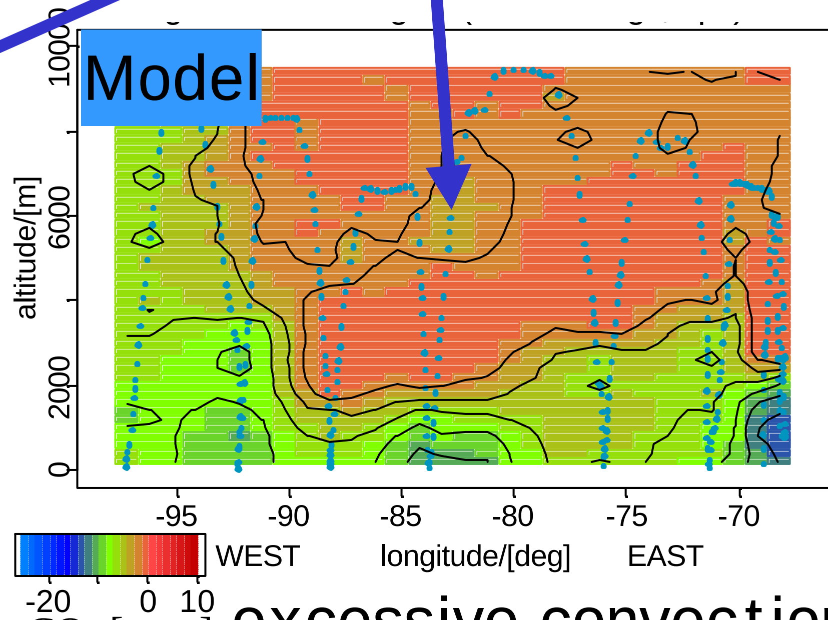
Large-scale "biospheric" CO_2 distribution

COBRA 2000
northern survey



vertical mixing,
convection...



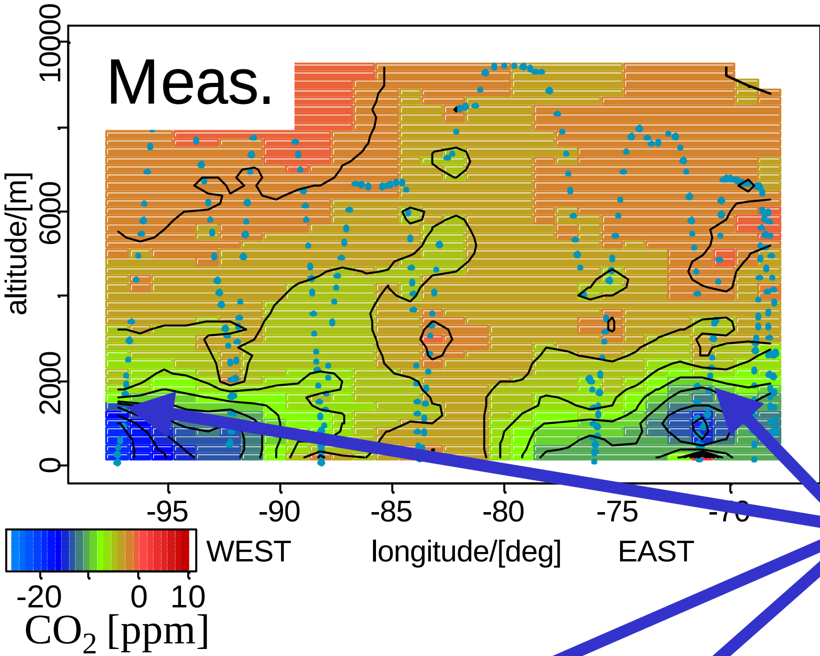


no subgr. conv.

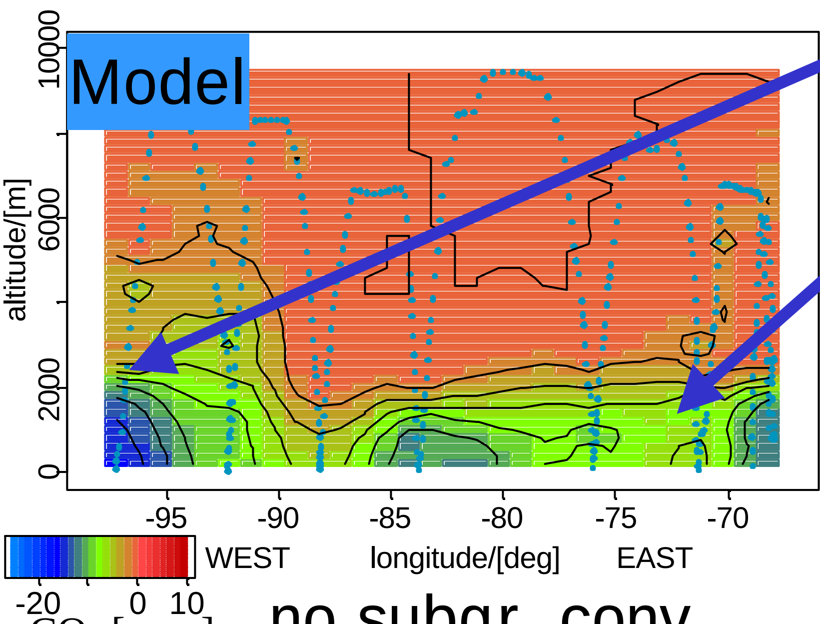
excessive convection

Large-scale “biospheric” CO_2 distribution

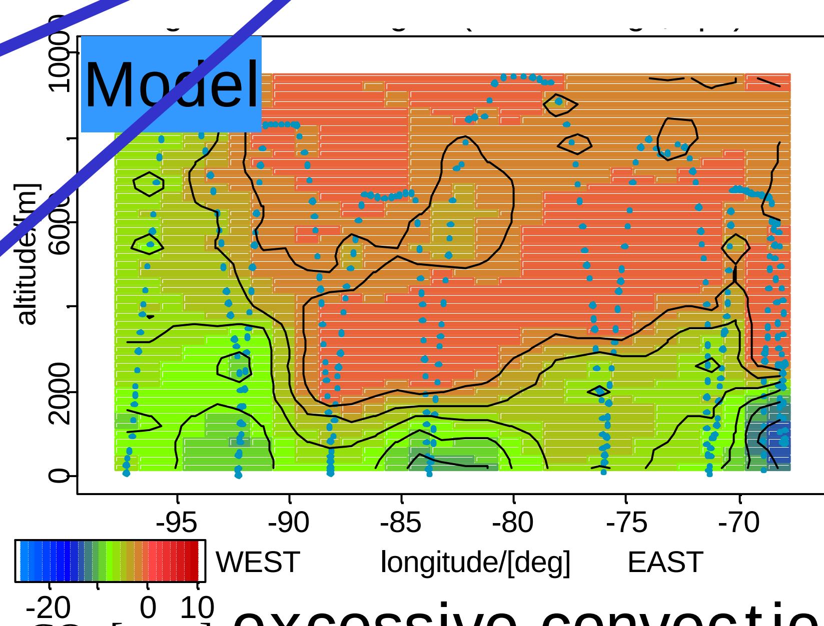
COBRA 2000
northern survey



vertical mixing,
„z_i“...



no subgr. conv.

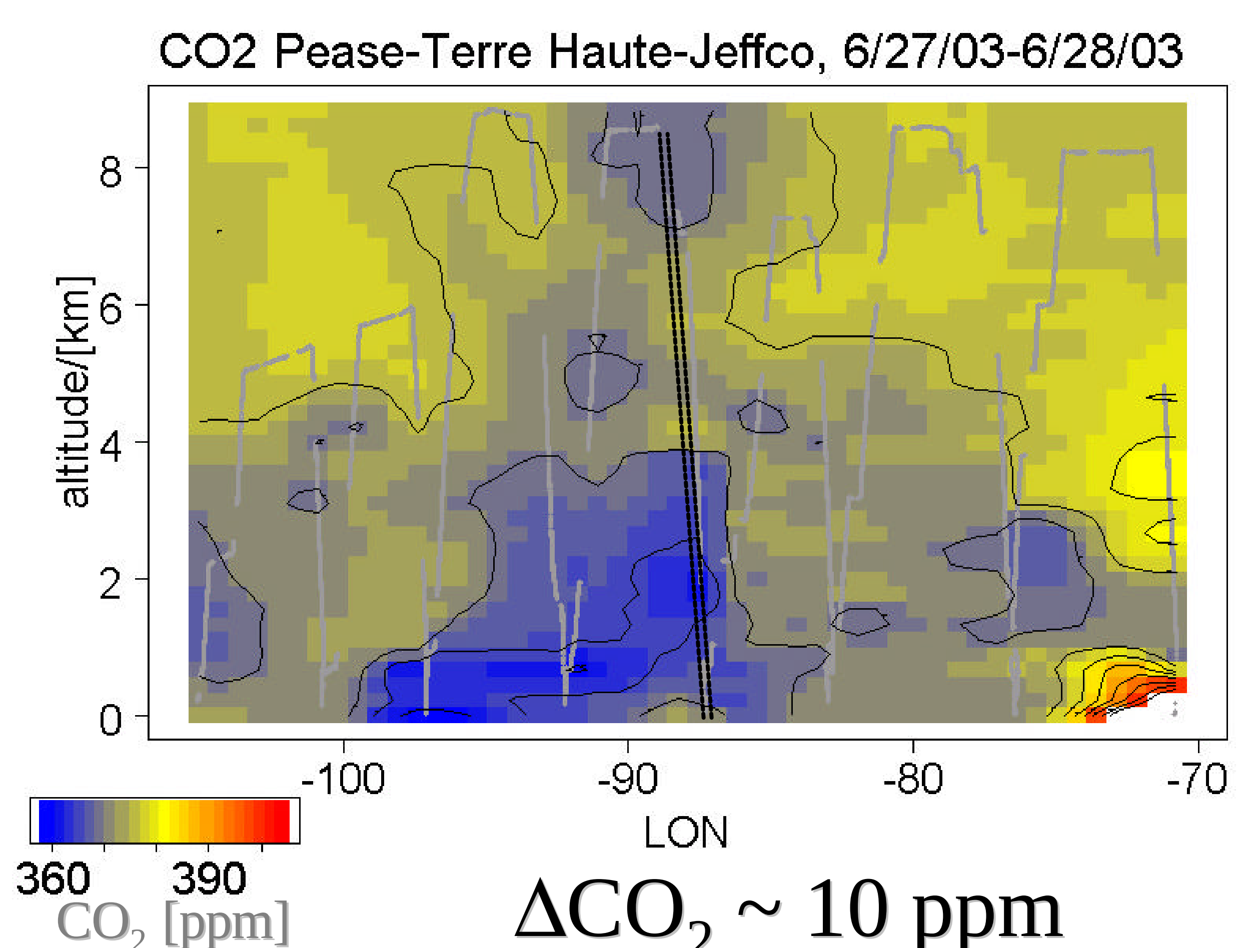


excessive convection

Constraints on Convective Fluxes

- COBRA-2003, June 2003

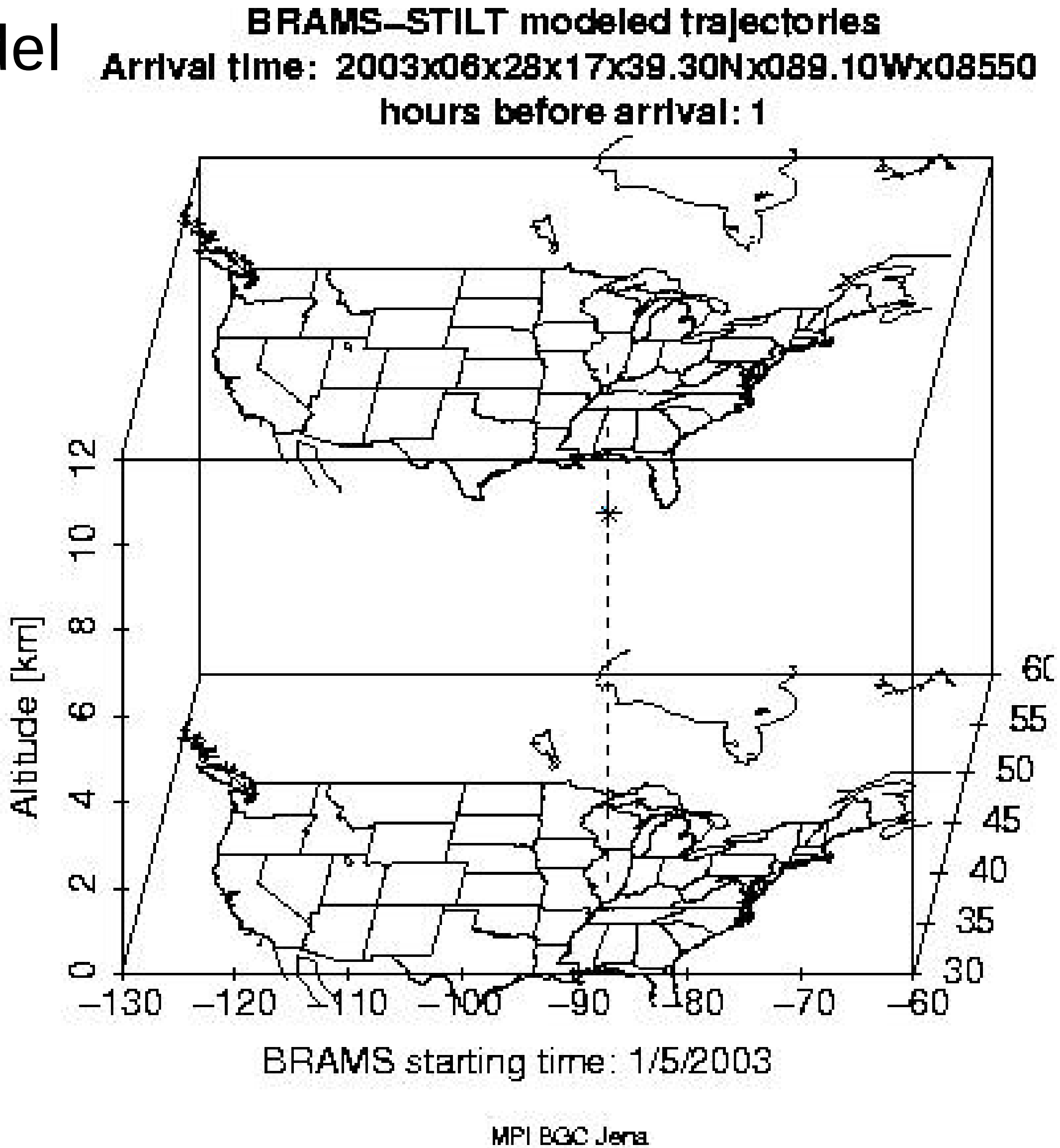
CO_2 Measurements over the U.S.



$\Delta CO_2 \sim 10$ ppm

STILT-BRAMS: convection

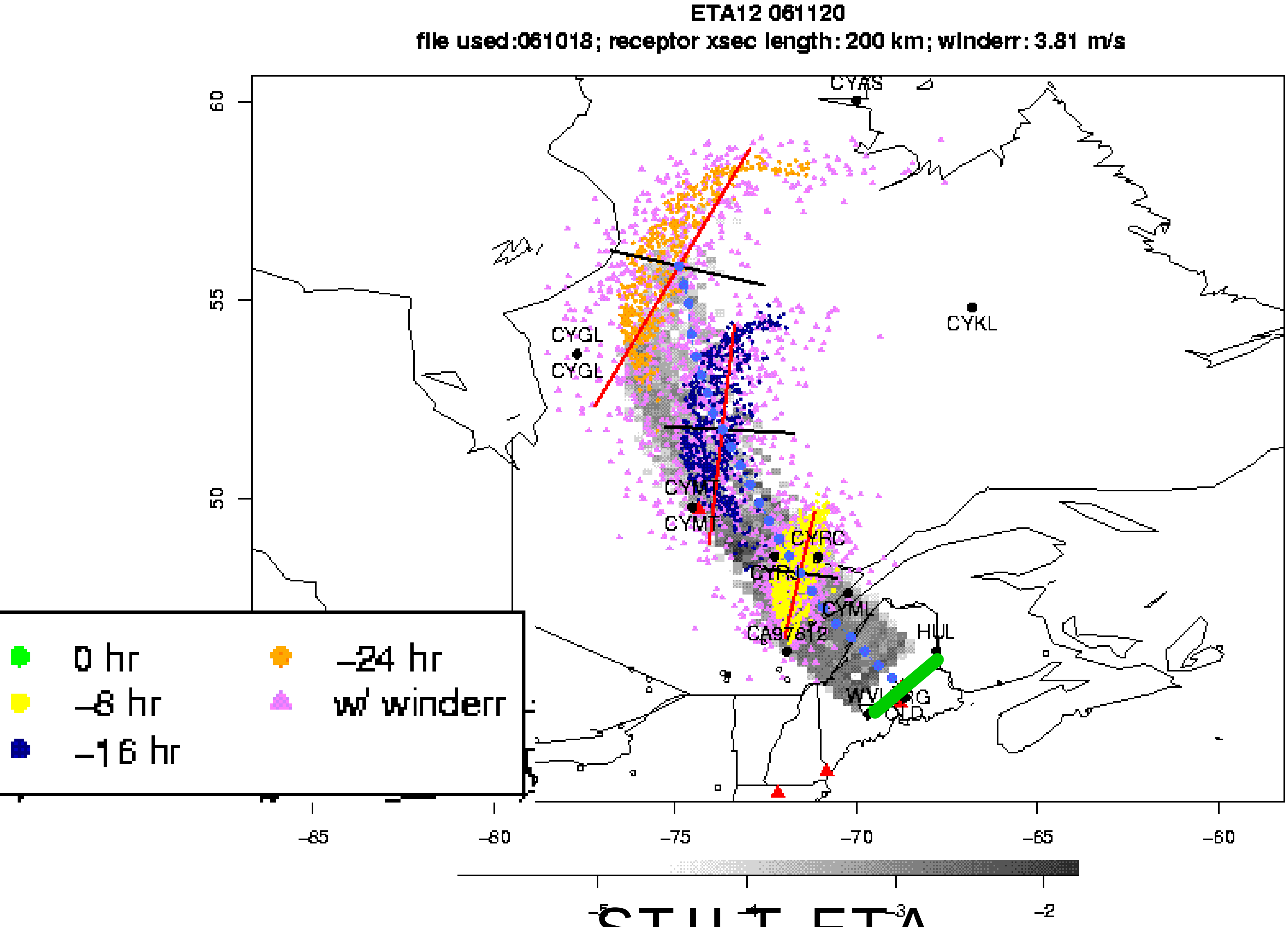
Stochastic Time Inverted Lagrangian Transport Model
coupled to
Brazilian Regional Atmospheric Modeling System



backward particle motion,
receptor at top of
COBRA profile
6/28/03, ~18:00

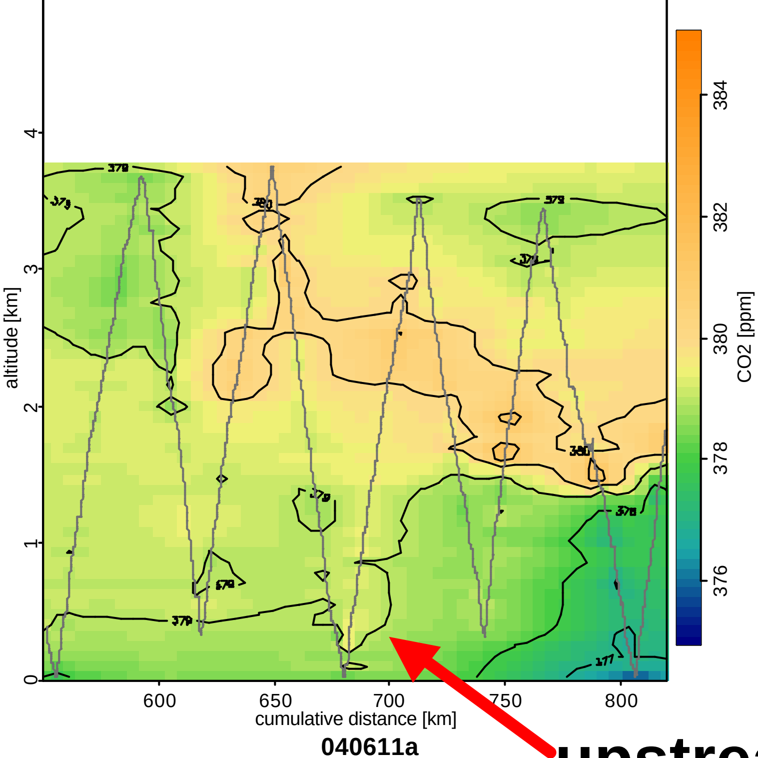
+ fluxes, + boundary condition

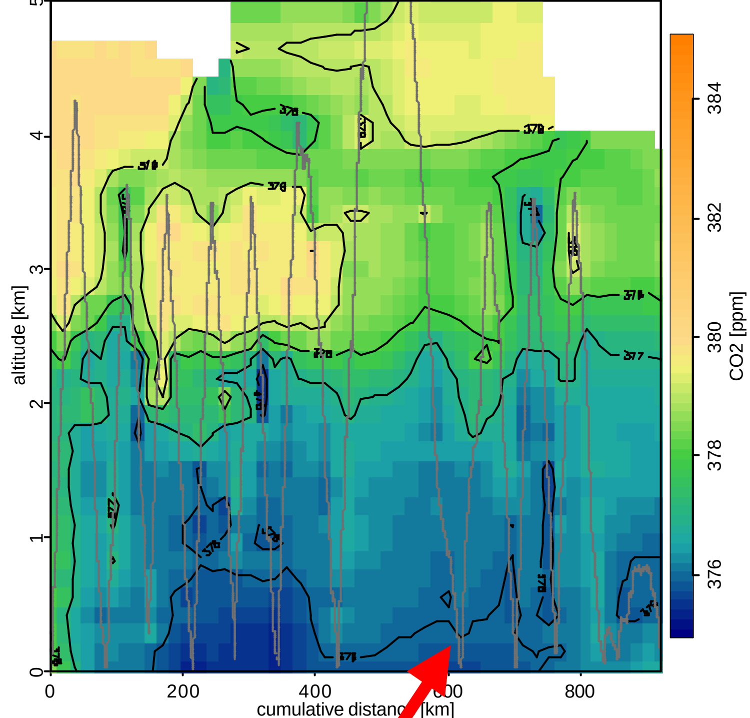
Forecasting of airmass history: Lagrange Experiment



STILT-ETA

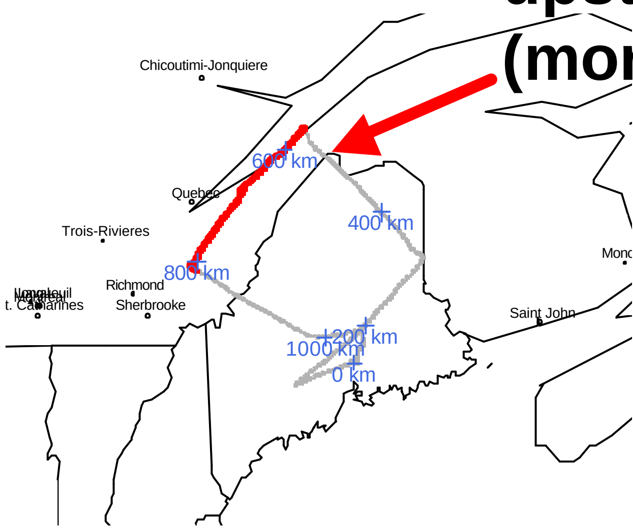
CO_2

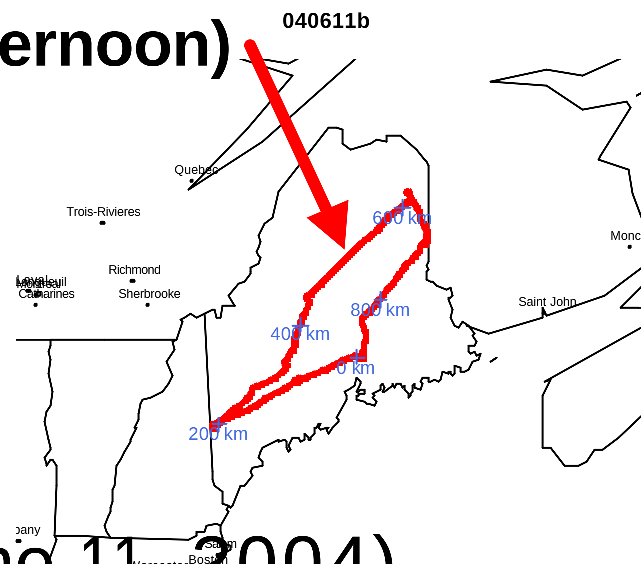




upstream (morning)

downstream (afternoon)





COBRA Maine (June 11, 2004)

Concluding Remarks

Future observational network:

- More continental sites that are closer to processes
- Vertical distribution:
  - CMDL: rental aircraft
  - IAGOS: Integration of routine Aircraft measurements into a Global Observing System
  - remote sensing (ground based and satellite based)

Airborne intensive data can provide

- Constraints on fluxes / terrestrial processes
  - Tight constraint on regional scale: Lagrangian experiments
- “Testbed” for a modeling framework
  - we can only learn from discrepancies models vs. measurements (mixing, convective redistribution)

How we can learn: Interplay between modeling and experiment

- Model => Measurement: utilize the little flexibility we have in the experiments (many constraints by sensors/physics, platforms)
- Measurement => Model (example: grain size): models are more flexible than we often think, need to design models to match measurements (thus they become falsifiable)