ECN

Energy research Centre of the Netherlands

# Going where the action is: Using in situ observations to verify greenhouse gas emissions

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ECN **Outline**

- The greenhouse gas signal in the atmosphere
  - The role of the planetary boundary layer
- Observations: scales in time and space
- Inverse transport model techniques
- Results
  - Local
  - Global
  - Regional
- Outlook
  - Measurement techniques
  - Modelling
  - Networks

## ECN Take home messages

- The answer is in the (lower) atmosphere:
- We will need all observations and more, the system is still poorly constrained
- We cannot relive the past, we should measure (more) now!

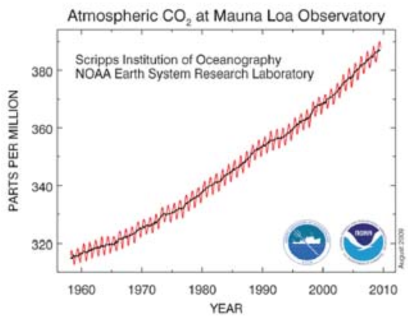


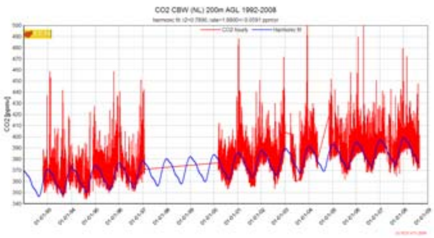
## ECN Why greenhouse gas observations in the atmosphere?

- Actual concentrations in air determine the greenhouse effect
- Direct message to public and policy
- Airborne fraction of fossil fuel $CO_2$ is key parameter
- Emissions are uncertain: long atmospheric life-time of GHG allows us to trace location and size of emission (hopefully)

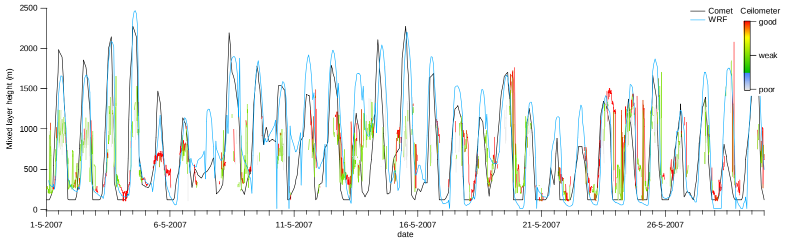
Main goals:

- Improved process understanding and calibration of biogeochemical models
- Monitor the trends of regional to global fluxes as a response to climate change and mitigation
- An independent emission verification system



## ECN Traceability of emissions in the atmosphere

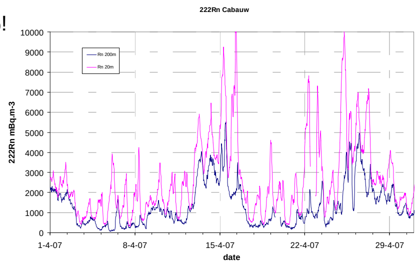



Emissions + planetary boundary layer height and wind speed determine concentration for ~90%!

Daily variation dilutes the signal during transport

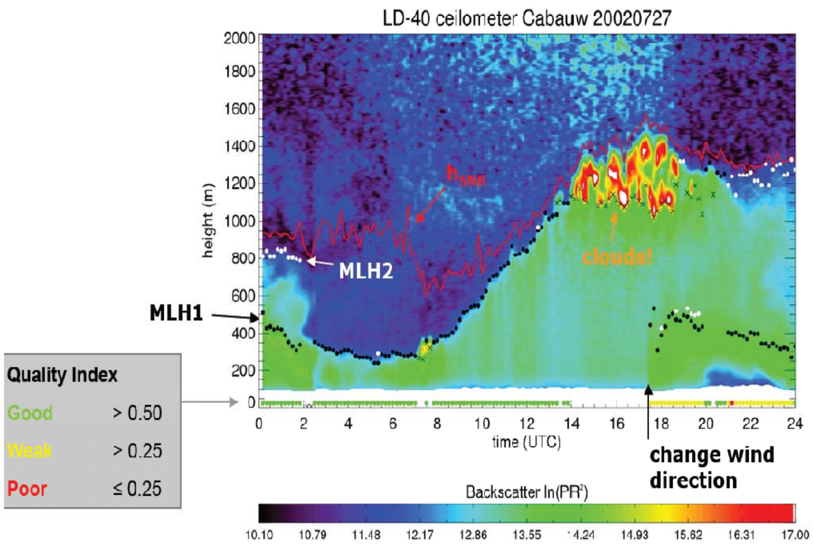
Remote stations receive a signal that is diluted with a factor 10-100! ->Need for high accuracy. OK for global balance

But for regional estimates:
Only way out: observations in the emission area!

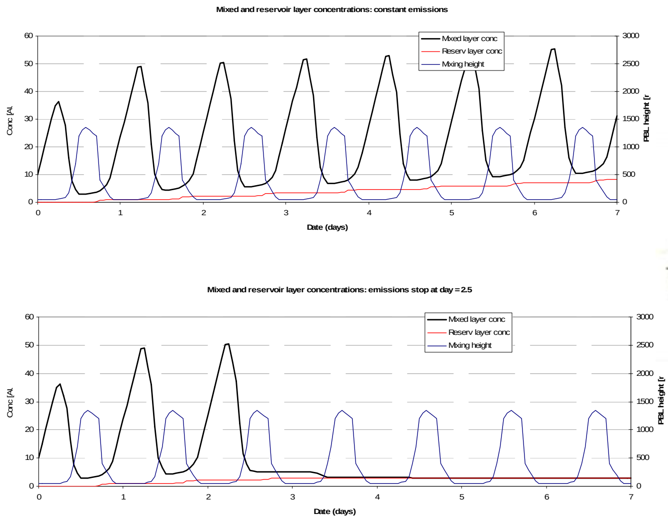





## ECN PBL height observations CBW (ceilometer)

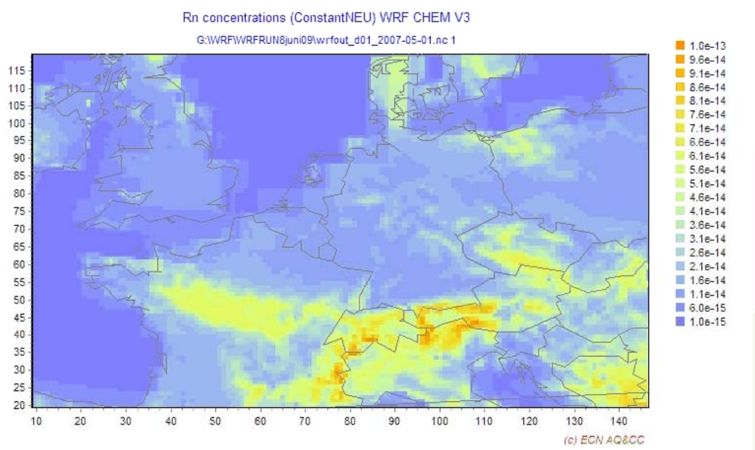


## Simplest model illustration of diurnal signal attenuation



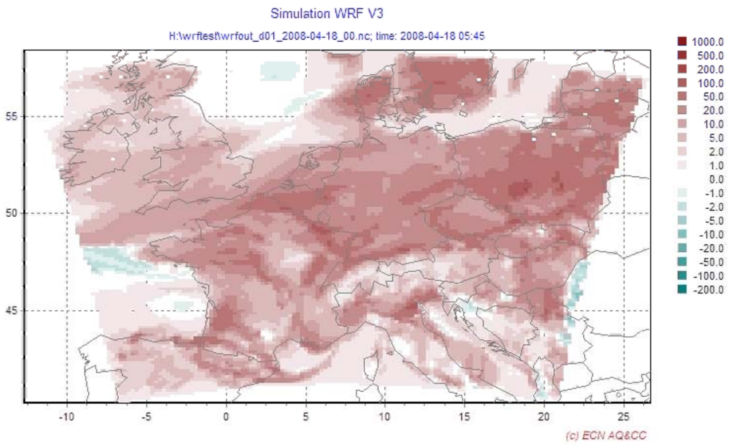



## Constant emissions modulated by PBL and transport



## $CO_2$ hourly fluctuating emissions modulated by PBL and transport (WRF hi-res)

CO2: 5 km res vegetation model; MODIS satellite LAI
Edgar-4 0.1° res fossil fuel; taka08 ocean uptake






## In situ observations: classification in space and time

- Time:
  - Grab samples (flasks, cylinders, satellite): daily-weekly
  - Semi-continuous (half-)hourly
  - Continuous (20 Hz – 5 minute averaging)
- Space:
  - Remote (days of transport time from sources)
  - Regional (one to several hours transport time)
  - Polluted (less than 1 hour transport time)
- Vertical
  - Surface
  - Tower (vertical profile)
  - Column (ground based or remote sensing)
- Mobile (aircraft, ship, train, balloon)

## Representativity of in situ sampling

- Local climatology
- Local sources and sinks
- Vertical extent of the measurement
- Timing of the sampling
- The rectifier effect, correlation of fluxes with:
  - Nighttime shallow boundary layer
  - Daytime well mixed high boundary layer

- High resolution (time+space) & accurate modelling is required

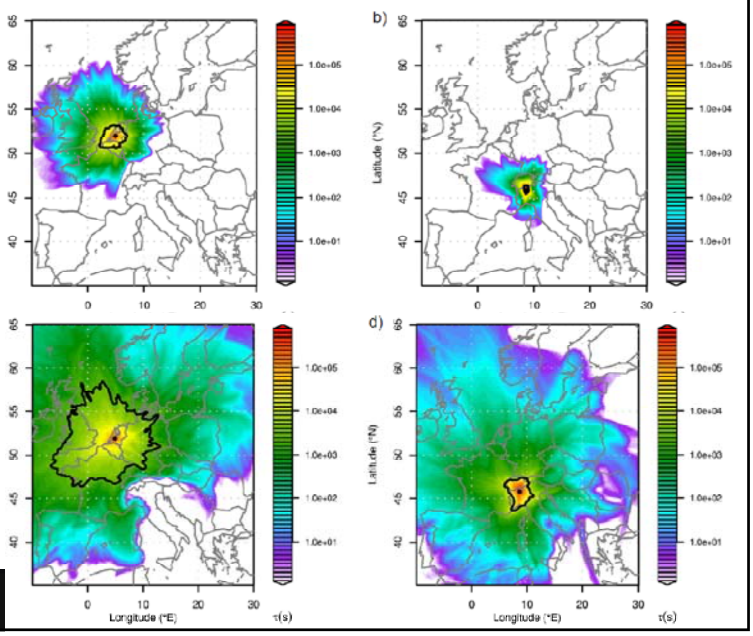


## Footprints: two extremes CBW and Ispra

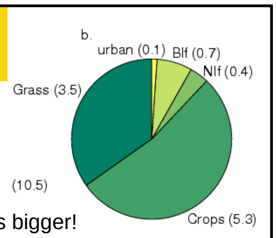
Henne et al, ACPD, 2009

Annual footprint
1/2 day backwards

Annual footprint
2 days backwards



## Atmospheric $CO_2$ s/s apportionment

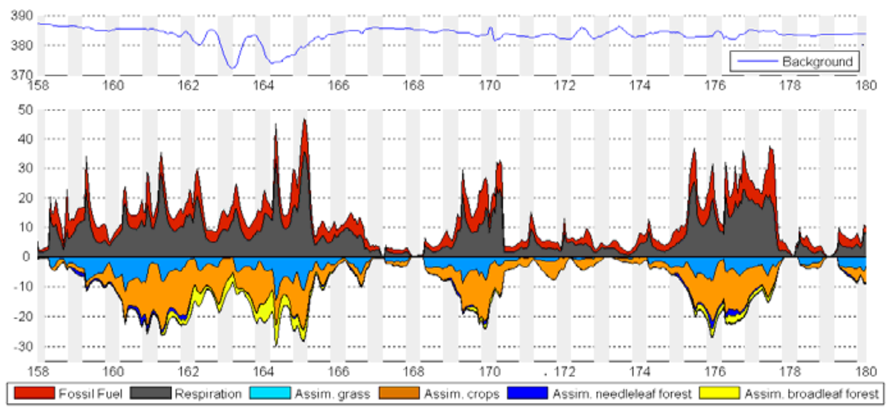



Tolk et al, BG, 2009

RAMS mesoscale simulation

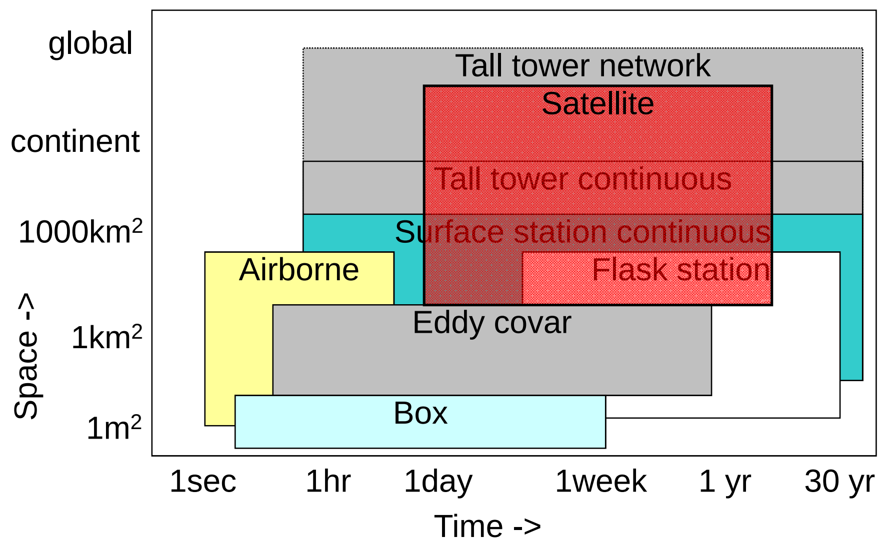
Simplified but hires biosphere, IER hires fossil fuel fluxes

Transport errors big, but atmospheric signal due to variability in s/s is bigger!



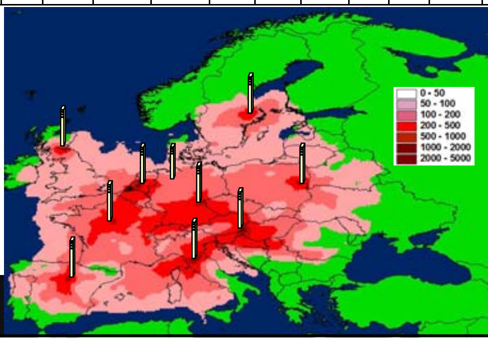



## Measurement platforms and scales in time and space



## An observational (tall) tower network in Europe

| | | Hght | Position | | Concentration measurement (levels) | | | | | | | Flux meas | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Name | | (m) | Lon | Lat | $CO_2$ | $CH_4$ | $N_2O$ | $SF_6$ | CO | $^{222}Rn$ | Flasks | $CO_2$ | $CH_4$ | Operator |
| Cabauw | NL | 200 | 04°56’ | 51°58’ | 4 | 4 | 4 | 4 | 4 | 1 | ✓ | 2 | | ECN |
| Griffin/Angus | UK | 232 | -2°59' | 56°33’ | 1 | 1 | 1 | 1 | | 1 | | | | UEDIN |
| Hegyhatsal | H | 117 | 16°39’ | 46°57' | 4 | 1 | 1 | 1 | 1 | | ✓ | 2 | | ELTE |
| Orleans/Trainou | F | 131 | 2°07’ | 46°58’ | 3 | 3 | 3 | 3 | 3 | 1 | ✓ | | | LSCE |
| Norunda | S | 102 | 17°28’ | 60°05’ | 4 | 2 | | | | | | 2 | 2 | LUPG |
| Florence | I | 245 | 11°16’ | 43°49’ | 1 | 1 | 1 | 1 | 1 | | | | | UNITUS |
| Ochsenkopf | D | 163 | 11°49’ | 50°03’ | 3 | 3 | 3 | 3 | | | ✓ | | | MPIBGC |
| Bialystok | PL | 300 | 22°45’ | 52°15’ | 5 | 5 | 5 | 5 | 5 | | ✓ | | | MPIBGC |
| Lutjewad | NL | 60 | 6°21’ | 53°24’ | 2 | 2 | 2 | 2 | 2 | 1 | ✓ | 2 | | CIO-RUG |
| La Muela | ES | 84 | 1°06’ | 41°35’ | 1 | | | | | | ✓ | 1 | | PCB |





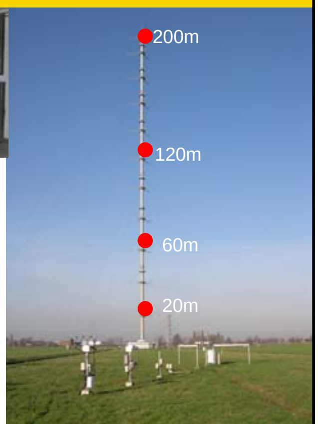

## Tall Tower Example: Cabauw GHG measurements

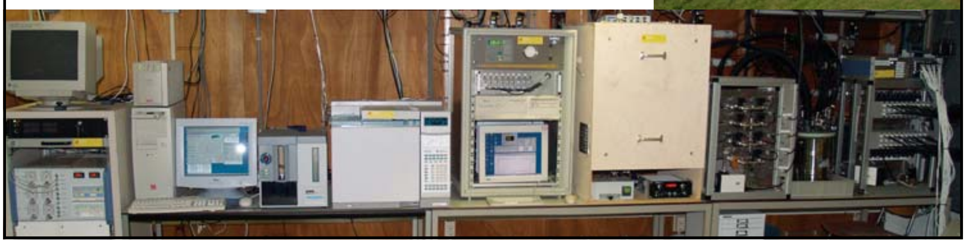
51° 58' N 4° 56' E
Constructed 1972: KNMI
super-site: CESAR

GHG observations by ECN 1992-now
Tower at -2m ASL, 213 AGL
Inlets at **20, 60, 120, 200 m** AGL

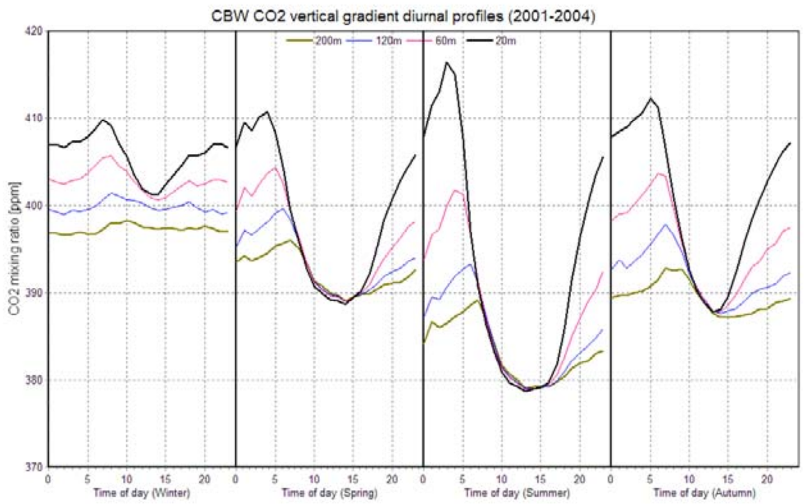
Concentrations (precision up to 0.05%)
GC: **$CH_4$, $N_2O$, CO, $SF_6$, $H_2$**
NDIR: **$CO_2$**
Gradient of **$^{222}Rn$** (20, 200 m ASL; 2005)
Eddy **flux $CO_2$** (KNMI, WUR) at 3 levels

http://www.cesar-observatory.nl



## Vertical profile data (CBW)






## (Inverse) modelling techniques (1)

- Global models have in last 10 yrs evolved from coarse (6°x8°) to medium resolution (0.5°-1°)
- Mesoscale models have evolved to resolutions of ~2x2 km
- Most driven by global meteorological fields from Numerical Weather Prediction models: ECMWF IFS, UKmo, GFS
- Typical examples
  - Eulerian global models: TM5, LMDZ, TM3
  - Eulerian mesoscale: RAMS, WRF, Chimere
  - Lagrangian models: Flexpart, NAME, Stilt

## (Inverse) modelling techniques (2)

- Direct (matrix) inversions
  - No need for prior estimates, variances or covariance
- Data assimilation (Bayesian)
  - Needs information on error variation and covariances
  - Needs prior estimate

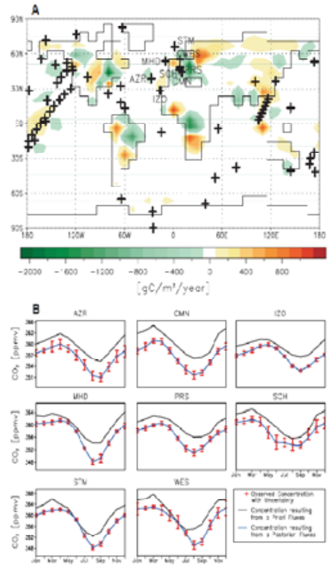
Examples:

Fan et al, Science, 1998

Bousquet, Science, 2002

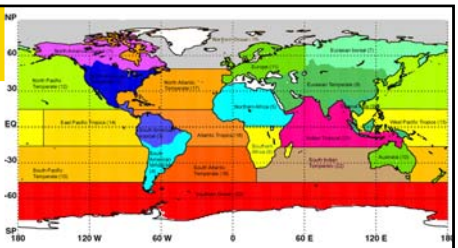
Kaminski, Science, 2002->

Transcom 3

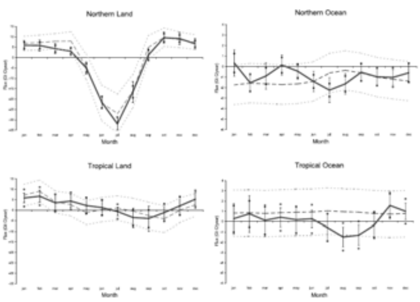




## Global budget results

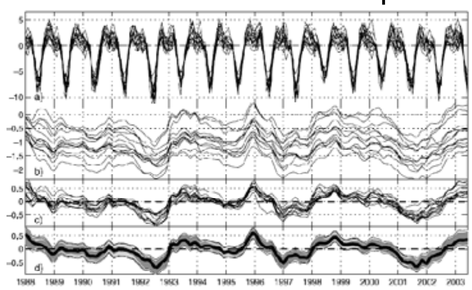


Transcom 3:
12 global models
Big region approach (22 regions of the world)
Common prior fluxes
Common inversion routines
Invert monthly mean daytime concentration of global network
Large offsets in derived fluxes, but relative changes relatively robust




Guerney et al, GBC, 2004

Europe:



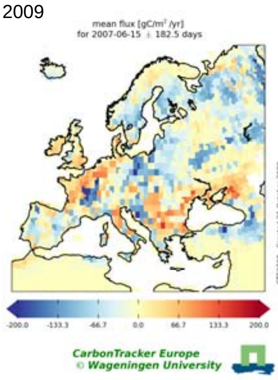
Baker et al, GBC, 2005

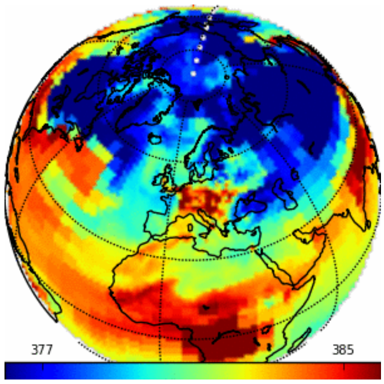
## ECN (Inverse) modelling techniques (3)

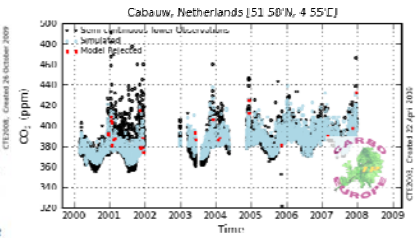
- CarbonTracker (US+EU)
- http://www.carbontracker.eu/
- High resolution TM5: 1x1 degree
- Optimizes 3 weekly parameters

for 18 pft's and 18 ecoregions using daily observations

Peters et al, GCB, 2009



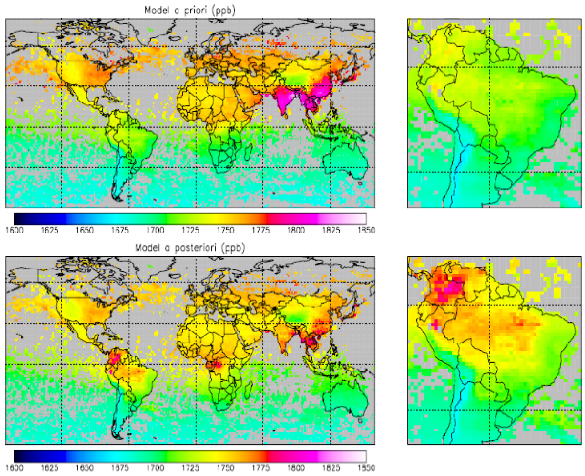






## ECN (Inverse) modelling techniques (4)

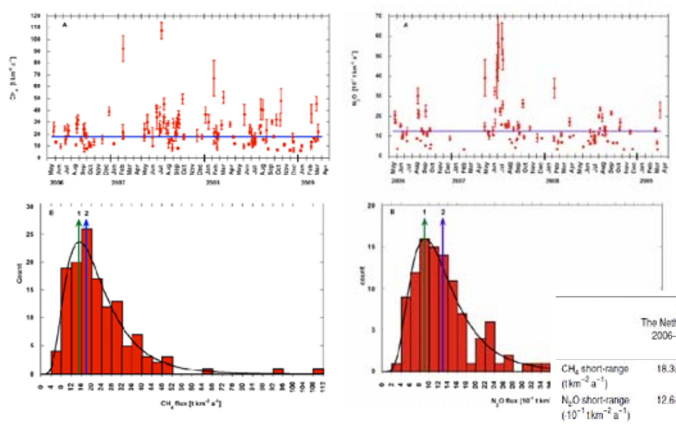
Global bayesian inversion for $CH_4$ based on satellite obs

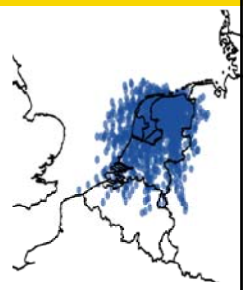
TM5 pixel based inversion at 1x1 degree using SCIAMACHY retrieved $CH_4$ concentrations




Meirink et al, JGR, 2008

# Regional inversion NL of $CH_4$ and $N_2O$ using $^{222}Rn$ tracer





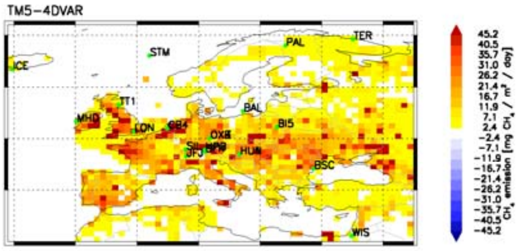
| | National inventories | | | Radon flux method | |
|---|---|---|---|---|---|
| | The Netherlands 2006–2007 | Belgium 2006 | Germany 2006 | Lognormal fit | Lognormal fit (combined uncertainty) |
| $CH_4$ short-range ($t\,km^{-2}\,a^{-1}$) | 18.3±3.3 | | | 15.2±0.4 | 15.2±5.3 |
| $N_2O$ short-range ($\cdot 10^{-1}\,t\,km^{-2}\,a^{-1}$) | 12.6±5.7 | | | 9.2±0.3 | 9.2±3.2 |
| $CH_4$ long-range ($t\,km^{-2}\,a^{-1}$) | | 11.0 | 5.8 | 8.9±0.3 | 8.9±3.1 |
| $N_2O$ long-range ($\cdot 10^{-1}\,t\,km^{-2}\,a^{-1}$) | | 8.8 | 5.4 | 4.2±0.3 | 4.2±1.5 |

vd Laan et al, ACPD, 2009

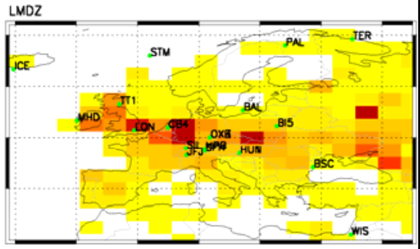


# Regional $CH_4$ inversions (2006)

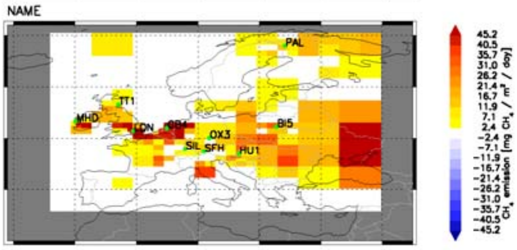
TM5−4DVAR



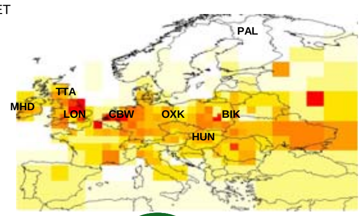

LMDZ




NAME




COMET

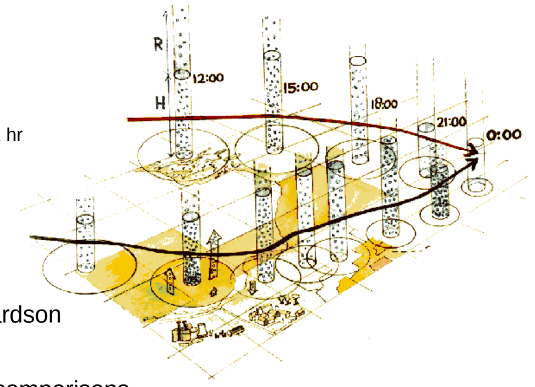



Bergamaschi et al, in prep

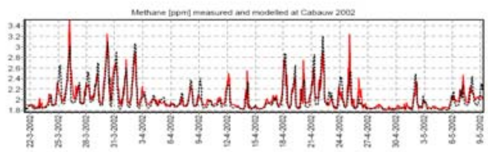
NitroEurope IP

## Transport model COMET

- Lagrangian model
- ECMWF meteorology
  - 0.2° resolution
  - timestep 3 hr, interpolated into 1 hr
- Hourly trajectories (flextra)
- Moving two layered box :
  - Mixing layer
  - Reservoir layer
- Mixing layer height: critical Richardson number
- High performance in model intercomparisons for tall tower stations




*Previous results for $CH_4$ mixed layer bulk concentration: $R^2$=0.8, bias =0 ppb*

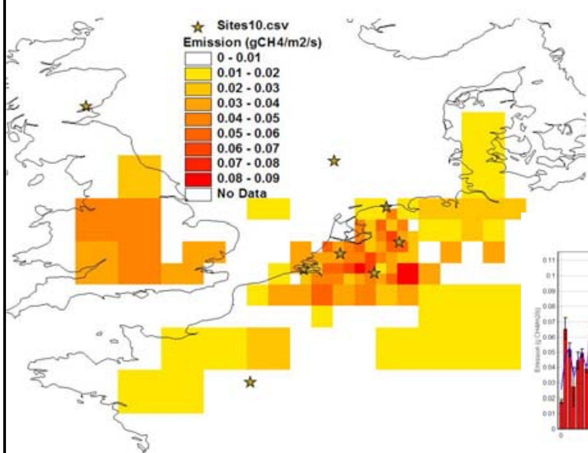


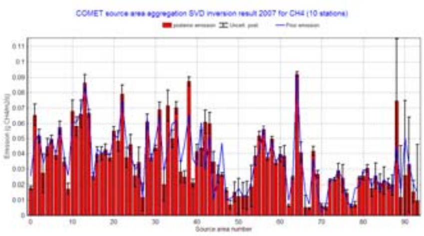

Vermeulen et al., Env. Sci. & Pol., 2, 1999
Vermeulen et al., ACPD, 2006



## Network density and potential for inversion

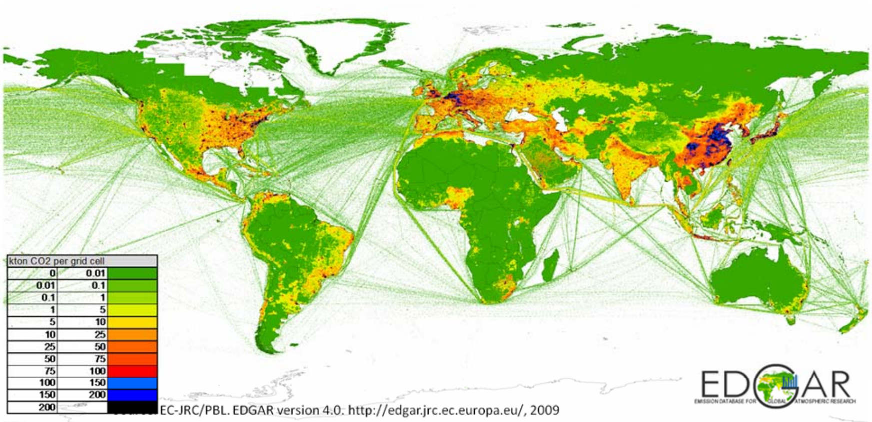
**Synthetic inversion: 6 months of continuous hourly observations 10 stations (MHD+BIK not shown)**



**COMET recursive source aggregation SVD inversion**
**$CH_4$ emissions of 90 regions when using a dense network**

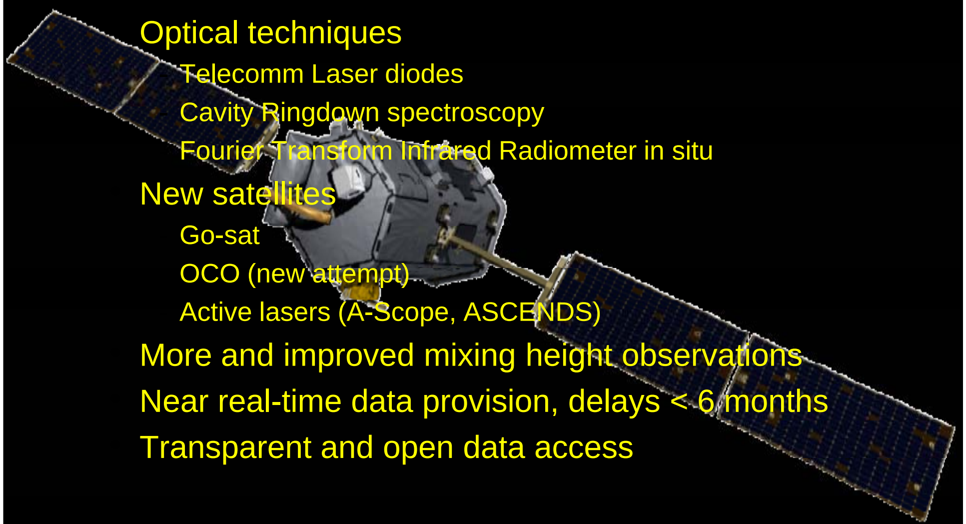
## Outlook for model development




- High resolution prior estimates (e.g. Edgar 4, biosphere models) in space and time



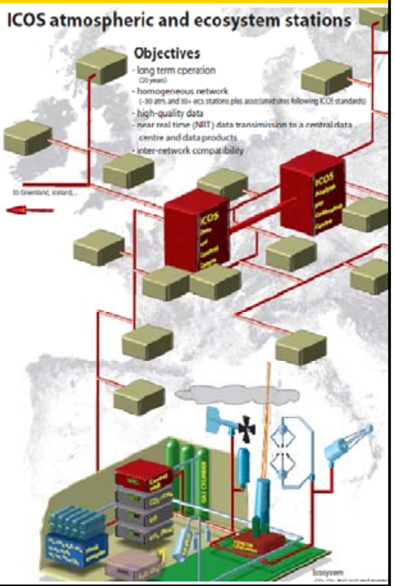
## Outlook for observation technologies



- Optical techniques
  - Telecomm Laser diodes
  - Cavity Ringdown spectroscopy
  - Fourier Transform Infrared Radiometer in situ
- New satellites
  - Go-sat
  - OCO (new attempt)
  - Active lasers (A-Scope, ASCENDS)
- More and improved mixing height observations
- Near real-time data provision, delays < 6 months
- Transparent and open data access

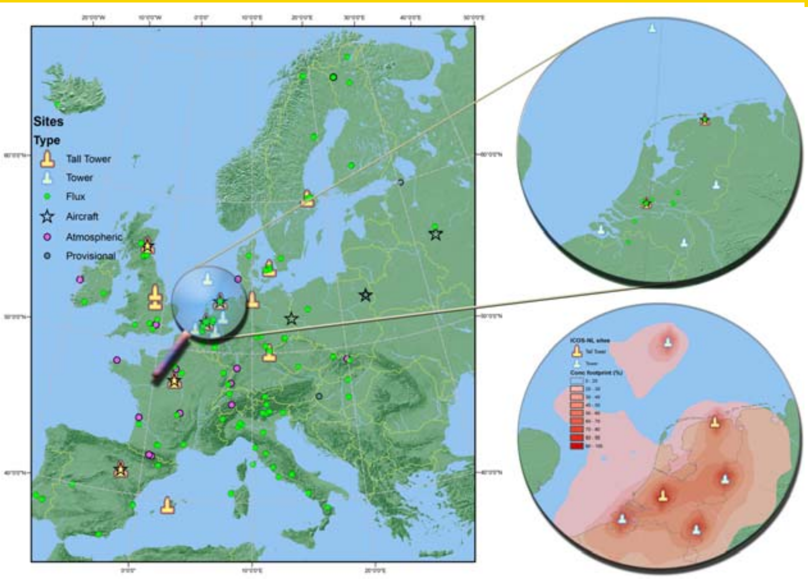
## ECN Outlook for regional networks and connections to the global network

- Europe plans the Integrated Carbon Observation System (ICOS) within ESFRI
- NOAA et al. build the Northern America network (GHGIS)
- Undersampled regions like Amazonia and Asia will develop their network
- Regional networks are coupled to the global network
- Combine in-situ and satellite observations






## ECN ICOS-nl



## ECN Conclusions and take home messages

Conclusions

- Continuous in situ observations in the PBL are representative for large areas
- High resolution inversions for independent emmision verification are becoming feasible now, provided the required observations

Take home menu:

- The answer is in the (lower) atmosphere
- We will need all current observations and more, the system is still poorly constrained
- We cannot relive the past, we should measure (more) now!
- Transport models will (always) need improvements



## ECN Acknowledgements

- EU FP5/6:
  - CHIOTTO
  - CarboEurope-IP
  - NitroEurope-IP
  - IMECC
  - Geomon
- FP7:
  - GHGEurope
  - ICOS
- VROM
- Senter/Novem ROB
- Klimaat voor Ruimte:
  - ME-2

ECN crew:

- Pim van den Bulk, Piet Jongejan, Gerben Pieterse, Rob Rodink, Bart Verheggen, Elena Popa

COP15, Copenhagen
Holland House
December 9, 2009
Using in situ observations to verify greenhouse gas emissions
www.ecn.nl

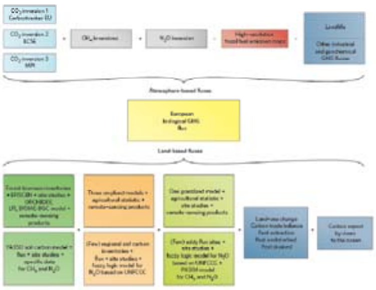
PROGRESS ARTICLES | FOCUS

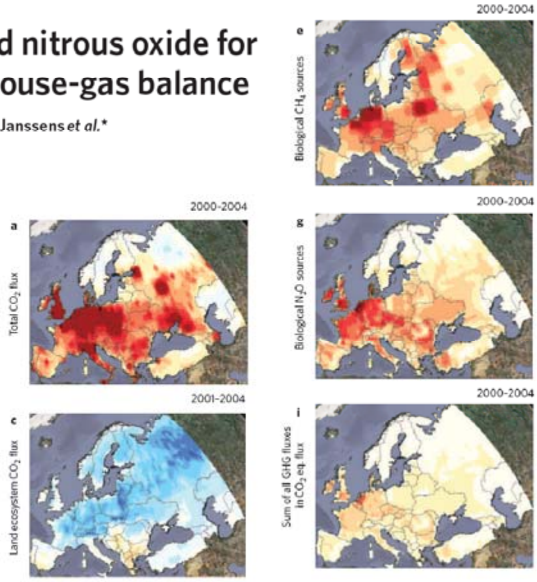
PUBLISHED ONLINE: 22 NOVEMBER 2009 | DOI: 10.1038/NGEO686

nature geoscience

# Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance

E. D. Schulze, S. Luyssaert, P. Ciais, A. Freibauer, I. A. Janssens et al.*






Research on land–atmosphere interactions should be extended to include the effects of land use and land management on the GHG balance as well as on the energy and water balances[37]. The previous perspective that centred mainly on $CO_2$ should be broadened in favour of integrated studies dealing with the biogeochemical and physical aspects of land use and land management as a tool to mitigate climate change.



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## Slide courtesy Pieter Tans (NOAA ESRL)

### WHAT CAN WE DO TO HELP MANAGE EMISSIONS REDUCTIONS?

$$\Delta X = \frac{E(mol/s)}{area} \times \frac{fetch(\sqrt{area})}{w(m/s)} \times \frac{1}{column(mol/m^2)}$$

Maintain high standards for quality control of the measurements.
Improved atmospheric transport, esp. boundary layer, and high resolution to represent flow near observations.

Full disclosure of all data and methods.

Data assimilation, combining inventories, process models, atmospheric and oceanic observations including flux measurements, and remote sensing data to produce optimal estimates of sources/sinks, including fossil fuel burning.

Communication with the public, and policy makers.

Scientific assessments of proposed geo-engineering solutions