

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

Alex Vermeulen, Han Dolman², Harro Meijer³, Ronald Hutjes⁴, Wouter Peters⁴, Lieselotte Tolk², Sander vd Laan³, Arjan Hensen, Petra Kroon, Jip Lenstra, ...

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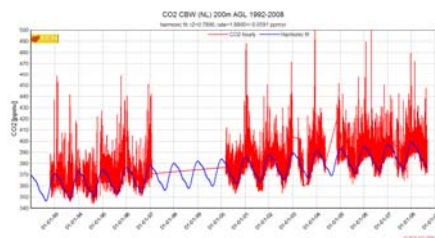
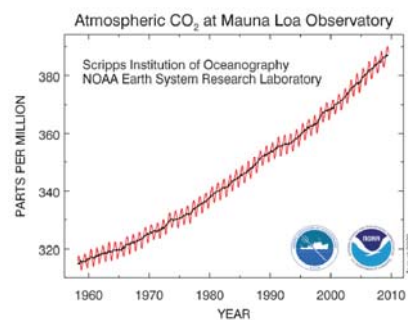
- The greenhouse gas signal in the atmosphere
 - The role of the planetary boundary layer
- Observations: scales in time and space
- Inverse transport model techniques
- Results
 - Local
 - Global
 - Regional
- Outlook
 - Measurement techniques
 - Modelling
 - Networks

- 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!

- Actual concentrations in air determine the greenhouse effect
- Direct message to public and policy
- Airborne fraction of fossil fuel CO₂ is key parameter
- Emissions are uncertain: long atmospheric life-time of GHG allows us to trace location and size of emission (hopefully)

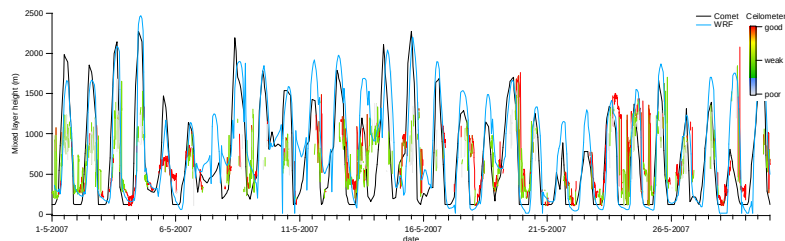
Main goals:

- 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



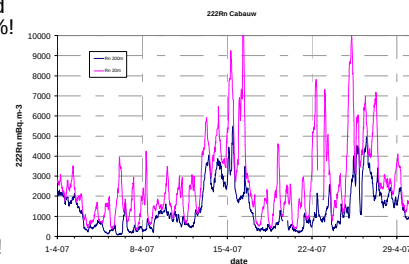
Emissions + planetary boundary layer height and wind speed determine concentration for ~90%!

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!



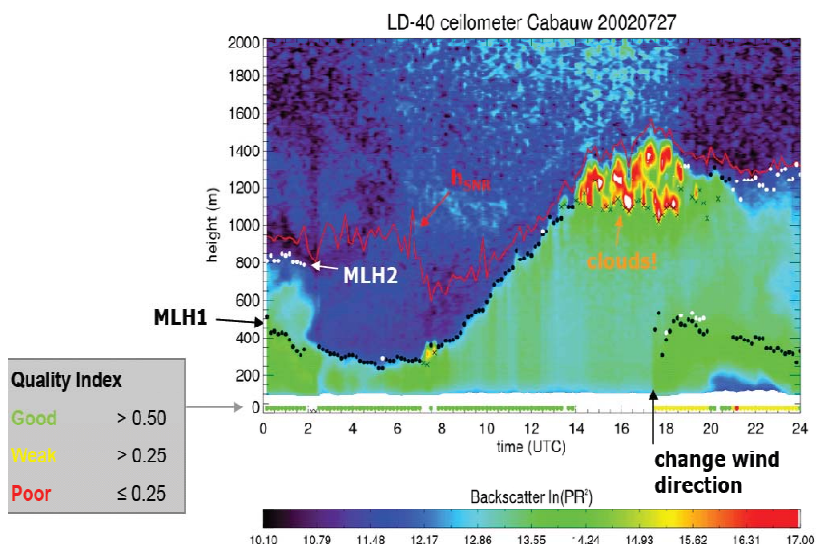
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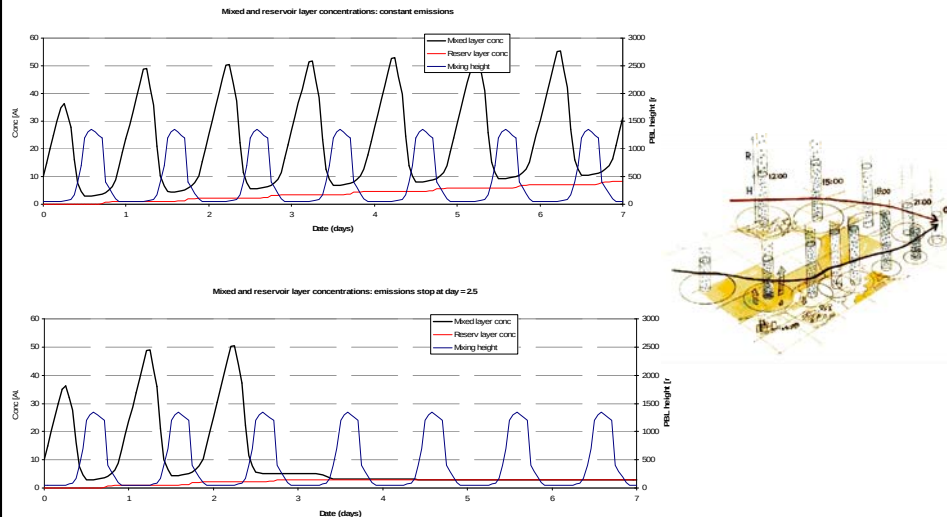
ECN PBL height observations CBW (ceilometer)



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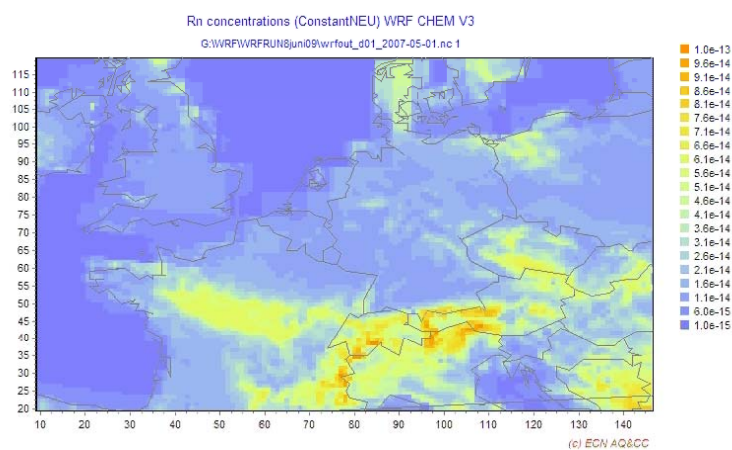
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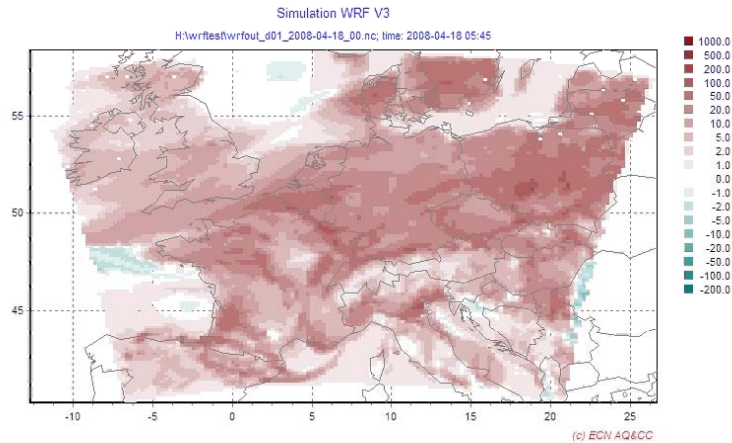


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CO₂: 5 km res vegetation model; MODIS satellite LAI
Edgar-4 0.1° res fossil fuel; taka08 ocean uptake



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- 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)



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ECN 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

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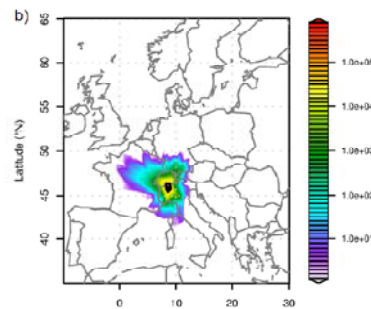
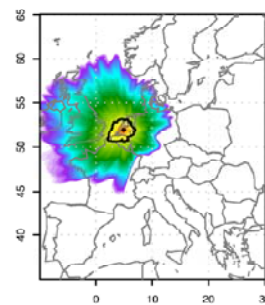
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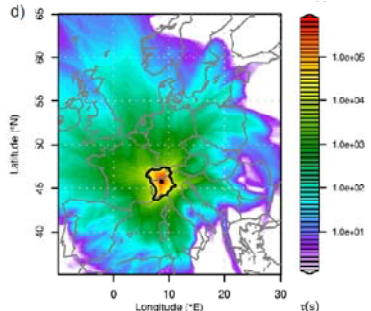
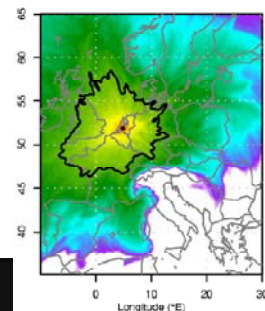
ECN Footprints: two extremes CBW and Ispra

Henne et al, ACPD, 2009

Annual footprint
1/2 day backwards



Annual footprint
2 days backwards



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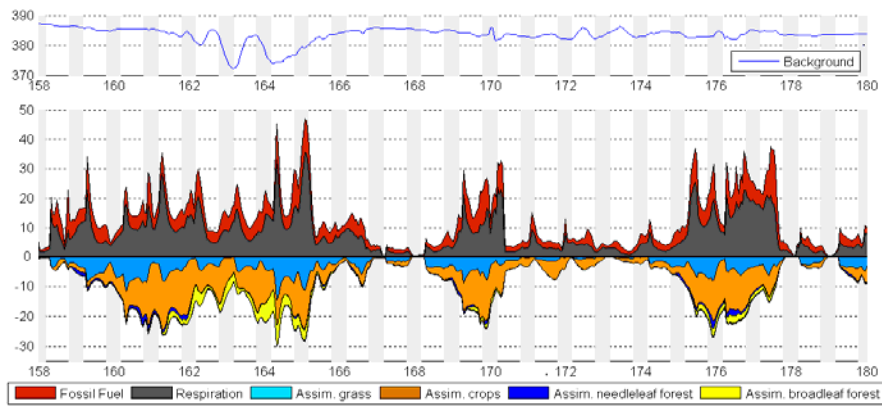
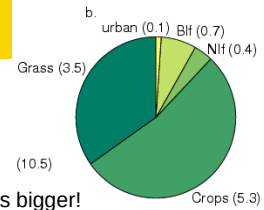
ECN Atmospheric CO₂ s/s apportionment

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!

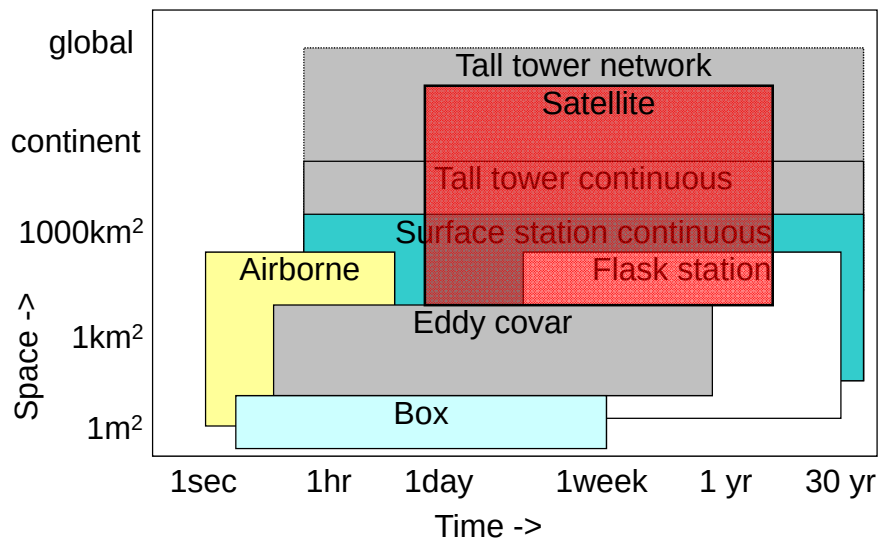


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ECN Measurement platforms and scales in time and space



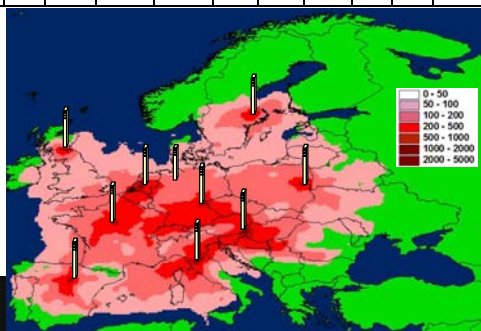
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ECN An observational (tall) tower network in Europe

Name	Hght (m)	Position		Concentration measurement (levels)							Flux meas		Operator
		Lon	Lat	CO ₂	CH ₄	N ₂ O	SF ₆	CO	²²² Rn	Flasks	CO ₂	CH ₄	
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



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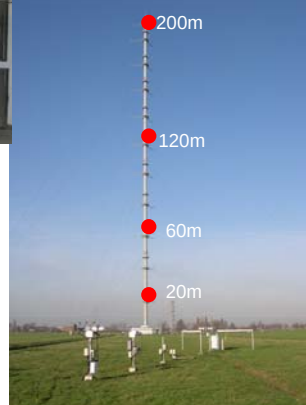
ECN Tall Tower Example: Cabauw GHG measurements

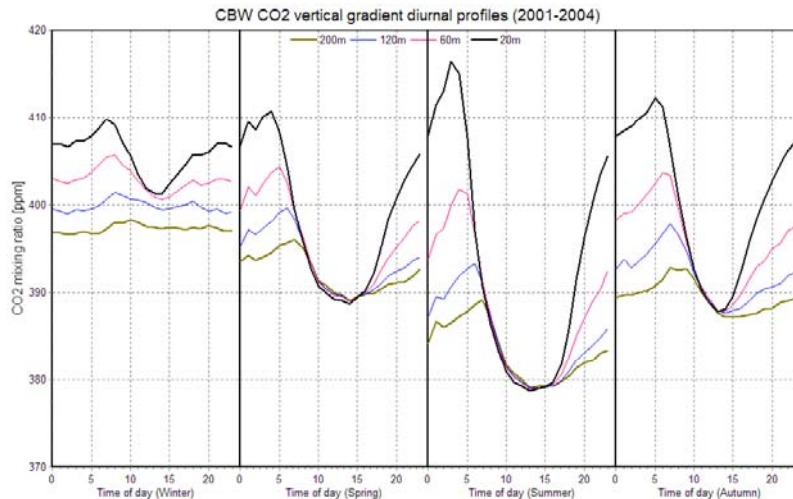
51° 58' N 4° 56' E
Constructed 1972: KNMI
super-site: CESAR

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: CH₄, N₂O, CO, SF₆, H₂
NDIR: CO₂
Gradient of ²²²Rn (20, 200 m ASL; 2005)
Eddy flux CO₂ (KNMI, WUR) at 3 levels

<http://www.cesar-observatory.nl>





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- Global models have in last 10 yrs evolved from coarse ($6^\circ \times 8^\circ$) to medium resolution (0.5° - 1°)
- Mesoscale models have evolved to resolutions of $\sim 2 \times 2$ 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

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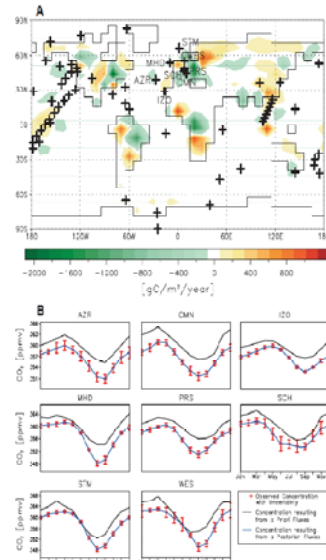
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- Direct (matrix) inversions
 - No need for prior estimates, variances or covariance
- Data assimilation (Bayesian)
 - Needs information on error variation and covariances
 - Needs prior estimate

Examples:

Fan et al, Science, 1998
 Bousquet, Science, 2002
 Kaminski, Science, 2002->
 Transcom 3

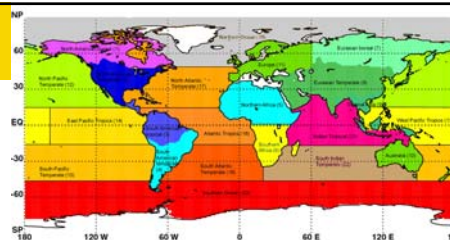


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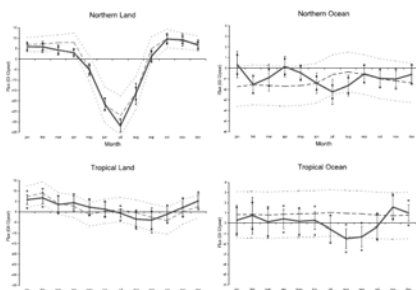
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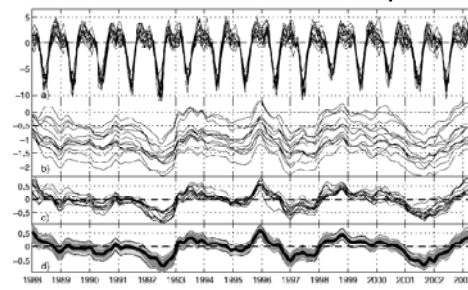
Transcom 3:
 12 global models
 Big region approach (22 regions of the world)
 Common prior fluxes
 Common inversion routines
 Invert monthly mean daytime concentration of global network
 Large offsets in derived fluxes, but relative changes relatively robust



Europe:



Guerney et al, GBC, 2004



Baker et al, GBC, 2005

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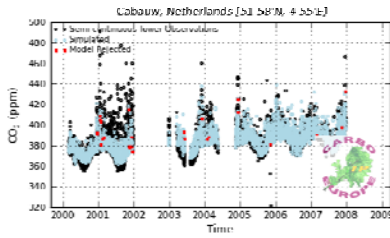
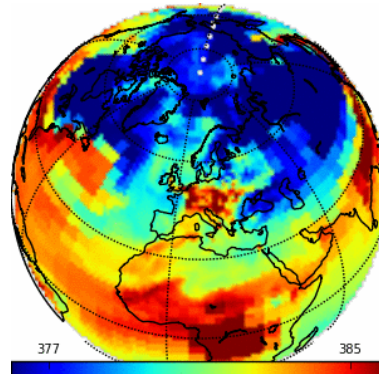
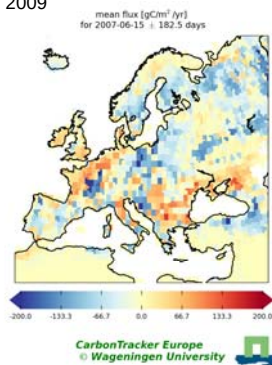
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ECN (Inverse) modelling techniques (3)

- 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

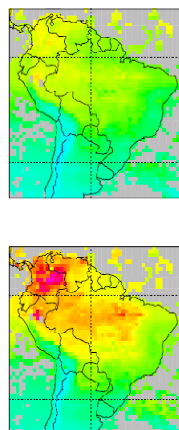
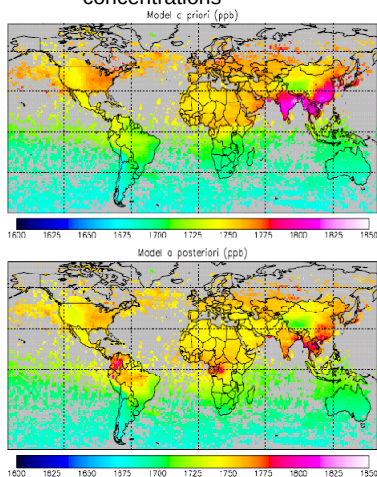


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ECN (Inverse) modelling techniques (4)

Global bayesian inversion for CH₄ based on satellite obs

TM5 pixel based inversion at 1x1 degree using SCIAMACHY retrieved CH₄ concentrations

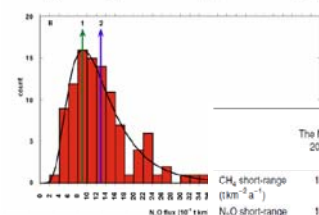
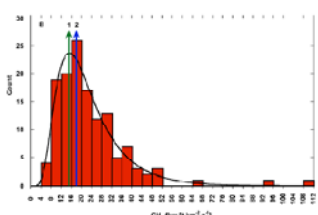
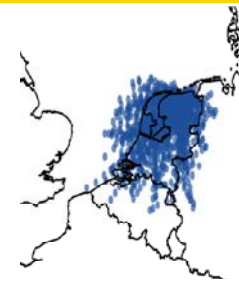
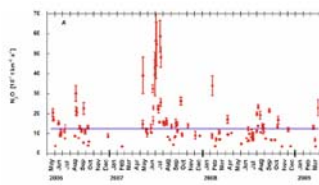
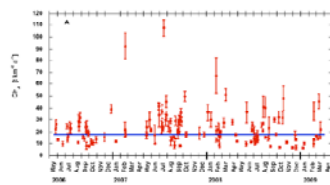


Meirink et al, JGR, 2008

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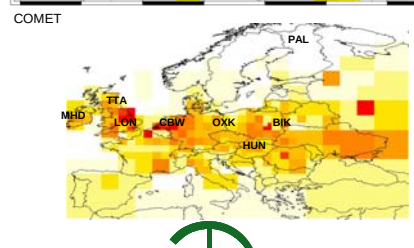
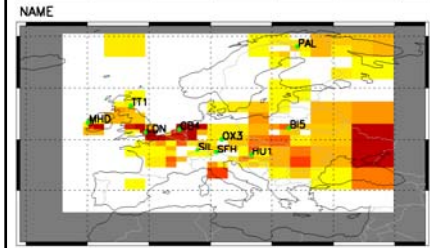
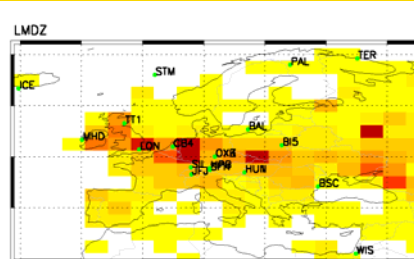
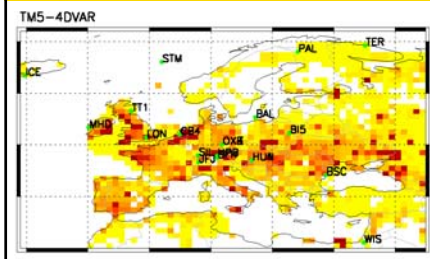
	National inventories			Radon flux method	
	The Netherlands 2006-2007	Belgium 2006	Germany 2006	Lognormal fit	Lognormal fit (combined uncertainty)
CH ₄ short-range ($\text{tkm}^{-2}\text{a}^{-1}$)	18.3±3.3			15.2±0.4	15.2±5.3
N ₂ O short-range ($10^{-1}\text{tkm}^{-2}\text{a}^{-1}$)	12.6±5.7			9.2±0.3	9.2±3.2
CH ₄ long-range ($\text{tkm}^{-2}\text{a}^{-1}$)		11.0	5.8	8.9±0.3	8.9±3.1
N ₂ O long-range ($10^{-1}\text{tkm}^{-2}\text{a}^{-1}$)		8.8	5.4	4.2±0.3	4.2±1.5

vd Laan et al, ACPD, 2009

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Bergamaschi et al, in prep

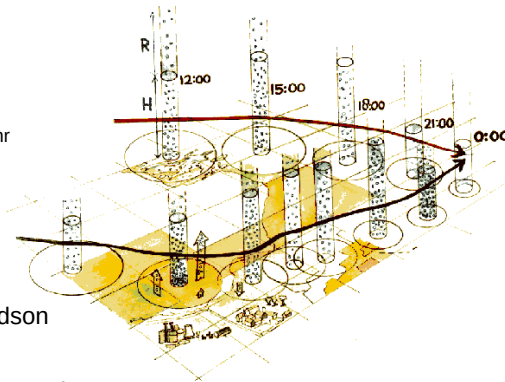


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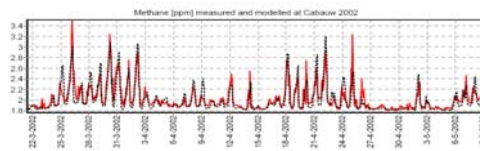
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- Lagrangian model
- ECMWF meteorology
 - 0.2° resolution
 - timestep 3 hr, interpolated into 1 hr
- Hourly trajectories (flextra)
- Moving two layered box :
 - Mixing layer
 - Reservoir layer
- Mixing layer height: critical Richardson number
- High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



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



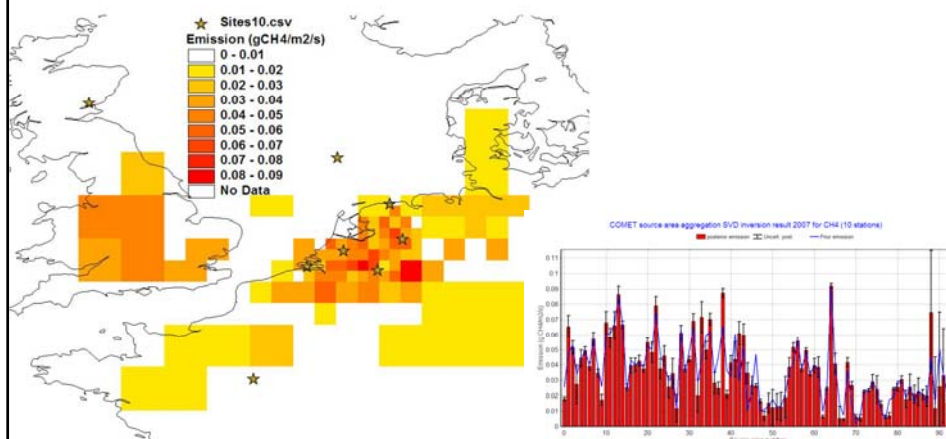
Vermeulen et al., Env. Sci. & Pol., 2, 1999
Vermeulen et al., ACPD, 2006

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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

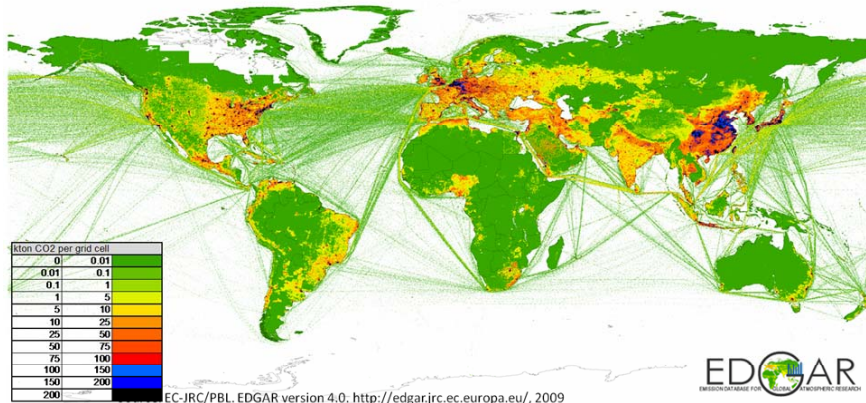
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ECN Outlook for model development



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

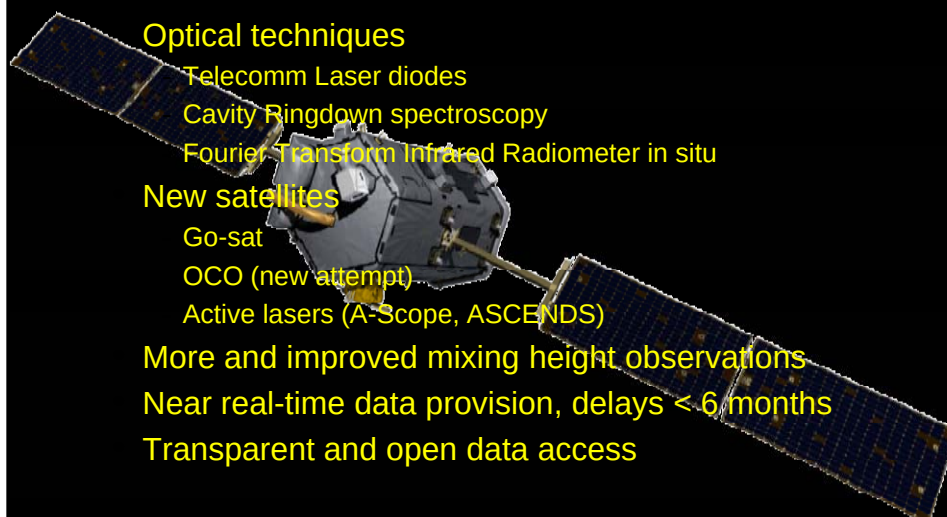
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ECN Outlook for observation technologies

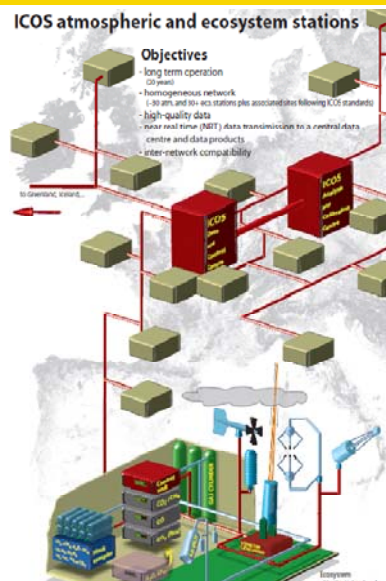


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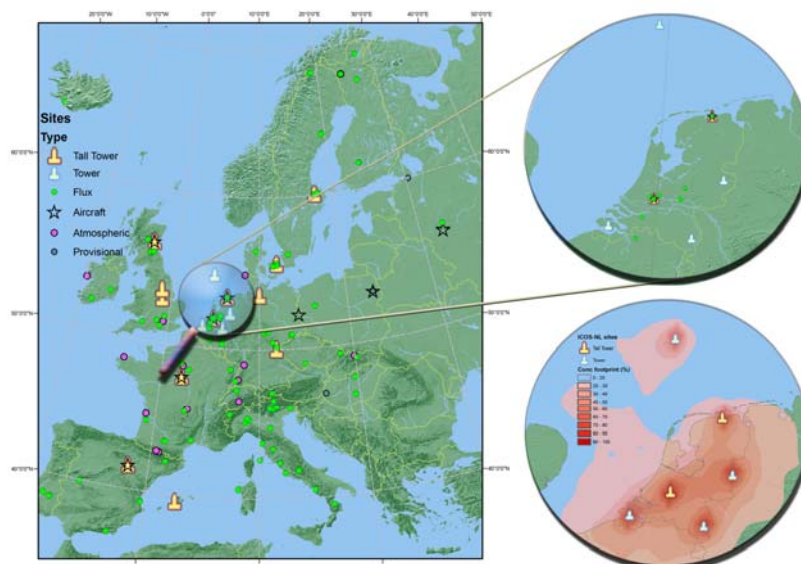
- Europe plans the Integrated Carbon Observation System (ICOS) within ESFRI
- NOAA et al. build the Northern America network (GHGIS)
- Undersampled regions like Amazonia and Asia will develop their network
- Regional networks are coupled to the global network
- Combine in-situ and satellite observations



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ECN Conclusions and take home messages

Conclusions

- Continuous in situ observations in the PBL are representative for large areas
- High resolution inversions for independent emission 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

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- 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

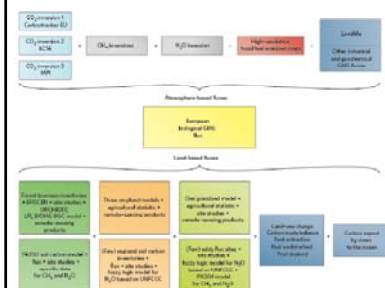
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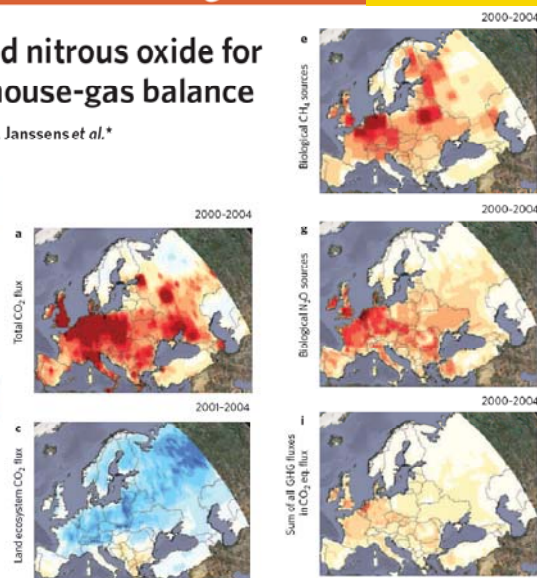
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Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance

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 balances³⁷. The previous perspective that centred mainly on CO₂ 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?

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

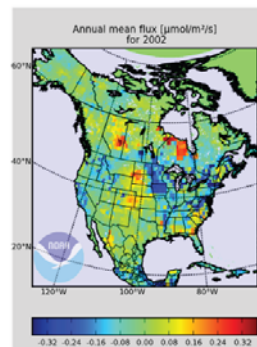
Maintain high standards for quality control of the measurements.
Improved atmospheric transport, esp. boundary layer, and
high resolution to represent flow near observations.

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



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