Estimating Methane Emissions in the Surat Basin, Australia, including turbulent vertical Fluxes

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This work was funded under the Climate and Clean Air Coalition (CCAC) Oil and Gas Methane Science Studies (MSS), hosted by the United Nations Environment Programme.
Funding was provided by the Environmental Defense Fund, Oil and Gas Climate Initiative, European Commission, and CCAC.

The overarching project was introduced before

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James France

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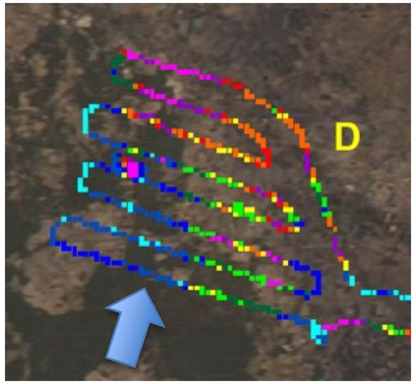
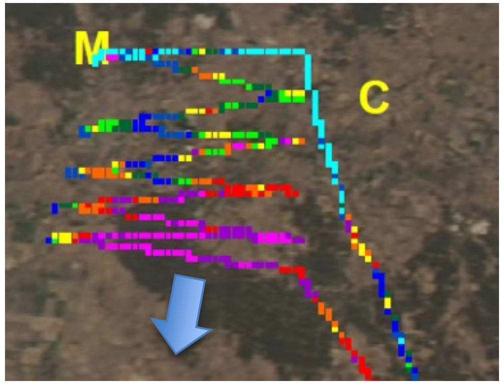
Technical aspects of the airborne measurements see pp. 13 below

7 days with complete observations

Sept 10 scanning the SE-cluster of sources



Sept 12 scanning the NW-cluster of sources



Lagrangian
Sept 15 along basin

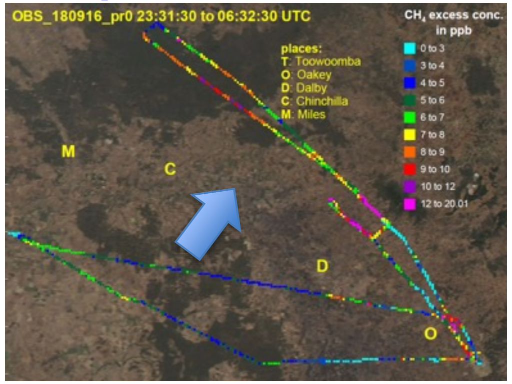
places:
T: Toowoomba
O: Oakey
D: Dalby
C: Chinchilla
M: Miles

CH_4 excess conc. in ppb

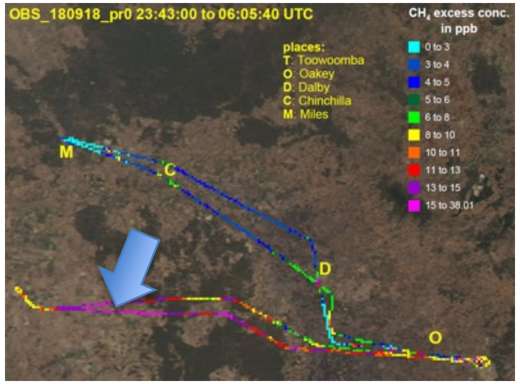
- 0 to 4
- 4 to 6
- 6 to 7
- 7 to 8
- 8 to 9
- 9 to 10
- 10 to 12
- 12 to 15
- 15 to 20
- 20 to 68.01

4 different wind regimes along the Surat Basin (NW/SE), and crossing it (SW/NE) with 4 perfectly Lagrangian patterns (one for each regime) and 3 other patterns all during with well-mixed convective conditions

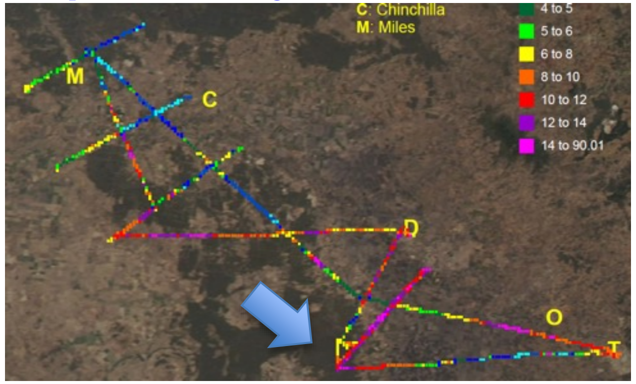
Lagrangian
Sept 16 across basin



Lagrangian
Sept 18 across basin

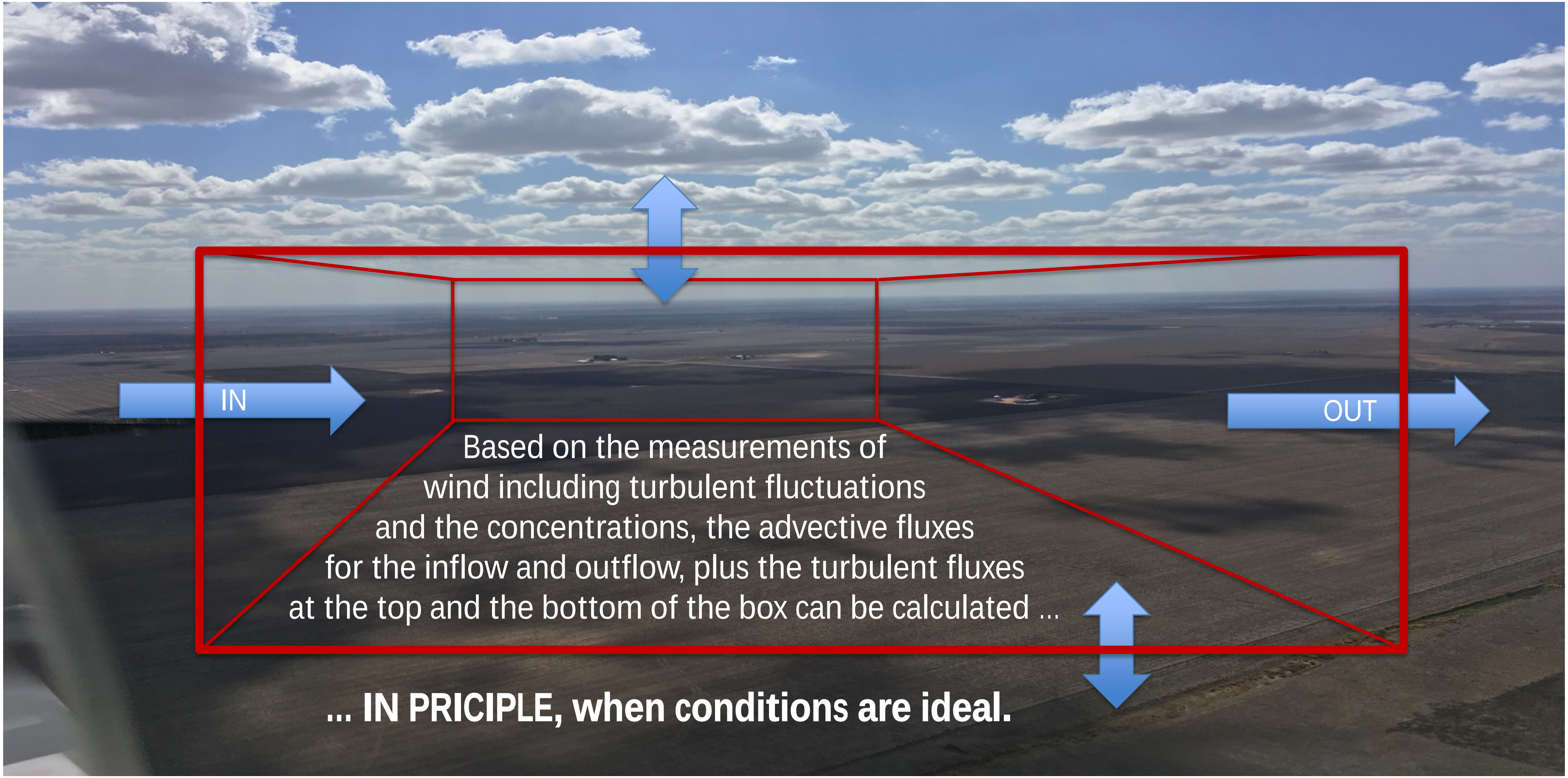


Lagrangian
Sept 19 along basin

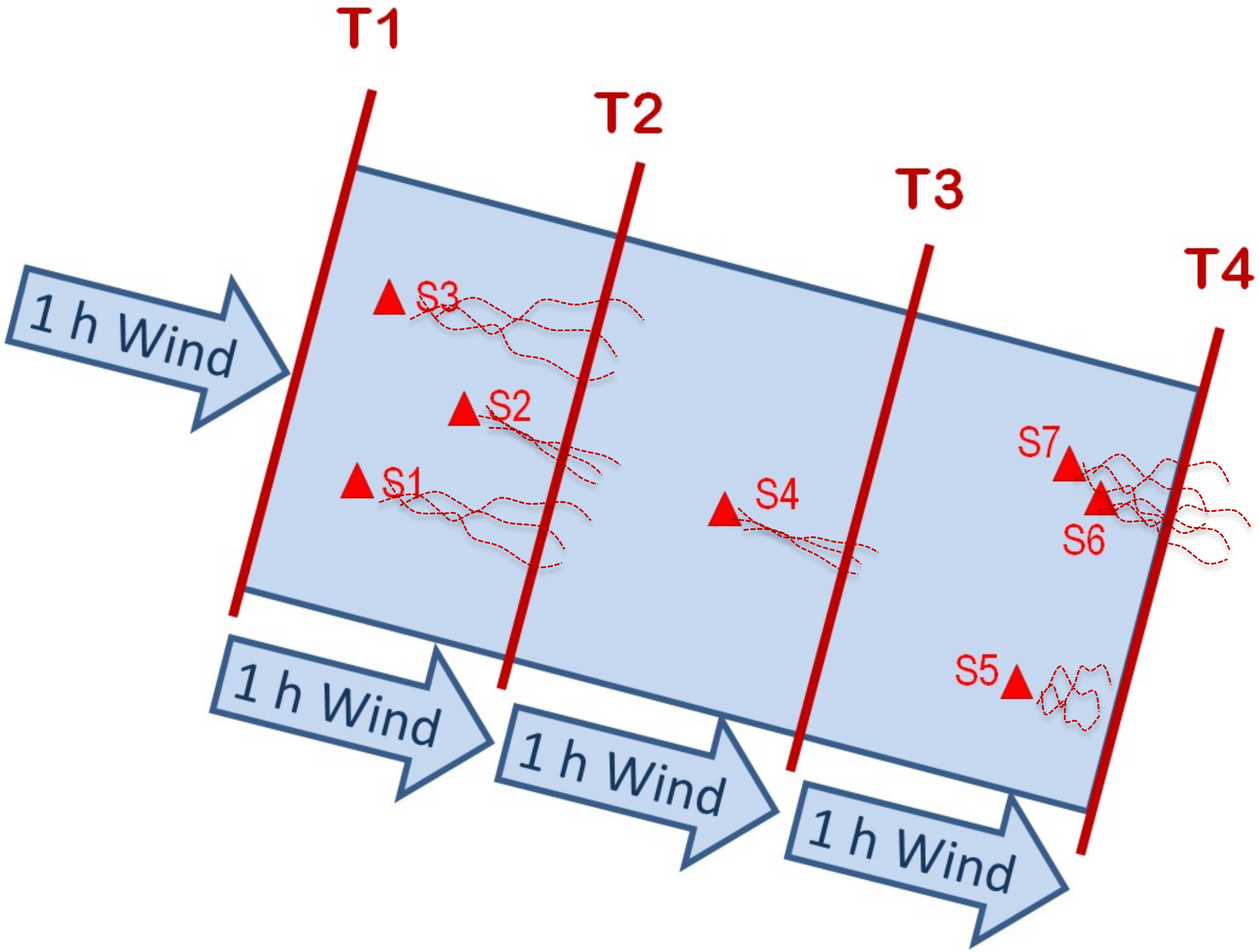


Sept 21 plume chasing in the NW

The basic Concept as already introduced at EGU 2019



The same box seen from above



In this 2-d-view from above into the box, the air mass is moving from left to right, starting at Transect T1, arriving three hours later at T4.

The accumulated CH_4 is enhancing the average concentration at T4 compared to T1 as a result of the horizontal wind and the vertical mixing.

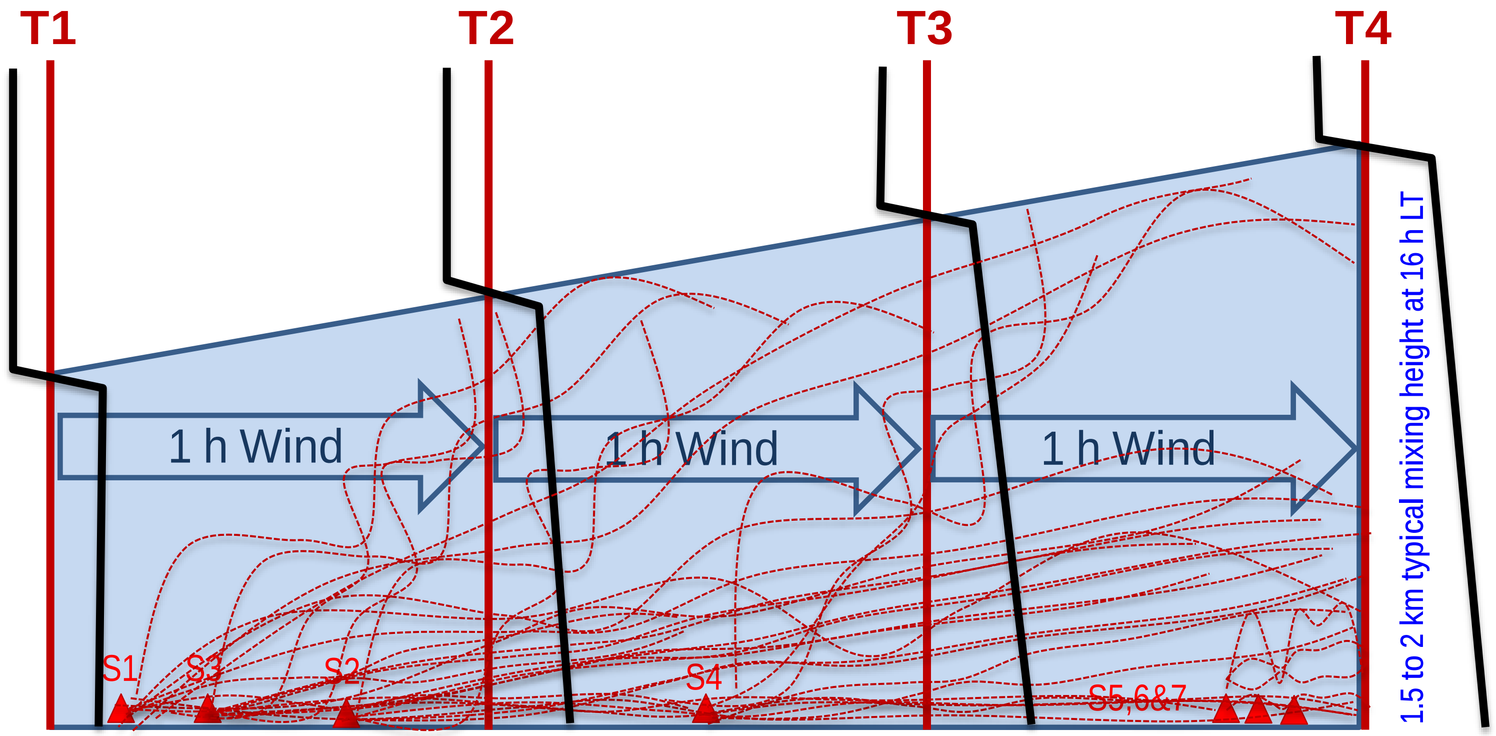
Within the sub-boxes between T1 and T2, etc., sub-regional emissions can be seen.

When flying along the transects, the plumes from individual emission sources are captured as well.

The same box seen from the side (vertical cross section along the wind)

A very schematic drawing of the important processes:

- **The seven sources are emitting CH_4 into the growing convective boundary layer (CBL)**
- **The vertical profile of CH_4 is nearly mixed below the top of the actual CBL**
  (the vertical mixing is even faster than depicted here – typically 0.5 to 1 hours for reaching the top)
- **Nevertheless, the plumes of the individual sources are still detectable on the cross sections perpendicular to this side-view.**



Three key questions:

1) **Which enrichment of CH_4 (ppb) do we expect at T4 when the total emissions in a box of 50 x 50 x 2 km^3 are 10 tons/hour (wind 5 m/s)?**
2) **How would the vertical profile of CH_4 develop when no emissions are injected?**
3) **What kind of data do we need for calculating a complete budget (mass balance)?**

Discussing the three key questions from before

1) **The answer for a complete mixing is, that 10 t/h emissions are only influencing T4 with about 10 ppb!** (625 kmol/h or 174 mol/s are diluted with about $5 \cdot 10^8$ m^3 $\cdot 37$ mol/m^3 or $1.85 \cdot 10^{10}$ mol/s of air, resulting in about 10 ppb!
2) **Assuming 10 ppb difference between above and below the CBL at T1, and regarding the top concentration as an infinite reservoir, the concentration at T4 would sink in the order of 5 ppb when the CBL height would double between T1 and T4.**
3) **We need to measure the concentrations in the CBL very complete and very accurate!**

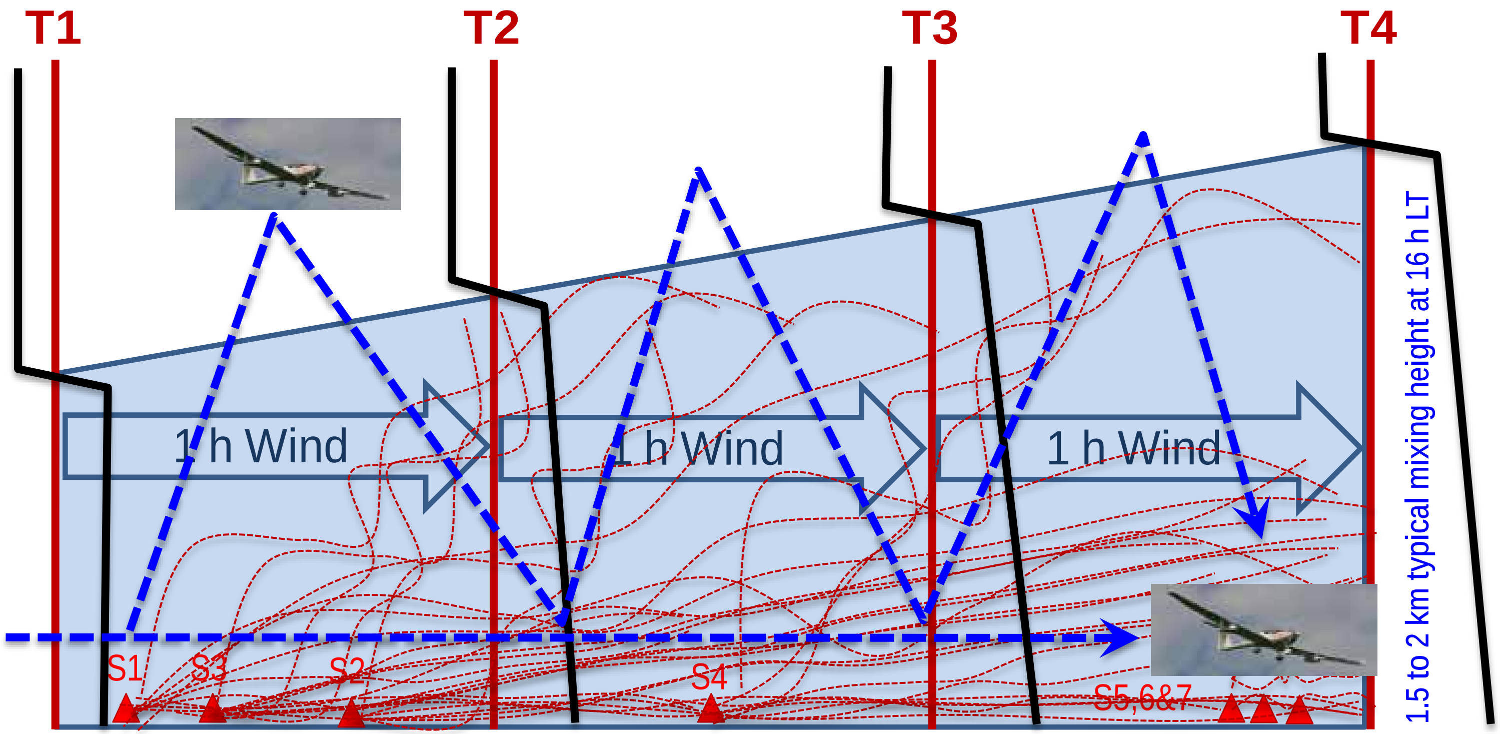
Consequences for the measurements, and now for the methods resulting in emission estimates:

ü **Assuring highest precision for the dry CH_4 mol-fractions was clear from the beginning. Since we are dealing with concentration <u>differences</u>, the absolute accuracy is less important, but nice to have. The priority is on avoiding any drift during one day (1 or 2 flights), what we are checking when flying back in "background concentrations" after we probed enhanced downwind concentrations.**

ü **Concentrating in the lower CBL (typically 150 to 300 m above the surface), with vertical soundings above the CBL before, between and after T1 to T4 seems to be a good balance for a good coverage near the emissions, and having some information about the history of the CBL and above.**

ü **Achieving quasi Lagrangian measurements eliminates a lot of difficult questions (therefore not treated).**

1. **Classical mass balance approach:**

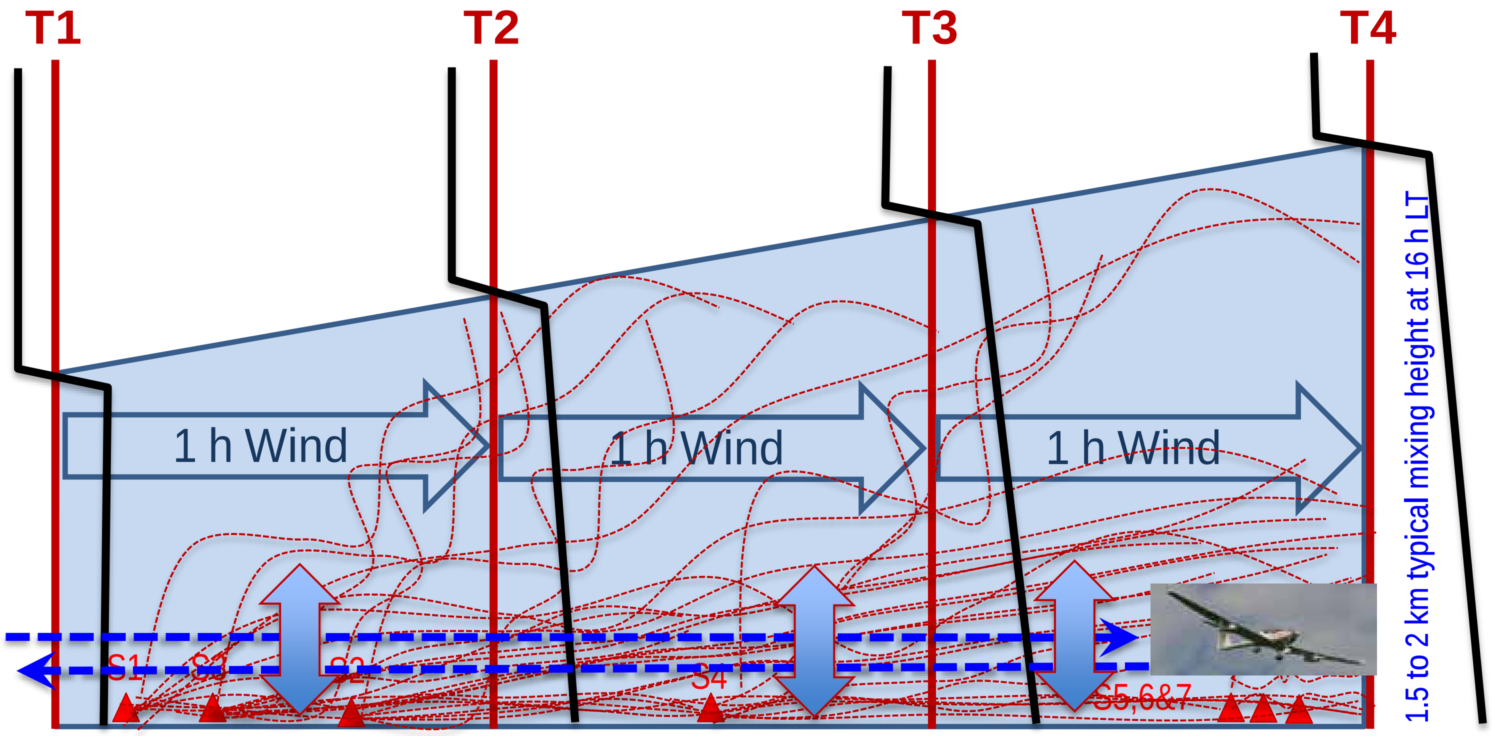


The measurements along the transects in the lower CBL (drawn along the box here, but perpendicular to the picture in reality) **and the soundings are combined in a way that the concentration and wind fields across T1 to T4 can be subtracted from each other for getting the emission estimates.**

Main disadvantage: We do not really know what's going on above the altitude of the majority of low flight legs.

2. Measuring directly the vertical exchange between the lower and higher CBL

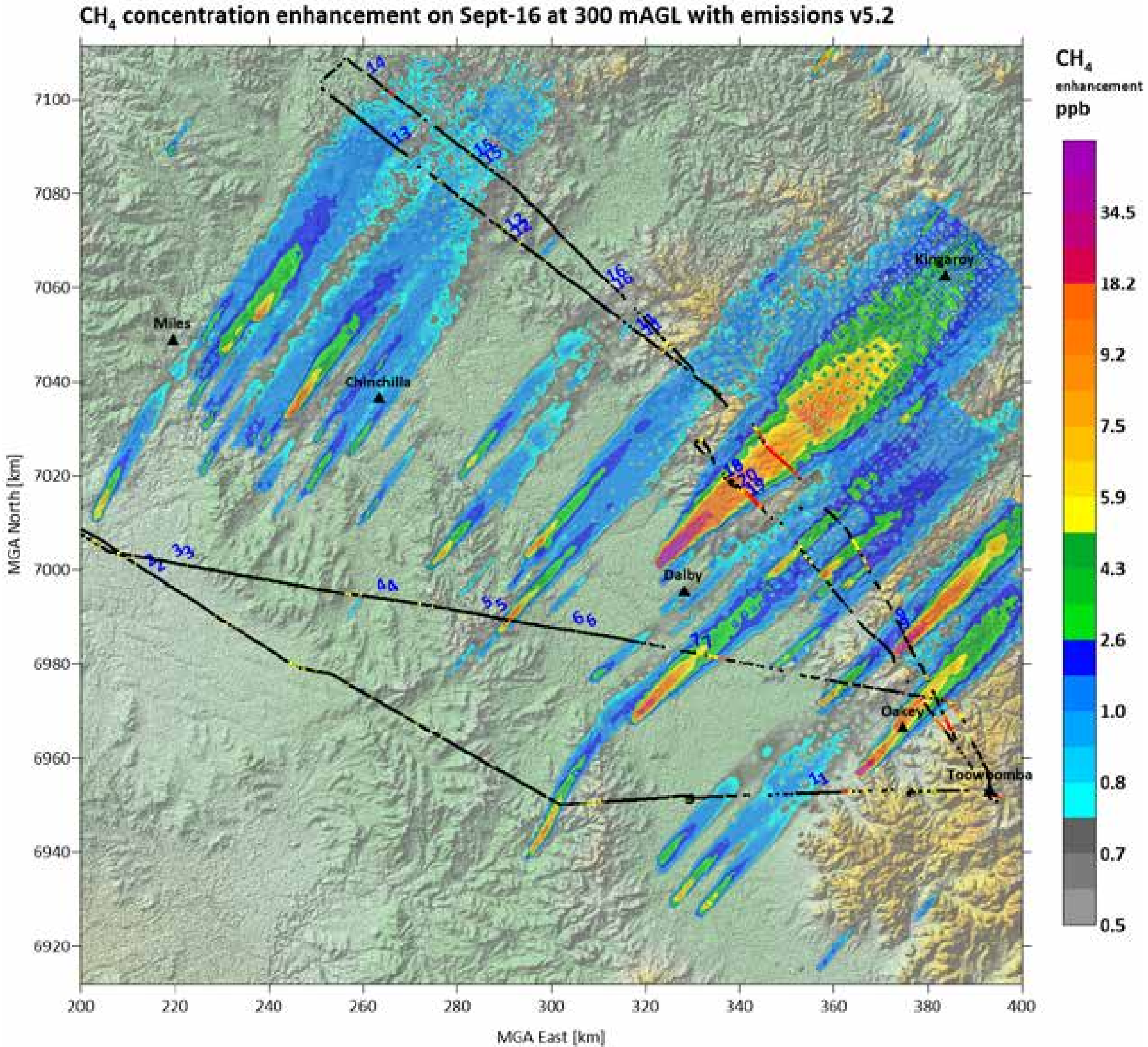
(a well known method in micro-meteorology, applied by ARA/MetAir since decades)



Instead of loosing time with a lot of soundings (a minimum is indispensable) and guessing how the vertical mixing is aloft, we MEASURE the turbulent exchange in the lower boundary layer (eddy covariance fluxes).

Challenge: Fast (10 Hz), well synchronised and precise measurements of wind and concentrations on adapted flight tracks.

3. Using all the available measurements for reconstructing the observed concentrations along the flight tracks

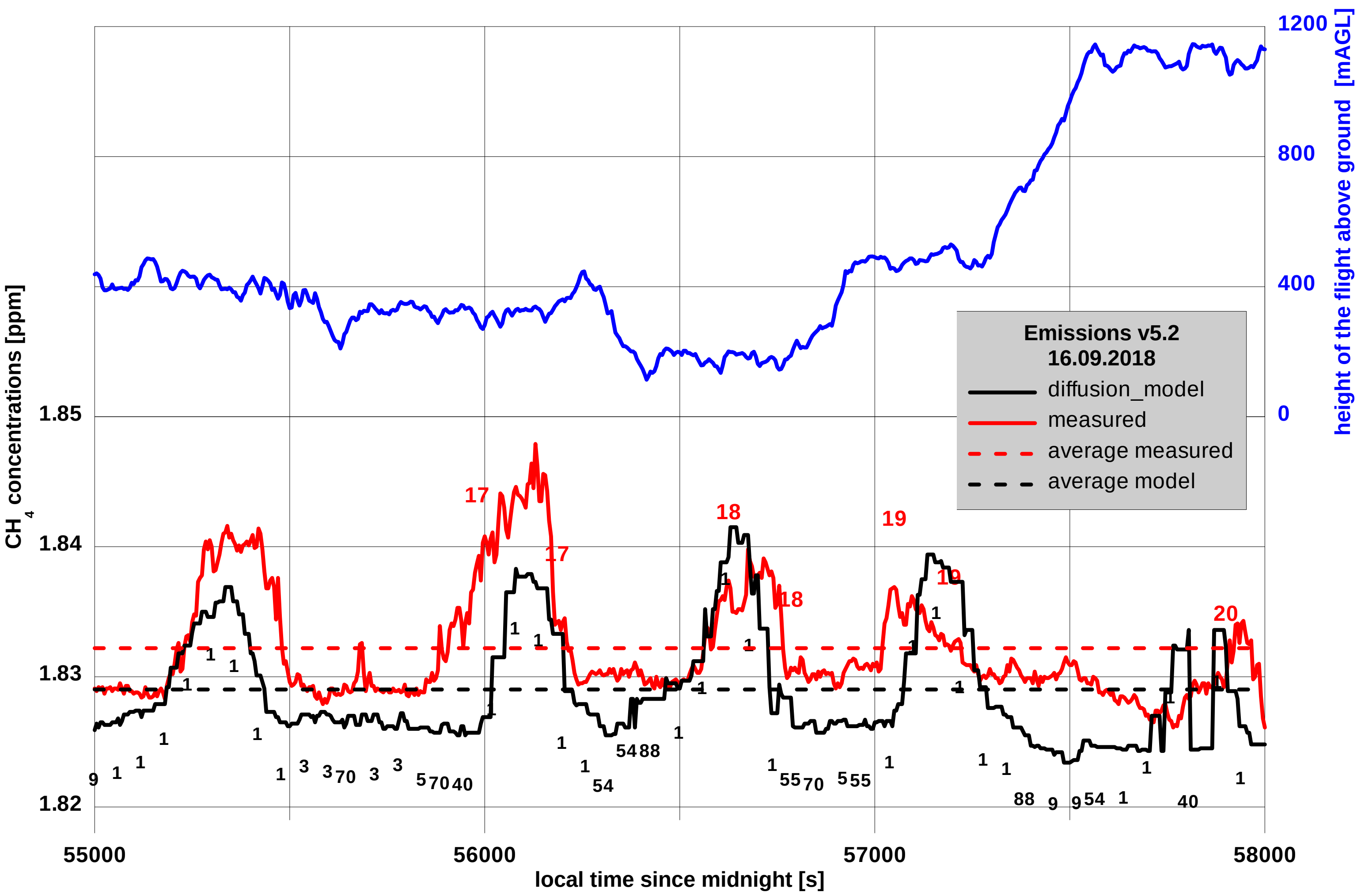


Based on an initial emission inventory, using the wind and the turbulence measured along the flight tracks, a 4-d concentration field is calculated by a Monte-Carlo dispersion model, including all aspects discussed above (e.g. growing CBL).

Numbers are bag samples; color coding on the flight track is indicating measured concentrations (not yet the same colours as in the plumes).

The iterative adjustment of the emission estimates

Working graph: Comparing the measurements with the dispersion model, allowing iterative adjustments of the underlying emission inventory



This is the result of a preliminary adjustment for a yet unknown source. The measured signal from crossings on different heights is compared with the dispersion model. Differences in amplitude and width can be used to adjust the distance and strength of the source, after careful adjustment of the basic diffusion parameterisation per flight.

The deficit in the average concentrations from the model (black) against the measurement (red) is indicating underestimated diffuse sources.

Black numbers at the bottom are denoting the dominant sources for the enhanced concentrations against background on this altitude on upwind leg. The red numbers on top of the measured concentrations are identifying bag grab sample numbers (begin and end of fillings).

This offers a maximum of information for continued iterations.

Summary

- The carefully planned and successfully performed Lagrangian flight patterns with the measurements of 3-d wind and concentrations at high temporal resolution allowed to supplement the classical mass balance approach with two new methods for achieving emission estimates for a large region.
- Since the observed region was large (up to 20’000 km^2), with many small and partly unknown sources emitting into the high reaching diluting convection, the classical mass balance is difficult. The preliminary results were demonstrating the limitations - especially for the smaller sub-regions .
- The second method using the turbulent vertical fluxes of constituents (CH_4, CO_2, H_2O and sensible heat) allows to concentrate on the lower boundary layer, avoiding the uncertainties above. This concept delivered a perfect closure for sensible heat already (proof of concept), and also the budgets for CO_2 and H_2O are comparable. For CH_4 the method suffers from a reduced temporal resolution of the measurement (0.5 Hz or less instead of 10 Hz for the other species). With an increased data rate (stronger pump for the Los Gatos UGGA) and optimised flight tracks, this deficit should be eliminated in the future.
- The third method is very promising because it includes all known processes in the evaluation, and can even identify yet unknown emissions, especially when all the seven days with different wind regimes are combined. Although some simulation is involved it has to be emphasised that it is fully based on the measurements along the flight tracks, i.e. does not need an atmospheric model with assumptions like Gaussian plumes. It’s the observed turbulence we are using for “random-walk-plumes”. The “prize” for this method is quite a lot of manual work for the iterations, which is work in progress.

Airborne Measurements for estimating Methane Emissions in the Surat Basin, Australia

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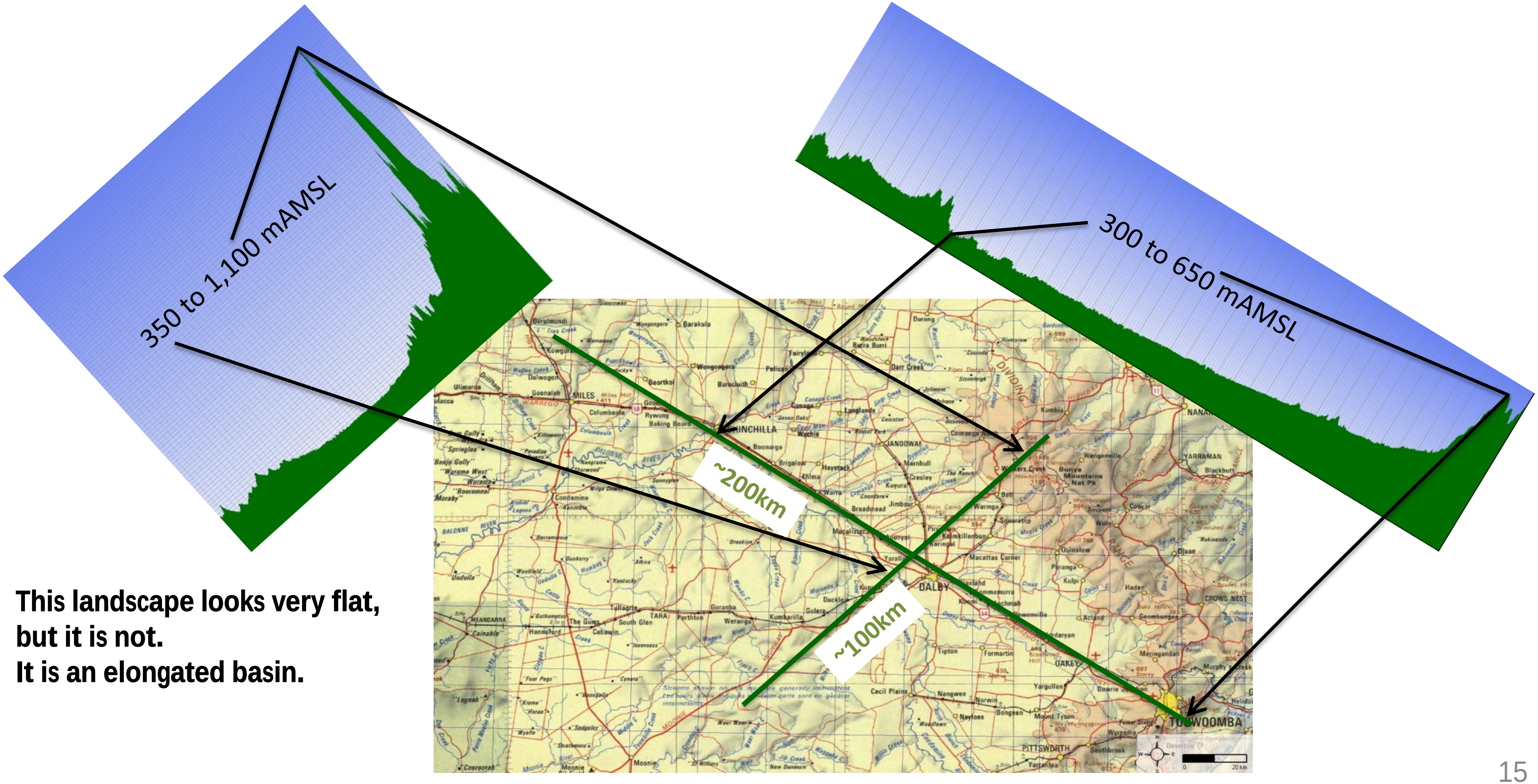
Some slides from our last years contribution introducing the campaign and the airborne platform.
The original is available as
https://presentations.copernicus.org/EGU2019/EGU2019-13189_presentation.pdf

Back to 2020

Typical distribution of wells in the NW of the region

The picture was taken during a sounding to an altitude above the mixed laxer (see page 11); the usual heights flown were between 100 and 300 metres above ground.

Surat Basin Topography

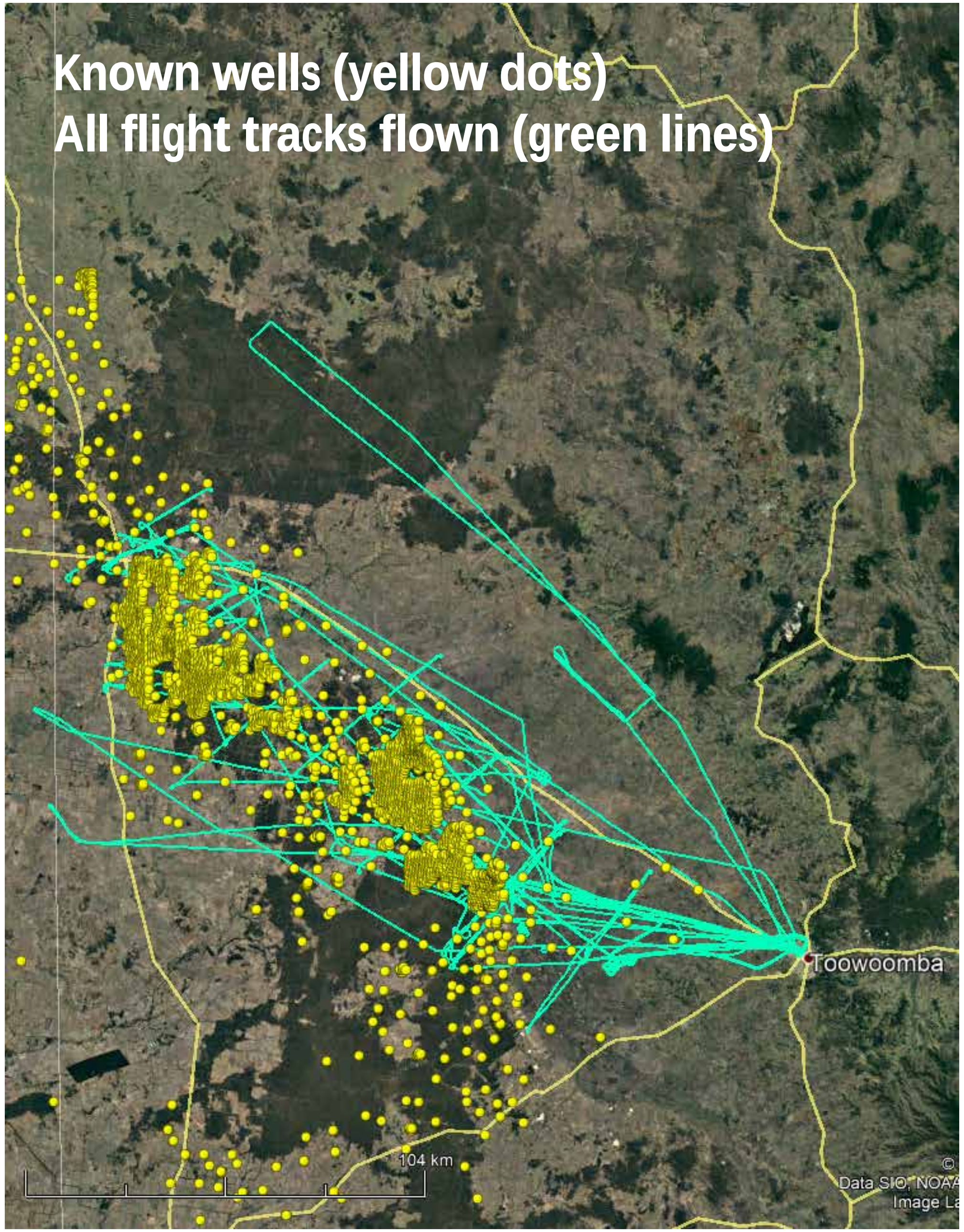


This landscape looks very flat, but it is not.
It is an elongated basin.

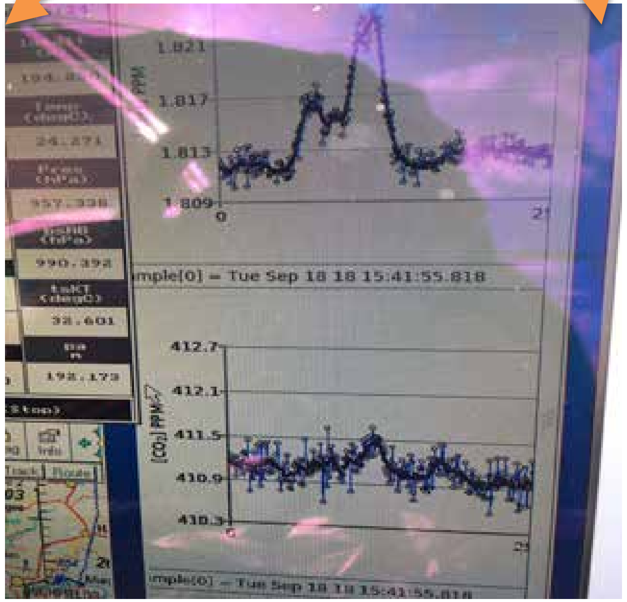
Impressions (2/4): Typical Gas-Related Facilities

Impressions (3/4): A Feedlot with about 50’000 cattles

Impressions (4/4): All tracks and cockpit view



Mission Scientist's view in and out of the Cockpit



Real-time Data Display

The instrumented airborne Platform (1/3)

All data was captured by sensors mounted on one of ARA's small research aircraft (Diamond Aircraft HK 36 TTC-ECO; short name DIMO).

The ARA-DIMO is a highly modified special mission version of a motorglider featuring two under-wing pods and two additional pylons for sensing equipment.

The aircraft can carry two crew plus ~150kg of scientific instrumentation for flights of typically 5-6 hours over distances of up to ~800km and altitudes up to 7km.

All missions were flown from Toowoomba Airport with occasional intermediate refuelling stops at Dalby Airport.

The environmental footprint of the aircraft is minimal in terms of noise and CO_2 emission (17 ltr/h unleaded car fuel).

11 science flights on 7 days over 15 day deployment period

(plus 1 demo flight with some additional results for one source on another day)

The instrumented airborne Platform (2/3)

- **RH underwing pod and pylon - meteorological instrumentation:**
    - 10Hz air temperature, humidity, 3D-wind
    - 250Hz position, speed and attitudes (IMU/GPS)
    - laser altimeter for flying height above ground
    - air intake/pumps for bag samples
    - fast (20Hz) additional gas analyzer (modified LiCor-7500) for CO_2 and H_2O
    - Aerosol/particle counter (MetOne)
    - Nadir-looking Canon 5D Mk4 RGB-camera

- **Fuselage:**
    - flight crew (pilot/scientist and mission scientist/systems operator)
    - data system with real-time data display
    - manual bag sampling

- **LH underwing pod – main gas analyzer:**
    - Los Gatos gas analyzer (high accuracy CH_4, CO_2 and H_2O) with external pump for achieving a temporal resolution of about 2 seconds

The instrumented airborne Platform (3/3)

ARA/Metair Flight Crew from right to left:

Jorg Hacker: Pilot and Chief Scientist of ARA

Shakti Chakravarty: Operator for the first flights

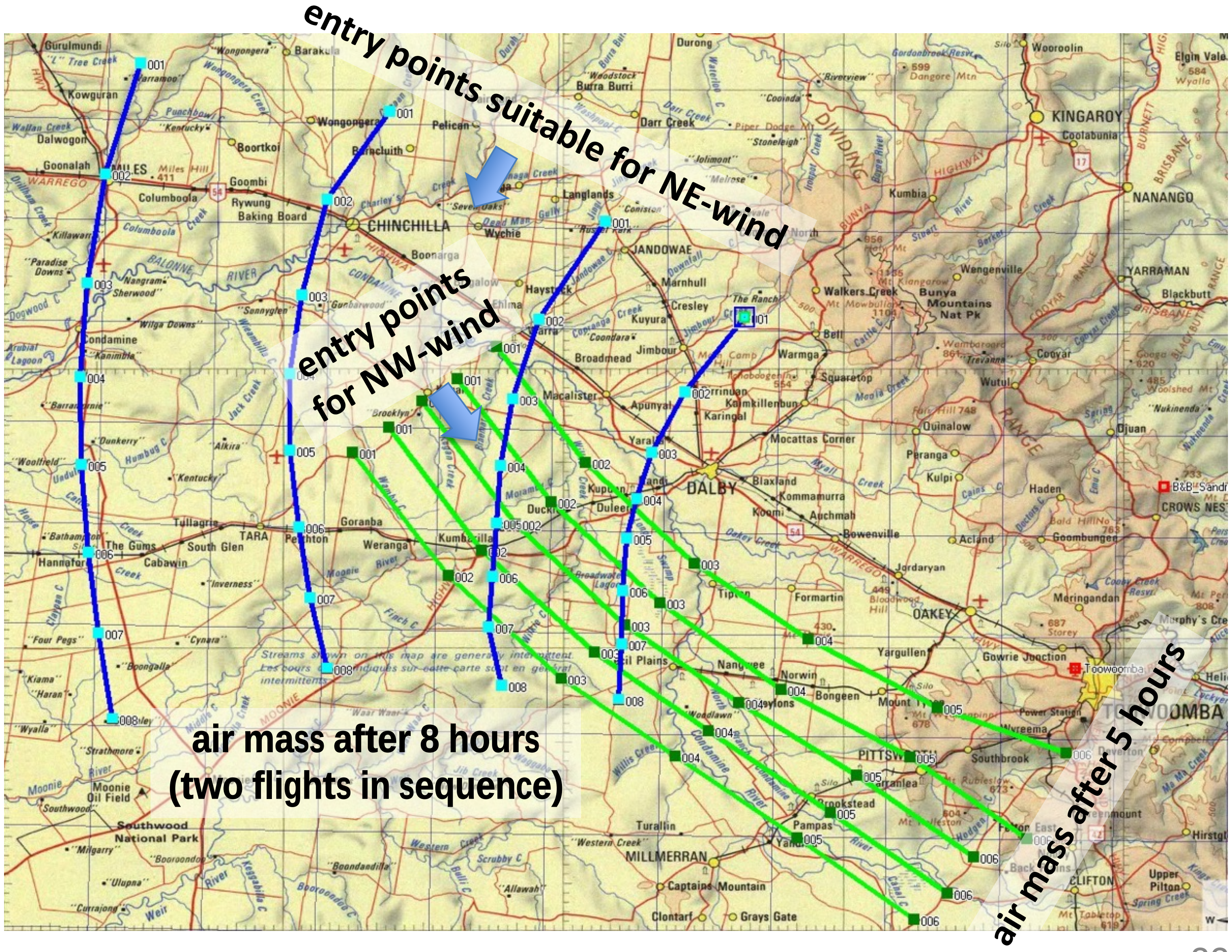
Bruno Neininger (MetAir): Operator for the remaining flights

Two cases of flight planning based on forecast trajectories (GFS grid data, own adjusted trajectory calculation)

a) Along valley flow: When the general wind regime is known (NW), suitable entry points were defined. The trajectories were then suggesting, where the 'walls' have to be flown after N hours (depending on the size of the box)

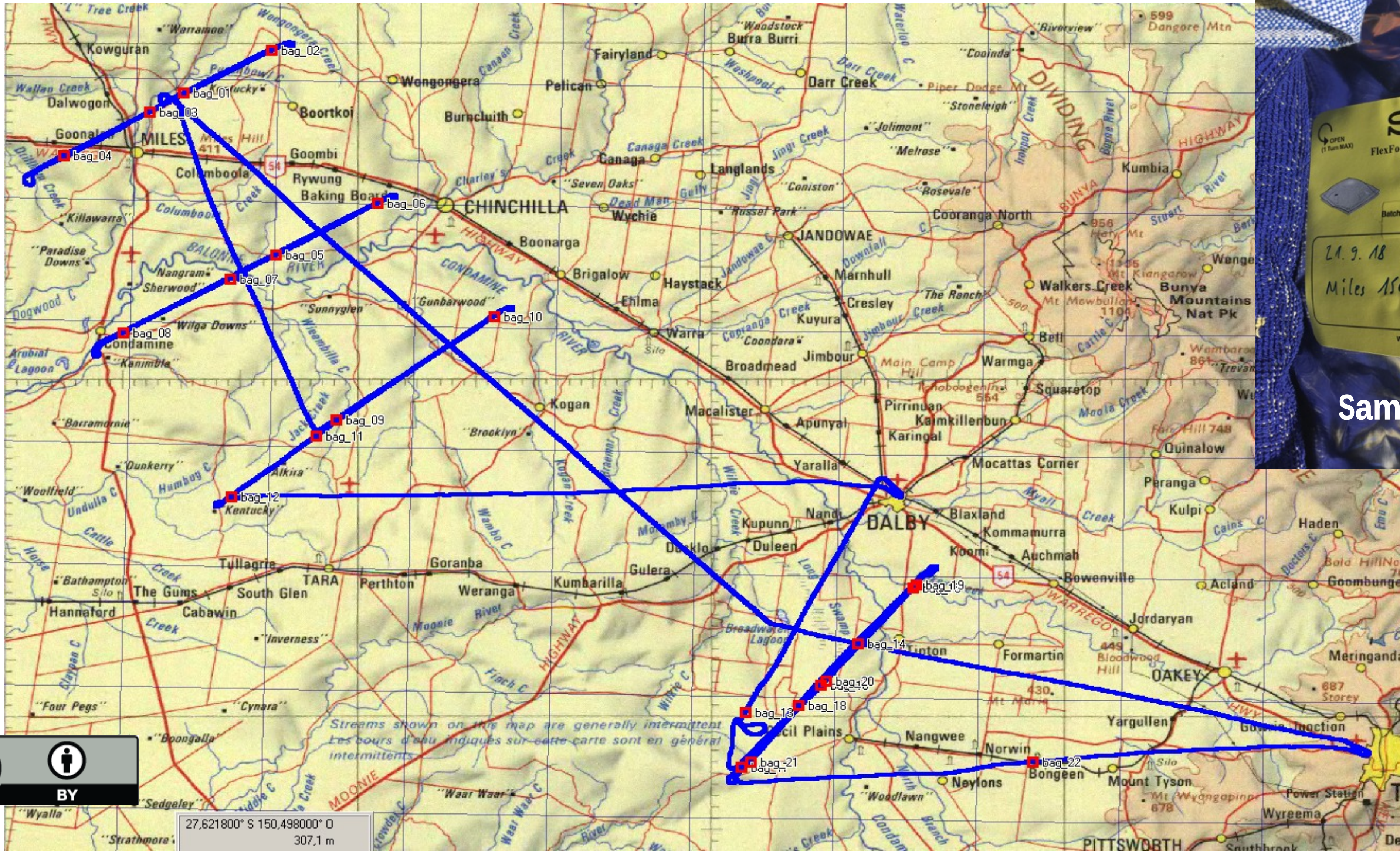
b) The same procedure for cross-valley flow from the NE, in this case turning to NNW during the planned flights.

The suitable flight legs were then defined by observing additional aspects like airspaces, endurance, actual wind observations (leading to ad-hoc adjustments during flights), etc.
Examples on previous and next slides.



Example of a Flight Track with grab samples (up to 25 bags/flight)

Flight track with 22 bag samples



Sampling bag

General Remarks about the Data Processing

Airborne data is four-dimensional (x,y,z,t),

covering time scales from 0.05s to hours and spatial scales from metres to 10-100 km.

- Many measured parameters are interdependent
  Example: air temperature and hence air density affects both, the wind and chemical measurements
- System has many redundant features enabling to check/confirm measured and processed parameters
  Example: true altitude measured by the IMU/GPS is used to verify various pressure measurements
- Accurate synchronization between all measurands is essential has to be checked and adjusted
  Example: intake line delays
- Cross-checks with non-aircraft derived data is required, such as overall meteorological data from observations as well as output from numerical models.

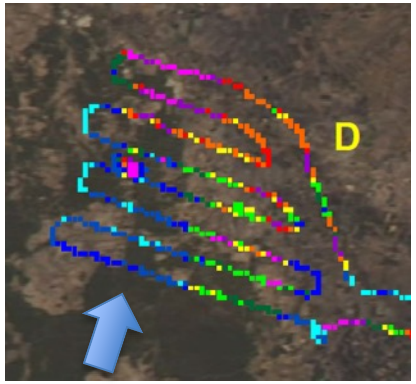
To achieve accurate, reliable and meaningful results, careful analysis of all aspects was required.

This was a rather time consuming process.

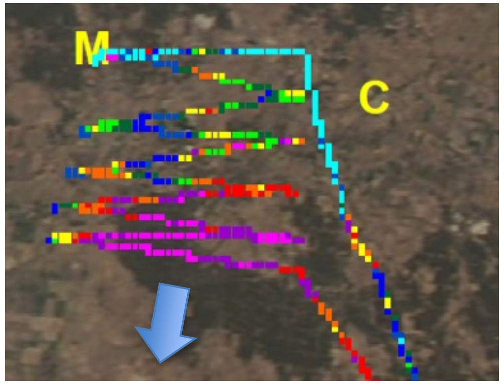
The final and Quality-Controlled results have become available in January 2019.

All tracks and First Results

Sept 10 in the SE



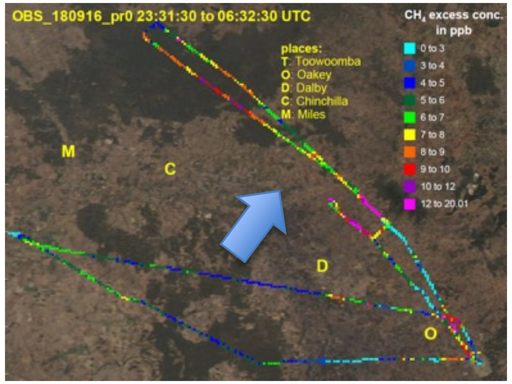
Sept 12 in the NW



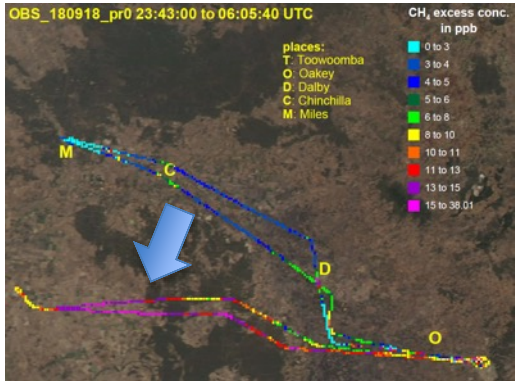
Sept 15 along basin

7 cases with different wind regimes; all with well mixed convective boundary layer

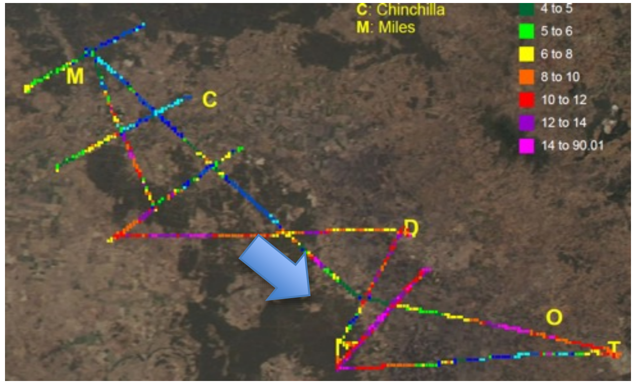
Sept 16 across basin



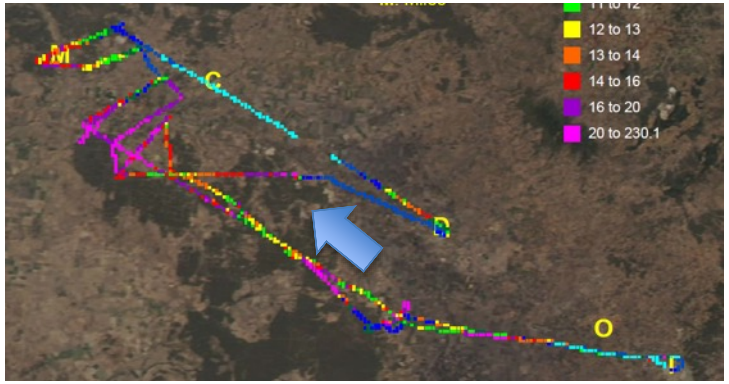
Sept 18 across valley



Sept 19 along valley

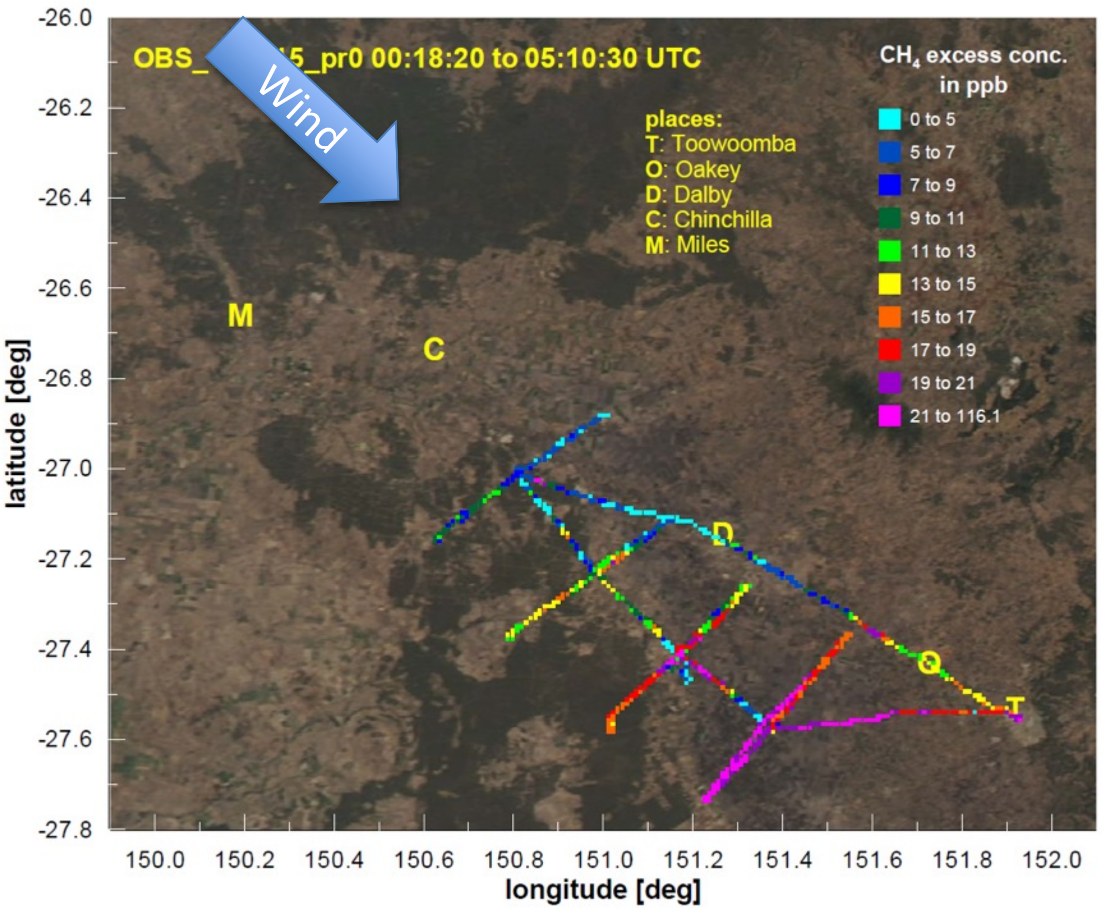


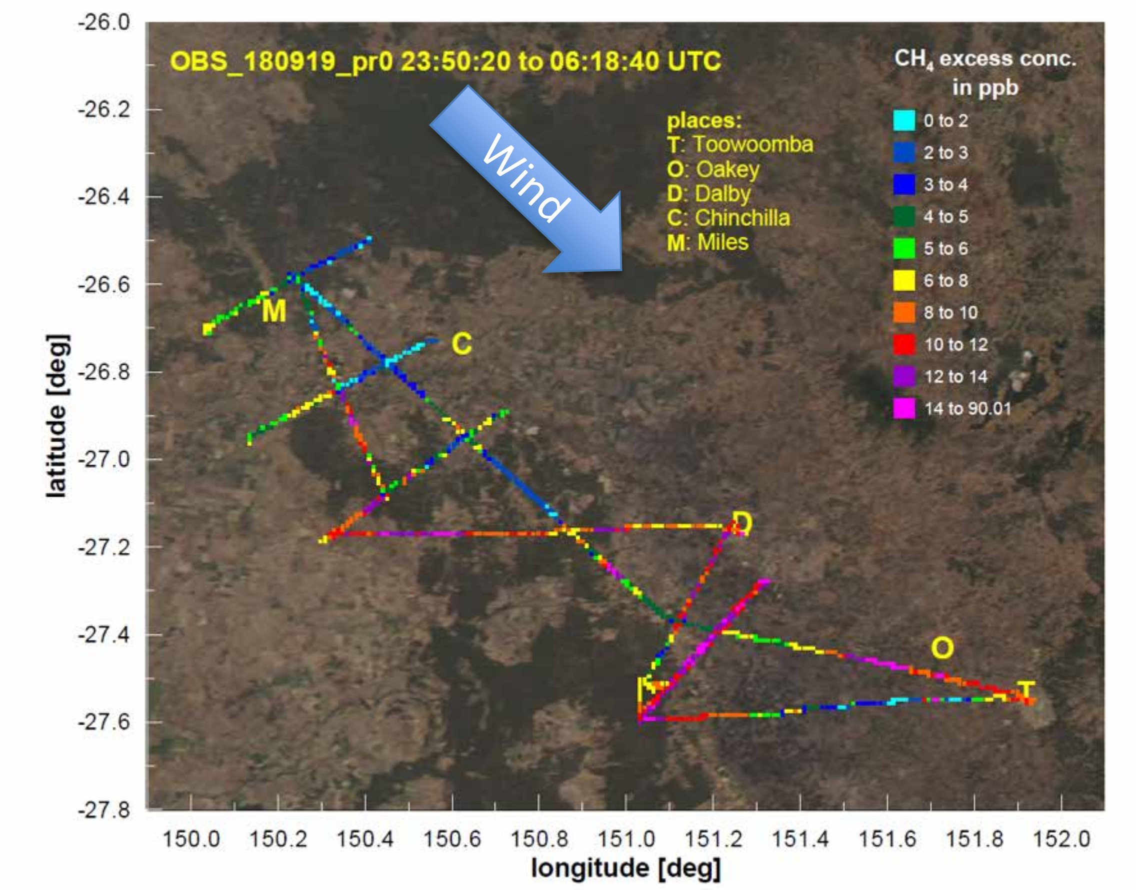
Sept 21 plume chasing in the NW



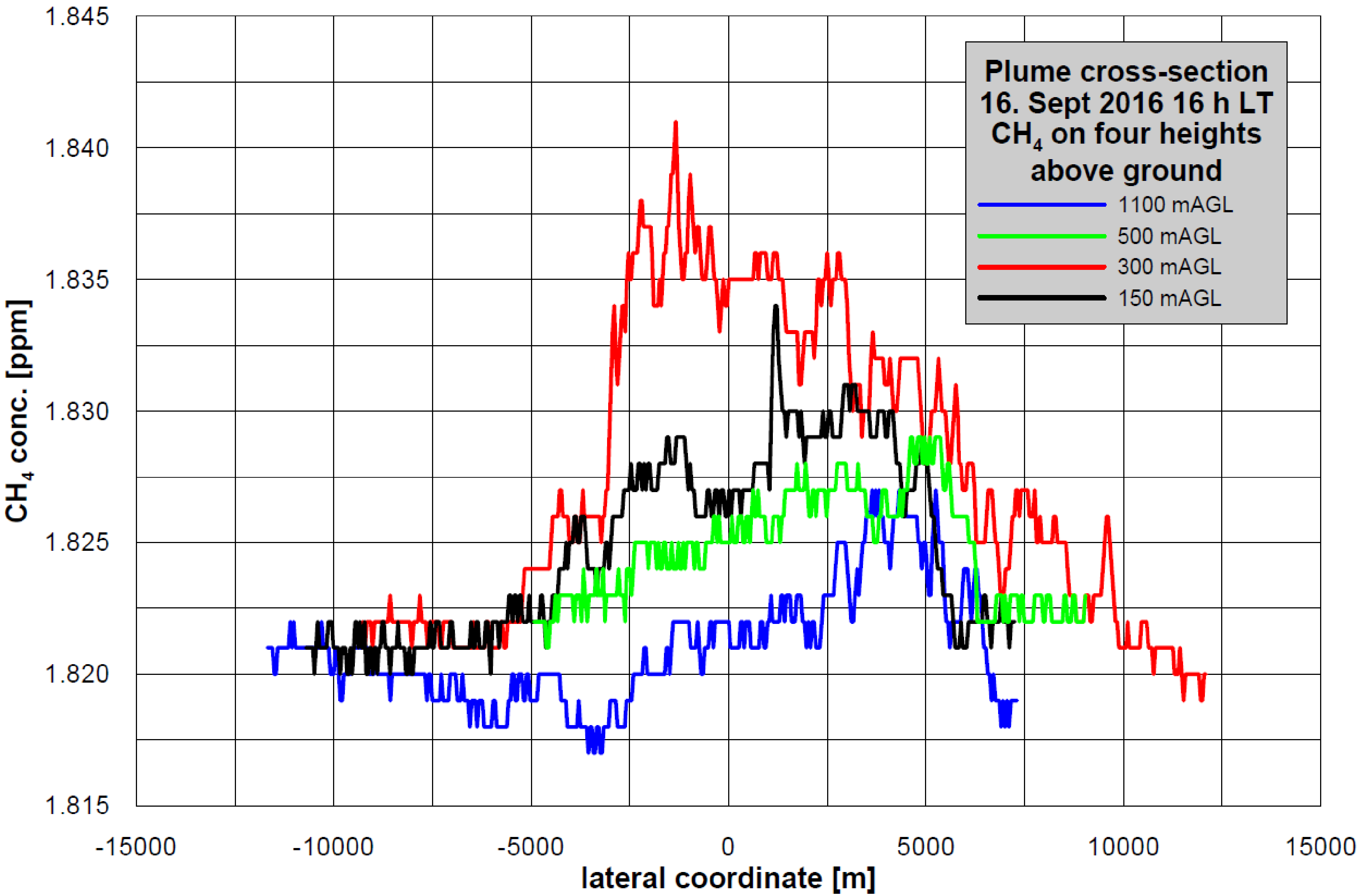
Two more detailed examples for along-valley flow

The increasing concentrations are visible already now.
However, for a quantitative assessment, all the fluxes in and out of the box will have to be calculated.





Example of an individual plume in about 20 km distance



A preliminary calculation of the flux resulted in about 750 g/s or 2.7 tons/hour

(corrected after the EGU 2019)

Emission vs. concentrations airborne vs. near the source

Discussing the order of magnitude of concentration enhancements in a large region compared to near-source measurements near the ground (Kelly et al. by car):

Assuming a CH_4 source of 16 g/s (1 mol/s, or 58 kg/h) somewhere.

Case 1: Diluted in wind of 3 m/s (100 mol s^{-1} m^{-2}) in a plume of 1'000 m^2 cross-section (red shaded ellipse below; 1 m^3 of air is containing roughly 30 mol N_2+O_2)
ð 100 kmol s^{-1} diluting air, resulting in a concentration enhancement of 10 ppm

Case 2: Diluted in Wind of 6 m/s (200 mol s^{-1} m^{-2}) on an exit cross section of 50 km x 2'000 m
ð concentration enhancement of 0.05 pp<u>b</u> only!

Conclusion: Typical concentration enhancements of 10 pp<u>b</u> over the region are indicating emissions in the order of magnitude of 10 t/h (sum of very different sources including feedlots)

Typical convective mixing up to 2'000 mAGL

Four publications describing some related details

From previous first work on CH_4 in Switzerland:

Hiller R.V., B. Neininger, D. Brunner, C. Gerbig, D. Bretscher, T. Künzle, N. Buchmann, W. Eugster, 2014: Aircraft based CH4 flux estimates for validation of emissions from an agriculturally dominated area in Switzerland. Journal of Geophysical Research: Atmospheres 03/2014; DOI:10.1002/2013JD020918.

From a previous project with a focus on one big rural CH_4 source in Australia:

Hacker, J.M., D. Chen, M. Bai, C. Ewenz, W. Junkermann, W. Lieff, B. McManus, B. Neininger, J. Sun, T. Coates, T. Denmead, T. Flesch, S. McGinn and J. Hill, 2016: Using airborne technology to quantify and apportion emissions of CH4 and NH3 from feedlots. Animal Production Science, 2016, 56, 190-203.

About a first feasibility study around other Oil & Gas fields near Groningen, NL:

Yacovitch T.I., B. Neininger, S.C. Herndon, H.D. van der Gon, S. Jonkers, J. Hulskotte, J.R. Roscioli, D. Zavala-Araiza: Methane Emissions in the Netherlands, 2018: The Groningen Field. Elem Sci Anth, 6: 57. DOI: https://doi.org/10.1525/elementa.308.

About some special aspects of calculating horizontal and vertical fluxes from our airborne data

Krings T, Neininger B, Gerilowski K, Krautwurst S, Buchwitz M, et al. 2016. Airborne remote sensing and in-situ measurements of atmospheric CO2 to quantify point source emissions. Atmos Meas Tech Discuss 2016: 1-30. DOI:10.5194/amt-2016-362. https://www.atmos-meas-tech.net/11/721/2018/amt-11-721-2018.pdf