RPA-Borne Measurements of Convective and Stable Boundary-Layers over the Near-Coastal North Sea during Strong Winds

David Tupman, Andreas Platis, Alexander Rautenberg, Norman Wildmann, Jens Bange

University of Tubingen
david-james.tupman@uni-tuebingen.de

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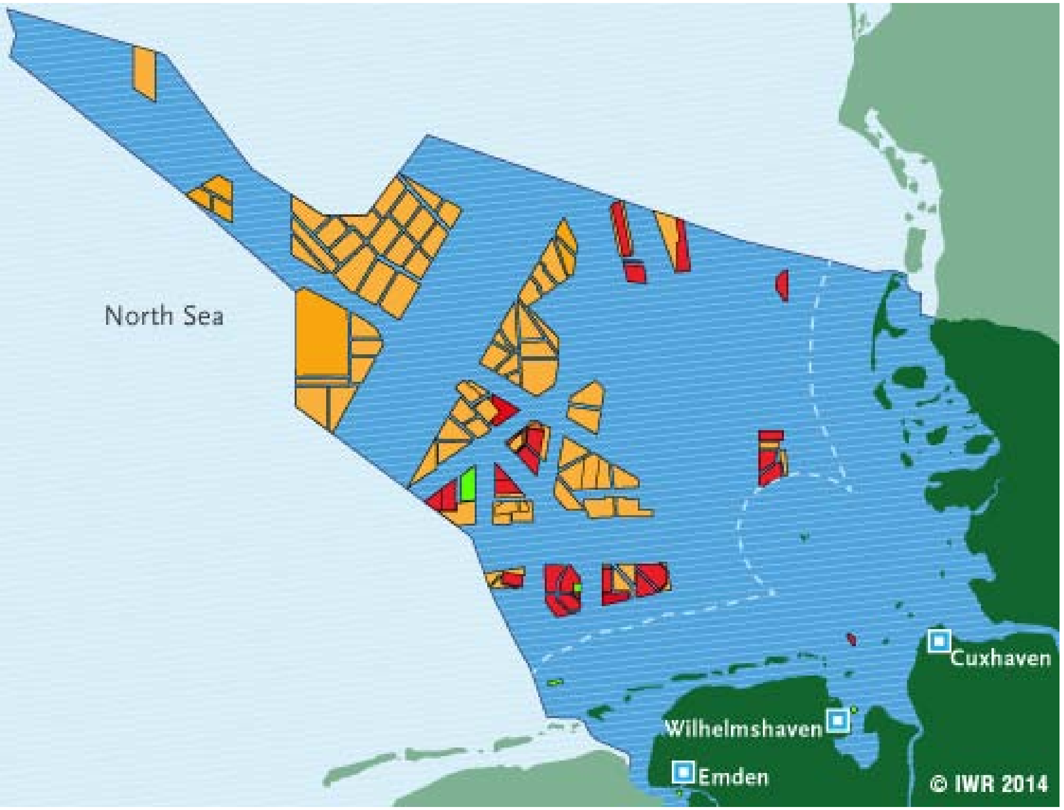
The OWEA LOADS project - motivation



Green: operating. Red: under construction. Orange: planned

- North Sea wind energy: operating 865 MW; under construction 2'400 MW; planned up to 40'000 MW
- Main objective: assess the structural loads borne by current and future offshore wind turbines, new generation up to 300 m ASL
- Role of Tubingen: obtain in-situ turbulent-scale measurements up to 500 m ASL, as close to Alpha Ventus (green) as possible
- Method: use of our Multiprobe Airborne Sensor Carrier. (relatively) Cheap and (relatively) easy to deploy
- Status: all five campaigns complete; preliminary analysis ready to present today

MASC: Multi-purpose Airborne Sensor Carrier

Operated by the **University of Tübingen**

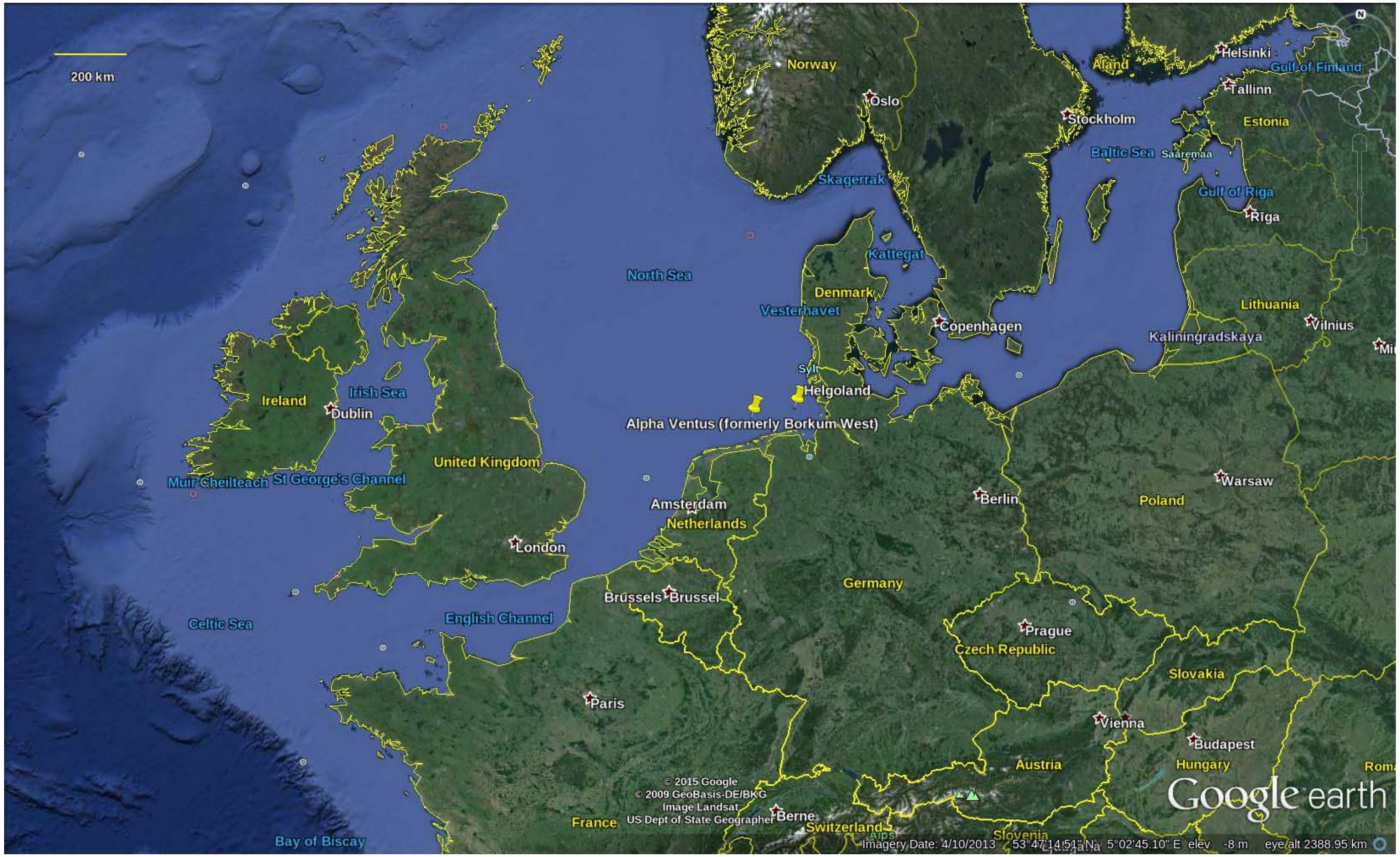
(I told the designer, that I don't mind what colour, as long as it's well visible!)

wingspan:	2.7...3.5 m
total weight:	< 6 kg
incl. sci. payload:	1.5 kg
cruising speed:	25 m/s
endurance:	$\approx$ 1 hour
electrical engine	
autopilot:	U Stuttgart

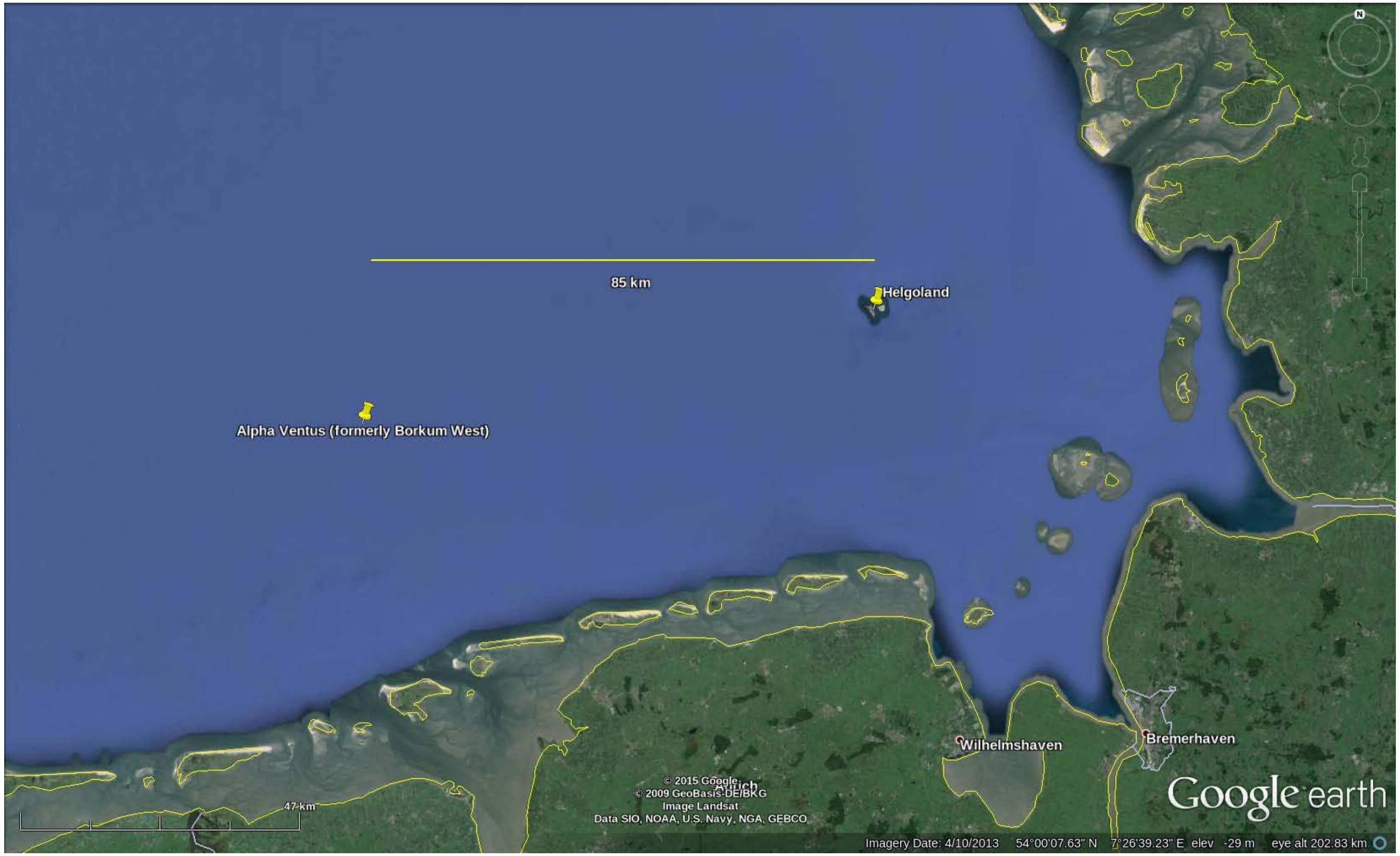
Measurements:

- 3D wind vector (30 Hz; 1 m)
- air temperature (30 Hz; 1 m)
- water vapour (not used here)

North Sea region



Legal requirement for line-of-sight



Helgoland

Permitted airspace highlighted, to the southwest of Helgoland

- Permitted airspace is 1 km square x 500 m ASL
- **North-east**; flow distortion from 50 m cliffs; **reject** data
- **East to south-west**; flow from mainland Europe (approx. 100 km); **convective and stable**
- **West to north**; flow from open sea (at least 500 km); **neutral**
- 80 flights, all in autumn and winter due to permission restrictions

Typical flight strategy

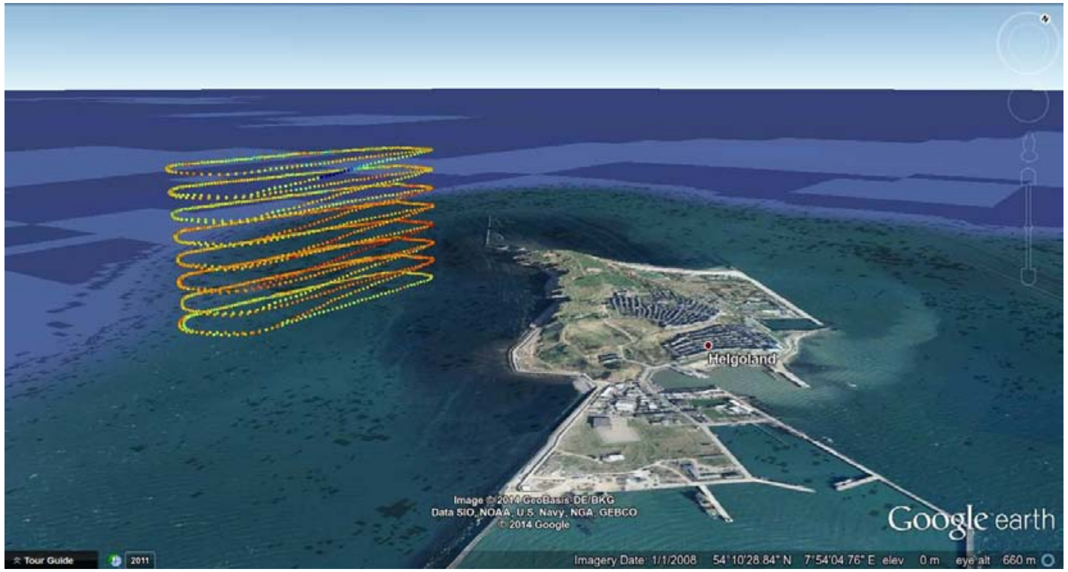
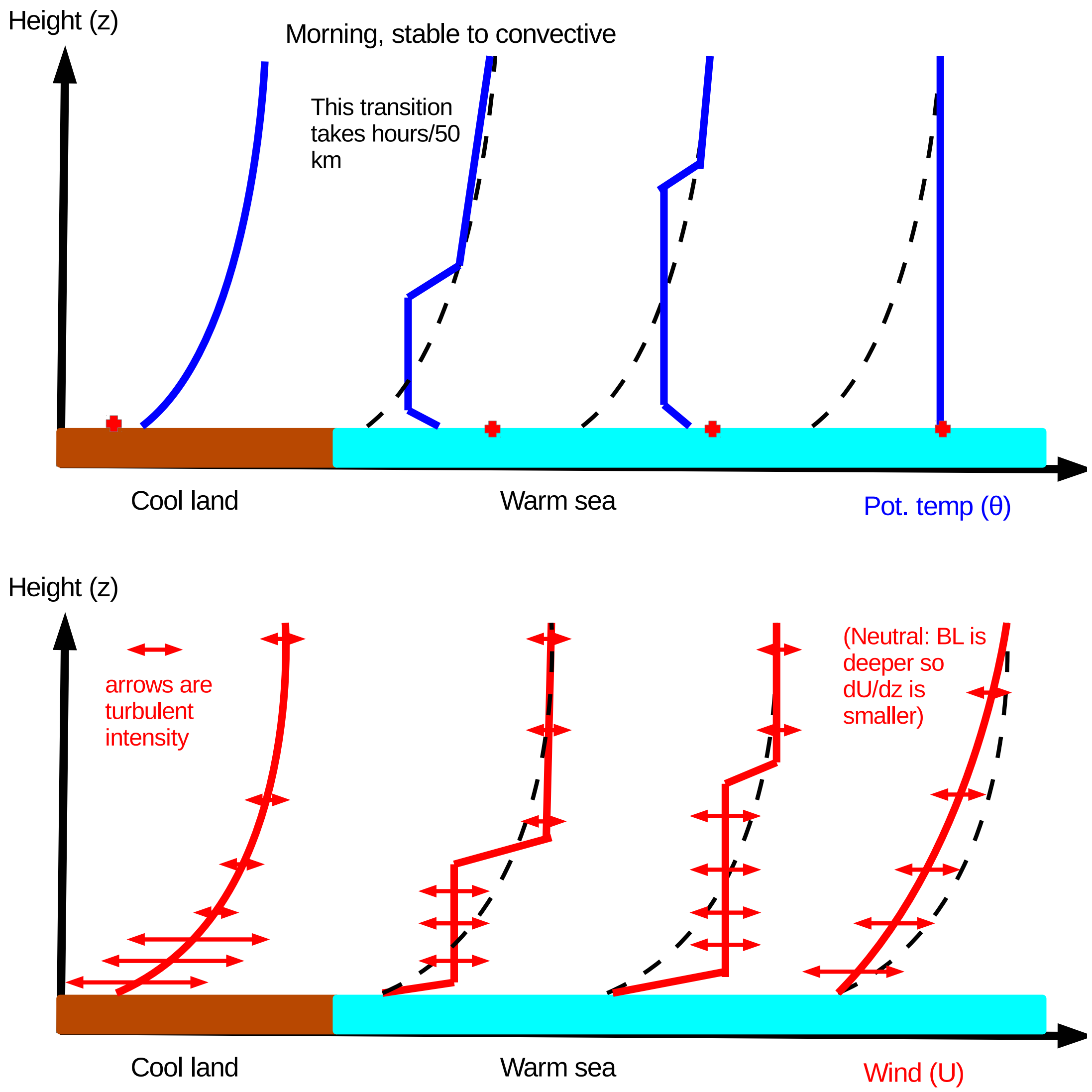


Image credit: Norman Wildmann

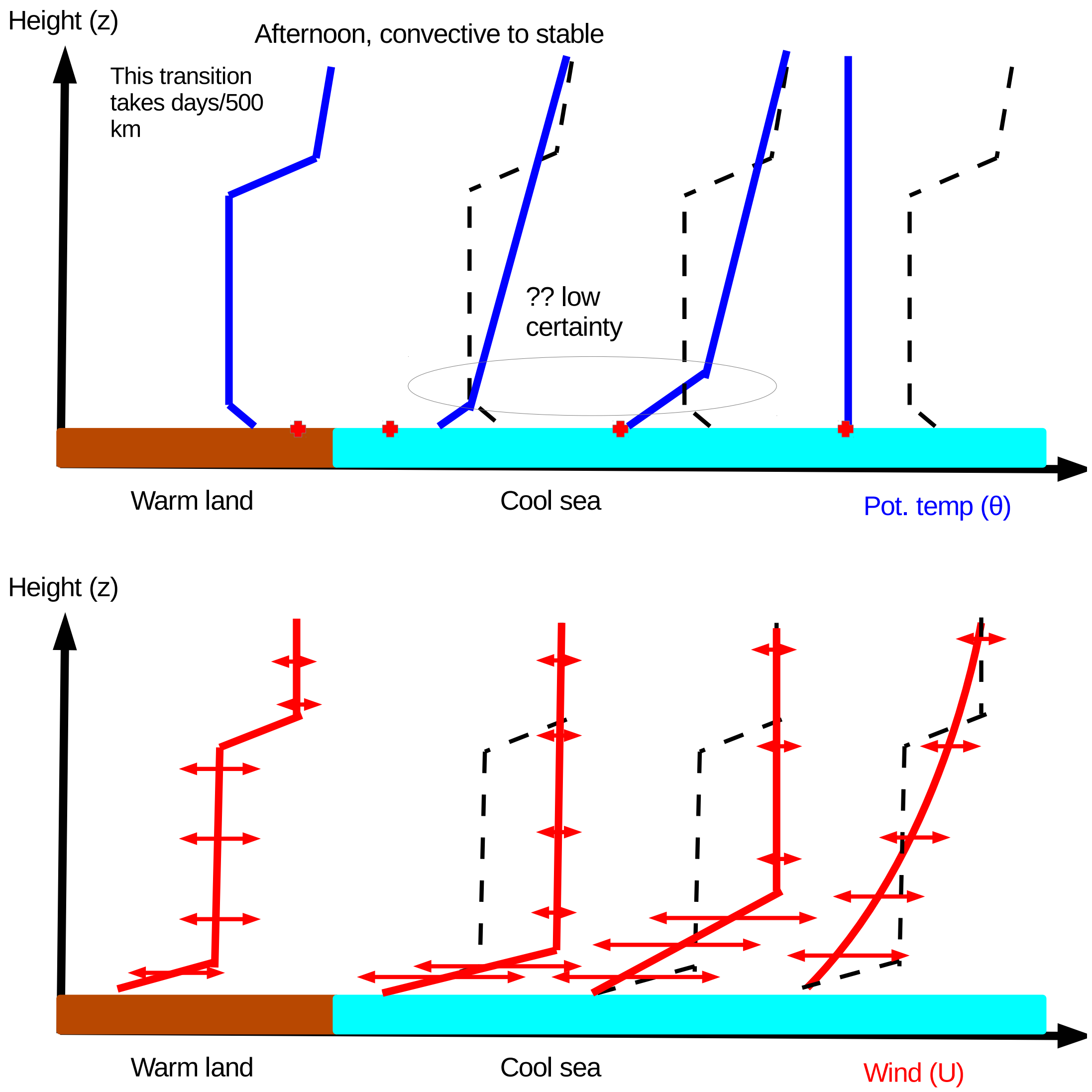
- Generally followed a 'racetrack' pattern, as straight legs are required for the wind measurement system
- Each headwind leg was 25-50 seconds, so 500-1000 m flow past the sensors
- Typically 90 minutes flying time during two or three hours, allowed 'case studies' to be developed. i.e. measurements grouped together during stationary conditions
- Each case study requires stationarity tests... not presented here but we did this!

Convective boundary layer (CBL)



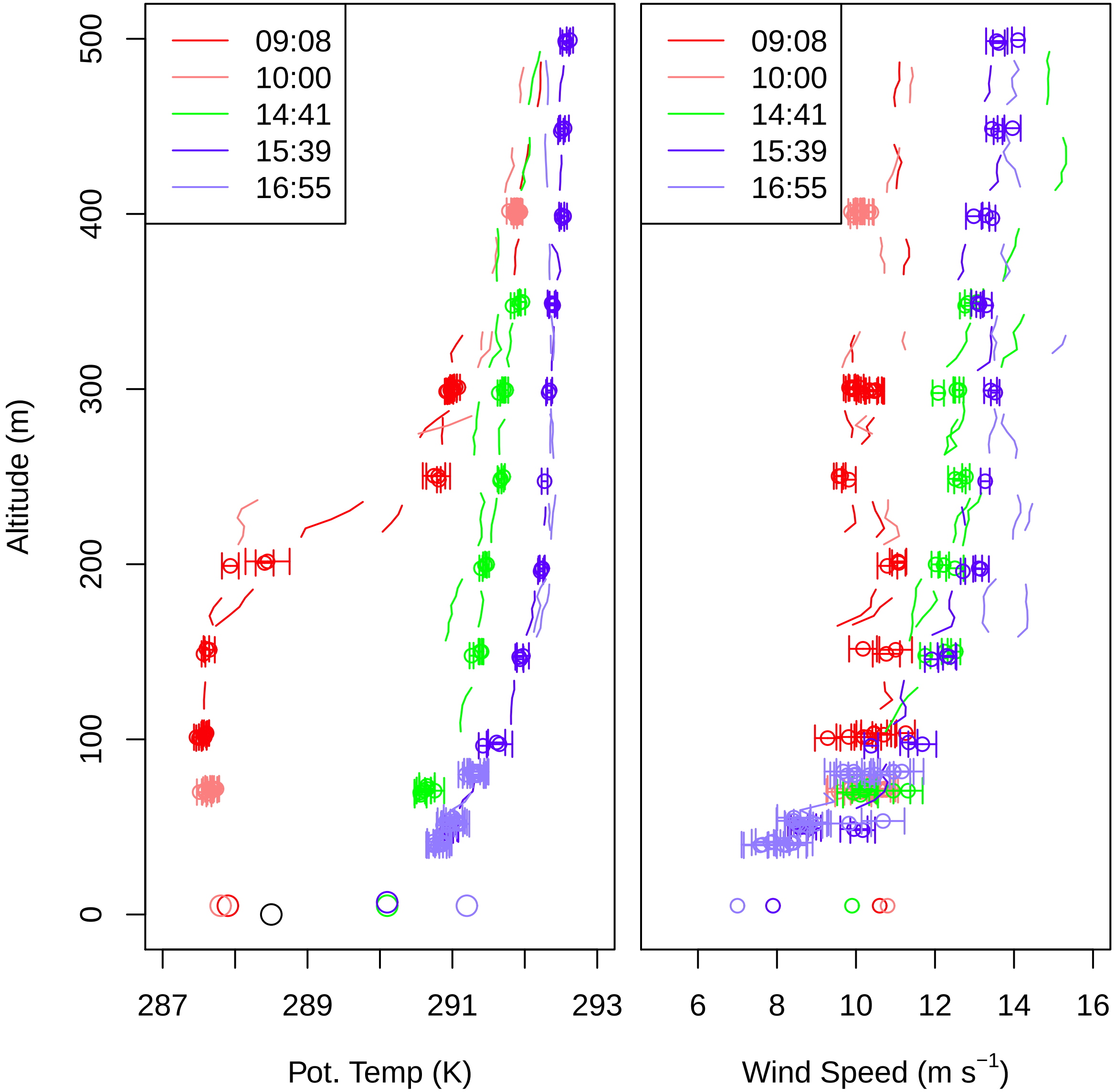
- Well mixed vertical profiles up to the inversion base
- Strong turbulence dominated by large convective motions
- Our CBL cases are 200 to 400 m deep, layer depth well defined

Stable boundary layer (SBL)



- Strong gradients in vertical profiles
- Strong turbulence near the surface, shear stress greater than stable supression
- No turbulence above, shear stress less than stable supression
- Our SBL cases are 100 to 200 m deep, layer depth sometimes ambiguous

Diurnal cycle, CBL to SBL



- During morning flights, mainland Germany was relatively cold
- During afternoon flights, mainland Germany was relatively warm
- These example profiles are reasonably representative of all other cases presented today

Research Question

- Question: Do turbulent statistics across similar BL cases converge, when normalised using the boundary conditions of layer depth, and the air-sea fluxes of heat and momentum?

Preliminary plots in the next slides. Looks pretty good compared to a quick scan of Stull, but needs a rigorous comparison!

- Input 1: turbulent statistics

We directly measure these with MASC

- Input 2: boundary layer depth

Taken from potential temperature profiles. Very clear during CBLs, not always during SBLs

- Input 3: air-sea fluxes

Not measured. We used the COARE 3.5 bulk flux algorithm (e.g.: Fairall et al., 2003, Edson et al., 2013)

Case Studies, unambiguous CBLs

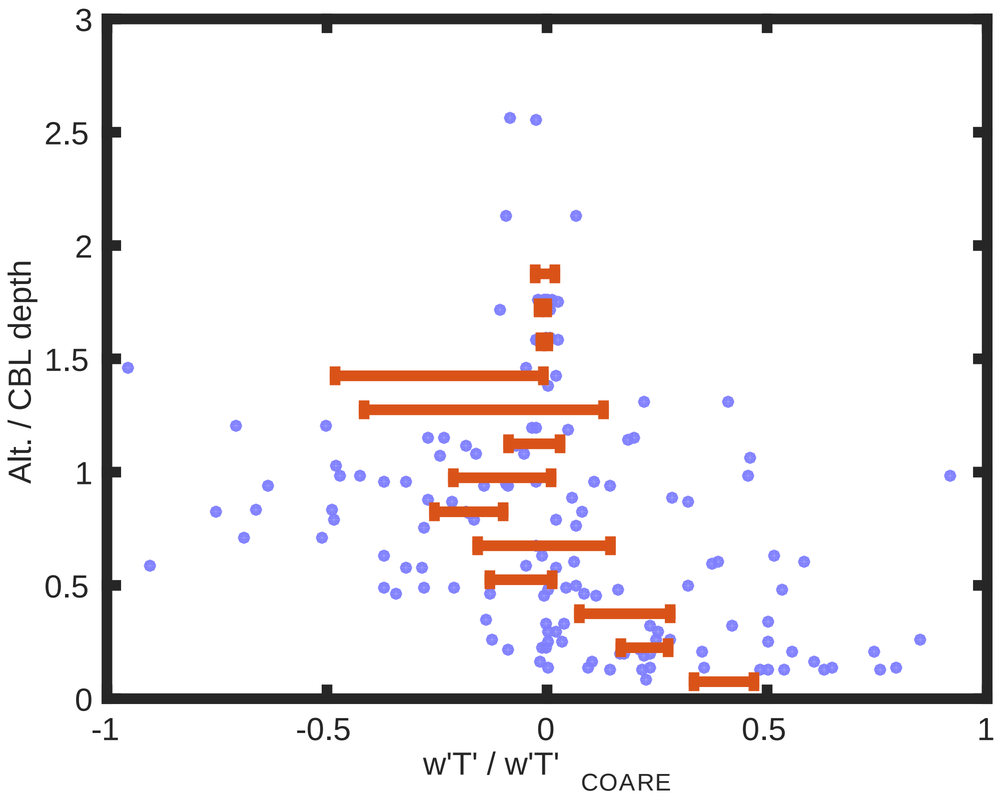
Data from German Weather Service instrumentation:

Date	Time (UTC)	10 m Wind	10 m Tair	Tsea	Cloud
4th Oct 2014	0700-0900	10.7 m s^{-1}SSE'ly	15.7 C	16.8 C	zero
6th Oct 2014	0720-0950	14.0 m s^{-1}SEE'ly	14.0 C	16.4 C	haze only
8th Oct 2014	1200-1320	7.2 m s^{-1}S'ly	14.1 C	16.2 C	6/8 low
28th Feb 2015	0830-1000	9.7 m s^{-1}S'ly	3.5 C	5.2 C	8/8 mid alt.
5th Oct 2015	0700-0900	7.1 m s^{-1}S'ly	14.6 C	16.2 C	2/8 low

CBL height and results from COARE algorithm:

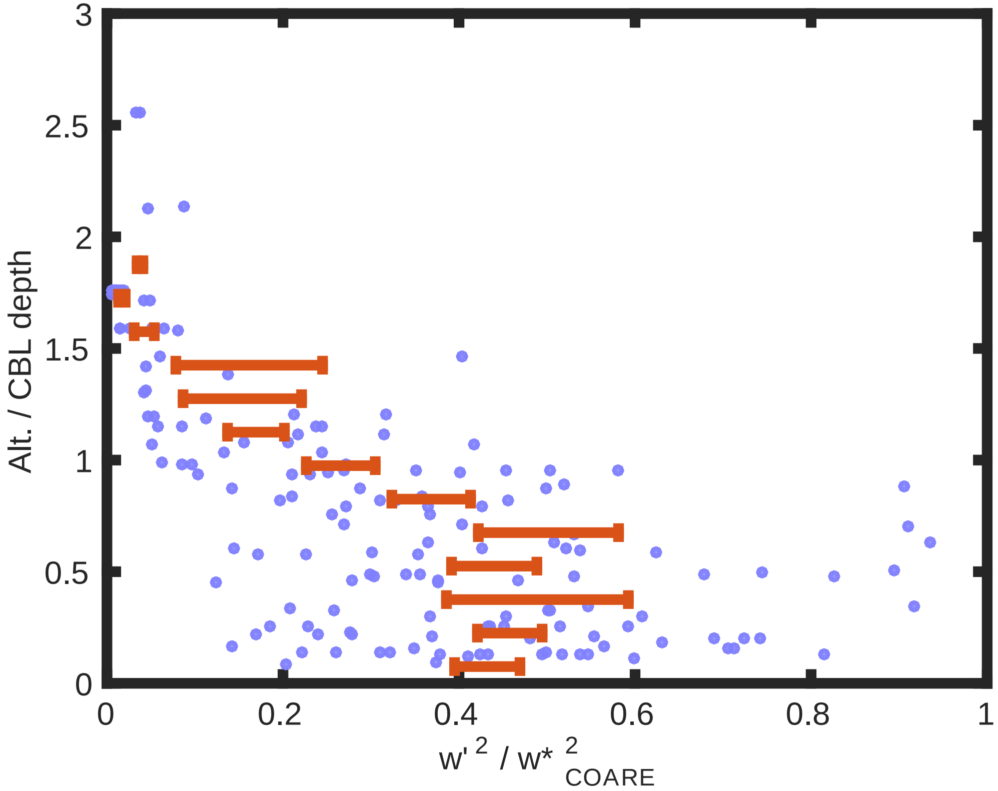
Date	CBL depth	Sens. Heat Flux	ustar
4th Oct 2014	200 m	15 W m^{-2}	0.39 m s^{-1}
6th Oct 2014	300 m	45 W m^{-2}	0.60 m s^{-1}
8th Oct 2014	400 m	20 W m^{-2}	0.23 m s^{-1}
28th Feb 2015	200 m	25 W m^{-2}	0.35 m s^{-1}
5th Oct 2015	180 m	15 W m^{-2}	0.21 m s^{-1}

CBL Sensible heat fluxes



- Expected linear profile, a good sanity check!
- Entrainment zone, depth, and flux magnitude, match textbook free convective BL relations (e.g. Deardorff 1974, Lenschow et al. 1980) well
- Large scatter within each height bin, but our flux magnitudes are tiny compared to publications (20 W m^{-2}compared to 200 W m^{-2})
- Lowest altitude aircraft fluxes are systematically too small

CBL Vertical wind variance



- Excellent match to textbook relations of free convective CBLs, except, again, at the lowest altitudes; does not tend to zero
- Strong shear generation contribution? And/or are we missing the bottom of the BL at 50 m (lowest flight altitude)?
- Similar quality of results for horizontal wind and temperature variances

Case Studies, unambiguous SBLs

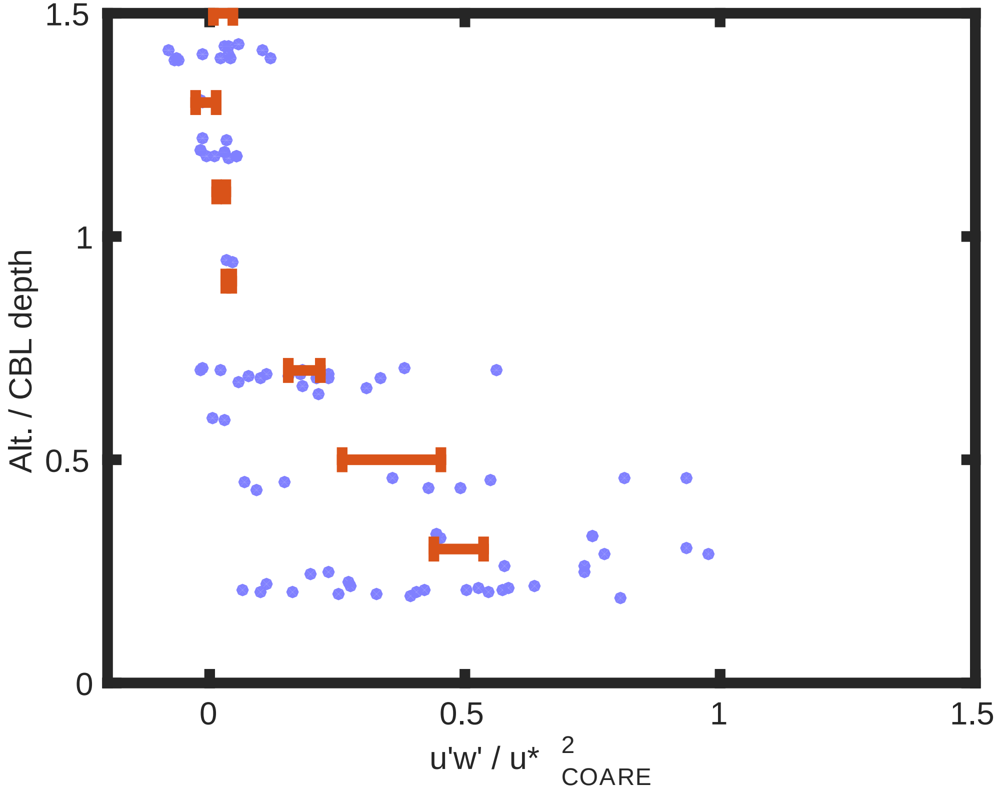
Data from German Weather Service instrumentation:

Date	Time (UTC)	10 m Wind	10 m Tair	Tsea	Cloud
4th Oct 2014	1330-1530	7.5 m s^{-1}SSE'ly	18.4 C	16.8 C	zero
24th Feb 2015	1000-1500	14.2 m s^{-1}SW'ly	6.0 C	5.2 C	8/8 low
26th Feb 2015	1420-1630	10.5 m s^{-1}S'ly	5.7 C	5.1 C	8/8 low
27th Feb 2015	0900-1530	6.2 m s^{-1}NW'ly	5.9 C	5.4 C	zero
5th Oct 2015	1430-1500	9.1 m s^{-1}E'ly	16.3 C	16.2 C	4/8 low

SBL height and results from COARE algorithm:

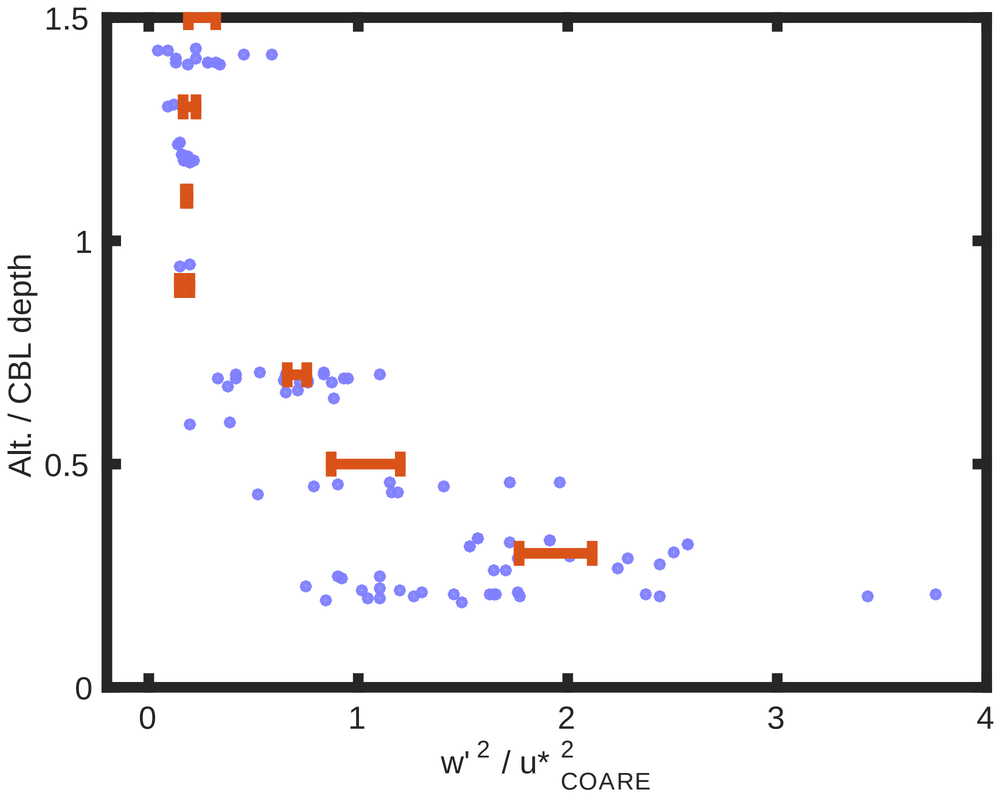
Date	CBL depth	Sens. Heat Flux	ustar
4th Oct 2014	140 m	-14 W m^{-2}	0.22 m s^{-1}
24th Feb 2015	110 m	-14 W m^{-2}	0.57 m s^{-1}
26th Feb 2015	90 m	-9 W m^{-2}	0.36 m s^{-1}
27th Feb 2015	200 m	-5 W m^{-2}	0.22 m s^{-1}
5th Oct 2015	200 m	NA W m^{-2}	0.31 m s^{-1}

SBL Momentum flux



- Far fewer records
- Although sensible trends and data grouping are observed
- We simply were not permitted to fly during the right conditions (spring and summer!)

SBL Vertical wind variance



- Trend and sensible data grouping is observed
- Matches textbook relations well (Andre et al., 1978, Caughey et al., 1979)
- Heat fluxes were too pitifully small to merit presentation

Summary

- Plots of the best cases of CBLs and SBLs show that we can quantitatively compare them to published work, this is the most obvious next step
- Our boundary layers are very weak - small heat fluxes, strong winds and shear - compared to the literature. Can one extend the textbook relationships derived from studies of stronger CBL/SBLs to the very weak regime?
- In particular at the bottom of the CBLs, is there a significant shear generation term? Turbulent Kinetic Energy budget terms should be studied
- Further analysis required regarding error quantification, particularly for CBLs. Analyses of integral length scales and flux cospectra are currently underway