DLR's Wake Vortex and Turbulence Research

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Germany

- Wake Vortex Encounter over the Arabian Sea
- Wake Vortex Prediction and Warning Systems – WSVBS, WEAA
- Mountain Wave Hazards on Aviation

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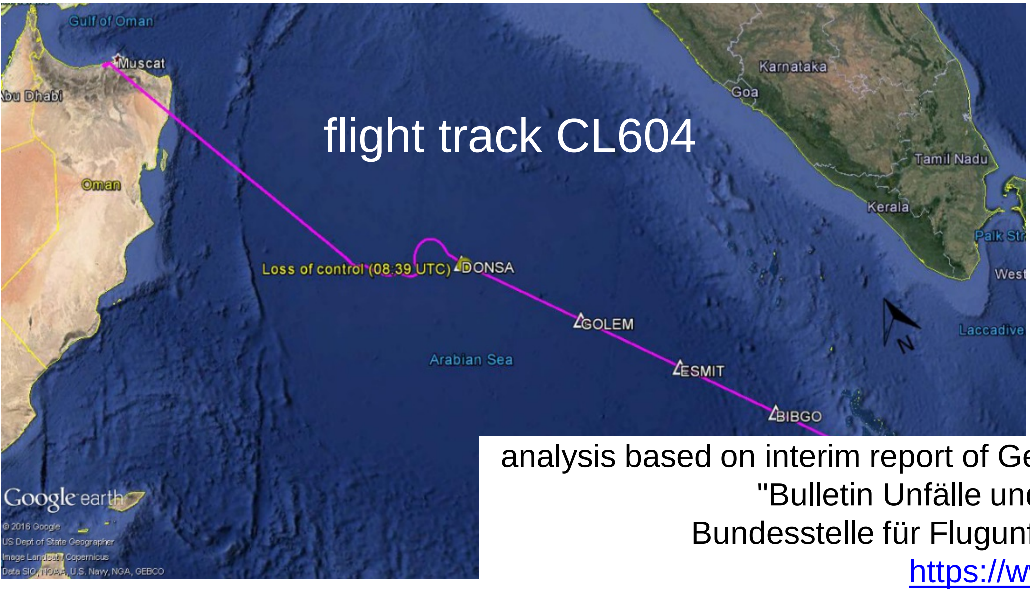
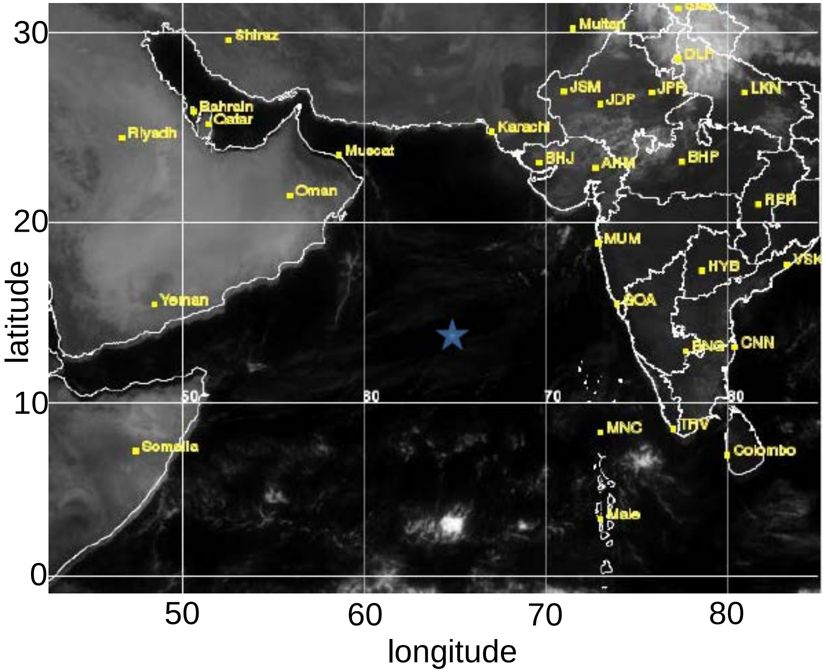
Wake Vortex Encounter over the Arabian Sea

encounter situation – 7 Jan 2017, 8:39 UTC





satellite image of visible channels of Indian KALPANA-1 satellite, 8:45 UTC, 7 Jan 2017
6 min after the encounter.

analysis based on interim report of German Federal Bureau of Aircraft Accident Investigation (BFU):
"Bulletin Unfälle und Störungen beim Betrieb ziviler Luftfahrzeuge, Januar 2017,"
Bundesstelle für Flugunfalluntersuchung (BFU), Braunschweig, Germany, 2017, p. 43.
https://www.bfu-web.de/DE/Publikationen/Bulletins/bulletins_node.html

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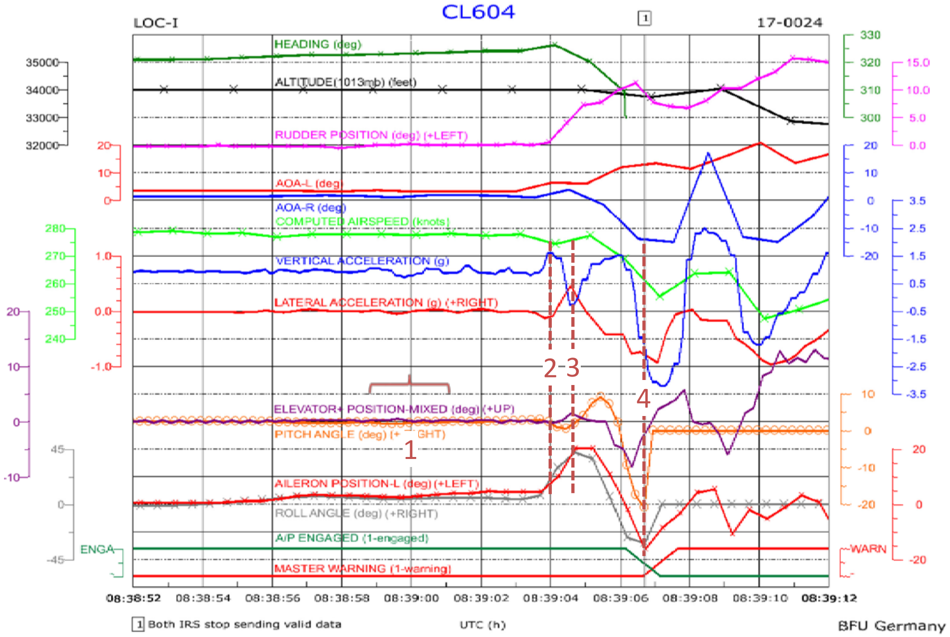
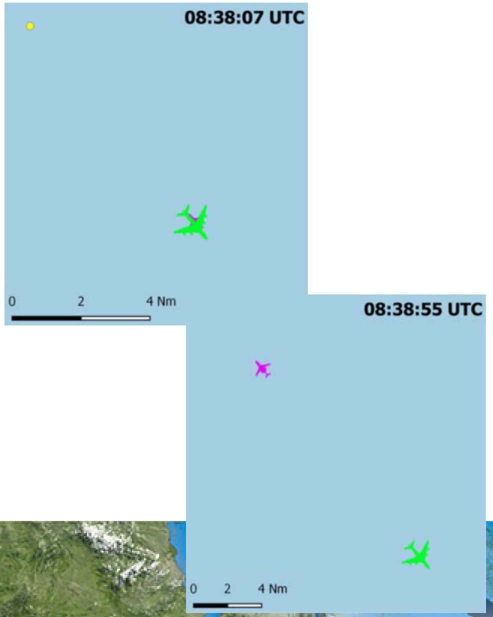
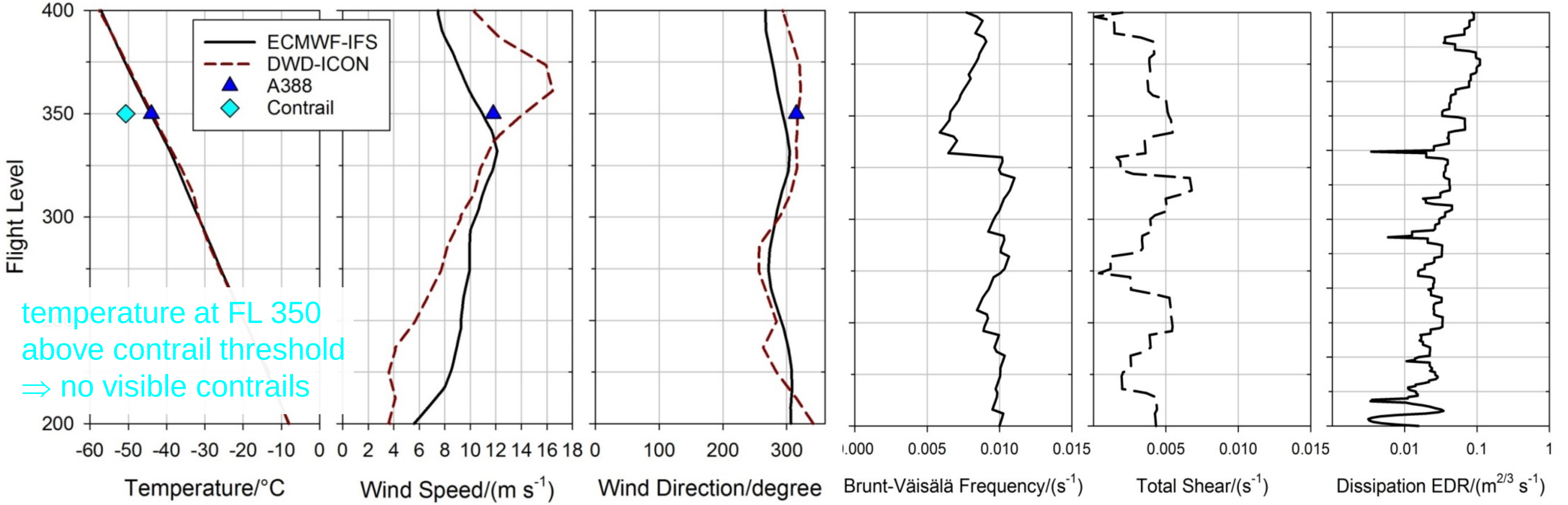


- 08:38:55 (1) bank angle right 5°, aileron deflection left, fluctuating vertical accelerations
- 08:39:04 (2) strong a/c response begins
- (3) bank angle 42°, aileron 20°, vertical acceleration 1.6 g
- (4) 08:39:06 rolling left -31°, downwards acceleration -3.2 g, autopilot shut off, IRS inoperative ⇒ subsequent attitude angles unknown
- 08:39:09 altitude loss of 2700 m



Meteorological Environment

Integrated Forecasting System (IFS) of the European Center for Medium Range Weather Forecasts (ECMWF)
Icosahedral Nonhydrostatic Model (ICON) of the German Weather Service (Regine Zinkhan, DWD)



derived from ECMWF temperature & wind profiles

Schumann, U., "On conditions for contrail formation from aircraft exhausts," Meteorologische Zeitschrift 5 (1) 1996, pp. 4-23.

U. Schumann, T. Gerz, "Turbulent mixing in stably stratified shear flows," *Journal of Applied Meteorology* **34** (1) 1995, pp. 33-48.

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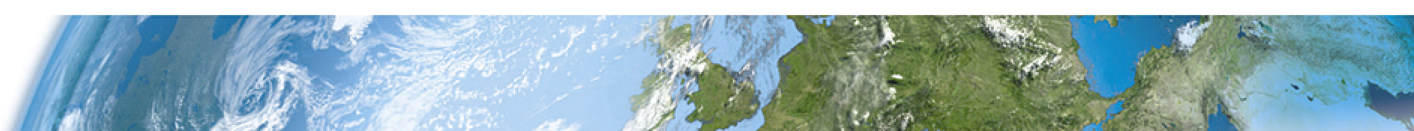
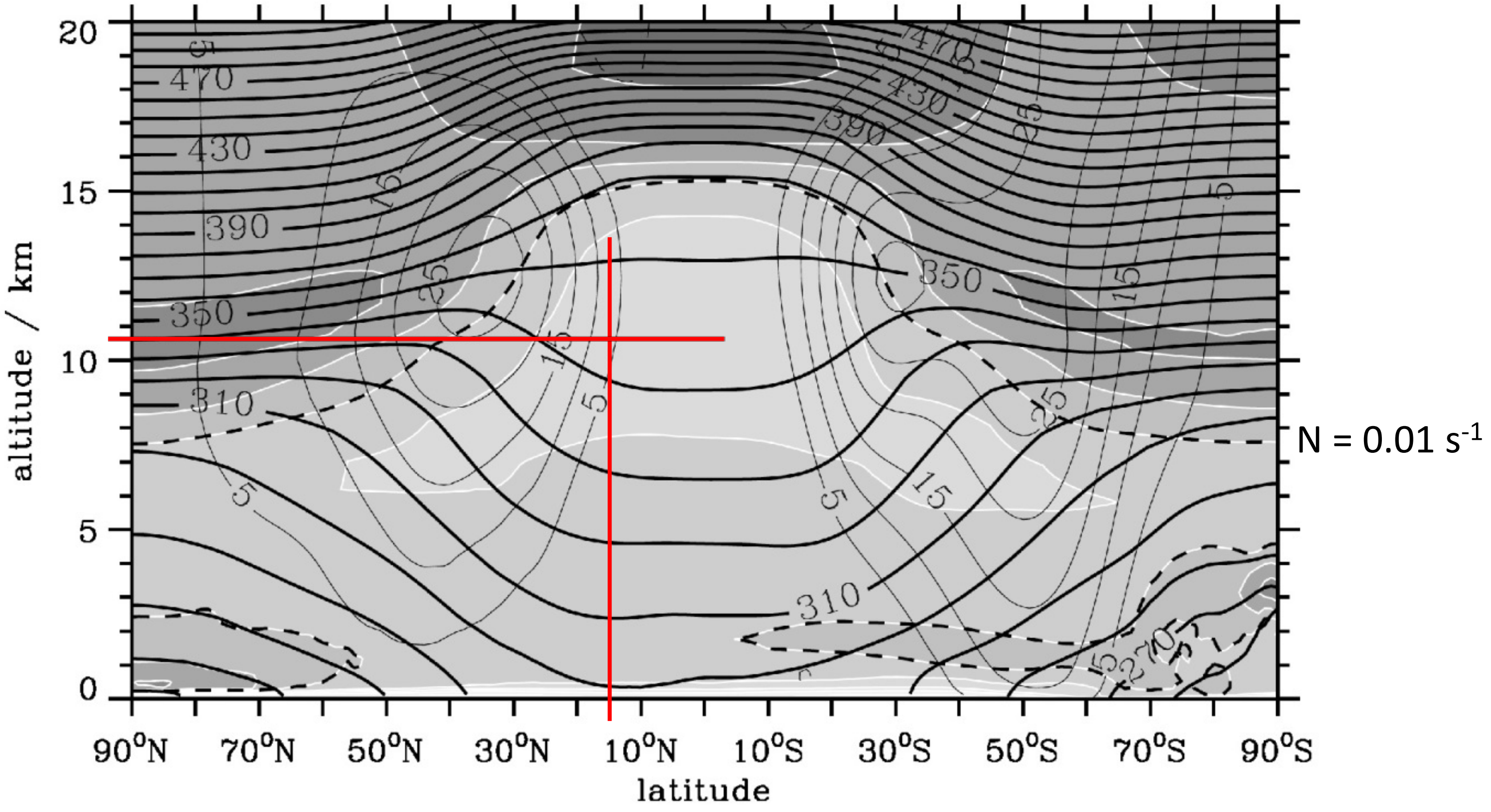
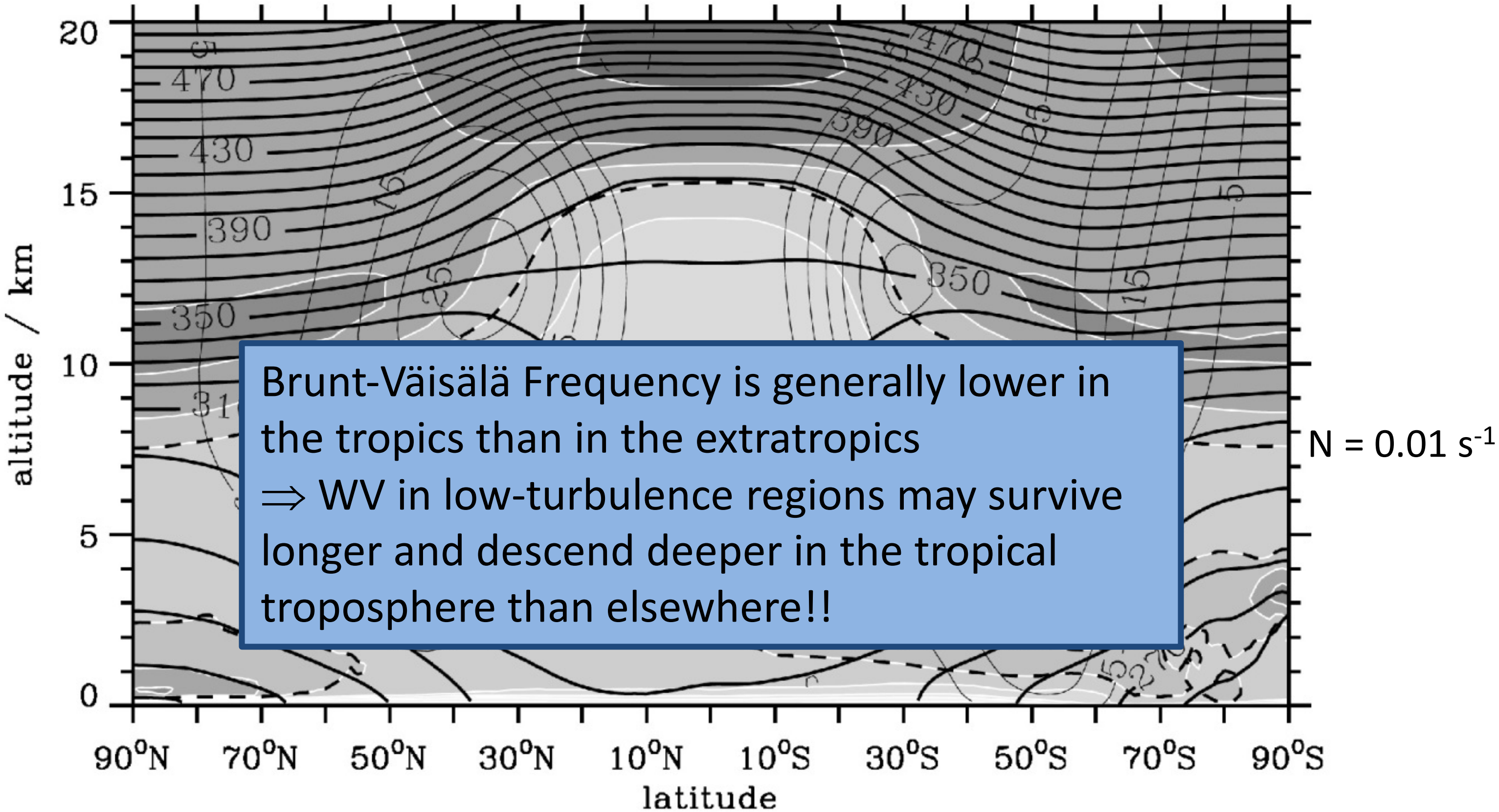


Climatology – Zonal mean potential temperature, wind and Brunt-Väisälä frequency



derived from 39 years of ERA-Interim data

Climatology – Zonal mean potential temperature, wind and Brunt-Väisälä frequency

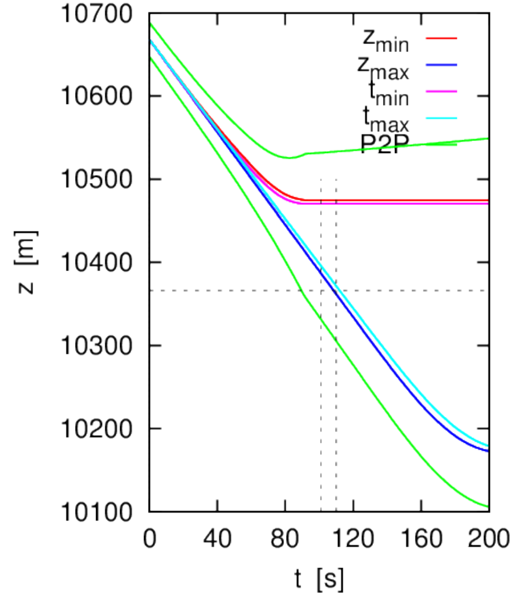


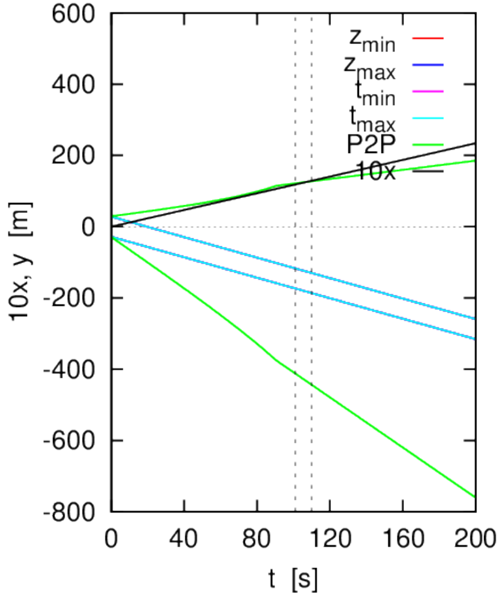
Brunt-Väisälä Frequency is generally lower in the tropics than in the extratropics
$\Rightarrow$ WV in low-turbulence regions may survive longer and descend deeper in the tropical troposphere than elsewhere!!

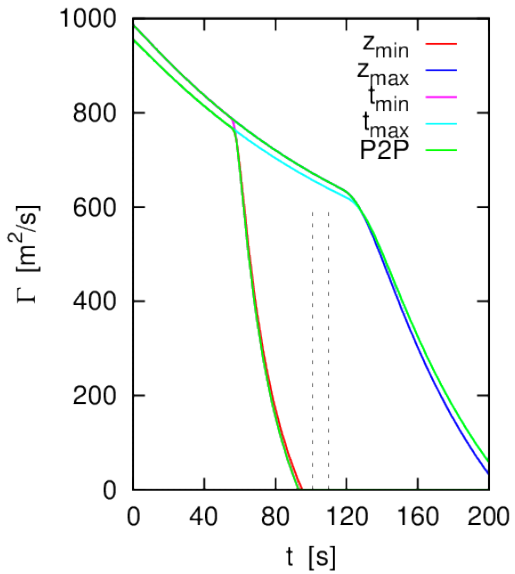
derived from 39 years of ERA-Interim data

Airborne Probabilistic 2-Phase wake vortex model – P2P[a] with A388 wind & ECMWF data

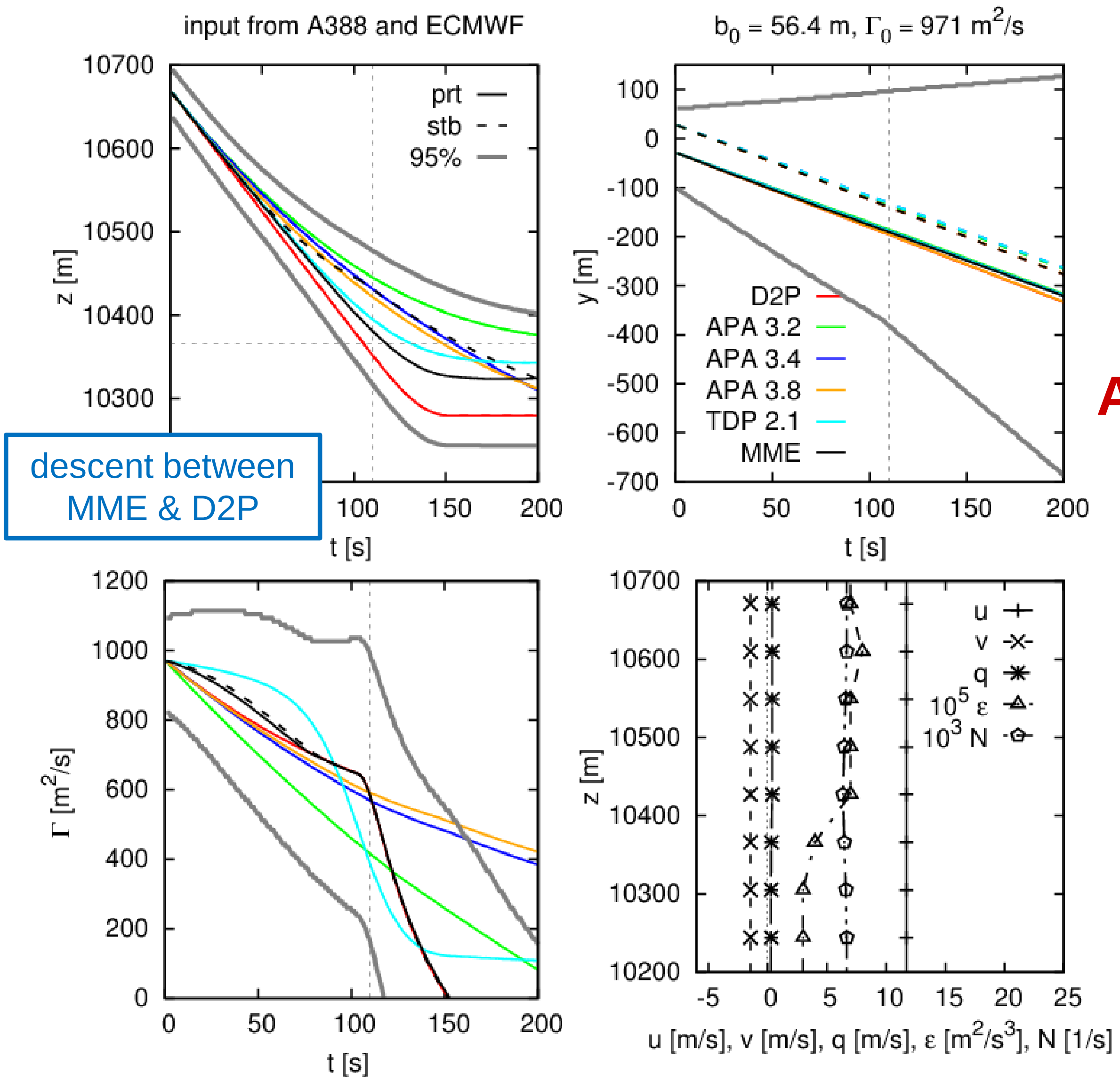
10% inboard loading







Holzäpfel F. 2003: A Probabilistic Two-Phase Wake Vortex Decay and Transport Model, Journal of Aircraft **40**, 323-331.
Holzäpfel F., Robins R.E. 2004: Probabilistic Two-Phase Aircraft Wake-Vortex Model: Application and Assessment, J. Aircraft **41**, 1117-1126.
Holzäpfel F. 2006: Probabilistic Two-Phase Aircraft Wake-Vortex Model: Further Development and Assessment, J. Aircraft **43**, 700-708.



Multi-model ensemble wake vortex prediction

combining WV models of NASA and DLR

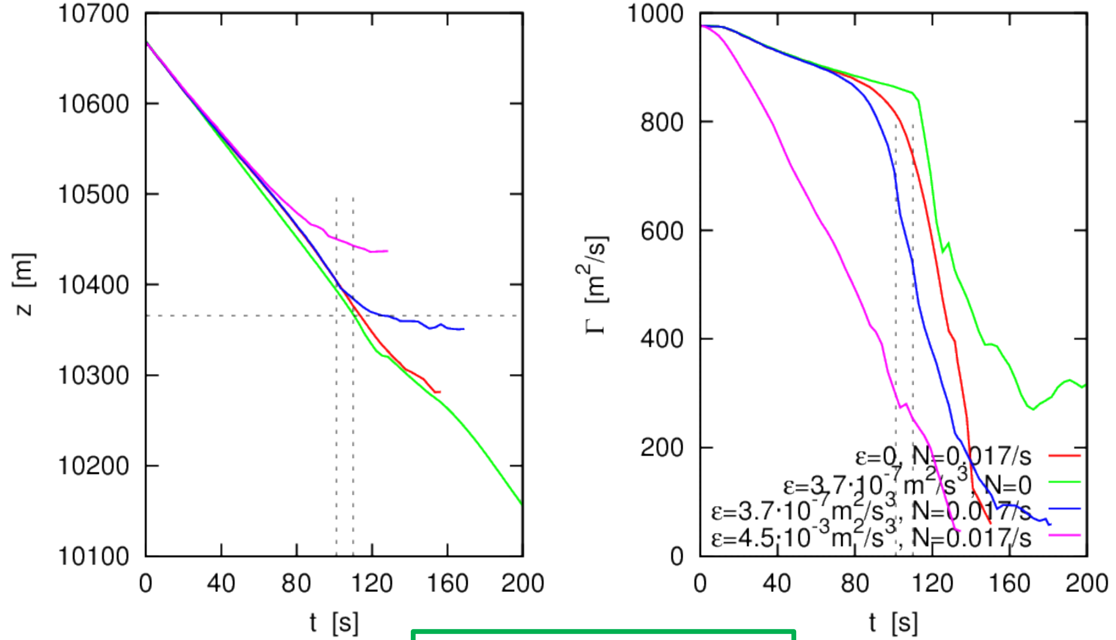
A388 wind & ECMWF data for vortex decay

10% inboard loading

S. Körner, F. Holzäpfel, “Multi-Model Wake Vortex Prediction”, Aircraft Engineering and Aerospace Technology **88** (2) 2016. http://dx.doi.org/10.1108/AEAT-02-2015-0068

S. Körner, N.N. Ahmad, F. Holzäpfel, R.L. Van Valkenburg: MultiModel Ensemble Methods for Prediction of Wake-Vortex Transport and Decay, J. Aircraft **54** (5) 2017, 1849-1859. http://dx.doi.org/10.2514/1.C034287

Results of highly resolved numerical simulations (LES) scaled to A388 vortices (10% inboard loading)

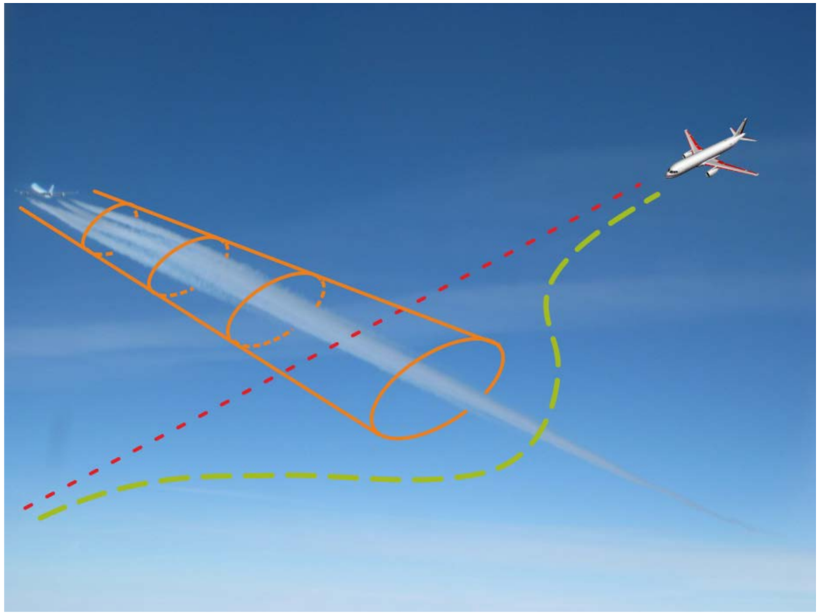


vortex rings
keep descending
in neutral stratification

T. Misaka, F. Holzäpfel, T. Gerz, M. Manhart, F. Schwertfirm, Vortex bursting, tracer transport, and decay mechanisms of a counter-rotating vortex pair, Physics of Fluids **24** (2) 2012, 25104-1 - 25104-21, doi: 10.1063/1.3684990

Wake Encounter Avoidance & Advisory (WEAA)

- airborne information and warning system
- prevention of dangerous wake vortex encounters in all phases of flight



- functionality as safety net / assistance system (increase of situational awareness)
- identification of a predicted, imminent or even current wake vortex encounter
- resolution of conflict by recommendation of tactical small-scale evasion manoeuvres

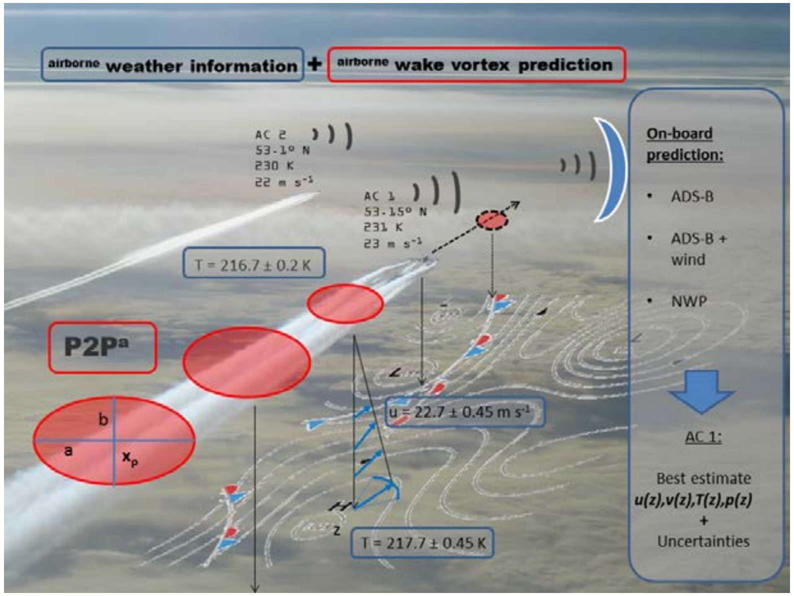
T. Bauer et al., "In-Flight Wake Encounter Prediction with the Wake Encounter Avoidance and Advisory System," *AIAA 2014-2333*, 2014. doi: 10.2514/6.2014-2333

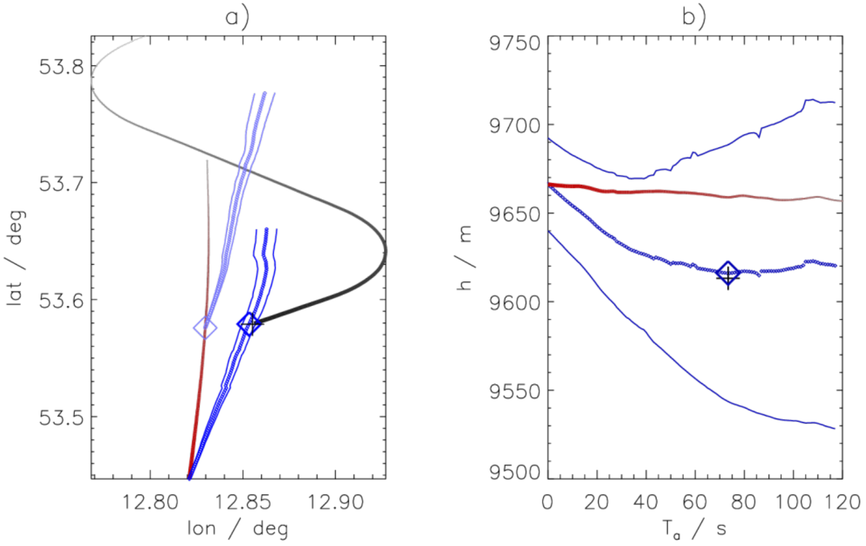
Wake Encounter Avoidance & Advisory (WEAA)

flight tests in April 2014 and Nov/Dec 2016

with DLR's Falcon and ATRA

new tests planned with NRC's T33 (WAVE App)





encounter on 11/04/2014

I. Sölch et al. "Performance of on-board wake vortex prediction system employing various meteorological data sources", J. Aircraft **53** 2016.
DOI: 10.2514/1.C033732

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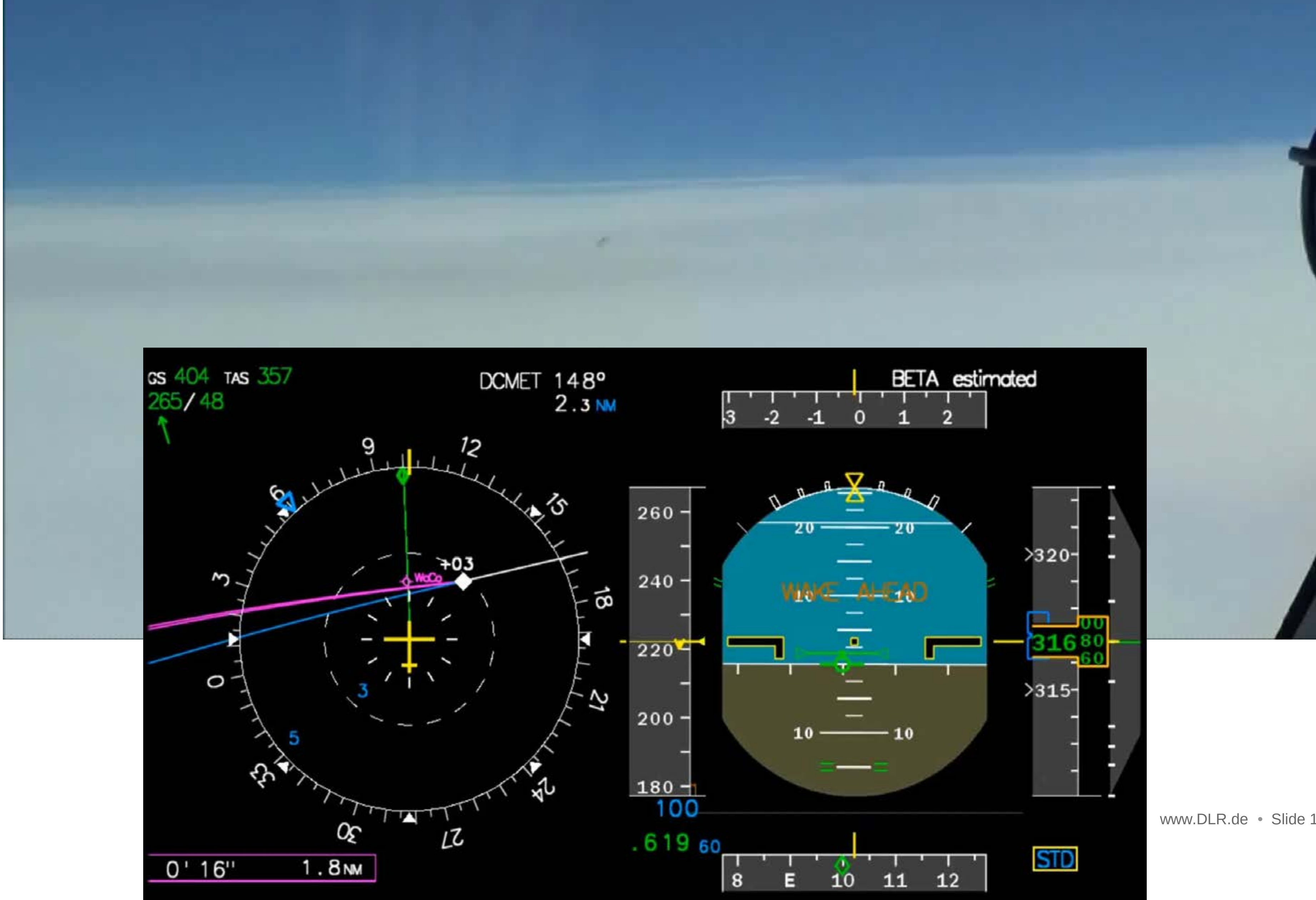
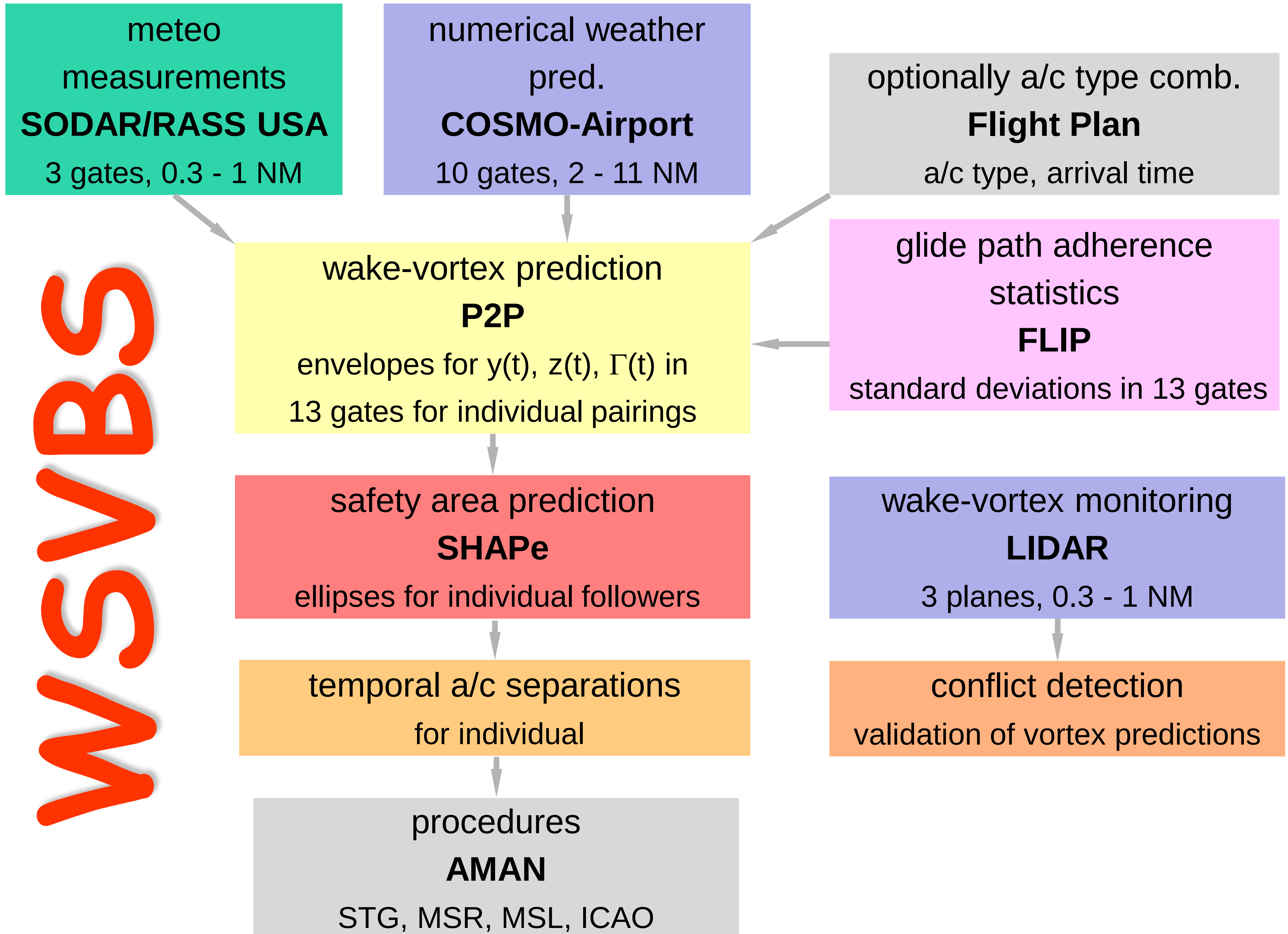
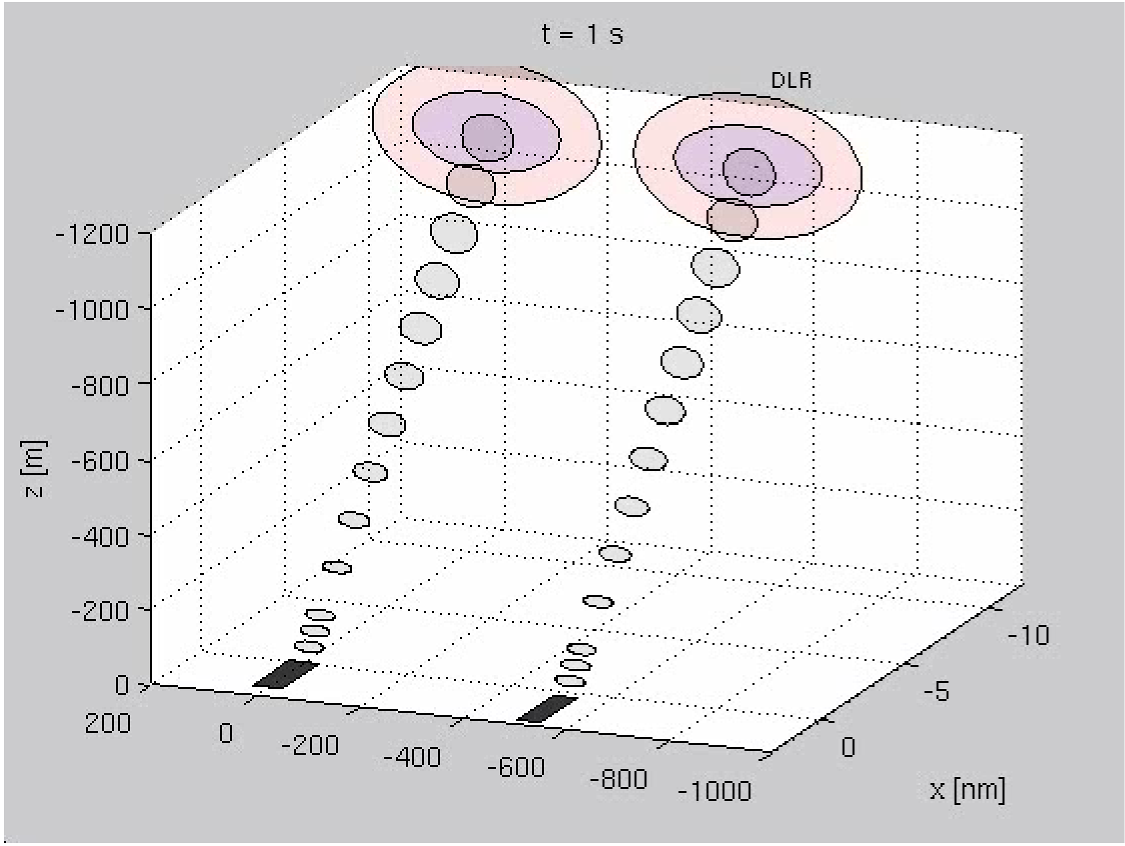
WEAA Encounter Video





Wake-Vortex Prediction & Monitoring System WSVBS



WSV Strategy
Animated
strong crosswind

- modified staggered left
- reduced sep. single rwy

F. Holzäpfel, T. Gerz, M. Frech, A. Tafferner, F. Köpp, I. Smalikho, S. Rahm, K.-U. Hahn, C. Schwarz, The Wake Vortex Prediction and Monitoring System WSVBS Part I: Design, Air Traffic Control Quarterly, Vol. 17, No. 4, 2009, pp. 301-322. https://doi.org/10.2514/atcq.17.4.301

T. Gerz, F. Holzäpfel, W. Gerling, A. Scharnweber, M. Frech, K. Kober, K. Dengler, S. Rahm, The Wake Vortex Prediction and Monitoring System WSVBS Part II: Performance and ATC Integration at Frankfurt Airport, Air Traffic Control Quarterly, Vol. 17, No. 4, 2009, pp. 323-346. https://doi.org/10.2514/atcq.17.4.323

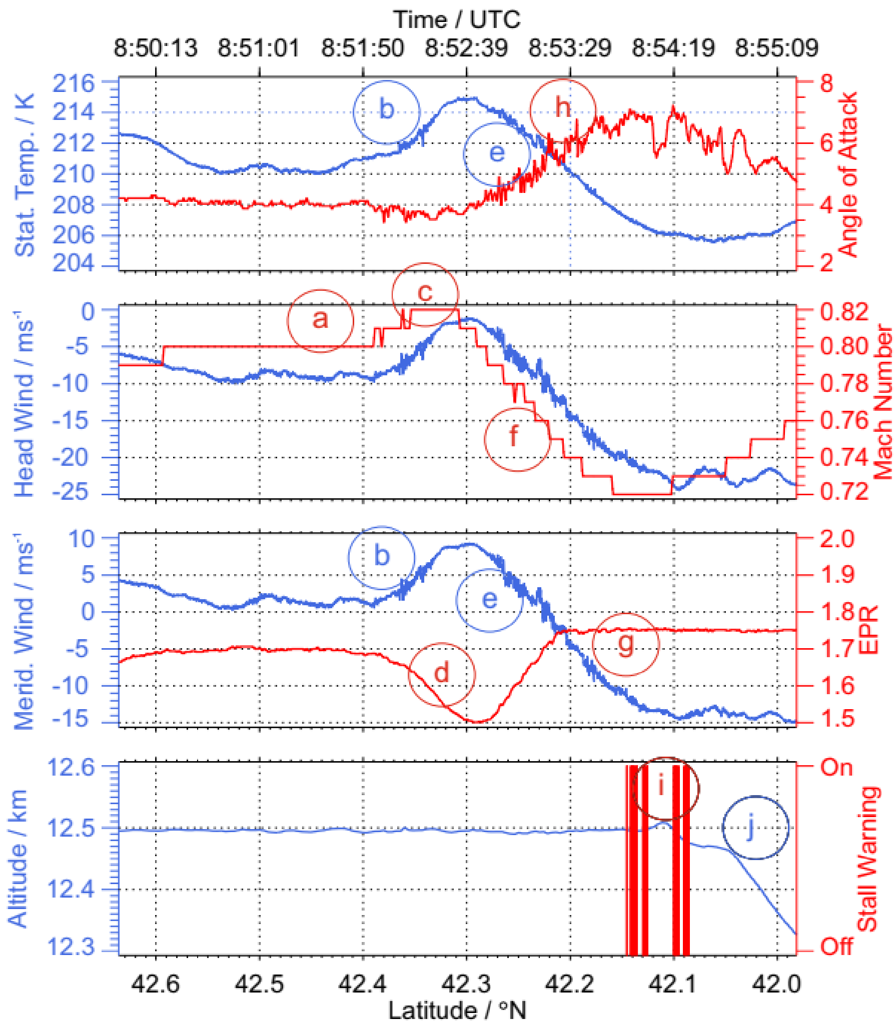
F. Holzäpfel, K. Dengler, T. Gerz, C. Schwarz, Prediction of Dynamic Pairwise Wake Vortex Separations for Approach and Landing, AIAA Paper 2011-3037, 3rd AIAA Atmospheric Space Environments Conference, 27-30 June 2011, Honolulu, Hawaii, 15 pages.

Mountain Wave (MW) Hazards on Aviation

Propagating MWs

Case study on stall warning event of the DLR research aircraft HALO caused by vertically propagating MWs

- ➢ In situ aircraft measurements
  - characterisation of MWs (amplitudes, wavelength, energy- & momentum fluxes)
  - Comparison to ECMWF and WRF forecasts
- ➢ Numerical simulations
  - 3D idealized simulations to analyse relevant processes
  - Attribution of measured fluctuations to propagating MWs



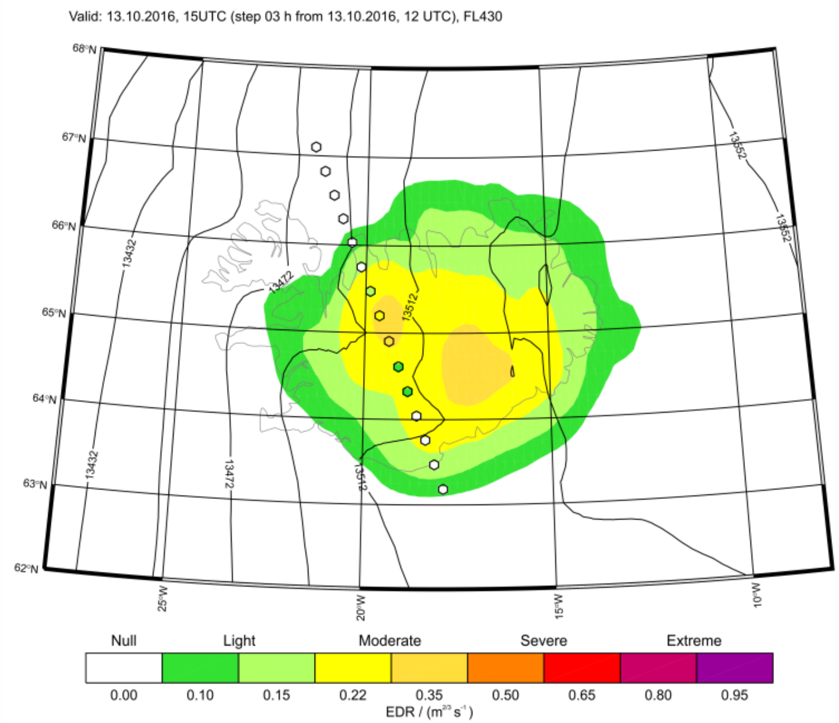
Bramberger et al., 2018, JAMC

Mountain Wave (MW) Hazards on Aviation

MW Turbulence

Case study on MWT encounter of HALO above Iceland in lower stratosphere

- ➢ In situ aircraft measurements
  - Calculation of TKE and EDR
  - Comparison to turbulence diagnostics based on ECMWF (GTG) and WRF
- ➢ Numerical simulations
  - Identification of MW breaking as cause for strong turbulence
  - Possible intensification of turbulence due to superposition of MWs



under preparation:
Bramberger et al.: Impact of model resolution on MWT predictability
Wilms et al.: Intensification of MWT due to superposition of MWs

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Further Research Topics

Focus on MW turbulence and predictability

Plans for analyzing turbulence distribution along jets

- Large dataset available from former research campaigns with high quality in-situ meas.
  - Further case studies
  - Statistical analysis of turbulence distribution
- Collaborations:
  - German Weather Service (DWD): Turbulence forecasts with ICON
  - LITOS (balloon based turbulence measurements in the stratosphere)
- Optical turbulence: first study started using GTG for planning of astronomical observations (Uni Durham)
- Interested in EDR measurements from commercial aircraft
- Strong interest in collaboration for measurement campaigns (martina.bramberger@dlr.de, henrike.wilms@dlr.de)

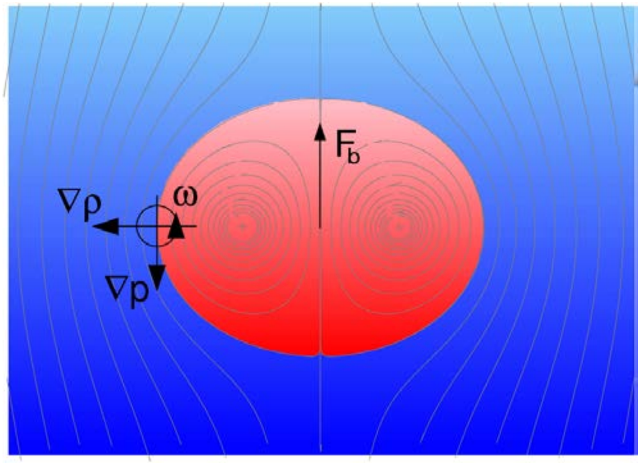

wishing you always smooth and safe flights

Conclusions

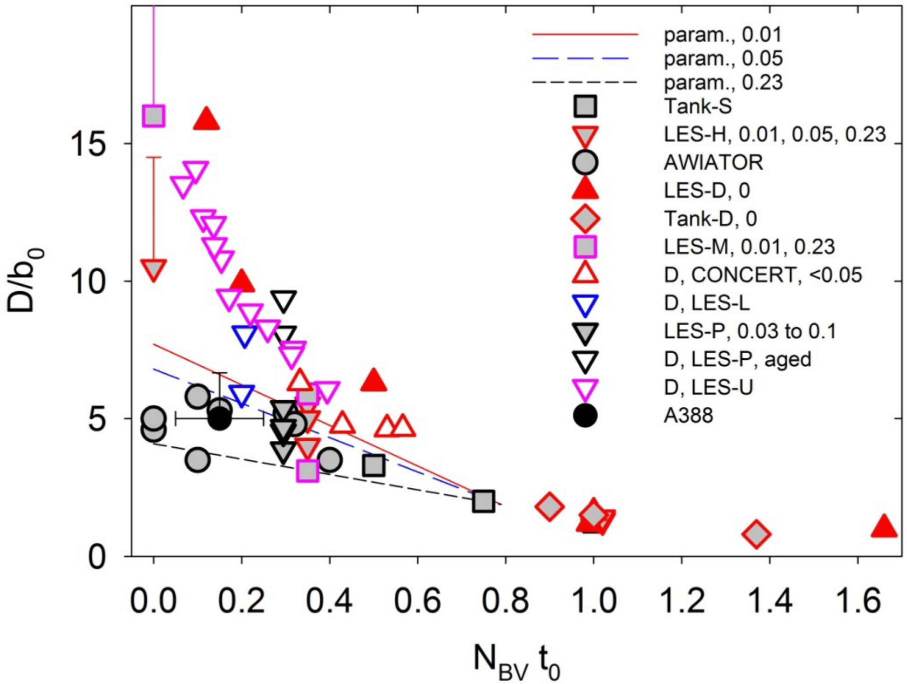
- accident cannot be explained by meteorological disturbances
- no contrails formed that could have warned the pilots
- WV encounter appears plausible employing different methods (P2P[a], MME, LES) assuming root loading of the A388 (10% reduced b_0)
- encounter occurs right before onset of rapid decay such that A388 vortices are still very strong
- vortex deformation according to Crow instability close to vortex linking
- WV descend deeper & live longer in tropics than at mid-latitudes due to weaker thermal strat.
- DLR’s WEAA System might have avoided the encounter
- initial vortex spacing highly relevant for prediction skills of fast-time models
- more detailed analysis will be published after release of final BFU report

Vortex descent and Brunt-Väisälä frequency, N_{BV}

bouyancy force



wake vortex descent distance[1]



[1]U. Schumann, A. Heymsfield, "On the lifecycle of individual contrails and contrail cirrus," *Meteorological Monographs* **58** (3) 2017, 3.1-3.24, doi: 10.1175/AMSMONOGRAPHS-D-16-0005.1

Multi-model ensemble wake vortex prediction

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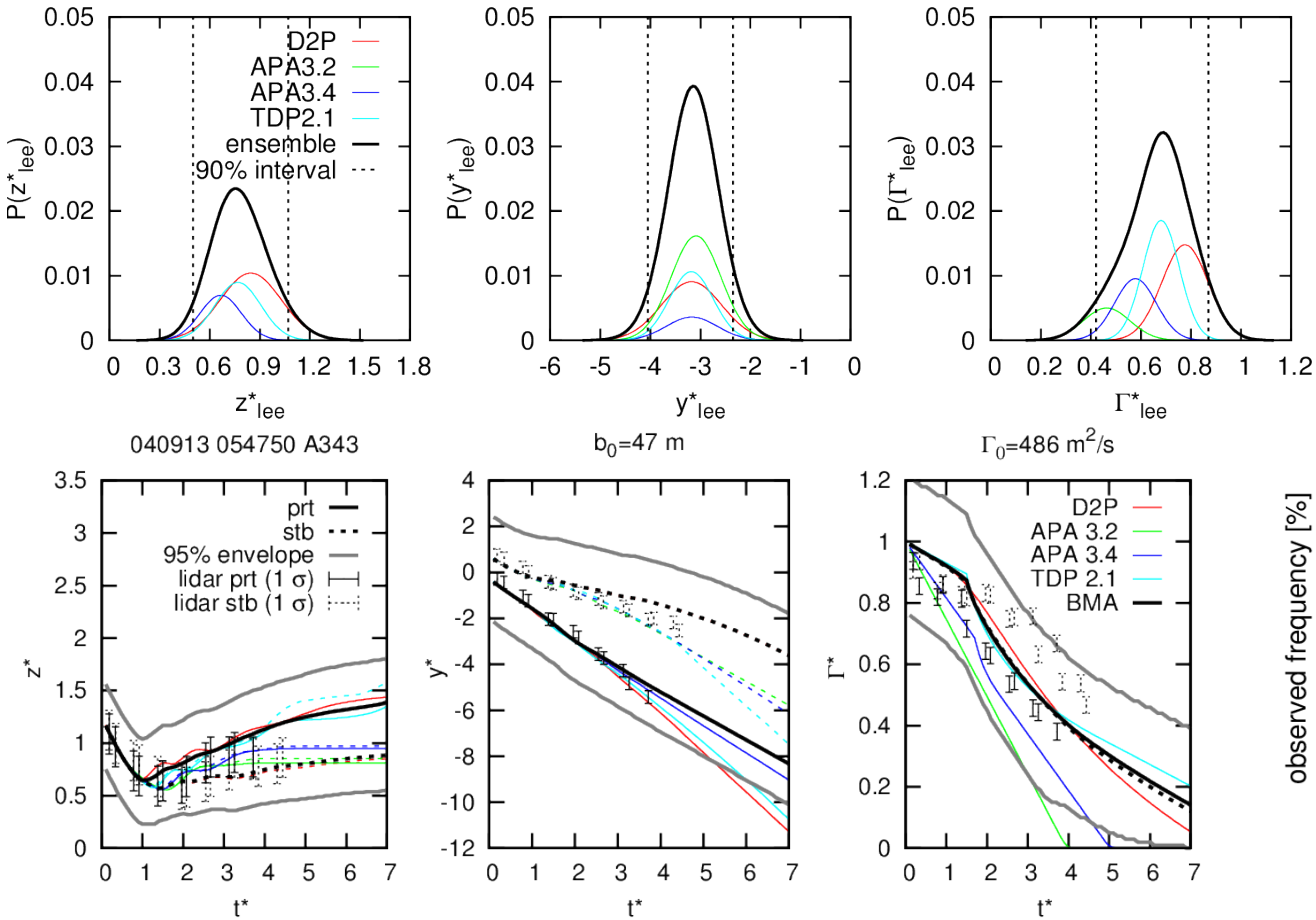
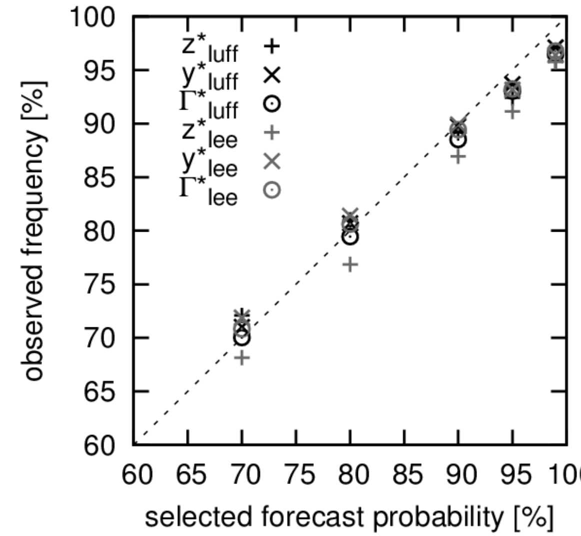


Bayesian Model Averaging



S. Körner, F. Holzäpfel, "Multi-Model Wake Vortex Prediction", Aircraft Engineering and Aerospace Technology **88** (2) 2016. http://dx.doi.org/10.1108/AEAT-02-2015-0068

S. Körner, N.N. Ahmad, F. Holzäpfel, R.L. Van Valkenburg: MultiModel Ensemble Methods for Prediction of Wake-Vortex Transport and Decay, J. Aircraft **54** (5) 2017, 1849-1859. http://dx.doi.org/10.2514/1.C034287