

Airborne active remote-sensing observations of the extratropical troposphere and lower stratosphere with a special focus on the NAWDEX field experiment

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1. **Active remote-sensing observations at DLR**
2. The NAWDEX field experiment
3. Recent example on the combined use of observations and simulations:

   Systematic meteorological analysis errors of jet stream winds
4. Selected examples of relevance for NWP
   - The role of lower tropospheric humidity
   - Observation of O_3 and H_2O in the UTLS
   - Synergetic use of lidar and radar data
   - Large scale CO_2 and CH_4 columns
5. Summary

1. Active remote-sensing observations at DLR

Background on airborne research at DLR IPA

- **German Aerospace Center** (DLR) is the German national aeronautics and space research center
- **Institute of Atmospheric Physics (IPA)**
    - physics and chemistry of the global atmosphere from the Earth's surface up to the upper boundary of the middle atmosphere
    - variety of methods: sensor development, observations on local to global scales, data analysis, theory construction, and numerical modelling
- **Department Lidar:**
    - development of ground-based, airborne and space-borne lidar systems
    - active remote sensing of key meteorological parameters and atmospheric trace gases for research in weather and climate

Location of DLR close to Munich

Aerial view of DLR Oberpfaffenhofen

Research aircraft HALO and Falcon

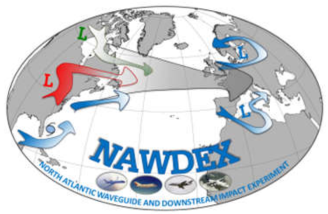
1. Active remote-sensing observations at DLR

IPA's airborne research activities

- Atmospheric trace gas emissions and transport
- Aerosol microphysics and transport
- Aerosol-cloud-interaction
- Cloud physics, contrail and natural cirrus, PSCs
- Alternative fuels for aviation
- Preparation, calibration and validation of satellite missions
- Transport and mixing processes in the UTLS
- …

Atmospheric dynamics

- campaigns with a focus on mid-latitude dynamics
- strong involvement of IPA's active remote sensing payload



- Advertise observational products to stimulate cooperation's
- Selected studies demonstrating the **combined use of observations and simulation**…
  - … to identify short-comings in the global observing system
  - … to investigate physical processes that are expected to impact NWP

1. Active remote-sensing observations at DLR

Historic background

- WMO The Observing System Research and Predictability Experiment (**THORPEX**; Parsons et al. 2017) coordinated several **campaigns**

  → focus on the **impact of additional observations** on improving forecast accuracy
  → **average improvement** but weaker than originally anticipated (Majumdar 2016)

- Growing evidence that forecast errors originate in regions where **diabatic processes** are strong and observation and modeling systems are least reliable

  → **NAWDEX in 2016**: **Aircraft measurements to** provide **independent data** with **high accuracy** in dynamically relevant regions that are poorly represented by the operational observing system

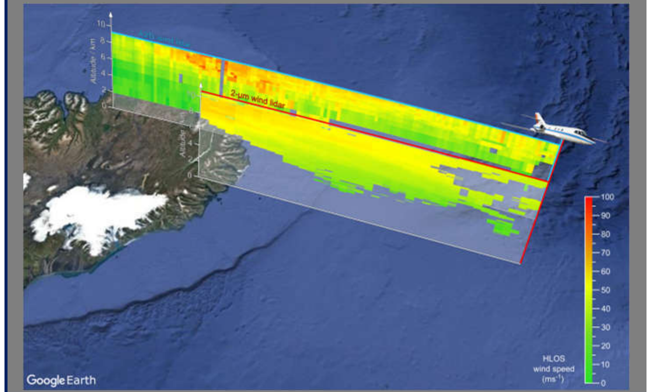
Related presentations

- Is it time for interactivity and 3D? New approaches to analysing NWP data for observational campaigns using **3D and ensemble visualization** – *Marc Rautenhaus (U Hamburg)*
- **Forecast products** for flight planning from a researchers' perspective – *Julian Quinting (KIT Karlsruhe)*
- The **impact of dropsonde and extra radiosonde observations** from the field campaigns NAWDEX and SHOUT in 2016 – *Martin Weissmann (DWD/LMU)*
- Global forecasts of **atmospheric gravity waves** for observational campaigns – *Isabell Krisch (DLR)*

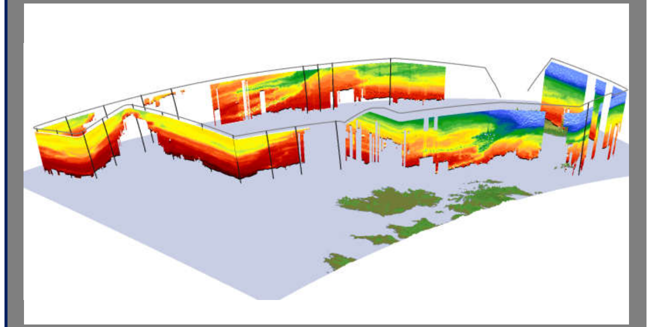
1. Active remote-sensing observations at DLR

Airborne instruments with relevance for NWP research

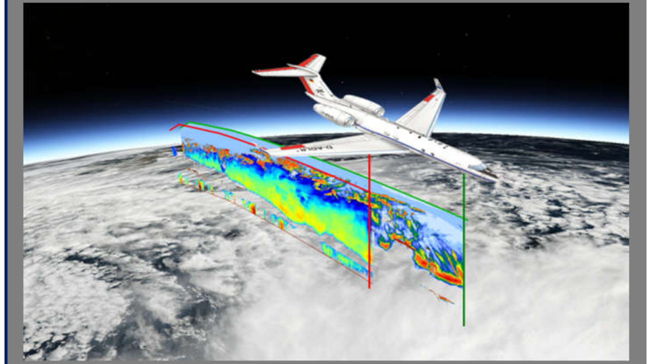
- **Doppler wind lidar (DWL)**
  - Coherent 2-µm DWL system → **horizontal and vertical wind profiles**, fluxes when combined with trace gas lidar
  - UV (355 nm) DWL ALADIN Airborne Demonstrator (A2D) → line-of-sight **wind profiles** for the satellite mission Aeolus
- **Differential Absorption lidar (DIAL):**
  - Multi-wavelength H2O-DIAL WALES → **water vapor profiles** from lower stratosphere to lower troposphere, HSRL system for aerosol properties
  - WALES DIAL UV channel → **ozone profiles** across TP
- Ka-Band (35.6 GHz) **cloud radar** for radar reflectivity, depolarization ratio and vertical velocity profiles (jointly with MPI Hamburg and University of Hamburg)
- **Integrated Path Differential Absorption** (IPDA) CHARM-F → **Carbon dioxide and methane columns**: airborne system
- Temperature, winds, gravity waves between altitudes of 25 and 100 km with airborne sodium resonance and Rayleigh lidars



DWL Wind observations



DIAL water vapor observations



Synergistic cloud radar and lidar observations

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2. **The NAWDEX field experiment**
3. Recent example on the combined use of observations and simulations: Systematic meteorological analysis errors of jet stream winds
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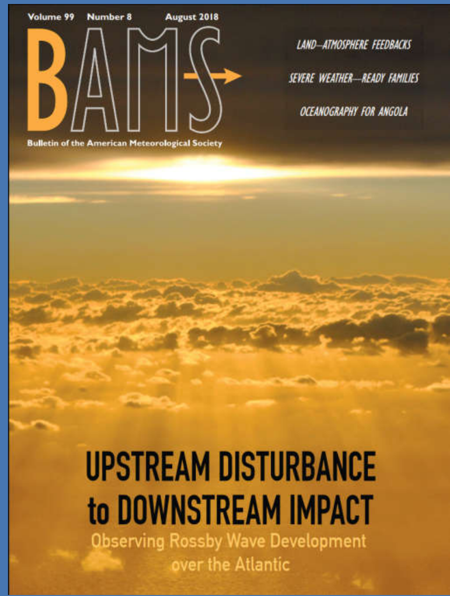
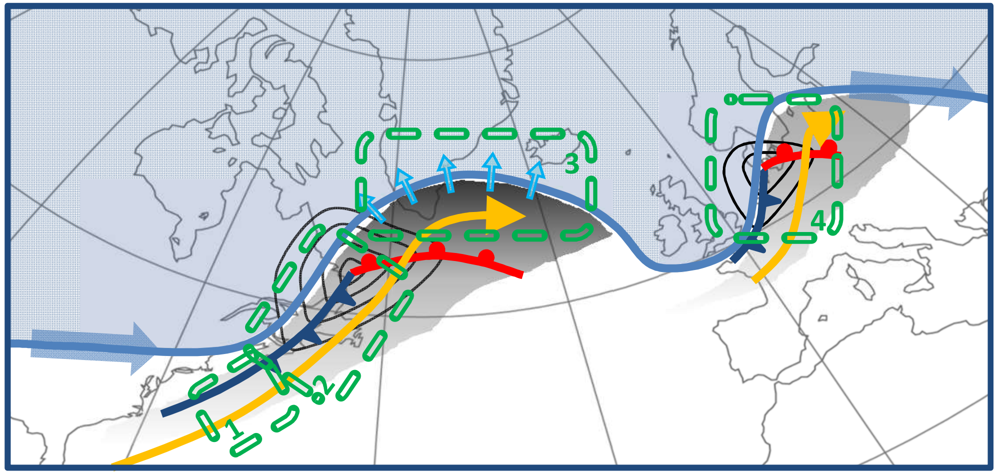


(Schäfler et al. 2018, BAMS)

2. The NAWDEX field campaign

Scientific motivation

Diabatic processes over the North Atlantic have a major influence on jet stream meanders, the downstream development of Rossby waves on the tropopause and high impact weather over Europe



4: Impacts of tropopause waveguide uncertainty on HIW

- Relevance of **amplifying small errors at tropopause level** for uncertainty in surface weather downstream

1: Low level moisture

- **Structure and evolution and impact** of low level moisture flowing into mid-latitude cyclones

2: Diabatic effects on cyclonic systems

- **Representation of clouds, wind, humidity and temperature** related to strongly ascending air masses

3: Upper level PV and moisture and cloud structure at tropopause

- Characterization of **wind and moisture gradients** at the tropopause and **role of uncertainties** for downstream weather evolution

2. The NAWDEX field campaign
Highlights

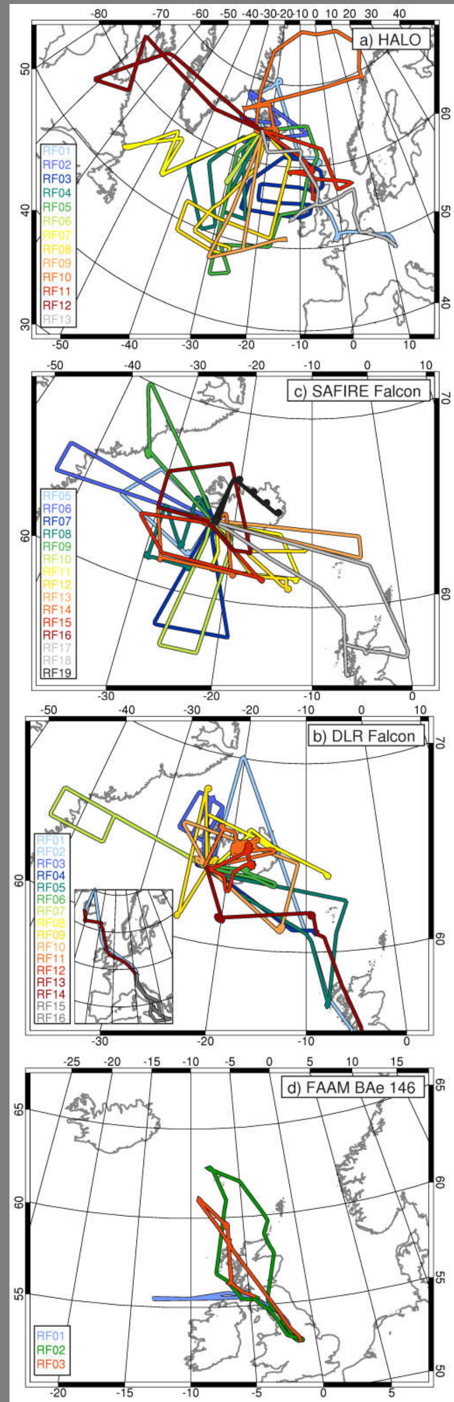
- **Multi-aircraft deployment at Iceland from 17 Sept to 22 Oct 2016**
- Unique **combination of the four aircraft** and first deployment of HALO in a campaign focusing on midlatitude dynamics
- Most complete set of combined **wind, humidity, temperature and cloud profile observations from the entrance to the exit region of the storm track** to investigate the **role of diabatic processes**
- 13 IOPS contributed to all science goals (**favorable synoptic conditions)**
- Episodes of **reduced predictability**
- **Aeolus and EarthCARE-like airborne measurements** to prepare calibration and validation activities

G: HALO

G: DLR Falcon

F: SAFIRE Falcon

UK: FAAM BAe146



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3. A combined use of observations and simulations

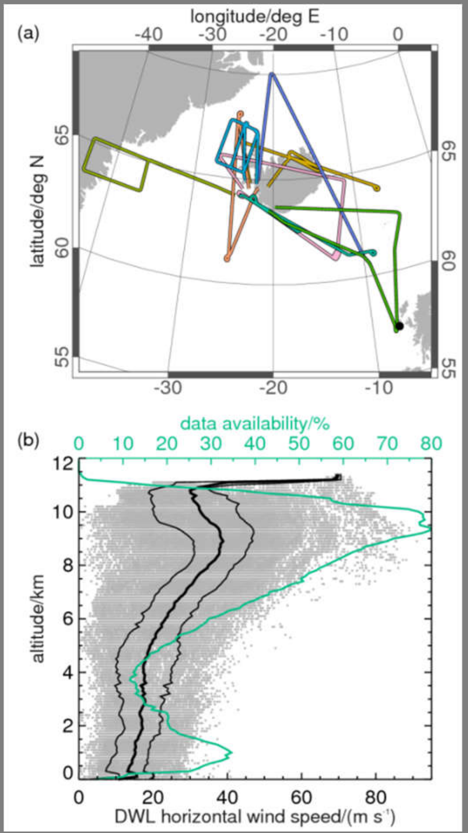
Systematic meteorological analysis errors of jet stream winds

To what extent are NWP analyses able to reproduce observed wind speeds and especially the sharpness of wind gradients at the tropopause?

- large biases 5-10% detected in 1990s and early 2000s
  (Tenenbaum 1991, 1996, Rickard et al. 2001, Cardinali et al. 2003).
- Since then: continuous increase of resolution, quality and amount of aircraft and satellite observations and their improved application
- Average uncertainty of 2-3 m s^{-1} expected over the NA Ocean
  Baker et al. (2014)
- Clear need for vertically resolved wind data
  (→ ESA Aeolus satellite mission)
- NWP models fail to maintain sufficiently sharp tropopause gradients with increasing lead time
  (Gray et al. 2014; Saffin et al. 2017)

→ evaluation of errors and uncertainty in meteorological analyses and forecasts requires high resolution profile observations across the tropopause (→ NAWDEX)

NAWDEX DWL observations



- DWL winds: **1885 profiles** (59443 wind vector obs) during **8 flights**
- max. in data availability at high wind speeds (8 -10 km)
- winds up to 90 m s^{-1}
- comparison with DSO winds → bias of 0.12 m s^{-1} and standard dev. of 1.58 m s^{-1}

3. A combined use of observations and simulations

Systematic meteorological analysis errors of jet stream winds

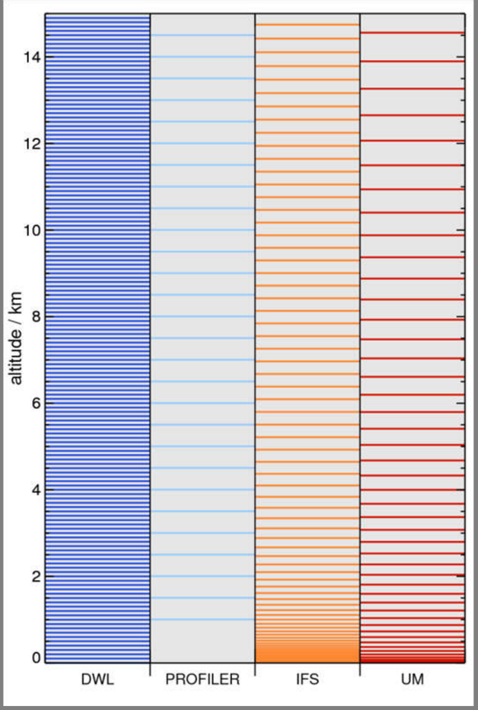
ECMWF:

- IFS operational HRES AN and FC fields (cycle 41r2) with TCo1280 horizontal resolution: 6-h AN (00, 06, 12 18 UTC) and 1-h FC initialized from 00 / 12 UTC
- 0.125°/0.125° grid resolution (16 km), 137 ML

Met Office:

- Unified Model (UM) N768 (~17km) and 70 vertical levels,
- 6-h analysis fields (00, 06, 12 18 UTC) and 1-hourly FC initialized from 00, 06, 12 and 18 UTC

- **DSO/profiler data** were sent to GTS and **assimilated at ECMWF and Met Office**
- comparisons between obs and NWP performed at the vertical resolution of the DWL (100 m)
- between 8-14 km (across TP):
  - UM: 11 ML with a vert. separation of $\Delta z \approx 550$ m
  - IFS: 19 ML, $\Delta z \approx 300$ m
  - Wind Profiler $\Delta z = 500$ m

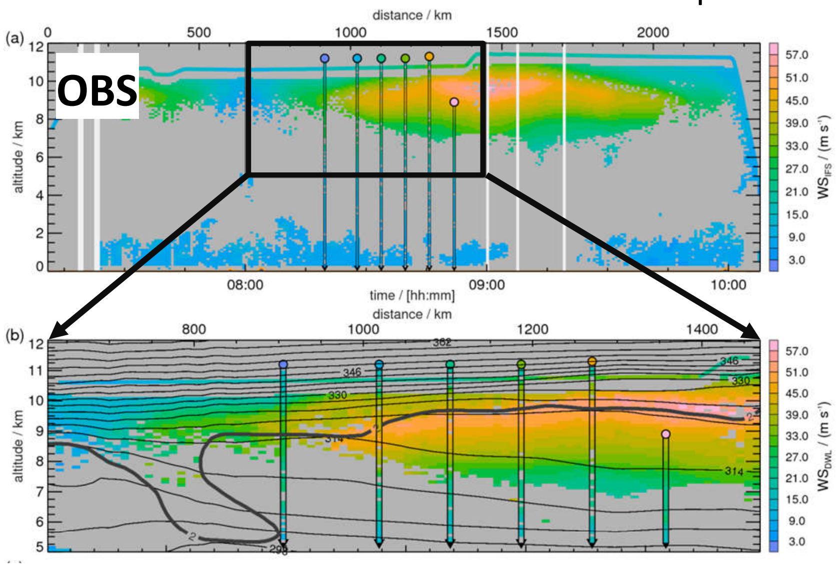


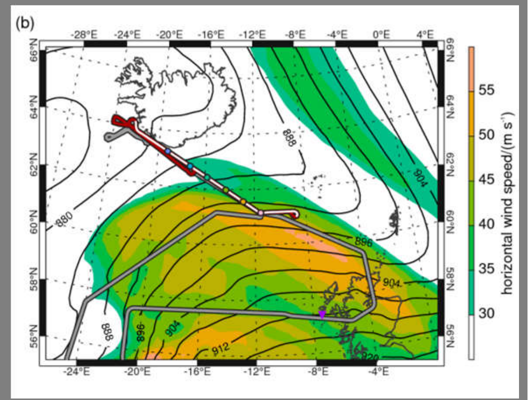
Vertical distribution of observed and simulated wind data

3. A combined use of observations and simulations

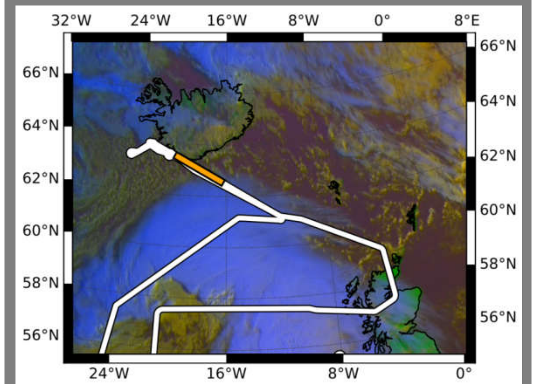
Systematic meteorological analysis errors of jet stream winds

IOP 3 on 23 Sep 2016





300 hPa Winds and flight track



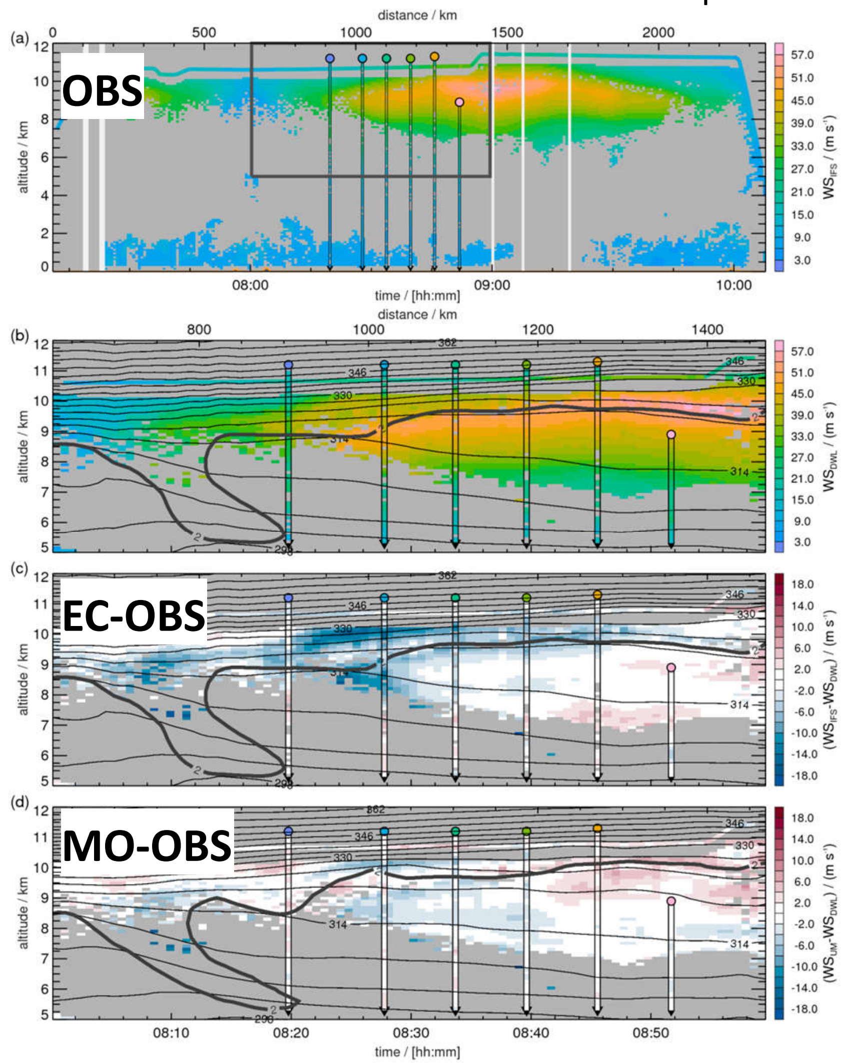
Meteosat Seviri Image

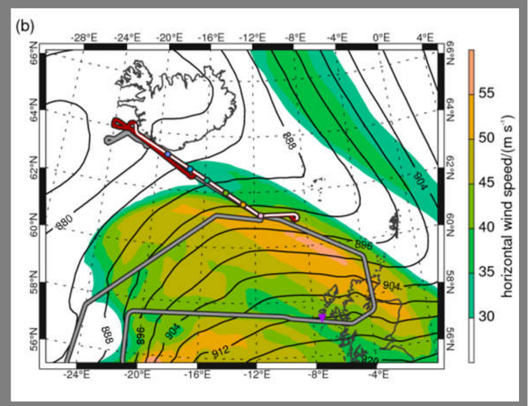
- low data coverage in clean and dry air
- data coverage and the observed wind speeds (up to 58 m s^{-1}) increase in upper-level cirrus
- dropsonde winds show that DWL captured the whole vertical extent of the jet stream

3. A combined use of observations and simulations

Systematic meteorological analysis errors of jet stream winds

IOP 3 on 23 Sep 2016



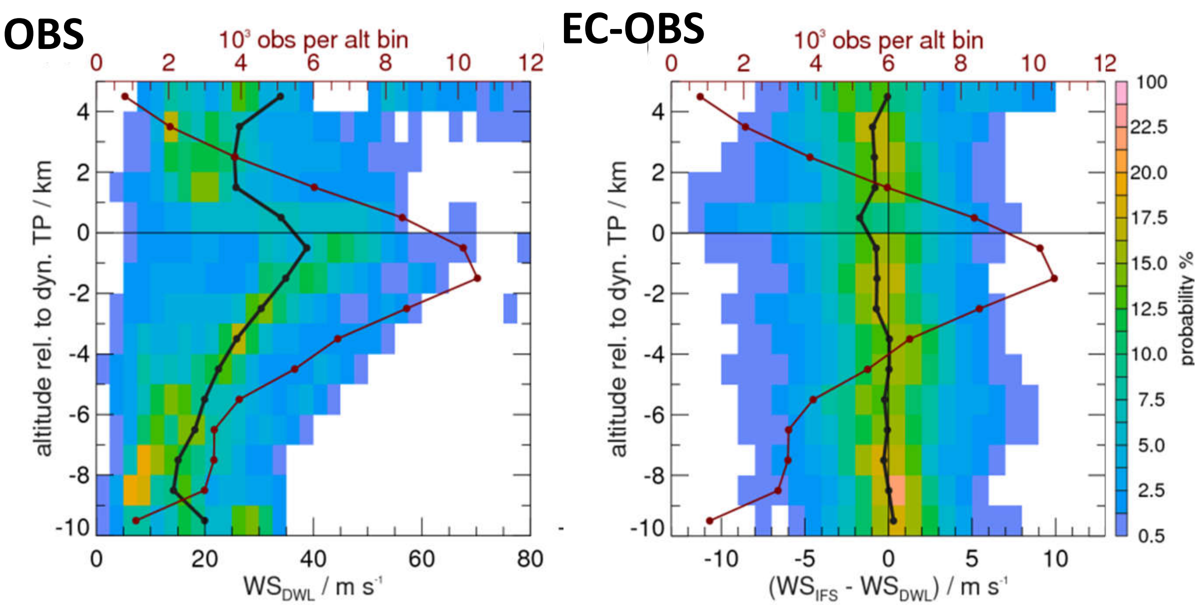


300 hPa Winds and flight track

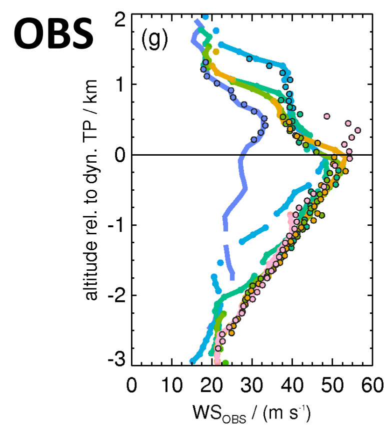
- coherent areas of increased differences above and below the tropopause
- consistent difference fields for DWL, in-situ and dropsondes → underlines the reliability of the result
- IFS and UM differences differ substantially but most negative differences occur at the same location
- Differences are result of a complex interplay of uncertainties related to the
  - wind speed (maximum) representation
  - strength of vertical wind gradients
  - tropopause altitude
  - misrepresentation of complex vertical wind structures

3. A combined use of observations and simulations

Systematic meteorological analysis errors of jet stream winds



Campaign statistic of observed winds and wind differences in tropopause-relative coordinates



Observed wind in tropopause-relative coordinates

- In tropopause-relative coordinates wind profiles nicely collapse on each other
- highest average winds peak around the tropopause (maximum average wind of ~40 m s^{-1})
- Highest number of observations around the tropopause
- highest variability in the differences in the altitude bin directly above the tropopause in both models
- With tendency of underestimation of the wind field

3. A combined use of observations and simulations

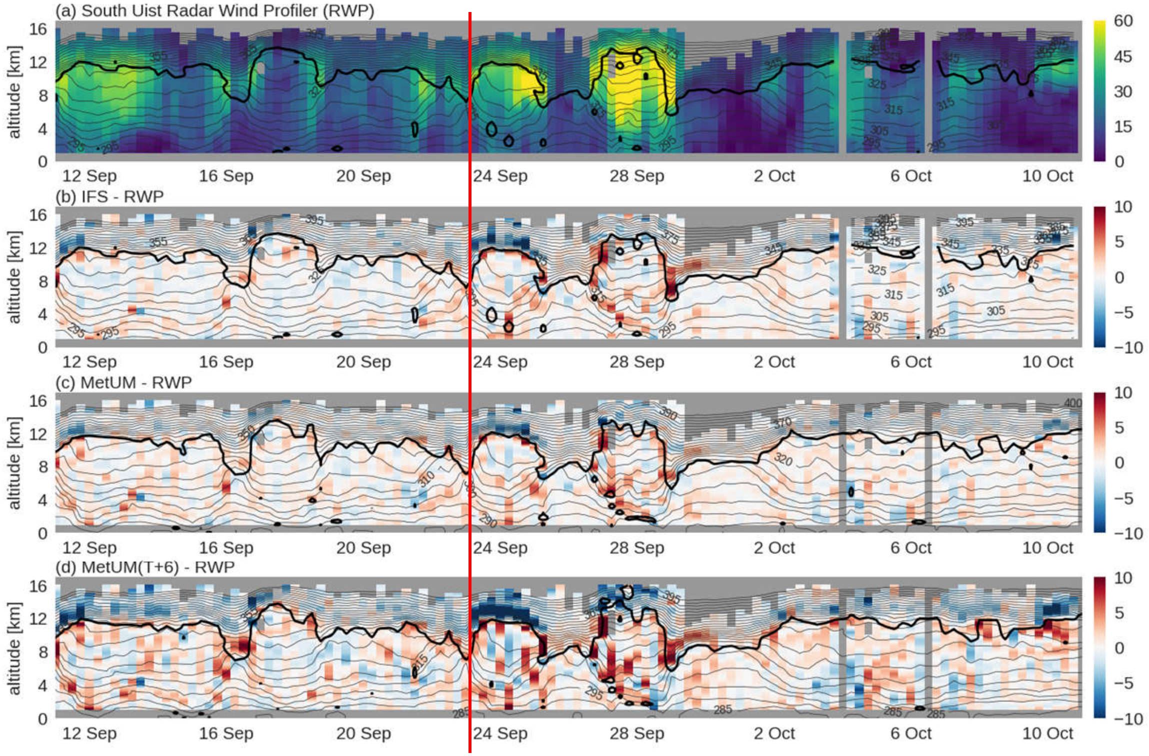
Systematic meteorological analysis errors of jet stream winds

OBS

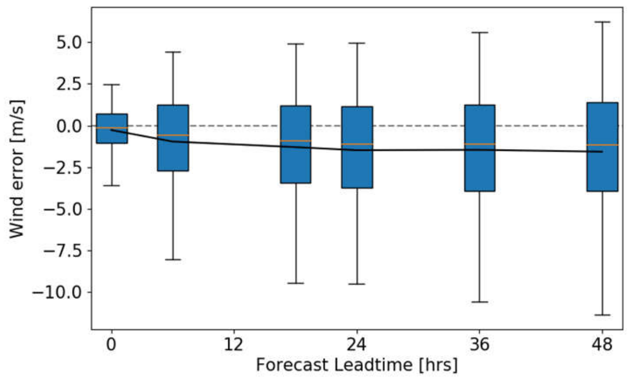
ECOA – OBS

MOOA – OBS

UMFC (+6h) – OBS



- repeated passages of strong wind events
- ECOA and UMOA differences look very similar
- UM short FC provides comparable error structures with higher magnitudes



- the magnitude of these errors grows and saturates at about 24 hours.

3. A combined use of observations and simulations

Systematic meteorological analysis errors of jet stream winds

- **Small average biases (-0.6/-0.2 m s^{-1})** → significant wind field improvement in the mid-latitudes
- Statistics of tropopause-relative analysis errors → **increased uncertainty of jet stream winds** in situations of high tropopause altitudes directly **above the tropopause** with strong vertical shear
- **Spatial structure** of near-tropopause analysis errors is **similar in two state-of-the-art global operational analyses**, even though the forecast models and data assimilation schemes largely differ
- Magnitude of these **analysis errors grows rapidly in forecasts**, even over the data assimilation window, while **retaining similar structure**, and saturate at about 24 hours.

  → analysis errors are dominated by model error in both systems and exceed obs. uncertainty

  → model error is resulting in similar differences in both op. models

  → assimilation reduces the systematic analysis error but cannot eliminate it

- A. Schäfler, B. Harvey, J. Methven, S. Rahm, O. Reitebuch, F. Weiler, B. Witschas: **Observation of jet stream winds during NAWDEX and systematic meteorological analysis errors**, to be submitted to MWR
- Open PhD position at DLR**: Model error and uncertainty at the midlatitude tropopause** within second phase of the collaborative research center "Waves to Weather" (W2W) - http://www.wavestoweather.de/positions/

Folie 17

AS1 Schäfler, Andreas; 29.05.2019

AS2 Schäfler, Andreas; 29.05.2019

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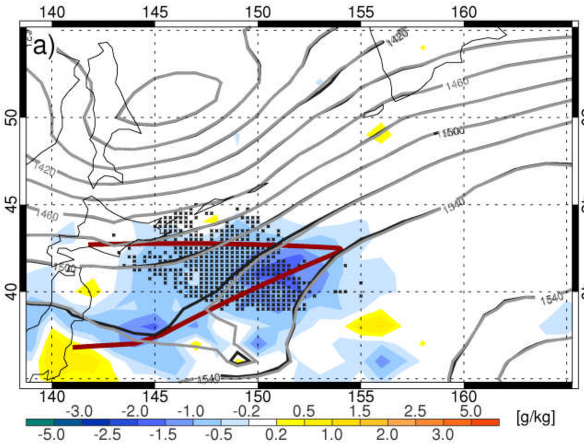
The role of lower tropospheric humidity

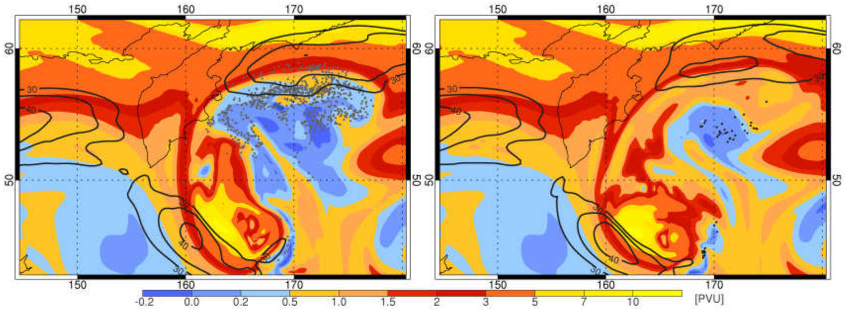
How well is the observed moisture (transport) reproduced in ECMWF analyses? What errors do occur? Can uncertainties in moisture impact the evolution of cyclones and the upper-level flow?

Analysis differences DIAL – NO DIAL

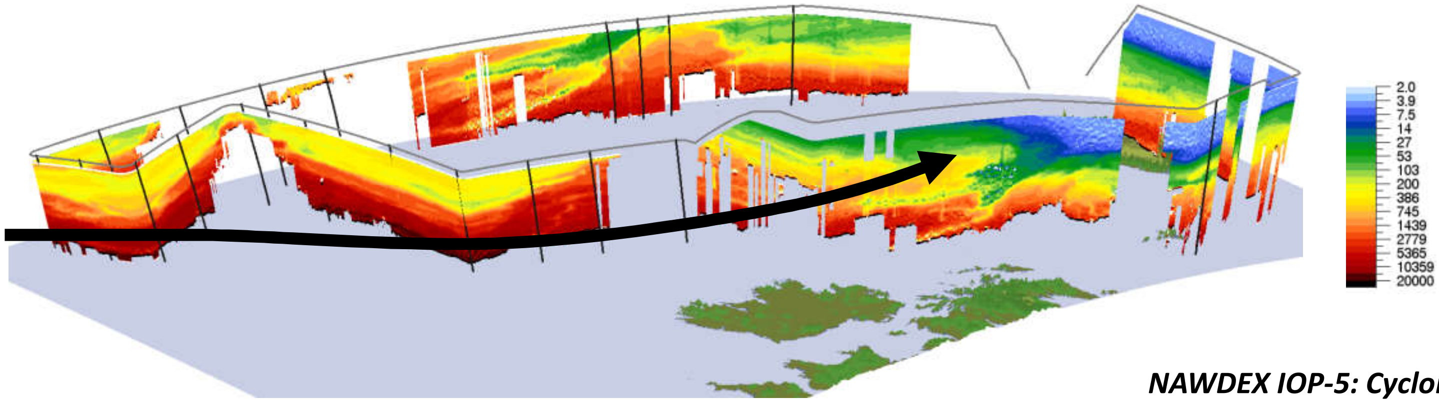


Schäfler and Harnisch (2015), QJ
Schäfler et al. (2011), QJ

NO DIAL ***PV @ 322 K*** ***DIAL***



- Several cases with overestimated BL humidity detected
- Assimilation of DIAL profiles reduced BL humidity
- Impact on downstream tropopause structure



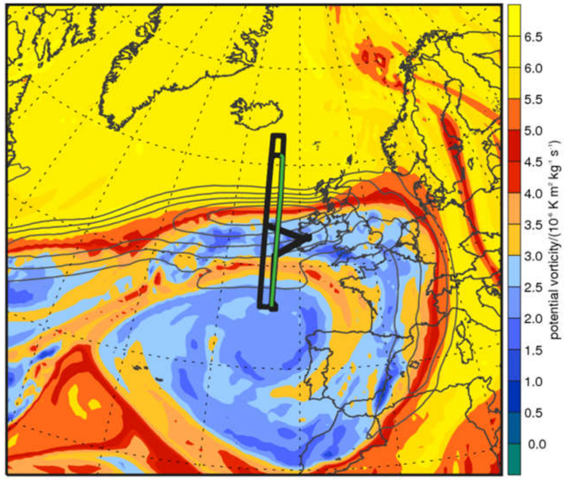
NAWDEX IOP-5: Cyclone Walpurga on 27 Sep 2016

4. Selected examples of relevance for NWP

DIAL observation of O_3 and H_2O in the UTLS

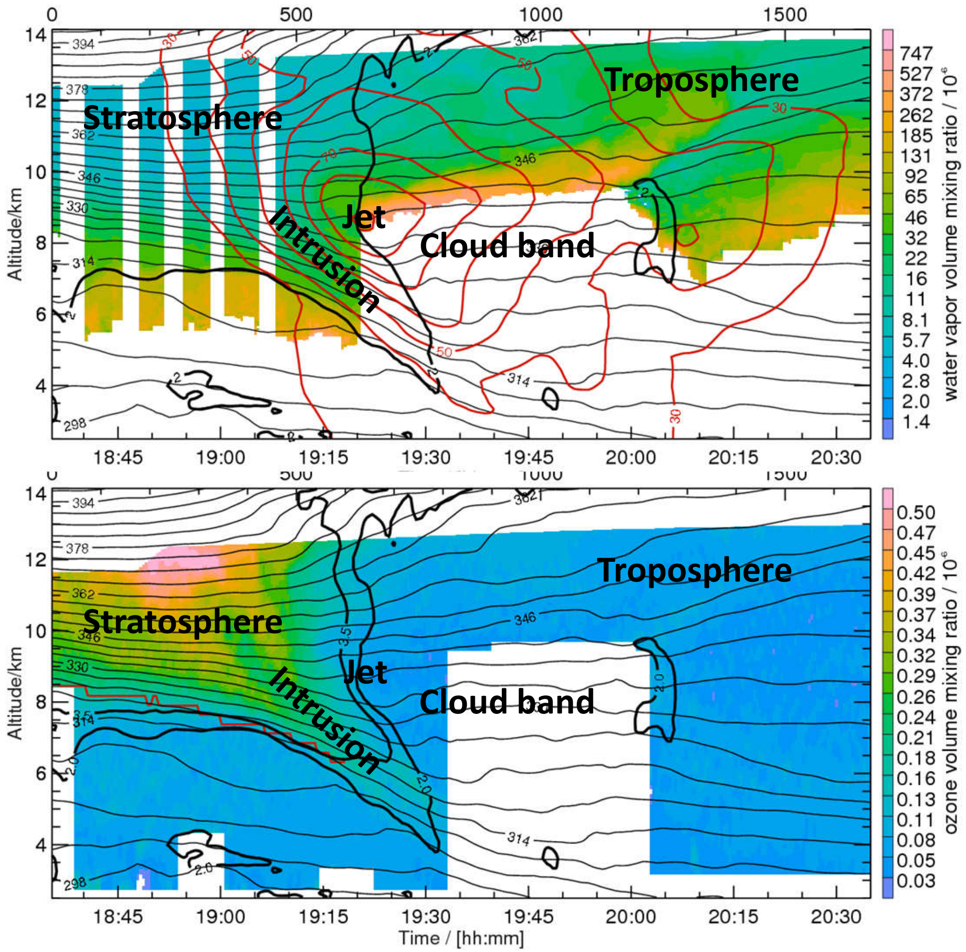
Where do mixed air masses occur in the extratropical UTLS? How are dynamical and chemical discontinuities related? How do models represent the distribution at the TP?

PV and Wind @340 K



H_2O

O_3

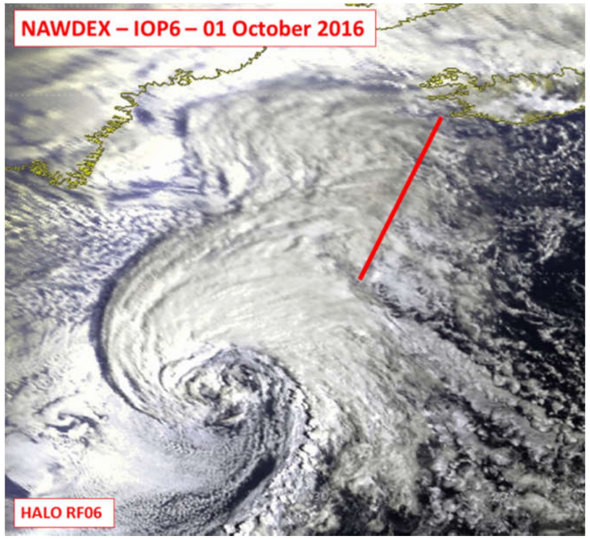


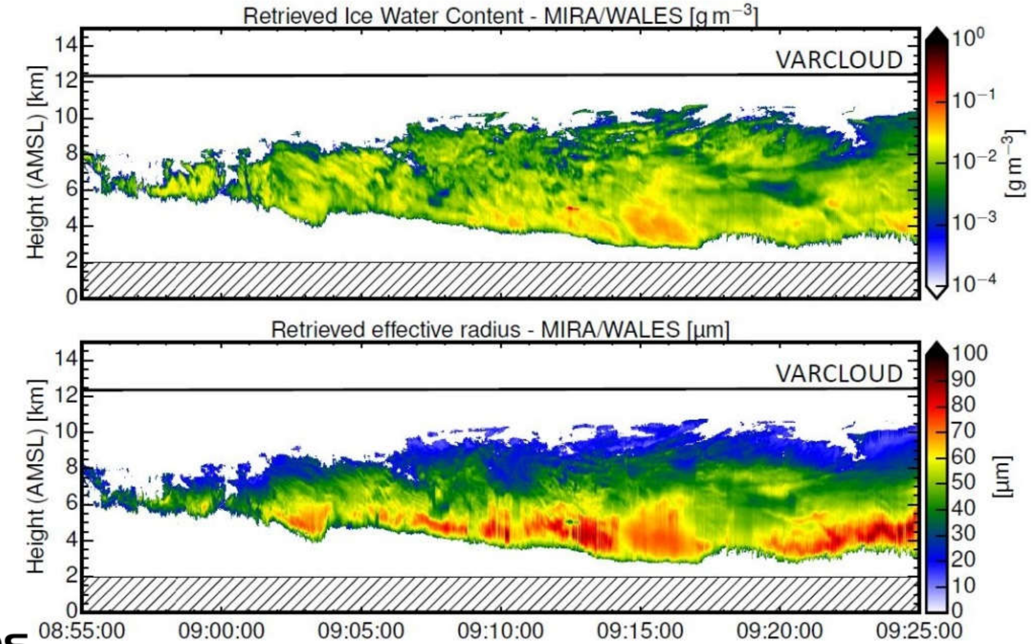
- 2017: first-ever collocated H_2O and O_3 DIAL obs across the tropopause
- Analysis of tropopause as a dynamical and chemical discontinuity
- Possibility for model validation (e.g. CAMS)

4. Selected examples of relevance for NWP

Synergetic use of lidar and radar data

Retrieving microphysical properties from combined radar/lidar measurements





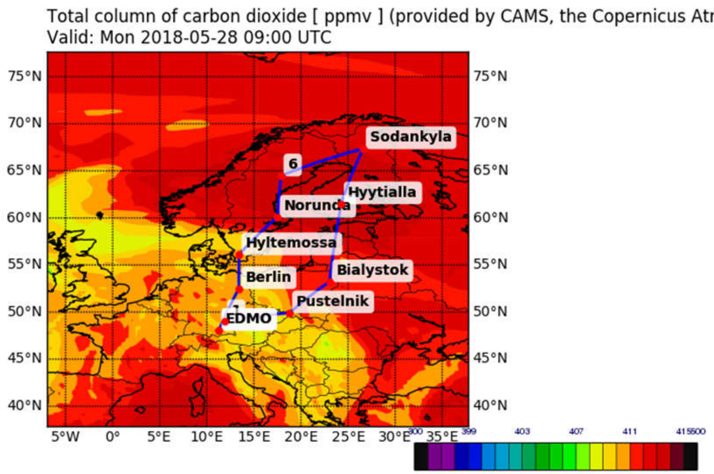
- In a French-German collaboration HALO radar and lidar data is used to retrieve clouds microphysical properties
- „RALI: the French radar-lidar airborne platform for cloud dynamics and microphysics studies“ - Julien Delanoë

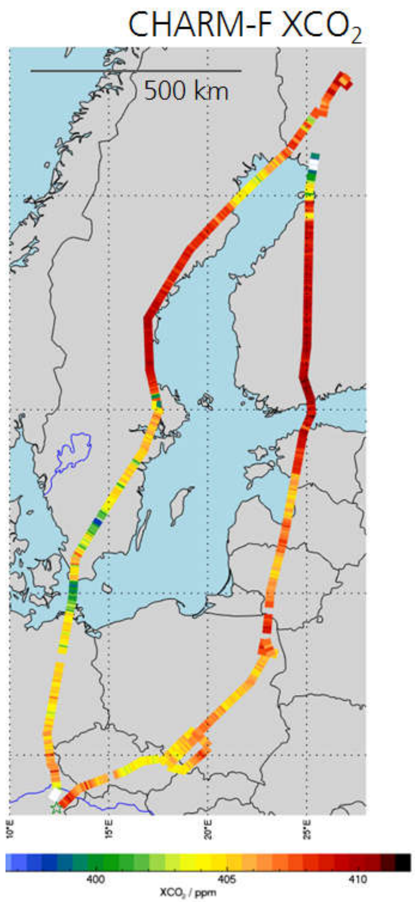
4. Selected examples of relevance for NWP

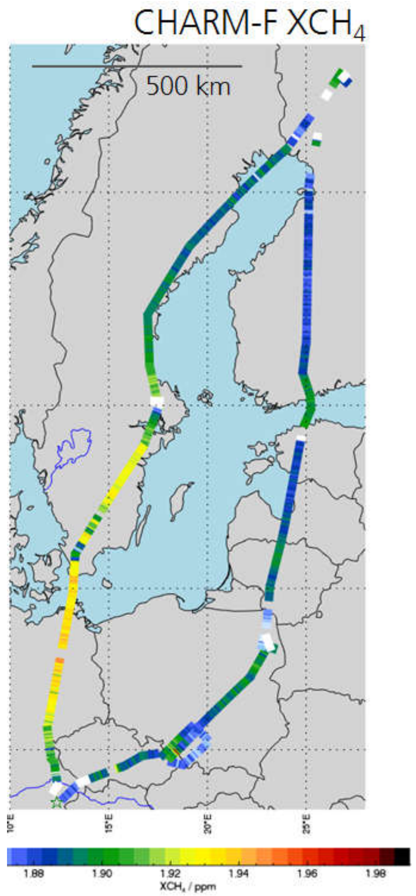
Large scale CO2 and CH4 column observations

CoMet in 2018: An airborne mission to simultaneously measure CO2 and CH4 using lidar to identify local and regional GHG sources

→ CAMS forecast products used for flight planning







CoMet 1.0

5. Summary

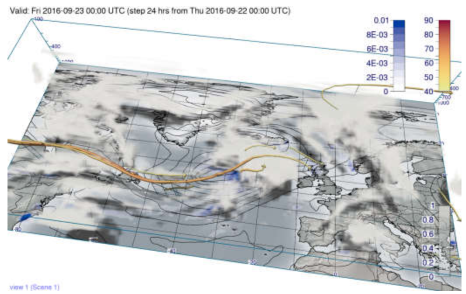
- How can observational campaigns help us identify **and diagnose problems in models, observation operators**, etc.?
  → active airborne remote-sensing lidar observations provide a unique picture of horizontal and vertical gradients of dynamically relevant parameters (e.g. moisture, ozone, winds) due to high accuracy and resolution
  → dedicated independent jet stream wind observations during NAWDEX revealed systematic analysis errors near the tropopause

- How can knowledge and diagnosis of NWP problems help **define future field campaigns**? What gaps in knowledge could future campaigns address?
  →a fruitful discussion on areas of interest at weather centers, relevant processes, missing parts in the GOS may encourage the development of new instruments and the design of new observational campaigns
  → NAWDEX is a success-story for such a process

5. Summary

- What diagnostic tools can help **improve the links** between observational **campaigns and NWP** development? How can these tools be improved?
  - Combined approach using observations and simulations to validate NWP models
  - → *M. Weissmann's talk: Data assimilation studies to test the impact of observations*

- How can observational campaigns learn from each other in terms of their usage and diagnosis of ECMWF forecasts?
  - Looking forward to learn more about the use of forecast products
  - Flight planning and preparation of field experiments used ECMWF products during multiple campaigns motivated new visualization approaches → *Talks by M. Rautenhaus and J. Quinting*



- What can ECMWF do to optimize the **utility of data and modelling capabilities** to support observational campaigns?
  - The preparation and planning of DLR IPA field experiments largely profited from the excellent support and access to ECMWF forecast products for many years
  - A strengthened exchange to make use of presented data is of great interest and ideally would result in cooperation's

Thanks to NAWDEX consortium

- NAWDEX – North Atlantic Waveguide and Downstream Impact Experiment
- LMU MIM
- DLR
- IACETH
- W2W Waves to Weather
- LATMOS
- LMD
- University of Reading
- DFG Deutsche Forschungsgemeinschaft
- Institut Pierre Simon Laplace
- cnrs INSU Observer & comprendre
- MANCHESTER 1824 The University of Manchester
- Max-Planck-Institut für Meteorologie
- EUFAR
- Universität Hamburg – Der Forschung | Der Lehre | Der Bildung
- EUMETNET
- Environment Canada
- Icelandic Met Office
- JGU
- KIT
- esa European Space Agency
- EarthCARE
- ADM-Aeolus
- METEO FRANCE
- Met Office
- Meteorologisk institutt

Picture by A. Minikin