3.2-O Comparison of Airborne Water Vapor Lidar Observations with ECMWF Analyses and first Assimilation Experiments

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1. Introduction

Water vapor is the most important greenhouse gas and controls cloud formation and the evolution of weather systems. As its tropospheric concentration may rapidly vary over four orders of magnitude, accurate monitoring of water vapor, especially in the upper troposphere and lower stratosphere (UT/LS) and in remote areas remain important scientific and logistical issues. Water vapor assimilation is still limiting the accuracy of numerical weather prediction (NWP) models, most of which are based on lower and middle tropospheric humidity from regular radiosonde soundings that do not provide reliable water vapor at altitudes > 300 hPa or in dry regions < 0.1 g/kg. Moreover, major “birth” regions of severe continental weather to which short-term forecast errors are most sensitive are often only covered by few radiosonde stations. It is therefore obvious to question the accuracy of water vapor distributions in weather service's analyses, particularly with respect to the scales, lifetime and geographical location of investigated structures.

Between 2002-2005 the DLR Falcon research aircraft performed a couple of long-range transfer flights to various remote campaign destinations in Oklahoma, Brazil and Australia, carrying the water vapor Differential Absorption Lidar (DIAL) in nadir looking arrangement. The DIAL transmitter is based on a Nd:YAG pumped, injection seeded KTP-OPO (Optical Parametric Oscillator) which produces 18 mJ per pulse at 925 nm at 100 Hz. Atmospheric backscatter is measured simultaneously. Using the 925 nm spectral region allows to cover typical water vapor concentrations from the PBL to the upper troposphere with vertical and horizontal resolutions of some 100 m to 1 km and few km to about 10 km, respectively. Main sources of systematic errors are the uncertainty in the determination of the water vapor absorption line cross section (5% estimated uncertainty), laser spectral impurity (1-2%), atmospheric temperature uncertainty (<1%), and the Rayleigh-Doppler absorption line broadening (<1.5%), about 5% in geometric total (Poberaj et al., 2002). The statistical error, controlled by horizontal and vertical averaging, mostly remains below 10%.

2. Airborne Water Vapor Lidar Observations Compared to ECMWF Analyses

In spring 2004 and 2005 the airborne DIAL obtained extended 2D vertical cross sections of water vapor and particle backscatter ratio across the sub-tropical and tropical Atlantic on its way between Germany and Brazil (Fig. 1) by profiling the troposphere from ~10 km to the ground. The large scale flow on 14 March 2004 is characterized by the extended Azores-anticyclone in the west and a depression system over Gibraltar in the north-east of the aircraft track. The flight roughly went along the axis of the Gibraltar-cyclone’s trough and entered the mid-latitude flow regime near 20-30°N. Near the equator, mixing ratios q > 2 g/kg reach up to about 9 km. The top of the humid layer slopes down to about 4 km near the Cape Verde Islands (23°W, 16°N). Above 8 km, another humid layer extends from the equator to about 15°N. The layers are the lower and upper branch of the tropical Hadley circulation. 7-day back-trajectories trace the traversed air masses back to far apart origins. A significant transport component is perpendicular to the plotted plane. Selected back-trajectories depicted in Fig. 3 show that air in the upper humid layer is participating in the Hadley circulation. The dry air north and below the layer emanates from the eastern Pacific UT. The slightly drier air near 3-5°N at 300 hPa comes from the Amazonian region. The Hadley circulation is evident up to ~ 14.2 km, as shown by ECMWF analyses in Fig. 4. The lower sloping layer with q > 2 g/kg is advected from central Africa by north-easterly trade winds.

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T511/L60 operational analyses of the European Centre for Medium Range Weather Forecast (ECMWF) are used for the comparison and trajectory calculations. They are interpolated onto a regular 0.5°×0.5° latitude-longitude grid; 60 sigma-pressure levels span the earth's surface up to 0.1 hPa. In Figure 4, the DIAL water vapor cross section is compared to ECMWF analyses, interpolated linearly to the transfer flight path and time. The spatial resolution of the DIAL data is degraded to the analyses such that observed small scale features closest resemble those in the ECMWF fields. The large-scale circulation is reproduced by the ECMWF analyses but differences are found at smaller scales where strong gradients occur and rapid temporal development takes place due to advection perpendicular to the measurement plane. Remarkably small analysis errors are associated with the stratospheric intrusion which is nearly stationary over one day in spite of its relatively small scales. ECMWF is somewhat too humid in the UT but the overall agreement on large scales is better than 10%.

3. First 4D-VAR Assimilations of Airborne Water Vapor and Wind Lidar Observations

Water vapour and aerosol/cloud distributions have been measured with the DLR airborne DIAL in May 2002 during the transfer flights to the International H2O Project (IHOP_2002) across the Northern Atlantic Ocean (Flentje et al., 2005). The flights went from Germany via Iceland, Greenland and Canada to Oklahoma. Owing to intense dynamical activity over the Atlantic a variety of complex atmospheric structures was observed during the transects like stratospheric intrusions, PV streamers, frontal zones, gravity waves, convection and patches of vertical turbulence. Stratospheric intrusions and extended extremely dry layers even in the lower troposphere turn out to be the normal case rather than the exception. The large dynamical range of tropospheric water vapour is impressively demonstrated. Large gradients in the H_2O and backscatter fields dominate the scene and in general can *qualitatively* be reproduced by mesoscale simulations and even to a large extent by ECMWF analyses. However, the gradients and the minimum mixing ratios can not yet be satisfactorily reproduced in a quantitative sense.

Recently the DIAL data set was submitted to ECMWF for assimilation experiments. In a first approach the DIAL data were assimilated along with all operational data and compared to a reference run using only the operational data. Both experiments were made using 4D-VAR with a 12 hour data window at operational resolution (T511 outer loops and T95-T159 inner loops). The first results (Fig. 5) show that the DIAL data have measurable impact with 5-10% reduction of the short-term forecast error, although they only represent thin slices in model space and although they come in addition to all operationally available data. Even 50% data losses due to clouds (between 18 W and 9 E) still give considerable impact. Note that the forecast error increase close to the flight path is an artefact due to calculation truncation errors. Analyses show that the DIAL instrument and representativeness errors are small (~10% in total), so that the data get high weight in the assimilation. These results are encouraging and show the impact DIAL may have on NWP.

During the Atlantic THORPEX Regional Campaign in autumn 2003, the DLR airborne Doppler lidar measured 3D-wind fields in predicted sensitive regions. During eight flights the lidar measured a total of 1600 wind profiles that were experimentally assimilated into the ECMWF global assimilation system. It could be shown that the lidar observations have a significant impact on the analyses as well as on forecasts due to high accuracy and spatial resolution (Weissmann and Cardinali, 2006). The measurements reduce the errors of the 1-4 day forecasts of geopotential height, wind and water vapor over Europe throughout the troposphere. On average, Doppler lidar measurements reduce by 3% the 2-4 day forecast error of geopotential height over Europe. This is a promising result, considering that observations have been gathered from only 29 flight hours. Dropsondes released in the same area show good agreement in terms of measured winds, but smaller analysis impact and less forecast error reduction.

4. References

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5. Appendix: Figures

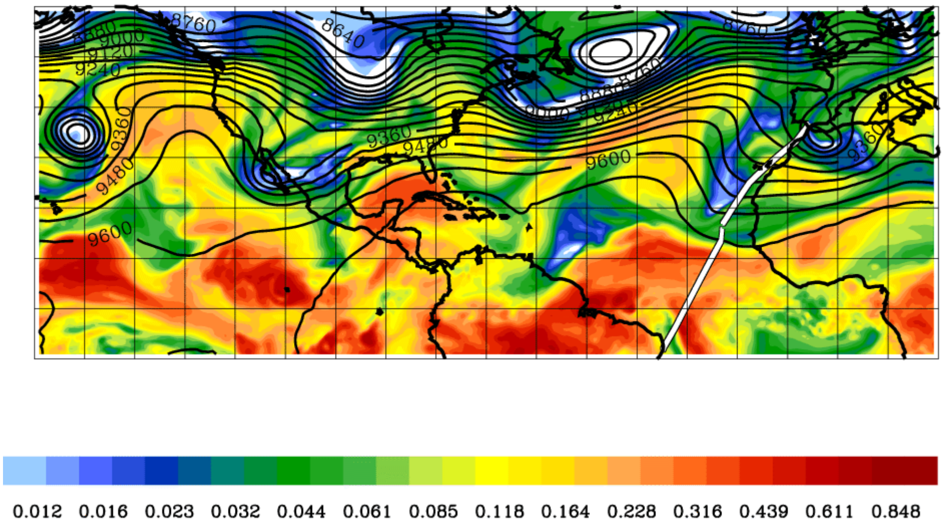

Fig. 1: Water vapor mixing ratio (g/kg) and geopotential height (m) analysed at 300 hPa by the ECMWF (T511/L60) on 14 March 2004, 1200 UT. The Falcon flight path is marked by a white line. Air mass transitions and transport of water vapor are clearly linked to the large scale flow roughly along the height contours. Alternating pre-/post-frontal advection of humid/dry air along the meandering planetary wave flow is stronger at high latitudes but occasionally also affects the water vapor distribution in the tropics.

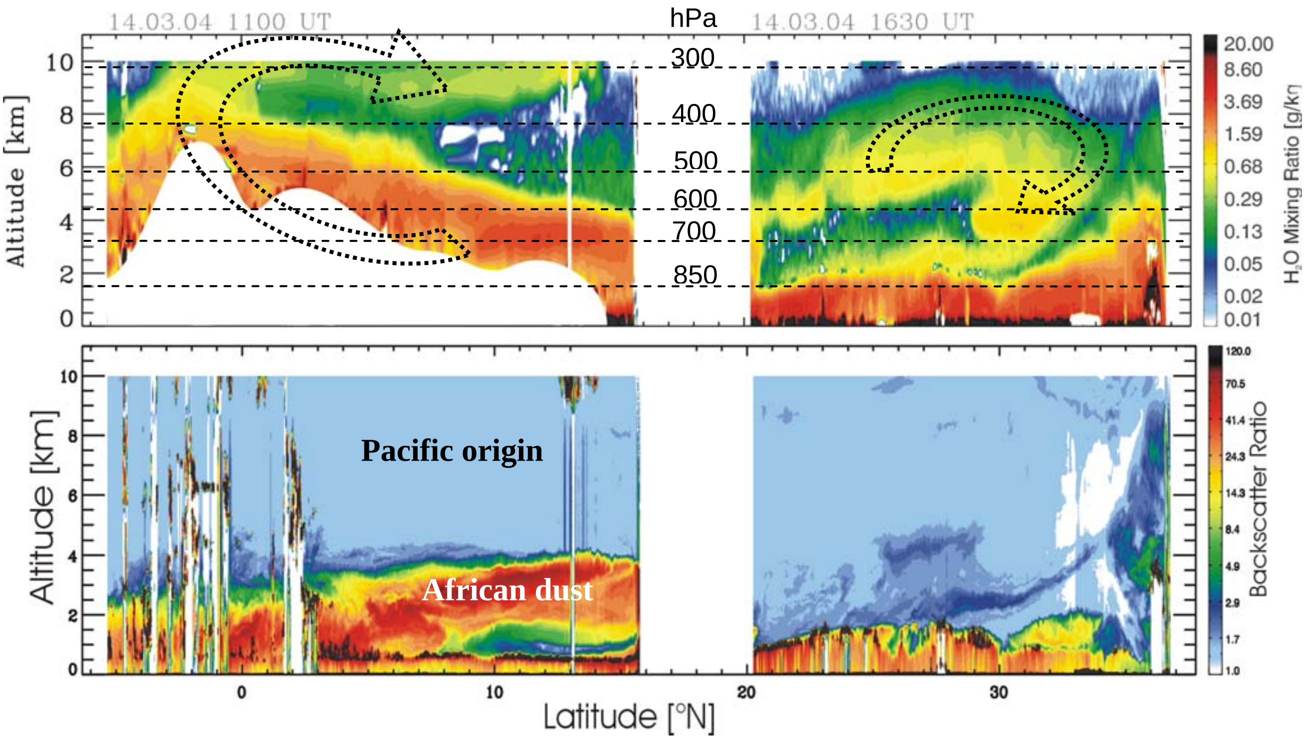

Fig 2: DIAL measurements of water vapor mixing ratio and aerosol backscatter ratio along two Falcon flights from Brazil to Spain via the Cape Verde Islands, on 14 March 2004 from 1100-1400 UT and 1630-1900 UT. H_2O profiles are averaged over 700 m vertically and roughly 3 km horizontally. Low H_2O values are accentuated by a logarithmic color scale. Approximate pressure levels and the Hadley circulation as well as the origin of the air masses are indicated.

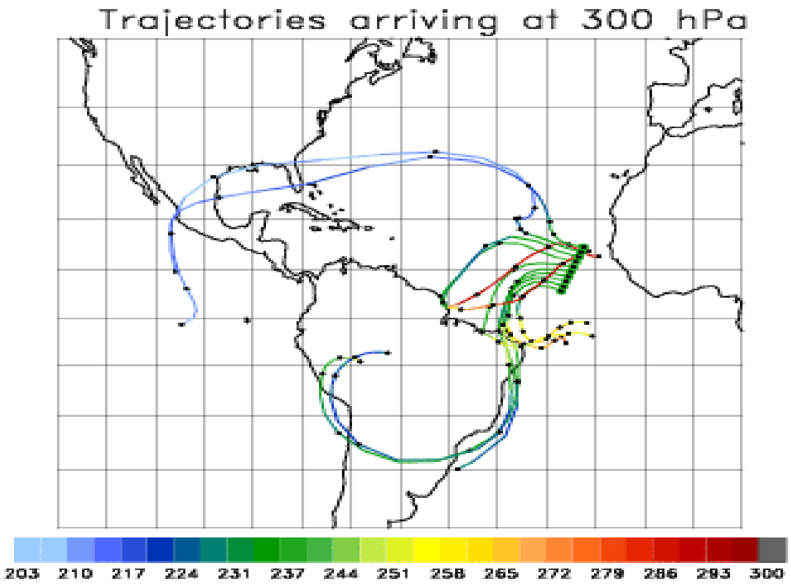

Fig. 3: Seven day ECMWF backward trajectories arriving at the DLR Falcon flight track at 300 hPa on 14 March 2004 12 UTC. The backward trajectories were calculated with the Lagrangian Analysis Tool LAGRANTO, developed at the ETH Zürich by Wernli and Davis [QJRMS, 1997]. They are driven by 6 hourly ECMWF-analyses, interpolated to an incremental time step of 1h and allow for the tracking of various meteorological parameters (here temperature) along the flow.

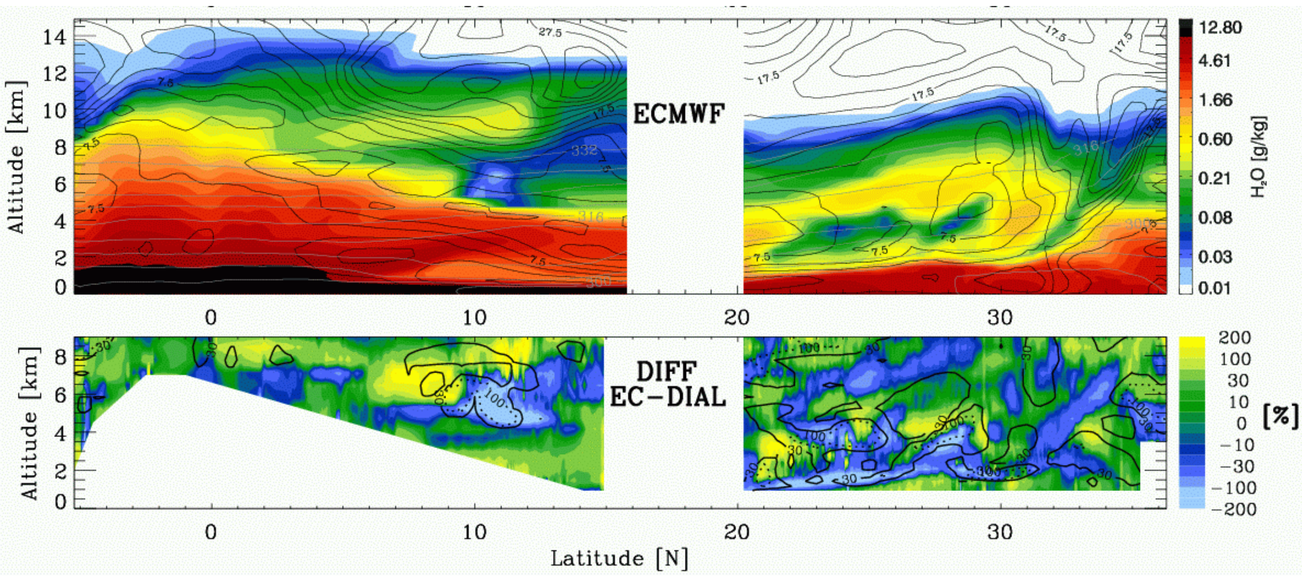

Fig 4: Water vapor mixing ratio on 14 March 2004 on log color scale. Upper panel: ECMWF T511/L60 operational analysis interpolated in space and time to the flight tracks. Superposed contours are potential temperature (grey) and horizontal wind speed (black). Lower panel: Difference of water vapor mixing ratios normalized by the mean between q_{ECMWF} and q_{DIAL}, i.e. $2(q_{ECMWF} - q_{DIAL})/(q_{ECMWF} + q_{DIAL})$. Note the different altitude range in the ECMWF panel.

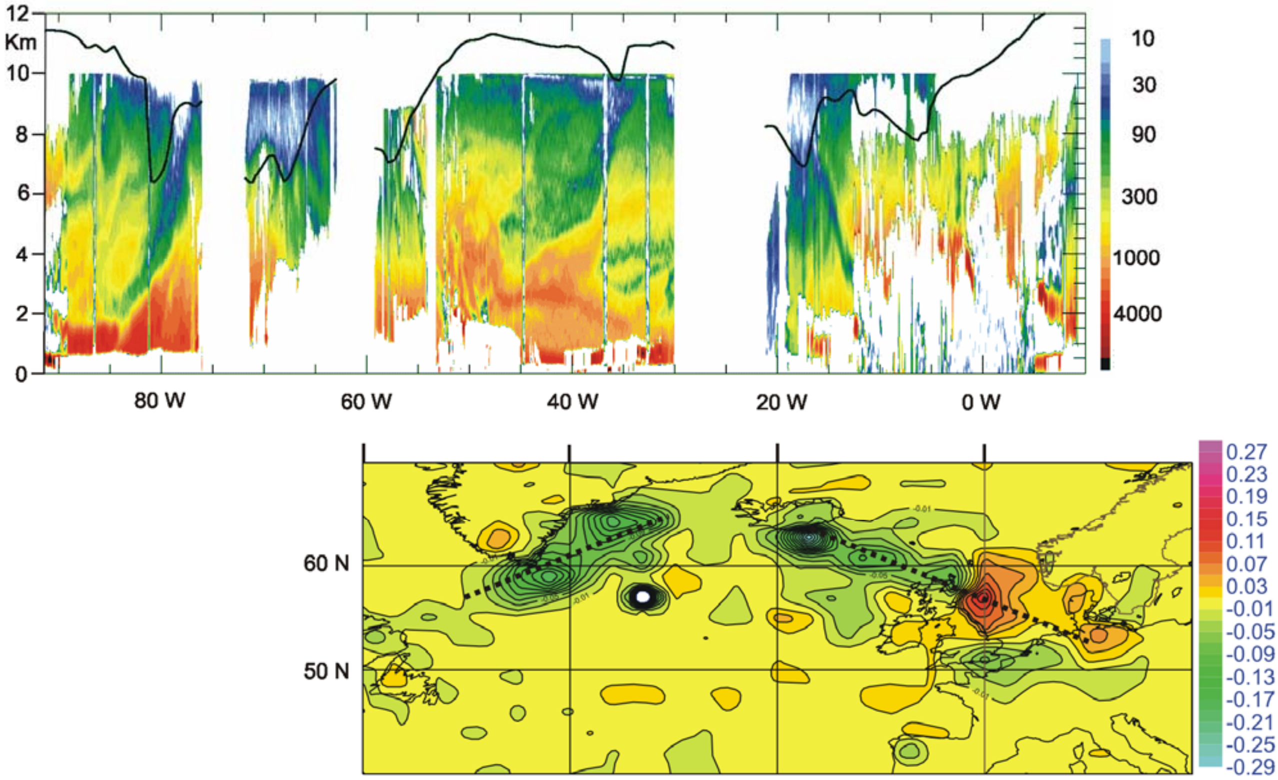

Fig. 5: DIAL water vapour mixing ratio cross section (mg/kg) along transfer flights from Germany via Iceland to Canada on 13 – 14 May 2002. The black line marks the 2 PVU surface based on T511 ECMWF analyses as an indicator for the tropopause height. Bottom: Fractional reduction (negative numbers, green colors, isoline interval 0.02) of the 12-h ECMWF forecast error estimates for total column water vapour by 4D-VAR assimilation of the DIAL data between 50 W and 9 E. The error estimates are obtained by comparing the 12-h forecasts of the control and lidar runs with the analysis. Flight tracks dotted.