Meridional Water Vapor Transport in Tropical and Sub-Tropical Regions

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Abstract

Airborne differential absorption lidar (DIAL) measurements of tropospheric water vapor and aerosol from south Europe to Brazil in mid-March 2004 are presented and compared to operational analyses of the European Center for Medium Range Weather Forecast (ECMWF). The two 2-D sections across the tropical and sub-tropical Atlantic (5°S–37°N) reveal two different meteorological regimes. South of 20°N the Hadley circulation is evident as a humid fountain near the equator with synoptic scale inflow below 4 km (16°N) to 8 km (0°N), upper tropospheric (UT) outflow till 15°N and a dry sub-tropical subsidence layer in between. The 2^{nd} section along the north-west African coast is controlled by mid-latitude dynamics. A deep stratospheric intrusion is associated with the cyclonic shear along a trough from the Canary Islands towards Gibraltar. In the sub-tropical layer and the intrusion, H_2O mixing ratios $q \approx 0.01$-0.1 g/kg are measured while $q > 0.5$ g/kg is found in the lower tropospheric air having been lifted to UT levels. The dynamical features and the water vapor mixing ratios are quite accurately analysed by the ECMWF at T511/L60 operational resolution. Largest deviations arise from shifts of structures/gradients and occasionally from assimilation inaccuracies. The averaged q-bias between both data fields is below 10%. While at mid-latitudes low water vapor regions are associated with filaments of enhanced particle backscatter, the H_2O signature of the tropical circulation is not correlated with the aerosol.

Introduction

Water vapor is the most important greenhouse gas [Möller, 1963], it controls cloud formation [Kiehl and Trenberth, 1997] and the evolution of weather systems. A primary source of water vapour in the stratosphere is transport across the tropical tropopause which thus controls the stratospheric water vapor budget, whereby the humidity entering the stratosphere is limited by freeze drying of the air within the coldest layer [Jensen and Pfister, 2004]. As it's concentration at a given tropospheric location 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 < 0.0622 g/kg. Moreover, major "birth" regions of severe continental weather to which short-term forecast errors are most sensitive are only covered by a few radiosonde stations, see Marseille and Bouttier, [2001]. 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.

The TROCCINOX campaign provides a suitable data set for such a comparison. Long-range airborne Differential Absorption Lidar (DIAL) measurements of water vapor and particle backscatter ratio across the sub-tropical and tropical Atlantic from Brazil (5°S, 36°W) to Spain (35°N) on 14 March 2004 profiled the troposphere from ~10 km to the ground. The DLR water vapor DIAL [Poberaj et al., 2002] has been installed onboard the DLR research aircraft Falcon 20E (http://www.dlr.de/FB/OP) in nadir looking arrangement. The 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 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 total. The statistical error, controlled by horizontal and vertical averaging mostly remains below 10%.

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 1 hPa [ECMWF, 1999]. The backward trajectories were calculated with the **La**grangian **An**alysis **To**ol LAGRANTO, developed at the ETH Zürich by Wernli and Davis [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 along the flow.

Discussion of H_2O Sections and Comparison with ECMWF

Figure 1 depicts the water vapor mixing ratio q and the geopotential height Φ at 300 hPa. Air mass transitions and transport of water vapor are clearly linked to the large scale flow roughly along the Φ-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. Large q-gradients, frequently associated with upper level fronts, indicate sign-changes in vertical transport V_H, driven by baroclinic adjustment near the jet streams. 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 northeast 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. The dry sub-tropical subsidence belt is disturbed by humid streamers emanating from the tropics and mid-latitudes. A tongue of dry air runs along the anticyclonic shear side of the NW-African trough. With 0.06 g/kg as a threshold for stratospheric air, the hygropause is above 200 hPa in the tropics and in regions of large scale frontal upwelling, while it typically reaches down to below 400 hPa on the cyclonic shear side of the planetary wave as described e.g. by Flentje et al. [2004] and references therein. Patches if the intertropical convergence zone (ITCZ) were crossed NE of Brazil.

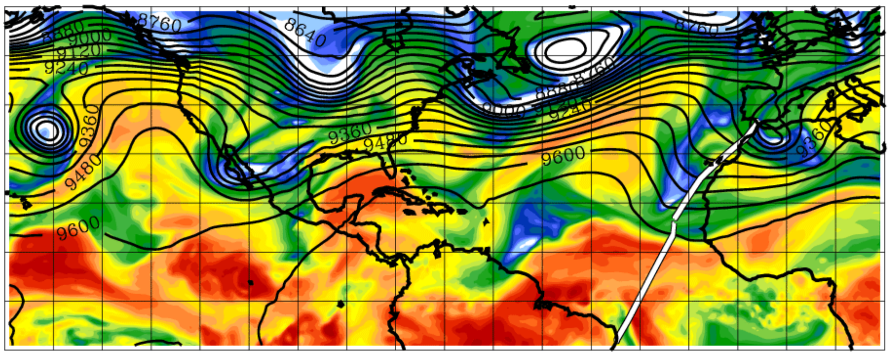

Fig. 1: Water vapor mixing ratio (g/kg) and geopotential height (m) analysed at 300 hPa by the ECMWF (T511/L60) on 14 March 2004, 1200 UT. The Falcon flight path is marked by a white line.

In the DIAL water vapor and particle backscatter distributions along the flight (Fig. 3), low values are accentuated by logarithmic scales. Large gradients and humidity changes occur throughout the troposphere. While water vapor and backscatter ratio are not correlated in the first (tropical) flight leg, they are anti-correlated in the sub-tropical/mid-latitude region: As discussed by Flentje et al. (2004), enhanced backscatter ratios are frequently found in stratospheric intrusions at mid-latitudes and may originate from e.g. forest fires injected into the stratosphere by high-reaching, frontally strengthened convection. In the tropics the atmosphere looks clean above 4 km altitude while the air at lower levels is loaded with dust from the African continent.

***Flight - Fernando de Naronha – Cape Verdes**:* 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 with q ≈ 0.2 - 0.6 g/kg extends from the equator till 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 Figure 3, show that air in the upper humid layer is participating in the Hadley circulation. The dry air north and below the layer (q ≈ 0.05-0.1 g/kg) emanates from the eastern Pacific UT. The slightly drier air near 3-5°N (@ 300 hPa) comes from the Amazonian region.

The Hadley circulation is evident up to ≈ 14.2 km, as shown by ECMWF analysis in Fig. 4. The lower sloping layer with $q > 2$ g/kg is advected from central Africa by north-easterly trade winds.

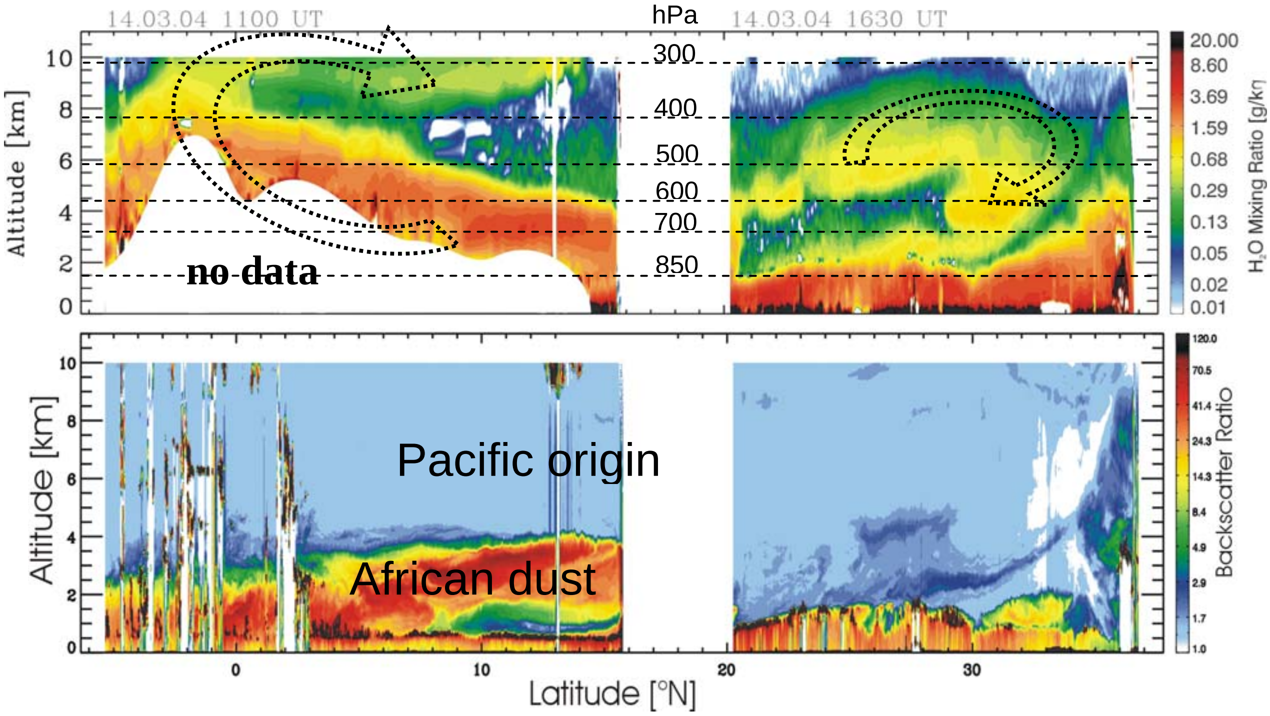

Fig 2: DIAL measurements of water vapor mixing ratio in g/kg and aerosol backscatter ratio along the Falcon flight path from Fernando de Naronha (Brazil) to Seville (Spain) via the Cape Verde Islands, on 14 March 2004 from 1100-1400 UT and 1630-1900 UT. H_2O profiles are averaged over 700 m vertically and roughly 3 km horizontally. Low H_2O values are accentuated by a logarithmic colour scale. Approximate pressure levels at 300, 400, 500, 600, 700 and 850 hPa and the Hadley circulation (upper panel) as well as the origin of the air masses are indicated.

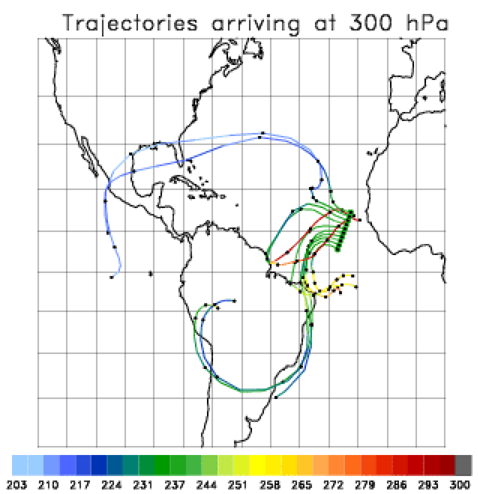

Fig 3: Seven day ECMWF backward trajectories arriving at the DLR Falcon flight track at (a) 300 hPa and (b) 700 hPa on 14 March 2004 12 UTC.

Flight - Cape Verdes – Spain: Along the West African coast dry and humid air masses, advected along largely different trajectories interpenetrate in a complex water vapor scene. Large gradients occur near the top of the planetary boundary layer (PBL), a stratospheric intrusion and a humid tropical air mass entering the region at mid-tropospheric levels. The moist ($q \approx 2$-5 g/kg) maritime PBL covers the lowest 1.5 - 2 km, inside the Gibraltar cyclone upward-spiraling motion lifts high humidity up to 4 km. Above the lifted PBL, a narrow intrusion of UT/LS air tilts downward and southward from NW-Morocco towards the Canary Islands (≈ 30°N) with $q < 0.1$ g/kg. Above the intrusion, a bean-shaped humid air mass from the Caribbean Sea extends along the section. The drier layer above the PBL originates from the Pacific mid-troposphere. The narrow dry intrusion is generated by cyclonic interleaving of different flows inside the cyclone where strong shears separate air masses with substantially different characteristics and source areas.

Comparison with ECMWF Analyses: In Figure 4, the DIAL water vapor is compared to ECMWF T511/L60 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%.

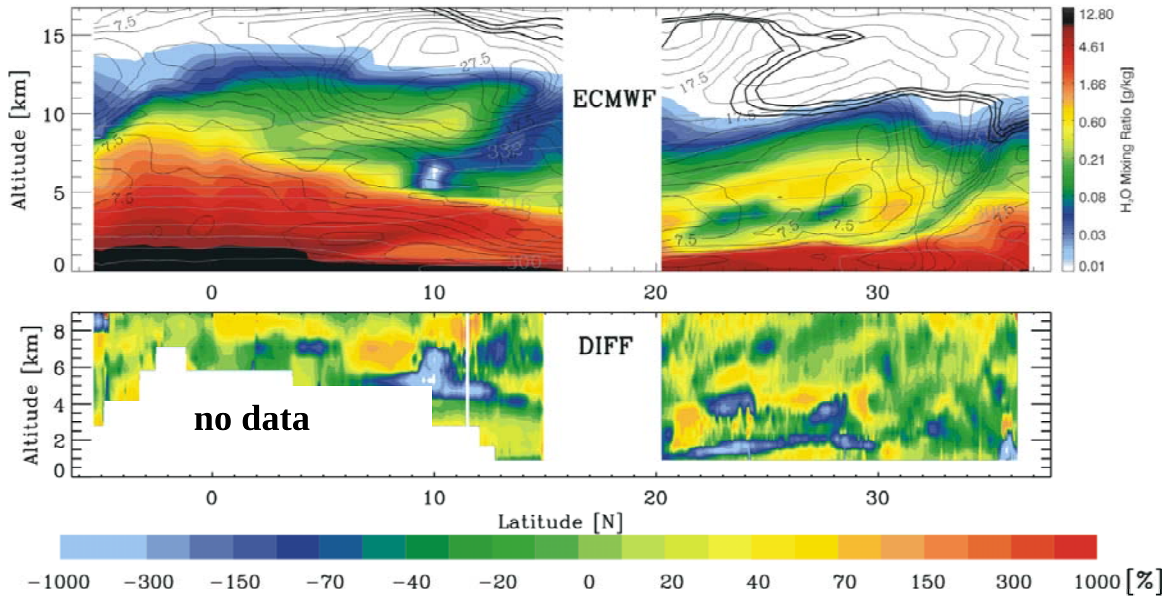

Fig 4: Water vapor mixing ratio q on 14 March 2004 on log-q color scale. Upper panel: ECMWF T511/L60 operational analysis interpolated in space and time to the flight tracks. Superimposed contours are potential temperature (grey), horizontal wind speed (black) and potential vorticity at 2, 2.5 and 3 PVU. Lower panel: Difference of water vapor mixing ratios $q_{DIAL} - q_{ECMWF}$. Note the different altitude range of the ECMWF panel.

References

ECMWF, Increased stratospheric resolution in the ECMWF forecasting system, ECMWF newsletter No. 82 – winter 1998/99, 1999. Available at http://www.ecmwf.int/publications.

Flentje, H,. A. Dörnbrack, G. Ehret, A. Fix, C. Kiemle, G. Poberaj, and M. Wirth, Water vapor heterogeneity related to stratospheric intrusions over the northern Atlantic revealed by airborne water vapor, *J. Geophys. Res.*, accepted, November 2004.

Kiehl, J.T. and K.E. Trenberth, Earth’s annual global mean energy budget, *Bull. Am. Met. Soc., 78*, 197-208, 1997.

Möller, F., On the influence of changes in the CO2 concentration in air on the radiation balance of the Earth's surface and on the climate, *J. Geophys. Res., 68*, 3877-3886, 1963.

Marseille, G. J. and Bouttier, F., Climatologies of sensitive areas for short-term forecast error over Europe. A EUMETNET-EUCOS study. ECMWF Technical Memorandum No. 334, ECMWF, Reading 2001.

Poberaj, G., A. Fix, A. Assion, M. Wirth, C. Kiemle, and G. Ehret, All-Solid-State Airborne DIAL for Water Vapor Measurements in the Tropopause Region: System Description and Assessment of Accuracy, *Appl. Phys. B 75*, 165-172, 2002.

Wernli, H., and H. C. Davis, A Lagrangian-based analysis of extratropical cyclones. I: The method and some applications, *Q. J. R. Meteorol. Soc., 123*, 467-489, 1997.