Aircraft Observation of a Small-scale Solitary Wave near the Tropopause

Thomas Hauf
DLR, Institut für Physik der Atmosphäre

Abstract

Aircraft observations at 10100 m height provide evidence of a small-scale solitary wave with 130 m half-amplitude-width. The measurements are discussed and the structure of the solitary wave is analyzed.

1. Introduction

Solitary waves are large-amplitude single-crested waves with amplitude-dependent propagation speeds (Drazin and Johnson, 1989). They are weakly nonlinear, where, crudely explained, at least in the case of atmospheric gravity waves the excitation of high-frequent modes in the crest due to the nonlinearity is balanced exactly by the dispersion such that the shape of the solitary wave is preserved. Those waves can travel as one entity over long distances, e.g. distances much greater than their typical length scale. They carry information as well as energy. The propagation speed is similar to the group velocity of a wave packet. Theoretically, solitary waves are solutions of the Korteweg-de Vries equation or associated equations with similar properties.

Atmospheric solitary waves are found as acoustic waves, Rossby-waves or buoyancy waves (Dodd et al., 1982). Most studies of atmospheric solitary waves, however, including the present one, are concerned with the latter type. Buoyancy solitary waves may be either waves of elevation or waves of depression depending on the detailed fluid density and shear structure (Lin and Goff, 1988). In order for the wave to develop and propagate in the atmosphere with little or no attenuation, there must be a waveguide (Doviak and Thomas, 1988). Some studies deal with mesoscale solitary waves on the order of 100 km where a mid-tropospheric inversion, resp. critical level and a surface inversion serve as a wave-guide (Ramamurthy et al., 1990). A lot of studies were performed by Doviak, Christie and coworkers on the formation and propagation of solitary waves in the boundary layer (Doviak and Ge, 1984), (Doviak et al., 1991), (Christie and Muirhead, 1983), (Christie et al., 1981), (Doviak and Chen, 1988). Generally, stable boundary layers were considered where an inversion aloft makes the boundary alyer a wave-guide. The scale is ususally on the order of 500 m to several kilometers with the outflow of cold air from a thunderstorm serving as the primary source of gravity waves. The cold air outflow of the thunderstorm itself shows the basic characteristics of a gravity current. Under certain conditions which are discussed in the forementioned papers a solitary wave may emerge from the gravity current travelling ahead of it. Both processes may lead to spectacular phenomena (Smith, 1988) but are also a source of concern regarding air traffic safety (Christie and Muirhead, 1983).

All of the observed solitary waves have length scales greater than 500 m and all were observed in the lower troposphere. In this study, however, I present results dealing with an atmospheric solitary wave of elevation with length scale of about 130 m and which was observed just beneath the tropopause. Observations were made with the

DLR research aircraft Falcon during a flight which will be analyzed in more detail in a subsequent paper. The observation is based on typical signatures in the temperature, humdity and wind field which are explicable in terms of a solitary wave. Although the idendification of any wave in principle requires a spatial *and* temporal analysis it is hypothesized that the pure spatial analysis performed in this study is sufficient to relate the observed spatial structure to a moving solitary wave.

2. Measurements

The flight was performed with the Falcon during the early afternoon hours on July 28, 1989 over the Bavarian Lowlands. The Falcon is an instrumented aircraft fully equipped for turbulence measurements. Instrumentation, accuracy and further details of the equipment can be found by Hauf (1984). The flight pattern consisted of four vertically staggered horizontal legs of approximately 60 km length and which where oriented in SE-NW direction. Each leg was flown twice with the hihgest flight level at 10100 m. At one of the two legs at 10100 m the solitary wave was observed. Flight speed at that level was 182.2 m/s yielding a spatial resolution of 1.8 m for the given sampling frequency of 100 Hz. The synoptic situation at that day was characterized by a cold front which passed Southern Germany the previous night and a high pressure system over Norther Germany with weak to moderate northwesterly winds in the measurement area. Fields of cumulus clouds developed in the convective boundary layer with tops at 2800 m. The mid-troposphere was very dry with relative humidity of ≈ 20 % while in the upper troposphere light cirrus clouds prevailed with cloud cover less 1/8. Temperature, relative humidity, wind direction, and wind speed in 10100 m were -51 C, 30 %, 345 °, and 14 m/s, respectively. The local Richardson number was about +9.

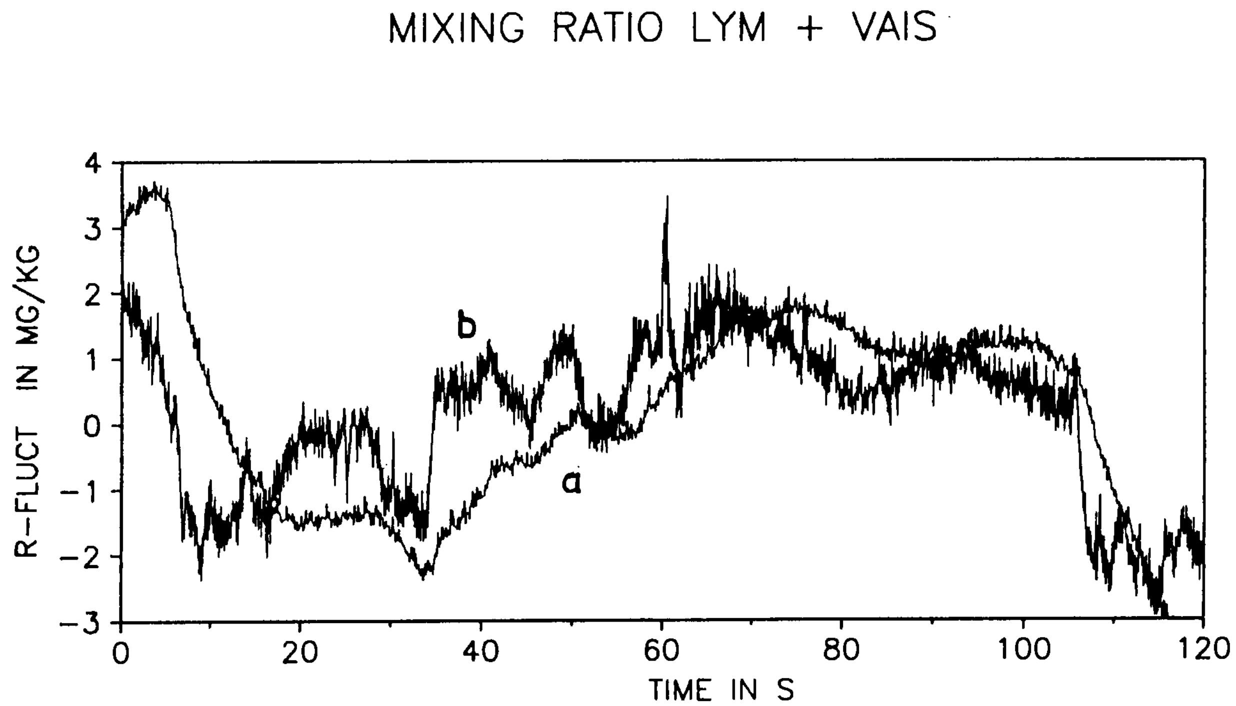

Figure 1: Time series of water vapour mixing ratio measured with the Väisälä-humicap hygrometer (a) and the Lyman-α hygrometer (b), for a time interval of 120 seconds, corresponding to a flight distance of 21.8 km at 10100 m altitude. A linear trend was removed from the data.

3. The solitary wave

The solitary wave was first noticed when Väisälä-Humicap and Lyman-α humidity measurements where intercompared. Figure 1 shows such an intercomparison for a time period of 120 seconds at 10100 m altitude. One clearly recognizes a little peak of approximately 0.0025 g/kg in the Lyman-α trace which was not detected by the Väisälä instrument. The subsequent analysis confirmed the peak to be real as simultaneously a similar one was found in the temperature, as well as in the wind velocity traces. The small scale and high-frequent humidity fluctuation lasting only 1 s was not resolved by the Väisälä-instrument due to its inertia which increases strongly with decreasing temperature as well as with decreasing humidity values. Figure 2 shows vertical wind velocity together with temperature (upper plate), resp. humidity (lower plate). As the single wave crest has a positive vertical wind velocity, the solitary wave is referred to as an internal wave of elevation (Lin and Goff, 1988). The central upward motion lifts air with higher humidity from lower levels to the observational level, thus it is related with a positive humidity deviation. The negative temperature deviation indicates the wave being already in the tropopause or at least close to it. As the wave is nonlinear fluctuations in passive tracers and vertical wind velocity are not necessarily shifted in phase by 90 degrees. The proximity of the tropopause suggests the latter to serve as the upper part of a waveguide in which the solitary wave develops. It seems that the wave is heading against the airplane as for most quantities the first crest is followed by a second of opposite sign which is typical for an approaching solitary wave. The wind vector plot (Figure 3) reveals a strong deviation of the horizontal wind vector related with the solitary wave and which is correlated with vertical wind velocity. This means that the 3-d wind vector moves in a plane which is approximately perpendicular to the flight path. If the solitary wave is assumed to be a purely 2-d phenomenon, propagation direction is parallel to the plane. In conclusion, it is hypothesized that the solitary wave headed against the airplane at an angle of slightly less than 90 degrees from either the left or the right side. Typical peak-to-peak fluctuations of u,v, w, q and T associated with the solitary wave are 0.6 m/s, 1.6 m/s, 0.9 m/s, 0.003 g/kg, 0.05 K resp., while the r.m.s.-values of the total leg are 0.4 m/s, 0.4 m/s, 0.12 m/s 0.002 g/kg and 0.09 k respectively. Peak-to-peak values are about 1.5 - 7 times the r.h.s. values of the total leg. The r.m.s temperature value is not considered due to instrumental noise. The half-amplitude width is approximately 130 m. It should be noted that in all figures a linear trend was removed from the data.

4. Conclusions

The instant snapshot taken with the aircraft is consistent with what is known from solitary waves. Although the propagation could not be observed I nevertheless suggest the phenomenon being a traveling solitary wave. An instrumental error can be excluded. All instruments with time constants less than 1s recorded the solitary wave. Noticeable is the length scale of 130 meters. This is small compared with what is reported from boundary layer solitary waves which are of the order of at least 500 m and more. Nothing can be said about the source of the solitary wave. An analysis as in Doviak et al (1991) was not performed. This study demonstrate the advanced measurement technics, especially of the Falcon research aircraft, which allow the discovery of such small scale phenomena at high altitudes, resp. low temperatures and low humidities. It is hypothesized that further research will discover more of such phenomena. Whether such small-scale solitary waves have an impact on other processes is not known but is doubted. Nevertheless the mere existence of such a solitary wave is interesting and serves some attention.

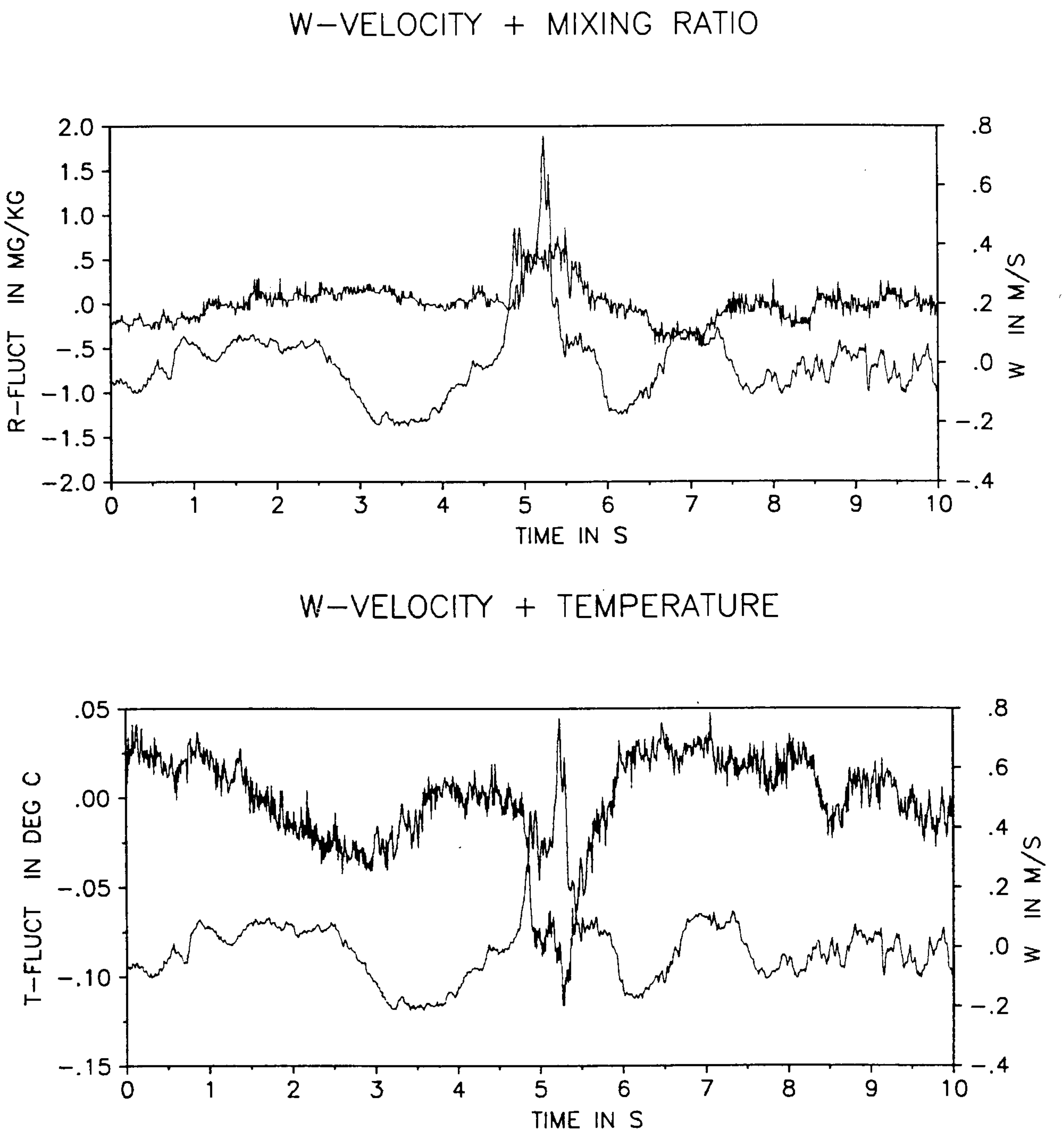

Figure 2: Time series of vertical wind velocity (lower traces) and temperature (lower plate), resp. humidity (upper plate) centered around the solitary wave peak.

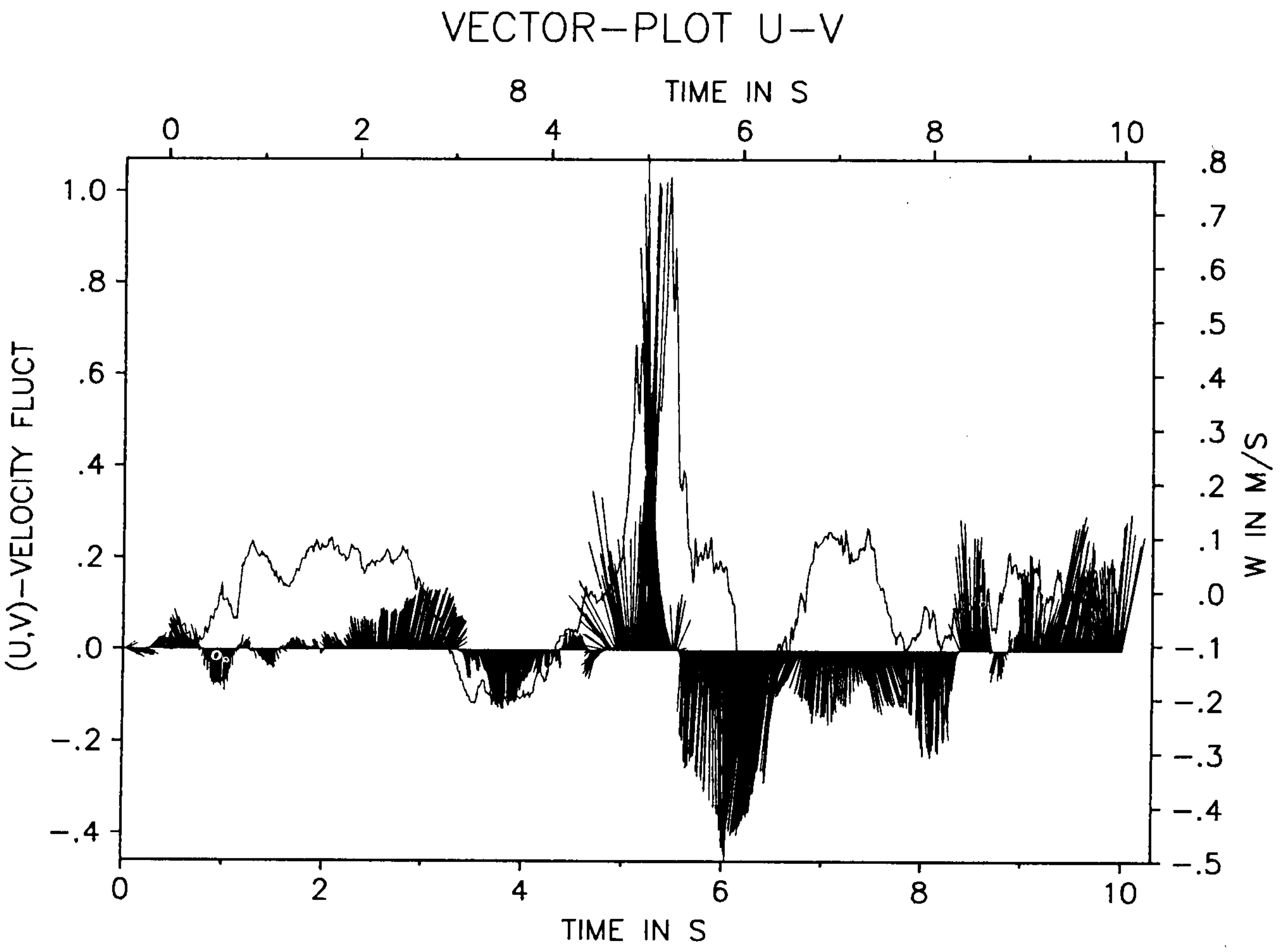

Figure 3: Plot of horizontal wind vector fluctuations along the flight path. Spatial resolution is 1.8 m. Vertical wind velocity is overlaid to demonstrate the 3-d structure.

References:

Christie D.R., Muirhead K.J. and R.H. Clarke, 1981: Solitary waves in the lower troposphere. Nature, 293, 46 - 49.

Christie D.R. and K.J. Muirhead, 1983: Solitary Waves A Low-Level Wind Shear Hazard To Aviation. Int. J. of Aviation Safety, 129 - 256.

Dodd R.K., Eilbeck J.C., Gibbon J.D. and H.C. Morris, 1982: Solitons and Nonlinear Wave Equations. Academic Press London.

Doviak R.J., S. Chen and D.R. Christie, 1991: A Thunderstorm-Generated Solitary Wave Observation Compared with Theory for Nonlinear Waves in a Sheared Atmosphere. J. Atmos. Sci., 48, 87 - 11.

Doviak R.J. and S. Chen, 1988: Observations of a Thunderstorm Generated Gust Compared with Solitary Wave Theory. US Dept. of Transp., Federal Aviation Administration, DOT/FAA/SA-88/1.

Doviak R.J. and RunSheng Ge, 1984: An Atmospheric Solitary Gust Front Observed with a Doppler Radar, a Tall Tower and a Surface Network. J. Atmos. Sci., 41, 2559 - 2573.

Doviak R.J. and K.W. Thomas, 1988: The Wavefront Shape and Position of a Great Solitary Wave of Translation. Proc. IGARSS '88 Symp., Edinburgh, Scotland, 13 - 16 Sept. 1988, ESA SP-284 (IEEE 88CH2497-6).

Drazin P.G. and R.S. Johnson, 1989: Solitons: An Introduction. Cambridge University Press, Cambridge.

Hauf T., 1984: Turbulenzmessungen mit dem Forschungsflugzeug Falcon. Meteorol. Rdsch., 37, 163 - 176.

Lin Yuh-Lang and R. Craig Goff, 1988: A Study of a Mesoscale Solitary Wave in the Atmosphere Originating near a Region of Deep Convection. J. Atmos. Sci., 45, 194 - 205. 1990:

Ramamurthy M.K., Collins B.P., Rauber R.M. and P.C. Kennedy, Evidence of very-large-amplitude solitary waves in the atmosphere. Nature, 348, 314 - 317.

Smith R.K., 1988: Travelling Waves and Bores in the Lower Atmosphere: The 'Morning Glory' and Related Phenomena. Earth-Sci. Rev., 25, 267 - 290.