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TDLAS Trace Gas Measurements within Mountain Waves over Northern Scandinavia during the POLSTAR Campaign in early 1997

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Abstract. Trace gas measurements of CO and N_2O were performed over Northern Scandinavia during a mountain wave event in the night 1./2. February 1997. The data were taken during the POLSTAR I campaign on board the DLR research aircraft Falcon by the newly developed tunable diode laser absorption spectrometer TRISTAR. Strong tropospheric winds almost perpendicular to the Scandinavian mountain ridge led to the formation of mountain waves. Due to the steep gradient in the CO mixing ratio around the tropopause these mountain waves resulted in extensive modulations in the CO signal. Peak-to-peak amplitudes of up to 70 ppbv and horizontal wavelengths in the order of 10 to 20 km were recorded. Vertical fluxes of CO in the tropopause region are calculated using the CO data and the vertical wind data taken from the standard meteorological equipment of the DLR aircraft. The vertical eddy exchange coefficient shows values comparable to or even greater than those calculated for tropopause folds. We conclude that mountain wave events seem to play an important role as a mechanism for troposphere/ stratosphere exchange of chemical constituents.

Introduction

Recently, mountain waves became an important part in our understanding of the chemistry and the dynamics of the lower stratosphere. Gravity waves of horizontal extents of 10-200 km lead to local adiabatic cooling of several Kelvin. The air passing through such mesoscale temperature anomalies cools in time scales of 10 to 30 min. The resulting enhancement of PSC (polar stratospheric cloud) occurence with activation of inert chlorine compounds cause enlarged destruction of ozone [*Carslaw et al.*, 1998].

In this study we investigate the effect of mountain induced waves on the troposphere/ stratosphere exchange in the vicinity of the tropopause. Since mountain waves and especially lee waves with horizontal wave lengths of 10 - 20 km are too small in their spatial extent to be resolved in most meteorological models their effects on global atmospheric dynamics and chemistry needs to be described by parameters based on in-situ and/or remote sensing measurements with sufficient temporal and spatial resolution. We have performed such in-situ measurements in the scope of the Arctic winter campaign POLSTAR I (Polar Stratospheric Aerosol Experiment) which took place from 20 January to 7 February 1997 from Kiruna, North Sweden, in order to study dynamical and chemical processes at tropopause altitudes. In this paper we will concentrate on high resolution measurements of CO performed on 1./2. February 1997 on the DLR Falcon aircraft during a mountain wave event.

Measurements

We have developed a new instrument called TRISTAR (TRacer In-Situ Tunable diode laser absorption spectrometer for Atmospheric Research) which is capable of detecting up to three trace gases simultaneously with a time resolution of ~1 s limited by the gas exchange time of the instrument measurement cell. The CO measurements were performed with a total uncertainty of ~5% [*Wienhold et al.*, 1998].

The POLSTAR flight P4 took place in the night 1./2. February 1997 in order to investigate mountain wave effects in the vicinity of a synoptic cold area above the Scandinavian mountain ridge. Based on meteorological forecast

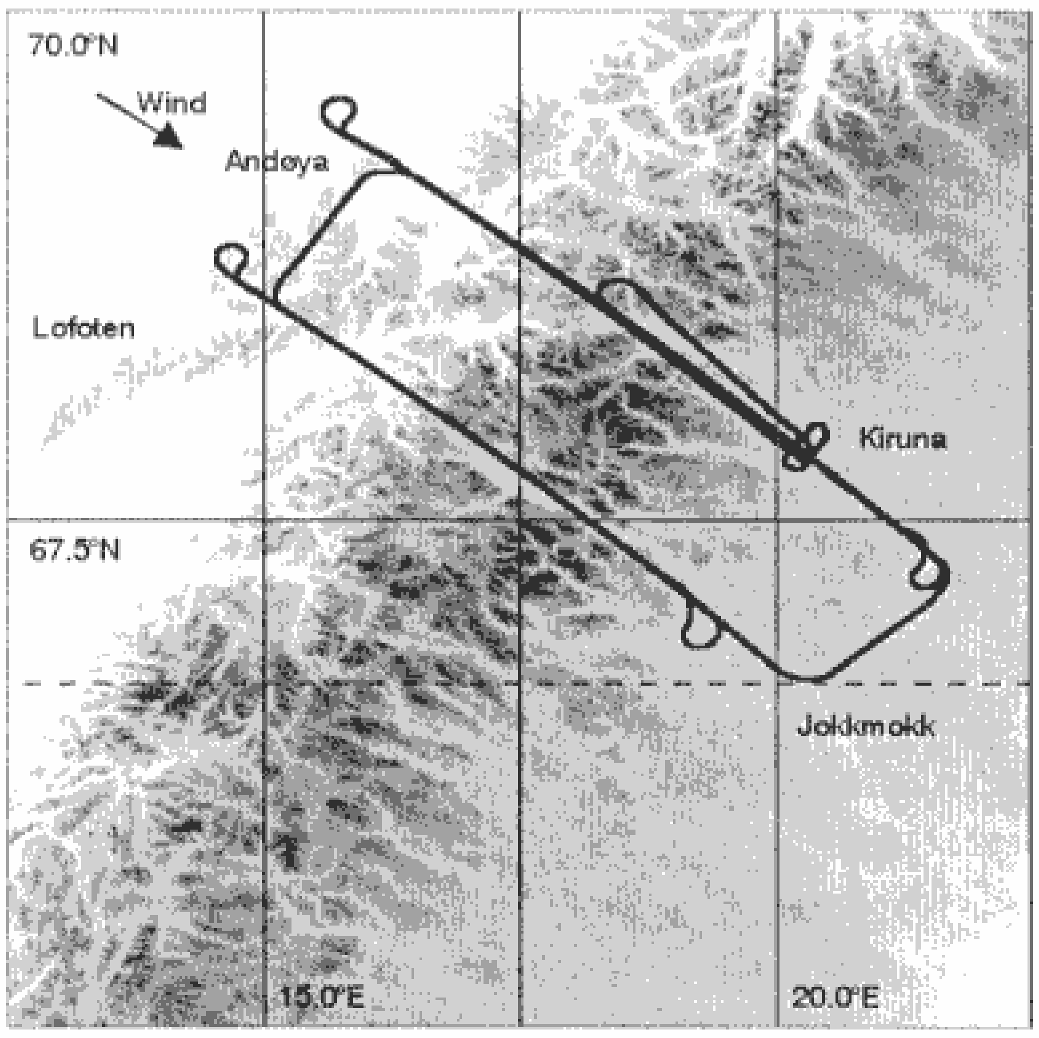

Figure 1. POLSTAR flight P4 on 1./2. February 1997. The flight track is shown projected on an orographic map of Northern Scandinavia.

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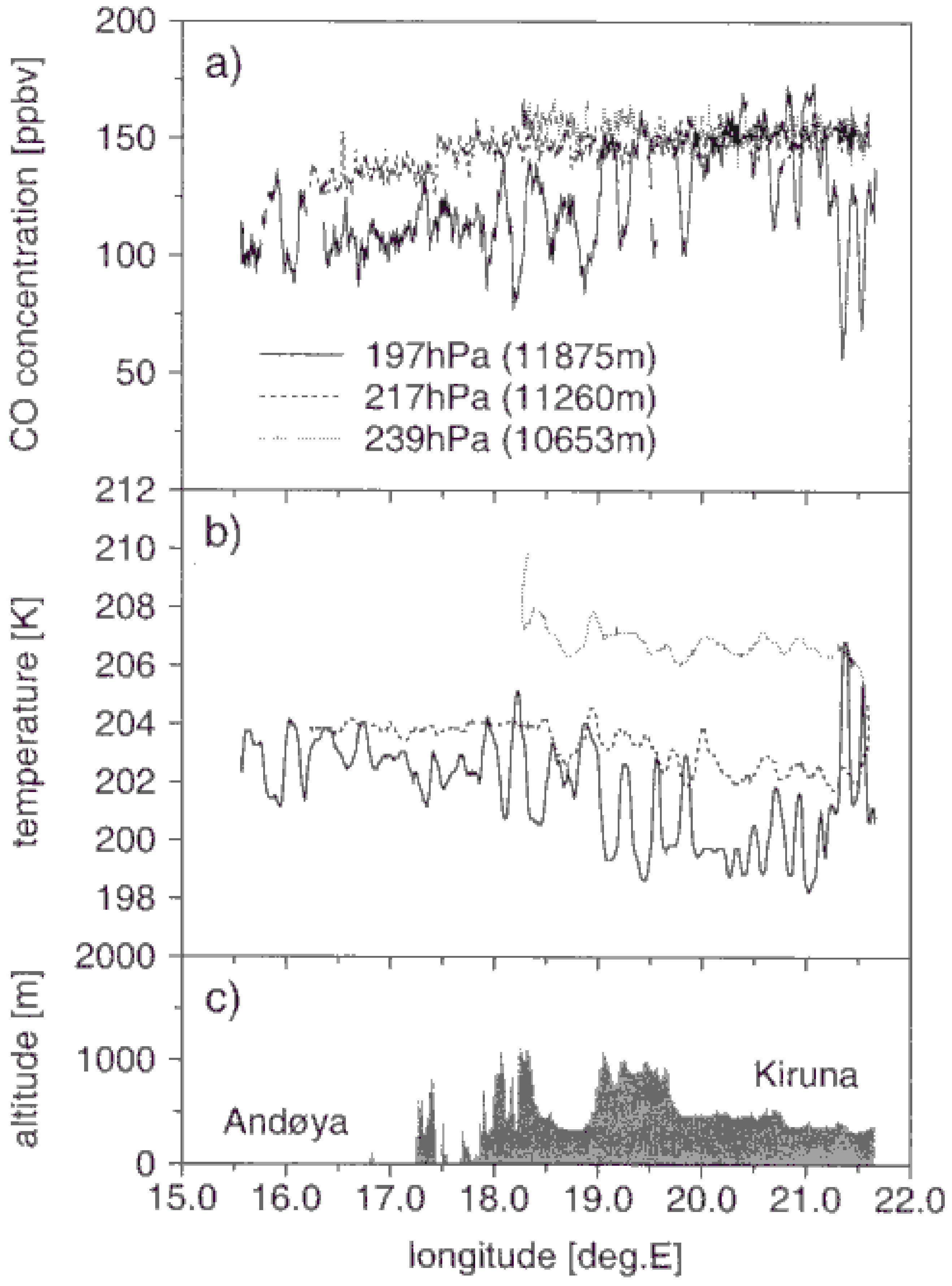

Figure 2. CO concentration (a), temperature (b), and orography (c) for the northern flight track of flight P4.

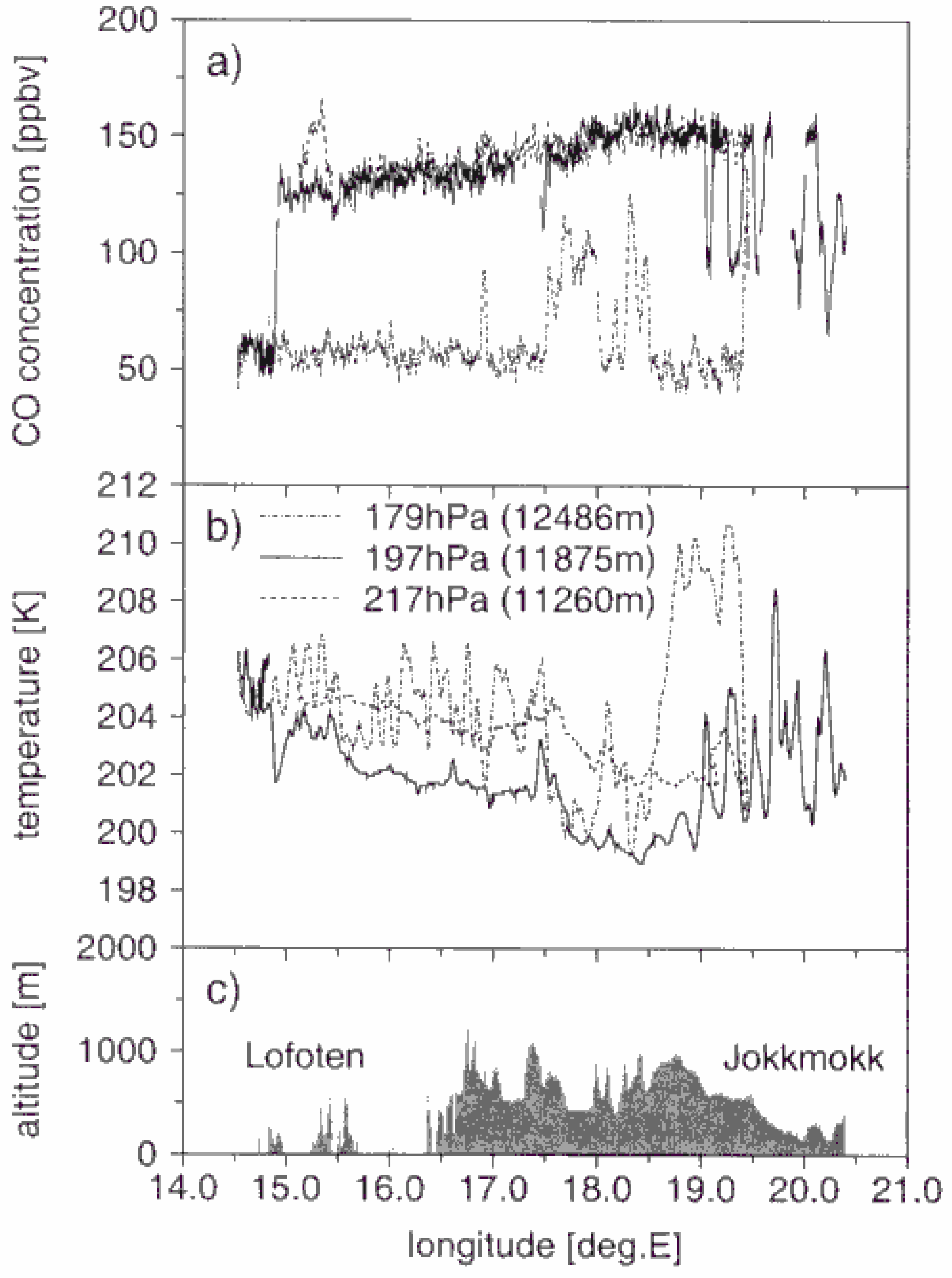

Figure 3. Same as Figure 2, but for the southern flight track.

a flight pattern was chosen to optimize detection of mountain waves [*Dörnbrack et al.*, 1998]. The flight was directed in two legs being orientated perpendicular to the Scandinavian mountain ridge near Kiruna, and parallel to the mean horizontal wind direction. We flew on four height levels (12486 m, 11875 m, 11260 m and 10653 m pressure altitude) in a northern leg between Andøya and Kiruna and a southern leg between the Lofoten and Jokkmokk (Figure 1). The mountain ridge has a maximum elevation of approximately 2000 m and mean width of ~400 km.

The meteorological instrumentation of the Falcon aircraft shows strong winds from northwest (~315°) almost perpendicular to the mountain ridge during the ascent and descent. The vertical profile of the horizontal wind vector shows wind speeds of ~25 and ~35 m/s at an altitude of 3 and 11 km, respectively, and vertical shear of the horizontal wind vector of 5 - 9 m/s km^{-1}. In addition, strong vertical winds are found with speeds between 2.5 and 5.7 m/s.

The CO concentration at the flight altitude of 11875 m is characterized by a mean value of 100 ppbv at the upwind side above Andøya and increases to values of 140 ppbv downwind the mountain ridge above Kiruna (Figure 2). Some degrees further east (~ 21°E) the mean CO concentration again sharply decreases to 100 ppbv. The temperature values show the opposite behaviour with decreasing mean values and wave induced lowest temperatures around 198 K above Kiruna, this is a reduction of 5 K compared to a synoptic mean temperature of ~203 K. Above and downstream the mountain ridge wavelike structures are found in the measured CO concentration as well as in the temperature. Prominent wave structures are present at wavelengths of 8-10 km, 13-14 km, and 18-20 km. The peak-to-peak amplitude of the waves is 50-70 ppbv CO, and 3-7 K temperature, respectively.

At the highest flight level of 12486 m flown at the southern flight leg mean values of 50 ppbv CO are observed with peak values of 125 ppbv above the mountain ridge (Figure 3). The enhancements of CO are accompanied by reduced temperature values ($\Delta T=-5$ K). At the downwind side (~ 19°E) a sharp increase in temperature is observed. At the upwind side of the mountain ridge, located above the Lofoten, temperature variation of 3 K peak-to-peak is found, but no corresponding CO variation is detected. At the two lowest flight levels of 11260 m and 10653 m at the northern and the southern flight track only small temperature fluctuation of 1 K, and no considerable CO variation is present.

Discussion

The data suggest that the wave-like disturbed CO and temperature values at the flight tracks can be explained by air parcels which have been vertically displaced due to mountain wave activity. By using an adiabatic lapse rate of -10 K/km a vertical displacement of 300-700 m is calculated from the temperature modulations. As can be seen in the vertical profiles of temperature and CO (Figure 4) an upward air parcel displacement from lower levels into the 11875 m flight level leads to lower temperature and higher CO concentration and vice versa. Consequently an anti-

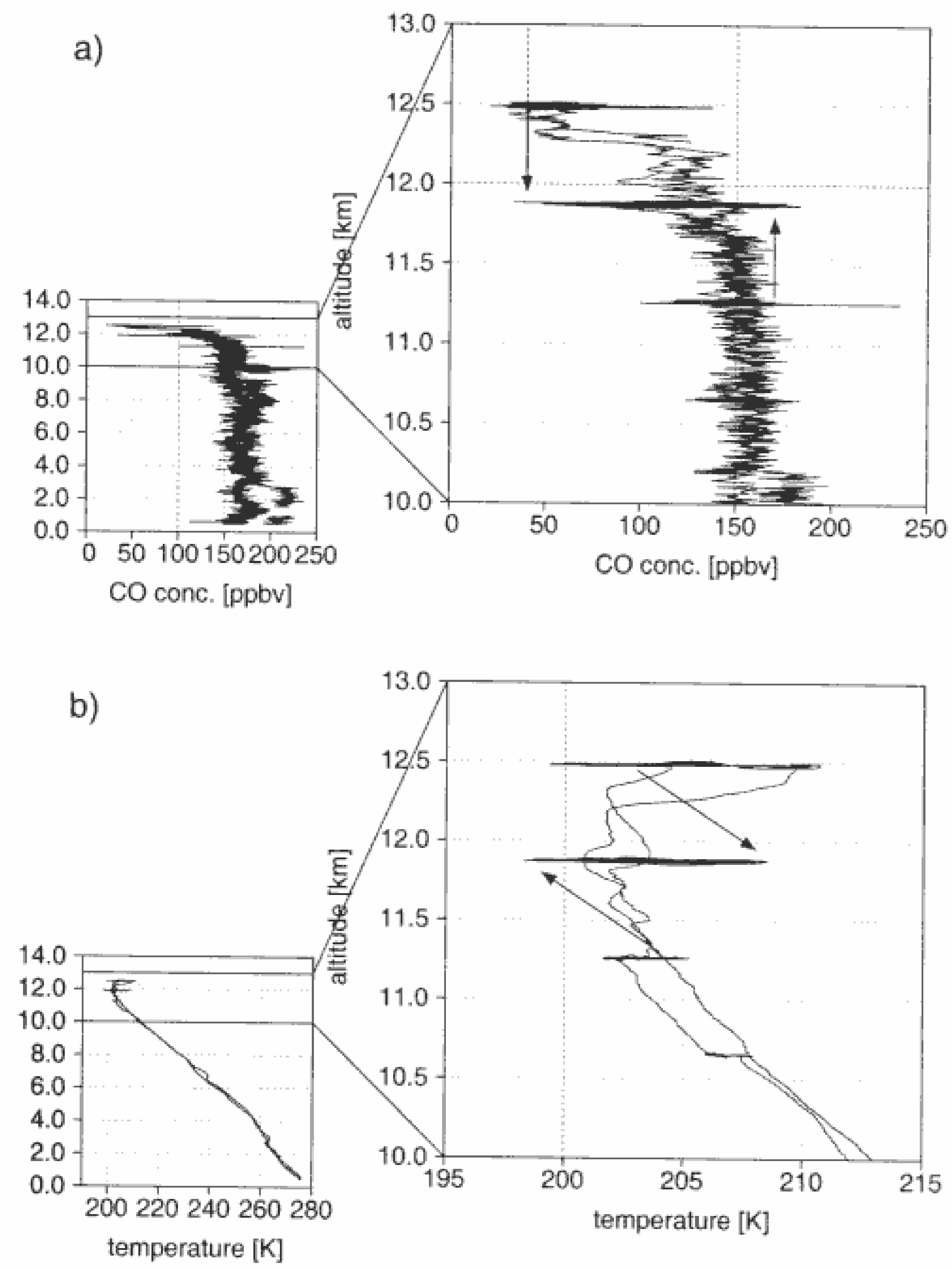

Figure 4. Vertical profiles of CO (a) and temperature (b). The arrows indicate how a vertical exchange process (e.g. a mountain wave) will alter the measured values on a specific flight altitude.

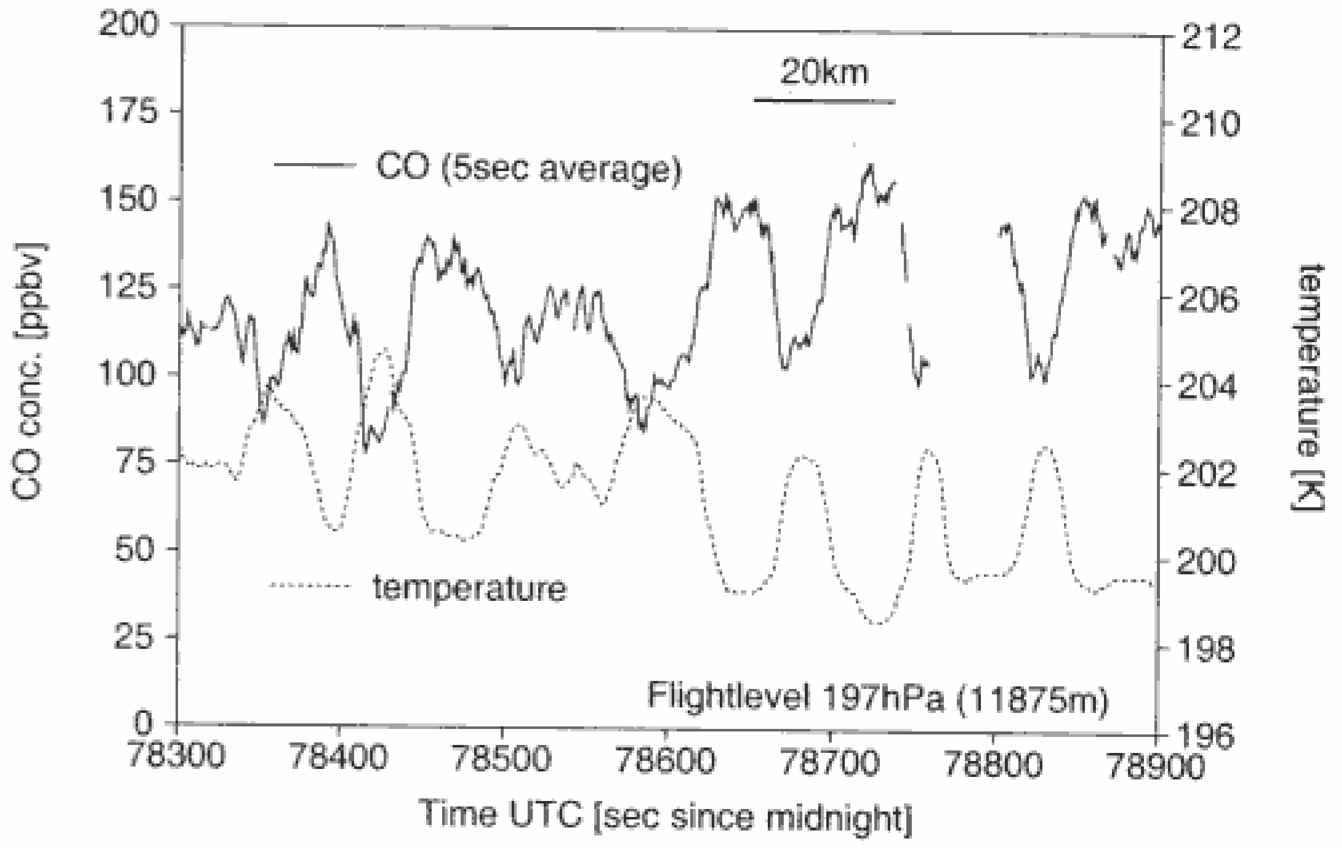

Figure 5. Small section of the data shown in Figure 2. There is a strong anticorrelation of CO and temperature in this part of the flight.

correlation between CO and temperature is expected for air parcel displacements due to mountain waves. As can be seen in Figure 5 this anticorrelation is indeed observed in the regions of distinct wave activity. It should be noted, that this anticorrelation can only be observed if the tracer concentration shows a vertical gradient, and the temperature gradient differs from the adiabatic lapse rate. Therefore only at the tropopause height level wave induced changes in CO concentration are visible. The analysis of the meteorological data showed that the tropopause was indeed centered near our flight level of 11875 m. At the highest flight level of 12486 m stratospheric air masses (50 ppbv CO) with no considerable CO variation were measured. On the other hand areas with highly enhanced CO concentration up to 125 ppbv and lower potential temperature indicate that at these sites tropospheric air must have been transported into this flight level. This is a first indication of extensive vertical air mass transport.

From the 1 Hz CO data and the vertical winds we have determined the vertical flux of CO given by $\overline{q'_{\mathrm{CO}} w'}$, where q'_{CO} and w' are the deviations of the CO concentrations and the winds, respectively, from a running mean calculated over 40 km (Figure 6). The smallest scale detectable is $\approx$2000 m which is given by the instrumental noise and the speed of the aircraft. Simple model calculations show that a linear mountain wave with parameters similar to those obtained during the flight will not produce any flux. Even if we take into account a non-linear CO altitude gradient in the tropopause region the resulting flux for a linear mountain wave would be more than an order of magnitude smaller than actually observed. We suppose that non-linear processes in the mountain wave must have produced the observed flux.

Figure 6 shows positive fluxes above the mountain ridge, i.e., CO rich tropospheric air is transported into the lower stratosphere above the flight track, and/ or CO poor stratospheric air is transported into the upper troposphere below the flight track. From this, it is not possible to decide whether the flux is from the troposphere to the stratosphere or vice versa. However the enhanced CO concentration in the stratospheric level (see above) indicates that transport in the stratosphere has taken place. A cospectral analysis of the tracer flux shows maximum values in the dominant wavelength mode around 15 km wavelength (Figure 7). The total flux is ~10.5 ppbv m/s integrated over all wavelengths for the region of maximum flux (~ 19.5°E). Taking into account the vertical gradient $\partial\overline{q}/\partial z$ of the mean carbon monoxide concentration $\overline{q}$ we have estimated the vertical exchange coefficient K_q from $\overline{w'q'} = -K_q \frac{\partial \overline{q}}{\partial z}$.

The mean vertical gradient at 11875 m deduced for an altitude region of ±500m is on the order of -6 to $-9 \cdot 10^{-2}$ ppbv/m. From this we arrive at an upper limit for

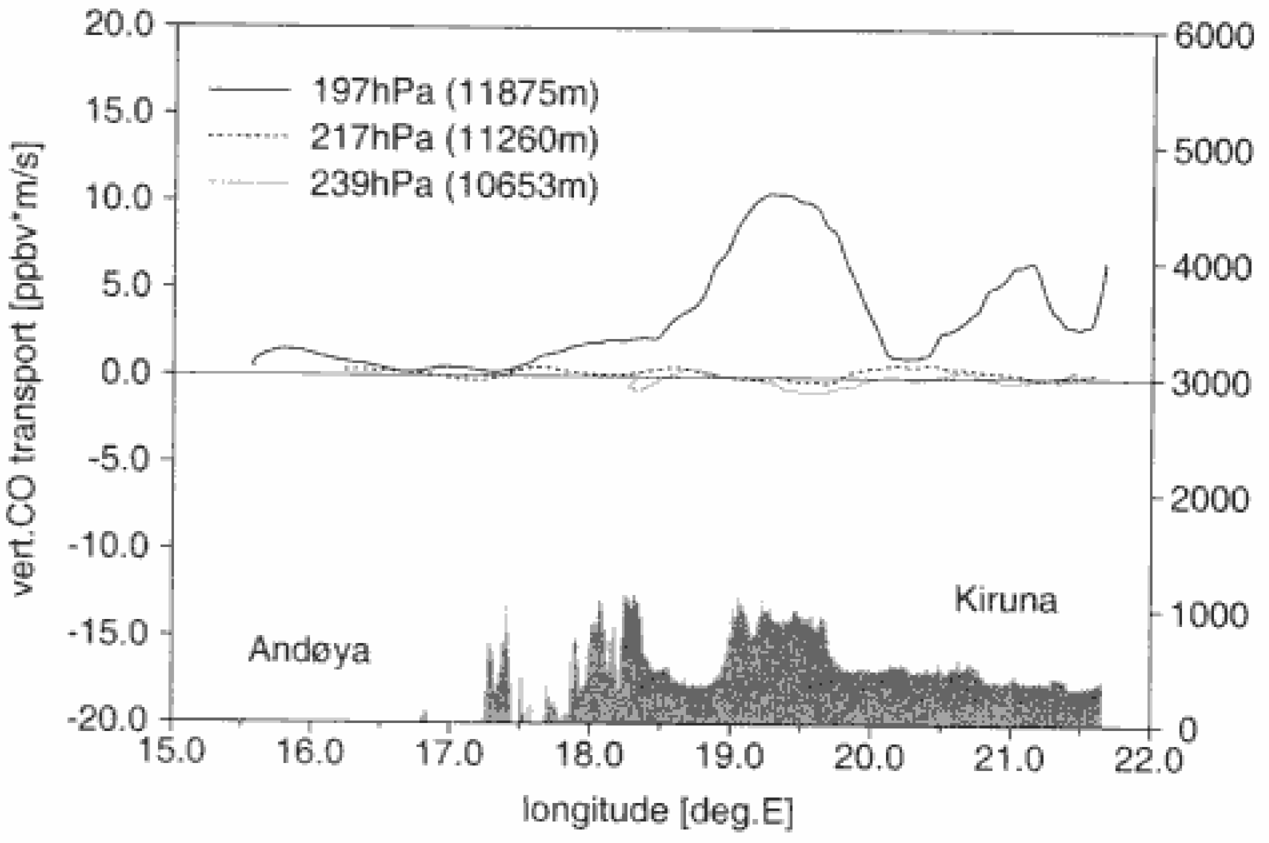

Figure 6. Vertical flux of CO versus longitude obtained on the northern flight track for scales less than 40 km.

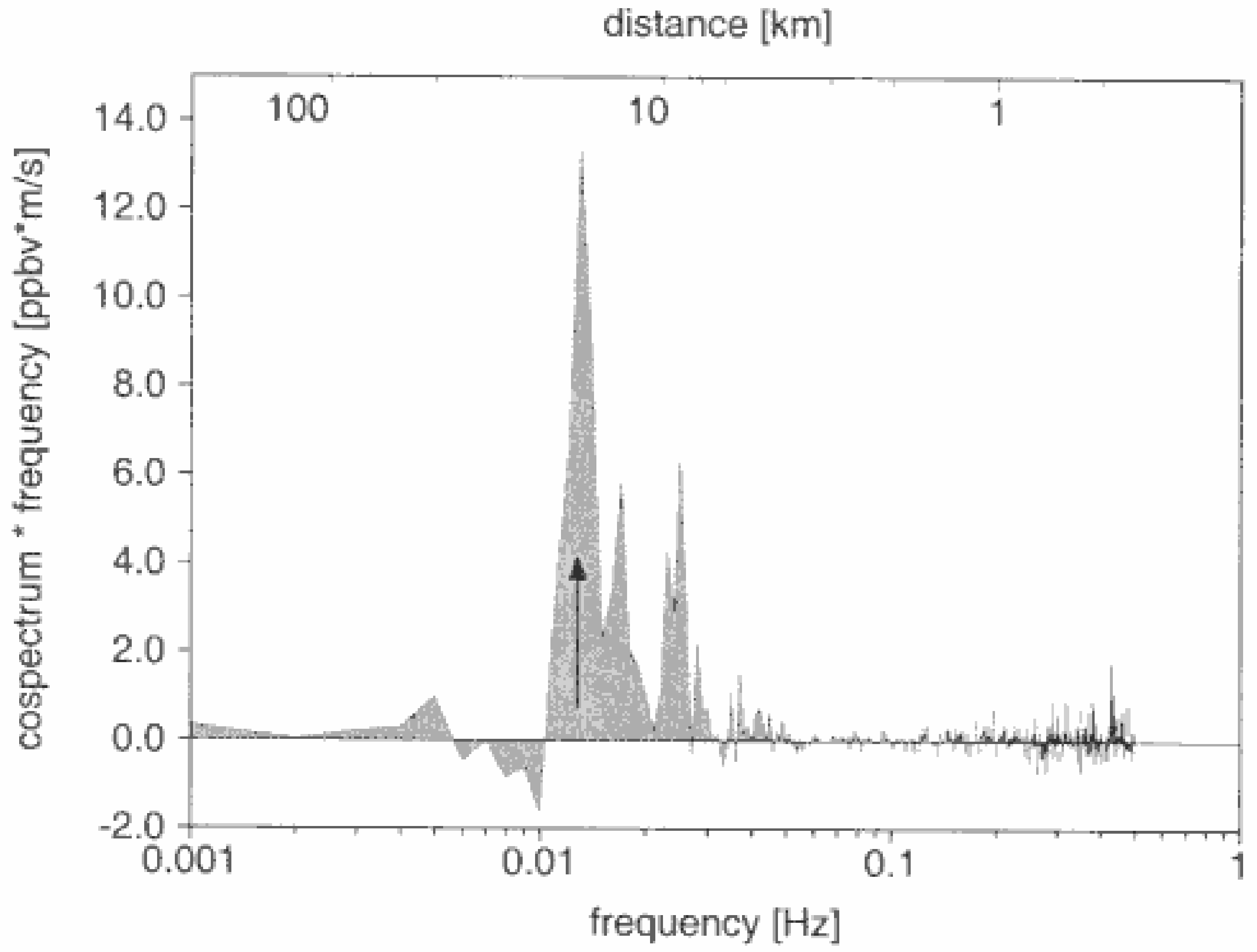

Figure 7. Frequency multiplied cospectrum of vertical wind w and CO for the northern flight track at 11875 m altitude.

a vertical exchange coefficient of 115–175 m^2/s. This value is two times larger than typical values obtained in tropopause folds by a comparable calculation [*Shapiro*, 1980]. This difference is accompanied by rather large displacement heights deduced from our data set (600 m; see above) compared to typical values derived from measurements within tropopause folds (from Figure 6 in *Shapiro*, 1980, we estimate $\Delta h = 250$ m). Our exchange coefficient is also significantly larger than values used in models (1–30 m^2/s , see *Reiter*, 1975). Apart from statistical fluctuations this difference could be systematic since our measurements were performed in a specific meteorological situation with mountain waves with a broad spectrum of horizontal scales, whereas model values apply to mean conditions averaged over large spatial and temporal scales.

Since we would not expect a net transport by an undisturbed linear wave we conclude that nonlinear effects associated with instabilities in the wave must have caused the observed flux. Stability analysis (not shown here) based on an one-dimensional mountain wave parameterization according to *Bacmeister* (1994) showed that wave breaking and convective overturning due to instable air masses were very likely in the investigated region during our flight. Therefore the coincidence of critical levels and a vertical tracer gradient can produce substantial tracer fluxes. If this criterion is met at the tropopause mountain wave activity with large vertical air parcel displacement and associated small scale mixing processes can be an important stratospheric/tropospheric exchange process.

Finally we note that our measurements do not allow for an unambiguous detection of stationary and isotropic three-dimensional turbulence since the temporal resolution of our instrument is not sufficient to detect spatial scales expected in the inertial subrange of turbulence (typically from some centimeters to a few tens of meters). We have analyzed the fluctuations of CO concentrations, temperatures, horizontal and vertical winds, and found a wavenumber dependence of power spectral densities proportional to k^{-3}. This indicates that these fluctuations are located in the so called buoyancy subrange of turbulence which adjoins the inertial subrange at larger scales.

Conclusions

We have observed wave-like CO and temperature fluctuations with amplitudes of 50-70 ppbv and 3-7 K respectively and wavelengths of $\approx$ 15 km in the height interval between 10.6 and 12.5 km altitude. These observations can be explained by vertically propagating mountain waves above the Scandinavian mountain ridge. From the CO and the vertical wind data a maximum vertical flux of 10.5 ppbv m/s near the tropopause during the wave events was calculated. The vertical transport reaches values which are comparable to or even larger than fluxes associated with tropopause folds. We conclude that mountain waves may play an important role in the transport of trace gases between the troposphere and the stratosphere.

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