30 years Montreal Protocol, 50 years ozone measurements at Hohenpeißenberg

30 years ago, on September 16th 1987, 24 states and the EEU (the predecessor of the EU) signed a protocol in Montreal, Canada, to ban ozone depleting substances (ODS). Over time, this protocol has been ratified by all 197 states on Earth. The Montreal Protocol is the prime example for a successful international treaty protecting our environment. Thanks to the protocol (and its later amendments), production and consumption of ozone depleting substances (ODS) ended in the 1990s. Since the late 1990s, the stratospheric concentrations of harmful chlorine and bromine have been declining slowly. Imminent destruction of our vital ozone layer was avoided. In its last amendment in October 2016, the protocol was expanded in Kigali, Ruanda, by a ban on climate damaging hydro-fluoro-carbons (HFCs).

50 years ago, two decades before the Montreal protocol, a comprehensive ozone measurement program started at Hohenpeißenberg: Regular balloon ozone sondes were flown since November 1966 (compare Fig.1 or bulletin #133). Total ozone columns have been measured since late 1967 / early 1968 by a Dobson spectrometer, since 1984 also by an automatic Brewer spectrometer. In September 1987, a laser-radar (=lidar) was added to measure the ozone profile in the upper stratosphere. Only a few stations world-wide have such a long and comprehensive ozone program!

Trend analysis of the Hohenpeißenberg total ozone record in Fig. 2 (green line) very clearly demonstrates how the ozone layer reacts to the anthropogenic changes of stratospheric chlorine and bromine due to ODS (magenta line): Substantial ozone decline was caused by increasing chlorine and bromine from the end of the 1960s until the mid-1990s. Thanks to the Montreal Protocol, this decline has stopped. Since about 2000, chlorine and bromine concentrations have been de-

Figure 1: Left: Ozone sounding in the late 1960s. Note the tent used for filling the balloon. Middle, top: Brewer spectrometer in front of the Alps (total ozone measurements since 1984). Middle, bottom: Dobson spectrometer (total ozone measurements since late 1967). Right: Lidar to measure ozone profiles (since 1987).
creasing slowly. Ozone has reacted with a positive tendency and slightly increasing values (right part of green line in Fig. 2). Of course, other factors also play a role, for example, the 11-year solar cycle, enhanced aerosol from volcanic eruptions, or long-lasting tropospheric circulation patterns (see bulletins #123, 127).

Model-simulations for the future (Fig. 3) indicate that substantial recovery of the ozone layer, to values like in the 1960s, can only be expected after 2050. This is due to the long lifetime of most ODS. In the second half of the century, nitrous oxide (N₂O), methane (CH₄) and CO₂ will become increasingly important. Large future increases of non-regulated short-lived ODS, e.g. dichloromethane, might delay the expected ozone recovery. In addition, feedbacks and interactions between climate change and the ozone layer will become more intense, and more important.

Figs. 2 and 3 show quite clearly that we are only at the beginning of ozone recovery. In the past, ODS have played the main role. In the future we will have to monitor more influences and more substances. The complexity of the system will probably increase, not decrease. Nevertheless, we should be optimistic – like Hohenpeissenberg ozone groups in Fig. 4, in the past and in the present.

**Figure 2**: Annual mean total ozone columns above Hohenpeissenberg (HPB) since 1968 (blue dots). Ozone trend, with change of trend in 1997 (green line, from multiple linear regression). Chlorine and bromine content of the stratosphere (magenta line, reverse scale on the right).

**Figure 3**: Model simulations of global ozone columns in the future. Black: Baseline, considering all changes. Magenta: Only chlorine and bromine (ODS) are changed, CO₂, CH₄ and N₂O fixed at 1960 levels. Red: Only CO₂ is changed, rest as in 1960. Orange: only CH₄ changed. Green: only N₂O changed. Blue: Annual mean total ozone above Hohenpeissenberg (for comparison, scaled, same data as in Fig. 1). Adapted from Fleming et al., ACP, 2011.

http://www.dwd.de/ozon
Figure 4: Top: Ozone group in summer 1987 after test flights with the University of Bonn chemoluminescence sonde. Back, from left: Dr. K. Wege, U. Faßbender, H. Barnsteiner, H. Claude, F. Schönenborn, R. Hartmannsgruber, S. Steiner. Front, from left: S. Sahand, W. Speuser. 1 = University Bonn.