**WMO GAW Greenhouse Gases:**

The WMO GAW long-lived greenhouse gas (LLGHG) measurement community is largely a research community. High-quality measurements of LLGHGs and related tracers are made to quantify LLGHG trends as input to calculations of changing radiative forcing, to constrain global and large scale budgets, and to leverage spatial patterns in the observations to infer emissions at regional to continental scales. GAW provides a framework to ensure the quality of these measurements though:

● meetings of measurement experts every two years

● detailed recommendations on measurement compatibility selected to meet scientific requirements

● publication of measurement guidelines

An important aspect of the GAW framework is that all GAW GHG participants are asked to use standards to calibrate their analytical instruments that are derived from Central Calibration Laboratories (CCLs) that maintain common standard scales. Figure 1 shows histograms of repeated measurements of (a) CO2, (b) CH4, (c) N2O, and (d) SF6 by the respective CCLs covering a wide range in gas mole fractions centered on ambient values. Ordinate axis shows number of observations and abscissa shows differences between initial and subsequent calibrations. Other central facilities help insure quality of measurements through standard and measurement comparisons, and through site audits.

GAW networks for measurements of essential climate variables CO2, CH4, and N2O are part of the GCOS (Global Climate Observing System) Global Baseline Observing Network and the Global Comprehensive Observing Network (see map and photos of GAW sites). While these GCOS networks normally fall within operational regimes of the agencies involved, GAW GHG observations are driven almost entirely by research needs. LLGHGs are the main drivers of climate change, and long-term GAW observations, shown in Figure 2, are used to calculate radiative forcing as shown in Figure 3. Since 1990, CO2 is the largest contributor to the increase in RF contributing 80%. It is followed by N2O at 7.5%, replacements of ozone depleting substances at 6.5%, and CH4 at 5%. Despite their declining atmospheric abundances, the sum of the RF from CFC-11 and CFC-12 has increased by 1% since 1990.

Measurements of GHGs by GAW members can be used in a mass-balance to provide an important constraint on global emissions when a lifetime can be defined. This approach is not as effective for atmospheric CO2, which rapidly exchanges with the terrestrial biosphere and surface ocean. But for gases that are predominantly removed by atmospheric chemistry (e.g., reaction with OH and photolysis), knowledge of their lifetimes can be used to estimate emissions. A simple example is sulfur hexafluoride (SF6), which is destroyed predominantly by photolysis and reactions with electrons in the mesosphere and has an estimated atmospheric lifetime of 3200 years. With the long lifetime, the atmospheric rate of increase is directly related to emissions and can be used to verify emissions inventories. Using atmospheric measurements, Levin et al. (2010) showed that emissions reported to the UN Framework Convention on Climate change were underestimated by 70 to 80% (Figure 4). Developed nations (Annex I, in essence) are significantly underestimating their emissions. This emphasizes the need for estimates of emissions to be verified by direct atmospheric measurements (Nisbet and Weiss, 2010).

Because atmospheric mixing is not instantaneous, the observed spatial patterns in LLGHGs can be combined with a chemical transport model (CTM) to estimate emissions at continental to country scales. The quality of the emissions estimates depends on the compatibility (internal-consistency) of the measurements used. Artificial gradients resulting from some laboratories using different standards than others will result in errors in emissions. This is especially true for N2O, which has relatively small, very diffuse emissions and a 130 year lifetime. The pole to pole gradient at background sites for N2O is ~1.4 ppb. With traditional analytical methods of gas chromatography with doped-electron capture detection of N2O, meeting the intra-network compatibility target is extremely difficult. To compensate for this in CTM studies of N2O emissions, biases are removed based on comparisons of measurements arranged between measurement programs. Thompson et al. (2014) used data from GAW partners and contributors to estimate global fluxes. Fluxes calculated by the model are shown in Figure 5 in g m-2 yr-1 N. The largest source of N2O is from natural and fertilized soils, and the flux map reflects that. Similar studies have estimated emissions of CH4 and other LLGHGs.

Further importance of GAW’s long-term high-quality LLGHG measurements is seen in the time series for CH4 in Figure 2b. Stabilization of the global atmospheric CH4 burden from 1999 to 2006 was unexpected. It was in contrast to what bottom-up inventories were saying, which indicated that emissions were increasing. While the specific changes to methane’s global budget of emissions and sinks responsible for this stabilization are still under discussion, without high-quality GAW measurements from a globally distributed network of air sampling sites, we may have missed this unexpected surprise. In the future, as climate continues to warm and ecosystems respond, the GAW LLGHG measurement community will be closely watching for the next surprise.