WMO’s Global Atmosphere Watch (GAW) programme coordinates climate-quality atmospheric measurements of long-lived greenhouse gases (LLGHG) and related tracers. These gases, chief among them being CO₂, CH₄, N₂O, and CFC refrigerants, are the main anthropogenic drivers of climate change. Increasing atmospheric burdens of LLGHGs are committing society to a dramatically changing world. Impacts include a warmer and wetter atmosphere; changes to precipitation patterns; warmer, rising, and more acidic oceans; decreased land and ocean ice; and changes to natural cycling of CO₂, CH₄, and N₂O by the terrestrial biosphere. In 2015, LLGHGs have altered Earth’s energy balance by 2.97 W m⁻² compared to 1750.

In the mid-1950s, scientific literature indicated that atmospheric CO₂ was about 0.03% (mole fraction) and highly variable. This assessment was based on an imprecise and potentially inaccurate chemical method to determine CO₂ in air and with little regard for the potential impacts of sampling location on the air sample. Investigating this common perception, C.D. Keeling developed a manometric method to accurately determine the CO₂ dry-air mole fraction in discrete samples of atmospheric air. He found that under certain meteorological conditions, atmospheric CO₂ abundance in oceanic air was rather constant at 310 ppm, but it did vary diurnally when near vegetation and significantly in cities. Additional measurements of a related tracer, δ¹³C-CO₂, in some of the same air samples measured for CO₂ helped Keeling understand the effect of local vegetation on atmospheric CO₂. In 1958, as part of the International Geophysical Year (IGY), Keeling began the first systematic measurements of CO₂ at background observatories, on ships, and on aircraft using a non-dispersive infrared (NDIR) analyzer. These measurements were complemented by measurements of CO₂ in discrete air samples from additional locations to give a snapshot of CO₂ in the background atmosphere. This IGY CO₂ measurement program, the predecessor to WMO GAW, was the beginning of LLGHG monitoring at the global scale. Keeling understood the importance of ensuring accuracy in the measurements, so he used the absolute manometric method he developed to measure CO₂ in discrete samples to prepare accurate standards that were used to calibrate NDIR systems.

In response to increasing environmental concerns from industrialization, WMO initiated the Background Air Pollution Monitoring Network (BAPMoN) program in 1968 to coordinate atmospheric measurements of a variety of species, including those that destroy stratospheric ozone (many of them are also strong GHGs) and affect Earth’s climate. In 1975, WMO co-
sponsored the first meeting of CO2 measurement experts at Scripps Institution of Oceanography (SIO) to provide guidance to WMO members on making high-quality measurements of atmospheric CO2, including calibration, measurement site location, air sampling protocols, and data management and reporting. (So called “experts meetings”, where participants in the measurement network discuss technical details of all aspects of LLGHG measurements, continue today with a meeting every other year. BAPMoN was merged with the Global Ozone Observing Network to form GAW in 1989.) Recognizing the small spatial and temporal variations in observed atmospheric CO2, attendees appointed SIO as Central CO2 Laboratory, CCL (“CCL” is now used more generally within GAW to refer to “Central Calibration Laboratory”, and it applies to a range of parameters). Scientists present at this meeting recognized that a common standard scale could be propagated with less uncertainty than they could be prepared by individual laboratories, so it was recommended that all laboratories participating in CO2 measurements obtain CO2 standards from SIO. This strategy of a stable common scale, internally consistent over a range of CO2 mole fractions and decades in time, was critical to meeting the scientific requirements for measurements of CO2 across BAPMoN. And it is still the foundation of GAW’s quality assurance system.

Since the early standards produced by SIO for CO2, many advances have been made. The original standards were CO2 in N2 until a “matrix effect” was realized. Differences in pressure broadening of CO2 absorption lines in NDIR analyzers between N2 and air (~78% N2, 21% O2, and 1% Ar) resulted in biased CO2 measurements. Matrix effects are also important with chromatographic measurement methods, so modern standards contain all species that could affect a measurement. The manometric method is still used to maintain primary CO2 standards within WMO GAW, but technological advances have lowered the uncertainty on absolute calibrations. Digital pressure sensors are now used in place of the mercury manometer used by SIO. In combination with other smaller changes, uncertainties on individual CO2 calibrations are about a factor of 5 smaller now than in the 1970s allowing faster and more accurate detection of drift in the scale. For other species whose primary standards are prepared with gravimetric methods, auto-calibrating balances and other smaller improvements have resulted in at least a factor of 2 lower uncertainty.

GAW participants have embraced new technologies to improve the quality of observations. For example, analog signals from NDIR analyzers were originally recorded on strip-chart recorders; voltages were then measured manually and recorded. This limited repeatability of measurements to ±0.2 ppm. Replacement of strip chart recorders with analog to digital converters improved repeatability to a few hundredths of a ppm. Similar improvements were made with devices to integrate chromatographic peaks. Instrumentation, from NDIRs to mass spectrometers commonly used for low abundance compounds like HFCs and HCFCs, gradually improved over time, too. In the past decade, measurement technologies for the most important LLGHGs (CO2, CH4, and N2O) have shifted from those developed in the mid-20th century to new laser-based optical sensors using cavity-enhanced absorption spectroscopy. These new analyzers still require
standards provided by a GAW Central Calibration Laboratory to ensure observed small spatial and temporal gradients measured across national networks are real and not measurement artefacts, but their stability and low power requirements make new measurement platforms more accessible.

Along with changes in measurement technology have been changes in sampling network strategy. Historically, GAW participants were interested in monitoring trends in LLGHGs in the background atmosphere. Such measurements were used to understand the causes of seasonal and interannual variability in LLGHG growth rates, and to determine their contribution to changes in Earth’s climate forcing. In the early 1990s, scientific focus shifted to determining budgets of emissions and sinks from atmospheric measurements. To support this new focus, GAW’s network strategy has evolved to include observations from continents, particularly from tall towers (> 200 m above ground level) and vertical profiles from aircraft. More recently, to meet policy needs of quantifying emissions at national or smaller scales, the density of observations has increased further. In the past decade, GAW participants have greatly expanded quasi-continuous measurements from continental sites, from remote sites, from ships, and from commercial aircraft. These changes have been facilitated by the new commercially available measurement technologies that allow much easier unattended operation of instruments and far less frequent calibration than in the past.

Significant holes still exist in the in situ observation network. With that in mind, GAW also supports the development of techniques for retrieving LLGHG column-averaged mole fractions from radiances measured from space, recognizing that high-quality in situ measurements by GAW participants are important to this process.

Keeling’s measurements of the isotopic composition of CO2 showed the power of using complementary tracers to inform us on the science of LLGHGs. Despite the difficulty in making measurements for many of these species to levels of quality scientifically necessary, GAW participants have continued to pursue new tracers. Measurements of the isotopic composition of atmospheric CH4 help constrain its budget of emissions and sinks, and how that budget changes with time. Measurements of parts-per-million changes in the atmospheric ratio of O2/N2 provide quantitative information on the relative strengths of the oceans and terrestrial biosphere as sinks for CO2 from fossil fuel combustion. Measurements of other species are exploited to test meteorology in chemical transport models and as tracers for specific processes that emit LLGHGs.

For nearly 60 years, the WMO GHG measurement community has been a community of scientific researchers who use their observations in their own scientific studies. They’ve embraced new technologies for measurements, identified new complementary tracers to improve understanding of LLGHG cycling, and adapted strategies for sampling networks to meet evolving scientific and policy needs.