GREENHOUSE GASES GLOBAL MONITORING SYSTEMS: ECOLOGICAL AND METROLOGICAL ASPECTS

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Abstract – Ecological and metrological aspects of greenhouse gases global monitoring systems are considered. The possibilities and features of the calibration of measuring equipment for the global monitoring systems are selected. The analysis results of international comparisons of national standards and calibration capabilities of national metrology institutes for greenhouse gases are reduced.

Keywords: measurement, greenhouse gases, climate change.

1. INTRODUCTION

Climate change (CC) can be driven by changes in the Earth's atmospheric concentrations of a number of radiatively active gases and aerosols. The increased concentrations of key greenhouse gases (GHGs) are a direct consequence of human activities. Naturally occurring GHGs include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and troposphere ozone (O_3). Tropospheric ozone is formed by two precursor pollutants, nonmethane volatile organic compounds (NMVOCs) and nitrogen oxides (NO_x) in the presence of ultraviolet light.

The U.N. Framework Convention on Climate Change (UNFCCC) sets an overall framework for intergovernmental efforts to tackle the challenge posed by CC. It recognizes that the climate system is a shared resource whose stability can be affected by industrial and other emissions of carbon dioxide and other GHGs.

The UNFCCC ultimate objective is to stabilize GHGs concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. This would require significant reductions in global GHGs emissions. Parties of the UNFCCC must estimate GHGs anthropogenic emissions and to develop annual national GHG inventories.

Intergovernmental Panel on Climate Change (IPCC) developed special guide IPCC 2006 [1] for assists in compiling complete national GHGs inventories. This guide is based on the assumption that all carbon burned as fuels is emitted mostly as CO_2, N_2O, CH_4, CO and NMVOCs except for the unoxidized fraction which remains as ash or soot. CO and NMVOCs are eventually oxidized to CO_2 in the Earth's atmosphere.

For evaluation of the GHGs emissions should be considered not only ecological aspects [2], but also metrological aspects. This will allow improving the reliability of these evaluations.

2. ECOLOGICAL ASPECT

2.1. Basic provisions

Table 1 illustrates the average gaseous composition of dry air of Earth's atmosphere [3–5].

TABLE 1 Composition of dry air of Earth's atmosphere

GHG	Volume
Nitrogen (N_2)	780,840 ppmv (78.084 %)
Carbon dioxide (CO_2)	390 ppmv (0.039 %)
Methane (CH_4)	1.79 ppmv (0.000179 %)
Nitrous oxide (N_2O)	0.3 ppmv (0.00003 %)
Carbon monoxide (CO)	0.1 ppmv (0.00001 %)
Nitrogen dioxide (NO_2)	0.02 ppmv (2×10^{-6} %) (0.000002 %)
ppmv: parts per million (10^6) by volume	

Accompanying the increasing concentrations of GHGs in the Earth's atmosphere has been an increase in greenhouse radiative forcing (enhanced greenhouse effect) due to the enhanced absorption of terrestrial infrared radiation. The 2007 Fourth Assessment Report compiled by the IPCC (AR4) [3] concluded that increases in anthropogenic GHGs concentrations is very likely to have caused most of (more than 50 %) the increases in global average temperatures since the mid-20th century.

Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years. Table 2 illustrates pre-industrial and current levels of GHGs in Earth's atmosphere [3–6].

TABLE 2 Levels of GHGs in Earth's atmosphere

GHG	Pre-industrial level (1750)	Current level (2009)	Increase, %
Carbon dioxide (CO_2)	280 ppm	386.8 ppm	38
Methane (CH_4)	700 ppb	1803 ppb	158
Nitrous oxide (N_2O)	270 ppb	322.5 ppb	19
ppb: number of molecules of the gas per billion (10^9) molecules of dry air			

Some impacts of the increased GHGs concentrations may be slow to become apparent since inertia is an inherent characteristic of the interacting CC, ecological, and socio-economic systems.

Carbon dioxide is a chemical compound composed of two oxygen atoms covalently bonded to a single carbon atom. It is a gas at standard temperature and pressure and exists in Earth's atmosphere in this state. The abundance of carbon dioxide in the Earth's atmosphere in 2009 was 386.8 ppm, up from 280 ppm in 1750 (increasing on 38 %) [6].

Carbon dioxide is the single most important anthropogenic GHG in the atmosphere, contributing 63.54 % to the overall global radiative forcing. It is responsible for 85 % of the increase in radiative forcing over the past decade.

Methane is a relatively potent GHG and contributes 18.1 % to the overall global radiative forcing. Compared with carbon dioxide, it has a high global warming potential of 72 (calculated over a period of 20 years) [3]. The abundance of methane in the Earth's atmosphere in 2009 was 1803 ppb, up from 700 ppb in 1750 (increasing on 158 %) [6].

Nitrous oxide (oxide of nitrogen) is a chemical compound with the formula N_2O. It is also a major GHG and air pollutant. Considered over a 100 year period, it has 298 times more impact per unit weight than carbon dioxide [3]. The abundance of nitrous oxide in the Earth's atmosphere in 2009 was 322.5 ppb, up from 270 ppb in 1750 (increasing on 19 %) [6].

Nitrous oxide contributes 6.24 % to the overall global radiative forcing. Anthropogenic sources may account for approximately 40 % of total nitrous oxide emissions. It is removed from the atmosphere by photochemical processes in the stratosphere.

Carbon monoxide has an indirect radiative forcing effect by elevating concentrations of methane and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical, OH) that would otherwise assist in destroying methane and tropospheric ozone.

Carbon monoxide, also called carbonous oxide, is created when carbon-containing fuels are burned incompletely. Through natural processes in the atmosphere, it is eventually oxidized to carbon dioxide. Carbon monoxide is present in small amounts in the atmosphere, but it is concentrations are both short-lived in the atmosphere and spatially variable.

The primary CC effects of nitrogen oxides (i.e., NO and NO_2) are indirect and result from their role in promoting the formation of ozone in the troposphere and, to a lesser degree, lower stratosphere, where it has positive radiative forcing effects. Additionally, NO_x emissions from aircraft are also likely to decrease methane concentrations, thus having a negative radiative forcing effect. Concentrations of NO_x are both relatively short-lived in the atmosphere and spatially variable.

Nitrogen dioxide is the chemical compound with the formula NO_2. One of several nitrogen oxides, NO_2 is an intermediate in the industrial synthesis of nitric acid, millions of tons of which are produced each year [5, 6].

2.2. Global GHGs monitoring systems

The Global Atmosphere Watch Programme (GAW) of World Meteorological Organization (WMO) [2, 7] coordinates global atmospheric chemistry observations, analysis and scientific assessments related to the changing composition of the Earth's atmosphere and its effects on weather, CC, water and the environment.

GAW is the lead programme for implementing recommendations of the Global Climate Observing System (GCOS) on the essential climate variables (GHGs, ozone and aerosols). It is a major contributor to the Global Earth Observation System of Systems (GEOSS) coordinating integrated global atmospheric chemistry observations and research for GHG, ozone, aerosols, reactive gases and precipitation chemistry.

Global observations are archived and made available by GAW World Data Centres (WDCs). The purpose of the WDCs is to collect and archive processed GAW data, to make them publicly available, and to provide support in the quality assurance, analysis and interpretation of these data for scientific advances and policy decisions.

A network of measurement stations is the backbone of the GAW. This network consists of GAW Global and Regional measurement stations with additional measurements from Contributing stations. Both Global and Regional stations are operated by their host countries, either by their National Meteorological Services or by other national scientific organizations. More than 80 countries actively host GAW stations. As of 2009, GAW coordinates activities and data from 26 Global stations, 410 Regional stations, and 81 Contributing stations [7].

The WDC for Greenhouse Gases (WDCGG), as one of the WDCs under the GAW, has been operating at the Japan Meteorological Agency (JMA). Under agreement with the GCOS recognizing the GAW global atmospheric CO_2 and CH_4 monitoring network as a comprehensive network of GCOS, the WDCGG is charged with providing data and other services, as well as supplying value-added products to support GCOS and the UNFCCC.

WDCGG collects and distributes data on the mixing ratios of GHGs (CO_2, CH_4, N_2O, etc.) and related reactive (CO, NO_x, VOC, etc.) gases in the atmosphere and the ocean. As of 2008, 252 stations from 57 countries submitted observational data for 34 species of greenhouse and related gases to the WDCGG. The WDCGG periodically publishes WMO WDCGG Data Summary, which includes averaged results from the past and present conditions on regional, and global scales [7].

The GAW coordinates systematic observations and analysis of atmospheric composition, including GHGs and other trace species. The rest of the GAW network is maintained by Australia, Canada, China, Japan and many European countries. The measurement data are reported by participating countries and archived and distributed by the WDCGG. WMO publishes a WMO Greenhouse Gas Bulletin annually to report on the atmospheric burdens of the most influential GHGs – CO_2, CH_4 and N_2O – based on observation data from contributing stations of the GAW. The WDCGG takes charge of data analysis to contribute to the preparation of this Bulletin [6, 7].

Five types of central facilities dedicated to six groups of measurement variables are operated by WMO Members and form the basis of quality assurance and data archiving for the GAW global monitoring networks. They include Central Calibration Laboratories (CCLs) that host 16 primary standards, World Calibration Centres (WCCs), Regional Calibration Centres (RCCs), Quality Assurance/Science Activity Centres (QA/SACs), and WDCs. GAW WCCs or RCCs are operated by institutions participating in the GAW programme [7].

The principles of the GAW QA system include, specifically: network-wide use of only one reference standard or scale (only one institution that is responsible for primary standard); full traceability to the primary standard of all measurements made by global, regional and contributing GAW stations; establishment of guidelines on harmonized measurement techniques based on measurement guidelines (MGs) and standard operating procedures (SOPs) for these measurements; use of detailed log books for each parameter containing comprehensive meta information related to the measurements, maintenance, and internal calibrations, etc.

Block diagram of the calibration of measuring equipments for GAW stations is shown on Figure 1. Metrological traceability of primary standards provides national metrological institutes (NMIs), International Bureau of Weights and Measures (BIPM), CCLs, WCCs, and RCCs.

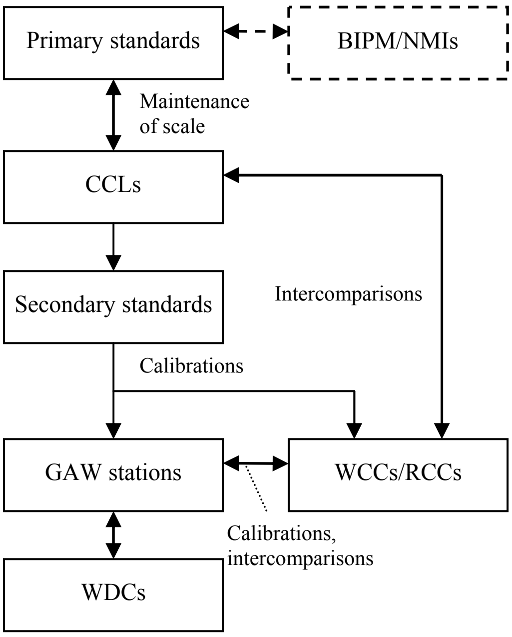

Fig. 1. Block diagram of the calibration of measuring equipments for GAW stations

The main tasks of WCCs and RCCs as outlined in are: develop quality control procedures and SOPs for traceability of measurements to the reference standards; maintain laboratory and transfer standards that are traceable to the reference standards; perform regular calibrations and audits at GAW sites, etc. Reference standards designated for each species to be used for all GAW measurements of that species [7].

The following WCCs and RCCs have been established and recognized for specific parameters:

WCC for carbon dioxide measurements – NOAA/ CMDL, Boulder, CA USA;

WCC for methane in Asia and the South-West Pacific – JMA, Tokyo, Japan;

WCC for Surface Ozone, carbon monoxide and methane – Swiss Federal Laboratories for Materials Testing and Research (EMPA), Dübendorf, Switzerland;

WCC for nitrous oxide and NMVOCs – Forschungs-zentrum Karlsruhe, Institute for Meteorology and Climate Research (IMK-IFU), Garmisch-Partenkirchen, Germany;

The Center for Global Environmental Research (CGER) is the core organization for research on climate change at the Japan National Institute for Environmental Studies (NIES). CGER has been establishing series of NIES standards for GHGs. In Table 3 using measurement methods of GHGs and NIES scales are shown [2, 8, 9].

TABLE 3 Measurement methods of GHG and NIES scales

Measurement methods	GHG	NIES Scale	Range
Non-depressive infrared analyser	CO_2	NIES-95, NIES-00	320–390 ppm (95)
Gas chromatograph equipped	CH_4 N_2O CO NO	NIES-94 NIES-96 96Wk, NIES-98 Under prepara-tion	1.2–2.5 ppm 250–400 ppm 70–350 ppm 0–200 ppm

3. METROLOGICAL ASPECT

3.1. Basic provisions

Confidence in measurements is an essential prerequisite to international activity in many fields. To a large extent this confidence already exists and is based on the SI, which is the cornerstone of the international measurement system, as realized by the NMIs.

The directors of the NMIs of Member States of the BIPM signed a Mutual Recognition Arrangement (CIPM MRA) [10, 11] for national measurement standards and for calibration and measurement certificates issued by NMIs.

This is an arrangement between NMIs which specifies terms for the mutual recognition of national measurement standards and for recognition of the validity of calibration and measurement certificates issued by NMIs.

The technical basis of CIPM MRA is the set of results obtained in the course of time through key comparisons (KC) carried out by the Consultative Committees (CC) of the CIPM, the BIPM and the regional metrology organizations (RMOs), and published by the BIPM and maintained in the KC database [11].

A Joint Committee of the RMOs and the BIPM (JCRB), created by the CIPM, is responsible for the coordination of data provided by the RMOs, and other actions undertaken by them to promote confidence in calibration and measurement certificates.

Participation in a CIPM KCs is open to laboratories having the highest technical competence and experience, normally the member laboratories of the appropriate CC. Those laboratories that are not members of a Consultative Participation in KCs organized by an RMO is open to all RMO members and to other institutes that meet the rules of the regional organization and that have technical competence appropriate to the particular comparison.

3.2. Key comparisons of national standards and CMCs of NMIs for GHGs

Under the MRA, information on CIPM and RMOs KCs, together with results interpreted in terms of equivalence specified in Appendix B of Key Comparison Data Base (KCDB) of the BIPM [11].

Results of KCs of national measurement standards for GHGs (CO_2, N_2O, CO and NO_x) are shown on Table 4. Those KCs were carried out in 1993–2010's advisory CC for Amount of Substance (CCQM) of CIPM and three RMOs (EURAMET – European Association of NMIs, APMP – Asia Pacific Metrology Programme, COOMET – Euro-Asian Cooperation of National Metrological Institutions) for some nominal values of gases [11–21].

In most KCs was attended by such NMI: NPL, NMi (EURAMET), NIST (SIM – Inter-American Metrology System), KRISS, NMIJ (APMP) and VNIIM (COOMET, APMP).

Under the MRA, all participating NMIs recognize the validity of each other's calibration and measurement certificates for the quantities, ranges and measurement uncertainties specified in Appendix C of KCDB [11].

Metrology areas for GHGs classified according to the nomenclature of the CCQM as QM/4 – category "Gases" (4) and subcategory "Environmental" (4.2). Total by QM is 4846 CMCs; total by QM/4 – 1824 CMCs (37.6 %) from KCDB on 21.01.2011.

CMCs NMIs for GHGs are shown on Table 5. More than 100 CMCs for QM/4 have the next six countries: Russia (323); Korea (300); United Kingdom (294); The Netherlands (230); Japan (144) and United States (134).

3. CONCLUSION

Global monitoring systems for main greenhouse gases are implemented, which are used calibrated measuring equipment in special calibration centers. Working standards of calibration centers have metrological traceability to primary standards of NMIs.

NMIs participate in international comparisons of their national standards and have the appropriate CMCs for greenhouse gases. NMIs all provide traceability of measuring equipment of calibration centers of global monitoring systems.

REFERENCES

[1] 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme. – Published: *IGES*, Japan, 2006.

[2] Velychko O., Gordiyenko T. New tasks of metrology on global environmental problems // XVIII IMEKO World Congress "Metrology for a Sustainable Development". – Rio de Janeiro, Brazil, 2006 (17–22 September). – CD. – 6 p.

[3] Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. – Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. – *IPCC*, 2007– 996 pp.

[4] http://www.esrl.noaa.gov/

[5] http://www.ace.mmu.ac.uk/

[6] The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2009. *WMO Greenhouse Gas Bulletin*. No. 6: 24 November 2010.

[7] http://www.wmo.int/gaw

[8] http://www.cger.nies.go.jp/en/

[9] Global Environmental Monitoring. – NIES/CGER's Initiative. – *Center for Global Environmental Research*. – 2004. – 38 p.

[10] Mutual recognition of national measurement standards and of calibration and measurement certificated issued by national metrology institutes. – Paris. – *BIPM*. – October 14, 1999.

[11] http://www.bipm.org/en/cipm-mra/

[12] Alink A. The first key comparison of primary standard gas mixtures // *Metrologia*. – 2000. – 37. – Numb. 1. – PP. 35–49.

[13] A van der Veen. CCQM key comparison CCQM-K3 of measurements of CO, CO_2, and C_3H_8 in N_2 // *Metrologia.* – 2002. – 39. – PP. 121–122.

[14] Botha A., Janse van Rensburg M., Tshilongo J., et al. International comparison CCQM-K51: Carbon monoxide (CO) in nitrogen (5 μmol mol^{-1}) // *Metrologia*. – 2010. – 47. – Tech. Suppl., 08008.

[15] Wessel R. M., Adriaan van der Veen M. H., Ziel P. R., et al. International comparison CCQM-K52: Carbon dioxide in synthetic air // *Metrologia*. – 2008. – 45. – Tech. Suppl., 08011.

[16] A van der Veen M. H., Nieuwenkamp G., Oudwater R., et al. Final report of International Comparison EUROMET.QM-K1c: Comparison of measurements of nitrogen monoxide in nitrogen // *Metrologia*. – 2005. – 42. – Tech. Suppl., 08002.

[17] Oh S.-H., Kim B. M., Han Q., Zhou Z. International key comparison APMP.QM-K1.c: Comparison of primary standards of nitrogen monoxide (NO) in nitrogen // *Metrologia*. – 2010. – 47. – Tech. Suppl., 08002.

[18] Konopelko L. A., Kustikov Y. A., Gromova E. V., et al. Final report on International Key Comparison COOMET.QM-K1: Carbon monoxide in nitrogen // *Metrologia*. – 2010. – 47. – Tech. Suppl., 08010.

[19] A van der Veen, J. van Wijk I. T., R. van Otterloo P., et al. EUROMET.QM-K3: automotive emission gas measurements // *Metrologia*. – 2002. – 39. – Tech. Suppl., 08005.

[20] Kim J. S., Moon D. M., Kato K. et al. APMP.QM-K3: automotive emission gas measurements // *Metrologia*. – 2003. – 40. – Tech. Suppl., 08009.

[21] Konopelko L. A., Kustikov Y. A., Kolobova A. V., et al. International Comparison COOMET.QM-K3: National measurement standards in the field of analysis of gas mixtures of CO_2, CO and C_3H_8 in nitrogen (automobile gases) // *Metrologia*. – 2007. – 44. – Tech. Suppl., 08005.

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TABLE 4. Results of KCs of national measurement standards for GHG

GHG	Key comparisons	Nominal value	Results	Years	NMI participant
CO_2	CCQM-K1.b (in N_2)	100 µmol/mol 1000 µmol/mol 150 mmol/mol	KC Reference Value (KCRV): there is no single reference value	1993–1994	**NPL**, **NIST**, **NMi**, BAM, BNM-LNE, **KRISS**, NRLM, NRCCRM, **VNIIM**, OMH (10 NMIs)
	CCQM-K3 (in N_2)	135 mmol/mol	U = 0.0003 mmol/mol	1998–1999	**NPL**, **NIST**, **NMi-VCL**, BAM, LNE, **KRISS**, METAS, **NMIJ**, PTB, SMU, NRCCRM, **VNIIM**, OMH (13 NMIs)
	EURAMET.QM-K3 (in N_2)	135 mmol/mol		2000	SMU, IMGS, IPQ, CSIR-NML, GUM, CMI (6 NMIs)
	APMP.QM-K3 (in N_2)	124 mmol/mol	KCRV: there is no single reference value		**NMIJ**, CSIR-NML, CMS/ITRI, **KRISS** (4 NMIs)
	COOMET.QM-K3 (in N_2)	135 mmol/mol		2005	**VNIIM**, BAM, *UkrCSM*, BelGIM (4 NMIs)
	CCQM-K52	320 µmol/mol		2006	**NMi-VCL**, INMETRO, NMIA, CEM, **NPL**, SMU, **NMIJ**, CERI, CENAM, NMISA, **NIST**, INRIM, NPLI, BAM, **VNIIM**, LNE, NIM, **KRISS** (18 NMIs)
N_2O	CCQM-K68 (in N_2)	320 nmol/mol	Draft B	2008–2009	**KRISS**, NIM, **NIST**, **NMIJ**, **VNIIM**, **VSL** (6 NMIs)
	CCQM-K74 (in N_2)	10 µmol/mol	Draft A	2009–2010	BIPM, BAM, CEM, CERI, FMI, INRIM, **KRISS**, LNE, METAS, NIM, **NIST**, NMIA, **NMIJ**, NMISA, **NPL**, SMU, **VNIIM**, **VSL** (18 NMIs)
CO	CCQM-K1.a (in N_2)	100 µmol/mol 1000 µmol/mol 60 mmol/mol	KCRV: there is no single reference value	1994–1995	**NPL**, **NIST**, **NMi**, BAM, BNM-LNE, **KRISS**, NRLM, NRCCRM, **VNIIM**, OMH (10 NMIs)
	COOMET.QM-K1.a (in N_2)	100 µmol/mol	D = –0.36 µmol/mol U = 0.37 µmol/mol	2007–2008	**VNIIM**, *UkrCSM*, BelGIM, BAM (4 NMIs)
		1000 µmol/mol	D = 1.24 µmol/mol U = 1.59 µmol/mol		
	CCQM-K3 (in N_2)	32 mmol/mol	KCRV: there is no single reference value	1998–1999	**NPL**, **NIST**, **NMi-VCL**, BAM, BNM-LNE, **KRISS**, METAS, **NMIJ**, PTB, SMU, NRCCRM, **VNIIM**, OMH (13 NMIs)
	EURAMET.QM-K3 (in N_2)	32 mmol/mol	U = 0.0003 mmol/mol	2000	SMU, IMGS, IPQ, CSIR-NML, GUM, CMI (6 NMIs)
	APMP.QM-K3 (in N_2)	28 mmol/mol	KCRV: there is no single reference value		**NMIJ**, CSIR-NML, CMS/ITRI, **KRISS** (4 NMIs)
	COOMET.QM-K3 (in N_2)	30 mmol/mol		2005	**VNIIM**, BAM, *UkrCSM*, BelGIM (4 NMIs)
	CCQM-K51 (in N_2)	5 µmol/mol		2008	BAM, CEM, CENAM, CERI, FMI, GUM, INMETRO, IPQ, JRC, **KRISS**, LNE, METAS, NIM, NIMT, **NIST**, NMIA, **NMIJ**, NMISA, **NPL**, NPLI, SMU, UBA(DE), **VNIIM**, **VSL** (24 NMIs)
NO_x	CCQM-K1.c (NO in N_2)	100 µmol/mol 1000 µmol/mol	KCRV: there is no single reference value	1995–1996	**NPL**, **NIST**, **NMi**, BNM-LNE, **KRISS**, NRLM, NRCCRM, **VNIIM**, OMH (9 NMIs)
	EURAMET.QM-K1.c (NO in N_2)	100 µmol/mol		2002–2003	BNM-LNE, **NPL**, **VNIIM**, **NMi-VCL**, GUM, CEM, METAS, CHNI, FMI, IPQ (10 NMIs)
	APMP.QM-K1.c (NO in N_2)	100 µmol/mol		2005–2006	NIM, **KRISS** (2 NMIs)
	CCQM-K26.a (NO in N_2)	720 nmol/mol		2004	CENAM, CERI-**NMIJ**, CHMI, FMI, JRC, **KRISS**, LNE, **NIST**, **NMi-VSL**, **NPL**, UBA, **VNIIM** (12 NMIs)

TABLE 5. CMCs of NMIs for GHG

GHG	NMI	Measurand level or range	Expanded uncertainty	Mechanism of measurement service delivery	Matrix
CO_2	United Kingdom	100–200000 µmol/mol	0.4–0.1 %	calibration	nitrogen
		100–100000 µmol/mol	0.4–0.1 %		synthetic air
	The Netherlands	10–200000 µmol/mol	0.4–0.1 %		nitrogen
		100–1000 µmol/mol	0.4–0.2 %		synthetic air
	Russia	0.05–300 mmol/mol	1–0.15 %		nitrogen
		1–300 mmol/mol	0.2–0.15 %		air
	Korea	0.09–180 mmol/mol	0.1 %	certified reference material (CRM)	nitrogen
	Japan	100–160000 µmol/mol	0.65–0.35 %	CRM	nitrogen
		350–70000 µmol/mol	0.2–0.1 %	calibration	synthetic air
	United States	0.05–24 %mol/mol	0.2–0.5 %	CRM	nitrogen
		200–1000 µmol/mol	0.2–0.5 %		synthetic air
CH_4	United Kingdom	10–100 mmol/mol	0.4 %	calibration	nitrogen
		1–10000 µmol/mol	0.5–0.4 %		synthetic air
	The Netherlands	10–100000 µmol/mol	1–0.3 %		nitrogen
	Russia	5–20 mmol/mol	0.5 %		nitrogen
		10–5000 µmol/mol	1 %		synthetic air
	Korea	0.001–100 mmol/mol	3–1 %	CRM	nitrogen
		1–1000 µmol/mol	3–1 %		air
	Japan	1–50 µmol/mol	0.6 %		synthetic air
	United States	0.5–125 µmol/mol	0.5–2 %		nitrogen
		0.5–125 µmol/mol	0.5–2 %		air
N_2O	The Netherlands	0.3–30 µmol/mol	3–1 %	calibration	synthetic air
	Korea	0.1–1000 µmol/mol	1–0.2 %	CRM	air
CO	United Kingdom	1–100000 µmol/mol	0.2–0.06 %	calibration	nitrogen
		1–10000 µmol/mol	0.3–0.07 %		synthetic air
	The Netherlands	1–100000 µmol/mol	0.2–0.06 %		nitrogen
		1–100 µmol/mol	1–0.2 %		synthetic air
	Russia	1–100000 µmol/mol	5–0.2 %		nitrogen
		1–100000 µmol/mol	5–0.2 %		air
		1–1000 µmol/mol	0.5 %		synthetic air
	Korea	0.09–100 mmol/mol	0.5 %	CRM	nitrogen
	Japan	3–150000 µmol/mol	0.6–0.3 %		nitrogen
	United States	10–150000 µmol/mol	0.3–1 %		nitrogen
		10–130000 µmol/mol	0.3–1 %		synthetic air
NO_x	United Kingdom	0.1–100 µmol/mol	0.4–0.3 %	calibration	nitrogen
	The Netherlands	0.1–1000 µmol/mol	3–1 %		synthetic air
	Russia	0.1–25000 µmol/mol	5–0.3 %		nitrogen
		0.1–25000 µmol/mol	5–0.3 %		air
	Korea	100–1000 µmol/mol	2 %	CRM	nitrogen
	Japan	5–50 µmol/mol	3 %		synthetic air
	United States	1–10000 µmol/mol	1–3 %	calibration and CRM	air