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Australian HFC, PFC, Sulfur Hexafluoride & Sulfuryl Fluoride Emissions

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August 2014

Report prepared for the Department of the Environment



CSIRO Oceans and Atmosphere Flagship /Centre for Australian Weather and Climate Research

Citation

Fraser P., B. Dunse, P. Krummel, P. Steele & N. Derek (2014) Australian HFC, PFC, Sulfur Hexafluoride and Sulfuryl Fluoride emissions, Report prepared for Australian Government Department of the Environment, by the Centre for Australian Weather and Climate Research, CSIRO Oceans and Atmosphere Flagship, Aspendale, Australia, ii, 27 pp.

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Acknowledgments

The authors would like to thank the Cape Grim staff for the maintenance and operation of the AGAGE (Advanced Global Atmospheric Gases Experiment) instruments at Cape Grim and for the collection of the Cape Grim Air Archive; Dr D. Ivy (MIT USA), Dr B. Miller (SIO USA and NOAA USA), Dr D. Oram (UEA UK) and the late Mr L. Porter (BoM) for gas chromatography-mass spectrometry analyses of the Cape Grim Air Archive; Dr A. Manning (UKMO) for synthetic greenhouse gas (SGG) emissions calculations (NAME-InTEM); Dr H. Wang (Georgia Institute of Tachnology, USA) and Dr M. Rigby (U. Bristol UK) for SGG emissions calculations (AGAGE 12-box model); Mr M. Hunstone and Ms. A. Gabriel (Department of the Environment) for SGG import and emissions data; Mr S. Walsh (EPA Victoria) for Port Phillip carbon monoxide emission and concentration data; CSIRO, BoM, NASA/Massachusetts Intstitute of Technology, Department of the Environment and RRA (Refrigerant Reclaim Australia) for funding in support of the Cape Grim AGAGE program.

1 Introduction

Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF₆) and nitrogen trifluoride (NF₃) are potent greenhouse gases (GHGs), which can be collectively described as Kyoto Protocol synthetic GHGs (KP-SGGs). HFCs are used extensively in Australia, largely in air conditioning and refrigeration, initially as 'ozone-friendly' replacements for chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). Minor uses of HFCs in Australia are as aerosol propellants, including metered dose inhalers (MDIs), as foam blowing agents and in fire extinguishers. PFCs are a by-product of the production of aluminium in Australia and overseas and, in addition, are used overseas in the electronics industry during the manufacture of integrated circuits and plasma screens. Refrigeration represents a very minor use of PFCs in Australia and overseas. Sulfur hexafluoride is used extensively in the electricity distribution industry, both in Australia and overseas, for dielectric insulation and current interruption in circuit breakers, switchgear, and other electrical equipment, and as a cover gas in metal production, for example magnesium. There does not appear to be any significant use of nitrogen trifluoride in Australia, which is used internationally in the semi-conductor production industry, initially as a replacement for PFCs.

Sulfuryl fluoride (SO₂F₂) and trifluoromethyl sulfurpentafluoride (CF₃SF₅) are potent synthetic greenhouse gases that are not part of the Kyoto Protocol suite of SGGs (KP-SGGs). Sulfuryl fluoride use in Australia is growing rapidly, as a replacement for phosphine (PH₃) and possibly methyl bromide (CH₃Br), in grain fumigation. It is unlikely that trifluoromethyl sulfurpentafluoride is used in Australia. Its occurrence in the atmosphere is largely as a by-product of the production of perfluorooctanesulfonic acid (PFOS: CF₃(CF₂)₇SO₃H), which has never been manufactured in Australia, but is a key ingredient in fabric stain repellants (e.g. 3M's Scotchguard®).

Rapidly growing HFC-emissions are seen as a significant driver of climate change over the next 50 years (Velders *et al.*, 2007, 2009, 2012; Estrada *et al.*, 2013; Harris *et al.*, 2014; Myhre *et al.*, 2014;) and projections suggest that unmitigated HFC growth could result in Global Warming Potential (GWP)-weighted emissions approaching 9 Gt CO₂-e (carbon dioxide equivalent) per year by 2050 (Daniel & Velders, 2011). It has been suggested that an amended Montreal Protocol could phase out the production and consumption of HFCs (with high GWPs) sooner than possible emission mitigation under a revised Kyoto Protocol or similar agreement (Molina *et al.*, 2009).

The US Environmental Protection Agency (EPA) has proposed delisting or controls on a number of high GWP HFCs by end use which were previously considered acceptable alternatives to ozone depleting substances (ODSs). There are no mandated global or Australian targets to phase-down KP-SGG emissions at present, except as contributors to the 'basket' of GHGs (CO_2 , methane – CH_4 , nitrous oxide – N_2O , HFCs, PFCs, SF₆, NF₃) whose total emissions from most developed countries are regulated under the Kyoto Protocol. In early 2010, the Australian Government committed conditionally to reduce its total GHG emissions by 5 per cent below 2000 levels by 2020, but will revisit this committment at a later date, depending on the extent of comparative international action. There are no global or Australian targets to phase-down SO₂F₂ or CF₃SF₅ emissions.

Australia emitted a total of 544 million tonnes (Mt) CO_2 -e from all GHG sources in 2012 (not including land-use change), which was an increase from 2011 emissions (542 Mt) of 0.4%. HFC emissions were 7.9 Mt (7945 k tonnes) CO_2 -e in 2012, while the sum of HFC, PFC and SF_6 emissions was 8.3 Mt (8333 k tonnes, Table 3) CO_2 -e, 1.5% of total greenhouse gas emissions and an increase in this sector of 5% compared to 2011 (Table 3; DoE, 2014). The total emission of KP-SGGs is the fastest growing emissions sector in the Australian National Greenhouse Gas Inventory (referred to subsequently as the *Inventory*).

In this Report we estimate Australian emissions of HFCs, PFCs, SF_6 and SO_2F_2 derived by inter-species correlation (ISC), inverse and forward atmospheric modelling techniques, using Cape Grim atmospheric observations. These so-called 'top-down' estimates are compared to estimates of HFCs, PFCs and SF_6 emissions submitted by the Australian government to the United Nations Framework Convention on Climate Change (UNFCCC) (e.g. DIICCSRTE, 2013; DoE, 2014), based on Intergovernmental Panel on Climate Change (IPCC)-recommended 'bottom-up' methodologies for estimating national GHG emissions. At present, Cape Grim measurements of NF_3 and CF_3SF_5 have only been made on the Cape Grim Air Archive – these data are not suitable for estimating Australian emissions of these species.

2 Measurements of HFCs, PFCs, SF₆, NF₃, SO₂F₂ & CF₃SF₅ at Cape Grim, Tasmania

Concentrations of HFCs, PFCs, SF₆, NF₃, SO₂F₂ and CF₃SF₅ have been measured *in situ* in the Southern Hemisphere atmosphere at Cape Grim, Tasmania, and/or in the Cape Grim Air Archive (1978-2013) at CSIRO (Aspendale), at the Scripps Institution for Oceanography (SIO, USA), and on a sub-set of the Cape Grim Air Archive at the University of East

Anglia (UEA, UK). Other flask air samples from Cape Grim have been analysed at CSIRO, at SIO, at UEA and at the University of Heidelberg (Germany). The SGGs have been measured by CSIRO in situ in the atmosphere (baseline and non-baseline) at Cape Grim, Tasmania, since the late-1990s (HFCs, PFC-116: CF₃CF₃) and the mid-2000s (other PFCs, SF₆, SO₂F₂). Nitrogen trifluoride (up to 2013) and trifluromethyl sulfurpentafluoride (up to 2008) have only been measured on the Cape Grim Air Archive. These data are used, in conjunction with similar data collected from other Northern and Southern Hemispheric sites, to estimate global and regional concentration trends, atmospheric lifetimes, emissions and radiative forcings for these species:

HFCs Oram et al., 1996, 1998; Oram, 1999; O'Doherty et al., 2004, 2009, 2014; Greally et al., 2007; Stohl et al., 2009; Miller et al., 2010; Vollmer et al., 2011; Fortems-Cheney et al., 2013; Arnold et al., 2014; Fraser et al., 2014a; Krummel et al., 2014; Rigby et al., 2014 PFCs Oram, 1999; Fraser et al., 2007, 2011, 2013; Mühle et al., 2010; Ivy, 2012; Ivy et al., 2012; Laube et al., 2012; Oram et al., 2012; Kim et al., 2014; Krummel et al., 2014; Rigby et al., 2014 SF_6 Maiss et al., 1996; Oram, 1999; Fraser et al., 2004, 2014a; Levin et al., 2010; Rigby et al., 2010, 2014; Ganesan et al., 2014; Krummel et al., 2014 NF_3 Weiss et al., 2008; Arnold et al., 2013; Rigby et al., 2014 SO_2F_2 Muhle et al., 2009; Krummel et al., 2014

 CF_3SF_5 Sturges et al., 2012

The abundances and trends of HFCs, PFCs, SF₆, NF₃ and CF₃SF₆ in the global background atmosphere, as measured at Cape Grim, Tasmania, or in the Cape Grim air archive, are shown in Table 1 (2012-2013) and Figure 1 (1978-2013).

Table 1. Concentrations (2012, 2013) and growth rates (2012-2013) for HFCs, PFCs, SF₆, NF₃, SO₂F₂ and CF₃SF₅ measured in situ at Cape Grim, Tasmania or on air samples collected at Cape Grim (references: see text above; CSIRO unpublished Cape Grim Air Archive data).

Species	Species Formula		Conc. (ppt)		th	Species	Formula	Conc. (ppt)		Growth	
		2012	2013	ppt/yr	%/yr			2012	2013	ppt/yr	%/yr
HFC-134a	CH ₂ FCF ₃	62.7	67.0	4.2	6.5	PFC-14	CF_4	79.3	79.9	0.56	0.7
HFC-23	CHF ₃	24.4	25.1	0.78	3.2	PFC-14(a) ¹	CF_4	44.4	45.0	0.56	1.3
HFC-143a	CH_3CF_3	12.5	13.6	1.1	8.4	PFC-116	C_2F_6	4.18	4.25	0.06	1.5
HFC-125	CHF ₂ CF ₃	10.1	11.4	1.3	12	PFC-318	c-C ₄ F ₈	1.31	1.36	0.05	3.7
HFC-32	CH_2F_2	5.2	6.0	0.85	-	PFC-218	C_3F_8	0.56	0.57	0.016	2.8
HFC-152a	CH_3CHF_2	4.4	4.4	-0.01	0.0	PFC-5114 ²	C_6F_{14}	0.27	0.27	0.005	1.8
HFC-245fa	$CH_3CF_2CF_3$	1.3	1.4	0.13	10	PFC-3110 ²	$C_{4}F_{10}$	0.17	0.17	0.002	1.2
HFC-227ea	$CHF_2CF_2CF_3$	0.69	0.77	0.084	12	PFC-4112 ²	$C_{5}F_{12}$	0.12	0.12	0.001	1.1
HFC-365mfc	$CH_3CH_2CF_2CF_3$	0.56	0.60	0.038	6.6	PFC-6116 ²	$C_{7}F_{16}$	0.12	0.12	0.004	3.4
HCFC-4310mee	$CF_3(CHF)_2C_2F_5$	0.20	0.21	0.01	4.8	PFC-7118 ²	C_8F_{18}	0.09	0.09	0.001	1.1
HFC-236fa	$CH_2FCF_2CF_3$	0.088	0.094	0.006	6.5	total PFCs		86.1	86.8	0.70	0.9
total HFCs		122	131	8.6	6.8	total PFC(a)		51.2	51.9	0.70	1.4
HFC fluorine		448	480	32	7.1	PFC fluorine		368	371	3.3	0.9
sulfur hexafluoride	SF ₆	7.4	7.7	0.27	3.6	nitrogen trifluoride	NF_3	0.90	1.00	0.10^{3}	11
sulfuryl fluoride	SO_2F_2	1.68	1.78	0.10	5.8	total fluorine		862	904	43	4.8
trifluoromethyl	CF_3SF_5	0.16^{4}	0.16	0.0	0.0						

sulfurpentafluoride

PFC-14 (a) = CF₄ (anthro.) = total CF₄ – natural CF₄ (=34.9 ppt, Mühle *et al.*, 2010)

extrapolated from 2011 data (Ivy et al., 2012)

estimated from Cape Grim & global data; assumed = 2011-2012 growth rate (Arnold et al., 2013)

⁴ assumed = 2007 concentration (zero emissions after 2007), no growth observed in *in situ* measurements (uncalibrated) since 2010

The major HFC in the background atmosphere at Cape Grim (and around the globe) is HFC-134a (67 ppt in 2013), followed by HFC-23 (25 ppt), HFC-143a (14 ppt), HFC-32 (6.0 ppt) and HFC-152a (4.4 ppt). The cumulative concentration of the minor HFCs (HFC-227ea, HFC-236fa, HFC-365mfc, HFC-4310mee) is 1-2 ppt (2013). The total HFC concentration in the background atmosphere is 131 ppt (2013).

The rates of increase of the major HFCs in the global background atmosphere (HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a) are now slowing, suggesting the rates of increase in global emissions are in decline (Rigby et al., 2014). Specifically, the annual rate of increase of HFC-134a has declined from 5.6 ppt (2011-2012) to 4.2 ppt (2012-2013); the HFC-23 increase (0.8 ppt, 2011-2012 & 2012-2013) has remained steady; the HFC-143a annual increase (1.1 ppt, 2012-2013) has declined from 1.3 ppt (2011-2012); the HFC-125 annual increase (1.3 ppt per year, 2012-2013) has declined from 1.6 ppt per year (2011-2012); the HFC-152a annual increase (0.2 ppt, 2011-2012) has declined (0.0 ppt, 2012-2013) such that HFC-152a is no longer growing in the background atmosphere; the HFC-32 increase (0.9 ppt, 20122013) has declined from 1.1 ppt (2011-2012). The minor HFCs (HFC-227ea, HFC-236fa, HFC-365mfc, HFC-4310mee) are growing in the background atmosphere with a cumulative annual growth rate of 0.2-0.3 ppt (2012-2013). The annual growth in total HFCs (9 ppt, 2012-2013) has declined from 11 ppt (2011-2012) and is now similar to the annual increase observed in 2010-2011 (9 ppt). Total HFCs in the atmosphere are growing currently (2012-2013) at 7% per year.

The major PFC in the background atmosphere at Cape Grim (and around the globe) is PFC-14 (80 ppt in 2013, about half of which is naturally-occurring), followed by PFC-116 (4.3 ppt), PFC-318 (1.4 ppt) and PFC-218 (0.57 ppt). The cumulative concentration of five minor PFCs (PFC-3110, PFC-4112, PFC-5114, PFC-6116, PFC-7118) observed at Cape Grim is 0.8-0.9 ppt (2013). The total PFC concentration in the background atmosphere is 87 ppt (2013), currently growing at 0.7 ppt per year (0.9% per year). The total anthropogenic PFC concentration in the background atmosphere is 51 ppt growing at 1.4% per year.

The annual rate of increase of PFC-14 (CF₄) in the atmosphere is declining: 0.56 ppt (2012-2013) compared to 0.83 ppt (2011-2012), consistent with declining global emissions of PFC-14. The anthropogenic component (from aluminium production and the electronics industries) of the PFC-14 atmospheric abundance is growing at 1.4% per year. The annual rate of increase of PFC-116 (CF₃CF₃) has remained steady at 0.06 ppt in 2012-2013 compared to 2011-2012; the CF₃CF₂CF₃ annual increase (0.016 ppt, 2012-2013) is similar to the increase observed over the previous two years (2010-2012, 0.1-0.2 ppt per year); c-C₄F₈ increased by 0.05 ppt (2012-2013) is similar to the increase in 2011-2012 (0.04 ppt). The minor PFCs (PFC-3110, PFC-4112, PFC-5114, PFC-6116, PFC-7118) are growing in the background atmosphere with a cumulative annual growth rate likely to be of order 0.2-0.3 ppt (2012-2013). Total industry-derived atmospheric PFCs are growing (2012-2013) at 1.4% per year.

Annual mean SF₆ levels reached 7.7 ppt in 2013 at Cape Grim, growing at 0.27 ppt per year (3.6% per year), lower than the 2011-2012 growth rate (0.30 ppt, 4.1% per year). Annual mean SO₂F₂ levels reached 1.8 ppt in 2013 at Cape Grim, growing at 0.1 ppt per year (5.8% per year), compared to the 2011-2012 growth rate of 4.0% per year. Trifluoromethyl sulphurpentafluoride stopped growing in the Cape Grim atmosphere in 2007 (0.16 ppt), as seen in Cape Grim Air Archive measurements, following 3M's decision to cease PFOS production (Santaro, 2000). *In situ* measurements (uncalibrated) at Cape Grim show zero growth in CF₃SF₅ since measurement began in 2010. If there is no further production/release of CF₃SF₅, its concentration in the atmosphere will remain effectively constant due to its very long atmospheric lifetime (800 yr). With zero emissions, atmospheric concentrations should decline by about 0.05% (<0.01 ppt) per year.

Nitrogen trifluoride is growing rapidly in the background atmosphere (0.11 ppt per year, 11% per year). Following the recent inclusion of NF_3 into the Kyoto Protocol 'basket' of GHGs, it is anticipated that the current rapid growth rate will decline as alternatives are introduced into the semiconductor manufacturing industry.

3 Australian HFC, PFC and SF₆ Emissions

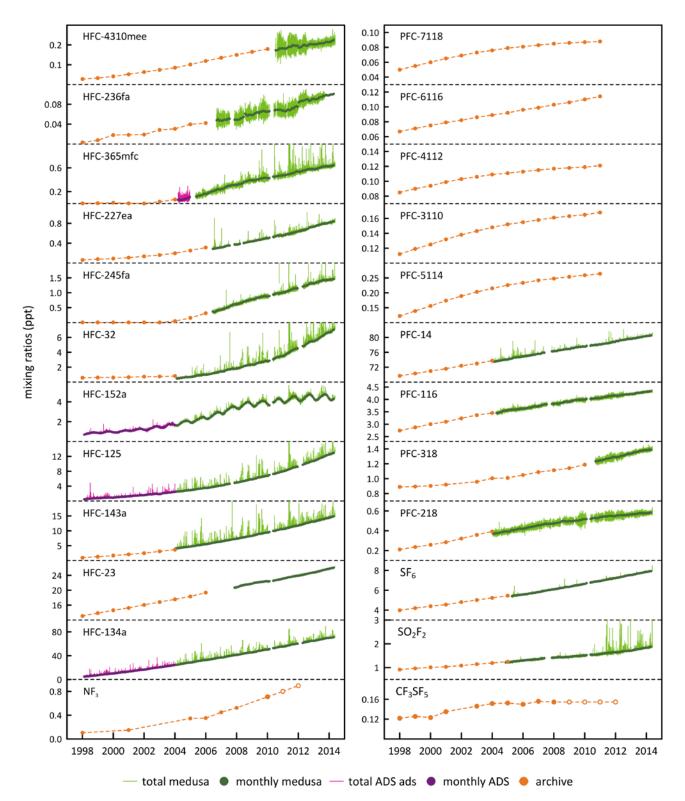
3.1 Australian National Greenhouse Accounts

The National Greenhouse Gas Inventory (the *Inventory*: ageis.climatechange.gov.au) in 2014 contains estimates of Australian emissions of HFC-23, HFC-32, HFC-125, HFC-134 (CHF₂CHF₂, not measured currently at Cape Grim), HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, HFC-4310mee, PFC-14, PFC-116 and SF₆, up to 2012, and is part of the *National Inventory Report 2012* (DoE, 2014), which is the Australian government submission to the UNFCCC and which forms a part of the Australian National Greenhouse Accounts (NGA). Note the annual emissions in the *Inventory* and in the *National Inventory Report* are for fiscal years, i.e. '2012' emissions are emissions for July 2011 to June 2012.

The HFC emissions (Table 4) are based on HFC import data (Table 2; HFCs are not manufactured in Australia), as bulk HFCs or pre-charged equipment (PCE), leading to an estimate of 'banks' of HFCs stored in equipment or products (refrigerators, air conditioners, fire extinguishers, foams, aerosols - largely metered-dose inhalers) and appropriate application-dependent emission factors from those 'banks', which allow for emissions during the lifetime of the application as well as emissions from initial charging/re-charging of equipment and equipment disposal. The HFC emissions model contains some assumptions that simplify HFC emissions calculations. For example, the Australian HFC mix, as determined by HFC imports, is assumed to be invariant across all HFC use categories and the application-specific emission factors are time-invariant. This means that the emissions model is likely to be more representative for total HFC emissions than for individual HFC emissions.

The Australian HFC mix in the emissions model is 53% HFC-134a, 40% HFC-125, 5.2% HFC-143a, 0.5% HFC-32 and 1.4% HFC-227ea. The HFC mix in the 2012 import data (Table 2) is 49% HFC-134a, 24% HFC-125, 13% HFC-143a,

13% HFC-32, <1% HFC-227ea and 1% other HFCs. The HFC mix in the Australian bank in 2012 is 44% HFC-134a, 5.3% HFC-125, 28% HFC-143a and 23% HFC-32 (Brodribb & McCann, 2013).



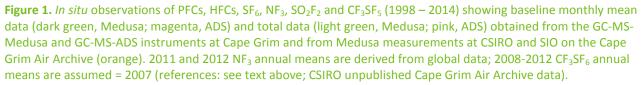


Table 2. Australian SGG (HFC, PFC and SF₆) imports (tonnes) and HFC banks for 2012 and 2013 (Brodribb & McCann, 2013; A. Gabriel, Department of Environment, 2014); PCE = pre-charged equipment

Species	bulk		P	CE	to	otal	total	SGGs	HFC bank		
	SGGs & H	FC blends	SGGs & H	FC blends	bulk	& PCE					
	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	
HFC-23		0.1		<0.1	1	0.1	1	0.1			
HFC-32	58	0.3	11	67	1072	67	1141	941	7404		
HFC-125	104	<0.1	14		2001	<0.1	2119	899	1709		
HFC-134	2	2	1	2		4	3	4			
HFC-134a	3992	93	65	802	258	895	4315	930	14093		
HFC-143,-143a	58		3	0.2	1065	0.2	1126	20	8890		
HFC-152a		1		12		13		13			
HFC-227ea	70		1	1		1	70	1			
HFC-245fa	44	74				74	44	74			
HFC-365mfc	53	86				86	53	86			
total HFCs		257		884		1141		2968			
R-404	1805	9		27		36					
R-407	440	13		40		53					
R-410	1962	1		1718		1719					
R-417		1		0.3		1					
R-422		0.2		0.2		0.3					
R-427	34										
R-438	8	16		2		18					
R-507	243	1		1		2					
total blends		41		1788		1829					
total PFCs	0.9	0.1		0.1		0.2	0.9	0.2			
SF ₆	36	4		14		18	36	18			
total SGGs		301		2685		2986		2986	24696		

There have been a number of refinements to the HFC emissions model used for the 2014 submission:

- (i) use of country-specific (Australian) annual leakage rates for commercial refrigeration and air-conditioning, transport refrigeration and heavy vehicle air rather than default leakage rates;
- (ii) quality control checks on bulk import data showed that the previous version of the emissions model was not allocating 100% of bulk gas imports to domestic production or replenishment, leading to a minor systematic under-estimation of emissions from all equipment types; this has been corrected for the current submission to UNFCCC;
- (iii) a revision to the quantities of bulk gas allocated to foams, aerosols and fire protection equipment; and
- (iv) a minor revision to the calculation of emissions from initial charging of new equipment.

The relationship between HFC imports and emissions is not necessarily linear. For example there was a surge of HFC and SF_6 imports into Australia in 2012 in anticipation of the imposition of the carbon tax; this presumably did not lead to a significant surge in emissions, as the HFC and SF_6 imports, surplus to demand, presumably went into storage with minimal emissions.

In the Australian GHG emission inventory, PFC (PFC-14, PFC-116) emissions only arise from aluminium production, with total PFC emissions in 2012 of 0.25 Mt CO_2 -e (DoE, 2014). Less than 1 tonne of PFCs (PFC-14, PFC-116) were imported into Australia as refrigerant blends in bulk and in pre-charged equipment (see below). It is not clear whether these PFC imports are used to calculate corresponding contributions to PFC emissions – if they are, they are very small compared to PFC emissions from the aluminium industry.

Australian SF₆ emissions are largely from the electricity supply and distribution network. Emissions (1975-2012) are estimated as leakages from SF₆ 'banks' and from Australian manufacture of electricity supply equipment (Table 3), using a combination of default IPCC and Australian-specific emissions factors. There are only two years (2012, 2013) of SF₆ import data available, which could potentially be used to verify the calculations of SF₆ in banks and used in manufacture. However the 2012-2013 import data suggest SF₆ may have been stock-piled in these years in anticipation of an impending carbon tax impost on the SF₆ price.

Australian emission factors for electrical equipment stock are global IPCC default factors: 0.05 t/t (1975-1995), 0.02 t/t (2000); an Australian-specific factor (0.0089 t/t) has been estimated for 2009 and assumed constant thereafter. For 1995-2000-2009 periods, emissions factor are interpolated. The 2009-2012 emission factor is based on emission estimates from 15 utilities using their own data on SF_6 consumption (consumption = emissions, not defaulting to the IPCC method). The emission factors assumed for Australian equipment manufacture (0.15 t/t, 1975-1995; 0.06 t/t,

1996-2012) are IPCC default factors for Europe. The original global IPCC default factor for manufacturing (0.74 t/t) was significantly higher and currently IPCC recommends 0.30-0.35 t/t (prior to 1995) and 0.12 t/t after 1995, both significantly higher than the assumed Australian emission factor for equipment manufacture. These IPCC factors are for so-called gas insulated switchgear (GIS); significantly higher factors are recommended for circuit breakers (0.55 t/t prior to 1995, 0.29 t/t after 1995). Circuit breakers are used extensively in the USA, GIS in Europe. The Australian inventory assumed GIS values, presumably because Australia uses largely GIS equipment in its electricity distribution networks.

Australian SF₆ emissions from magnesium casting, tracer gas studies, eye surgery etc. have been estimated at 0.034 g per capita (M. Hunstone, DoE, 2014, personal communication). The components of the Australian SF₆ emission inventory are shown in Table 3.

There are no import data available for SO_2F_2 .

The emissions data (1995 to 2012) are detailed in Table 4. Australian HFC emissions were less than 100 tonnes in 1994, rising to 4579 tonnes (7945 CO_2 -e tonnes) in 2012. HFCs are the dominant emissions in CO_2 -e terms in this sector (95%, 2012). HFC-134a emissions increased by about 176 tonnes (6%) from 2011 to 2012, all other HFCs by about 73 tonnes (6%). Emissions of total HFCs (in CO_2 -e terms) in 2012 were 6% higher than in 2011. Australian PFC emissions were 190 tonnes in the mid-1990s, rising to 230 tonnes in the mid-2000s, before dropping to 37 tonnes in 2012. Total PFC emissions (in CO_2 -e terms) decreased by 2% from 2011 to 2012. Sulfur hexafluoride (SF₆) emissions are estimated to have been 13 tonnes in 1995 falling to 6 tonnes in 2012.

Total HFC, PFC and SF₆ emissions in CO₂-e in 2012 (8333 k tonnes) were 5% higher than in 2011; this compares to an 8% per year increase from 2007 to 2011. The overall uncertainty on the PFC/HFC/SF₆ emissions category in the *Inventory* is 25-30% (DCCEE, 2011). The HFC, PFC and SF₆ contributions to total emissions from this sector are shown in Figure 2. The significant impact on total emissions in 2005-2006 due to reduced PFC emissions (the Kurri Kurri aluminium smelter upgrade) can be clearly seen. Prior to the significant reduction in PFC emissions at Kurri Kurri in 2005, Australian HFC/PFC/SF₆ emissions grew at about 13% per year (Figure 2). After the Kurri Kurri upgrade, these combined emissions grew at about 7% per year. The Australian KP-SGG emissions are 95% HFCs, 3% PFCs and 2% SF₆.

Department of the Environment (2014) estimates of emissions (Table 4) in the *Inventory* (ageis.climatechnage.gov.au) are compared to emissions estimated from atmospheric observations below.

4 Australian HFC, PFC, SF₆ & SO₂F₂ emissions from atmospheric data

4.1 **PFC-14** emissions

South-East Australian emissions of PFC-14 (CF_4) are evident in the PFC-14 data collected at Cape Grim (Figure 3). Inspection of Figure 3 shows an overall decline in intensity of PFC-14 pollution episodes due to declining emissions. The year-to-year variability of the number and intensity of PFC-14 episodes seen at Cape Grim is large, so 3-yr averaging is used when deriving PFC emissions from these data (so the latest annual emission calculated from these data is for 2012). Detailed analysis of these PFC-14 pollution episodes shows clearly that the Cape Grim PFC-14 pollution originates largely from southern Victoria (from the Point Henry and Portland smelters), with some contribution from Bell Bay, Tasmania.

The Cape Grim PFC-14 pollution episode data have been used to estimate PFC-14 emissions from these South-East Australian smelters. A regional transport model (TAPM – The Air Pollution Model; Hurley, 2008; Hurley *et al.*, 2008) is used to calculate emissions in which PFC-14 is released into the model atmosphere from the Point Henry, Portland and Bell Bay locations, with annual emissions that are varied, so that the resultant PFC pollution episodes seen at Cape Grim in the model are a best-fit match to observations. The emissions are constant in any one year, varied year-by-year. Smelter-specific emission factors are calculated from the emissions by dividing by the smelter-specific annual aluminium production (Fraser *et al.*, 2007, 2011).

The NAME particle dispersion model (O'Doherty *et al.*, 2009; Manning *et al.*, 2003, 2011) is also used to calculate PFC-14 emissions from Victoria/Tasmania/NSW (Portland/Pt Henry/Bell Bay/Kurri Kurri/Tomago smelters).

Table 3. Australian stocks and emissions of SF₆ (tonnes, DoE, 2014).

				new equ amount	ipment m leak	anufacture emissions	other emissions	total emissions	total ¹ emissions
	tonnes	factor t/t	tonnes	tonnes	rate t/t	tonnes	tonnes	tonnes	tonnes
1975	2.4	0.05	0.1	1.3	0.15	0.2			1.6
1976	4.8	0.05	0.2	1.3	0.15	0.2			1.8
1977	7.2	0.05	0.4	1.4	0.15	0.2			2.0
1978	9.7	0.05	0.5	1.4	0.15	0.2			2.2
1979	12	0.05	0.6	1.5	0.15	0.2			2.3
1980	27	0.05	1.3	7.9	0.15	1.2			7.8
1981	41	0.05	2.1	8.3	0.15	1.2			8.8
1982	56	0.05	2.8	8.6	0.15	1.3			9.8
1983	70	0.05	3.5	9.0	0.15	1.3			10.8
1984	84	0.05	4.2	9.4	0.15	1.4			11.8
1985	93	0.05	4.6	6.5	0.15	1.0			10.1
1986	101	0.05	5.1	6.8	0.15	1.0			10.7
1987	110	0.05	5.5	7.0	0.15	1.0			11.3
1988	118	0.05	5.9	7.2	0.15	1.1			11.9
1989	127	0.05	6.3	7.4	0.15	1.1			12.5
1990	141	0.05	7.1	11	0.15	1.6			15.7
1991	156	0.05	7.8	11	0.15	1.7	0.6	10	16.7
1992	170	0.05	8.5	11	0.15	1.7	0.6	11	17.7
1993	185	0.05	9.2	12	0.15	1.8	0.6	12	18.7
1994	199	0.05	10	12	0.15	1.8	0.6	12	19.7
1995	214	0.05	11	13	0.15	1.9	0.6	13	21.0
1996	229	0.044	10	13	0.06	0.8	0.6	12	20.2
1997	244	0.038	9.3	12	0.06	0.7	0.6	11	19.1
1998	259	0.032	8.3	12	0.06	0.7	0.6	9.8	17.7
1999	274	0.026	7.1	11	0.06	0.7	0.7	8.6	16.2
2000	313	0.020	6.3	22	0.06	1.3	0.7	8.4	23.7
2001	352	0.0188	6.6	23	0.06	1.4	0.7	8.6	24.6
2002	390	0.0175	6.8	23	0.06	1.4	0.7	8.9	25.4
2003	429	0.0163	7.0	23	0.06	1.4	0.7	9.0	26.3
2004	468	0.0151	7.1	23	0.06	1.4	0.7	9.1	27.1
2005	481	0.0139	6.7	10	0.06	0.6	0.7	8.0	18.1
2006	495	0.0126	6.3	10	0.06	0.6	0.7	7.6	18.2
2007	509	0.0114	5.8	9.8	0.06	0.6	0.7	7.1	18.3
2008	523	0.0102	5.3	9.6	0.06	0.6	0.7	6.6	18.5
2009	534	0.0089	4.8	7.8	0.06	0.5	0.8	6.0	17.4
2010	544	0.0089	4.9	7.5	0.06	0.4	0.8	6.1	17.3
2011	542	0.0089	4.8		0.06		0.8	5.6	17.3
2012	541	0.0089	4.8		0.06		0.8	5.6	17.3

¹ based on SF₆ emission factor 0.034 g SF₆/capita,, M. Hunstone, DoE 2014, personal communication ² based on IPCC default emission factor (0.74 t/t) for electrical equipment manufacture

	HFC-134a	HFC-125	HFC-143a	HFC-32	HFC-227ea	HFC-134 H	HFC-4310mee	HFC-23	total	HFCs	PFC-14	PFC-116	total	PFCs	S	F ₆	total HF	Cs, PFCs, SF ₆
				te	onnes				tonnes	kt CO ₂ -e	ton	nes	tonnes	kt CO ₂ -e	tonnes	kt CO ₂ -e	tonnes	kt CO ₂ -e
1994	0.2	0.1	0.0	0.0	0.0	0.0	0.0	69	69	808	241	31	272	1856	12	296	322	2960
1995	32	11	1.1	0.6	0.4	0.0	0.0	61	107	793	171	22	193	1313	13	317	313	2419
1996	141	49	4.7	2.7	1.7	0.1	0.0	0.0	200	347	157	20	178	1209	12	283	389	1840
1997	242	85	8.1	4.7	2.9	0.1	0.1	0.0	343	595	137	18	155	1053	11	260	509	1910
1998	345	121	12	6.7	4.1	0.1	0.1	0.0	488	847	185	24	209	1424	9.8	234	707	2505
1999	476	166	16	9.2	5.7	0.2	0.1	0.1	673	1168	127	16	143	977	8.6	206	825	2351
2000	560	196	19	11	6.7	0.2	0.2	0.1	792	1375	143	19	162	1103	8.4	200	963	2678
2001	799	280	27	15	9.5	0.3	0.2	0.1	1131	1963	201	26	227	1545	8.6	206	1367	3714
2002	1014	355	34	20	12	0.4	0.3	0.1	1435	2490	193	25	217	1481	8.9	212	1661	4183
2003	1240	434	42	24	15	0.5	0.4	0.2	1755	3046	188	24	212	1444	9.0	216	1976	4706
2004	1479	517	50	29	18	0.6	0.4	0.2	2093	3632	191	25	216	1469	9.1	218	2318	5319
2005	1734	607	58	34	21	0.7	0.5	0.2	2455	4259	200	26	225	1536	8.0	191	2688	5985
2006	1892	662	63	37	22	0.7	0.5	0.2	2677	4646	76	10	86	589	7.6	181	2771	5415
2007	2120	745	71	41	25	0.8	0.6	0.3	3013	5228	65	8	73	499	7.1	170	3094	5897
2008	2366	828	79	46	28	0.9	0.7	0.3	3349	5811	50	6	56	382	6.6	158	3411	6350
2009	2587	905	87	50	31	1.0	0.7	0.3	3661	6353	40	5	45	308	6.0	143	3713	6805
2010	2827	989	95	55	34	1.1	0.8	0.4	4001	6942	33	3	36	243	6.1	145	4043	7331
2011	3059	1070	102	59	36	1.2	0.9	0.4	4329	7512	35	4	38	259	5.6	134	4373	7905
2012	3235	1132	108	63	38	1.3	0.9	0.4	4579	7945	34	4	37	254	5.6	134	4622	8333

Table 4. Australian HFC, PFC and SF₆ emissions (http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/7383.php). HFC-23 emissions in 1994 and 1995 from HCFC-22 production in Sydney. Not shown are small HFC-236fa emissions (0.004 tonnes in 2012)

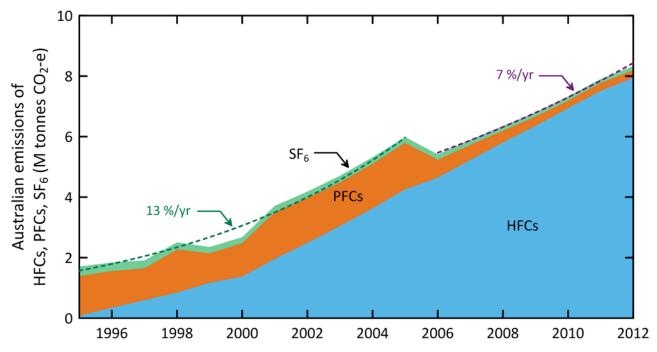


Figure 2. Australian HFC, PFC and SF₆ emissions (M tonne CO_2 -e) (DE, 2014). Note the impact on the reduction in emissions due to the refurbishment of potline #1 at the Kurri Kurri aluminium smelter in 2005-2006. Dashed lines are exponential best fits

NAME (Numerical Atmospheric Dispersion Modelling Environment) is a Lagrangian particle dispersion model driven by 3-dimensional wind fields from numerical weather predictions models. NAME has a horizontal resolution (grid boxes 40 km x 40 km) and a minimum boundary layer height of 100 m. NAME operates in a backward mode, so, for example, it identifies, within a 3 hr period at Cape Grim, which grid boxes in the prescribed domain impact on Cape Grim in the previous 12 days. NAME releases 33000 particles at Cape Grim over the 3 hr period and the resultant 12-day integrated concentrations in each of the domain boxes are calculated. Operating NAME in the backward mode is numerically very efficient and is a very close approximation to the forward running mode, which is what is used to identify emission sources impacting on Cape Grim. In the inverse calculation, NAME identifies pollution episode data at Cape Grim, and starts with randomly-generated emission maps and searches for the emission map that leads to a modelled pollution time series that most accurately mimics the observations. The inversion method assumes that baseline air enters the inversion domain regardless of direction i.e. it assume that sources outside the specified domain do not impact significantly on Cape Grim. One of the major advantages of the NAME method, especially when using Cape Grim data, is that it does not require a prior estimate of emissions. Other inversion methods used to estimate regional emissions using Cape Grim data often derive emissions that are not significantly different than the prior estimates.

The TAPM and NAME estimates of regional PFC-14 emissions are scaled to derive Australian emissions on an aluminium production basis. For example, if the PFC-14 emissions derived for the South-East Australian smelters, which account for about 35% of Australia's aluminium production, are assumed to be representative of all Australian aluminium production, then Australian PFC-14 emissions from aluminium production can be derived and compared to emissions in the *National Inventory Report 2012* (DoE, 2014) (Table 4). The emissions and emission factors calculated for the Point Henry, Portland and Bell Bay smelters are shown in Table 5 and Figure 4 and Figure 5, together with national average emission factors and emissions as published in the *National Inventory Report 2012* (DoE, 2014). The Australian PFC-14 emission factors for aluminium production (Figure 5) are below the self-imposed global industry target of 80 g/tonne aluminium by 2010 and are well on the way to achieving the 2020 target of 20 g/tonne by 2020.

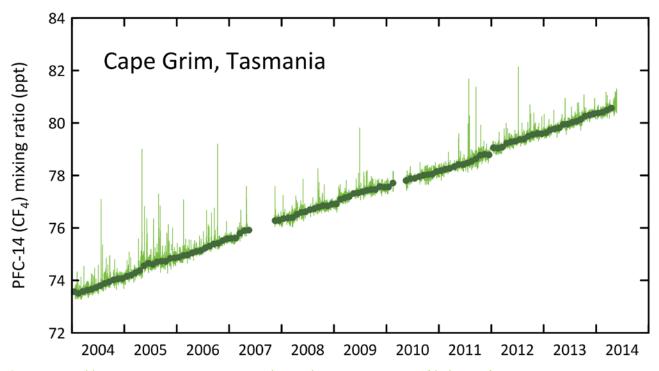


Figure 3. Monthly-mean PFC-14 concentrations observed *in situ* at Cape Grim (dark green), 2004 - 2013. PFC-14 pollution episodes (light green), typically lasting up to 12 hours in duration, are also seen at Cape Grim (Mühle *et al.*, 2010).

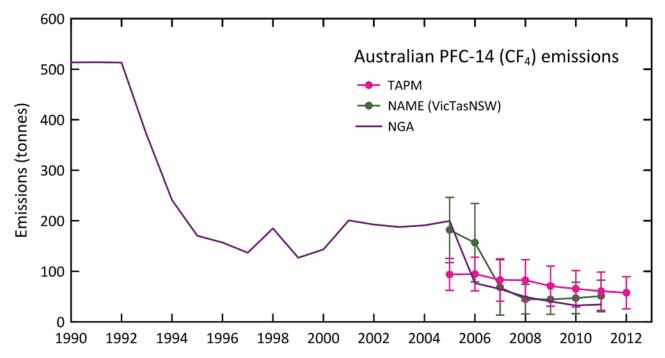


Figure 4. Australian emissions of PFC-14 as recorded in the *National Inventory Report 2012* (DoE, 2014; uncertainty 27%: DIICCSRTE, 2013) and as obtained from TAPM (scaled from Vic/Tas emissions) and NAME (scaled from Vic/Tas/NSW emissions) modelling.

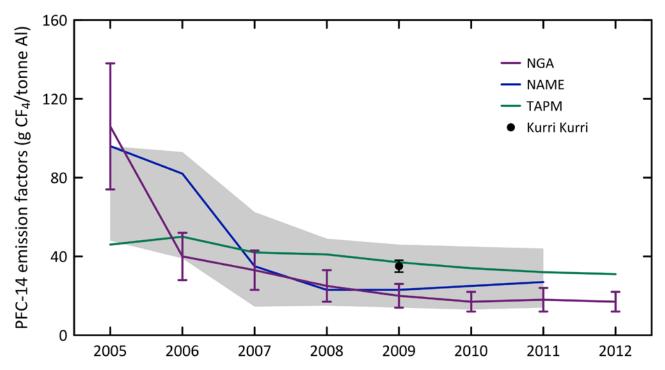


Figure 5. Australian PFC-14 emission factors as reported in the *National Inventory Report 2012* (DoE, 2014)) and as derived from atmospheric measurements at Cape Grim using NAME/TAPM modelling. The grey band is the average (±1 sd) emission factor derived from NAME/TAPM. The Kurri Kurri emission factor is based on direct PFC-14 measurements made at the Kurri Kurri smelter in 2009 (Fraser *et al.*, 2013).

The Australian emissions derived from atmospheric data prior to 2006, using TAPM or NAME (Vic/Tas) are likely to be underestimated due to the very significant PFC-14 emissions from a single pot-line (#1) at Kurri Kurri, which accounted for nearly half of all Australian PFC emissions from aluminium smelting in 2005. The pot-line was upgraded in 2006 and this accounts for the dramatic drop in PFC-14 emissions from 2005 to 2006 in the *National Inventory Report*. The large PFC emissions prior to 2006 are not seen in the TAPM estimates of emissions, as they are based on Bell Bay/Pt Henry/Portland data. The NAME inversion, based on the Vic/Tas/NSW domain, uses all pollution episode data, including any Kurri Kurri- or Tomago-affected data that may have impacted on Cape Grim. This is why the Australian PFC-14 estimates in 2005 (182 tonnes) based on the NAME (Vic/Tas/NSW) emissions are significantly greater than the TAPM estimates for 2005 (95 tonnes).

The average Australian PFC-14 emissions for 2005-2011 based on atmospheric data are similar: TAPM - 78 tonnes and NAME (Vic/Tas/NSW) - 85 tonnes, about 13% higher than reported in the *National Inventory Report 2012* (DoE, 2014; 72 tonnes). The average Australian 2008-2011 PFC-14 emissions derived from atmospheric data using NAME (Vic/Tas/NSW) are 47 tonnes, 20% higher than in the *National Inventory Report 2011* (39 tonnes). The TAPM average for the same period is 69 tonnes and 66 tonnes for 2008-2012. Arguably the NAME estimate is more accurate as it is based on 72% of Australian aluminium production (Portland, Pt Henry, Bell Bay, Kurri Kurri, Tomago), whereas the TAPM estimate is based on 35% of Australian aluminium production (Portland, Pt Henry, Bell Bay). These South-East Australian smelters could have higher average PFC-14 emission factors than the Australian average (see below).

The overall agreement between the PFC emission factors in the *National Inventory Report 2012 (DE, 2014)* and as derived from atmospheric data using TAPM/NAME over the period 2005-2011 is good (Table 5, Figure 5, TAPM: 41 g CF₄/tonne aluminium; NAME: 44 g/tonne; NGA: 37 g/tonne), with uncertainties overlapping throughout the record. For the period 2005-2012 the TAPM average CF₄ emission factor is 39 g/tonne compared to the NGA: 35 g/tonne.

The atmospheric data (NAME) show a factor of 3.5 decline in the emission factors over the period 2005-2011, whereas the NGA show a factor of 6.2 decline over the same period. This decline is dominated by the influence that Kurri Kurri had on national average emissions factors between 2006 and 2007; this decline is not captured in the TAPM data which do not 'see' Kurri Kurri emissions. Given the overlapping uncertainties on both NAME and the NGA estimates of PFC-14 emissions, this difference in emissions decline over the period 2005-2011 may not be significant. However, the difference could be due, in part, to a larger than average decline in the emission factor at Boyne Island, which is not seen in the atmospheric data at Cape Grim, by either NAME or TAPM.

Table 5. Australian aluminium production (kt: 10³ tonnes), Australian PFC-14, PFC-116, PFC-218, PFC-318 emissions (t: tonnes) and PFC-14, PFC-116 emission factors (g/t aluminium, 2005-2012) derived from atmospheric observations – remote (Portland, Pt Henry, Bell Bay) (3 yr averages, e.g. 2010 = average of 2009, 2010, 2011), using the TAPM and NAME models, directly at Kurri Kurri and as reported in the *National Inventory Report 2012* (DoE, 2014).

	2005	2006	2007	2008	2009	2010	2011	2012	average (2005- 12)
Inventory ¹									/
Al production									
Portland, Vic ¹	344	340	351	351	328	314	314	315	332
Point Henry, Vic ¹	190	190	197	198	185	176	177	177	186
Bell Bay, Tas ²	174	178	178	180	177	177	181	185	179
Vic/Tas	708	708	727	729	690	667	672	678	695
Kurri Kurri, NSW ³	151	164	173	173	177	179	180	67	158
Tomago, NSW ⁴	523	523	523	523	528	528	541	548	530
Vic/Tas/NSW	1382	1395	1423	1425	1395	1374	1393	1293	1389
Australia ⁵	1890	1912	1954	1965	1980	1926	1943	1943	1939
PFC-14 emiss.	200±60	76±22	65±19	50±15	40±12	33±10	35±10	34±10	67±20
emiss. fact.	106±32	40±12	33±10	25±8	20±6	17±5	18±6	17±5	35±10
PFC-116 emiss.	26±8	10±3	8±3	7±2	5±2	4±1	4±1	4±1	9±3
emiss. fact.	14±4	5±2	4±1	3±1	3±1	2±1	2±1	2±1	4±2
ТАРМ									
PFC-14 emiss.									
Portland, Vic	18±5	18±6	15±8	15±8	12±8	12±7	11±7	10±6	13±6
Point Henry, Vic	11±3	11±3	11±3	10±3	9±3	7±3	7±3	7±3	8±3
Bell Bay, Tas	5±2	5±3	4±3	4±3	4±2	3±2	3±2	3±2	4±2
Vic/Tas	34±10	33±12	30±10	29±12	25±12	22±10	21±11	20±10	25±11
Australia ⁶	94±30	95±30	83±40	82±35	71±35	65±30	61±30	58±30	75±30
NAME									
PFC-14 emiss. ⁷	182±65	157±75	68±55	45±30	44±30	47±30	51±30		85±50
PFC-116 emiss. ⁸	15±1	15±1	15±1	15±1	19±3	23±5	29±3	29 ¹³	20±2
PFC-218 emiss. ³	9±1	10±1	11±1	12±1	19±3	21±3	20±2	20	15±5
TAPM/NAME									
PFC-14 emiss.	138±46	125±54	75±43	63±33	58±34	55±30	56±30	56±31	78±37
PFC-116 emiss. ⁸	14±6	13±7	8±5	6±4	6±4	6±3	6±3	6±3	8±4
ISC	-	-		-	-				-
PFC-218 emiss.	8±3	9±3	10±4	7±3	9±4	14±6	16±6	15±6	11±5
PFC-318 emiss.	27	27	27	27 ¹²	27±18	23±9	21±7	18±6	1125
ISC/NAME									
PFC-218 emiss.	9±3	9±3	10±4	10±3	14±5	17±7	18±6	17±6	12±7
total PFC emiss.	187±60	174±60	120±50	10±5	104±40	102±35	101±35	114±35	126±45
CO_2 -e M t		1.29±0.55							120145
PFC-14 emiss. fact.	1.30±0.30	1.25±0.55	0.55±0.45	0.04±0.35	0.05±0.45	0.01±0.55	0.75±0.51	0.07±0.51	
Portland, Vic	54±17	56±18	44±25	44±25	37±25	39±24	36±24	33±23	43±24
Point Henry, Vic	62±20	60±18	55±19	53±17	52±18	40±17	30±24 39±21	39±23	43±24 50±19
Bell Bay, Tas	28±13	27±18	25±19	22±15	20±11	40±17 19±7	19±9	19±11	22±12
Australia (TAPM) ⁹	48±16	50±17	42±20	41±20	37±17	34±18	32±14	31±10	39±19
Australia (NAME) ¹⁰	96±34	82±40	35±28	23±14	23±15	25±15	27±15	51210	44±11
TAPM/NAME avg	72±24	66±27	39±24	32±17	30±16	29±16	29±15		42±15
emiss. fact. Kurri Kurri ¹¹	, 2:27	00±27	<u>3</u> 3≟2 4	52:17	35±10	23:10	23:13		72113

¹Alcoa Annual Sustainability Reports, 2003,2004, 2005, 2006, 2009, 2011/2012

²Bell Bay Aluminium Environmental Sustainability Report 2012

³ Dalzell, E., Hydro Australia 2013, personal communication

⁴Rio Tinto Annual Report 2012

⁵DoE (2014), uncertainty 25-30% - DCCEE (2012)

⁶ Australian emissions scaled from Portland, Pt Henry, Bell Bay emissions by aluminium production

⁷ Australian emissions scaled from Portland, Pt Henry, Bell Bay, Kurri Kuri, Tomago emissions by aluminium production

 ${}^{8}C_{2}F_{6}/CF_{4} = 0.1$, Kim *et al.*, (2014)

⁹ TAPM (Portland, Pt Henry, Bell Bay average emissions)/aluminium production

¹⁰ NAME (Vic/Tas/NSW) emissions/aluminium production NAME emissions for 2011 are preliminary – based on 2010-2011 data only

¹¹emission factor for 2009 (Fraser et al., 2013)

¹² assume = 2009 emissions

¹³ assume = 2011 emissions

4.2 Other PFC emissions

Australian PFC emissions are dominated by the aluminium industry – only aluminium production-derived emissions of PFC-14 and PFC-116 are currently listed in the *National Inventory Report* (Table 5). PFC imports in 2012 are small (Table 2 - PFC-14: 0.3 tonne, PFC-116: 0.5 tonne, PFC-318: 0.1 tonne). These imports are presumably for minor refrigeration and fire-fighting applications, and the corresponding emissions from these non-aluminium sources are likely to be less than 1 tonne per year.

Figure 6 shows the Australian PFC-116 emissions from the *National Inventory Report*, from PFC-14 emissions (TAPM/NAME) assuming a PFC-116/PFC-14 mass emission factor of 0.10 ± 0.01 , based on atmospheric observation at Aspendale on the Pt Henry/Portland PFC plumes and on direct measurements on the Kurri Kurri exhaust stack (Fraser *et al.*, 2013; Kim *et al.*, 2014). The overall agreement is good as expected, as the emissions are from the aluminium industry only, with current emissions (since 2009) of about 6 tonnes per year. However the PFC-116 emissions for Australia based on measurements at Cape Grim, again assuming coming from the aluminium industry only, show significant differences in emissions after 2007, with PFC-116 emissions rising to approaching 30 tonnes in 2011.

Since Cape Grim largely 'sees' PFC emissions from the Victorian smelters and any other emissions from the Melbourne/Port Phillip region, the data would suggest that significant, post -2007, a non-aluminium PFC-116 source is in operation, and this PFC-116 is not captured in the import data. Australia-wide, this source could be currently approaching 20 tonnes per year. The source of this additional PFC-116 is unknown. Further analysis of past and future Aspendale and Sydney PFC-116 data could help identify this source.

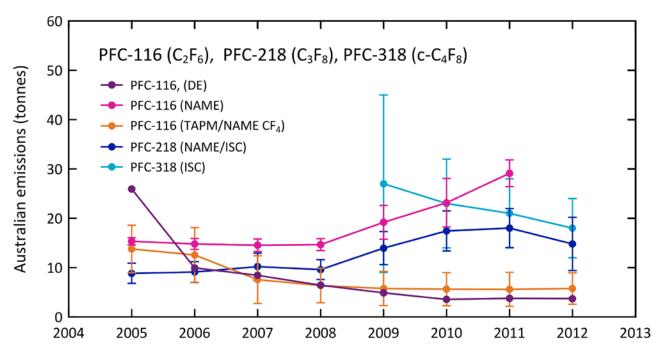


Figure 6. Australian PFC-116, PFC-218 and PFC-318 emissions from the *National Inventory Report 2012* (DE, 2014) and as derived from atmospheric measurements at Cape Grim using NAME, TAPM and ISC modelling; error bars are ± sd. Australian PFC-116 (NAME) are from Vic/Tas data scaled by aluminium production, PFC-116 (TAPM/NAME PFC-14) are from Australian TAPM/NAME PFC-14 emissions (Table 4) and the observed PFC-116/PFC-14 ratio (0.10±0.01) in Australian smelter plumes; PFC-218 and PFC-318 are from NAME and ISC modelling, with Australian emissions obtained from regional emissions by population scaling.

Cape Grim data also suggest that there are significant Australian PFC-218 and PFC-318 emissions, the former increasing from about 10 tonnes in the mid-2000s to nearly 20 tonnes in 2010, declining to 12 tonnes in 2012 currently and the latter declining from nearly 30 tonnes in 2009 to currently less than 20 tonnes. The sources of PFC-218 and PFC-318 are unknown; there are no significant PFC-218 or PFC-318 imports recorded. The PFC-218 emissions are about the same size as the non-aluminium PFC-116 emissions, with a similar growth pattern. This suggests their emissions may be related.

Total PFC emissions have declined from about 190 tonnes in 2005 (80% from aluminium production) to about 100 tonnes (60% from aluminium production) in 2010, rising to over 110 tonnes in 2012 (55% from the aluminium

industry), compared to the *Inventory*, which has total PFCs (PFC-14, PFC-116) declining from 225 tonnes in 2005 to 37 tonnes (all from the aluminium industry). In CO_2 -e terms, total PFCs have declined from 1.4 Mt CO_2 -e in 2005 to 0.8-0.9 Mt CO_2 -e in 2011-2012, compared to the *Inventory* figures of 1.5 Mt CO_2 -e in 2005 falling to 0.25 Mt CO_2 -e in 2012. This is because the *Inventory* only includes PFCs from the aluminium industry, whereas Cape Grim sees PFC emissions from all potential sources (aluminium, refrigeration, fire fighting and possibly other sources).

4.3 HFC, SF₆ & SO₂F₂ emissions

CSIRO estimates emissions of a number of trace gases from the Melbourne/Port Phillip region (Dunse *et al.*, 2001, 2005; Dunse 2002; Fraser *et al.*, 2014), utilising *in situ* high frequency measurements from the Cape Grim Baseline Air Pollution Station in Tasmania and employing the interspecies correlation (ISC) technique with co-incident carbon monoxide (CO) measurements.

Port Phillip HFC, PFC-116 and SF₆ emissions have been calculated, using ISC and Cape Grim data (2004-2013), obtained from the GC-MS-Medusa and GC-ECD instruments (Krummel *et al.*, 2011; Miller *et al.*, 2008) at Cape Grim, and presented as 3-year running averages (2005-2012; Table 6, Figure 7). The HFC, PFC-116 and SF₆ emissions are derived from Port Phillip emissions, scaled to Australian emissions on a population basis (using a population-based scale factor of 5.4). NOAA air mass back trajectory analyses (Draxler & Hess, 1997) are used to ensure that the pollution events at Cape Grim used to derive Port Phillip emissions are imbedded in air masses that only pass over the Port Phillip region and do not include other possible high CO source regions, in particular the Latrobe Valley, or high CO emission events (biomass burning).

For HFC emission calculations, the NAME particle dispersion model (Manning *et al.*, 2003, 2011) 'sees' emissions from Victoria/Tasmania (the domain used in the model) and are presented as 3-yr running averages of emissions (i.e. 2008 annual emissions are derived from 2007-2009 data). The Australian emissions are calculated from Victoria/Tasmania using a population based scale factor of 3.7 and are shown in Table 6 and Figure 7.

Cape Grim 'sees' SO_2F_2 emissions from South-East Australia. Cape Grim SO_2F_2 measurements commenced in 2004, but significant pollution episodes (as selected for ISC calculations) were not observed at Cape Grim until 2010. These pollution episodes are used to calculate South-East Australian (largely Victorian) SO_2F_2 emissions by ISC. Grain exported from Victorian grain terminals, or produced in Victoria, accounts for about 15-20% of Australia's grain production/exports (National Transport Commission, 2008; GrainCorp, 2012) and thus possibly 15-20% of Australia's emissions of SO_2F_2 . South-East Australian SO_2F_2 emissions calculated from Cape Grim data by ISC are scaled to Australian emissions by this factor (i.e. multiplied by 6.2±0.6) (Table 6, Figures 7 and 8). The NAME model domain used to derive SO_2F_2 emissions is Victoria/Tasmania/New South Wales, and the scale factor used to derive Australian emissions, based on grain production, is 2.1±0.2. Australian emissions of SO_2F_2 averaged about 40 tonnes per year (160 k tonnes CO_2 -e) over the period 2010-2012. Data on SO_2F_2 imports are not available.

5 Comparisons of NGA, ISC & NAME emission estimates

5.1 HFC-134a

The major HFC in the *Inventory* (ageis.climatechange.gov.au; DoE 2014) is HFC-134a, with emissions in 2012 of 3235 tonnes (Table 5). Based on Cape Grim data, Australian emissions of HFC-134a in 2012 were about 2010 tonnes (ISC), ~38% lower than reported in the *Inventory* (Table 6, Figure 7). For the 8-year period 2005-2012, the average Australian emissions of HFC-134a calculated from Cape Grim data (ISC/NAME) are about 27% lower than in the *Inventory*. From 2002 to 2011, the ISC and NAME emissions estimates agree to within 2% (NAME higher). For the period 1999-2004, Australian emissions based on Cape Grim data are higher than the *Inventory*, and, for 2006-2012, lower than the *Inventory*. As discussed in Section 3.1 above, the *Inventory* best represents total HFC emissions, not individual HFC emissions.

Cape Grim data suggest that Australian emissions of HFC-134a have been in decline since 2009, whereas the *Inventory* reports growing emissions through 2012. The assumes time-invariant emission factors, whereas the Cape Grim data may be seeing reduced emissions due to, for example, improved equipment maintenance practices, with better management of HFC emissions. Based on atmospheric data, global emissions of HFC-134a were 174 k tonnes in 2012 (Rigby *et al.*, 2014). Australian emissions are about 1.1% of global emissions based on ISC/NAME data, and 1.8% based on *Inventory* data.

5.2 HFC-125

The next major HFC emitted into the Australian environment is HFC-125 with current (2012) emissions estimated to be about 1130 tonnes in the *Inventory*. Based on Cape Grim data, Australian emissions of HFC-125 in 2012 were about 600 tonnes (ISC), about 47% lower than the *Inventory* data. For the period 2005-2012, the *Inventory* average emissions are 60% higher than emission estimates based on Cape Grim data (ISC/NAME). Over the period 2002-2011, NAME and ISC emission estimates agree to within 2% (NAME lower). ISC/NAME estimates of HFC-125 emissions have grown from 350 tonnes in 2005 to nearly 600 tonnes in 2012. Like HFC-134a, the Cape Grim HFC-125 data suggest near constant or perhaps declining emissions, whereas in the *Inventory* the emissions continue to grow through 2012 (Table 4). Based on atmospheric data, global emissions of HFC-125 were 41 k tonnes in 2012 (Rigby *et al.*, 2014). Australian emissions are about 1.5% of global emissions based on ISC/NAME data, and 2.6% based on *Inventory* data.

5.3 HFC-143a

According to the *Inventory* (Table 4), the next major HFC emitted into the Australian environment is HFC-143a with current (2012) emissions at about 110 tonnes. Based on Cape Grim data, Australian emissions of HFC-125 in 2012 were about 550 tonnes (ISC), a factor of 5 higher than *Inventory* estimates. NAME and ISC data agree to within 1% for the period 2005-2011 (NAME higher). Like HFC-134a and HFC-125, the Cape Grim HFC-143a data suggest near constant or perhaps declining emissions, whereas in the *Inventory* the emissions continue to grow through 2012 (Table 4). Based on atmospheric data, global emissions of HFC-143a were 23 k tonnes in 2012 (Rigby *et al.*, 2014). Australian emissions are about 2.4% of global emissions based on ISC/NAME data, and 0.5% based on *Inventory* data.

5.4 HFC-32

HFC-32 emission estimates are estimated in the *Inventory* to be 63 tonnes in 2012. The emissions based on Cape Grim data (211 tonnes in 2012) are significantly higher than in the *Inventory*. Over the period 2006-2011, ISC and NAME emission estimates agree to within 36% (NAME lower). Unlike HFC-134a, HFC-125 and HFC-143a, the Cape Grim data and the *Inventory* both suggest increasing emissions of HFC-32 through 2012. Based on atmospheric data, global emissions of HFC-32 were 20 k tonnes in 2012 (Rigby *et al.*, 2014). Australian emissions are about 1.1% of global emissions based on ISC/NAME data, and 0.3% based on *Inventory* data.

5.5 HFC-152a

HFC-152a emissions are not listed in the *Inventory*. The 2012 emissions have been estimated from Cape Grim data at 77 tonnes (ISC). Over the period 2002-2011, ISC and NAME estimates of Australian emissions agree to within 1% (NAME higher). With no recorded imports of HFC-152a into Australia, the source of the HFC-152a emissions is unknown. Like HFC-32, the Cape Grim data show that HFC-152a emissions continue to grow through 2012.

Based on atmospheric data, global emissions of HFC-152a were 54 k tonnes in 2012 (Rigby *et al.*, 2014). Australian emissions are about 0.1% of global emissions based on ISC/NAME data. It would be unusual for Australian emissions of an industrial chemical to be less than 0.1% of global emissions. The possible reasons for the low Australian emission (low use in Australia compared to rest of world) are being investigated. One suggestion (M. Bennett, RRA, personal communication, 2011) is that a significant major-volume use in other parts of the world for HFC-152a is as an aerosol propellant, a use not taken up in Australia.

5.6 HFC-23

HFC-23 emissions are not listed in the *Inventory*, except in the 1990s when Australian emissions were estimated as fugitive emissions from Sydney-based Australian HCFC-22 production. Since HCFC-22 production ceased in Australia, the *Inventory* does not record HFC-23 emissions. Imports are currently recorded at about 1 tonne in 2012. The 2012 emissions have been estimated from Cape Grim data at 46 tonnes (ISC). Over the period 2002-2011, ISC and NAME estimates of Australian emissions agree to within 18% (NAME lower). HFC-23 emissions have remained relatively constant since 2007. In CO₂-e terms, HFC-23 is currently the 4th largest HFC emitted in Australia (after HFC-134a, HFC-143a and HFC-125), larger than HFC-32. This is because the GWP of HFC-23, at nearly 12,000, is about 2.5 times larger than the next most potent HFC (HFC-143a, GWP 38000). Based on atmospheric data, global emissions of HFC-23 were

12 k tonnes in 2012 (Rigby *et al.*, 2014). Current Australian emissions are about 0.4% of global emissions based on ISC/NAME data, 0% based on the *Inventory*.

The origin of these Australian HFC-23 emissions is unknown. HFC-23 is a component of the R-508 series of refrigerants, but significant imports of R-508 refrigerants into Australia have not been recorded. The other component of the R-508 refrigerants is PFC-116; current Australian emissions of PFC-116 are significantly larger than result from to aluminium production and current imports. If significant amounts of R-508 refrigerants have been imported in the past into Australia, but not accounted for, then emissions of R-508 could explain these significant HFC-23 and PFC-116 emissions.

RRA (M. Bennett, private communication, 2014) is not aware of any significant historical use of R-508 refrigerants in Australia. RRA in their refrigerant reclaim operation have collected only one cylinder of R-508 from a CSIRO instrument testing laboratory in Sydney. It is unlikely that the unaccounted for HFC-23 and PFC-116 is from past or current use of R-508 refrigerants in Australia.

Aspendale atmospheric data on HFC-23 (unpublished) and PFC-116 (Kim *et al.*, 2014) show very different concentration/wind direction (so-called concentration 'roses') at Aspendale. The PFC-116 data show a clear, strong maximum in the direction (W of Aspendale) of the Pt Henry and Portland smelters, confirming an aluminium-production source, and essentially noise in the other wind sectors. The HFC-23 data show a significant, but small concentration maximum in the direction NE of Aspendale (as do HFC-134a, HFC-32, HFC-125 etc). It would appear that HFC-23 is in the general mix of refrigerant emissions from Melbourne, but has not been identified in any Australian refrigerant imports.

One possible explanation is that HFC-23 (CHF_3) is present in refrigerant blends as a contaminant – for example with blends containing HFC-32 (CH_2F_2). It is possible that overfluorination during the production of HFC-32 could produce HFC-23 and that the resultant refrigerant blends using HFC-32 could contain, likely small, amounts of HFC-23. CSIRO plan to test this hypothesis in a project designed to test the stated composition of the major refrigerants and refrigerant blends used in Australia, which are HFC-134a, R-410 (50% HFC-32, 50% HFC-125), R-404 (44% HFC-125, 4% HFC-134a, 52% HFC-143a) and R-407 (20% HFC-32, 40% HFC-125, 40% HFC-134a).

5.7 HFC-227ea

HFC-227ea emissions are now listed in the *Inventory*, with 2012 emissions at 38 tonnes. The 2012 emissions have been estimated from Cape Grim data at 19 tonnes and 26 tonnes in 2011 (ISC). The *Inventory* average emissions (2005-2012) are 29 tonnes compared to 23 tonnes from Cape Grim data. There are no NAME estimates of HFC-227ea emissions from Cape Grim data. The *Inventory* suggests that HFC-227ea emissions continue to grow through 2012, whereas the Cape Grim data suggest that emissions peaked at just over 30 tonnes in 2009.

Based on atmospheric data, global emissions of HFC-227ea were 3.3 k tonnes in 2012 (Rigby *et al.*, 2014). Australian emissions are about 0.6% of global emissions based on ISC/NAME data and 1.2% based on *Inventory* data.

5.8 HFC-236fa, HFC-245fa, HFC-365mfc

The 2012 emissions for HFC-236fa, HFC-245fa and HFC-365mfc have been estimated (ISC) from Cape Grim data at about 5 (steady), 117 (growing rapidly) and 66 tonnes (peaked in 2010 at 70 tonnes) respectively. NAME estimates of HFC-365mfc emissions are available (2005-2011). From 2009-2011, the ISC and NAME estimates agree to within 15%, prior to 2009 NAME estimates of emissions are significantly higher than ISC by a factor of 2-3. There are no estimates of emissions of these HFCs in the *Inventory*.

Based on atmospheric data, global emissions of HFC-236fa, HFC-245fa and HFC-365mfc were 0.2, 8.2 and 3.3 k tonnes respectively in 2012 (Rigby *et al.*, 2014). Australian emissions are about 2.1%, 1.4% and 2.0% of global emissions based on Cape Grim data.

5.9 HFC-134 & HFC-4310mee

Emissions of HFC-134 and HFC-4310mee in the *Inventory* were about 1 tonne each in 2012. HFC-134 is not measured at Cape Grim and, although HFC-4310meee is measured, no significant Australian emissions have been detected to date.

Table 6. Australian HFC, PFC, SF₆ and SO₂F₂ emissions (tonnes, 2005-2012) from atmospheric data, collected at Cape Grim, Tasmania - emissions calculated by interspecies correlation (ISC) and from inversions using the UK Met. Office NAME particle dispersion model. The emissions are 3-year running averages, i.e. '2010' = average of 2009, 2010, 2011 emissions. Australian HFC and SF₆ emissions are scaled from regional emissions by population; GWPs (to calculate CO₂-e emissions) are from the *National Inventory Report 2012* (DoE, 2014). PFC-14 emissions are the TAPM/NAME average from Table 4. Australian PFC-116 emissions are from NAME (Vic/Tas) scaled by aluminium production; Australian PFC-218 and PFC-318 emissions are from NAME and ISC scaled by population; Australian SO₂F₂ emissions are from ISC and NAME estimates of SE Australian emissions scaled by grain production.

	2005		2006		20	2007		08	20	09	2010		2011		2012
Refrigerant	ISC	NAME	ISC	NAME	ISC	NAME	ISC	NAME	ISC	NAME	ISC	NAME	ISC	NAME	ISC
	tonn	ies	ton	nes	tonnes		ton	onnes tonnes			tonnes		tonnes		tonnes
HFC-32	36±10	34±5	62±20	40±10	116±45	61±15	129±45	96±20	170±60	134±20	196±65	162±20	205±65	172±10	211±65
HFC-125	392±130	311±15	375±120	326±20	460±170	402±60	516±180	553±80	642±200	685±60	642±210	738±45	614±190	753±25	598±190
HFC-134a	1686±510	1613±90	1707±530	1668±110	1832±620	1830±150	1843±595	1997±165	2148±660	2279±120	2141±700	2262±120	2111±650	2169±140	2008±640
HFC-143a	454±155	337±20	436±150	352±30	481±170	451±65	503±170	550±60	624±200	687±55	597±195	750±60	505±165	771±35	555±185
HFC-23	50	34	50	34	50±25	34	56±20	34±3	58±20	43±4	44±15	44±6	41±15	55±5	46±15
HFC-152a	32±10	31±2	38±10	35±3	51±15	41±3	49±15	43±3	52±15	68±4	59±20	69±5	56±15	72±4	77±25
HFC-227ea	15±9	15	12±6	12	17±7	17	22±8	22	36±13	36	33±10	33	26±9	26	19±5
HFC-236fa	13±10	13	5±3	5	5±3	5	4±2	4	5±2	5	6±2	6	6±2	6	5±2
HFC-245fa	27±15	27	30±12	30	32±13	32	28±10	28	32±13	32	38±14	38	49±18	49	117±43
HFC-365mfc	8±3	13	25±10	13±1	33±13	15±2	50±18	16±3	61±20	47±13	74±25	64±10	69±24	68±3	66±23
total HFCs	2714±580	2428±95	2741±570	2515±115	3078±670	2888±175	3198±650	3343±195	3828±720	4016±145	3830±700	4166±145	3682±660	4139±150	3702±690
total HFCs NAME/ISC avg (t)	2571±	:340	2628:	2628±340		2983±420		3271±420		3922±430		±420	3911±405		3702±690
total HFCs (kt CO ₂ -e)	5364±	:550	5337:	337±570		6073±750		6765±790		8164±820		8252±820		±750	7357±1360
SF ₆ (tonnes)			75±25	29±2	44±26	31±3	33±12	34±2	34±13	44±3	37±14	43±3	33±12	44±2	31±11
SF ₆ NAME/ISC avg (t)	52		52±	:25	38±	:26	341	:12	39:	±13	40:	±14	38±	12	31±11
SF ₆ (kt CO ₂ -e)	1243±	:590	1243:	±590	908±	620	813±	280	932:	±310	956:	±330	908±	280	741±260
SO ₂ F ₂ (tonnes)		2±2		2±2		4±3		17±14	18±8	3±4	88±36	14±17	95±38	88±20	81±30
SO ₂ F ₂ NAME/ISC avg (t)	2±2	2	2±	:2	4±	:3	17±	:15	11:	±10	51:	±40	92±	:30	81±30
SO_2F_2 (kt CO_2 -e)	8±8	8	8±	:8	16±	:12	70 1	:60	45:	±40	209:	±160	375±	120	331±120
total PFCs (t, Table 5)	187±	:60	174:	±60	120:	±50	107	±40	104	±40	102	±35	101	±35	96±35
total PFCs (ktCO ₂ -e)	1378±	:500	1291:	±550	929±	:490	836±	:390	829:	±430	809:	±350	791 1	310	743±310
total HFCs, PFCs, SF ₆ avg	2810±	420	2854:	±420	3141:	±500	3412	±470	4066	±470	4140	±490	4049	±440	3829±740
total HFCs, PFCs, SF ₆ avg	7985±	:750	7870:	±830	7910:	±930	8414	±870	9924	±900	10016	5±880	9754	±810	8842±1650
(k tonnes CO ₂ -e)															

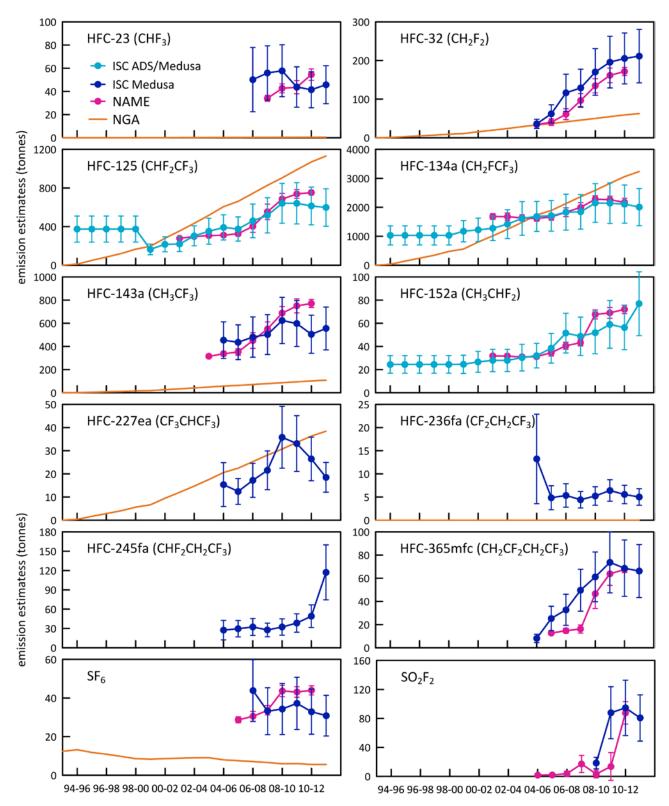
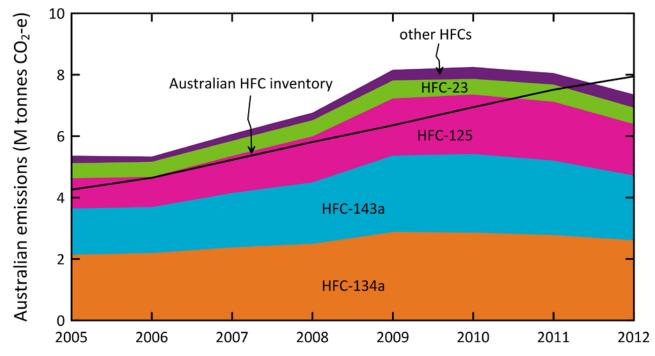


Figure 7. Australian HFC-32, -125, -134a, -143a, -152a, -365mfc and SF₆ emissions (NGA: DE 2014) compared to emissions calculated from Cape Grim data by interspecies correlation (ISC) and from the UK Met. Office NAME particle dispersion model. In the ISC calculations of HFC and SF₆ emissions, Australian emissions are scaled from Melbourne/Port Phillip emissions on a population basis (5.4, Australia/Port Phillip); in the NAME calculations, Australian emissions are scaled from Victorian/Tasmanian emissions, also on a population basis (a scale factor of 3.7). Also shown are Australian SO₂F₂ emissions from ISC and NAME, scaled on a grain production basis.

5.10 Total HFCs

Total HFC emissions (Table 6), based on Cape Grim observations, have grown from over 2500 tonnes in 2005 to 4000 tonnes in 2010, declining to about 3700 tonnes in 2012. The latter estimate is from ISC data only and may change once NAME 2012 data are incorporated. Total HFC emissions in 2012 are 19% lower than in the *Inventory*, due largely to the 38% lower emissions of HFC-134a emissions from atmospheric data compared to *Inventory* data. Over the period 2005-2012, total HFC emissions in the *Inventory* are in good agreement (within 4%) of total emissions based on Cape Grim data (ISC, NAME lower).

Total HFC emissions in the *Inventory* in 2012 are 7.95 Mt CO_2 -e, higher (within 8%) than emissions (7.36±1.3 Mt CO_2 -e, ISC) based on Cape Grim data (Table 4, Table 6, Figure 8). The uncertainties on the ISC emission estimates overlap the *Inventory* estimates. Over the period 2005-2012, the total HFC emissions in the *Inventory* are 49 Mt CO_2 -e, compared to 55 Mt CO_2 -e (11% higher) from Cape Grim data (ISC/NAME).





5.11 Sulfur hexafluoride

Sulfur hexafluoride emissions in the *Inventory* are about 6 tonnes per year in 2012 (Table 4, Figure 9). Estimates using Cape Grim data (ISC/NAME: Table 6, Figure 9) are 52 tonnes in 2006, decreasing to 31 tonnes in 2012, a decrease of about 8% per year. NAME estimates of SF₆ emissions are about 20% lower than ISC over the period 2006-2011, but 10% higher over the period 2007-2011. In CO₂-e terms SF₆ emissions have fallen by 0.5 Mt CO₂-e, from 1.24 Mt CO₂-e in 2006 to 0.74 Mt CO₂-e in 2012 based on Cape Grim data, whereas in the *Inventory* SF₆ emissions have fallen by only 0.05 Mt CO₂-e, from 0.19 to 0.13 Mt CO₂-e over the same period.

A recent inversion study, using a combined Eulerian chemical transport model and a Lagrangian particle dispersion model (CTM-LPDM; Rigby *et al.*, 2011) has been used to derive global and regional (including Australian) emissions. Using Cape Grim, the CTM-LPDM calculated emissions from Tasmania, Victoria and southern NSW (including Sydney). Scaling the results to Australian emissions, based on the fraction of the EDGAR prior estimate that is emitted into the prescribed domain (64%), results in average Australian emissions (2007-2009) of 16±10 tonnes. This study was repeated (Ganesan *et al.*, 2014), with an improved estimate of emissions and their uncertainties, resulting in Australian emissions in 2012 of 17±9 tonnes (with an expanded prior region, including Adelaide, containing 85% of Australian emissions). The combined ISC/NAME data over this period suggest emissions of 37 tonnes, whereas the *Inventory* reports 6-7 tonnes per year over this period. In these studies, Sydney, the likely largest SF₆ source region in Australia, is on the edge of the chosen model domain, and this may introduce potential errors into the inversion. If the

inversion is not accurately capturing (underestimating) the Sydney emissions, as seen in the Cape Grim data, then the scaling factor may be too low, resulting in an underestimate of Australian emissions.

Based on atmospheric data, global emissions of SF₆ were 8.1 k tonnes in 2012 (Rigby *et al.*, 2014). Australian emissions are about 0.4% of global emissions based on ISC/NAME data, but < 0.1% based on the *Inventory* data. It would be unusual for Australian emissions of a widely-used industrial chemical to be <0.1% of global emissions.

The Australian SF_6 emissions from atmospheric data and in the *Inventory*, and SF_6 import data, are shown in Figure 9. Also shown in Figure 9 are the *Inventory* emissions recalculated using default IPCC emission factors rather than the Australian specific emissions factors currently employed in the *Inventory*. The major difference between the default and Australian-specific SF_6 emission factor is for the manufacturing sector, where the current Australian-specific factor is 0.06 compared to the original IPCC default factor of 0.74. Clearly the 'bottom-up' estimates of SF_6 emissions are very dependent on assumed emission factors. These need to be independently verified.

Ultimately, accurate import data will approximately match the sum of emissions and a growth in the banked SF_6 , which have grown over the past 5 years by about 5 tonnes per year. The average imports for 2012-2013 are 27 tonnes per year which may be larger than required due to stockpiling. Eventually import data will match emissions plus bank growth. Clearly, at present, a SF_6 bank growth of 5 tonnes per year and emissions in the *Inventory* of 6 tonnes per year are not consistent with current imports of 27 tonnes per year.

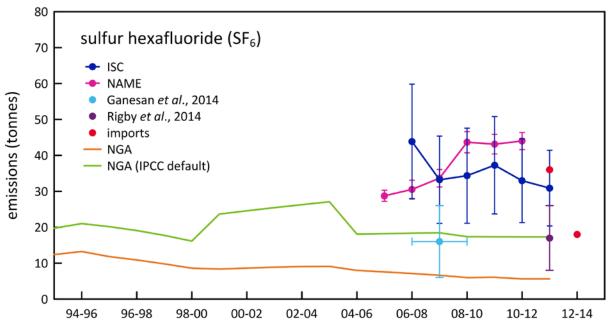


Figure 9. Australian SF₆ imports and emissions (tonnes) from Cape Grim data and from the NGA (Inventory)

5.12 Sulfuryl fluoride

Based on Cape Grim data, Australian sulfuryl fluoride emissions averaged less than 10 tonnes per year from 2005-2007, but then increased rapidly to average about 80-90 tonnes per year in 2011-1012. Presumably this reflects a change in grain fumigation practices away from using methyl bromide and phosphine. Global emissions were 3000 tonnes per year (2011-2012, Rigby *et al.*, 2014). Australian emissions are 2-3% of global emissions. Australia is responsible for 3% of global wheat production, but 10-15% of wheat exports. SO_2F_2 is more closely related to wheat production (grain storage in Australia's interior) than to wheat export (grain storage at export ports, fumigated with methyl bromide).

In CO₂-e terms, SO₂F₂ emissions averaged about 350 k tonnes CO₂-e in 2011-2012, compared to 820 k tonnes CO₂-e for SF₆ and 770 k tonnes CO₂-e for PFCs; HFCs averaged about 7700 k tonnes CO₂-e in 2011-2012.

In climate change terms, Australian SO_2F_2 emissions are now about 50% of the radiative forcing of PFCs, and possibly growing quite rapidly. Clearly there needs to be a close watch on future SO_2F_2 emissions in relation to their contribution to radiative forcing due to SGGs.

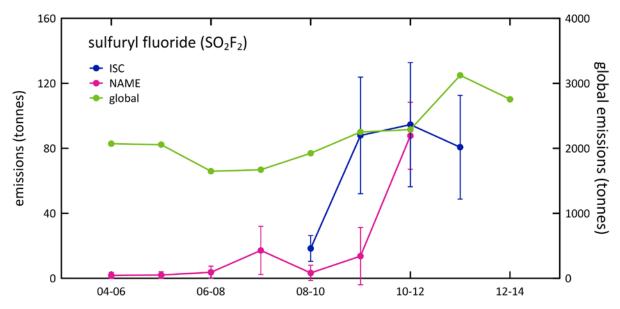


Figure 10. Australian SO₂F₂ emissions (tonnes), scaled from SE Australian emissions on a grain production basis, derived from Cape Grim in situ data, using ISC techniques; global emissions (tonnes) are from Rigby *et al.*, 2014.

5.13 Total HFCs, PFC and SF₆ emissions

Total HFCs, PFCs, SF₆ emissions in CO₂-e are shown in Table 6 and Figure 11.

Total Australian HFC, PFC and SF_6 emissions in the *Inventory* are 4.6 k tonnes in 2012, higher (19%) than estimates based on Cape Grim data: 3.8 ± 0.7 k tonnes (ISC). Over the period 2005-2012 the *Inventory* estimates are 1% higher than estimates based on Cape Grim data (ISC/NAME).

Total Australian HFC, SF₆ and PFC emissions, expressed as CO₂-e, in the *Inventory* are 8.3 Mt CO₂-e in 2012, 6% lower than estimates based on Cape Grim data: 8.8±1.6 Mt CO₂-e (ISC) (Figure 8). Over the period 2005-2012, total Australian emissions of HFCs, PFCs and SF₆, based on Cape Grim data (70 Mt CO₂-e) are about 30% higher than the same emissions in the *Inventory* (54 Mt CO₂-e). In all categories (HFCs, PFCs, SF₆) the atmospheric data give higher estimates of emissions than in the *Inventory*. The relative contributions to the difference (2.7 Mt CO₂-e) in 2011 are HFCs (~50%), SF₆ (~34%) and PFCs (16%).

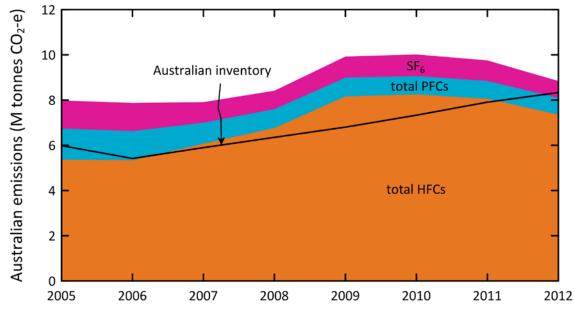


Figure 11. Australian HFC, PFC, SF₆ emissions calculated from Cape Grim observations and in the NGGI/NGA (ageis.climatechange.gov.au) in Mt CO₂-e.

Summary

- CSIRO, through involvement in the international AGAGE (Advanced Global Atmospheric Gases Experiment) program, has now measured and reported atmospheric concentrations, temporal trends and emissions for eleven HFCs (HFC-23, -32, -125, -134a, -143a, -152a, -227ea, -236fa, -245fa, -365mfc, -4310meee), nine PFCs (PFC-14, -116, -218, -318, -3110, -4112, -5114, -6116, -7118), SF₆, CF₃SF₅ and SO₂F₂, utilizing data from the background atmosphere at Cape Grim, Tasmania, and from the urban atmosphere at Aspendale, Victoria. The AGAGE program involves collaborating scientists from the USA, Australia, China, Italy, Korea, Norway, Switzerland and the UK, who operate a global measurement network and, through a variety of modelling initiatives, estimate lifetimes and emissions of all the significant non-CO₂ GHGs, from both ozone depletion and climate forcing perspectives.
- All HFCs (except HFC-152a), all PFCs, SF₆, SO₂F₂ (but not CF₃SF₅) show increasing concentrations in the background atmosphere at Cape Grim, which accurately reflects global background atmospheric changes. Significant increases in 2012 (ppt per year) are seen in HFC-134a (4.2), HFC-125 (1.3), HFC-143a (1.1), HFC-32 (0.9), HFC-23 (0.8), PFC-14 (0.6), SF₆ (0.3) and SO₂F₂ (0.1). Total HFCs are growing at 8.5 ppt per year or 6.5% per year, total anthropogenic PFCs at 0.70 ppt per year (1.4% per year), SF₆ at 3.6% per year and SO₂F₂ at 5.8% per year.
- Regional Australian emissions have been detected in the Cape Grim data for all HFCs (except HFC-4310mee), the first four PFCs listed above and SF₆. The emissions have been quantified using a variety of modelling techniques, including interspecies correlation (ISC), forward modelling using the CSIRO TAPM model and inverse modelling using the UK Meteorological Office model NAME. South-East Australian emissions of HFC-4310mee are expected to be seen at Cape Grim over the next few years.
- Import data for 2012 show significant use for most of these HFCs and SF₆ in Australia: HFC-134a (4315 tonnes), HFC-125 (2119 tonnes), HFC-32 (1141 tonnes), HFC-143a (1126 tonnes), HFC-227ea (70 tonnes), HFC-365mfc (53 tonnes), HFC-245fa (44 tonnes) and SF₆ (36 tonnes). Less than 1 tonne of PFCs are imported into Australia. There are no import data available for SO₂F₂. HFC-134 is imported into Australia (2 tonnes) but not measured currently at Cape Grim.
- The National Greenhouse Accounts (Inventory) reports significant Australian annual (2012) emissions of HFC-134a (3235 tonnes), HFC-125 (1132 tonnes), HFC-143a (108 tonnes), HFC-32 (63 tonnes), HFC-227 ea (38 tonnes), PFC-14 (34 tonnes), SF₆ (6 tonnes) and PFC-116 (4 tonnes). Emissions of other HFCs are about or less than 1 tonne each (HFC-23, HFC-134, HFC-4310mee). Emissions of all HFCs are increasing. The *Inventory* emissions calculations are constructed to best estimate total HFC emissions in CO₂-e terms, and are not necessarily representative of the emissions of individual HFCs. Emissions of PFCs (from aluminium production only) and SF₆ in the *Inventory* are declining. Overall the emissions of HFCs, PFCs and SF₆ are increasing due to the dominant influence of HFC emissions.
- Australian HFC, minor PFCs, SF₆ and SO₂F₂ emissions have been estimated from Cape Grim atmospheric data using two independent methods: ISC and NAME. ISC and NAME estimates for HFC, PFC and SF₆ emissions agree, on average over the period 2005-2011, to within 2% for HFC-125, HFC-134a, HFC-143a and HFC-152a, within 15% for HFC-23, HFC-365mfc and SF₆, within 35% for HFC-32, within 50% for SO₂F₂.
- PFC-14 and PFC-116 emissions from the aluminium industry have been estimated using NAME and TAPM (PFC-116 indirectly via PFC-14). TAPM and NAME estimates for PFC-14 emissions agree to within 8%.
- As indicated above, comparisons of emissions of individual HFCs (*Inventory* v. atmospheric data) are not likely to be meaningful, but comparisons of total HFCs could be informative. Over the period 2005-2012, total HFC emissions in the *Inventory* are about 4% higher than total HFC emissions estimated from Cape Grim data (NAME/ISC), with the *Inventory* reporting 4579 tonnes emitted in 2012, compared to 3702 tonnes estimated from Cape Grim data. Unlike the *Inventory*, which shows Australian total HFC emission continuing to grow, Cape Grim data suggest that total HFC emissions peaked in 2010 at close to 4000 tonnes, with 2012 emissions 7% below the peak. There will be an update of 2012 HFC emissions once NAME 2012 data are available.
- Over the period 2005-2012, total HFC emissions, expressed as CO₂-e emissions in the *Inventory* are about 7% lower than total HFC emissions (CO₂-e) estimated from Cape Grim data (NAME/ISC), with the *Inventory* reporting 7.9 M tonnes emitted in 2012, compared to 7.3 M tonnes estimated from Cape Grim data (2012 is the first year that *Inventory* estimates of HFC emissions in CO₂-e exceed estimates from Cape Grim data). Total HFC emissions in CO₂-e terms also peaked in 2010 at 8.2 M tonnes, with 2012 emissions 10% below the peak.

- Australian PFC-14 emissions over the period 2005-2012 have been estimated from atmospheric data by NAME and TAPM inverse and forward modelling respectively. Over the period 2005-2012, PFC-14 emissions in the *Inventory* are in decline and are about 15% lower than PFC-14 emissions estimated from Cape Grim data (NAME/ISC), with the *Inventory* reporting 34 tonnes emitted in 2012, compared to 56 tonnes estimated from Cape Grim data. Both the *Inventory* and Cape Grim data show PFC-14 emissions from the aluminium industry have declined at a similar rate: 55% since 2006 or 9% per year.
- Total Australian PFC-116 emissions and PFC-116 emissions specifically from the aluminium industry have been
 estimated from atmospheric data using ISC, NAME and TAPM. Over the period 2005-2012, PFC-116 emissions in
 the *Inventory* (assumed only from the aluminium industry) and as seen at Cape Grim are in decline. The *Inventory*emissions are about 10% higher than emissions derived from Cape Grim data for the aluminium industry and, like
 PFC-14 emissions, have declined by close to 60% since 2006.
- Total PFC-116 emissions as seen at Cape Grim are increasing, approximately doubling since 2006, currently at 23 tonnes per year. The data suggest that a significant, post -2007, non-aluminium PFC-116 source is in operation in Australia, and this is not captured in the import data. The source of this additional PFC-116 is unknown. Globally, the primary non-aluminium source of PFC-116 is from etching processes used in the electronics industry. Further analysis of past and future Aspendale and Sydney PFC-116 data could help identify this source.
- There is a small but significant source of HFC-23 emissions in Australia. HFC-23 has not been identified in past or current imports of refrigerants or refrigerant blends. It may be present as an unidentified contaminant in imported refrigerant blends. This will be investigated in the 2015 Report.
- Cape Grim observations show that Australian emissions of PFC-218 are growing and PFC-318 emissions are declining, with current emissions for both at about 20 tonnes (PFC-218, 2012; PFC-318, 2011). There are no significant Australian imports identified for these PFCs. Globally PFC-218 and PFC-318 are used in the electronics industry (etching), in refrigeration, in fire suppression and in medical applications. As with PFC-116, further analysis of past and future Aspendale and Sydney PFC-218 and PFC-318 data could help identify source(s) of these PFCs.
- Not surprisingly, total Australian PFCs declined from 2005 to 2008, largely driven by emissions from the aluminium industry and then increased from 2008 to 2011, driven by increasing emissions of non-aluminium derived PFC-116, PFC-218 and PFC-318 emissions. NAME emissions for 2012 are required to confirm (or not) this trend.
- Over the period 2006 2012, both the *Inventory* and Cape Grim data show that Australian SF₆ emissions are in decline (25% decline in the *Inventory*, 40% seen at Cape Grim). However the *Inventory* SF₆ emissions are significantly lower than emissions estimated from Cape Grim data; over the period 2006 to 2012 the SF₆ emissions in the *Inventory* average 7 tonnes per year, about a factor of 6 lower than estimates from Cape Grim over the same period (39 tonnes per year). This is a major discrepancy and is currently under investigation. The *Inventory* estimates are sensitive to the assumed (and uncertain) emission factor in the manufacture of SF₆ containing equipment.
- Australian SF₆ emissions in the *Inventory* are less <0.1% of global emissions. It would be unusual for Australian emissions of a widely-used industrial chemical like SF₆ to be <0.1% of global emissions. A number approaching 1% would be consistent with several other widely used HFCs and HCFCs. The Cape Grim data indicate that Australian emissions of SF₆ were 0.4% of global emissions in 2012.
- Total Australian HFC, PFC and SF₆ emissions, expressed as CO₂-e emissions, over the period 2005-2012 estimated from atmospheric data (Cape Grim, ISC, NAME, TAPM) are about 30% higher than in the *Inventory*, although in 2012 the agreement is much closer (7%, *Inventory* lower). As indicated above, this comes about due to a reasonable agreement over the period 2005-2012 between the *Inventory* and atmospheric data for HFCs (7%, *Inventory* lower), whereas, for PFCs and SF₆, the *Inventory* emissions are substantially lower than those derived from Cape Grim data. In 2012, the combined PFC and SF₆ emissions calculated from Cape Grim data were 146 tonnes, more than a factor of 3 higher than combined PFC and SF₆ emissions in the *Inventory* (44 tonnes).

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