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Australian and global HFC, PFC, Sulfur Hexafluoride, Nitrogen Trifluoride and Sulfuryl Fluoride Emissions

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1 Introduction

Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) are potent greenhouse gases (GHGs), collectively described as synthetic GHGs (SGGs). SGGs are covered by Australia's emission reduction targets under the Kyoto Protocol (2013-2020) and the Paris Agreement (2021-2030). Both the Kyoto Protocol and the Paris Agreement are legally-binding instruments under the United Nations Framework Convention on Climate Change (UNFCCC). 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, solvents, in fire extinguishers and others.

Perfluorocarbons 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.

Nitrogen trifluoride is used internationally in the semi-conductor production industry, initially as a replacement for PFCs. DoEE (2018) has identified a small amount of specialty electronic components manufacturing, consuming around 20 kg of nitrogen trifluoride, which is destroyed in the process. Negligible amounts of electronics cooling fluids containing nitrogen trifluoride are consumed in Australia.

Sulfuryl fluoride (SO_2F_2) and trifluoromethyl sulfur pentafluoride (CF_3SF_5) are potent synthetic greenhouse gases that are not part of the Kyoto Protocol/Paris Agreement suite of SGGs. Sulfuryl fluoride use in Australia is growing, largely as a replacement for phosphine (PH_3) in grain fumigation at the farm level and at regional grain storage locations. Once grain is stored at ports for export, methyl bromide (CH_3Br) is the preferred fumigant. It is unlikely that trifluoromethyl sulfur pentafluoride is used in Australia. Its occurrence in the atmosphere is largely as a by-product of the production of the widely-used surfactant perfluorooctanesulfonic acid (PFOS: $CF_3(CF_2)_7SO_3H$), which has never been manufactured in Australia, but was a key ingredient in fabric stain repellants (e.g. 3M's Scotchguard®) and fire-fighting foams. It is unlikely that there were significant trifluoromethyl sulfur pentafluoride emissions in Australia or overseas associated with PFOS use, only with PFOS manufacture.

Increasing HFC emissions are seen as a significant driver of climate change over the next 50 years (Velders *et al.*, 2007, 2009, 2012, 2014, 2015; Estrada *et al*., 2013; Harris, Wuebbles *et al*., 2014; Myhre *et al*., 2014; Rigby *et al*., 2014). Projections from Daniel and Velders, 2009 suggest that unmitigated HFC growth could result in Global Warming Potential (GWP)-weighted emissions of 9 Gt CO_2-e (carbon dioxide equivalent) per year by 2050. This projection was updated by Velders et al., 2015 (based on more detailed and more current information on HFC use by sector and region) to 4.0-5.3 Gt CO_2-e per year by 2050. A HFC radiative forcing component as high as 0.4 W/m^2 by 2050 was estimated by Daniel and Velders, 2009 (Harris, Wuebbles *et al*., 2014), and was updated by Velders et al (2015) to 0.22-0.25 W m^{-2} (Montzka and Velders, 2018). Global average surface warmings of about 0.1°C by 2050 have been calculated based on the HFC scenarios of Velders *et al*., 2009, 2015 (Xu *et al*., 2013; Hurwitz *et al*., 2016).

Inventory-based reporting of HFC emissions from the United States and Europe are similar to, but higher (10%-20%), than emissions based on atmospheric HFC observations (Lunt *et al*., 2015; Graziosi *et al*., 2017; Brunner *et al*., 2017). United States emissions of HFCs have not increased significantly over the period 2008-2014, with decreasing emissions from mobile air-conditioning (automobiles) and increasing emissions from residential air-conditioning and foams (Hu *et al*., 2017). There is evidence in atmospheric HFC-134a data that the recent global increase in HFC-134a emissions results from increasing emissions (20%/yr) in East Asia, largely China (Fortems-Cheiney *et al*., 2015), offset in part by declining emissions from developed countries.

In 2016, the Kigali Amendment to the Montreal Protocol was adopted (enters into force 1 January 2019), which mandates a phaseout schedule for HFC production and consumption. With global adherence to this Amendment, radiative forcing from HFCs is expected to reduce from 0.22-0.25 W m^{-2} in the baseline scenario from Velders et al., 2015 to 0.13 W m^{-2} in 2050 (Montzka and Velders, 2018).

In 2015, the US Environmental Protection Agency (EPA) prohibited the use of a number of high GWP HFCs as replacements for ODSs in refrigeration. In 2017, a U.S. District Court overturned this regulation, a decision supported by a higher Federal Court in 2018. The European Union (EU) has had a HFC production and import phase-down in place since 2015. Australia's mandated HFC production and import phase down began on 1 January 2018 and will reach an 85% reduction in 2036. In early 2010, the Australian Government made a commitment, in light of the Kyoto

Protocol/Doha Amendment, to reduce its total GHG emissions by 5 per cent below 2000 levels by 2020. New GHG emission reduction targets for implementation post-2020 have been announced by the Australian government: 26%-28% reduction in 2005 emissions by 2030. This includes the commitment to phase down Australian HFC emissions by 85% by 2036. There are no global or Australian targets to phase-down sulfuryl fluoride or trifluoromethyl sulfur pentafluoride emissions, as these gases are not controlled in the Kyoto Protocol, or the subsequent Paris Agreement, due to their relatively low emissions.

The Australian National Inventory reported a total of 549 million tonnes (Mt) CO_2-e emitted from all GHG sources in 2016 (not including land-use change), which was an increase from 2015 emissions (533 Mt) of 3.0% (DoEE, 2017, 2018). HFC emissions were estimated to be 13.2 Mt (13176 k tonnes) CO_2-e in 2016, 2.8% above 2015 emissions, while the sum of HFC, PFC and sulfur hexafluoride emissions was 13.6 Mt (13572 k tonnes, Table 3) CO_2-e, 3.2% above 2015 emissions, and 2.5% of total Australian greenhouse gas emissions (DoEE, 2017, 2018). The total emission of Kyoto Protocol SGGs is the fastest growing emissions sector in the *Australian National GHG Inventory* (referred to subsequently as the *Inventory*).

In this Report, we estimate Australian emissions of HFCs, PFCs, sulfur hexafluoride and sulfuryl fluoride 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 sulfur hexafluoride emissions submitted by the Australian government to the UNFCCC (DoEE, 2017), based on Intergovernmental Panel on Climate Change (IPCC)-recommended 'bottom-up' methodologies for estimating national GHG. Australian HFC, PFC and sulfur hexafluoride emissions are compared to global emissions estimated from AGAGE (Advanced Global Atmospheric Gases Experiment; Prinn *et al*., 2000, 2018; Rigby *et al*., 2014 and updates) atmospheric observations.

Cape Grim *in situ* measurements of nitrogen trifluoride commenced in February 2015 and trifluoromethyl sulfur pentafluoride in late-2010. Preliminary inspections of the data suggest that there are no significant Australian emissions of these species.

2 HFCs, PFCs, sulfur hexafluoride, nitrogen trifluoride, sulfuryl fluoride and trifluoromethyl sulfur pentafluoride at Cape Grim, Tasmania

Concentrations of HFCs, PFCs, sulfur hexafluoride, nitrogen trifluoride, sulfuryl fluoride and trifluoromethyl sulfur pentafluoride have been measured *in situ* in the Southern Hemisphere atmosphere at Cape Grim, Tasmania, as part of the AGAGE program (Prinn *et al*., 2000, 2018) and/or in the Cape Grim Air Archive (1978-2017) 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) (Fraser *et al*., 2016). 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: CF_3CF_3) and the mid-2000s (other PFCs, sulfur hexafluoride, sulfuryl fluoride). Nitrogen trifluoride (up to 2013) and trifluromethyl sulfur pentafluoride (up to 2008) have been measured on the Cape Grim Air Archive. *In situ* measurements of nitrogen trifluoride and trifluoromethyl sulfur pentafluoride have recently become available (February 2015 for nitrogen trifluoride and recently calibrated trifluoromethyl sulfur pentafluoride going back to late 2010). 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; Arnold *et al*., 2014; Fraser *et al*., 2014a, 2016; Krummel *et al*., 2014; Rigby *et al*., 2014; Fortems-Cheney *et al*., 2015; Lunt *et al*., 2015; Simmonds *et al*., 2015, 2016, 2017, 2018; Meinshausen *et al*., 2017; Leedham Elvidge *et al*., 2018; Liang *et al*., 2017
PFCs	Oram, 1999; Fraser *et al*., 2007, 2011, 2013, 2016; 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; Wong *et al*., 2015; Trudinger *et al*., 2016; Meinshausen *et al*., 2017; Leedham Elvidge *et al*., 2018; Droste *et al*., 2018
SF_6	Maiss *et al*., 1996; Oram, 1999; Fraser *et al*., 2004, 2014a, 2016; Levin *et al*., 2010; Rigby *et al*., 2010, 2014; Sturges *et al*. 2012; Ganesan *et al*., 2014; Krummel *et al*., 2014; Meinshausen *et al*., 2017; Leedham Elvidge *et al*., 2018
NF_3	Weiss *et al*., 2008; Arnold *et al*., 2013; Rigby *et al*., 2014; Meinshausen *et al*., 2017
SO_2F_2	Muhle *et al*., 2009; Krummel *et al*., 2014; Meinshausen *et al*., 2017
CF_3SF_5	Sturges *et al*., 2012

The abundances and trends of HFCs, PFCs, sulfur hexafluoride, nitrogen trifluoride, sulfuryl fluoride and trifluoromethyl sulfur pentafluoride in the global background atmosphere, as measured at Cape Grim, Tasmania, or in the Cape Grim air archive, are shown in Table 1 (2016-2017) and Figure 1 (1998-2017).

Table 1. Concentrations (2016, 2017) and growth rates (2016-2017) for HFCs, PFCs, sulfur hexafluoride, nitrogen trifluoride, sulfuryl fluoride and trifluoromethyl sulfur pentafluoride 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	Formula	Concentration		Growth		Species	Formula	Concentration		Growth	
		2016	2017	ppt/yr	%/yr			2016	2017	ppt/yr	%/yr
HFCs						**PFCs**					
HFC-134a	CH_2FCF_3	83.4	89.4	6.0	7.0	PFC-14	CF_4	82.2	83.0	0.84	1.0
HFC-23	CHF_3	28.3	29.2	0.86	3.0	PFC-14(a)[1]	CF_4	48.1	48.9	0.84	1.7
HFC-143a	CH_3CF_3	18.2	19.9	1.7	8.7	PFC-116	C_2F_6	4.5	4.6	0.093	2.0
HFC-125	CHF_2CF_3	19.1	21.7	2.6	12.8	PFC-318	c-C_4F_8	1.5	1.6	0.063	4.0
HFC-32	CH_2F_2	10.5	12.5	2.1	17.8	PFC-218	C_3F_8	0.62	0.64	0.011	1.7
HFC-152a	CH_3CHF_2	4.5	4.5	0.059	1.3	PFC-5114	C_6F_{14}	0.29	0.30	0.007	2.4
HFC-245fa	$CHF_2CH_2CF_3$	2.1	2.3	0.19	8.6	PFC-3110	C_4F_{10}	0.19	0.19	-0.001	-0.044
HFC-227ea	CF_3CHFCF_3	1.2	1.3	0.13	10.5	PFC-4112[2]	C_5F_{12}	0.12	0.12	0.0	0.0
HFC-365mfc	$CH_3CF_2CH_2CF_3$	0.88	0.94	0.063	7.0	PFC-6116[2]	C_7F_{16}	0.12	0.12	0.0	0.0
HFC-43-10mee	$C_5H_2F_{10}$	0.25	0.26	0.008	3.2	PFC-7118[2]	C_8F_{18}	0.09	0.09	0.0	0.0
HFC-236fa	$CF_3CH_2CF_3$	0.15	0.16	0.011	7.5						
total HFCs		**168**	**182**	**14**	**7.8**	**total PFCs**		**89.7**	**90.7**	**1.0**	**1.1**
HFC fluorine		**625**	**676**	**51**	**7.9**	**total PFC(a)**		**55.6**	**56.6**	**1.0**	**1.8**
sulfur hexafluoride	SF_6	8.7	9.0	0.34	3.8	**PFC fluorine**		**384**	**389**	**4.6**	**1.2**
sulfuryl fluoride	SO_2F_2	2.1	2.2	0.11	5.0	nitrogen trifluoride[3]	NF_3	1.4	1.5	0.18	12.3
trifluoromethyl sulfur pentafluoride	CF_3SF_5	0.17	0.17	-0.001	-0.45	**total fluorine**		**1068**	**1126**	**58**	**5.3**

[1] PFC-14 (a) = CF_4 (anthropogenic) = total CF_4 – natural CF_4 (= 34.1 ppt, Trudinger *et al.*, 2016)
[2] extrapolated from 2011 data (Ivy *et al.*, 2012)
[3] estimated from Cape Grim and global data; assumed = 2011-2012 growth rate (Arnold *et al.*, 2013)

The major HFC in the background atmosphere at Cape Grim (and around the globe) is HFC-134a (89 ppt in 2017), followed by HFC-23 (29 ppt), HFC-125 (22 ppt), HFC-143a (20 ppt), HFC-32 (12 ppt) and HFC-152a (4.5 ppt). The cumulative concentration of the minor HFCs (HFC-245fa, HFC-227ea, HFC-236fa, HFC-365mfc, HFC-4310mee) is 5.0 ppt (2017), 2.7% of the total HFC concentration in the background atmosphere (182 ppt, 2017).

The global annual growth rates for all the major HFCs (except HFC-23) have increased from 2015-2016 to 2016-2017. The increases in growth rates are as follows: HFC-134a (0.2 ppt/yr), HFC-143a (0.1), HFC-125 (0.2), HFC-32 (0.2) and HFC-152a (0.06 ppt). HFC-152a concentrations had stopped growing in the background atmosphere however, for the last two years the concentrations have been increasing again. The HFC-23 growth rate has decreased by 0.12 ppt/yr.

The minor HFCs (HFC-245fa, HFC-227ea, HFC-236fa, HFC-365mfc, HFC-4310mee) are growing in the background atmosphere with a cumulative annual growth rate of 0.4 ppt (2016-2017). The annual growth in total HFCs has increased from 12 ppt (2015-2016) to 13 ppt (2016-2017). Total HFCs in the atmosphere are growing currently (2016-2017) at 7.5%/yr.

Global HFC data have shown that the total level of HFCs in the background atmosphere is consistent with total emissions from 'bottom-up' inventories, but there are significant differences between atmospheric data and emissions inventories for individual HFCs. For HFC-134a, global emissions from atmospheric observations are seasonal (NH summer maximum, Fortems-Cheiney et al., 2015) and 20%-30% lower than inventory estimates of emissions (2007-2012, Fortems-Cheiney et al., 2015, Lunt et al., 2015), whereas HFC-31, HFC-125, HFC-143a global emissions are 20%-30% higher than inventory estimates (Lunt et al., 2015). Over-reporting of HFC-134a, HFC-32 and HFC-125 emissions (10%-100%, 2004-2014, Simmonds et al., 2015; Hu et al., 2017) and under-reporting of HFC-143a emissions (40%-60%, 2007-2012, Simmonds et al., 2015) have occurred in the USA inventory compared to emissions based on atmospheric observations . The global growth rate of HFC-23 emissions slowed significantly, reaching a minimum in 2009, when resources under the Kyoto Protocol (the Clean Development Mechanism - CTM) were used to improve HCFC-22 (CHClF2) production methods and

capture the co-produced HFC-23. The cessation of CTM funding has resulted in global HFC-23 emissions growing again (Simmonds et al., 2018).

Regional inverse studies have shown that the growing levels of HFCs in the background global atmosphere result from growing emissions from (20%/yr) from China/East Asia (Fortems-Cheiney et al., 2015), offset by declining HFC emissions from developed countries (USA, Europe).

HFC replacement chemicals (HFC-1234yf – CF3CFCH2, HFC-1234ze - CF3CHCHF) have been detected (2013-2014) in urban and background atmospheres in Europe (Switzerland: Dubendorf and Jungfraujoch, Vollmer et al., 2015) at the sub-ppt level and will likely soon be found in Cape Grim air.

Total fluorine from HFCs reached 674 ppt in 2017 growing at 7.5%/yr (2016-2017).The major PFC in the background atmosphere at Cape Grim (and around the globe) is PFC-14 (CF_4: 83 ppt in 2017, about 40% of which is naturally-occurring), followed by PFC-116 (4.6 ppt), PFC-318 (1.6 ppt), PFC-218 (0.64 ppt), PFC-5114 (0.31 ppt) and PFC-3110 (0.19 ppt). The cumulative concentration of three minor PFCs (PFC-4112, PFC-6116, PFC-7118) observed at Cape Grim is 0.33 ppt (2017, extrapolated from 2011 data). The total PFC concentration in the background atmosphere is 90.6 ppt (2017), currently growing at 0.93 ppt/yr (1%/yr). The total anthropogenic PFC concentration in the background atmosphere is 56.5 ppt growing at 1.7%/yr.

The annual rate of increase of PFC-14 in the atmosphere increased from 0.73 ppt (2015-2016) to 0.78 ppt (2016-2017), close to the decadal average annual increase of 0.71 ppt (2008-2017). The anthropogenic component (from aluminium production and the electronics industries) of atmospheric PFC-14 is growing at 1.7%/yr. The annual rate of increase of PFC-116 (CF_3CF_3) is 0.078 ppt (2016-2017), slightly lower than the decadal average annual increase (0.08 ppt, 2008-2017); the PFC-218 annual increase (0.012 ppt, 2016-2017) is lower than the decadal annual average (0.016 ppt, 2008-2017); the PFC-318 annual increase (0.059 ppt, 2016-2017) is higher than the 8-year average annual increase (0.05 ppt, 2010-2017). 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 the order 0.01-0.02 ppt (2013-2017).

Total fluorine from PFCs reached 388 ppt in 2017, growing at 1.1%/yr (2016-2017).

The amount of PFC-14 in the global atmosphere is significantly higher than calculated to be there due to the accumulated emissions from the aluminium and semiconductor industries (Muhle *et al*., 2010). There appears to have been significant under-reporting of emissions by the semiconductor industry over the past decades and a recent under-reporting of emissions by the aluminium industry, possibly associated with the rapid growth in aluminium production in China (Kim *et al*., 2014). Under-reporting of PFC emissions from the aluminium industry may be due to the assumption that PFC emissions only occur during so-called 'anode effect events', whereas there may be quasi-continuous PFC emissions throughout the aluminium production process (Wong *et al*., 2015). PFC-14 emissions have been shown to respond to economic/industrial activity, with enhanced emissions during WWII due to the demand for aluminium for aircraft, and reduced emissions during the recent GFC (Trudinger *et al*., 2016).

Annual mean sulfur hexafluoride levels reached 9.0 ppt in 2017 at Cape Grim, growing at 0.32 ppt/yr (3.6%/yr, 2016-2017), similar to the 2014-2015 and 2015-2016 annual average growth rate. The decadal annual average growth rate is also 0.32 ppt/yr (2008-2017). Annual mean sulfuryl fluoride levels reached 2.2 ppt in 2017 at Cape Grim, growing at 0.10 ppt/yr (4.8%/yr), significantly higher than the 10-yr average growth rate (0.08 ppt/yr, 2008-2017). Trifluoromethyl sulfur pentafluoride stopped growing in the Cape Grim atmosphere in 2007 (0.16 ppt), as seen in UEA Cape Grim Air Archive measurements (Sturges *et al*., 2012), following 3M's decision to cease PFOS production (Santaro, 2000). *In situ* measurements at Cape Grim have recently been calibrated (SIO-14 scale) and show annual mean concentrations of 0.17 ppt in 2016 and in 2017. The current measurement precision is (±0.004 ppt, 1 standard deviation). If there is no further production/release of trifluoromethyl sulfur pentafluoride, its concentration in the atmosphere should remain effectively constant due to its very long atmospheric lifetime (800 yr). With zero emissions, atmospheric concentrations should decline by only 0.05% (<0.001 ppt)/yr. Given the uncertainty in the measurements, a longer record is required to define a possible trend in this species.

Nitrogen trifluoride is growing rapidly in the background atmosphere. In February 2015, *in situ* measurements of nitrogen trifluoride began at Cape Grim. The mean concentration of nitrogen trifluoride is 1.4 ppt for 2016 and 1.5 ppt for 2017, growing at 0.16 ppt/yr (11%/yr). Following the recent inclusion of nitrogen trifluoride into the post-Kyoto Protocol 'basket' of GHGs (Paris Agreement), it is anticipated that the current rapid growth rate will decline as alternatives are introduced into the semiconductor manufacturing industry.

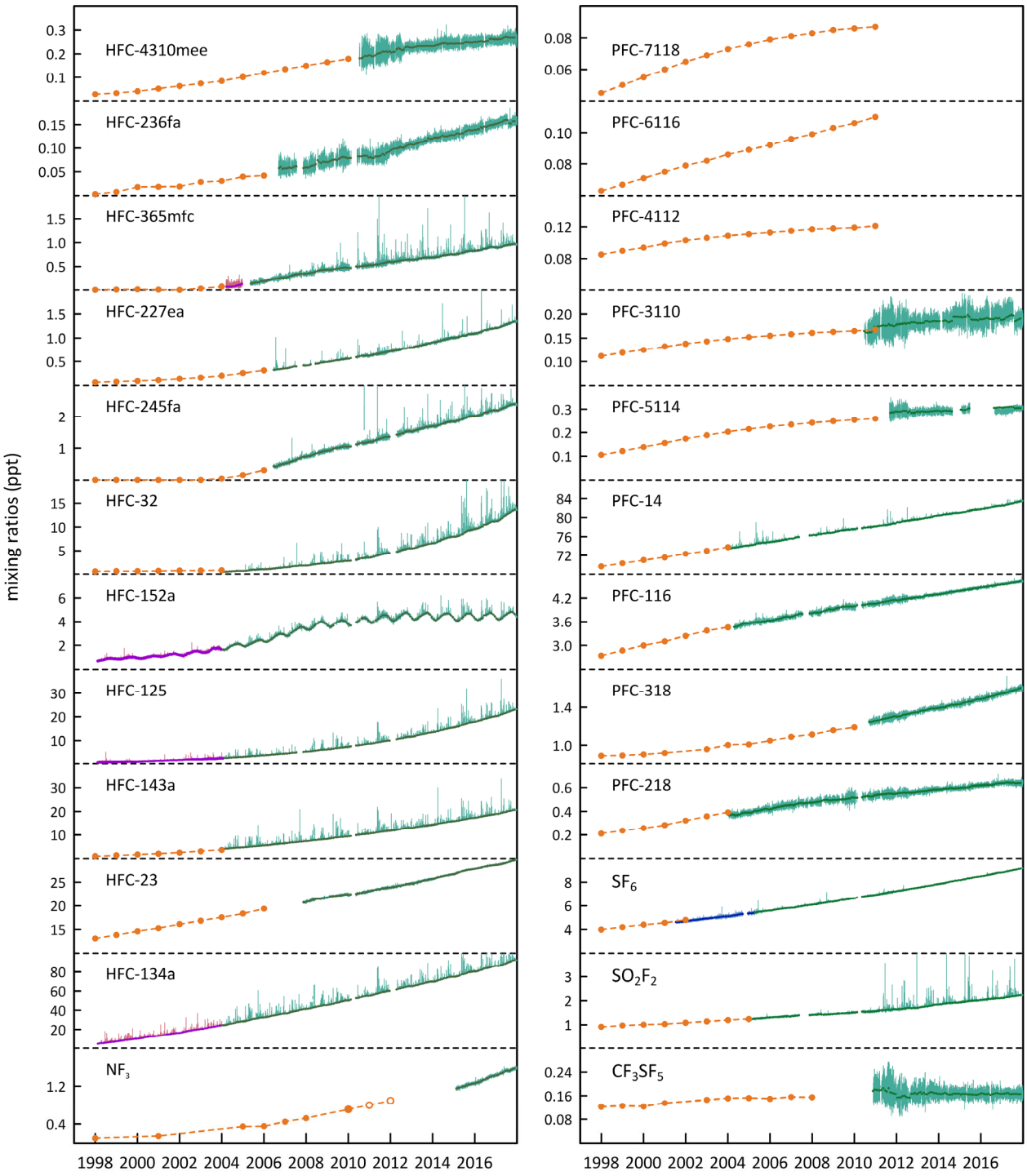

Figure 1. *In situ* observations of PFCs, HFCs, sulfur hexafluoride, nitrogen trifluoride, sulfuryl fluoride and trifluoromethyl sulfur pentafluoride (1998 – 2017) showing baseline monthly mean data (dark green, Medusa; purple, ADS; blue, ECD) and total data (light green, Medusa; pink, ADS; blue, ECD) obtained from the GC-MS-Medusa, GC-MS-ADS and GC-ECD (SF_6) instruments at Cape Grim and from Medusa measurements at CSIRO and SIO on the Cape Grim Air Archive (orange). 2011 and 2012 nitrogen trifluoride annual means are derived from global data (references: see text above; CSIRO unpublished Cape Grim Air Archive data).

3 Global HFC, PFC, sulfur hexafluoride, nitrogen trifluoride and sulfuryl fluoride emissions

Global emissions of HFCs, PFCs, sulfur hexafluoride, nitrogen trifluoride and sulfuryl fluoride have been estimated from AGAGE global data (including Cape Grim data) by inverse modelling up to 2016 (Figure 2; Rigby *et al*., 2014 and Rigby, unpublished data).

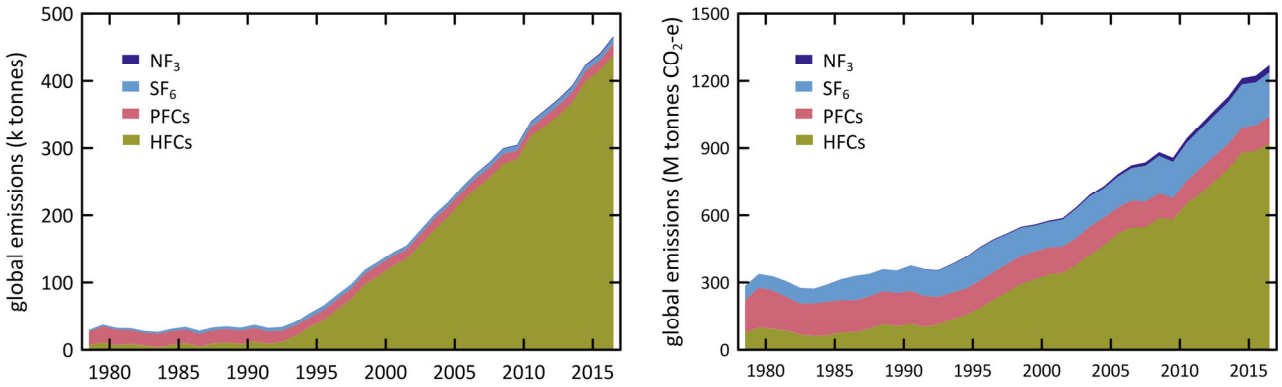

Figure 2. Global HFC, PFC, sulfur hexafluoride and nitrogen trifluoride emissions (left: k tonnes; right: M tonnes CO_2-e) from global AGAGE atmospheric measurements (Rigby *et al*., 2014 and unpublished data 2018). CO_2-e emission estimates use GWPs from the IPCC 4th Climate Assessment (AR4 GWPs).

Total global HFC emissions were 440 k tonnes in 2016, rising by nearly 20 k tonnes/yr since 1995; total global HFC emissions in 2016 were 6% higher than in 2015. Global emissions of the major HFCs (HFC-32, HFC-125, HFC-134a, HFC-143a) increased from 2015 to 2016: 9%, 7%, 6%, 6% respectively; global emissions of HFC-152a peaked in 2011 and were in decline, but have increased over the last 2 years, by 4% from 2014 to 2015 and 3% from 2015 to 2016. HFC-23 global emissions declined by 6% from 2015 to 2016. HFC-134a emissions exhibit significant seasonality, in particular at the mid-latitudes of the northern hemisphere, with summer emissions 2-3 times winter emissions (Xiang *et al*., 2014; Fortems-Cheiney *et al*., 2015; Simmonds *et al*., 2015).

Total PFC emissions have declined from 19 k tonnes/yr in the late-1970s to 17 k tonnes/yr in 2016. Emissions have remained steady, at around 15 k tonnes/yr since 1993 until 2014. From 2014-2015 there was an increase in total PFC emissions of 4.6% and an increase of 5% from 2015-2016. Global emissions of the major PFCs (PFC-14, PFC-116, PFC-318) increased from 2015 to 2016 by 5%, 1%, 10% respectively.

Sulfur hexafluoride emissions have been increasing steadily from about 3 k tonnes per year in the late-1970s to approaching 9 k tonnes per year in 2016 (an increase of around 0.15 k tonnes/yr). Sulfur hexafluoride emissions increased by 3% from 2015 to 2016.

Nitrogen trifluoride emissions (>0.1 k tonnes per year) were first observed in the mid-1990s, growing at 0.08 k tonnes/yr since 1995 to nearly 2 k tonnes per year in 2016. The 2015-2016 increase was 12%.

Total global HFC, PFC, sulfur hexafluoride and nitrogen trifluoride emissions have risen (11 k tonnes/yr, largely HFCs) from about 30 k tonnes per year in the late-1970s to around 467 k tonnes per year in 2016, with a 2015-2016 increase of 6%.

Global sulfuryl fluoride emissions (not shown in Figure 2) were 1.5 k tonnes per year in the late-1970s, peaking at 3.7 k tonnes per year in 2016. There is significant year to year variability in emissions, presumably due to the global demand for sulfuryl fluoride being dependant on, in part, variable global grain production.

4 Australian HFC, PFC and sulfur hexafluoride imports, banks and emissions

HFCs and sulfur hexafluoride are not manufactured in Australia and estimates of Australian HFC and sulfur hexafluoride emissions, reported annually to the UNFCCC (see below), are based on import data (Table 2). HFCs and sulfur hexafluoride are imported as bulk chemicals or in pre-charged equipment (PCE), leading to estimates of 'banks' of HFCs and sulfur hexafluoride stored in equipment or products such as refrigerators, air conditioners, fire extinguishers, foams, aerosols and electrical equipment. Only small amounts of PFCs are imported into Australia (Table 2) and these are not considered to be a significant source of PFC emissions; Australian PFC emissions are assumed to originate exclusively from aluminium production (see below).

HFC imports in 2017 were 9377 tonnes, 60% in bulk, 40% in pre-charged equipment (PCE), 36% higher than HFC imports in 2016, possibly due to increased imports before the HFC phase-down was enacted. PFC imports in 2016 and 2017 were about 0.18 and 0.17 tonnes respectively. The previous highest annual HFC imports were 8871 tonnes in 2012. HFC imports have grown by 10% per year over the period 2008-2017. The HFC bank has been estimated at 74 Mt CO_2-e in 2016, 2.8% higher than in 2015 (DoEE, 2018).

Sulfur hexafluoride imports in 2017 were 19 tonnes, 46% higher than 2016 imports. Sulfur hexafluoride imports vary significantly year-to-year. Thirty four (34) tonnes of sulfur hexafluoride were exported in 2016, presumably from a stockpile of sulfur hexafluoride imported in anticipation of a large carbon tax (36 tonnes imported in 2012) but none exported in 2017. Since 2012, sulfur hexafluoride imports have totalled 120 tonnes and exports 37 tonnes, leaving 83 tonnes in Australia or about 14 tonnes per year over this period.

Table 2. Australian HFC, PFC, sulfur hexafluoride imports (2016, 2017, tonnes, A. Gabriel, Department of Environment and Energy, 2018); PCE = pre-charged equipment.

Species	bulk		PCE		bulk		Total		Total		Total Imports		Total Imp-Exp	
	Imports		Imports		Exports		Imports		Imp-Exp		Mt CO_2-e		Mt CO_2-e	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
HFC-23	0.71	3.8	0.13	0.06			0.84	3.9	0.84	3.9	0.01	0.06	0.01	0.06
HFC-32	383	590	1350	1611	56	1.4	1732	2202	1676	2200	1.2	1.5	1.1	1.5
HFC-125	839	1761	927	1014	60	4.3	1766	2775	1706	2771	6.2	9.7	6.0	9.7
HFC-134	25		0.25	0.74			25	0.74	25	0.74	0.03	0.00	0.03	0.00
HFC-134a	1705	2124	980	1048	99	8.2	2684	3172	2586	3164	3.8	4.5	3.7	4.5
HFC-143a	507	1049	17	15	3.2	3.1	525	1063	521	1060	2.3	4.8	2.3	4.7
HFC-152a	0.72		26	25			27	25	27	25	0.00	0.00	0.00	0.00
HFC-227ea	15	46	0.08	0.00	1.3	0.13	15	46	14	46	0.05	0.15	0.04	0.15
HFC-236fa		0.20	0.11	0.00			0.11	0.20	0.11	0.20	0.00	0.00	0.00	0.00
HFC-245fa	63	38	0.10	0.02	3.3	2.8	63	38	59	35	0.06	0.04	0.06	0.04
HFC-365mfc	66	52			10	5.1	66	52	55	47	0.05	0.04	0.04	0.04
total HFCs	**3604**	**5664**	**3300**	**3713**	**233**	**25**	**6903**	**9377**	**6671**	**9352**	**14**	**21**	**13**	**21**
PFC-14	0.01	0.01	0.02	0.00	0.00		0.03	0.01	0.03	0.01	0.00	0.00	0.00	0.00
PFC-116	0.01	0.05	0.08	0.06	0.00		0.09	0.10	0.09	0.10	0.00	0.00	0.00	0.00
PFC-218	0.00	0.00	0.00		0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PFC-318	0.06	0.05	0.00		0.00		0.06	0.05	0.06	0.05	0.00	0.00	0.00	0.00
total PFCs	**0.08**	**0.11**	**0.10**	**0.06**	**0.00**		**0.18**	**0.17**	**0.18**	**0.17**	**0.002**	**0.00**	**0.00**	**0.00**
SF_6	2.4	7.5	10	12	34		13	19	-21	19	0.29	0.43	-0.48	0.43
total HFCs, PFCs, SF_6	**3604**	**5664**	**3300**	**3713**	**233**	**25**	**6904**	**9377**	**6671**	**9352**	**14**	**21**	**13**	**21**

The *National Greenhouse Gas Inventory* (NGGI: ageis.climatechange.gov.au) published in 2018 contains estimates of Australian emissions of HFC-23, HFC-32, HFC-125, HFC-134 (CHF_2CHF_2, not measured currently at Cape Grim), HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, HFC-4310mee, PFC-14, PFC-116 and sulfur hexafluoride, up to 2016, which form part of the *National Inventory Report 2016* (DoEE, 2018). The *Inventory* 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 NGGI and in the *National Inventory Report* are for fiscal years, i.e. '2013' emissions are emissions for July 2012 to June 2013.

The HFC emissions (Table 3) are based on HFC import data (Table 2), as bulk HFCs or 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 emissions model can represent the time-dependent emissions of total HFCs expressed as CO_2-e, but cannot represent the annual emissions of specific HFCs or their time-dependent behaviour. This means that the ratio of 2005 to 2016 emissions, for example, for all 11 individual HFCs in the Australian emission *Inventory*, are exactly the same (2.7). Clearly this does not represent reality and cannot capture the recent likely strong growth in emissions of HFC-32, HFC-125 and HFC-143a due to the recent, growing industry use of refrigerants R-404a (45% HFC-125, 52% HFC-143a) and R-410a (50% HFC-125, 50% HFC-32).

Australian HFC emissions were about 110 tonnes in 1995, rising to 6525 tonnes (13176 CO_2-e tonnes) in 2016. HFCs are the dominant emissions in CO_2-e terms in this sector (97%, 2016). HFC-134a emissions increased by about 127 tonnes (3%) from 2015 to 2016, all other HFCs by about 53 tonnes (3%). Emissions of total HFCs (in CO_2-e terms) in 2016 were 3% higher than in 2015.

Table 3. Australian HFC, PFC and sulfur hexafluoride emissions (http://unfccc.int/national_reports/ annex_i_ghg_inventories/national_inventories_submissions/items/10116.php). HFC-23 emissions in 1995 from HCFC-22 production in Sydney. Not shown are small HFC-236fa emissions (0.005 tonnes in 2016). Note GWPs used are AR4.

	HFC-134a	HFC-125	HFC-143a	HFC-32	HFC-227ea	HFC-134	HFC-43-10mee	HFC-23	total HFCs		PFC-14	PFC-116	total PFCs			SF_6	total HFC,PFC,SF_6	
	tonnes								tonnes	kt CO_2-e	tonnes		tonnes	kt CO_2-e	tonnes	kt CO_2-e	tonnes	kt CO_2-e
1995	33	12	1.1	0.6	0.4	0.0	0.0	61	108	95	171	22	193	1531	14	316	315	1942
1996	145	51	4.9	2.8	1.7	0.1	0.0	0.0	205	414	157	20	178	1410	13	289	395	2114
1997	247	86	8.3	4.8	2.9	0.1	0.1	0.0	349	705	137	18	155	1228	12	266	516	2200
1998	349	122	12	6.8	4.1	0.1	0.1	0.0	494	998	185	24	209	1661	11	240	714	2899
1999	481	168	16	9.3	5.7	0.2	0.1	0.1	681	1374	127	16	143	1139	9.3	211	833	2725
2000	565	197	19	11	6.7	0.2	0.2	0.1	799	1613	143	19	162	1287	9.3	212	970	3113
2001	807	282	27	16	10	0.3	0.2	0.1	1142	2306	201	26	227	1802	9.6	219	1378	4327
2002	1024	358	34	20	12	0.4	0.3	0.1	1449	2927	193	25	218	1728	9.9	225	1677	4879
2003	1252	438	42	24	15	0.5	0.4	0.2	1772	3578	188	24	212	1684	10	229	1994	5491
2004	1493	522	50	29	18	0.6	0.4	0.2	2113	4267	191	25	216	1714	10	231	2339	6211
2005	1751	612	59	34	21	0.7	0.5	0.2	2477	5002	200	26	226	1792	8.6	196	2712	6990
2006	1875	656	63	36	22	0.7	0.5	0.2	2654	5359	77	10	87	687	8.2	186	2748	6232
2007	2231	780	75	43	26	0.9	0.6	0.3	3157	6374	65	8.4	73	583	7.7	175	3238	7132
2008	2619	916	88	51	31	1.0	0.8	0.3	3706	7484	50	6.4	56	445	7.2	163	3769	8092
2009	2924	1022	98	56	35	1.1	0.8	0.4	4138	8355	40	4.9	45	359	6.4	147	4189	8860
2010	3295	1152	110	64	39	1.3	0.9	0.4	4663	9415	32	3.5	36	283	6.3	144	4705	9843
2011	3583	1253	120	69	43	1.4	1.0	0.4	5071	10239	35	3.8	38	301	6.4	146	5115	10687
2012	3792	1326	127	73	45	1.5	1.1	0.5	5376	10835	34	3.7	37	295	6.6	150	5410	11280
2013	4038	1412	135	78	48	1.6	1.2	0.5	5716	11540	22	2.4	24	192	6.3	144	5746	11876
2014	4274	1495	143	83	51	1.7	1.2	0.5	6049	12214	22	2.4	24	193	7.1	162	6080	12568
2015	4484	1568	150	87	53	1.8	1.3	0.6	6346	12815	19	2.3	21	171	7.4	169	6375	13155
2016	4611	1613	154	89	55	1.8	1.3	0.6	6525	13176	26	2.9	29	225	7.5	171	6561	13572

In the Australian GHG emission inventory, PFC (PFC-14, PFC-116) emissions only arise from aluminium production, with total PFC emissions in 2016 of 29 tonnes (0.23 Mt CO_2-e, DoEE, 2018). About 0.17-0.18 tonnes of PFCs (PFC-14, PFC-116) were imported into Australia in 2016-2017 as refrigerant blends in bulk and PCE (Table 2). 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 (29 tonnes in 2016, Table 3). PFC emissions fell from 37 tonnes in 2012 to 24 tonnes in 2013 due to the closure of the Kurri Kurri smelter in NSW and from 24 tonnes in 2014 to 21 tonnes in 2015 due to the closure of the Point Henry smelter in Victoria. PFC emissions in 2016 are about 30% higher compared to 2015. This increase, the first in the past 12 years, is not due to the increase in aluminium production (0.2%, 2015-2016) but an increase in the reported average PFC emission factors (32% for PFC-14, 28% for PFC-116, 2015-2016, DoEE, 2018). These increased emission factors in 2016 (0.0155 kg PFC-14 per tonne aluminium produced, 0.00178 kg PFC-116 per tonne) lie within the range of the past seven years (2010-2016, PFC-14: 0.0149±17% kg per tonne; PFC-116: 0.00165±16% kg per tonne).

Australian sulfur hexafluoride emissions are largely (90%) from the electricity supply and distribution network, with 10% from electrical supply equipment manufacture. Emissions (1975-2016) are estimated as leakages from sulfur hexafluoride 'banks' in the electricity supply and distribution network and leakages from Australian manufacture of electricity supply equipment, using a combination of default IPCC and Australian-specific emissions factors (DoEE, 2018).

Australian emission factors for electrical equipment stock are global IPCC default factors: 0.05 tonne (t) emitted per year per tonne (t) of stock (1975-1995), 0.02 t/t (2000); an Australian-specific base emission factor (0.0089 t/t) has been estimated for 2009 and then scaled in subsequent years by the estimates of Australian sulfur hexafluoride emissions from Cape Grim atmospheric observations (DoEE, 2018). For 1995-2000-2009 periods, emission factors are linearly interpolated. The 2009 emission factor (0.0089 t/t) is based on emission estimates from 15 utilities (the major consumers of sulfur hexafluoride in Australia) using their own data on sulfur hexafluoride consumption (consumption = emissions, not defaulting to the IPCC method). The 2015 and 2016 emission factors (after scaling by Cape Grim data) are 0.0095 tonne sulfur hexafluoride per tonne sulfur hexafluoride banked i.e. 0.95% (DoEE, 2018).

The emission factors assumed for Australian equipment manufacture (0.15 t/t, 1975-1995; 0.085 t/t, 1996-2016) 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. Since the equipment manufacture sector emits only 10% of Australia's sulfur hexafluoride, total sulfur hexafluoride emissions are relatively insensitive to the choice of emission factors for this sector. Australian sulfur hexafluoride emissions in the Inventory are 7.1-7.5 tonnes for 2015-2017. Of the approximate 80 tonnes of sulfur hexafluoride imported into Australia since 2012, about 40 tonnes have been emitted to the atmosphere and 40 tonnes have gone into the electrical equipment bank (DoEE, 2018).

Australian sulfur hexafluoride emissions from magnesium casting, tracer gas studies, eye surgery etc. have been estimated at 1 kg of sulfur hexafluoride as CO_2-e per person per year or a total of 1.1 tonnes of sulfur hexafluoride per year (DoEE, 2018). Thus, total Australian emmissions of sulfur hexafluoride in 2016 (electrical equipment and other uses) was 8.6 tonnes.

The quantity of sulfuryl fluoride imported each year into Australia depends, in part, on the annual grain harvest. Before 2007, Australian sulfuryl fluoride imports were significantly less than 50 tonnes per year, reaching current levels of imports (approximately 150 tonnes per year) by 2011-12, continuing at about this level until 2015-16, with 2016-17 imports higher due to a record grain harvest (M. Stein, A-Gas, personal communication). Mühle *et al*. (2009) estimate that approximately 2/3 of sulfuryl fluoride used in fumigation escapes to the atmosphere, so current Australian sulfuryl fluoride emissions are likely to be about 100 tonnes per year (~0.5 M tonnes CO_2-e), 2-3 times larger than the CO_2-e emissions due to sulfur hexafluoride (0.2 M tonnes CO_2-e in 2016). Globally, the reverse is the case, with the CO_2-e emissions of sulfur hexafluoride (200 M tonnes, 2016) being significantly higher than for sulfuryl fluoride (15 M tonnes, 2016).

The HFC, PFC and sulfur hexafluoride contributions to total emissions from this sector are shown in Figure 3. 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/sulfur hexafluoride emissions grew at about 12%/yr (Figure 3). After the Kurri Kurri upgrade, these combined emissions grew at about 7%/yr. The Australian Kyoto Protocol/Paris Agreement-SGG emissions are 97% HFCs, 2% PFCs and 1% sulfur hexafluoride.

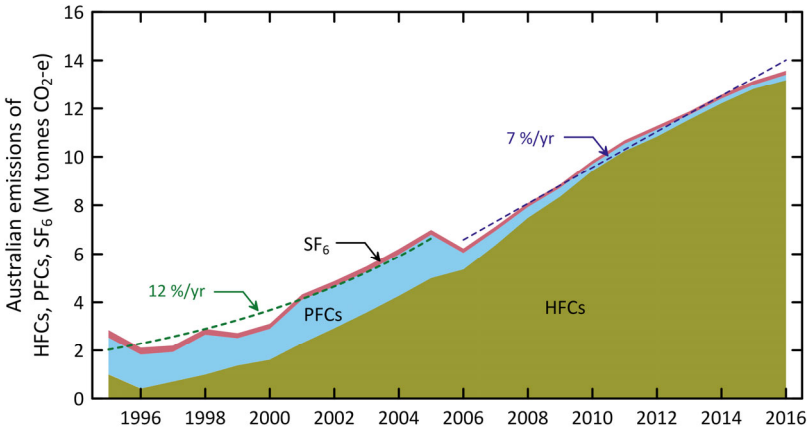

Figure 3. Australian HFC, PFC and sulfur hexafluoride emissions (M tonne CO_2-e) in the Inventory (DoEE, 2018). Note the impact on the reduction in emissions due to the refurbishment of potline #1 at the Kurri Kurri aluminium smelter in 2005-2006. Dashed lines are exponential and linear best fits.

5 Australian HFC, PFC, sulfur hexafluoride and sulfuryl fluoride emissions from atmospheric data

5.1 HFC, sulfur hexafluoride and sulfuryl fluoride emissions

CSIRO estimates emissions of a number of greenhouse and ozone depleting trace gases from the Melbourne/Port Phillip region (Dunse *et al*., 2001, 2005; Dunse 2002; Greally *et al*., 2007; Stohl *et al*., 2009; Fraser *et al*., 2014b, 2016; Simmonds *et al*., 2016), 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 or inverse modelling (InTEM).

Port Phillip HFC, PFC-116 and sulfur hexafluoride emissions have been calculated, by ISC from Cape Grim data (2004-2016, Krummel *et al*., 2014 and unpublished data) and presented as 3-year running averages (2005-2016; Table 4, Figure 4). The HFC, PFC-116 and sulfur hexafluoride emissions are derived from Port Phillip emissions, scaled to Australian emissions on a population basis. NOAA air mass back trajectory analyses (Draxler and 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 carbon monoxide source regions, in particular the Latrobe Valley, or high carbon monoxide emission events (biomass burning).

The NAME particle dispersion model coupled to the InTEM inversion model (O'Doherty *et al*., 2009; Manning *et al*., 2003, 2011; Redington and Manning, 2018) is used to calculate HFC, PFC (see below), sulfur hexafluoride and sulfuryl fluoride emissions. NAME (**N**umerical **A**tmospheric **D**ispersion **M**odelling **E**nvironment) 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 33,000 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, InTEM 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. For the 2018 InTEM inversions, emissions were calculated for the Victoria/Tasmania/New South Wales domain and, for the 2011 InTEM inversions, a Victoria/Tasmania domain was used.

The emissions are calculated as 3-yr running averages of emissions (i.e. 2008 annual emissions are derived from 2007-2009 data). The original NAME/InTEM Australian emissions were calculated (A. Manning, UKMO, 2011) using a Victoria/Tasmania domain, and scaled to Australian emissions using a population-based scale factor of 3.7. Later NAME/InTEM inversions (Redington and Manning, 2018) used a Victoria/Tasmania/New South Wales domain, with a population based scale factor of 1.7, and are shown in Table 4 and Figure 4. The InTEM emission data presented in this report are based on prior emissions uniformly distributed over the domain

Cape Grim sulfuryl fluoride 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 SE Australian (largely Victorian) sulfuryl fluoride emissions by ISC. Grain exported from Victorian grain terminals, or produced in Victoria, accounts for about 10-20% of Australia's grain production/exports (National Transport Commission, 2008; ABARES 2018) and thus possibly 10-20% of Australia's emissions of sulfuryl fluoride. SE Australian sulfuryl fluoride emissions calculated from Cape Grim data by ISC are scaled to Australian emissions by this factor (i.e. multiplied by 7.0±2.1) (Table 4, Figure 4). The InTEM model domain used to derive sulfuryl fluoride emissions is Victoria/Tasmania/New South Wales, and the scale factor used to derive Australian emissions, based on grain production, is 2.4±0.2. Australian emissions of sulfuryl fluoride averaged about 79 tonnes/yr (400 k tonnes CO_2-e) over the period 2011-2016, some 2%-3% of global emissions (see above), similar to Australia's fraction of global grain production (~2%). Australian sulfuryl fluoride imports are currently around 150 tonnes per year (M. Stein, A-Gas, personal communication).

Table 4. Australian HFC, PFC, sulfur hexafluoride and sulfuryl fluoride emissions (tonnes, 2005-2016) 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 and the InTEM inversion model (InTEM 2012, InTEM2018). For years when InTEM inversions are not available, ISC data are assumed. The emissions are 3-year running averages, i.e. '2010' = average of 2009, 2010, 2011 emissions. Australian HFC and sulfur hexafluoride emissions (ISC, InTEM) are scaled from regional emissions by population; GWPs (to calculate CO_2-e emissions) are from the *National Inventory Report 2015* (DoEE, 2017). PFC-14 emissions are the TAPM-InTEM average from Table 5. Australian PFC-116 emissions are from InTEM (Vic/Tas) scaled by aluminium production; Australian PFC-218 and PFC-318 emissions are from InTEM and ISC scaled by population; Australian sulfuryl fluoride emissions are from ISC and InTEM estimates of SE Australian emissions scaled by grain production.

SGGs	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Regulated species												
HFCs ISC (tonnes)												
HFC-32	33±11	50±19	102±43	105±40	137±49	129±44	151±50	156±52	154±50	277±94	288±98	265±89
HFC-125	392±131	344±114	444±170	465±166	561±183	456±156	484±159	465±153	496±160	657±218	672±225	595±198
HFC-134a	1613±503	1469±457	1593±544	1496±485	1736±542	1417±474	1541±495	1444±466	1375±434	1735±571	1827±608	1663±550
HFC-143a	420±145	368±125	421±153	409±141	502±162	394±136	366±122	408±139	446±149	449±153	440±150	370±125
HFC-23	46±25[1]	46±25[1]	46±25	45±19	46±18	33±13	34±13	35±13	37±12	29±10	30±10	26±9
HFC-152a	31±10	32±11	45±15	39±13	41±15	39±13	41±14	59±21	58±20	65±22	66±23	61±20
HFC-227ea	16±9	13±6	17±7	20±8	32±12	27±10	22±8	15±5	32±11	27±10	27±10	18±6
HFC-236fa	23±16	6±3	5±2	5±2	6±2	5±2	5±2	4±1	3±1	2±1	2±1	3±1
HFC-245fa	36±18	35±15	34±14	25±10	28±11	29±11	42±15	43±15	46±15	70±23	77±26	69±23
HFC-365mfc	9±4	25±10	30±12	44±16	55±19	58±21	57±20	54±19	50±17	52±18	54±18	46±15
HFC-32, HFC-125, HFC-134a, HFC-143a	2459±540	2231±485	2560±590	2475±535	2937±595	2396±520	2542±535	2474±510	2471±490	3118±635	3227±670	2893±605
Total HFCs	2619±540	2387±490	2737±595	2654±540	3144±605	2587±530	2743±545	2685±520	2696±495	3364±645	3482±680	3114±610
HFCs InTEM, 2012 (tonnes)												
HFC-23	34±3[2]	34±3[2]	34±3[2]	34±3	43±4	44±6	55±5	55±5[3]	55±5[3]	55±5[3]	55[3]±5[3]	55[3]±5[3]
HFC-152a	31±2	35±3	41±3	43±3	68±4	69±5	72±4	72±4[3]	72±4[3]	72±4[3]	72±4[3]	72±4[3]
HFC-227ea[4]	16±9	13±6	17±7	20±8	32±12	27±10	22±8	15±5	32±11	27±10	27±10	18±6
HFC-236fa[4]	23±16	6±3	5±2	5±2	6±2	5±2	5±2	4±1	3±1	2±1	2±1	3±1
HFC-245fa[4]	36±18	35±15	34±14	25±10	28±11	29±11	42±15	43±15	46±15	70±23	77±26	69±23
HFC-365mfc	13±1	13±1	15±2	16±3	47±13	64±10	68±3	68±3[3]	68±3[3]	68±3[3]	68±3[3]	68±3[3]
HFCs InTEM, 2018 (tonnes)												
HFC-32	70±39[5]	70±39	73±54	89±68	129±79	170±79	179±73	188±70	184±79	180±86	246±109	298±129
HFC-125	277±166[5]	277±166	323±194	387±194	428±195	439±181	506±155	563±161	587±191	600±232	703±245	741±252
HFC-134a	1000±386[5]	1000±386	1147±536	1421±632	1474±571	1386±474	1446±357	1404±421	1298±439	1183±491	1537±586	1849±597
HFC-143a	269±100[5]	269±100	307±130	360±164	379±176	383±160	419±145	455±143	460±152	441±183	441±195	450±178
HFC-32, HFC-125, HFC-134a, HFC-143a	1616±435[5]	1616±435	1850±585	2257±685	2410±635	2378±540	2550±420	2610±480	2529±510	2404±580	2927±675	3338±685
Total HFCs	1769±435[5]	1751±435	1996±585	2401±685	2632±635	2615±540	2813±420	2866±480	2803±510	2698±580	3228±675	3622±685
ISC-InTEM average (tonnes)												
Total HFCs	2194±490	2069±465	2367±590	2528±615	2888±620	2601±535	2778±485	2776±500	2750±505	3031±615	3355±680	3368±650
ISC-InTEM mean (M tonnes CO_2-e)	5.53±1.0	5.06±0.9	5.74±1.2	6.12±1.2	6.97±1.3	6.20±1.1	6.61±1.0	6.58±1.1	6.72±1.1	7.09±1.3	7.64±1.4	7.45±1.3
SF_6												
ISC (tonnes)	68±25	60±21	38±14	28±10	28±11	25±9	24±8	22±8	22±7	17±6	20±7	18±6

SGGs	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
InTEM, 2012 (tonnes)	29±2[5]	29±2	31±3	34±2	44±3	43±3	44±2	44±2[3]	44±2[3]	44±2[3]	44±2[3]	44±2[3]
ISC-InTEM mean (tonnes)	48±13	44±11	34±8	31±6	36±7	34±6	34±5	33±5	33±5	30±4	32±5	31±4
ISC-InTEM mean (k tonnes CO_2-e)	1098±302	1010±257	786±187	697±143	821±158	779±133	778±123	754±113	747±108	695±93	729±105	707±97
PFCs												
total (Table 5, tonnes)	160±40	146±45	92±35	77±25	101±30	91±25	99±25	92±15	81±10	76±15	89±15	132±40
total (Table 5, k tonnes CO_2-e)	1256±343	1146±399	727±326	607±210	872±385	760±271	827±285	793±192	666±146	682±149	738±197	1062±375
HFCs, SF_6, PFCs												
total (tonnes)	2402±327	2259±465	2493±590	2635±615	3025±620	2727±535	2911±485	2901±500	2863±505	3137±615	3476±680	3530±650
total (k tonnes CO_2-e)	7891±1100	7221±1040	7258±1265	7422±1260	8663±1355	7737±1165	8214±1070	8109±1085	8131±1135	8417±1345	9100±1440	9218±1385
Unregulated species												
SO_2F_2, ISC (tonnes)	9±6	8±5	12±9	17±11	18±12	67±40	85±53	71±43	74±44	102±61	100±60	126±75
SO_2F_2, InTEM (tonnes)		24±37	25±44	31±62	39±61	49±50	68±43	102±42	129±44	151±51	171±62	174±65
SO_2F_2, ISC-InTEM mean (tonnes)		16±17	19±22	24±32	29±32	58±48	77±49	87±46	101±50	126±62	135±68	150±77
SO_2F_2, ISC-InTEM mean (k tonnes CO_2-e)		79±10	93±112	120±159	144±158	291±240	383±245	433±229	507±251	632±312	677±341	749±383

[1]assumed = 2007 emissions [2]assumed = 2008 emissions [3]assumed = 2011 emissions [4]assumed = ISC data [5]assumed = 2006 emissions

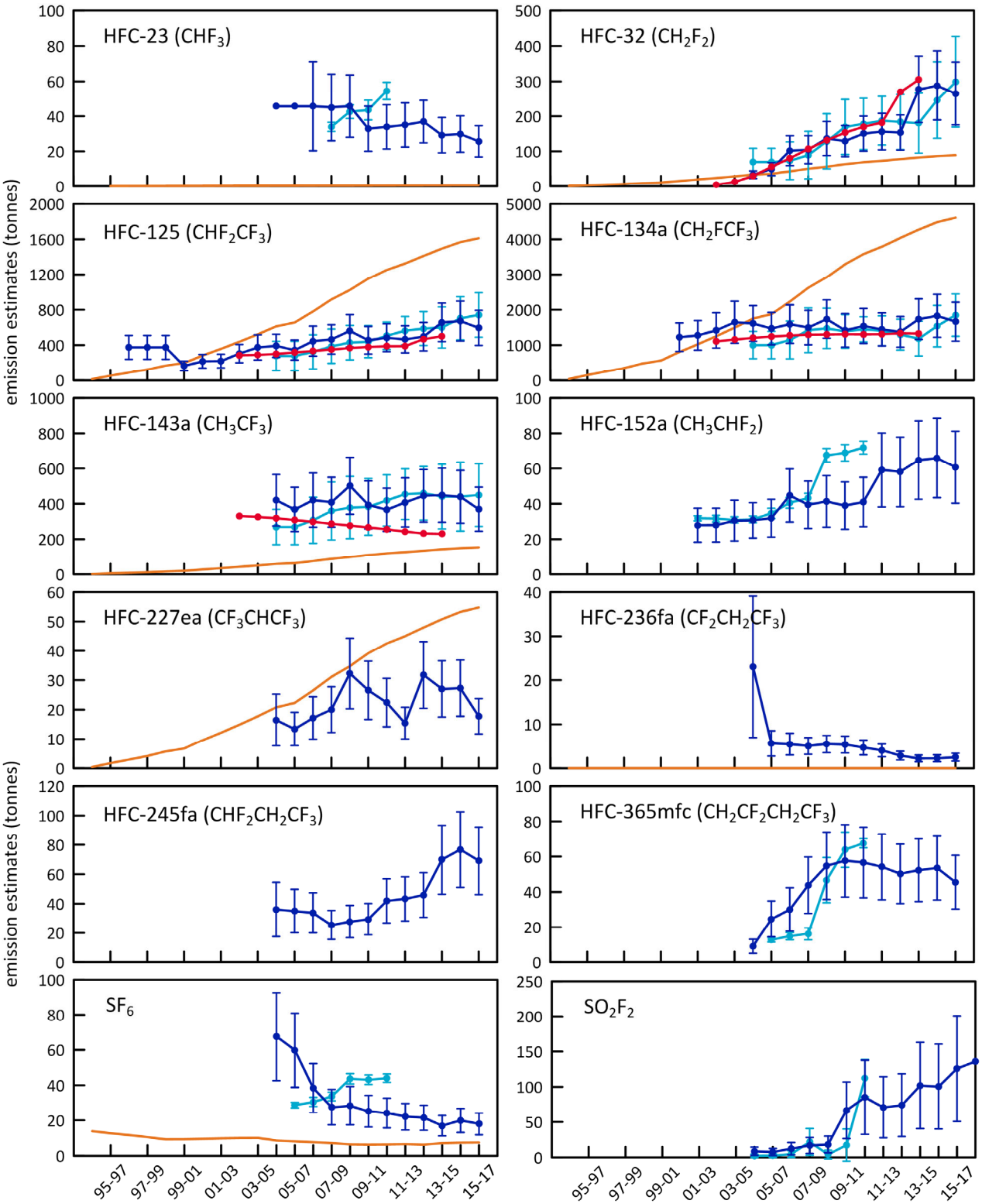

Figure 4. Australian HFC-32, -125, -134a, -143a, -152a, -365mfc, sulfur hexafluoride and sulfuryl fluoride emissions (NGA, orange: DoEE, 2018) compared to emissions calculated from Cape Grim data by interspecies correlation (ISC, blue) and from the UK Met. Office NAME (light blue) particle dispersion/InTEM inversion models. In the ISC calculations of HFC and sulfur hexafluoride emissions, Australian emissions are scaled from Melbourne/Port Phillip emissions on a population basis (5.4, Australia/Port Phillip); in the InTEM 2011 calculations, Australian emissions are scaled from Victorian/Tasmanian emissions, also on a population basis; for the InTEM 2018 inversions, Australian emissions are scaled from Victorian/Tasmania/New South Wales emissions, also on a population basis. Also shown are Australian sulfuryl fluoride emissions from ISC and InTEM, scaled on a grain production basis. The data shown in red are emissions from the refrigerant bank and are show in red (Brodribb and McCann, 2015).

5.2 PFC-14 emissions

SE Australian emissions of PFC-14 (CF_4) are evident in the PFC-14 data collected at Cape Grim (Figure 5). Inspection of Figure 5 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-year averaging is used when deriving PFC emissions from these data (so the latest annual emission calculated from these data is for 2016). 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 (Note: the Point Henry smelter closed in July 2014).

The Cape Grim PFC-14 pollution episode data have been used to estimate PFC-14 emissions from these SE 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 tarnsport and InTEM inversion models are used to derive PFC emissions from the Victoria/Tasmania/NSW domain containing aluminium smelters at Portland, Point Henry, Bell Bay, Kurri Kurri and Tomago smelters.

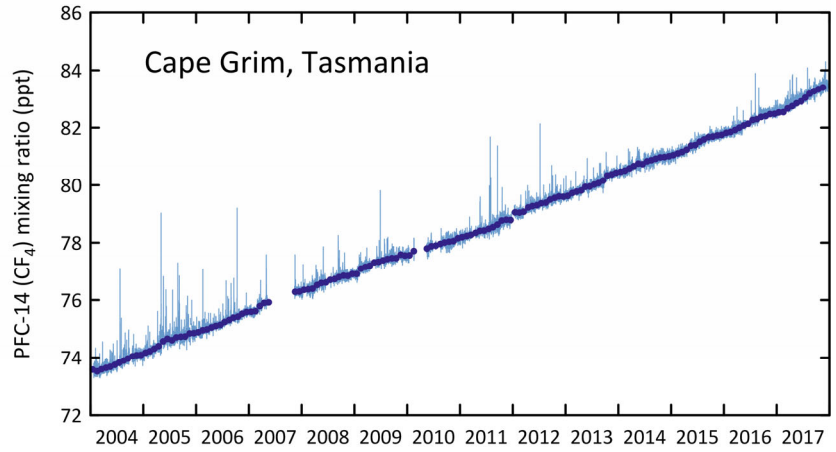

Figure 5. Monthly-mean PFC-14 concentrations observed *in situ* at Cape Grim (dark blue), 2004-2017. PFC-14 pollution episodes (light blue), typically lasting up to 12 hours in duration, are also seen at Cape Grim (Mühle *et al.*, 2010).

The TAPM and InTEME 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 SE 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 2016* (DoEE, 2018) (Figure 7). The emission factors and emissions calculated for the Point Henry, Portland and Bell Bay smelters are shown in Table 5. Australian PFC-14 emission factors as reported in the *National Inventory Report 2016* (DoEE, 2018) and as derived from atmospheric measurements at Cape Grim using NAME/TAPM (to 2011) and TAPM (to 2016) modelling are shown in Figure 6.

The Australian emissions derived from atmospheric data prior to 2006, using TAPM or InTEM (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 (the Kurri Kurri and Tomago smelters are located in the Hunter Valley, NSW). 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 (94 tonnes).

In 2016, Australian PFC-14 emissions (TAPM, 103 tonnes) were about 0.8% of global emissions (12.4 k tonnes). The only significant PFC-14 source in Australia is aluminium production, whereas globally both aluminium production and the semiconductor production industry are significant sources of PFC-14 emissions.

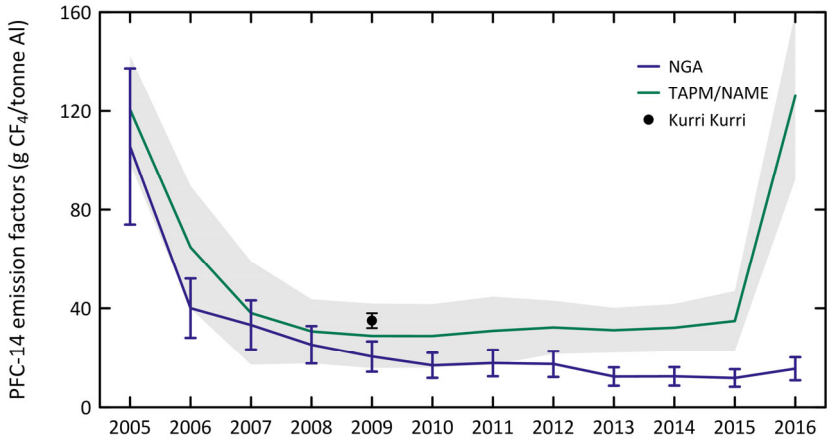

Figure 6. Australian PFC-14 emission factors as reported in the *National Inventory Report 2016*(NGA: DoEE, 2018) and as derived from atmospheric measurements at Cape Grim using NAME/TAPM (to 2011) and TAPM (to 2015) modelling. The grey band is the average (±1 sd) emission factor derived from NAME/TAPM. The Kurri Kurri emission factor is based on direct PFC-14 measurements made at the Kurri Kurri smelter in 2009 (Fraser *et al.*, 2013).

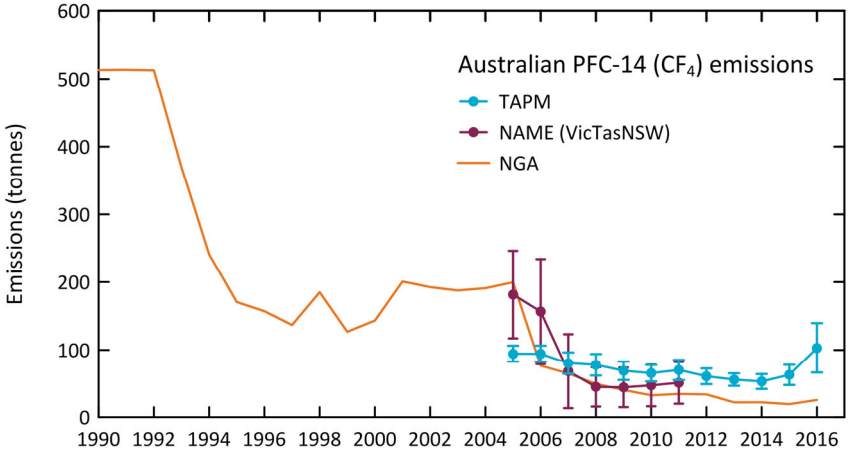

Figure 7. Australian emissions of PFC-14 as recorded in the *National Inventory Report 2016* (NGA: DoEE, 2018; uncertainty 27%: DIICCSRTE, 2013) and as obtained from TAPM (scaled from Vic/Tas emissions) and NAME-InTEM (scaled from Vic/Tas/NSW emissions) modelling.

Table 5. Australian PFC-14, PFC-116, PFC-218, PFC-318 emissions (t: tonnes) and PFC-14, PFC-116 emission factors (g/t aluminium, 2005-2016) 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.

Refrigerant	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2005-16 avg
TAPM emissions (tonnes)													
PFC-14													
Portland	18±3	18±4	14±4	15±5	12±4	12±3	12±4	10±3	10±2	12±3	15±4	18±6	14±4
Pt Henry	12±2	11±2	10±2	10±2	9±2	8±2	9±3	8±2	8±2	2±0[9]			9±2
Bell Bay	5±1	5±1	6±3	4±2	3±2	3±2	3±2	3±2	4±2	4±2	4±2	12±9	5±3
Australia	95±12	94±12	80±16	78±16	69±14	65±12	70±15	61±12	56±9	53±11	63±15	103±37	74±15
NAME emissions (tonnes)													
PFC-14[6]	182±65	157±77	68±55	45±29	44±30	47±31	51±31	51±31	51±31	51±31	51±31	51±31	71±39
PFC-116	15±1	15±1	15±1	15±1	19±3	23±5	29±3	29±3	29±3	29±3	29±3	29±3	23±2
PFC-218[1]	9±1	10±1	11±1	12±1	19±3	21±3	20±2	20±2	20±2	20±2	20±2	20±2	17±2
TAPM/NAME average emissions (tonnes)													
PFC-14	138±38	125±45	74±35	62±23	57±22	56±22	61±23	61±12[8]	56±9	53±11	63±15	103±37	76±24
PFC-116[4]	14±4	13±4	7±4	6±2	6±2	6±2	6±2	6±1	6±1	5±1	6±2	10±4	8±2
ISC emissions (tonnes)													
PFC-218	7±3	6±2	9±4	6±2	7±3	12±5	14±5	12±4	7±2	8±3	9±3	9±3	10±3
PFC-318	26±17	26±17	26±17	26±17	26±17	13±5	15±5	14±5	12±4	10±4	10±4	10±3	14±6
ISC/NAME average emissions (tonnes)													
PFC-218	8±2	8±2	10±3	9±2	13±3	16±4	17±3	12±4[8]	7±2	8±3	9±3	9±3	10±3
Total PFC emissions	160±40	146±45	92±35	77±25	101±30	91±25	99±25	92±15	81±10	76±15	89±15	132±40	103±27
CO_2-e (M tonnes)	1.26±0.34	1.15±0.40	0.73±0.33	0.61±0.21	0.87±0.38	0.76±0.27	0.83±0.28	0.77±0.19	0.67±0.14	0.63±0.15	0.73±0.19	1.06±0.38	0.84±0.27
PFC emission factors													
Portland, Victoria	52±10	52±11	40±12	42±15	37±12	39±11	40±13	34±10	32±8	39±10	51±13	63±20	43±12
Pt Henry, Victoria	63±12	60±11	52±11	51±9	48±10	40±11	45±13	43±11	42±8	38±8			48±10
Bell Bay, Tasmania	31±8	30±8	32±19	22±12	19±11	19±11	19±11	19±11	19±11	19±11	19±11	63±47	26±14
Australia (TAPM)[5]	48±10	48±10	41±14	38±12	35±11	33±11	35±13	32±11	31±9	32±10	35±12	126±134	39±13
Australia (NAME)[6]	96±34	82±40	35±28	23±14	23±15	25±15	27±15						44±23
TAPM/NAME average	72±22	65±25	38±21	31±13	29±13	29±13	31±14	32±11	31±9	32±10	35±12	126±134	41±16
Kurri Kurri					35±3[7]								

[1] Dalzell, E., Hydro Australia 2013, personal communication
[2] Australian emissions scaled from Portland, Pt Henry, Bell Bay emissions by aluminium production
[3] Australian emissions scaled from Portland, Pt Henry, Bell Bay, Kurri Kurri, Tomago emissions by aluminium production
[4] C_2F_6/CF_4 = 0.1, Kim *et al.*, (2014)
[5] TAPM (Portland, Pt Henry, Bell Bay average emissions)/aluminium production
[6] NAME (Vic/Tas/NSW) emissions/aluminium production; NAME emissions for 2011 are based on 2010-2011 data only
[7] emission factor for 2009 (Fraser *et al.*, 2013)
[8] TAPM or ISC only 2012 onwards
[9] Note: Pt Henry closure in July 2014

5.3 Other PFC emissions

Figure 8 shows the Australian PFC-116 emissions from the *National Inventory Report 2016*, 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/yr.

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 peak at 17 tonnes in 2010-2011, declining to 9 tonnes in 2016 and the latter declining from nearly 30 tonnes in 2009 to 10 tonnes in 2016. 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.

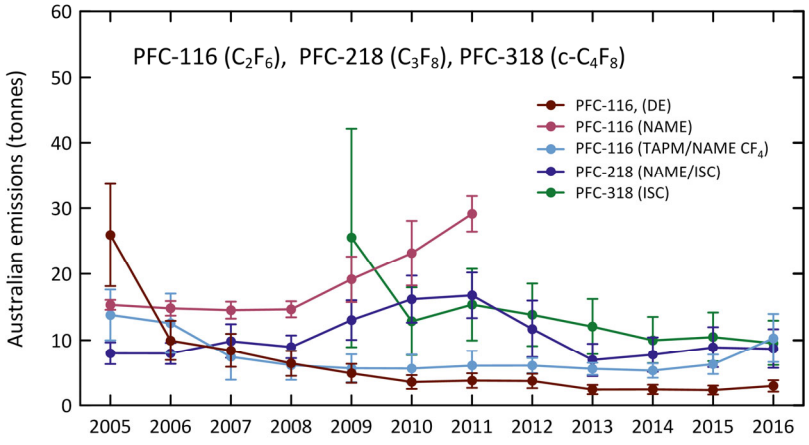

Figure 8. Australian PFC-116 emissions from the *National Inventory Report 2016* (DoEE, 2018) and Australian PFC-116, PFC-218 and PFC-318 from atmospheric measurements at Cape Grim using NAME, TAPM and ISC modelling; error bars are ± sd. Australian PFC-116 (NAME) are from Vic/Tas data scaled by aluminium production, PFC-116 (TAPM/NAME PFC-14) are from Australian TAPM/NAME PFC-14 emissions (Table 5) 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.

6 Comparisons of NGA, ISC and NAME emission estimates

6.1 HFC-134a

The major HFC in the *Inventory* (ageis.climatechange.gov.au; DoEE, 2018) is HFC-134a, with emissions in 2016 of 4611 tonnes (Table 3), an increase of 2.8% compared to 2015 emissions. Based on Cape Grim data, Australian emissions of HFC-134a in 2016 were 1756 tonnes (ISC-InTEM), 62% lower than reported in the *Inventory* (Table 3, Figure 4).

Cape Grim data suggest that Australian emissions of HFC-134a have grown significantly (30%) over the period 2013-2016, while the *Inventory* emissions have grown by 15% over the same period. However, since 2006, the Cape Grim data show that emissions have grown by only 42% compared to 145% in the *Inventory*. Both the *Inventory* and Cape Grim data show growing emissions through 2016 (Figure 4). Over the period 2005-2016, Cape Grim data suggest total HFC-134a emissions of 17.5 k tonnes (ISC-InTEM) compared to the *Inventory* total of 39.5 k tonnes, a factor of 2.3 higher. The ISC and InTEM total agree to within 17%.

As discussed in Section 4 above, the *Inventory* best represents total HFC emissions, not individual HFC emissions. The *Inventory* assumes a time-invariant fraction of HFC imports for individual HFCs and time-invariant HFC emission factors, whereas the Cape Grim data will reflect the time-dependent evolution of the use of individual HFCs (e.g. the recent transition from HFC-134a to HFC-32/HFC-125/HFC-134a/HFC-143a blends) and the time-dependent improved equipment maintenance practices, with better management of resultant HFC emissions (i.e. reflected as reduced emission factors).

Based on atmospheric data, global emissions of HFC-134a were 224 k tonnes in 2016 (Rigby *et al.*, 2014 and Rigby, unpublished data). Australian emissions are about 0.8% of global emissions based on Cape Grim data, and 2.1% based on *Inventory* data.

USA HFC-134a emissions as reported to UNFCCC are in decline, having peaked in 2010 at 69 k tonnes; however an analysis of air masses impacted by USA emissions arriving on the west coast of Ireland (Mace Head) suggest USA HFC-134a emissions continue to increase, reaching 70 k tonnes in 2012, increasing from 62 k tonnes in 2010. The USA HFC-134a emissions exhibit seasonal behaviour, with annual emissions about 20% higher than winter emissions, attributed to seasonal automobile ac emissions (Simmonds *et al*., 2015). Cape Grim 'sees' largely winter emissions of HFC-134a emissions from the Melbourne/Port Phillip region; this could offer a partial explanation of the large difference between Australian emissions of HFC-134a calculated from Cape Grim data and as reported in the *Inventory*.

The UK emissions of HFC-134a in 2015 were 4700 tonnes, as reported to UNFCCC, compared to 3300 tonnes estimated from HFC-134a pollution episodes seen at Mace head, Ireland (Manning *et al*., 2018). The respective *Inventory* emissions for Australia and the UK (4484 tonnes, 4700 tonnes) are similar (within 4%), whereas the atmosphere-based emissions (1682 tonnes and 3300 tonnes) have UK emissions nearly 97% higher than Australian emissions, perhaps consistent with the UK population being 170% higher than the Australian population (2016: 24 million, 65 million). The *Inventories* would suggest that *per capita* HFC-134a emissions in Australia are 2-3 times those in the UK. This seems unlikely. The atmosphere-based emission estimates suggest a *per capita* emission factor of about 70 g per year for Australia and 50 g per year for the UK. This seems more realistic.

6.2 HFC-125

The next major HFC emitted into the Australian environment is HFC-125 with current (2016) emissions estimated to be about 1613 tonnes in the *Inventory*, an increase of 2.9% compared to 2015 emissions. Based on Cape Grim data, Australian emissions of HFC-125 in 2016 were 668 tonnes (ISC-InTEM), a decrease of 2.8% compared to 2015 emissions and about 59% lower than the *Inventory* data. Over the period 2005-2016, Cape Grim data suggest total HFC-125 emissions of 5.9 k tonnes (ISC-InTEM) compared to the *Inventory* total of 13.8 k tonnes, a factor of 2.3 higher. The ISC and InTEM total agree to within 3%.

Based on atmospheric data, global emissions of HFC-125 were 64 k tonnes in 2016 (Rigby *et al*., 2014 and Rigby unpublished data). Australian emissions are 1.0% of global emissions based on ISC-InTEM data, and 2.5% based on *Inventory* data.

The UK emissions of HFC-125 in 2015 were 1470 tonnes, as reported to UNFCCC, compared to 900 tonnes estimated from HFC-134a pollution episodes seen at Mace head, Ireland (Manning *et al*., 2018). The respective *Inventory* emissions for Australia and the UK (1568 tonnes, 1470 tonnes) are similar (within 6%), whereas the atmosphere-based emissions (688 tonnes and 900 tonnes) have UK emissions 30% higher than Australian emissions.

6.3 HFC-143a

According to the *Inventory* (Table 3), the next major HFC emitted into the Australian environment is HFC-143a with current (2016) emissions of 154 tonnes, an increase of 2.7% compared to 2015 emissions. Based on Cape Grim data, Australian emissions of HFC-143a in 2016 were about 410 tonnes (ISC-InTEM), about 7% lower than 2015 emissions and about a factor of 2-3 higher than *Inventory* estimates. Emissions of HFC-143a peaked in 2013, declining for the next three years, whereas in the *Inventory* the emissions continue to grow from 2005 through to 2016 (Figure 4).

Based on atmospheric data, global emissions of HFC-143a were 29 k tonnes in 2016 (Rigby *et al*., 2014 and Rigby, unpublished data). Australian emissions are about 1.4% of global emissions based on ISC-InTEM data, and 0.5% based on *Inventory* data. Simmonds *et al*. (2015) report growing USA HFC-143a emissions through 2012 (8.5 k tonnes), with no obvious seasonality.

The UK emissions of HFC-143a in 2015 were 620 tonnes, as reported to UNFCCC, compared to 550 tonnes estimated from HFC-143a pollution episodes seen at Mace head, Ireland (Manning *et al*., 2018). The respective *Inventory* emissions for Australia and the UK (150 tonnes, 620 tonnes) are different (UK about a factor of 4 higher), perhaps consistent with population differences (UK nearly a factor of 3 higher), whereas the atmosphere-based emissions (440 tonnes and 550 tonnes) have UK emissions only 25% higher than Australian emissions.

6.4 HFC-32

The emissions based on Cape Grim data (282 tonnes in 2016), increased by 6% compared to 2015 emissions. A rapid increase in HFC-32 emissions occurred in 2013-2014 (35%) likely due to the popularity of HFC-32 in new air-conditioning systems on its own and as part of the refrigerant blend R410A. Similarly the largest increase (15%) in HFC-125 emissions

occurred in the same year – HFC-125 also being a component of R410a. The emissions based on Cape Grim data are significantly higher (factor of 3) than in the *Inventory* (89 tonnes in 2016).

Based on atmospheric data, global emissions of HFC-32 were 36 k tonnes in 2016 (Rigby *et al*., 2014 and Rigby, unpublished data). Australian emissions are 0.8% of global emissions based on ISC-InTEM data, and 0.2% based on *Inventory* data. Simmonds *et al*. (2015) report that USA HFC-32 emissions have stabilized through 2011-2012 (5-6 k tonnes), following strong growth in emissions during 2005-2010; there is no obvious seasonality in USA HFC-32 emissions.

Comparing differences between inventory and observation based emission estimates is useful when discrepancies are revealed and adjustments to methods can be made. In the UK, for example, the discrepancy identified between top-down and bottom-up estimates of HFC-134a emissions (Say et al., 2016) led to a revision of the bottom-up emissions.

The UK emissions of HFC-32 in 2015 were 690 tonnes, as reported to UNFCCC, compared to 450 tonnes estimated from HFC-32 pollution episodes seen at Mace head, Ireland (Manning *et al*., 2018). The respective *Inventory* emissions for Australia and the UK (87 tonnes, 690 tonnes) are very different (UK about a factor of 8 higher), whereas the atmosphere-based emissions (267 tonnes and 450 tonnes) have UK emissions about 70% higher than Australian emissions.

6.5 HFC-152a

The 2016 HFC-152a emissions have been estimated from Cape Grim data at 61 tonnes (ISC), 8% lower than 2015 emissions. The data suggest that HFC-152a emissions may have peaked in 2015 but confirmation from 2017 data will be sought. HFC-152a emissions have been approximately constant from 2012 to 2016, averaging around 62±21 tonnes per year. InTEM emissions are available for the period 2005-2011 and average 20% higher the ISC emissions. HFC-152a emissions are not listed in the *Inventory*. Imports of HFC-152a into Australia were 27 tonnes in 2016, 25 tonnes in 2017 (Table 2), 45% lower than 2015 imports, consistent with the peak emissions in 2015 shown from the Cape Grim data.

Simmonds *et al*. (2015) report that USA HFC-152a emissions have grown through 2012 (52-53 k tonnes); there is a suggestion of seasonality in USA HFC-152a emissions, with summer emissions lower than winter; however derivation of possible seasonality in the HFC-152a source is uncertain because HFC-152a is relatively short-lived in the atmosphere and there is a strong summer sink for HFC-152a.

Based on atmospheric data, global emissions of HFC-152a were 52 k tonnes in 2016 (Rigby *et al*., 2014 and Rigby unpublished data). Australian emissions are about 0.1% of global emissions based on ISC data.

6.6 HFC-23

HFC-23 emission estimates are estimated in the Inventory to be 0.5 tonnes in 2015. In the 1990s, Australian emissions were estimated as fugitive emissions from Sydney-based Australian HCFC-22 production. HCFC-22 production ceased in Australia in 1995. HFC-23 imports in 2016 were less than 1 tonne, averaging 0.9 tonnes per year since 2011. Imports in 2017 jumped up to 3.9 tonnes. The 2016 emissions have been estimated from Cape Grim data at 26 tonnes (ISC), dropping steadily from 46 tonnes in 2006. Although emissions of HFC-23 are small compared to the major HFCs (HFC-134a, HFC-143a and HFC-125), continued emissions of HFC-23 have significant potential to contribute to climate forcing due to its large GWP (Global Warming Potential) of 14,800.

Based on atmospheric data, global emissions of HFC-23 were 12 k tonnes in 2016 (Rigby *et al*., 2014 and Rigby, unpublished data). Current Australian emissions are about 0.2% of global emissions based on ISC data, less than 0.01% 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 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 possibly help explain these significant HFC-23 and PFC-116 emissions.

However, 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. Thus 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 a largely 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/firefighting emissions from Melbourne, but has not been identified, in any significant amounts, in any Australian 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.

The observation that the maximum emissions (46 tonnes, 2006) occurred in the first year of measurements suggests that peak emissions may have been pre-2006. The steady decline in HFC-23 emissions since 2006 is about 5% per year – if we assume this is from an 'old' bank, then the current bank could be of the order of 500 or more tonnes.

6.7 HFC-227ea

The 2016 emissions from Cape Grim data have been estimated at 18 tonnes (ISC), 35% lower than 2015 emissions. The HFC-227ea emissions are quite variable, ranging from 13 tonnes in 2006 up to a peak of 32 tonnes in 2009. In 2015, 26 tonnes of HFC-227ea were imported into Australia, 14 tonnes in 2016 (Table 2) and 15 tonnes were imported in 2016.

HFC-227ea emissions are now listed in the *Inventory*, with 2016 emissions estimated at 55 tonnes. The *Inventory* average emissions (2005-2016) are 37 tonnes compared to 22 tonnes from Cape Grim data. It is likely that the listed emissions of HFC-227ea in the *Inventory* are unrealistic as they are calculated from import data that are a fixed fraction of total HFC imports, GWP weighted. Over the period 2011-2016, HFC-23 imports average 30 tonnes per year, not inconsistent with the average emissions (ISC) over the same period of 24 tonnes per year.

There are no InTEM estimates of HFC-227ea emissions from Cape Grim data.

Based on atmospheric data, global emissions of HFC-227ea were 4.5 k tonnes in 2016 (Rigby *et al*., 2014 and Rigby, unpublished data). Australian emissions are about 0.4% of global emissions based on ISC data and 1.2% based on *Inventory* data.

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

The 2016 emissions for HFC-236fa, HFC-245fa and HFC-365mfc have been estimated (ISC) from Cape Grim data at about 3 (steady), 69 (declining?) and 46 tonnes (declining) respectively. There are no estimates of emissions of these HFCs in the *Inventory*. In 2016, 0.1, 59 and 55 tonnes of HFC-236fa, HFC-245fa and HFC-365mfc respectively were imported into Australia (Table 2); in 2017 the imports were 0.2, 35 and 47 tonnes respectively. HFC-236fa imports have never exceeded 0.2 tonnes per year, but emissions have averaged 6 tonnes per since 2005 – there must be unrecorded HFC-236fa imports, perhaps from foam. The imports of HFC-245fa and HFC-365mfc are in decline from peak imports of 200-250 tonnes each in 2011. Current emissions of HFC-236fa and HFC-365mfc are not inconsistent with current emissions (total emissions 2014-2016 = 367 tonnes, total imports = 402 tonnes).

InTEM estimates of emissions of HFC-365mfc for the period 2006-2011 are about 60% higher than ISC estimates of emissions over the same period.

Based on atmospheric data, global emissions of HFC-236fa, HFC-245fa and HFC-365mfc were 0.29, 12 and 4.7 k tonnes respectively in 2016 (Rigby *et al*., 2014 and Rigby, unpublished data). Australian emissions are about 0.1%, 0.7% and 2.0% of global emissions based on Cape Grim data.

6.9 Total HFCs

Total HFC emissions (Table 4), based on Cape Grim observations (ISC, InTEM mean) have grown from about 2200 tonnes in 2005 over 3300 tonnes in 2016, an increase of 52%. Total HFC emissions in 2016 are about 50% lower than in the *Inventory*, due largely to the about 60% lower emissions of HFC-134a emissions from atmospheric data compared to *Inventory* data. Over the period 2005-2016, total HFC emissions in the *Inventory* are 30% higher than total emissions based on Cape Grim data (ISC/InTEM average).

Total HFC emissions in the *Inventory* in 2016 are 13.2 Mt CO_2-e, higher (around 77%) than emissions (7.45 Mt CO_2-e, ISC-InTEM mean) based on Cape Grim data (Table 3, Table 4, Figure 9). Over the period 2005-2016, the total HFC emissions in the *Inventory* are 113 Mt CO_2-e, compared to 78 Mt CO_2-e (45% higher) from Cape Grim data (ISC-InTEM).

Based on atmospheric data, global total HFC emissions 3676 k tonnes (Rigby *et al*., 2014 and Rigby, unpublished data) in 2016. Based on Cape Grim data (ISC-InTEM), Australian emissions are 0.9% of global emissions or 1.8% based on the *Inventory* data.

For the combined HFCs (-32, -125, -134a, -143a) the Australian *Inventory* emissions in 2015 were nearly 6300 tonnes, whereas the UK inventory emissions for the same HFCs were about 7500 tonnes, implying *per capita* emissions of 262 tonnes per million people (Australia) and 115 tonnes per million people (UK). Cape Grim data (past 5 years) suggest that Australian *Inventory* emissions are a factor of 2 too high, suggesting the possibility that the emission factors for HFCs may be a factor of 2 too high.

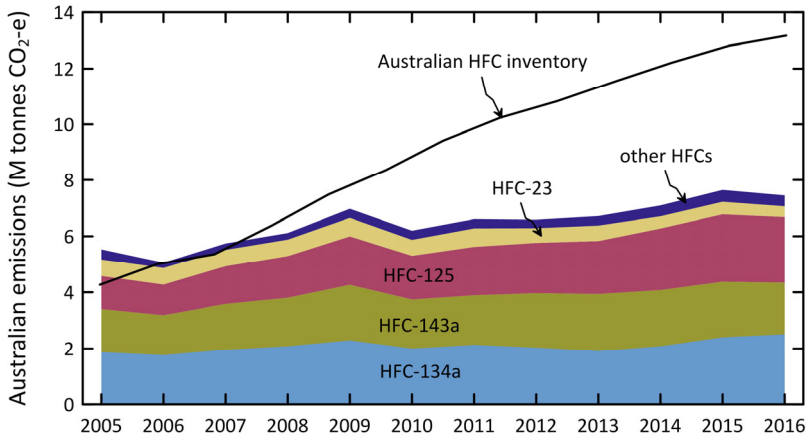

Figure 9. Australian emissions of HFCs (-125, -134a, -143a, -23) and other HFCs (-32, -152a, -227ea, -236fa, -245fa, -365mfc) estimated from atmospheric data (ISC-InTEM) measured at Cape Grim, and in the *Inventory* (DoEE, 2018), expressed in units of M tonne CO_2-e.

6.10 Sulfur hexafluoride

Sulfur hexafluoride emissions in the *Inventory* are 7.5 tonnes in 2016, 7.4 tonnes in 2015 (Table 3, Figure 4). Estimates using Cape Grim data (ISC-InTEM:Table 4, Figure 4) are 48 tonnes in 2005, decreasing to a low of 18 tonnes in 2016, an overall decrease of about 9% per year. In CO_2-e terms sulfur hexafluoride emissions have fallen by 0.69 Mt CO_2-e, from 1.10 Mt CO_2-e in 2005 to 0.41 Mt CO_2-e in 2016 based on Cape Grim data, whereas in the *Inventory* sulfur hexafluoride emissions have fallen by only 0.03 Mt CO_2-e, from 0.20 to 0.17 Mt CO_2-e over the same period.

A recent inversion study, using a hierarchical Bayesian method has been used to derive Australian (and other regions) emissions (Ganesan *et al*., 2014). Results show Australian emissions in 2012 of 17±9 tonnes. This compares with 22±8 tonnes in 2012 (ISC-InTEM data), whereas the *Inventory* reports 6.6 tonnes.

Based on atmospheric data, global emissions of sulfur hexafluoride were 8.6 k tonnes in 2016 (Rigby *et al*., 2014, Rigby, unpublished data). Australian emissions are about 0.2% of global emissions (ISC-InTEM), 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 sulfur hexafluoride emissions from atmospheric data and in the *Inventory*, and sulfur hexafluoride import data, are shown in Figure 10.

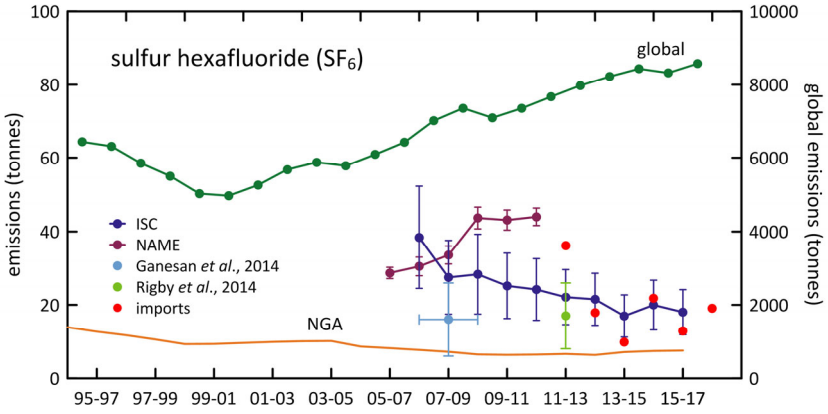

Figure 10. Australian and global sulfur hexafluoride imports and emissions (tonnes) from Cape Grim data using ISC and InTEM (Ganesan *et al.*, 2014; Rigby *et al.*, 2014) and from the *Inventory* (NGA: DoEE, 2018).

6.11 Sulfuryl fluoride

Based on Cape Grim data, Australian sulfuryl fluoride emissions averaged 20 tonnes/yr from 2005-2009, but then increased rapidly to 152 tonnes in 2016 (Table 4, Figure 11). Presumably this reflects a change in grain fumigation practices away from using methyl bromide and phosphine. Global emissions were 3650 tonnes in 2016 (Rigby *et al.*, 2014 and Rigby, unpublished data). Australian emissions are 3% of global emissions. Australia is responsible for 3% of global wheat production, but 10-15% of wheat exports. Sulfuryl fluoride 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 CO_2-e terms, sulfuryl fluoride emissions reached 758 k tonnes CO_2-e in 2016, compared to 411 k tonnes CO_2-e for sulfur hexafluoride and 1062 k tonnes CO_2-e for PFCs; HFCs averaged 7545 k tonnes CO_2-e in 2015-2016. In climate change terms, Australian sulfuryl fluoride emissions are now more than 70% of the radiative forcing of PFCs, and possibly growing quite rapidly. Clearly there needs to be a close watch on future sulfuryl fluoride emissions in relation to their contribution to radiative forcing due to SGGs.

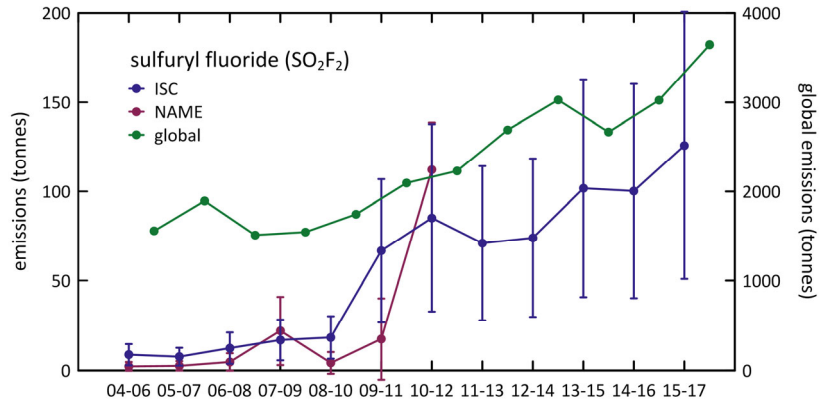

Figure 11. Australian sulfuryl fluoride emissions (tonnes), scaled from SE Australian emissions based on grain production, derived from Cape Grim *in situ* data, using ISC and InTEM techniques; global emissions (tonnes) are from Rigby *et al.*, 2014; Rigby, unpublished data.

6.12 Total HFCs, PFC and sulfur hexafluoride emissions

Total HFC, PFC and sulfur hexafluoride emissions in CO_2-e are shown in Table 4 and Figure 12. Total Australian HFC, PFC and sulfur hexafluoride emissions in the *Inventory* are 13.4 M tonnes CO_2-e in 2016, higher (50%) than estimates based on Cape Grim data: 8.9 M tonnes CO_2-e (ISC-InTEM). Over the period 2005-2016 the *Inventory* estimates are 22% higher than estimates based on Cape Grim data (ISC-InTEM). Over the period 2005-2016, total Australian emissions of HFCs, PFCs and sulfur hexafluoride, based on Cape Grim data (96 Mt CO_2-e) are about 17% lower than the same emissions in the *Inventory* (113 Mt CO_2-e). In two categories (PFCs and sulfur hexafluoride) the atmospheric data give higher estimates of emissions than in the *Inventory*. In the HFC category the atmospheric data give lower estimates of emissions than the *Inventory*.

Australian total HFC, PFC and sulfur hexafluoride emissions in 2016 from Cape Grim data (3487 tonnes, ISC-InTEM) are 0.7 % of global emissions (465 k tonnes).

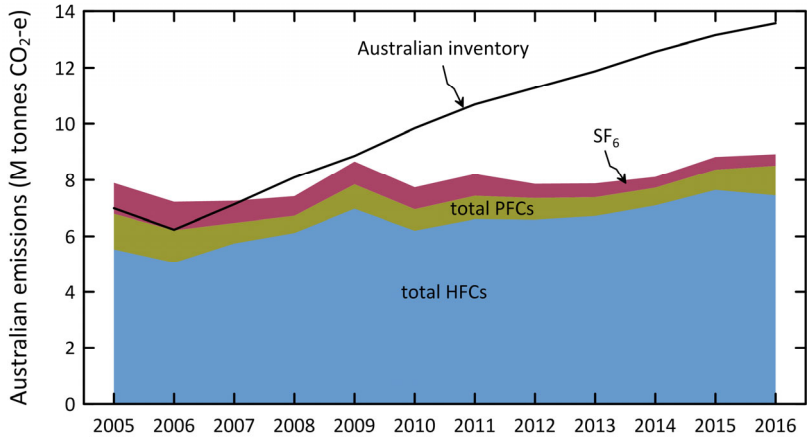

Figure 12. Australian HFC, PFC, sulfur hexafluoride emissions calculated from Cape Grim observations (ISC-InTEM) and in the *Inventory* (NGGI/NGA, ageis.climatechange.gov.au) in M tonne CO_2-e.

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, nine PFCs, sulfur hexafluoride, nitrogen trifluoride, trifluoromethyl sulfur pentafluoride and sulfuryl fluoride, utilizing data from the background atmosphere at Cape Grim, Tasmania. 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-CO_2 GHGs, from both ozone depletion and climate forcing perspectives.
- All HFCs, all PFCs, sulfur hexafluoride and sulfuryl fluoride, show increasing concentrations in the background atmosphere at Cape Grim, which accurately reflects global background atmospheric changes. Significant increases from 2016-2017 (ppt per year) are seen in HFC-134a (5.8), HFC-125 (2.5), HFC-143a (1.6), HFC-32 (1.9), HFC-23 (0.81), PFC-14 (0.78), sulfur hexafluoride (0.32) and sulfuryl fluoride (0.1). Total HFCs are growing at 13 ppt per year or 7.5% per year, total anthropogenic PFCs at 0.78 ppt per year (1.6% per year), sulfur hexafluoride at 3.6% per year and sulfuryl fluoride at 4.8% per year.
- Total global HFC, PFC, sulfur hexafluoride and nitrogen trifluoride emissions have risen from about 30 k tonnes per year in the late 1970s to around 467 k tonnes per year in 2016.
- Import data for 2016-2017 show significant use for most of these HFCs and sulfur hexafluoride in Australia. HFC imports in 2017 are approximately 36% higher than in 2016, and sulfur hexafluoride imports are 46% higher in 2017 compared with 2016, possibly due to increased imports before the HFC phase-down was enacted. Less than 1 tonne of PFCs are imported into Australia. The quantity of sulfuryl fluoride imported each year into Australia depends on the annual grain harvest, but is currently around 150 tonnes per year. There is no import data available for nitrogen trifluoride.
- The *National Greenhouse Accounts (Inventory)* reports significant Australian annual (2016) emissions of HFC-134a (4611 tonne), HFC-125 (1613 tonne), HFC-143a (154 tonne), HFC-32 (89 tonne), HFC-227ea (55 tonne), PFC-14 (29 tonne), sulfur hexafluoride (8 tonne) and PFC-116 (3 tonne). 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 from import data for total HFCs. The emissions model assumes a time-invariant distribution of total HFC import data into individual HFCs and time-invariant emission factors; thus the resultant individual HFC emissions are not necessarily reality. Emissions of PFCs (from aluminium production only) in the *Inventory* were about 35 tonnes per year for 2010-2012, declining to 20 tonnes per year for 2013-2015, rising again to over 25 tonnes in 2016. Overall the emissions of HFCs, PFCs and sulfur hexafluoride are increasing due to the dominant influence of HFC emissions.
- Regional Australian emissions have been detected in the Cape Grim data for all HFCs (except HFC-4310mee), the first four PFCs listed above, sulfur hexafluoride and sulfuryl fluoride. 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 transport model NAME and inversion model InTEM. SE Australian emissions of HFC-4310mee are expected to be seen at Cape Grim over the next few years. Australian emissions of all the major HFCs increased from 2014 to 2015, with an overall increase of 8%, but overall HFC emissions have now decreased (3%) from 2015 to 2016. Decreases were seen in HFC-143a (7%), HFC-23 (14%), HFC-125 (3%) and increases were seen in HFC-134a (4%) and HFC-32 (5%). Emissions of sulfuryl fluoride increased by 14%.
- Emissions of the all the minor HFCs (except HFC-4310mee) have been detected in the Cape Grim data. Emissions of three of the minor HFCs have decreased from 2015-2016 with HFC-227ea decreasing by 35%, HFC-245fa decreasing by 10% and HFC-365mfc decreasing by 15%. HFC-236fa emissons increased by 12%. SE Australian emissions of HFC-4310mee are expected to be seen at Cape Grim over the next few years.
- Comparisons of emissions of individual HFCs (*Inventory* v. atmospheric data) are not likely to be meaningful, but comparisons of total HFCs could be informative. Total HFC emissions in 2016 are about 50% lower than in the *Inventory*, due largely to the about 60% lower emissions of HFC-134a from atmospheric data compared to *Inventory* data. Over the period 2005-2016, total HFC emissions in the *Inventory* are 30% higher than total emissions based on Cape Grim data (ISC/InTEM average).
- For the combined HFCs (-32, -125, -134a, -143a) the Australian *Inventory* emissions in 2015 were nearly 6300 tonnes, whereas the UK inventory emissions for the same HFCs were about 7500 tonnes, implying *per capita* emissions of 262 tonnes per million people (Australia) and 115 tonnes per million people (UK). Could it be that

the Australian emission factors in the Inventory are more than a factor of 2 too high? Cape Grim data (past 5 years) suggest that Australian *Inventory* emissions are a factor of 2 too high, again suggesting the possibility that the emission factors for HFCs may be a factor of 2 too high.

- The *Inventory* shows Australian total HFC emissions continuing to grow, as do, by and large, Cape Grim data. The latter show that total HFC emissions were 3% lower in 2016 compared to 2015. Whether this represents some stabilization in emissions will be resolved with further data in the next few years.
- Total HFC emissions in the *Inventory* in 2016 are 13.2 Mt CO_2-e, higher (around 77%) than emissions (7.51 Mt CO_2-e, ISC-InTEM) based on Cape Grim data. Over the period 2005-2016, the total HFC emissions in the *Inventory* are 113 Mt CO_2-e, compared to 78 Mt CO_2-e (45% higher) from Cape Grim data.
- Over the period 2005 – 2016, both the *Inventory* and Cape Grim data show that Australian sulfur hexafluoride emissions are in decline overall (14% decline in the Inventory, 63% seen at Cape Grim), presumably reflecting the actions of Australian electricity distributors to reduce emissions. However the *Inventory* sulfur hexafluoride emissions are significantly lower than emissions estimated from Cape Grim data; over the period 2005 to 2016 the sulfur hexafluoride emissions in the inventory average 7 tonnes per year, about a factor of 4-5 lower than estimates from Cape Grim over the same period (30 tonnes per year). The Cape Grim data indicate that Australian emissions of sulfur hexafluoride were 0.2% of global emissions in 2016.
- Australian sulfuryl fluoride emissions from Cape Grim data have grown rapidly from 16 tonnes in 2005 up to 152 tonnes in 2016. This presumably reflects a change in grain fumigation practices away from using methyl bromide and phosphine to sulfuryl fluoride. Sulfuryl fluoride emissions are approaching 800 k tonnes CO_2-e, compared to about 400 tonnes CO_2-e for sulfur hexafluoride. In climate change terms, Australian sulfuryl fluoride emissions are now nearly twice the radiative forcing of sulfur hexafluoride and growing quite rapidly.
- PFC-14 and PFC-116 emissions from the aluminium industry have been estimated using InTEM and TAPM (PFC-116 indirectly via PFC-14). Over the period 2005-2016, PFC-14 emissions in the *Inventory* are in decline and are about 46% lower than PFC-14 emissions estimated from Cape Grim data (TAPM-InTEM). Emissions of PFC-14 using Cape Grim data have been steady at about 60 tonnes for the period 2012-2015, but increased significantly to 100 tonnes in 2016, 4 times the *Inventory* estimate. The fraction of Australian PFC-14 emission seen at Cape Grim has declined significantly since the closure of the Point Henry smelter in 2014. The 2016 increase in PFC-14 emissions is largely due to increases seen at the Bell Bay smelter. This needs to be confirmed with 2017 data.
- Over the period 2005-2015, PFC-116 emissions in the *Inventory* (assumed only from the aluminium industry) were in decline (although steady as seen at Cape Grim for the last few years). In 2016 the *Inventory* reports significant increase (30%) in PFC-116 emissions. The *Inventory* emissions have declined by 90% since 2005, and the TAPM-InTEM emissions have declined by 55%.
- Cape Grim observations show that Australian emissions of PFC-218 were growing until 2011, but are now declining, with current (2016) emissions for PFC-218 about 9 tonnes. PFC-318 emissions vary from 10-15 tonnes over the last 5 years. 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.
- Total Australian PFC emissions (from Cape Grim data) declined from 2005 to 2008, largely driven by emissions from the aluminium industry. From 2008 to 2016 emissions varied from 76 - 132 tonnes per year. Total Australian PFC emissions from the *Inventory* have declined by nearly 90% from 2005 to 2016.
- Total Australian HFC, PFC and sulfur hexafluoride emissions, expressed as CO_2-e emissions, over the period 2005-2016 estimated from atmospheric data (Cape Grim, ISC, InTEM, TAPM) are about 17% lower than in the *Inventory*.
- Importantly, Cape Grim data suggest that the combined Australian emissions of HFCs, PFCs and sulfur hexafluoride, which peaked in 2009 and plateaued over the period 2009-2014 at 2900 tonnes per year, have now reached a new maximum of about 3500 tonnes in 2016; the *Inventory* shows that emissions have continued to grow through 2016 to 6500 tonnes.

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