F-Gas Inventories and Comparisons with Atmospheric Observations

IPCC Meeting on Use of Atmospheric Observation Data in Emission Inventories

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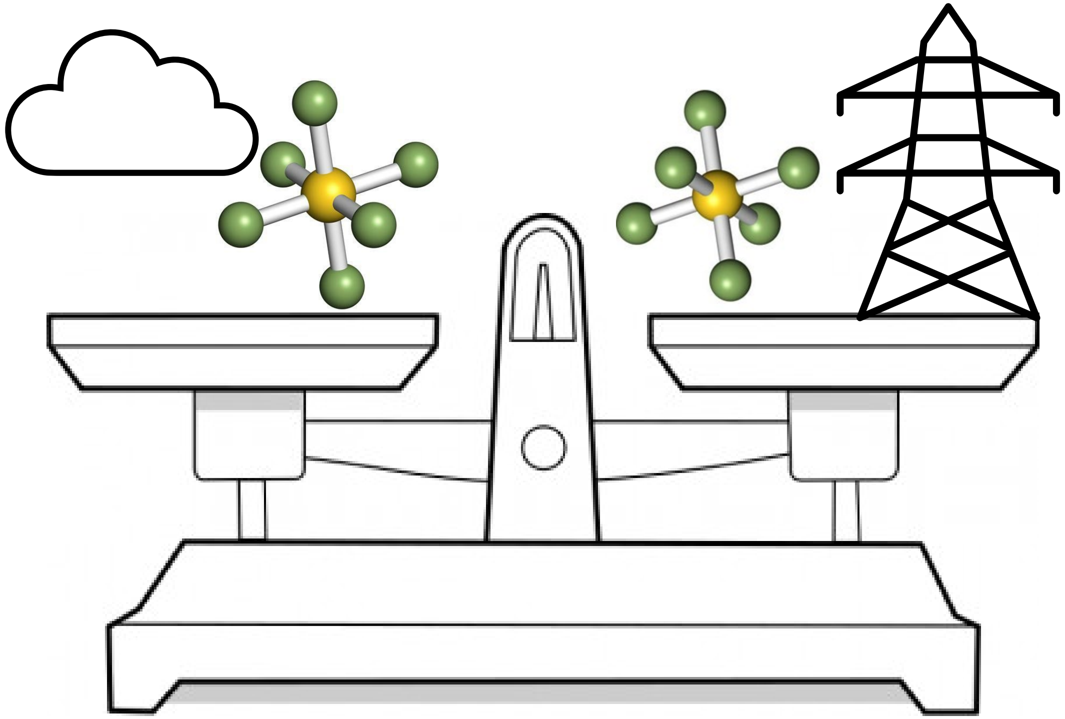

Acknowledgements

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- Lei Hu, University of Colorado-Boulder
- Steve Montzka, US NOAA

Meeting Objectives

- Assess and critique recent datasets as well as new and operational systems, platforms, instruments/sensors and methods/models to derive, from atmospheric observations, representative emission rates from source categories over time periods of interest.
- Assess and evaluate the usability of these recently available datasets as well as new operational systems, platforms, instruments/sensors and methods/models to derive, from atmospheric observations, comparative data to verify IPCC default factors and uncertainties as well as to allow inventory-compilers to verify their emission estimates through application of IPCC good practice methods and approaches.
- **Assess and evaluate useful examples of comparisons between atmospheric observations and national inventories that are consistent with good practice provided in the 2019 Refinement to the 2006 IPCC Guidelines on National Greenhouse Gas Inventories (e.g., following the steps provided in tables 6.3 and box 6.5 of Volume 1) that have led to implemented or planned improvements in national inventories.**
- **Assess and evaluate available examples where emission estimates derived from atmospheric observations have been incorporated into a bottom-up inventory framework, including the associated resources (technical, human, funds) needed in their implementation.**
- **Assess and evaluate the usefulness of efforts (including resource implications) to grid (spatially and temporally) national emissions inventory and the use of these gridded products in comparisons with atmospheric observations.**

By achieving these objectives, this Expert Meeting is expected to support the development of IPCC materials that will assist countries to make better estimates of emissions, for example the Methodology Report on SLCFs to be produced during the IPCC 7th assessment cycle (AR7 cycle).

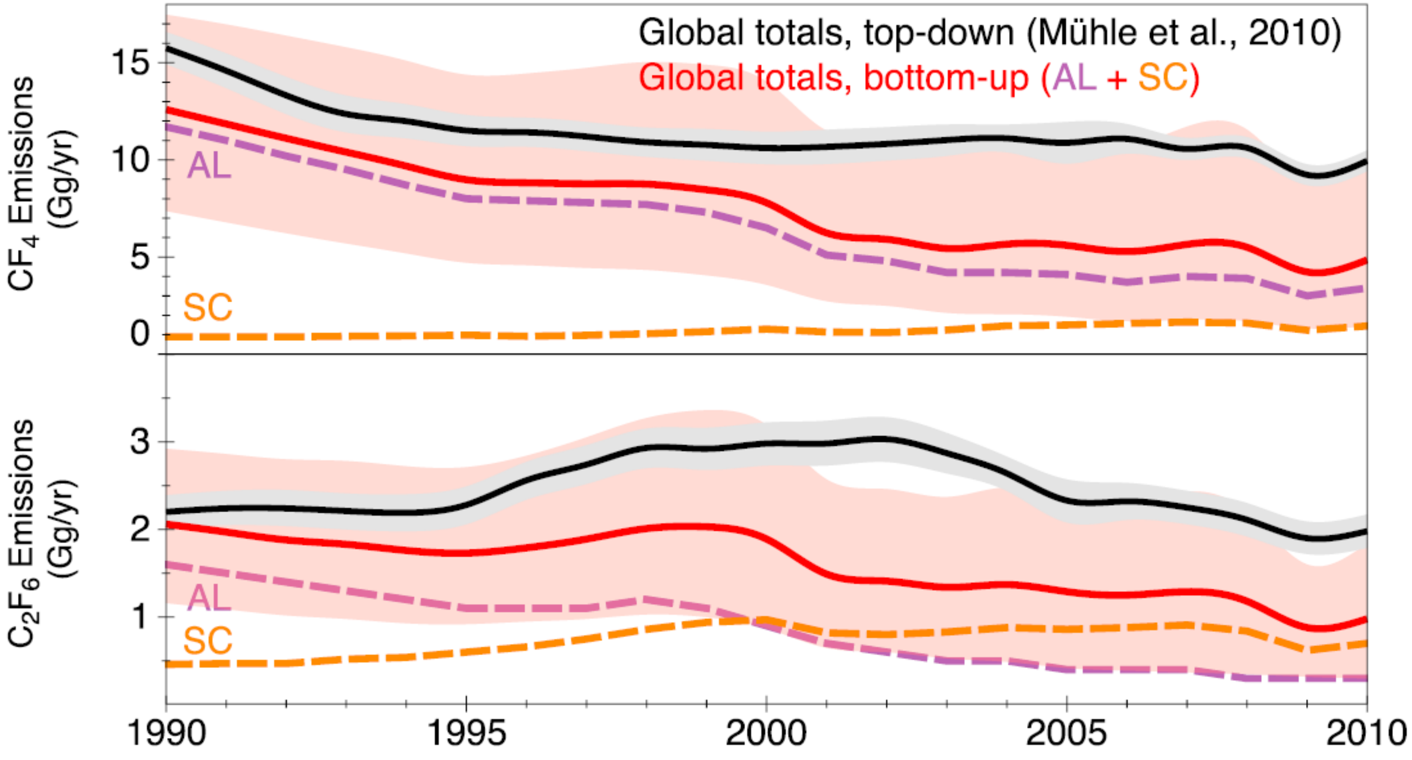
Key Question

What can we say in addition to the guidance in the 2019 Refinement to reflect what we've learned since then about using atmospheric measurements to inform or QA/QC F-GHG emissions inventories?

2019 Refinement on Using Atmospheric Measurements to Verify F-GHG Inventories

"Fluorinated gases and methane (CH_4) are considered the most suitable greenhouse gases for which inverse modelling could provide verification of emission estimates (Rypdal et al. 2005, Bergamaschi et al. 2004). The fluorinated compounds are considered good candidates for inverse modelling verification because: they have virtually no natural source interference in the atmospheric measurements, there can be considerable uncertainties in inventory methods, they are long-lived, and the loss mechanisms are well known."

Example: CF_4 and C_2F_6



Source: Kim, J., et al. (2014), "Quantifying aluminum and semiconductor industry perfluorocarbon emissions from atmospheric measurements," *Geophys. Res. Lett.*, 41, 4787-4797, doi: 10.1002/2014GL059783.

Using Atmospheric Measurements to Verify and Enhance F-GHG Inventories: US Experience

- Sulfur hexafluoride
- HFCs
- Conclusion: Long-term communication and collaboration between inventory compilers and atmospheric scientists are key to making the most of comparisons.

Using Atmospheric Measurements to Verify F-GHG Inventories: US Emissions of SF_6

SF_6 is most potent GHG, with 100-year GWP (AR5) of 23,500 and atmospheric lifetime of 3,200 years

Inventory methods

- 1999-2019 emissions estimated based on facility reporting through Greenhouse Gas Reporting Program (GHGRP), voluntary EPA-industry Partnerships, and national activity data x estimated emission factors for non-reporting facilities.

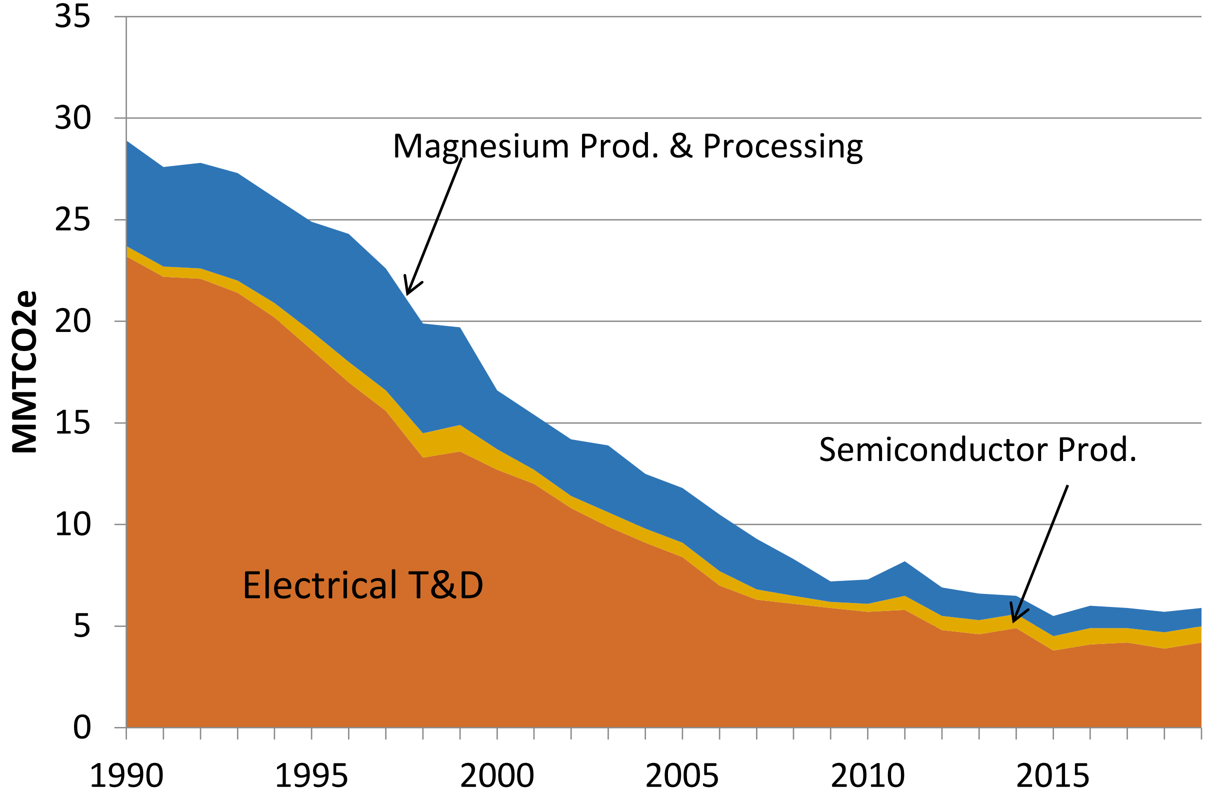
Atmospheric measurements

- 2007-18 emissions estimated using measurements made from ground-based and airborne whole-air flask samples collected from the U.S. National Oceanic and Atmospheric Administration (NOAA) Global Greenhouse Gas Reference Network and a regional inverse model.

US SF_6 Sources

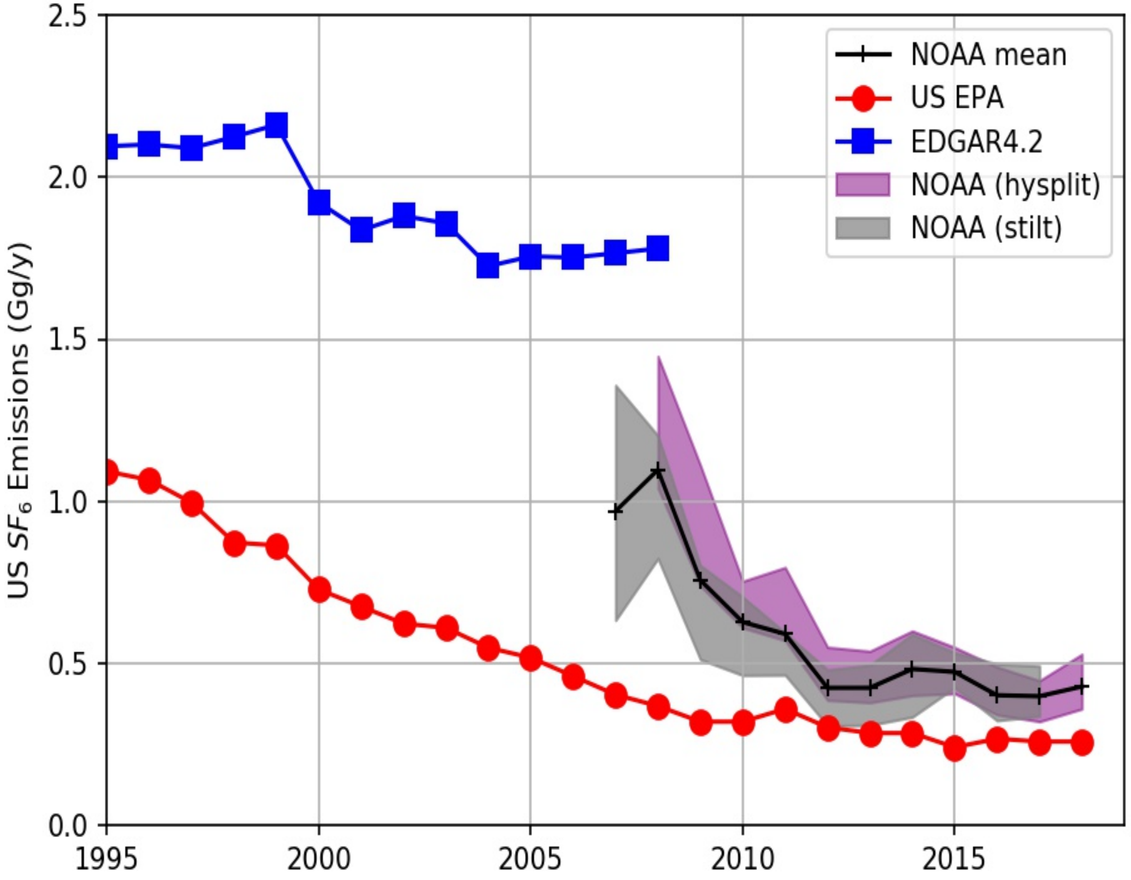
- Uses/sources include (**bold**=currently in US GHGI):
  - **Insulator and arc quencher in electrical transmission and distribution (ET&D) equipment**
  - **Source of fluorine for electronics manufacturing**
  - **Cover gas for magnesium production and processing**
  - Through 2010: Emissions from SF_6 production facility
  - Military uses (e.g., AWACs, torpedo propellant)
  - Insulator in research and medical accelerators
  - Other medical applications
  - Tracer gas and others

US GHGI: Emissions of SF_6 by Source Since 1990



Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2019. U.S. Environmental Protection Agency. April 2021.

Comparison Between Activity-Based and Atmosphere-Based Estimates of US Emissions of SF_6

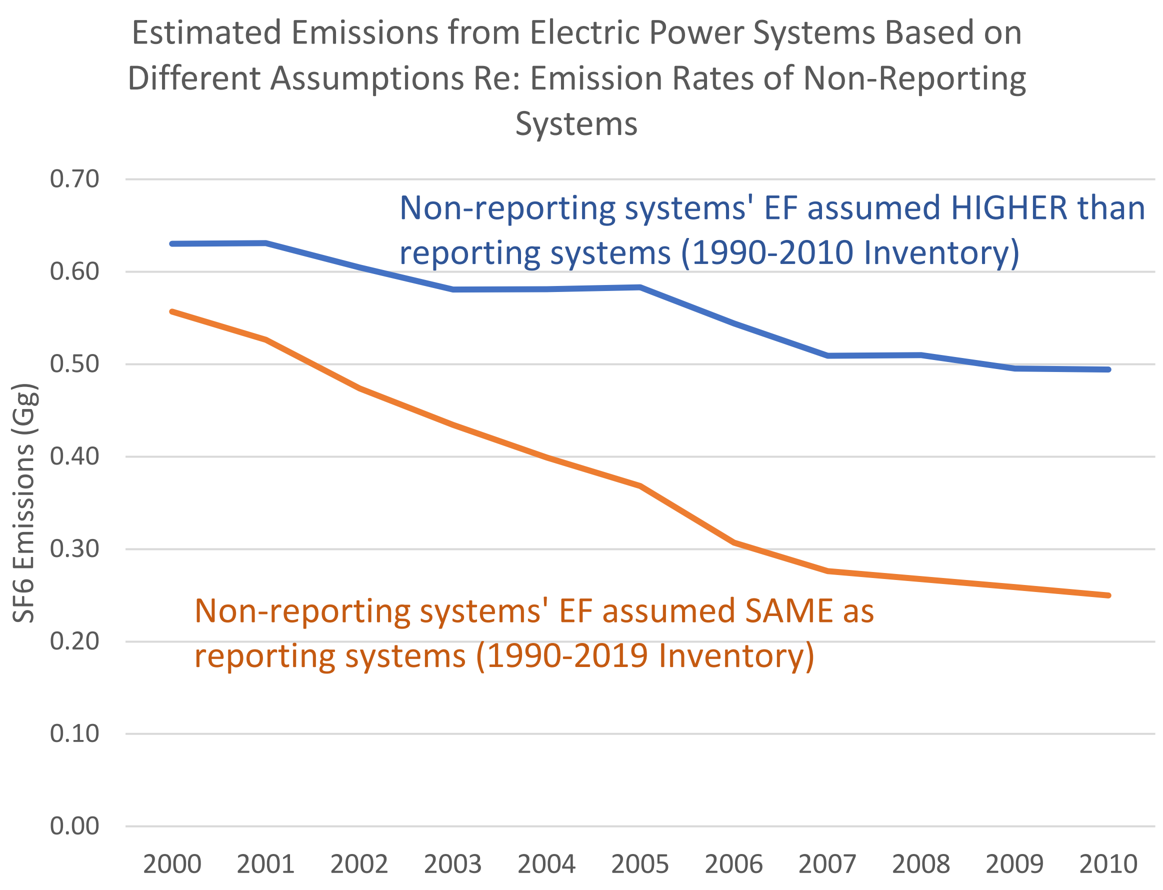


Source: Lei Hu, et al, "Atmosphere-based US emission estimates of SF_6 for 2007 – 2018", eGMAC (April 2021)

- Both GHG Inventory and atmospheric measurements show a declining trend in US SF_6 emissions.
- US EPA GHGI emissions lower than emissions inferred from atmospheric measurements
    - Gap especially large before 2011.
    - Gap smaller in 2011 and later years, after the GHGRP began.

Bottom-up Estimates Sensitive to Assumed Emission Rate of Non-Reporting Facilities

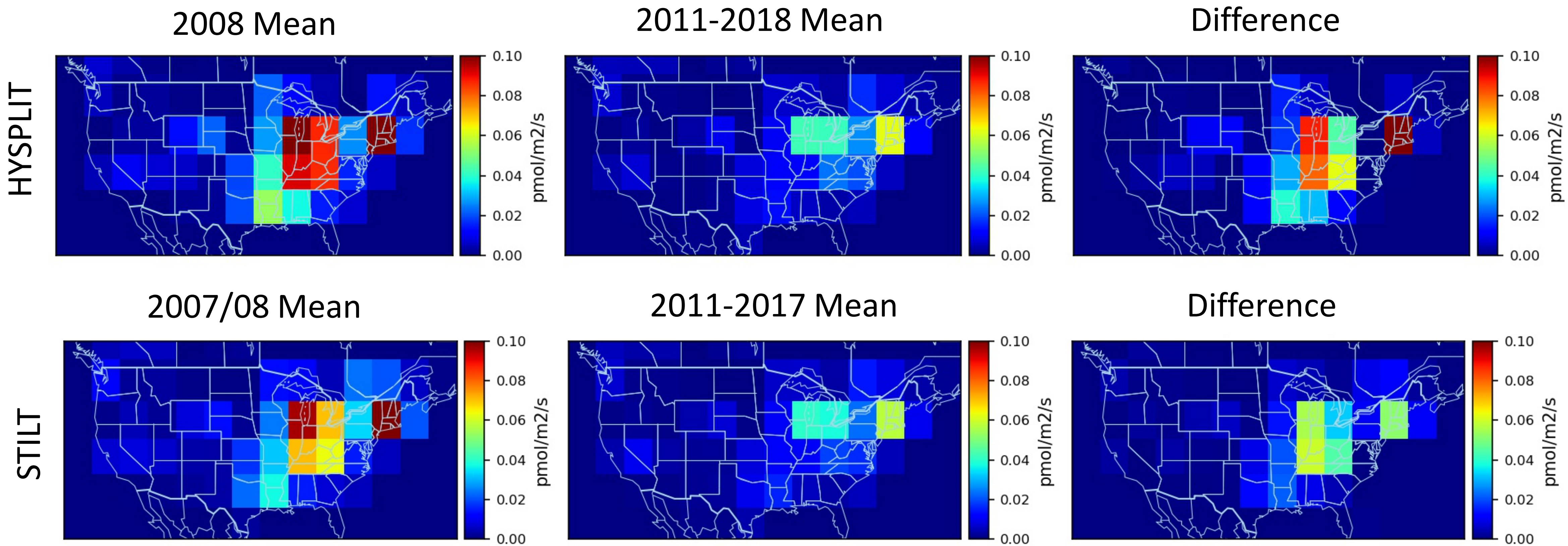
- Facilities reporting under both Partnership and GHGRP reduced emissions significantly, especially in first few years of reporting.
- In US GHG Inventories published *before 2013*, non-reporting facilities were assumed NOT to have reduced their emissions from the 1999 emission rate of Partners.
- In US GHG Inventories published in *2013 and later*, non-reporting facilities were assumed to have reduced their emissions at the SAME rate as reporting facilities throughout the time series.
- In fact, new GHGRP reporters may have acted to reduce emission rate only after draft GHGRP published in 2009.



Regional Comparison: Gridding US GHGI SF_6 Emissions

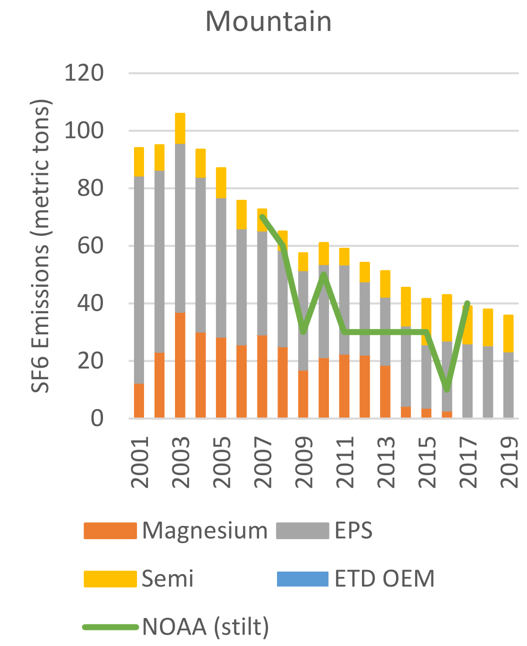
- Used EPA's 2021 state-by-state breakout of national GHG Inventory (1990-2019).
- For years after 2011, able to precisely locate point sources that report through GHGRP (semiconductor manufacturing, magnesium production).
- ET&D more challenging (even after 2011) because reporting "facilities" (ET&D networks) often span multiple states. In 2021 state-by-state breakout, only able to allocate 20 – 30 % of ET&D emissions to a single state by facility location (i.e. when the facility was only in one state). The remaining emissions were distributed based on the transmission miles in each state.
    - Limited regional resolution of SF_6 emissions data for current study.
    - Improving now—37-49% of emissions allocated by state in 2022 state-by-state inventory.
- Before 2011, ET&D and semiconductor emissions allocated to states based on activity data (transmission miles for ET&D; area x layers for semiconductors). Magnesium emissions allocated to states based on emissions reported by Partners.

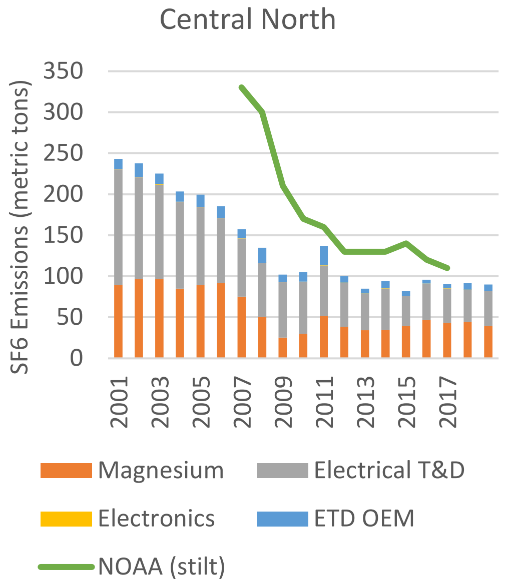
Atmosphere-Based Regional Emissions Distribution in 2007/8 vs 2011-17/18

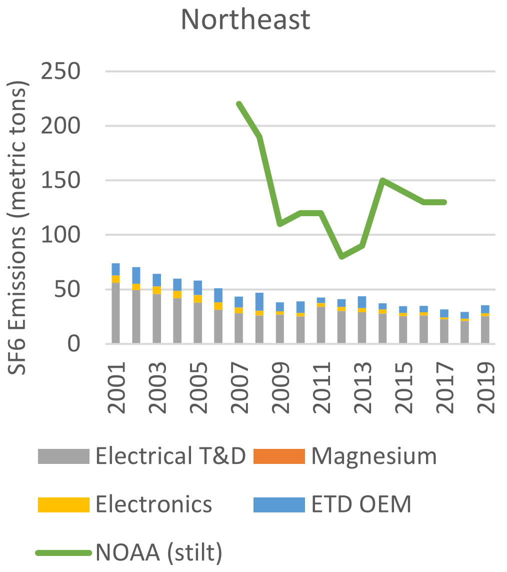


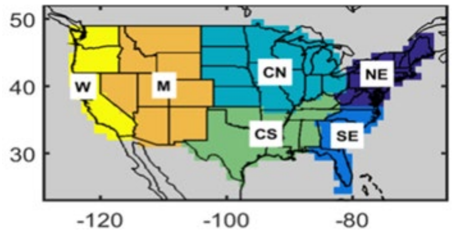
Source: Lei Hu et al., submitted, 2022.

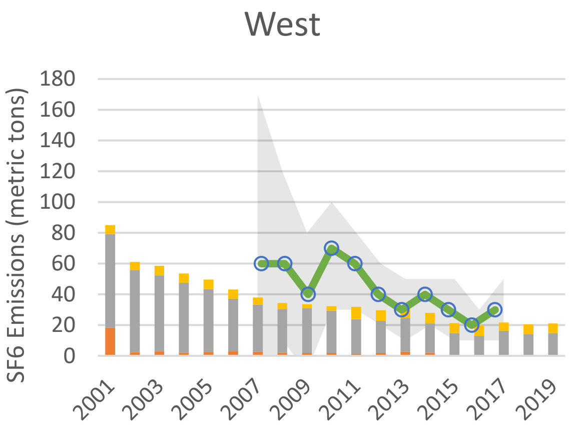
Regional SF_6 Trends

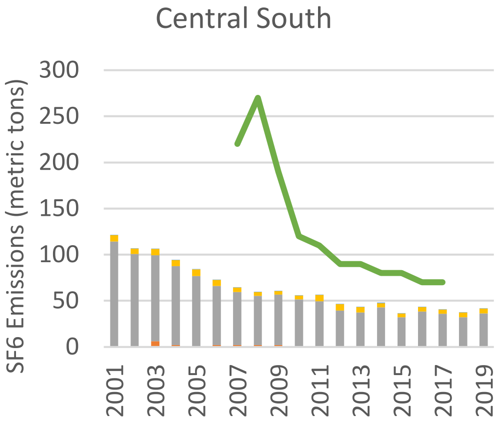


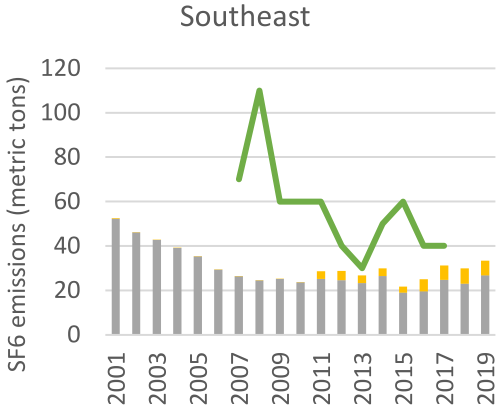






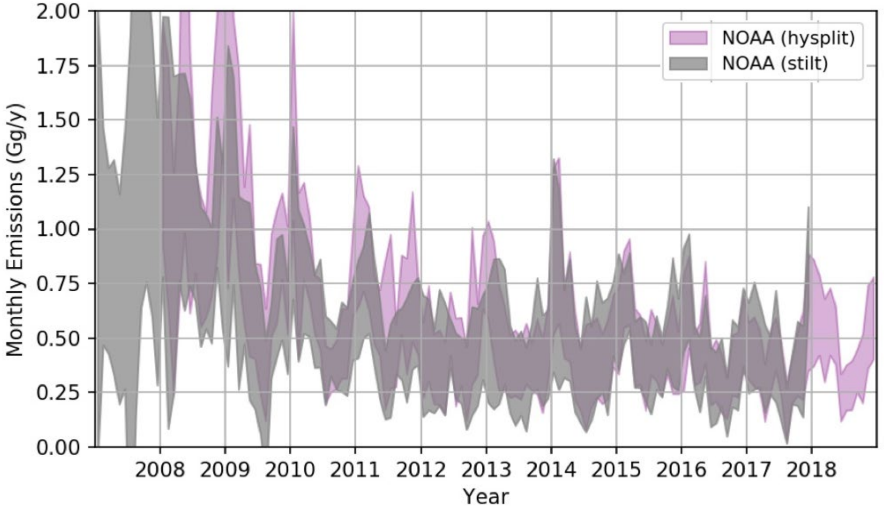


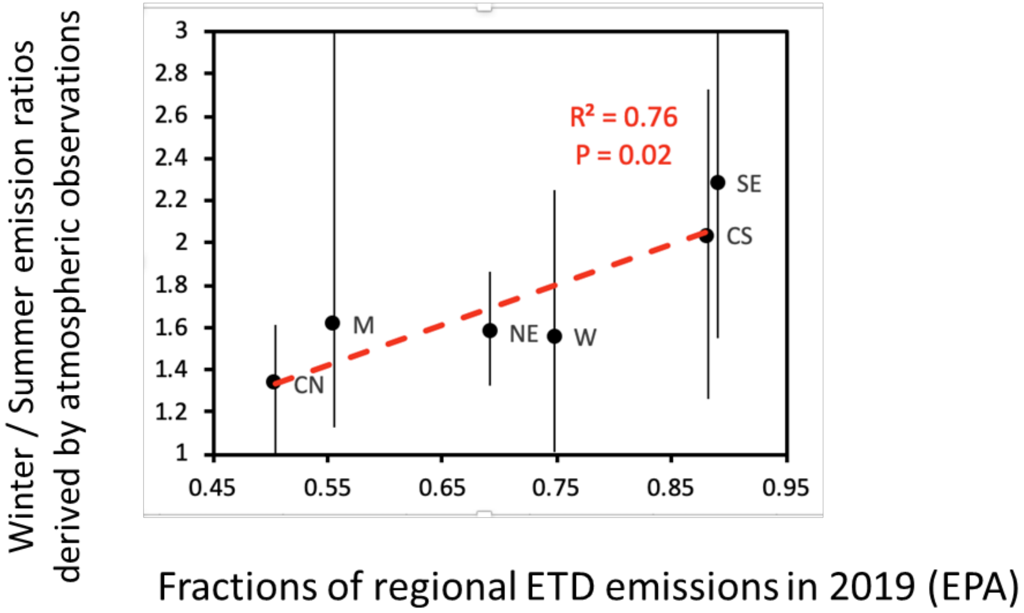




Source: Source: Lei Hu et al., submitted, 2022.

Seasonal SF_6 Trends

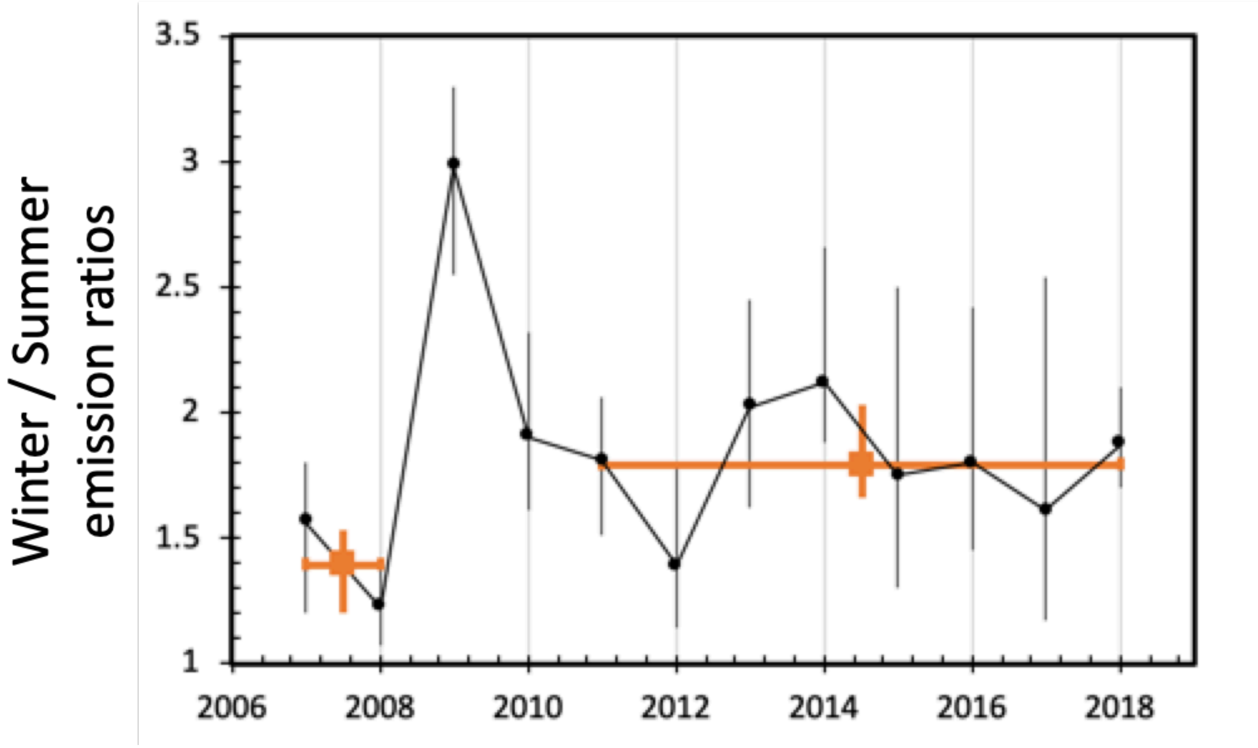




Source: Lei Hu, et al, “Atmosphere-based US emission estimates of SF_6 for 2007 – 2018”, eGMAC (April 2021)

- Atmospheric measurements show persistent seasonal variations, with the highest emissions in the winter.
- SF_6 use and emissions not expected to vary seasonally for magnesium or electronics production.
- Based on discussions with ET&D sector, higher winter SF_6 may be due to increased servicing of electrical equipment during off-peak (cooler) months. In addition, leaks may be larger in the winter due to hardening of seals during cold weather.
- Seasonal variation is most pronounced in regions of the country where the majority of SF_6 emissions are from ET&D, as is the case in the South.

Seasonal variation apparently grew between 2006-8 and 2011-18.



Source: Source: Lei Hu et al., submitted, 2022.

- Also see changes in seasonal variation over the time series.
- Largest variation seen in 2009, when Great Recession reduced semiconductor and magnesium production but didn't affect ET&D.
- Observe statistically significant difference between 2007-2008 variation and 2011-2018 variation.
- **Challenge:** This contradicts our hypothesis that underestimate from ET&D sector is primarily responsible for 2007-2010 overall underestimate.

What source(s) other than ET&D contributed to 2007-2010 underestimate?

- Uses/sources other than ET&D include **(bold**=currently in US GHGI)**:**
  - **Source of fluorine for electronics manufacturing**
  - **Cover gas for magnesium production and processing**
  - Through 2010: Emissions from SF_6 production facility
  - Military uses (e.g., AWACs, torpedo propellant)
  - Insulator in research and medical accelerators
  - Other medical applications
  - Tracer gas and others

Leading Candidate: SF_6 Production Facility

- Uses/sources other than ET&D include (**bold**=currently in US GHGI)**:**
  - **Source of fluorine for electronics manufacturing**
  - **Cover gas for magnesium production and processing**
  - Through 2010: Emissions from SF_6 production facility
  - Military uses (e.g., AWACs, torpedo propellant)
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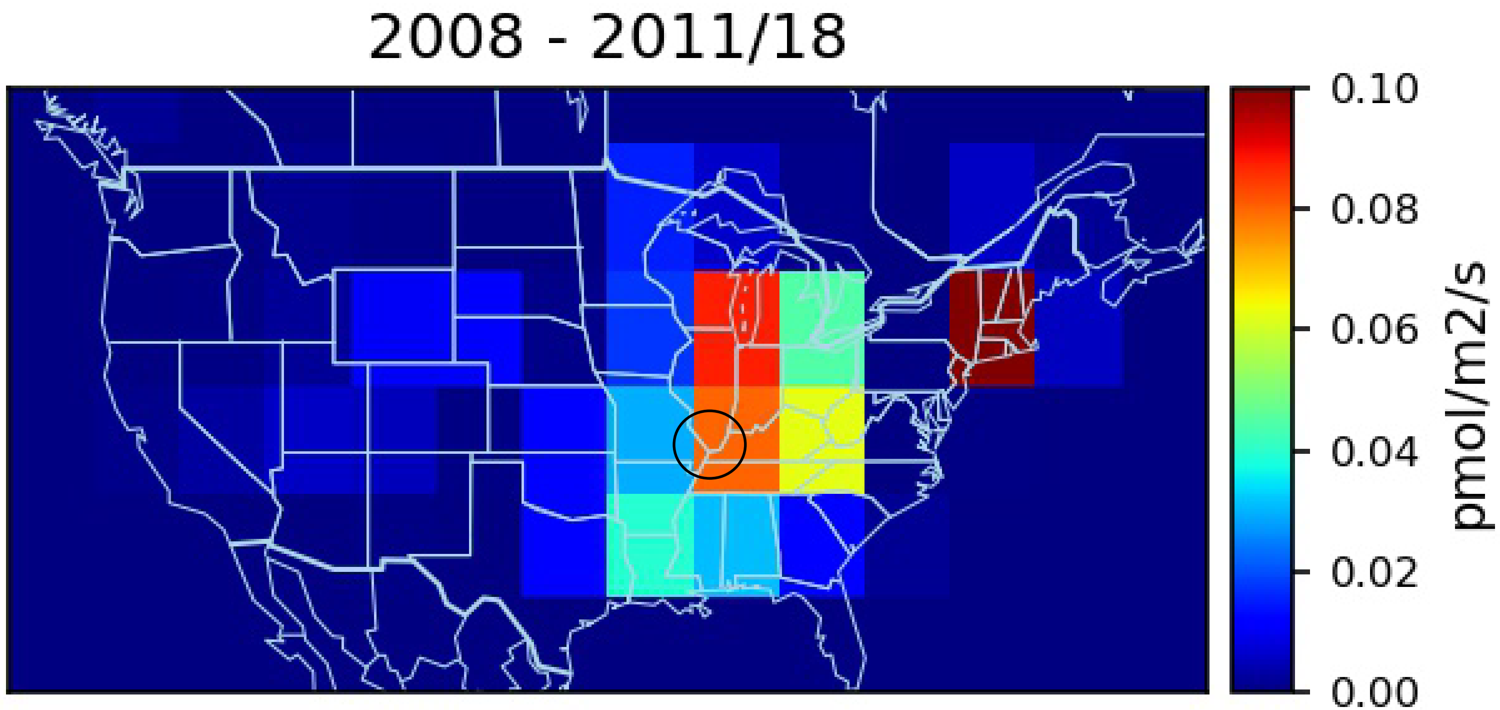
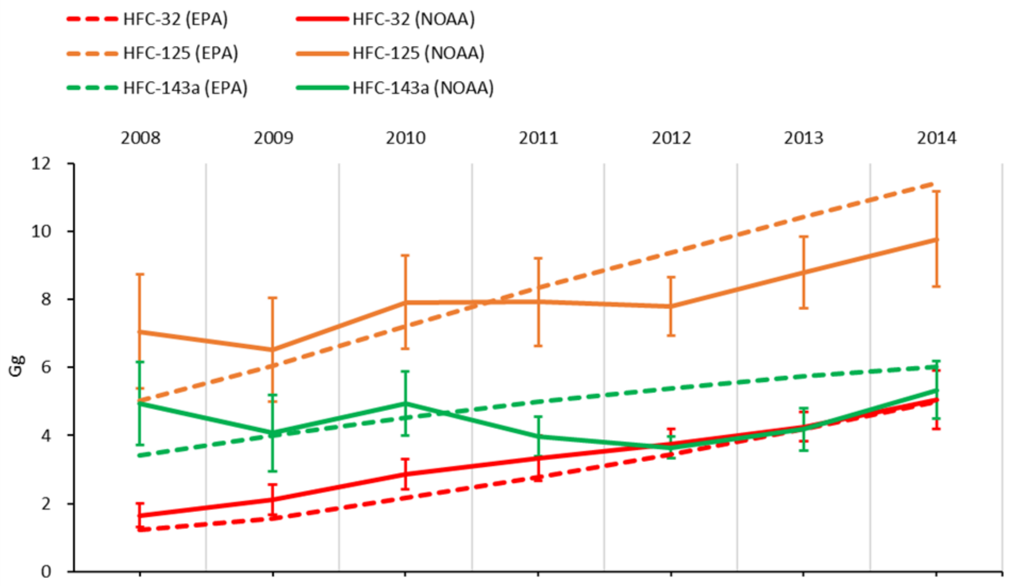


Once we account for (1) higher 2007-10 emissions from non-reporting ET&D facilities, and (2) 2007-10 emissions from the SF_6 production facility, mix of sources is consistent with seasonal variation seen in 2007 and 2008.

Using Atmospheric Measurements to Verify Country-Level Estimates of US HFC Emissions

- Latest USEPA GHGI report includes comparisons of HFC-32, HFC-125, HFC-134a, and HFC-143a derived in the Inventory and from atmospheric measurements and inversion models
- Results combined with knowledge of the ODS Substitutes industry highlight areas for future research that could improve Inventory estimates, such as:
    - Changes in the refrigeration market away from blends like R-404A or success in lowering emission rates
    - Use of “dry-charge” residential AC equipment in lieu of R-410A
- Uncertainty estimates by species would aid in comparisons to atmospheric data.
    - EPA will explore Monte Carlo analysis to differentiate between species

Figure 4-4: U.S. Emissions of HFC-32, HFC-125, and HFC-143a

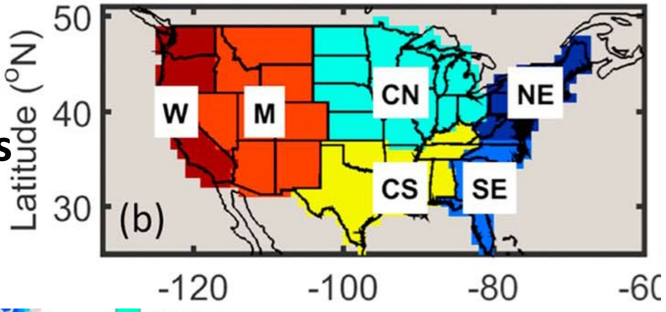


Source: Inventory of US Greenhouse Gas Emissions and Sinks, 1990-2020, 2022, p. 4-147.

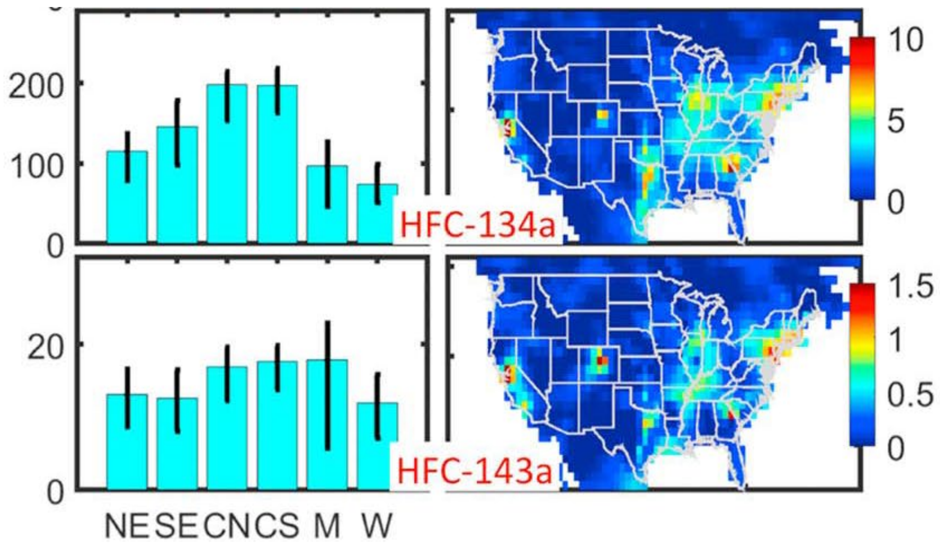
Using Atmospheric Data to Enhance Regional HFC Emissions Estimates

Approach

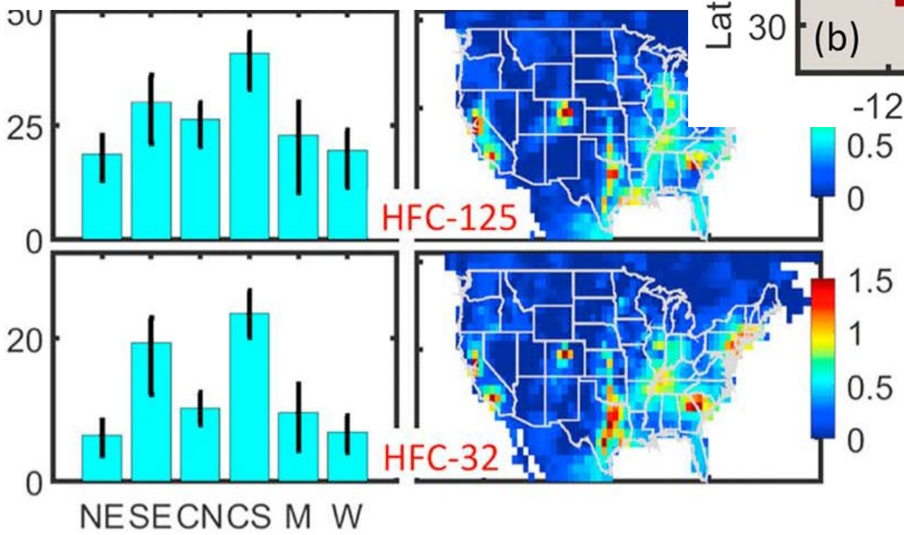
- National emissions were initially allocated to states based only on population, as state-level activity and emission factor data are limited.
- Subsequently, state-level estimates were adjusted based on NOAA atmospheric measurements.
  - The emissions distribution was modified with data from Hu et al. (2017), which used atmospheric measurements to estimate emissions from 6 regions in the contiguous states
  - Data for four HFCs were available: HFC-125, HFC-134a, HFC-143a (2008-2014), and HFC-32 (2010-2014).
  - Regional emissions were then divided into states by population.
  - For the other HFCs, population alone was used to estimate emissions.



g/year/person **pico mole/m²/s**



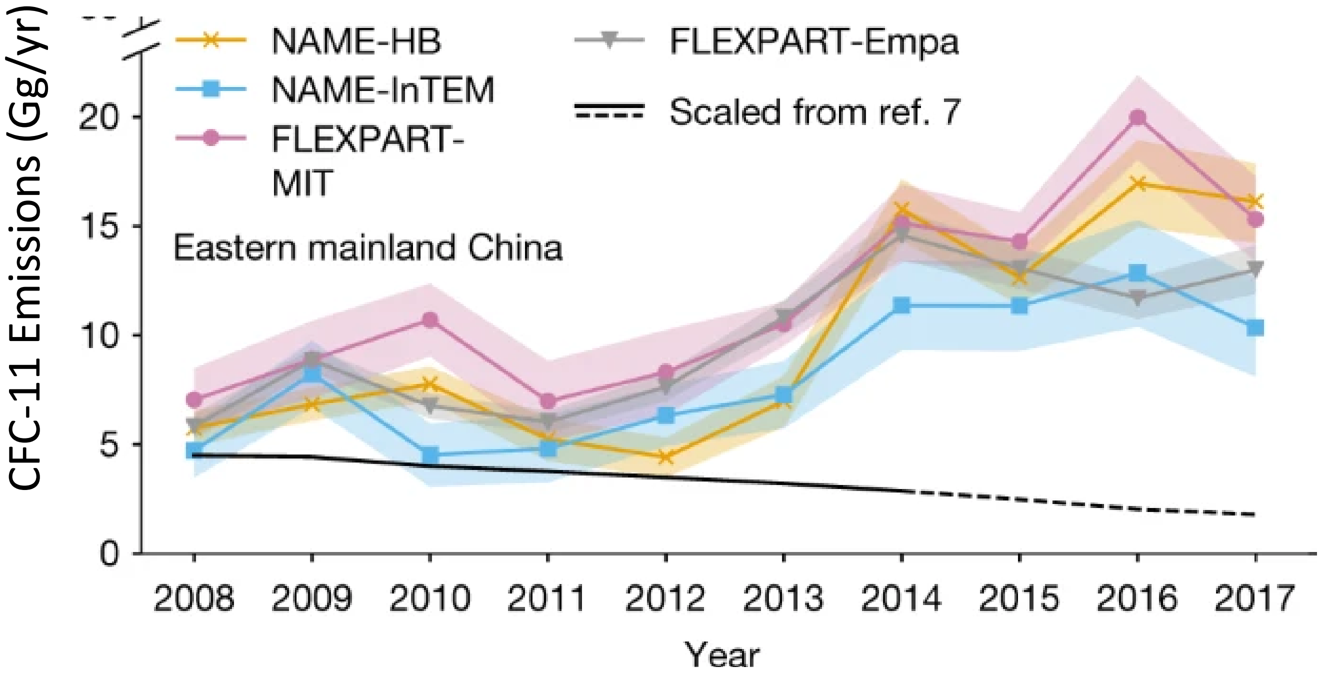
g/year/person **pico mole/m²/s**



Source: Hu, L., et al. (2017), Considerable contribution of the Montreal Protocol to declining greenhouse gas emissions from the United States, *Geophys. Res. Lett*., 44, 8075–8083, doi:10.1002/2017GL074388.

Reminder: Atmosphere-Based Estimates Are Also Uncertain

Chinese Emissions of CFC-11 Derived from Four Inverse Modelling Frameworks



Measurement or modeling uncertainties or errors can result in under-estimates, over-estimates, or incorrect regional attribution of emissions.

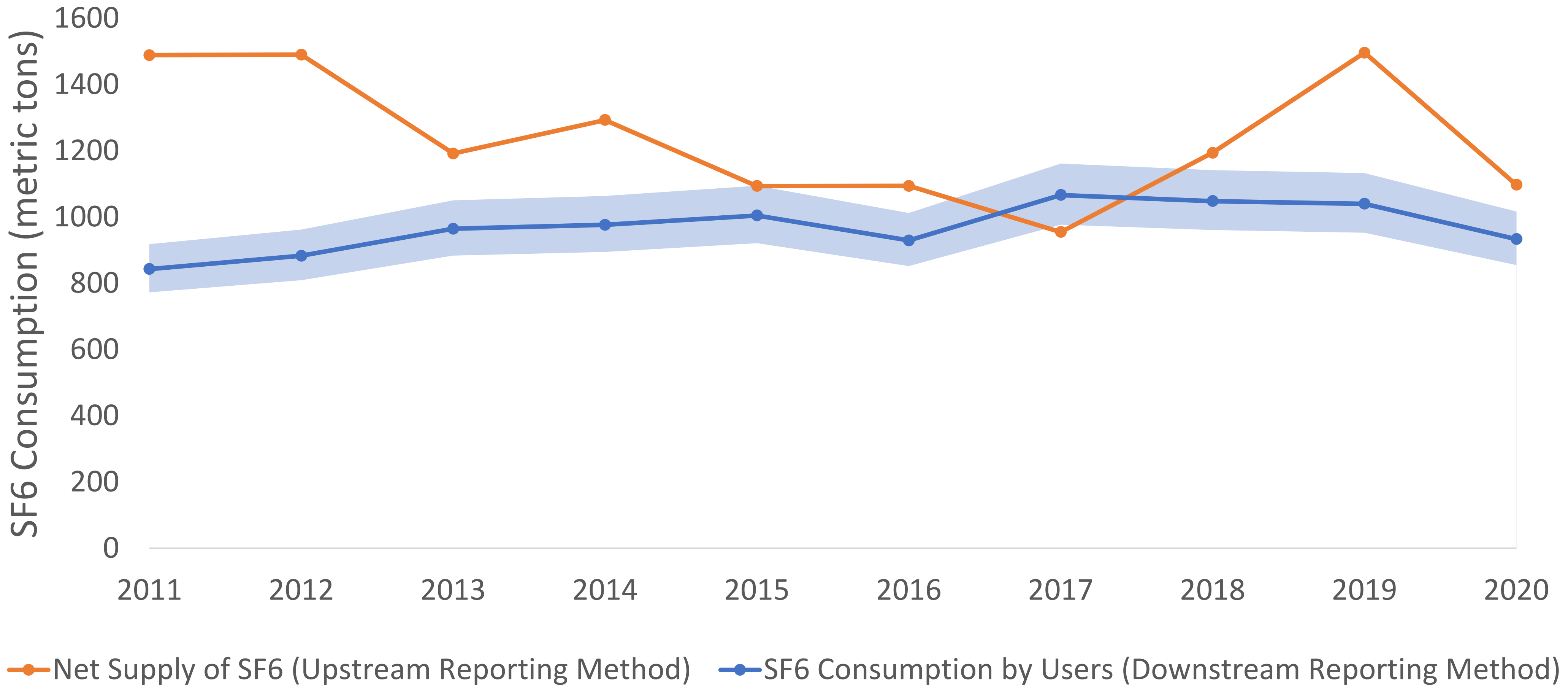
Source: Rigby, M., Park, S., Saito, T. *et al.* Increase in CFC-11 emissions from eastern China based on atmospheric observations. *Nature* **569**, 546–550 (2019). https://doi.org/10.1038/s41586-019-1193-4

Consider Enhancing Comparisons Using Additional Sources of Independent Data

- Can also compare F-GHG **consumption** reported by/inferred for users and emitters of F-GHGs to F-GHG **supplies** reported by producers, importers, and exporters.

  "[W]hen considered along with estimates of actual emissions, the potential emissions approach can assist in validation of completeness of sources covered and as a QC check by comparing total domestic consumption as calculated in this 'potential emissions approach' per compound with the sum of all activity data of the various uses" (IPCC, 2006 Guidelines).

U.S. SF_6 Supply vs. Consumption



Take-aways

- Long-term communication and collaboration between inventory compilers and atmospheric scientists are key to making the most of comparisons.
    - Plan on a lively back-and-forth process.
    - Consider bringing in additional expertise, e.g., from emitting industry.
- Useful comparisons take time; important to prioritize gases/sources.
- Insight into what is driving emissions can be gained by combining on-the-ground knowledge of sources with analysis of
    - temporal and spatial patterns in emissions (e.g., seasonality in emissions) and
    - emissions of different F-GHGs that may be emitted separately or together in characteristic ratios.
- If possible, establish a regular, predictable schedule for updated comparisons (ideally annually, but at least every few years). This avoids having to reassemble the relevant expertise and data on a case-by-case basis.
- Consider using additional sources of independent data to further QA/QC bottom-up inventories.
- Comparisons have added benefit of reminding us of the uncertainties in both activity-based and atmosphere-based estimates.

Additional Background

2019 Refinement: Atmospheric Measurements

"Atmospheric measurements are being used to provide useful quality assurance of the national greenhouse gas emission estimates (Manning et al. 2011; Fraser et al. 2014; Henne et al. 2016). Under the right measurement and modelling conditions (discussed further in this section), they can provide a perspective on the trends and magnitude of greenhouse gas (GHG) emission estimates that is largely independent of inventories."

2019 Refinement

- Operational verification systems exist in
  - Switzerland
  - UK
  - Australia

BOX 6.5: COMPARISON – VERIFICATION ACTIONS ON INVENTORY COMPILER SIDE

1. In cases where there are discrepancies between the two estimates, the effort to reduce this discrepancy should be taken by both the inverse modelling and inventory compiling groups. On the inventory compiler side, following steps are suggested to take:
2. Confirm that the observation-based emission estimates and the inventories represent the same time period, areas.
3. Determine what emission dataset was used as a prior, and how it compares to the emission inventory.
4. Assess how the estimation procedure treats anthropogenic and natural emissions, to confirm that the estimates compare with anthropogenic and natural emissions included in the inventory.
5. Confirm that seasonal variability of the emissions and other effects have been considered in the comparison.
6. Assess the uncertainties of the estimated emissions, and note whether the discrepancy is statistically significant.
7. For sub-national scale regions with the larger discrepancies, determine which emissions activities are occurring there, based on the gridded or regional GHG inventory:
   a. Recheck inventory activity data in that region;
   b. Assess factors that may make the regional emission rates different from the national inventory average (e.g. different regulations, different technologies), and assess the extent to which these have been taken into account in the national inventory and in its gridding/disaggregation.
8. In the national inventory improvement plan, prioritize emission sources/regions with larger discrepancies.

TABLE 6.3: IMPLEMENTATION STEPS AND SHARE OF RESPONSIBILITIES BETWEEN PARTNERS

Step	Work package	Responsible group
1	Acquisition of GHG observations from a surface network (and when available from aircraft and satellites) that has sufficient coverage of the country's emissions. The observation data have to be linked to the same calibration scale and be processed by the compatible routines across the network.	Observation /atmospheric modelling
2	Preparing gridded (spatially and temporally disaggregated) prior emissions data.	Gridded inventory
3	Preparing and operating the inverse model other observation-based emission estimation methods.	Atmospheric modelling
4	Quality Assurance / Quality Control to the inverse model output.	Atmospheric modelling
5	Comparison verification and reporting. Production of final outputs and update of the GHG inventory improvement plan.	Inventory/ Atmospheric modelling

Scope of GHGRP and Partnership SF_6 Data

Percentage of SF6 Emissions Accounted for by Facilities Reporting to EPA By Source Category

Source	Estimated Percentage of Partnership Emissions Coverage (1999-2009/2010)	Estimated Percentage of GHGRP GHG Emissions Coverage[a] (2010/2011+)
SF6 Users / Emitters		
Electronics Manufacturing	~69-81%	96-97%
Magnesium Production and Processing	88-95%	67-92%
Use of Electric Transmission and Distribution (ET&D) Equipment	60-65%	66-78%
Manufacture of Electric Transmission and Distribution (ET&D) Equipment	N/A	~50%
SF6 Suppliers		
Importers / Exporters	N/A	>95%
Production of Fluorinated Gases	N/A	100%

[a] Coverage estimates include both F-GHGs and other GHGs emitted from these sources and show the range in coverage from 2011-2019.

Seasonal Variation Also Seen for HFCs in US

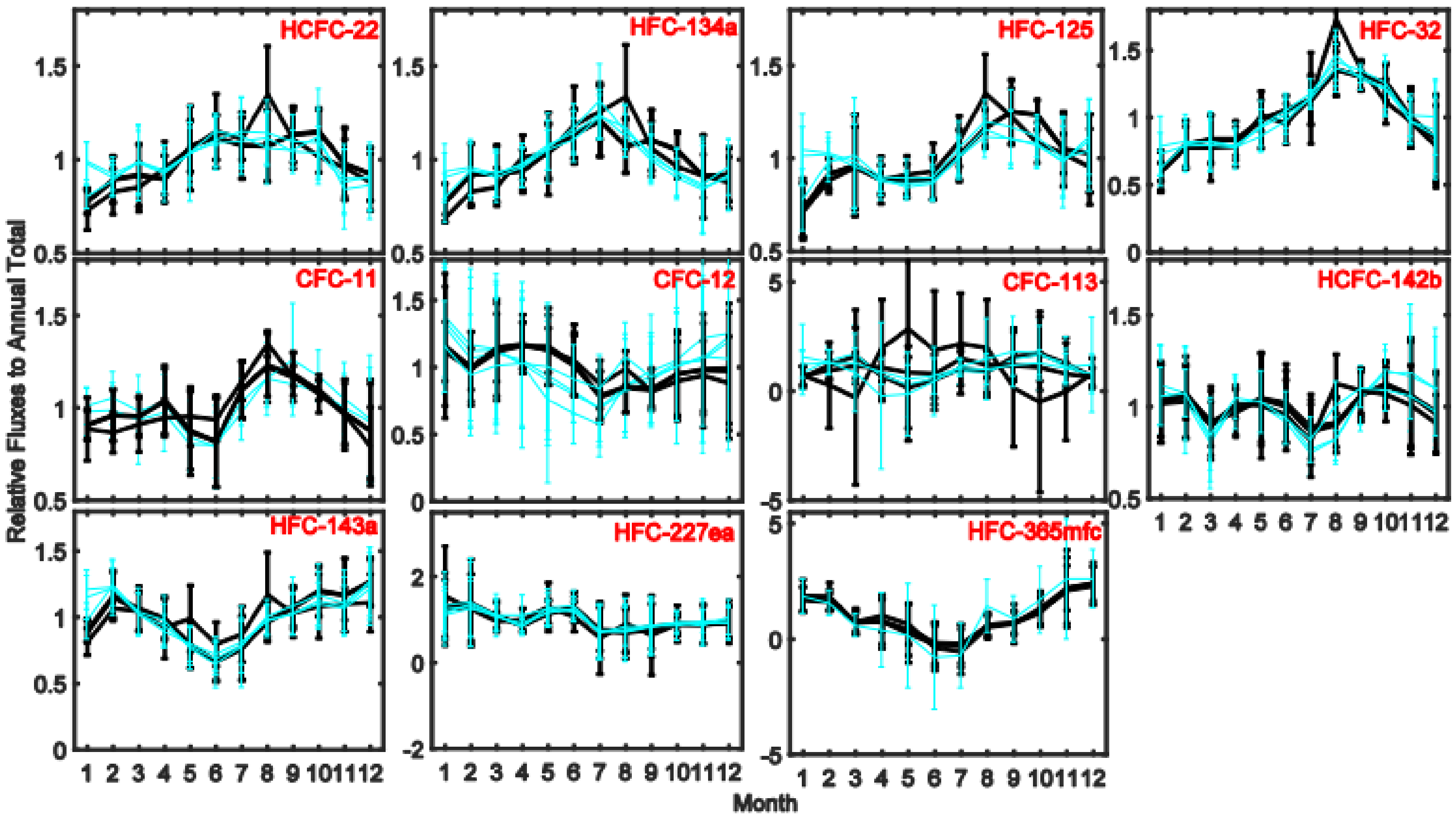


Figure S4: Derived monthly fluxes plotted relative to annual totals during 2008 to 2014.

- HFC emissions also found to vary seasonally.
- In contrast to SF_6 emissions, HFC emissions peak in the summer.
- Potential drivers include
  - Increased servicing of A/C&R equipment in summer, and
  - Higher pressures inside A/C&R equipment in summer.

Source: Hu, L., et al. (2017), Considerable contribution of the Montreal Protocol to declining greenhouse gas emissions from the United States, *Geophys. Res. Lett.*, 44, 8075–8083, doi:10.1002/2017GL074388.