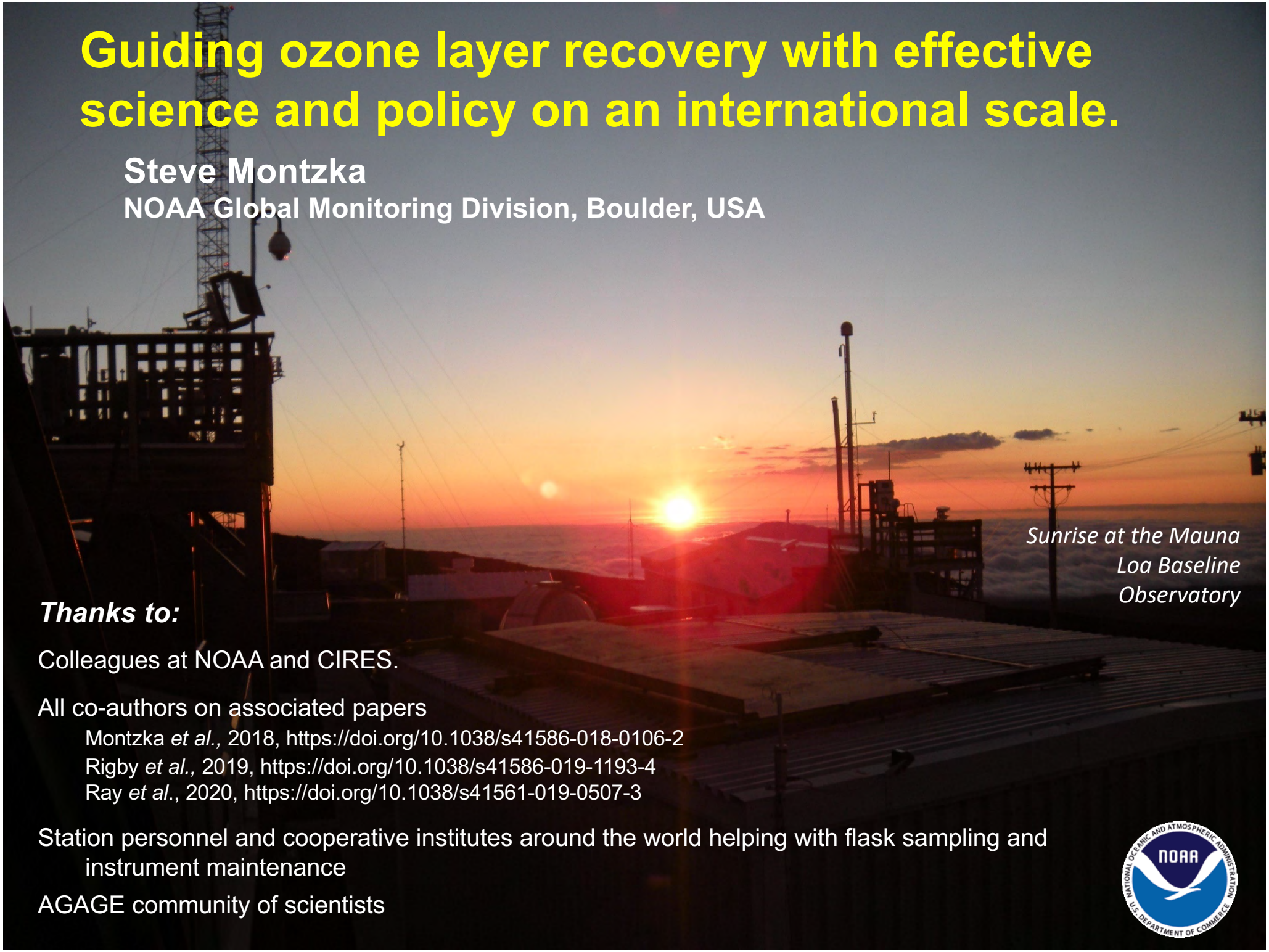
Guiding ozone layer recovery with effective science and policy on an international scale.

Steve Montzka
NOAA Global Monitoring Division, Boulder, USA



Sunrise at the Mauna Loa Baseline Observatory

Thanks to:

Colleagues at NOAA and CIRES.

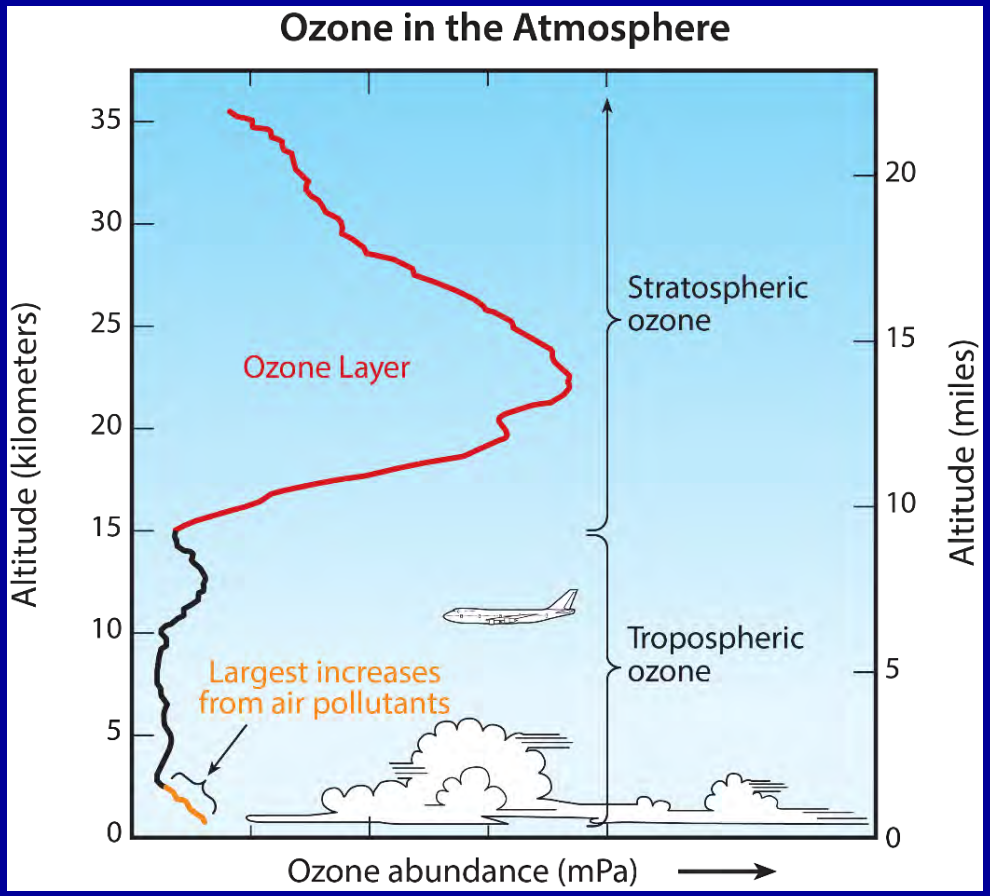
All co-authors on associated papers

Montzka *et al.,* 2018, https://doi.org/10.1038/s41586-018-0106-2
Rigby *et al.,* 2019, https://doi.org/10.1038/s41586-019-1193-4
Ray *et al*., 2020, https://doi.org/10.1038/s41561-019-0507-3

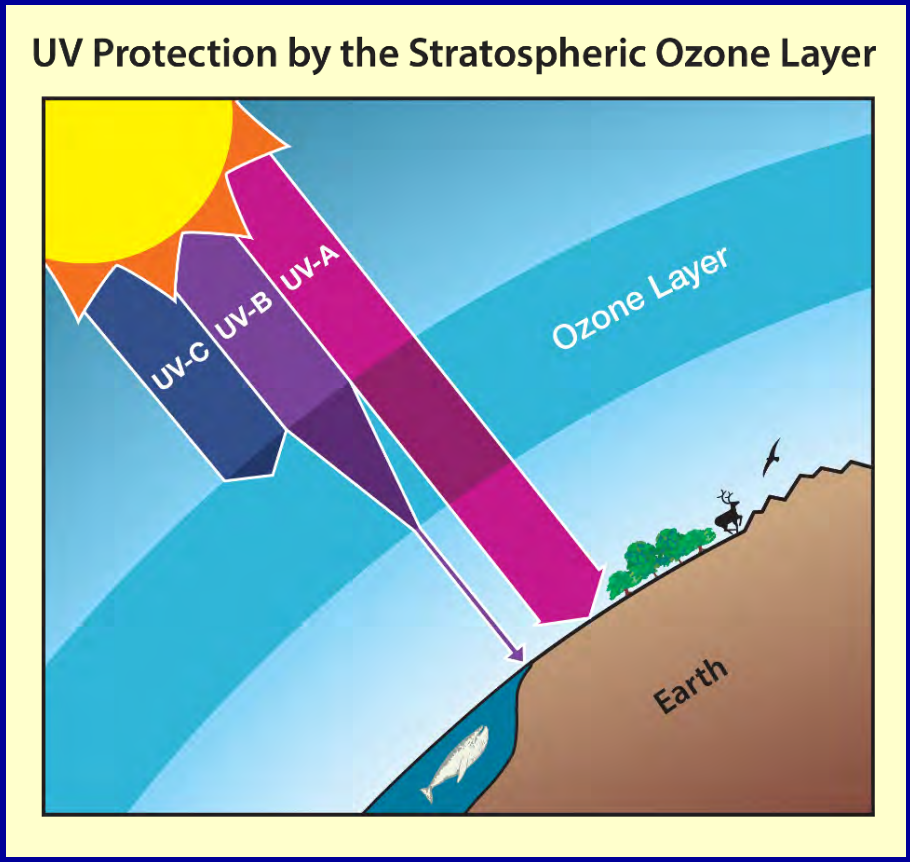
Station personnel and cooperative institutes around the world helping with flask sampling and instrument maintenance

AGAGE community of scientists

The upper atmosphere ***ozone layer*** filters out high energy UV radiation from the Sun:



Enhanced UV-B radiation from the sun
→ raises the risk of:
skin cancer
cataracts
immune system suppression
→ it also damages plants, crops, and aquatic ecosystems



Figures: 20 Questions and answers about the ozone layer: 2020 update

Depletion of the ozone layer:

→ First hypothesized in 1974 (Rowland & Molina)

Stratospheric sink for chlorofluoromethanes : chlorine atomc-atalysed destruction of ozone

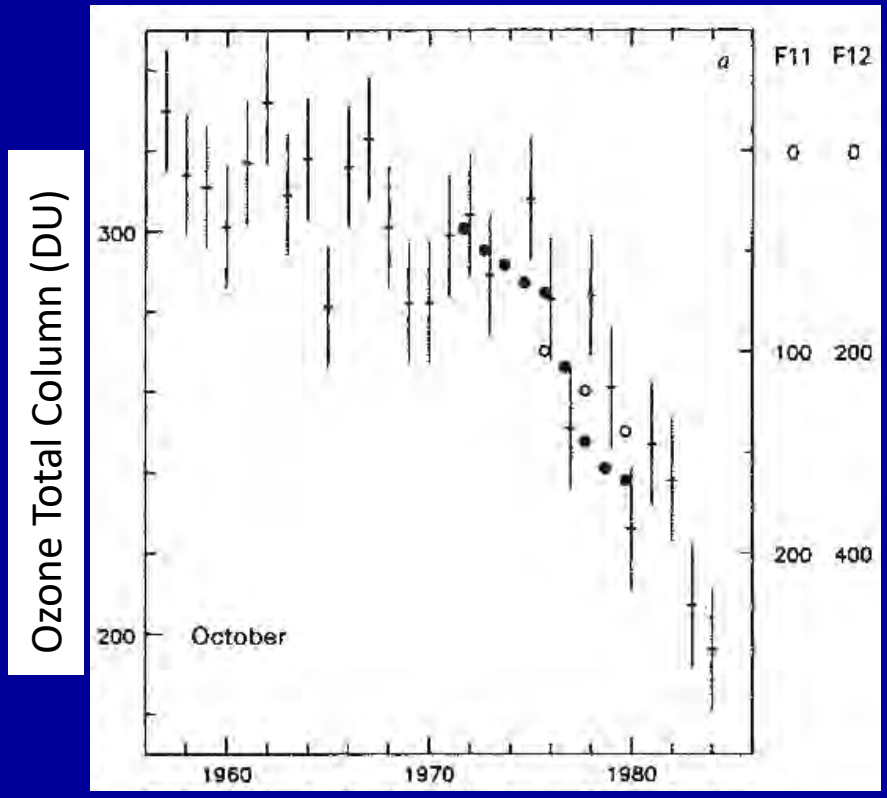
Mario J. Molina & F. S. Rowland

Department of Chemistry, University of California, Irvine, California 92664

Nature, 249, 810, 1974

…but was not expected to be a significant problem for many years

…but only a few years later dramatic springtime ozone depletion was observed over Antarctica! (Farman et al., 1985)



The 1987 Montreal Protocol

* Designed to heal the stratospheric ozone layer (limit UV exposure).
* Mandated a global phase-out of production & trade of ozone-depleting gases.
* The first universally ratified treaty in UN history.
* Parties have held 2 meetings/yr since the late 1980s to ensure continued success.

Step-wise phase-out of ozone-depleting gases:

Of chemicals (CFCs) used in refrigeration & air conditioning, foam-blowing, as solvents, in fire-extinguishing, as pesticide

1st generation substitutes:
HCFCs (hydrochlorofluorocarbons)

2nd generations substitutes:
HFCs (hydrofluorocarbons)

Full implementation to yield:
avoidance of more than 280 million cases of skin cancer and more than 45 million cases of cataracts in the United States by the end of the century, with even greater benefits worldwide.

A view of the Meeting of the Parties, Rome, Nov., 2019

The Montreal Protocol "*is perhaps the single most successful international agreement to date*" (K. Annan, 2003)

Adherence to the Montreal Protocol has led to:

1) Near elimination of ozone-depleting substance (ODS) production, particularly chlorofluorocarbons (CFCs)

Global reported production* (ODP-kt/yr)

CFC production reportedly phased-out in 2010

Minimal production reported by 2007

* Reported to the WMO/UNEP Ozone Secretariat

Despite a warning over 45 years ago…

Stratospheric sink for chlorofluoromethanes : chlorine atomc-atalysed destruction of ozone

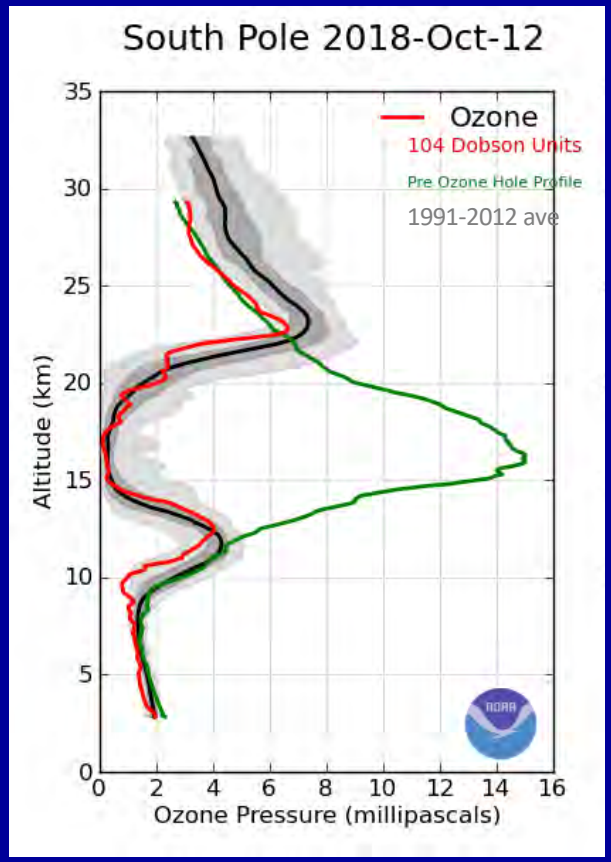
Mario J. Molina & F. S. Rowland
Department of Chemistry, University of California, Irvine, California 92664

Nature, 249, 810, 1974

…and the universal ratification of the Montreal Protocol on Substances that Deplete the Ozone Layer in 1987

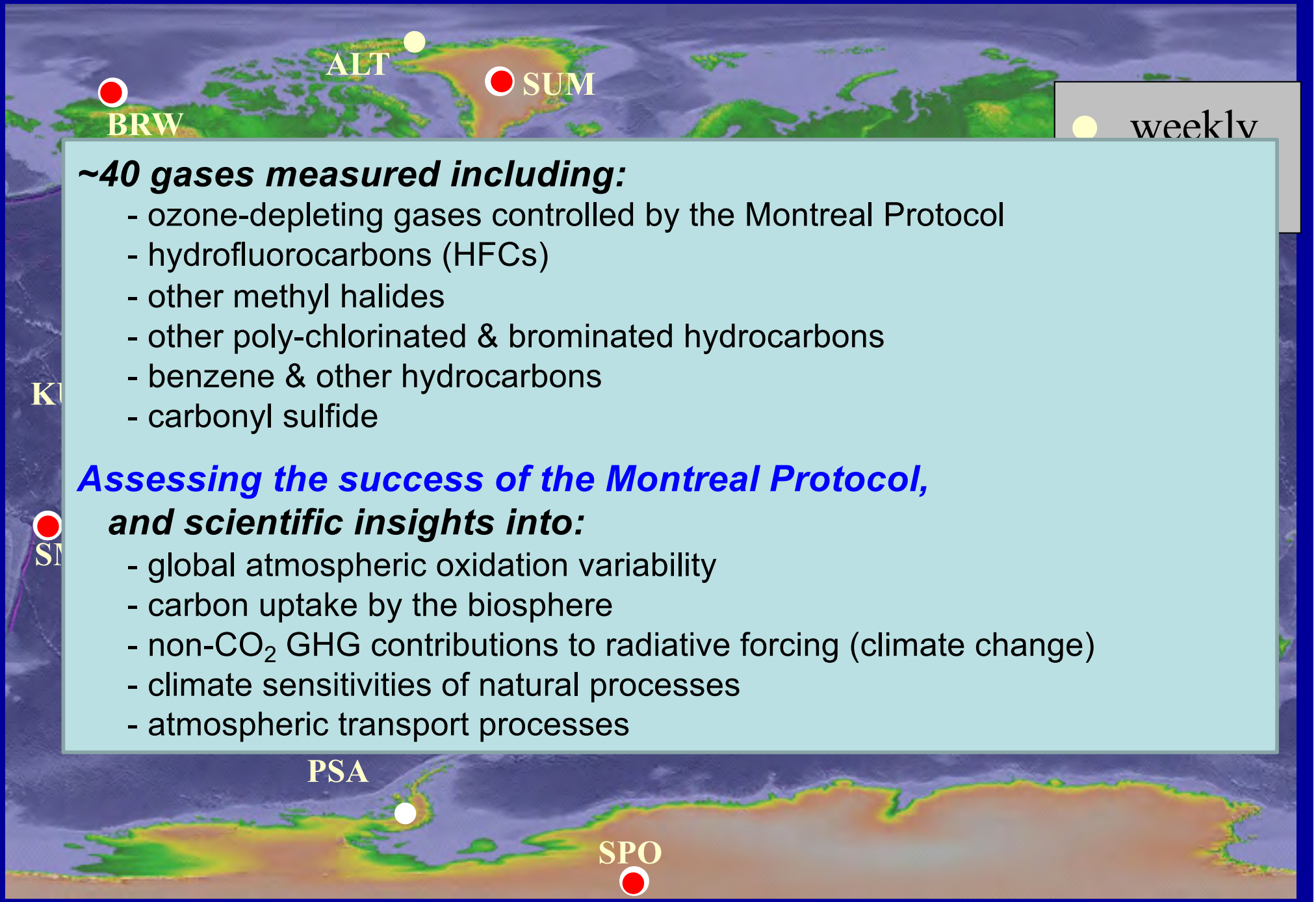
The stratospheric ozone layer is far from recovered:

Ozone over South Pole during October of 2018 (red line)
(ozonesonde flights by NOAA-GMD & CIRES):



…the good news is that there are signs of initial recovery in the mid-latitude stratosphere

NOAA/CIRES: Tracking ozone-depleting gas concentrations



~40 gases measured including:

- ozone-depleting gases controlled by the Montreal Protocol
- hydrofluorocarbons (HFCs)
- other methyl halides
- other poly-chlorinated & brominated hydrocarbons
- benzene & other hydrocarbons
- carbonyl sulfide

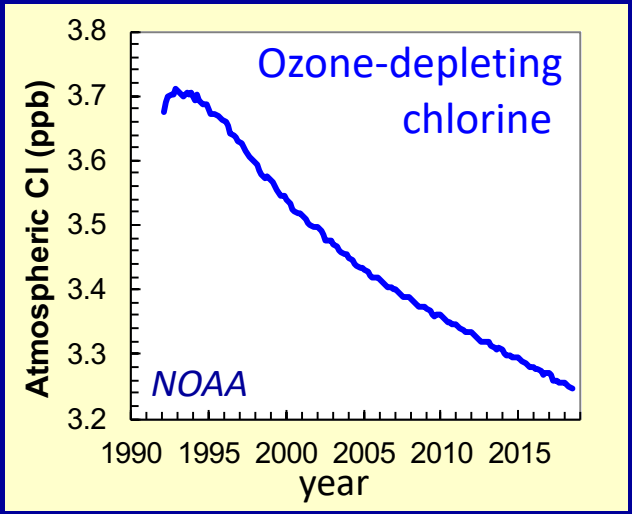
Assessing the success of the Montreal Protocol, and scientific insights into:

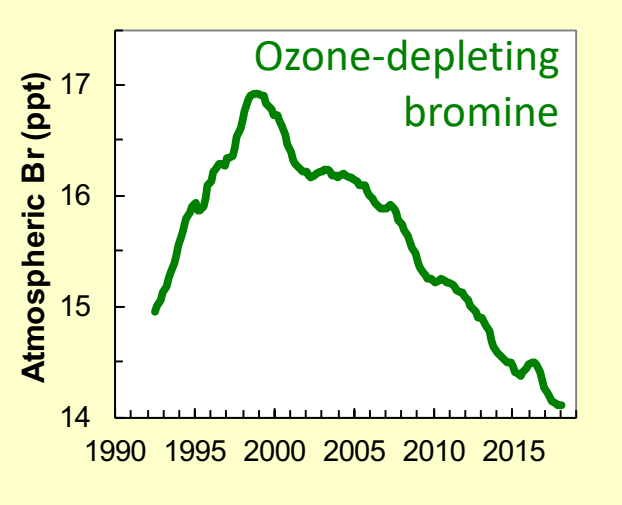
- global atmospheric oxidation variability
- carbon uptake by the biosphere
- non-CO_2 GHG contributions to radiative forcing (climate change)
- climate sensitivities of natural processes
- atmospheric transport processes

From NOAA/GMD & CIRES - measured tropospheric concentrations of CFCs, HCFCs, chlorinated solvents, methyl halides, halons…

Adherence to the Montreal Protocol has also led to:

→ declines in ODS emissions and concentrations:





→ Pre-ozone-hole concentrations of ODSs are projected for later in this century (WMO reports),

provided continued adherence to the Protocol's controls

(see updates at http://www.esrl.noaa.gov/gmd/odgi/)

Why will recovery take so long??

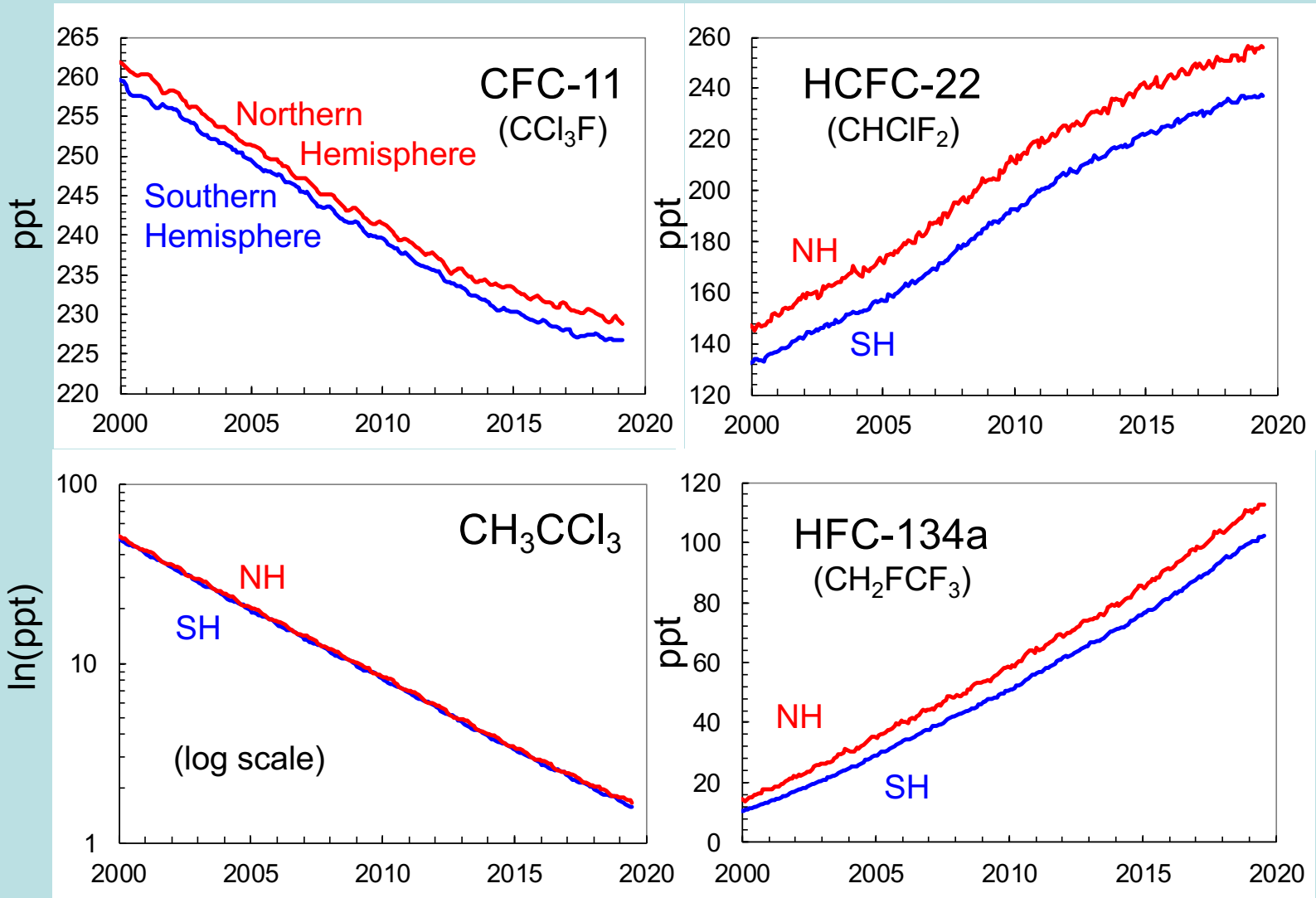
→ The recovery time-frame is set by natural removal rates of CFCs and other ODSs from the atmosphere:

Chemical	atmospheric lifetime (year)	destruction per year
Main ozone-depleting gases:		
CFC-11	50	2%
CFC-12	100	1%
CFC-113	85	1.2%
Substitute chemicals:		
HCFC-22	12	9%
HFC-134a	14	7%

These rates are set by the flux of high-energy light through the stratosphere and the concentrations of atmospheric oxidants

Atmospheric measurements for tracking the effectiveness of the Montreal Protocol

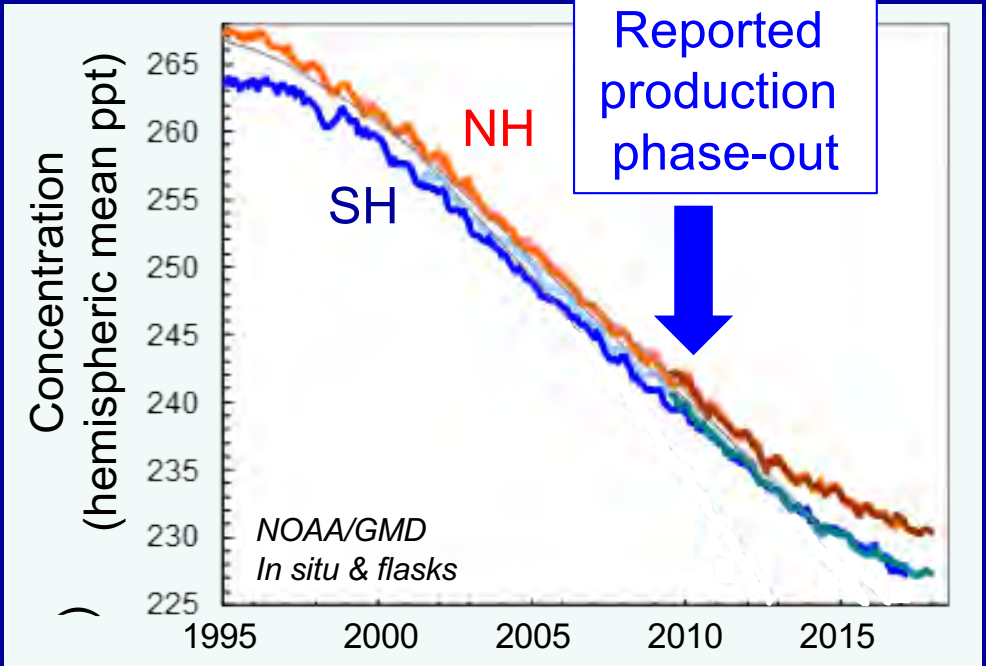
CFCs, CH_3CCl_3, *etc.* → HCFCs → HFCs → HFOs



Chemical lifetimes range from 5 to 50 years

NOAA/CIRES flask data

Atmospheric CFC-11



CFC-11:

→ ***Second most abundant ODS; accounts for 20-25% of*** ozone-depleting chlorine

→ ***Was the largest contributor to the overall decline*** of atmospheric Cl from 2007-2012

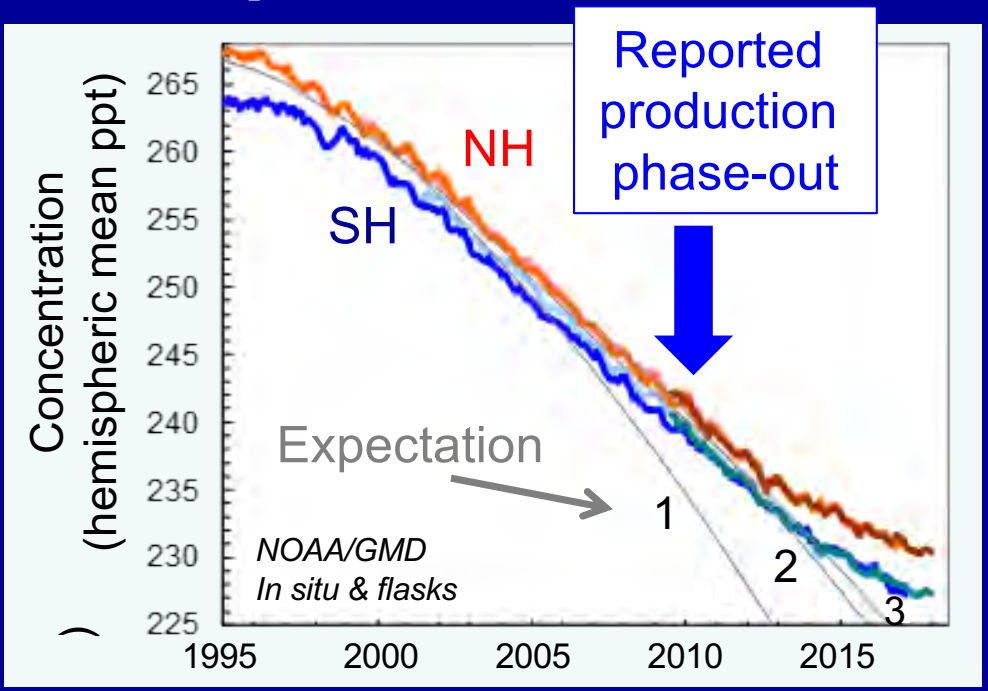
→ ***While production was reportedly phased out in 2010, significant emissions persist,*** primarily from a foam "bank" of ~900 kt currently

After a production phase-out:

* concentration decline ***should have accelerated*** as bank becomes depleted by emissions…

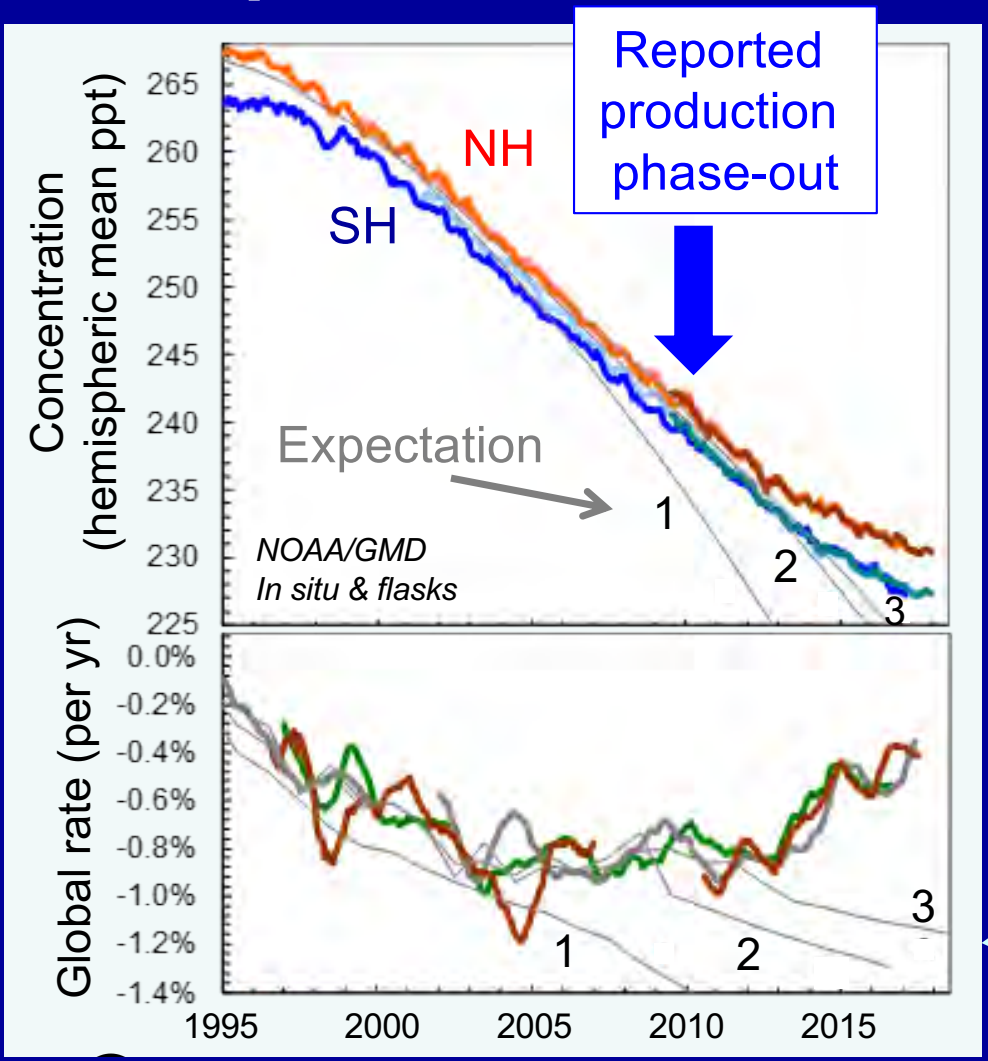
(the zero-emission limit is –2%/yr given its 50 yr lifetime)

Atmospheric CFC-11



Hemispheric mean concentration

Atmospheric CFC-11

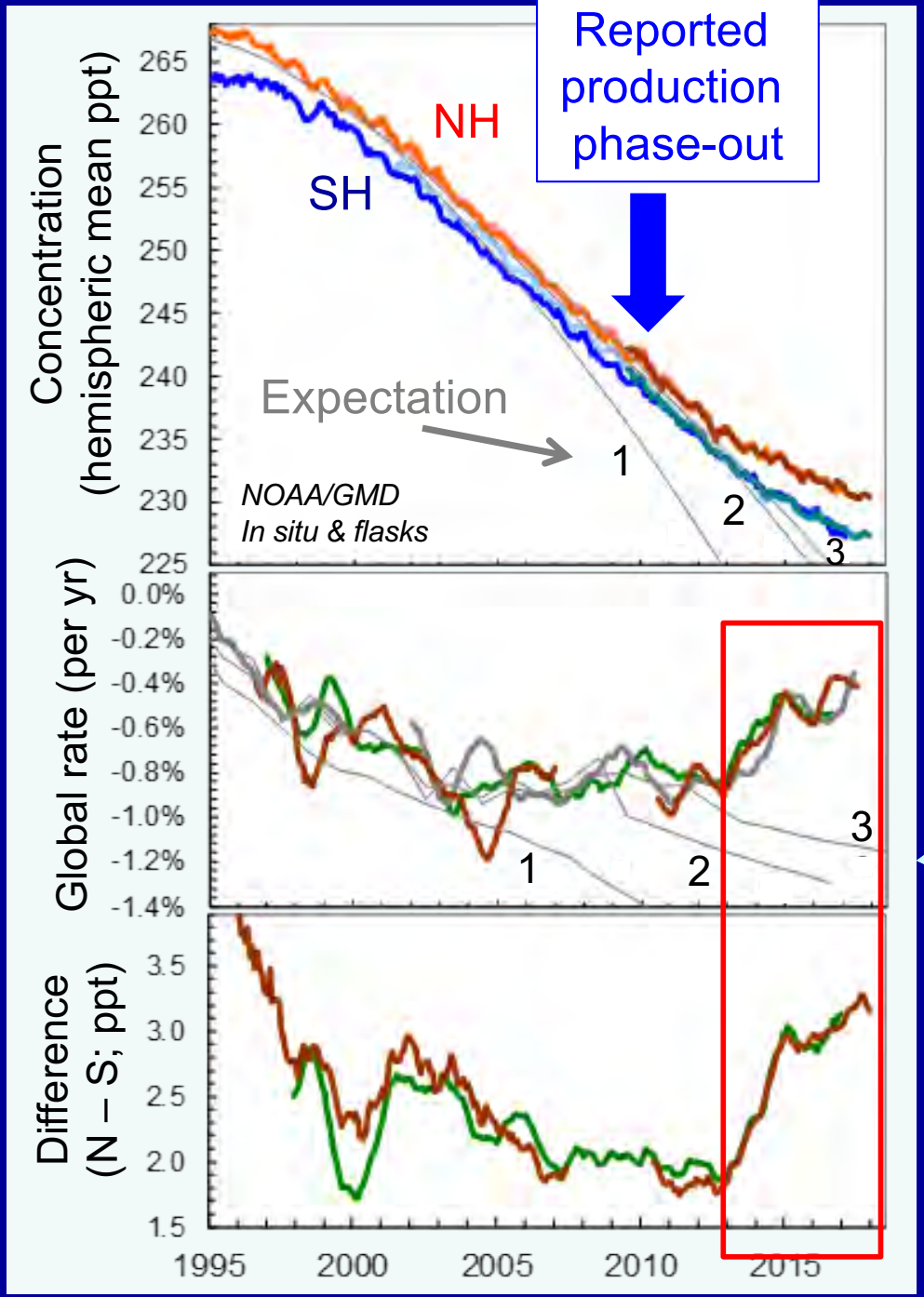


Hemispheric mean concentration

Global rate of change

Expectation

Atmospheric CFC-11



Hemispheric mean concentration

Global rate of change

Expectation

Hemispheric concentration difference

→Qualitatively consistent with an increase in NH emissions

Why the unexpected slowdown?

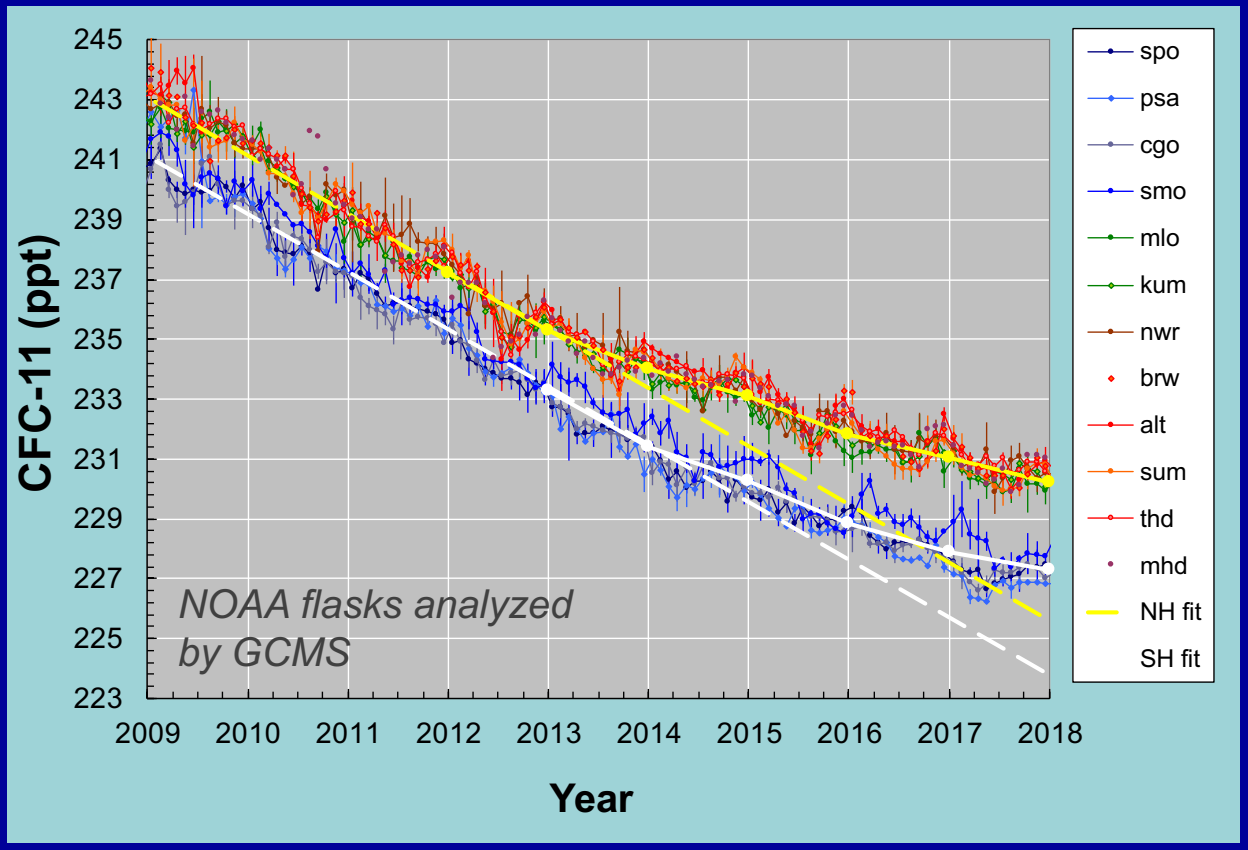
Consider the evidence:

Is it an instrument or measurement problem?

→ **NO**, slowdown observed by independent measurements (NOAA and AGAGE) using multiple techniques, and in different aspects of the data

Is it unique to certain sites??

→ **NO**, although initially noted in the NH, and then later in the SH

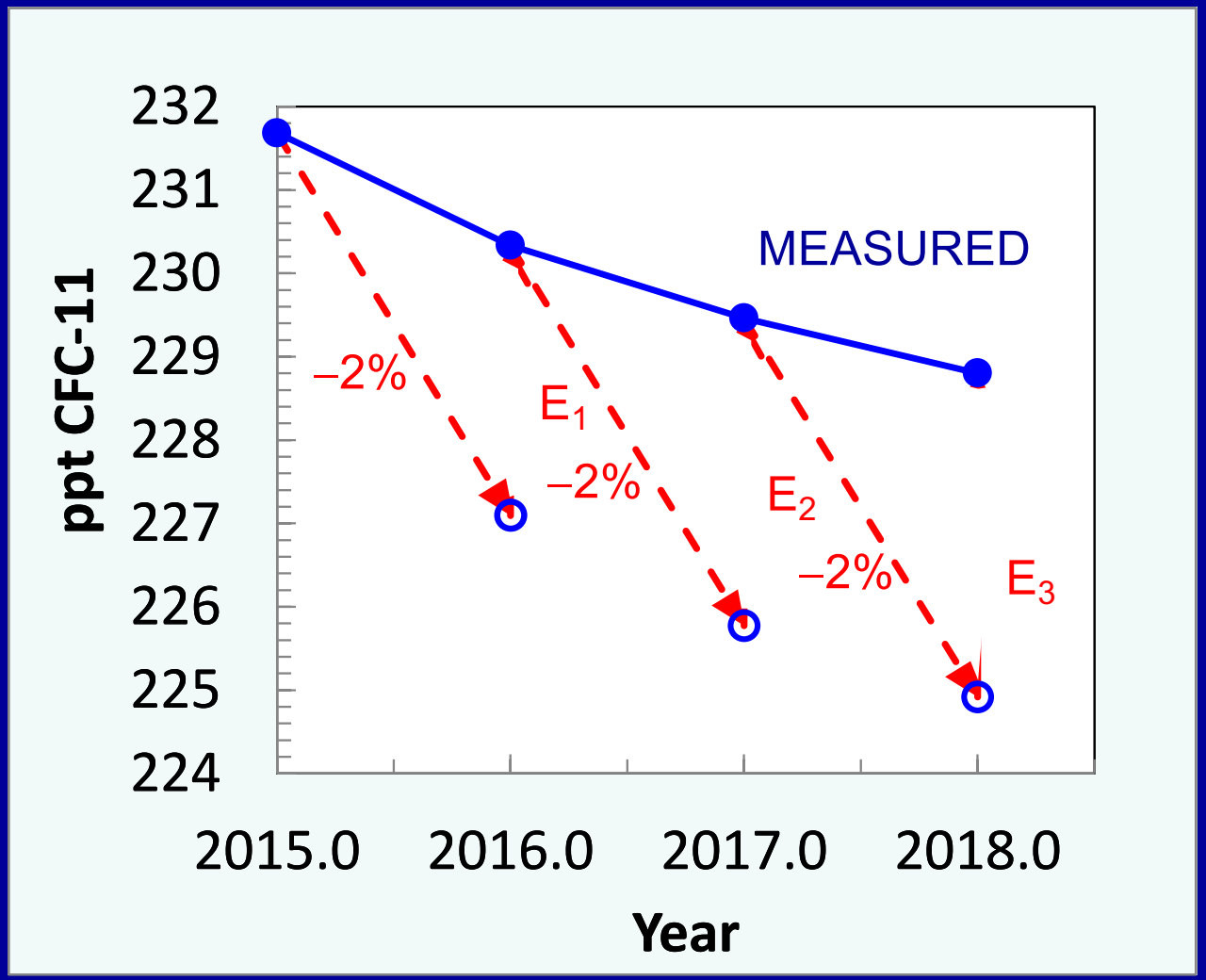


Deriving emissions from concentrations

Global CFC-11 concentration changes reflect the balance of

a) **EMISSION**

b) **REMOVAL** (*photolysis in the stratosphere*)

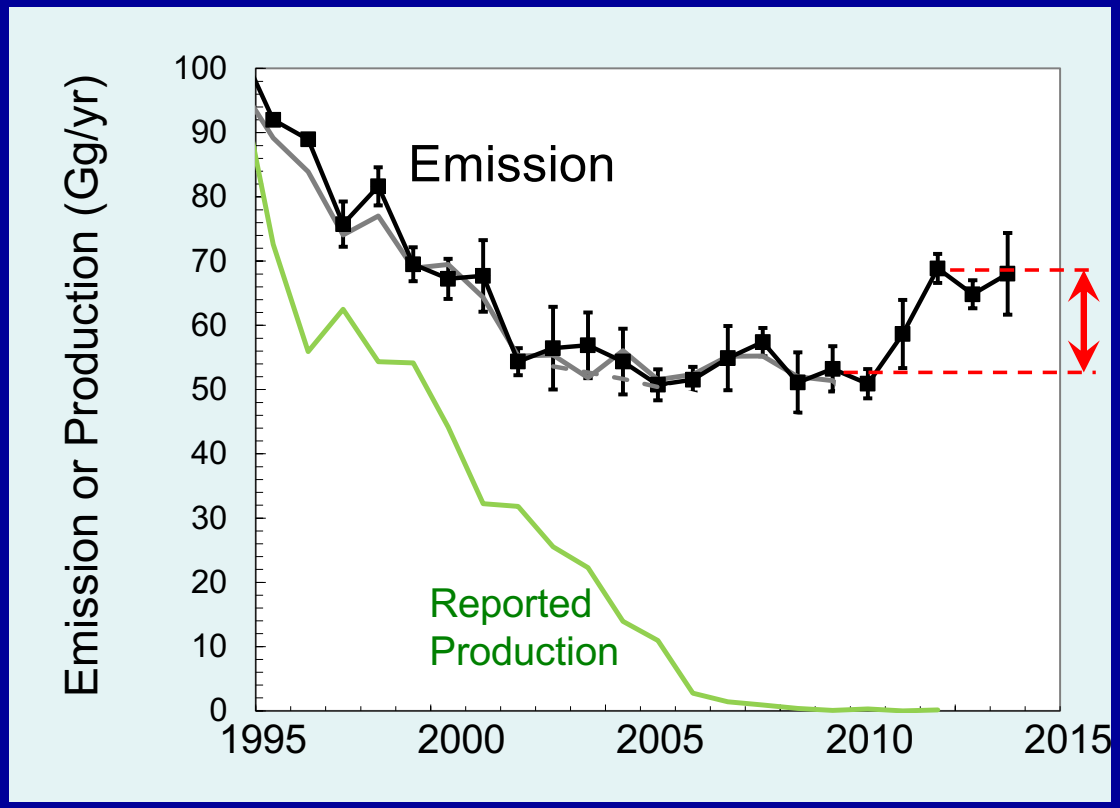


For a ~ 50 yr lifetime, atmospheric concentrations should decline at ~1/50 yr^{-1} or 2% yr^{-1} *in the absence of emissions.*

Deriving emissions from concentrations

Mass balance considerations (a simple box-model analysis):

$$dG_{F11}/dt = \text{Emission} - G/\tau_{F11}$$



Measured

13 ± 5 Gg/yr
(25%) increase

(2014-2016 *vs.* 2002-2012;
2017 is similarly elevated)

Are CFC-11 emissions *really* increasing despite the Montreal Protocol and reported phase-out by 2010?

Montzka et al., 2018

Deriving emissions from concentrations

Mass balance considerations (a simple box-model analysis):

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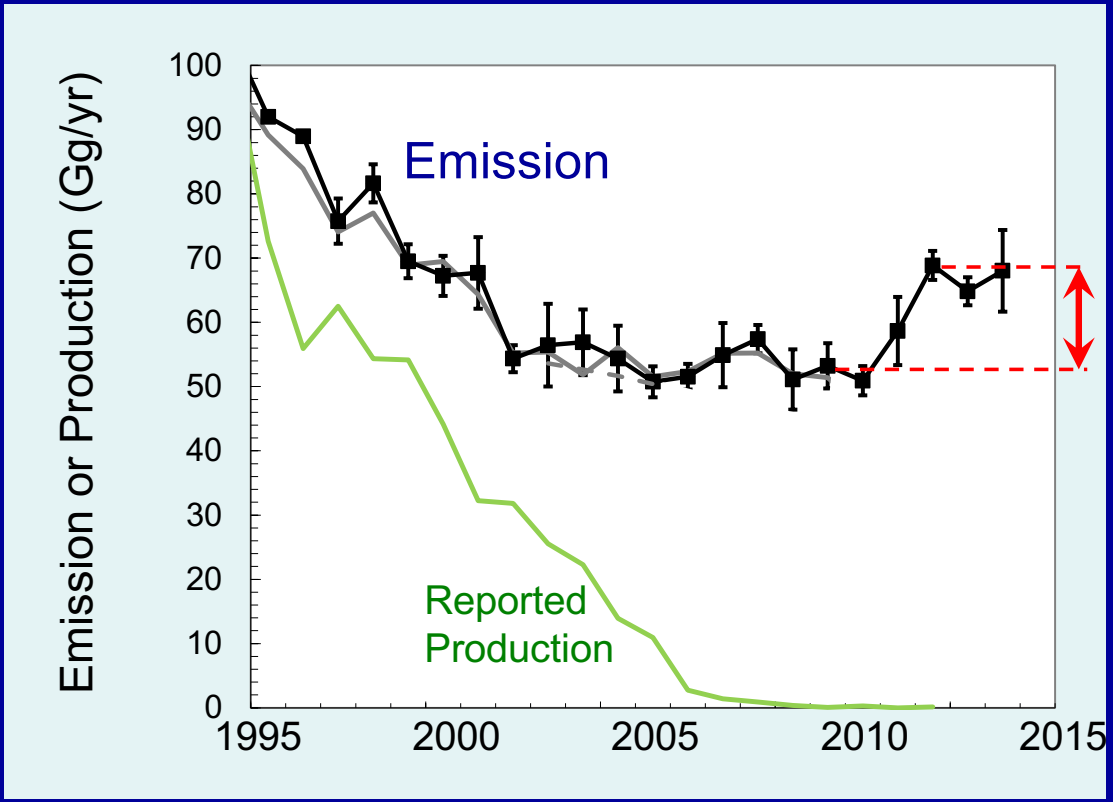
Measured



13 ± 5 Gg/yr
(25%) increase

(2014-2016 *vs.* 2002-2012;
2017 is similarly elevated)

Or has CFC-11 loss and transport changed ("τ_{F11}")?

3-D models suggest: maybe a bit…!

Montzka et al., 2018

Do the observations themselves suggest emissions increasing?

Air reaching Hawaii in autumn can be influenced by Eurasian emissions (Lin *et al*., 2014, DOI: 10.1038/NGEO2066).

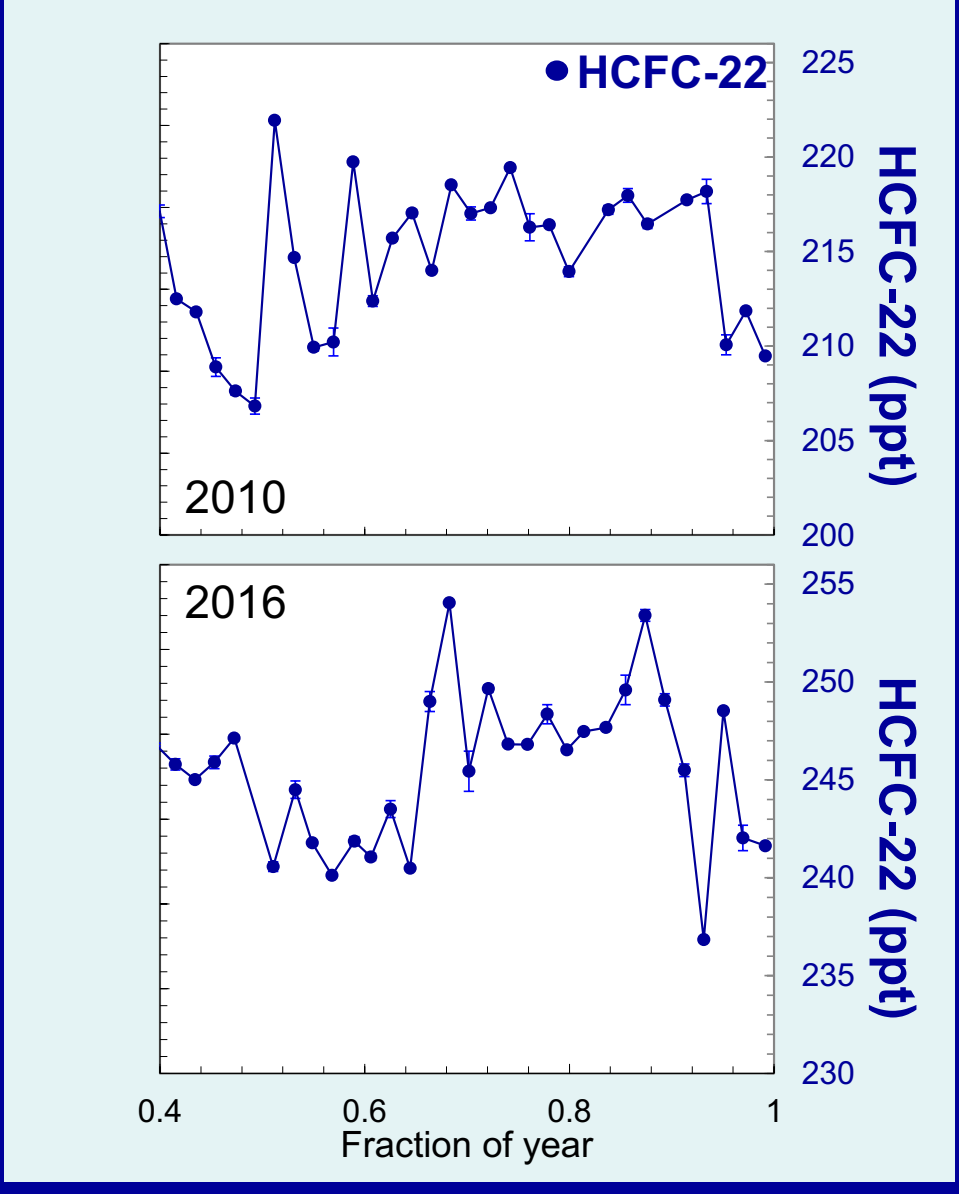
A close look at our results from the Mauna Loa station showed:

Before 2012: pollution plumes reaching Hawaii **DID NOT** contain elevated concentrations of CFC-11

After 2012: pollution plumes reaching Hawaii **NOW CONTAIN** elevated concentrations of CFC-11.

Do the observations themselves suggest emissions increasing?

Pollution plume events reaching Hawaii were identified by:



1) Increased concentrations of a number of gases:
HCFC-22, CH_2Cl_2, and CO

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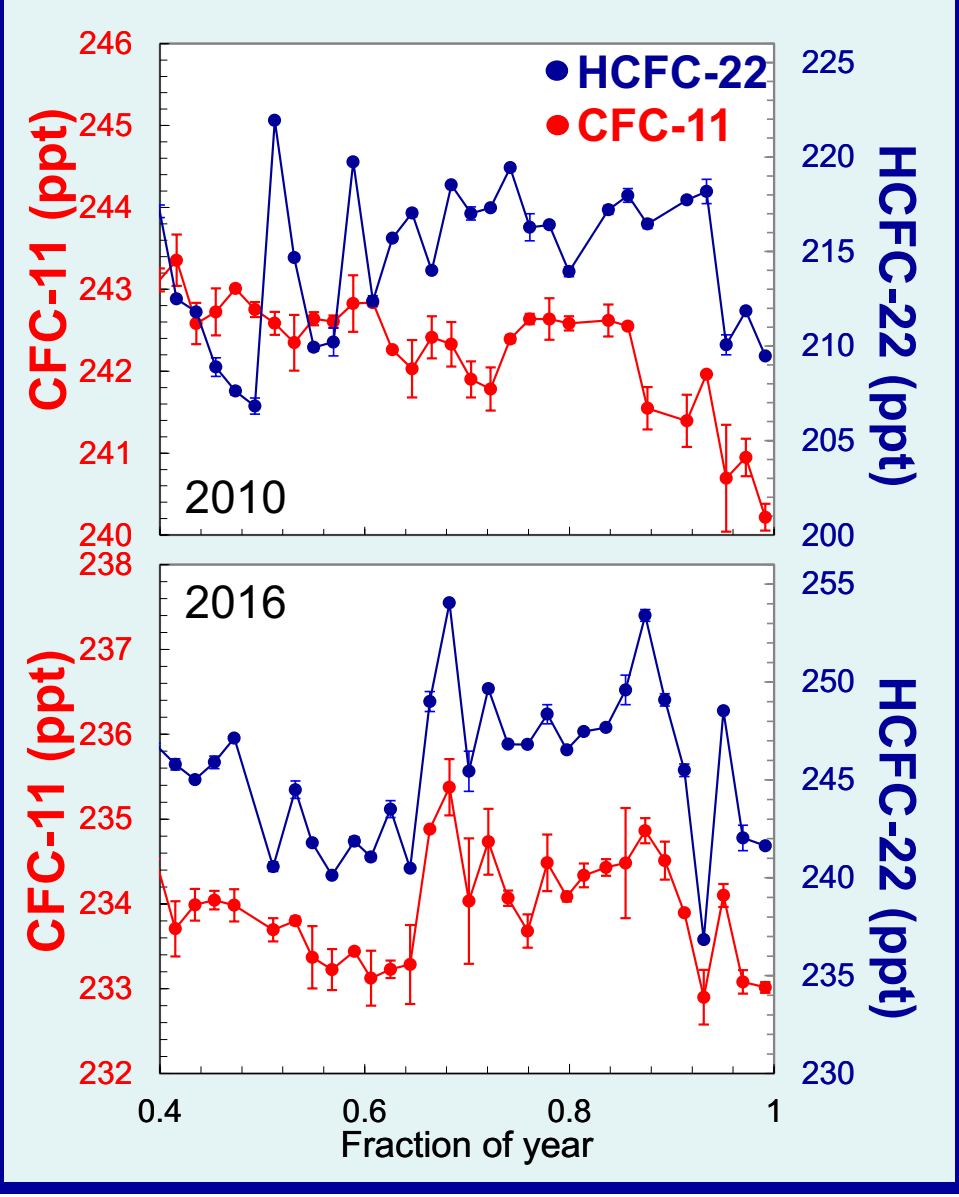

1) Increased concentrations of a number of gases:
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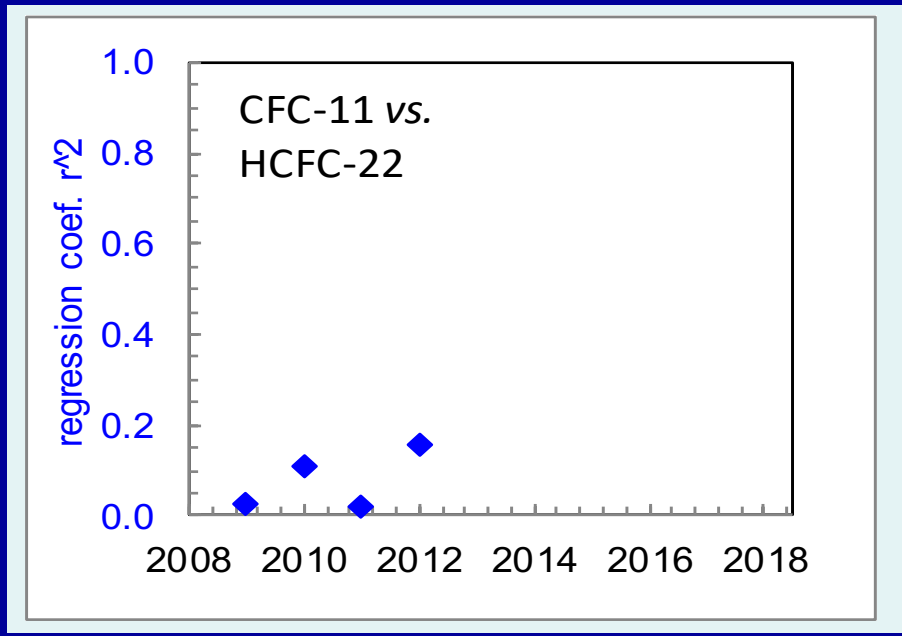
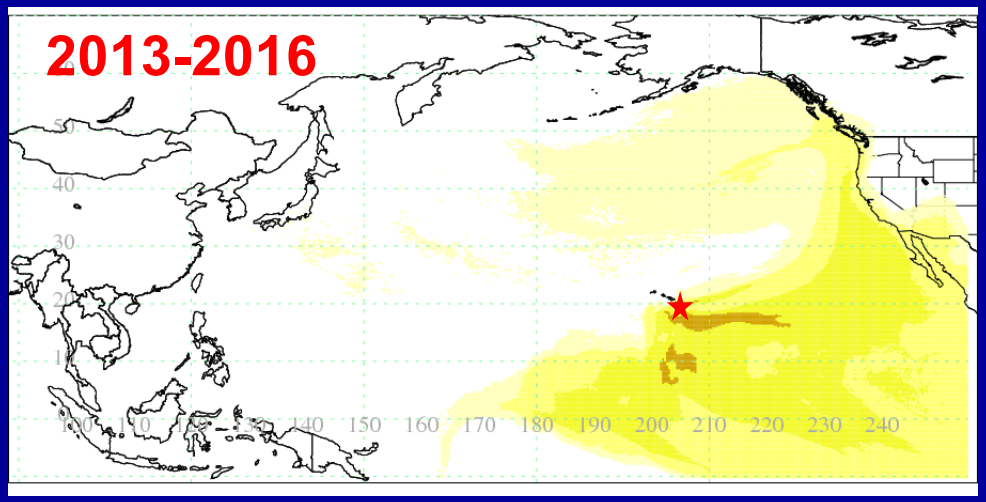


Only after 2012 do pollution plumes contain elevated CFC-11 concentrations

Correlations among HCFC-22, CH_2Cl_2, & CO are strong in all years

The source region for those pollution plumes reaching Hawaii were identified by meteorological models of air transport:

Lower [HCFC-22] & [CFC-11]



Darker colors indicate the surface region influencing samples collected in Hawaii

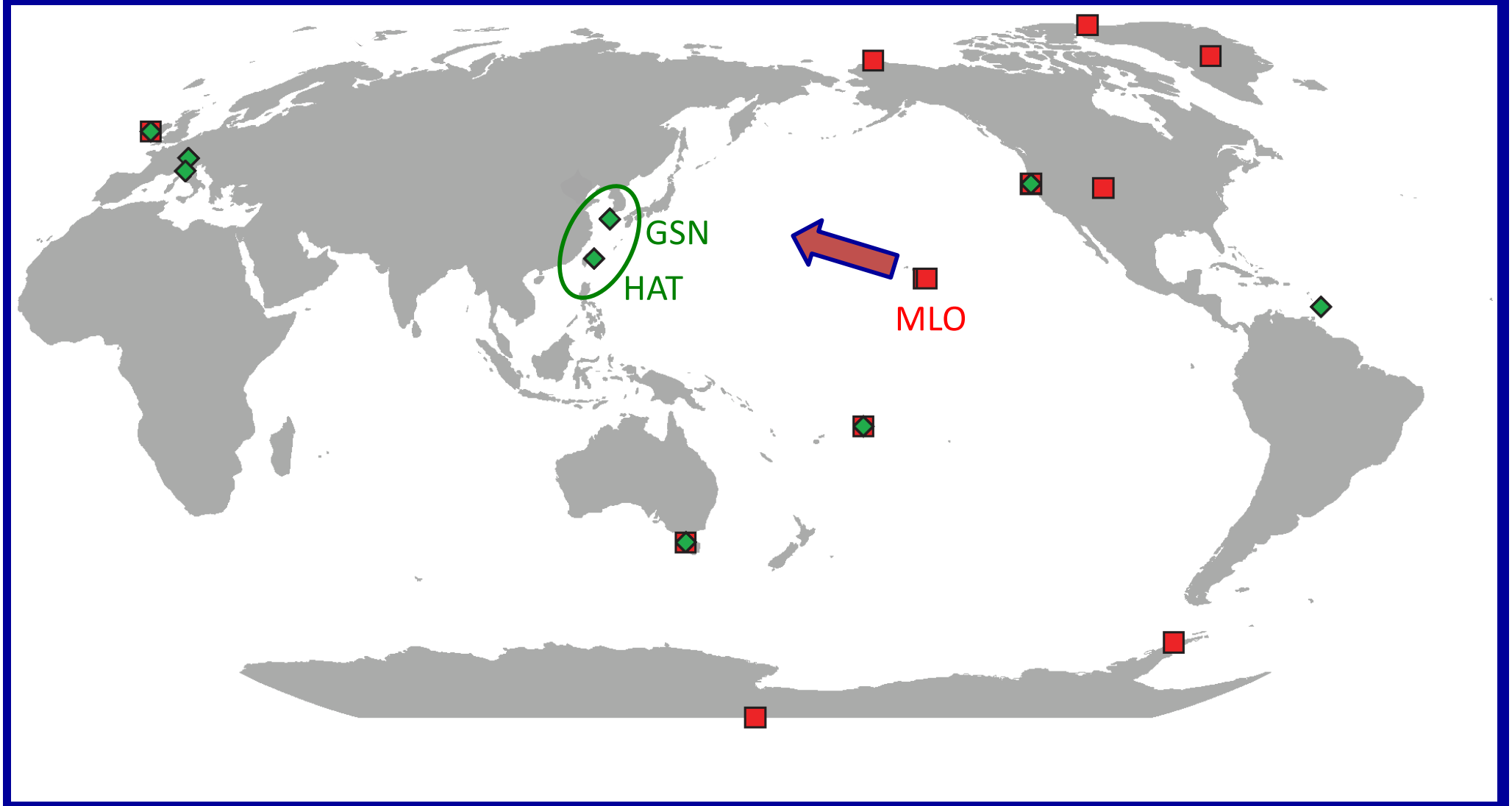
After 2012, air associated with eastern Asia contains relatively higher concentrations of CFC-11

→ Some portion of the global emission increase is from Eastern Asia

Montzka et al., 2018

In a second study (Rigby *et al*., 2019), measurements within eastern Asia are analyzed…

AGAGE & affiliates plus NOAA sampling locations (Rigby et al., 2019)

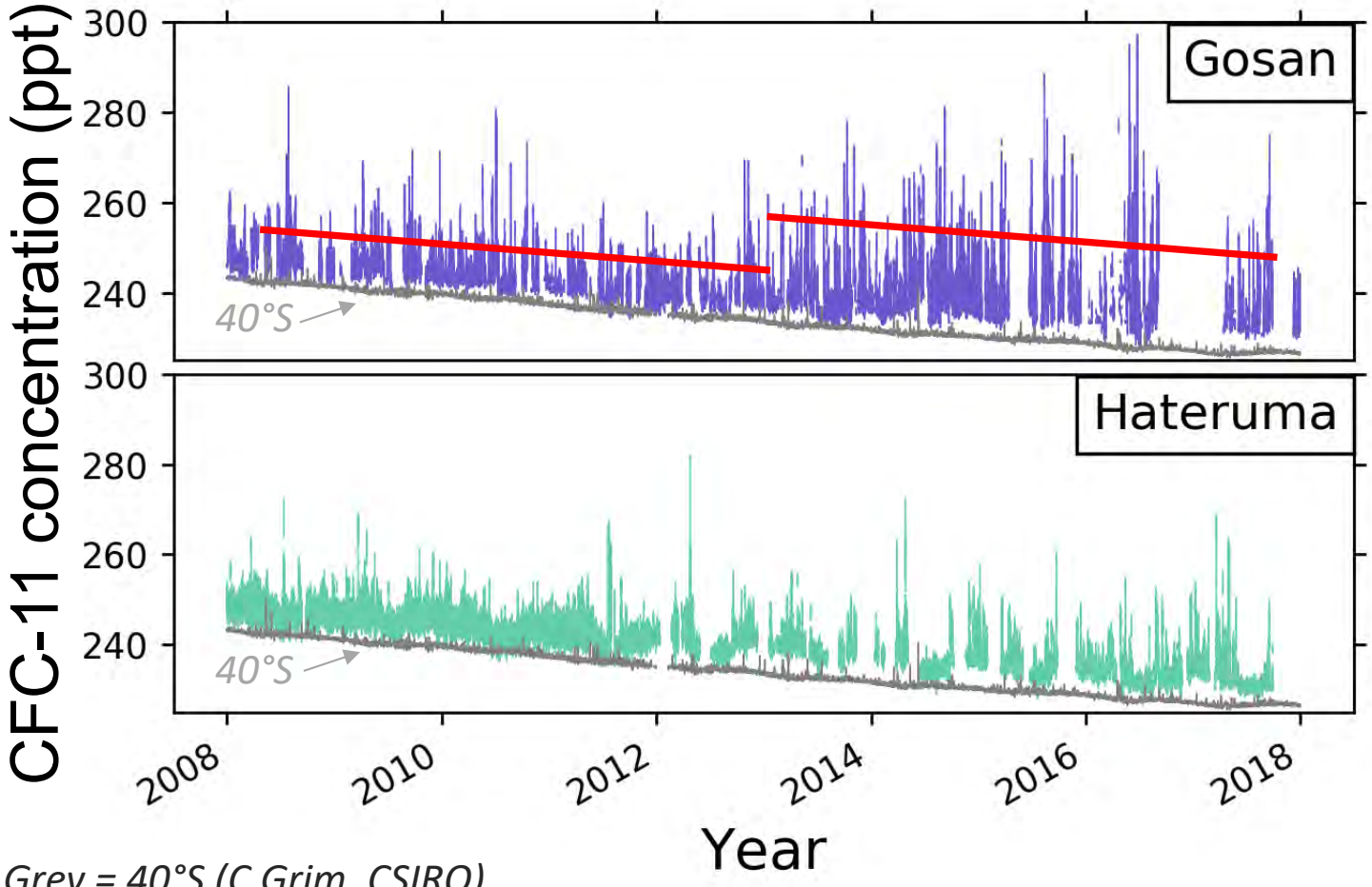


Between 12 and 34 measurements per day at AGAGE & affiliate sites

Rigby et al., 2019

From Rigby et al., 2019:

Discrete air sample results:



Grey = 40°S (C.Grim, CSIRO)

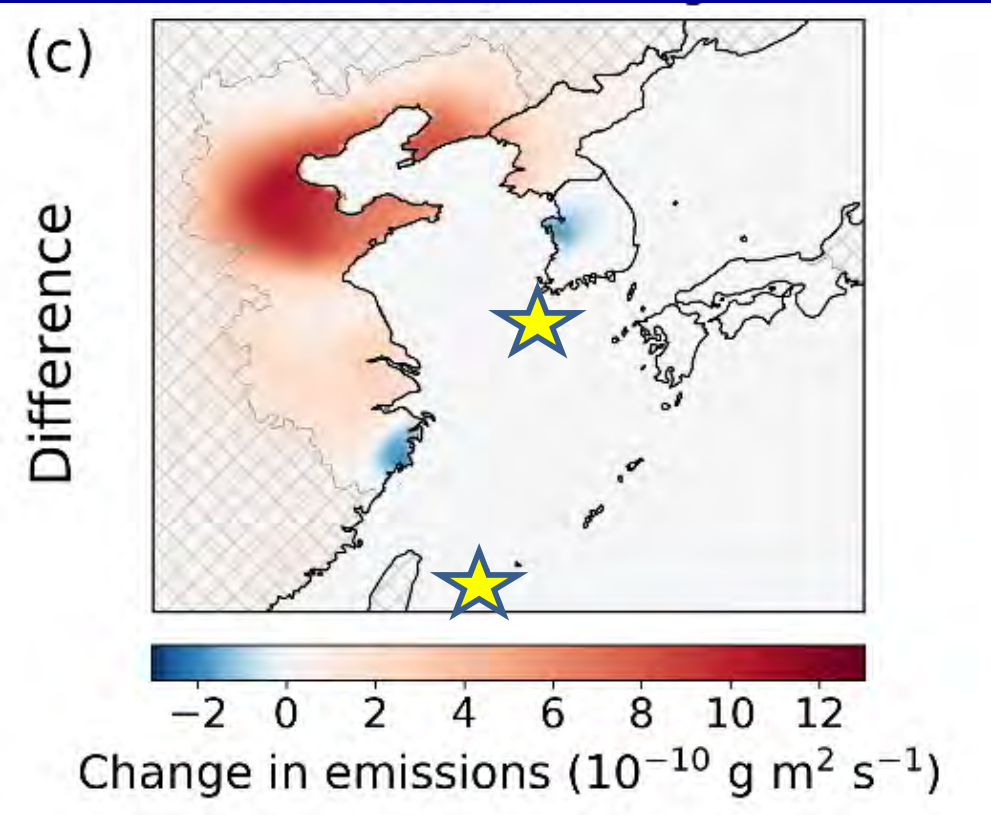
After 2012, CFC-11 concentrations are increasingly elevated in pollution plumes reaching these sites, particularly at GSN

AGAGE, R.O.K. (K.N.U.), and Japan (NIES)

Rigby et al., 2019

Inverse Lagrangian model analyses of these measurements in Rigby et al., 2019:

Red = regions where emissions increased after 2012>>



About 50% of the global emission increase comes from eastern Asia, specifically the Chinese provinces of Shandong and Hebei.
Where's the other half???

We don't know!

Similar inverse analyses of observations from the U.S., Europe, and Australia suggest low emissions (< 10 Gg/yr) and no recent increases.

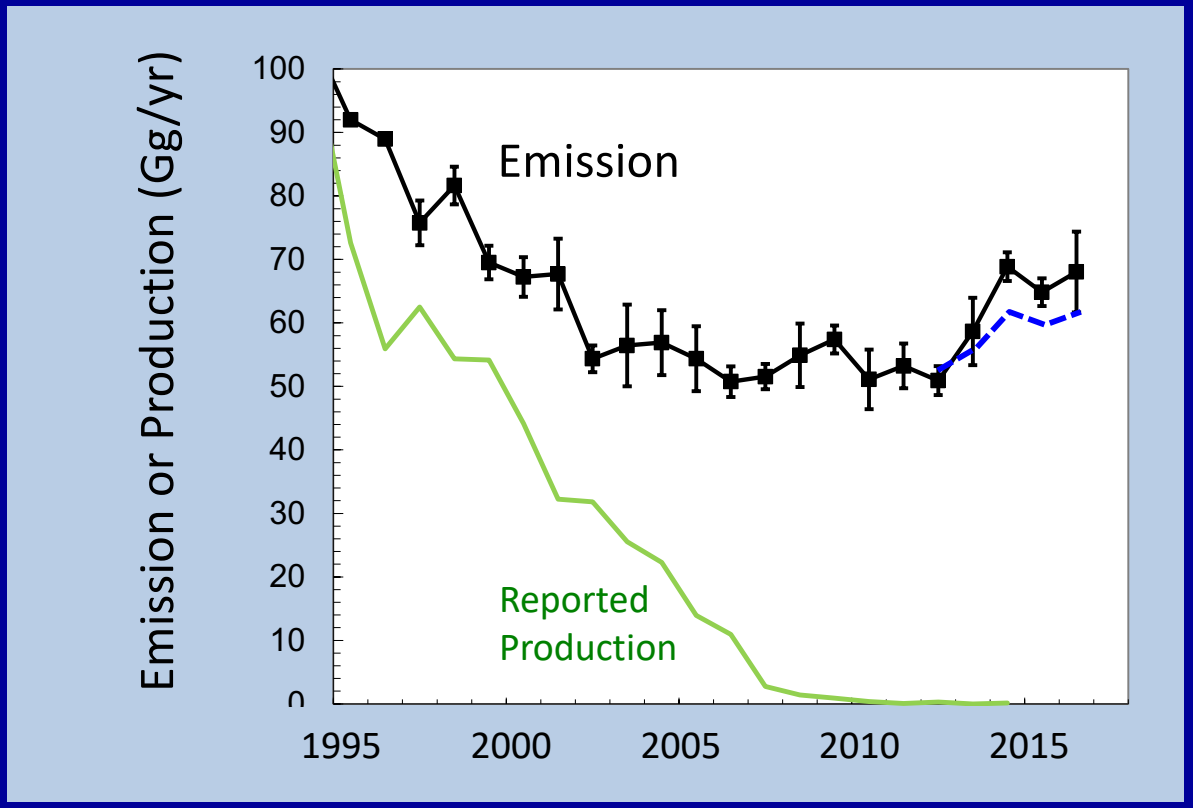
Regional estimates from many parts of the world are not possible.

AGAGE data
Rigby *et al.*, 2019,
https://doi.org/10.1038/s41586-019-1193-4

Rigby et al., 2019

Do the results imply renewed production?

→ is the Montreal Protocol being violated?



OR: is CFC-11 escaping more rapidly from the foam "bank" (~1200 Gg in 2012)?

Do the results imply renewed production?

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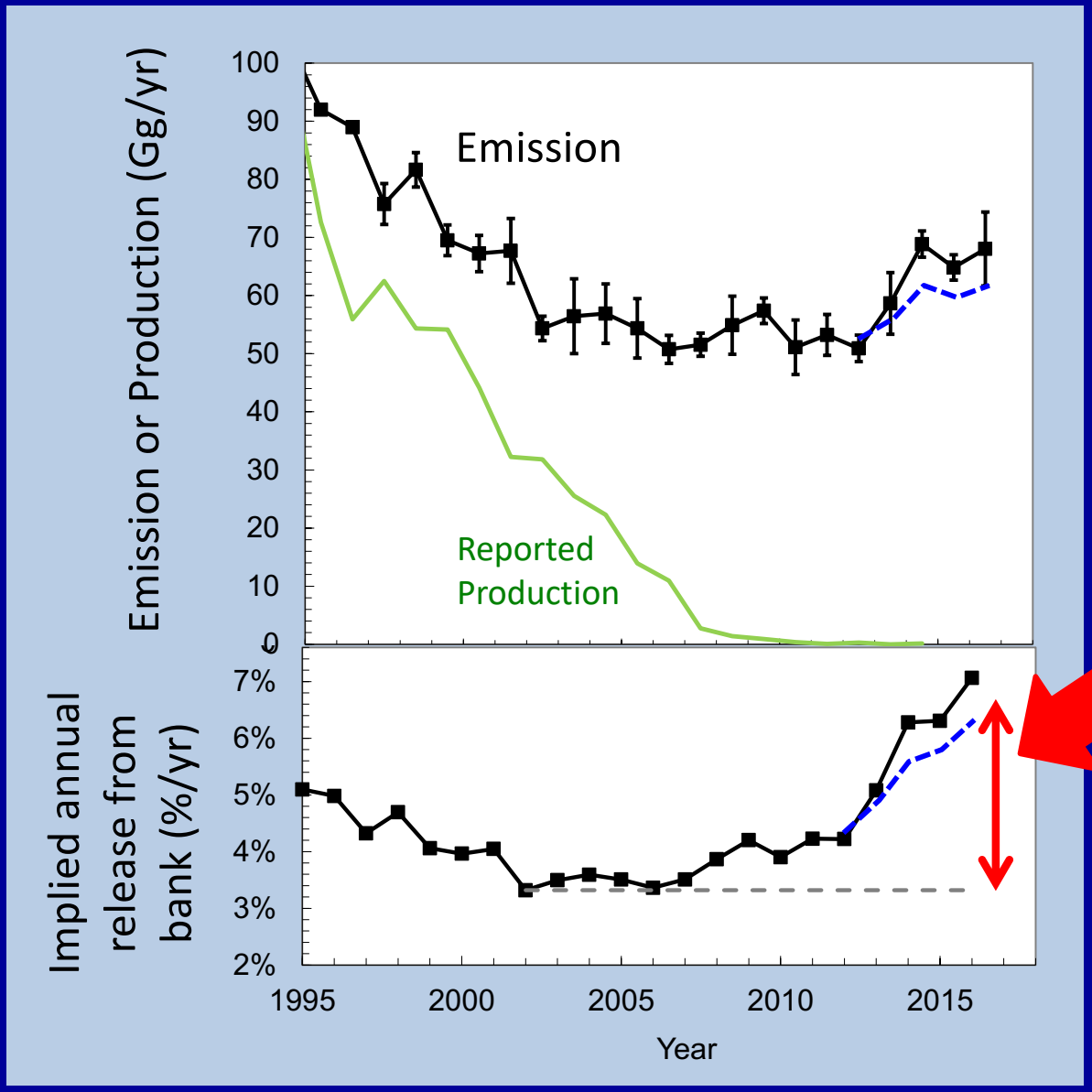


Montzka et al., 2018

OR: is CFC-11 escaping more rapidly from the foam "bank" (~1200 Gg in 2012)?

With no new production, the escape rate from the 'bank' **would have had to nearly double since the early 2000s…**

→ this seems highly unlikely

Implications for the ozone layer:

If the problem is rapidly fixed, the impact on the ozone layer should be small.

If these emissions continue → ozone recovery delay of 7 to 20 yr.
(WMO-SAP, 2018; Dhomse et al., 2019 & others)

Unlikely?

Perhaps, but the magnitude of the problem ultimately depends on the magnitude of unreported production.

Have we detected only the "tip of the iceberg"??

Most likely use of the new production:
Polyurethane insulating foams *(WMO-TEAP; 2019)*
→ if so, then, emissions detected are << associated production.
and enhanced emissions could be sustained even with effective mitigation.

25-30 Gg/yr ***emissions*** for foams implies
→ **50-100** Gg/yr of CFC-11 ***production*** (peak prod. was 400 Gg/yr)

Global reaction to our results:

On-the-ground investigative reporting by the NY Times and EIA

→ evidence for ongoing use and production of CFC-11 in China

→ *Overall quantities unknown…*

Ozone-Harming Gas Is Detected, Despite Ban

By Henry Fountain, NY Times
p. A4, May 16, 2018

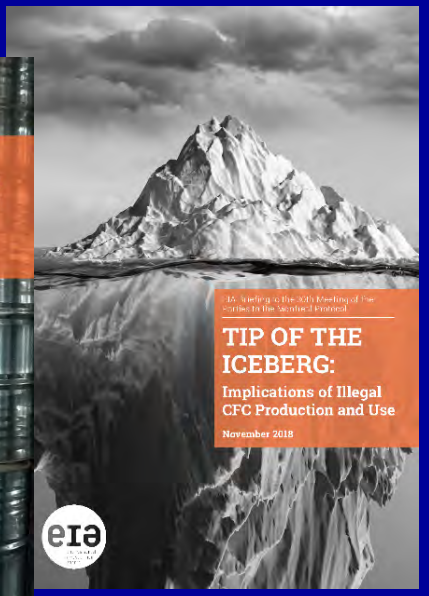
An Environmental Win Falters. Why? Some Clues Point to China

By Chris Buckley and Henry Fountain, NY Times
p. A1, June 24 2018

More Evidence Points to China as Source of Ozone-Depleting Gas

By Chris Buckley and Henry Fountain, NY Times
p. A14, November 3, 2018

…and the EIA



The EIA suggests that in 2018 ***most*** of the closed-cell foam industry in China had reverted back to using CFC-11

But this was from a very limited survey of users…

The Parties to the Montreal Protocol consider the findings in their annual meetings in 2018 and 2019:

Ecuadorian President Mr. Lenín Moreno and meeting co-chairs open the meeting

Science Assessment Panel members (+ Dave F.)

Presenting the science to the Parties in side events

Remaining questions:

What is being done about the issue?

The Parties to the Montreal Protocol are:

* ***taking the issue seriously*** (recent meetings dominated by this issue)
* ***looking for more information*** (meetings held, reports requested)
  - what will be the ozone layer impact? Are emissions increasing outside of NE China? What led to the issue? How is the CFC-11 being produced?

…to facilitate rapid mitigation; and maintain integrity of the Protocol

They are also:

* ***reconsidering $$ being transferred to China*** via the Multi-lateral Fund (the Protocol's fund for assisting developing countries with compliance; $1.3 billion has been dispersed to China via the MLF since the 1980s…)
  - China's most recent funding allotments were reduced

* ***considering punitive action*** (remedial too?)

* ***considering amendments to the Protocol*** to prevent future violations
  - for ODSs, and wrt the HCFCs phase-out and HFC phase-down (similar if not larger challenges to monitor adherence to these control schedules seem likely…)

China's response:

Has repeatedly indicated a commitment to work with other countries, scientists, and industry experts to locate and eliminate the true source of the increased CFC-11 emissions.

Has conducted inspections of 1,172 enterprises across the country, and found instances of illegal production and use (and prosecuted those responsible), but amounts were small (29.9 tonnes and 10 enterprises)

→ ***not enough to account for atmosphere-based results***

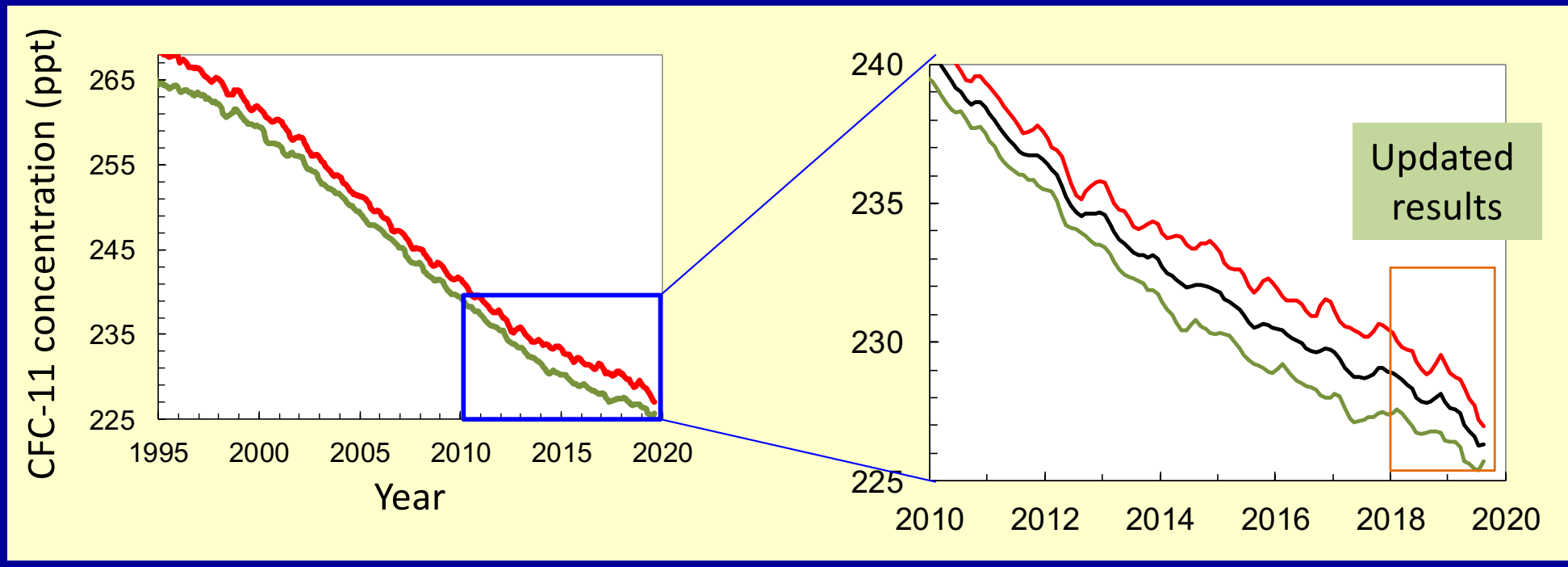
Has formulated a plan of action (with international input and before the Rigby et al paper fingering China in particular) that involves:

- **Developing national-scale atmospheric monitoring** of ODSs and HFCs
- **Building 6 testing laboratories** (will help with enforcement)
- **Strengthening inspections and enforcement** (ecology and environment bureaus, but difficult as businesses are many and officials are few)
- **Better tracking of CCl_4** (source material)
- **New programs to enhance enforcement**
- **Facilitating reporting of non-compliance** by industry (e.g., competitors)
- **Extending penalties to end-users** for non-compliance

Updated measurements (post 2017) hint at changes in three respects:

Preliminary NOAA results

1) an **accelerating** global concentration decline
2) a **decreasing** N-S hemispheric concentration difference
3) **decreased concentrations** in pollution plumes reaching Hawaii



→ These observations of declining concentrations suggest that **global CFC-11 emissions may be on the decline**

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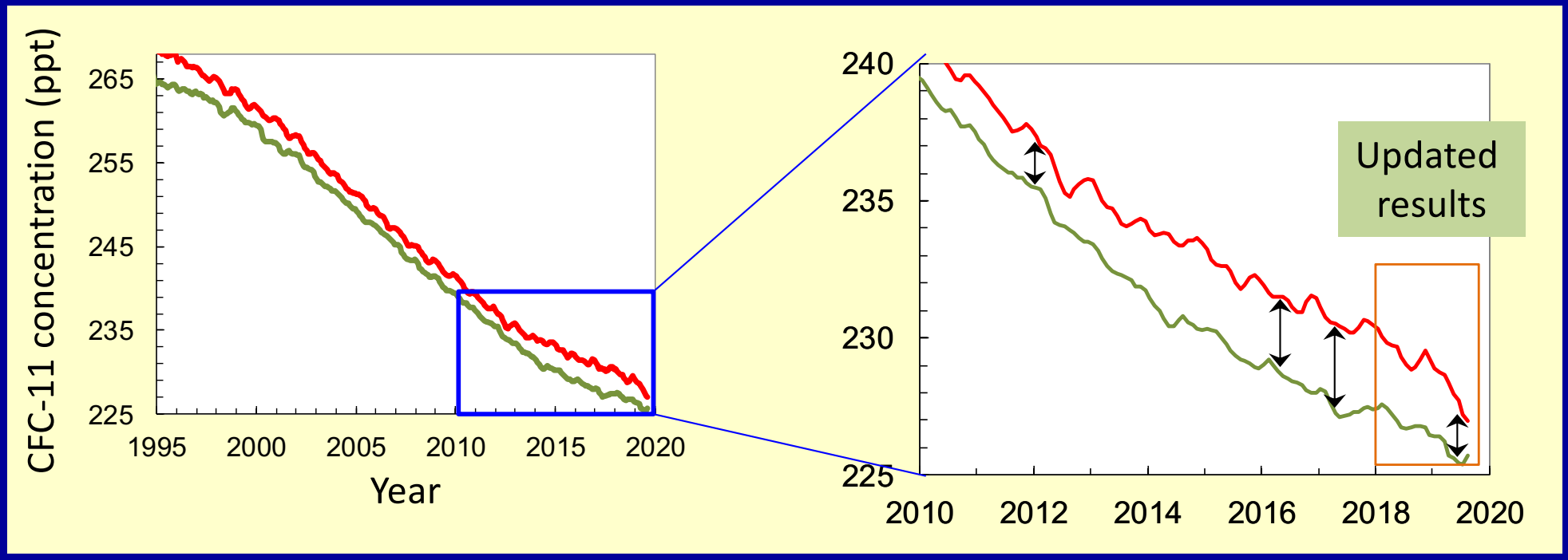


→ These observations of declining concentrations suggest that **global CFC-11 emissions may be on the decline**

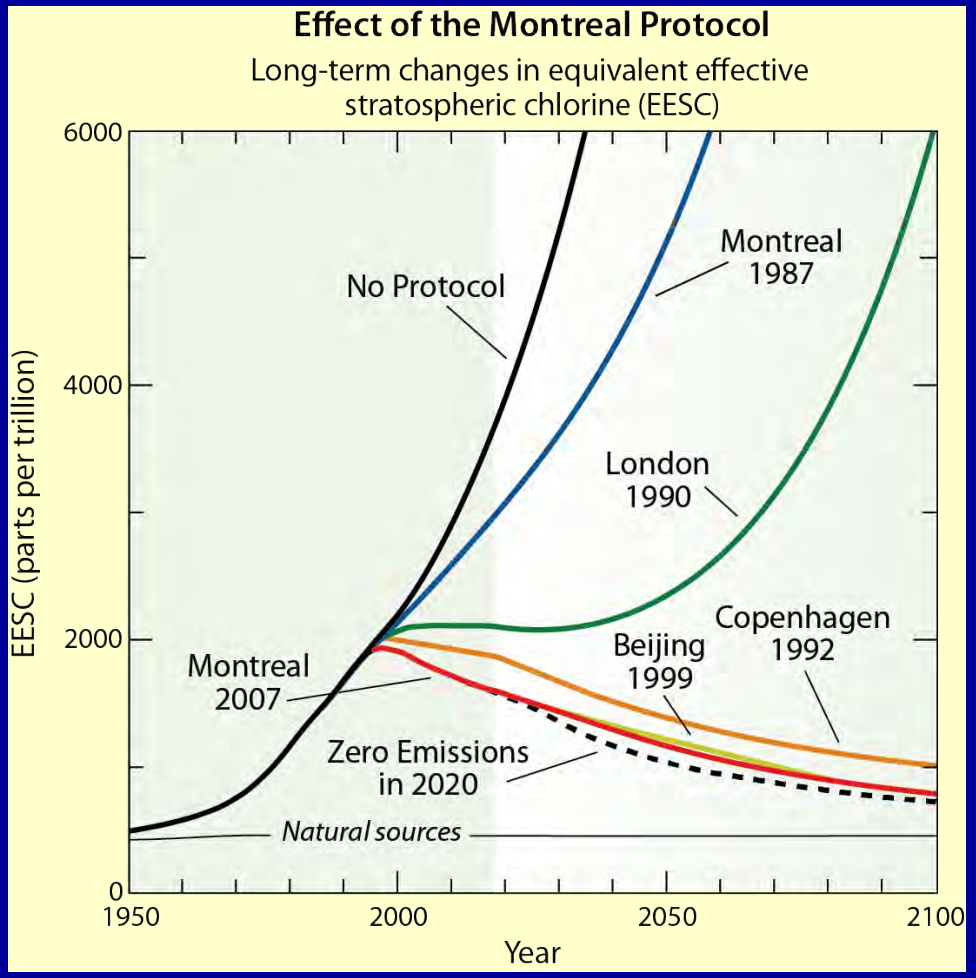
Key features of the Montreal Protocol enabling it's success:

It has repeatedly been revisited, adjusted, and amended by Parties.

Revisions are based on current knowledge that is assessed in quadrennial reports by three panels (Science, Technology and Economics, Environmental Impacts) drawn from worldwide experts.

Initial agreements would not have saved the ozone layer…

Only with subsequent revisions was ozone layer recovery a possible outcome



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Decisions are typically made by unanimous consent—everyone has to agree in order for decisions to move forward…

A 10-year grace period was allowed for developing countries for meeting the phase-out schedules.

Compliance by developing countries is assisted by a Multi-Lateral Fund for the Implementation of the Montreal Protocol, which is maintained by developed countries (>$3 billion USD distributed between 1995 and 2005). Management of the fund is by an executive committee with 14 member states (7 developed, 7 developing).

Concluding remarks:

* ***The Montreal Protocol represents a unique situation*** in which scientists and policymakers are working constructively to enable ozone layer recovery

* ***The information feedback loop*** (quadrennial reports) has led to strengthening of controls, thereby improving chances for success

* ***Scientists have input to Parties without interference*** via assessed scientific understanding communicated in quadrennial reports
  → providing "policy-relevant but policy-neutral information"

* ***Leverage on compliance by Parties enabled by multiple mechanisms***
  → particularly MLF funding of projects

<u>State-of-the-art atmospheric monitoring and modeling enabled:</u>

→ the early detection of a significant violation of the Montreal Protocol

→ an indication of the location of the renewed source of CFC-11

Many questions remain for CFC-11, but early signs suggest the path to rapid and lasting mitigation remains unclear

<u>Considering the future:</u>

is our atmospheric "vigilance" capability up to the task (obs., models)?
→ HCFC phase-out, HFC phase down… greenhouse gases??

Thanks for your attention