Ozone profile changes and the Montreal Protocol

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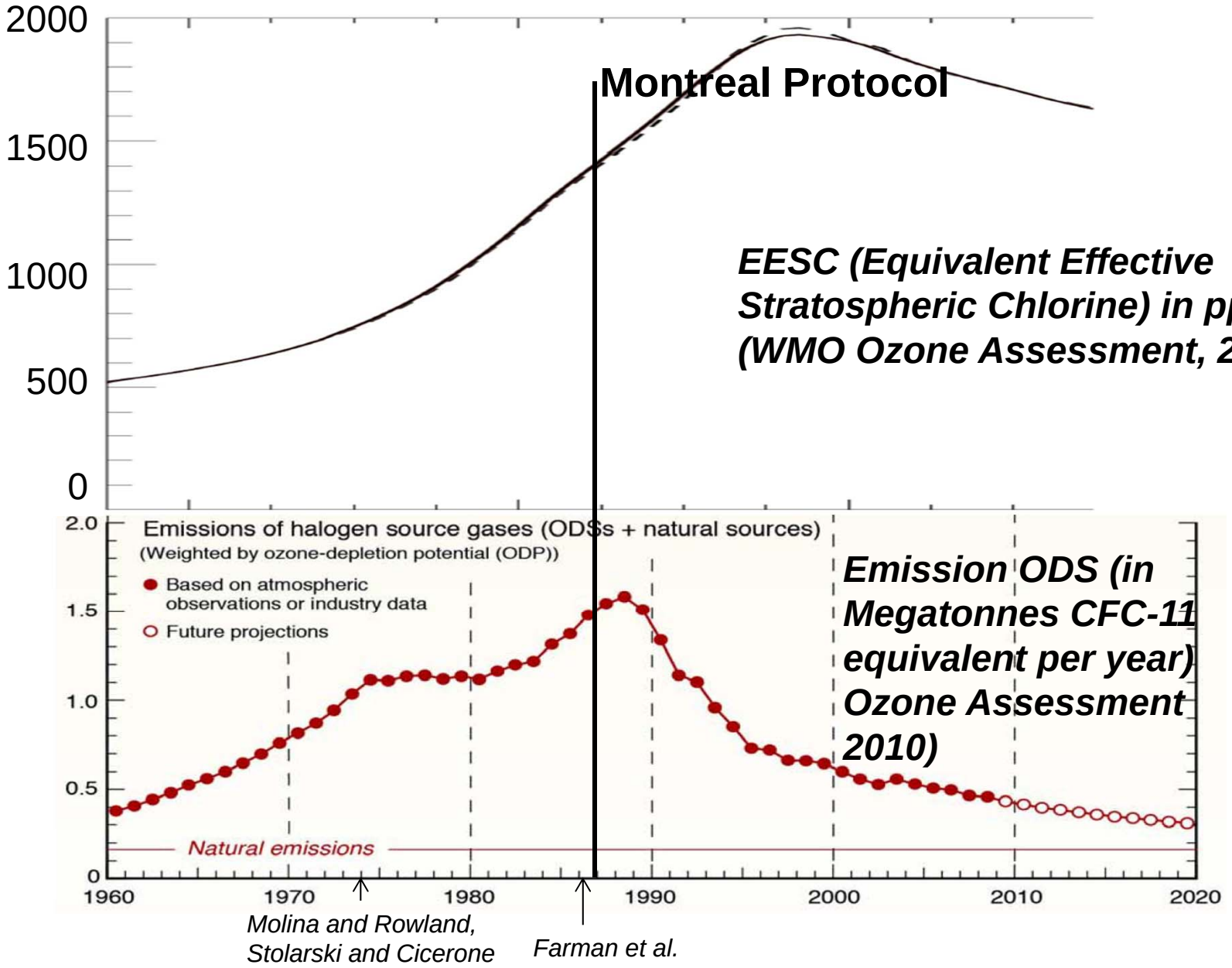
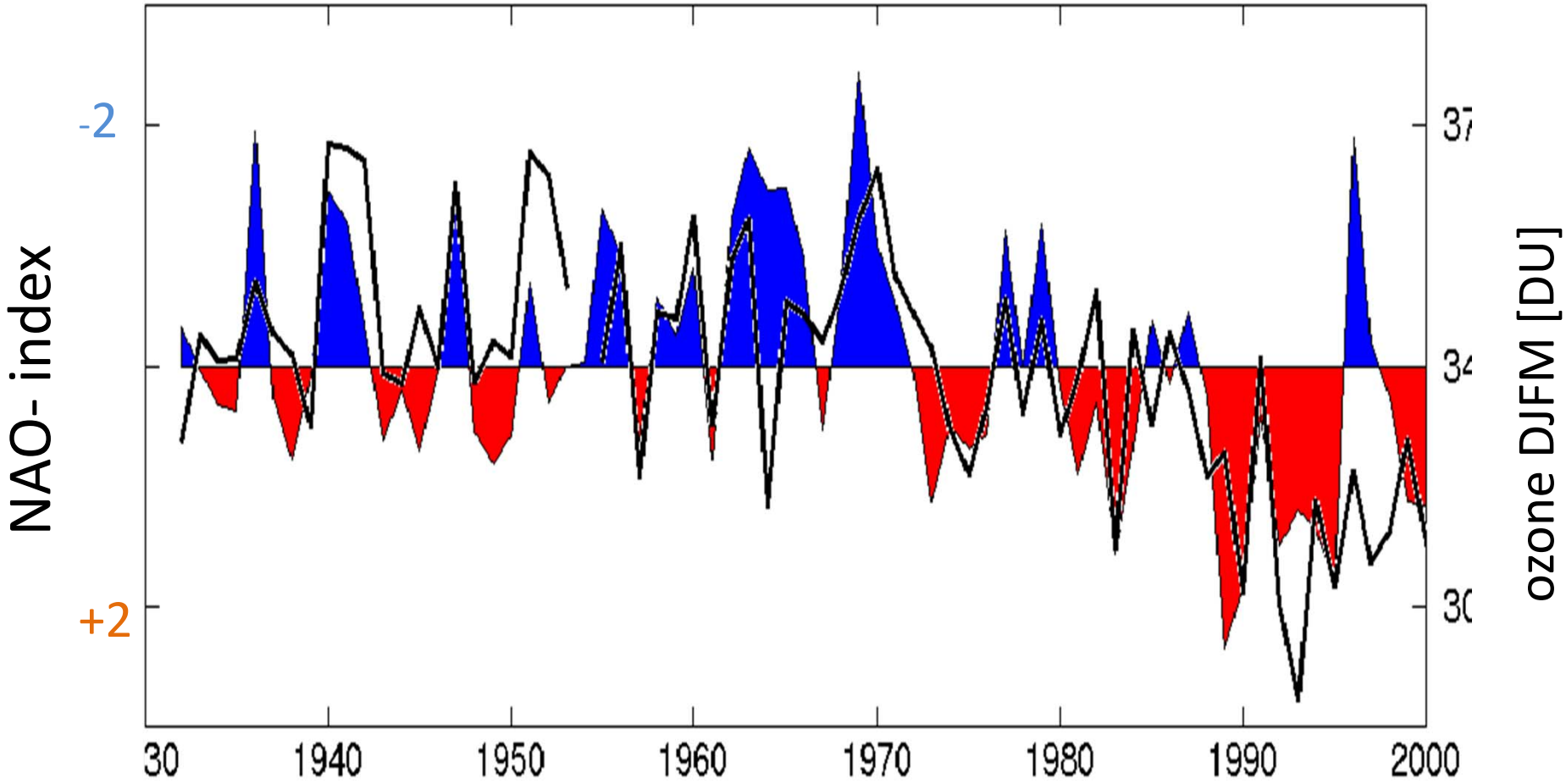
1. Introduction



Target of Montreal Protocol: ***Protection of the ozone layer***

Total Ozone: Precise measurements show long-term climate variability.

C. Appenzeller, A.K. Weiss, and J. Staehelin: *North Atlantic Oscillation* modulates total ozone winter trends, *Geophys. Res. Lett*. (2000).



Most direct impact of ODS: **upper stratosphere**

Bottom - up activity SI2N (**S**PARC, **I**nternational Ozone Commission (IO3C), **I**GACO (GAW (Global Atmosphere Watch of WMO), and **N**DACC (Network for the Detection of Atmospheric Composition Change)

- F. Tummon, B. Hassler, N.R.P. Harris, J. Staehelin, J. Anderson, G.E. Bodeker, A. Bourassa, S.M. Davis, D. Degenstein, S.M. Frith, L. Froidevaux, E. Kyrölä, M. Laine, C. Long, A. Penckwitt, C. Sioris, K.H. Rosenlof, C. Roth, H.J. Wang, J. Wild: **Intercomparison of Merged Satellite Data Sets for Trend Studies of the Vertical Distribution of Ozone**, *Atmos. Chem. Phys*., 15, 3021–3043, doi:10.5194/acp-15-3021 (2015).
- N.R.P. Harris, B. Hassler, F. Tummon, G. E. Bodeker, D. Hubert, I. Petropavlovskikh, W. Steinbrecht, J. Anderson, P. K. Bhartia, C. D. Boone, A. Bourassa**,** S. M. Davis, D. Degenstein, A. Delcloo, S. M. Frith, L. Froidevaux, S. Godin-Beekmann, N. Jones, M. J. Kurylo, E. Kyrölä, Laine, S. T. Leblanc, J-C. Lambert, B. Liley, E. Mahieu, A. Maycock1, M. de Mazière6, A. Parrish, R. Querel, K. H. Rosenlof, C. Roth, C. Sioris, J. Staehelin4, R. S. Stolarski, R. Stübi, J. Tamminen, C. Vigouroux, K. Walker, H. J. Wang, J. Wild, and J. M. Zawodny: **Past changes in the Vertical Distribution of Ozone, Part III: Analysis and Interpretation of Trends, ACPD.**

For more information: Changes in the vertical distribution of ozone – the **SI2N report**: ***Special issue jointly organized between Atmospheric Chemistry and Physics, Atmospheric Measurement Techniques, and Earth System Science Data*** Editor(s): P. K. Bhartia, N. Harris, M. Van Roozendael, M. Weber, R. Eckman, D. Loyola, J. Urban, C. von Savigny, M. Dameris, S. Godin-Beekmann

Outlook

2. Merged ozone satellite series

3. Trends: Multiple regression model

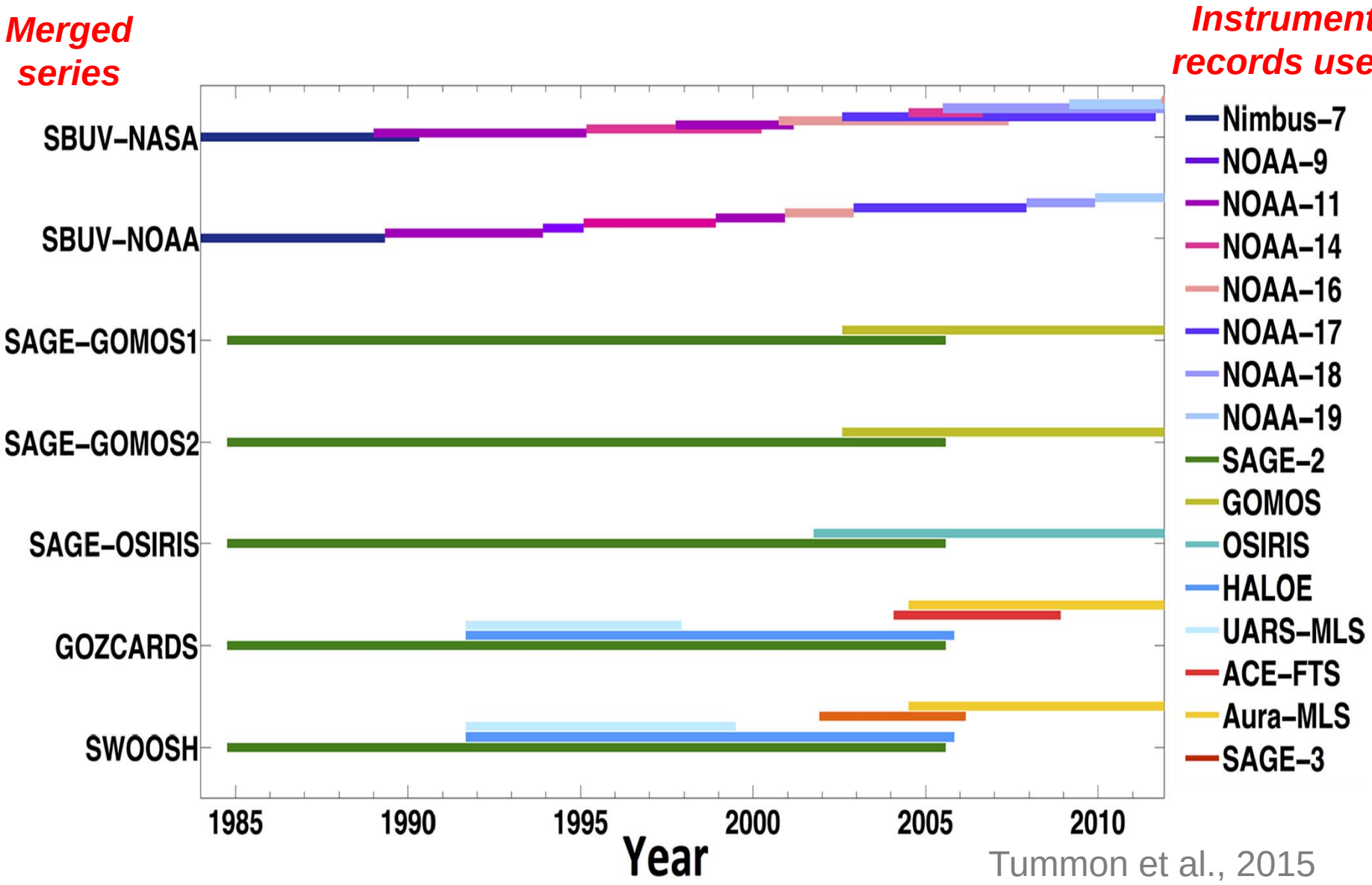
4. Trend results

5. Uncertainties and Sensitivity Analysis

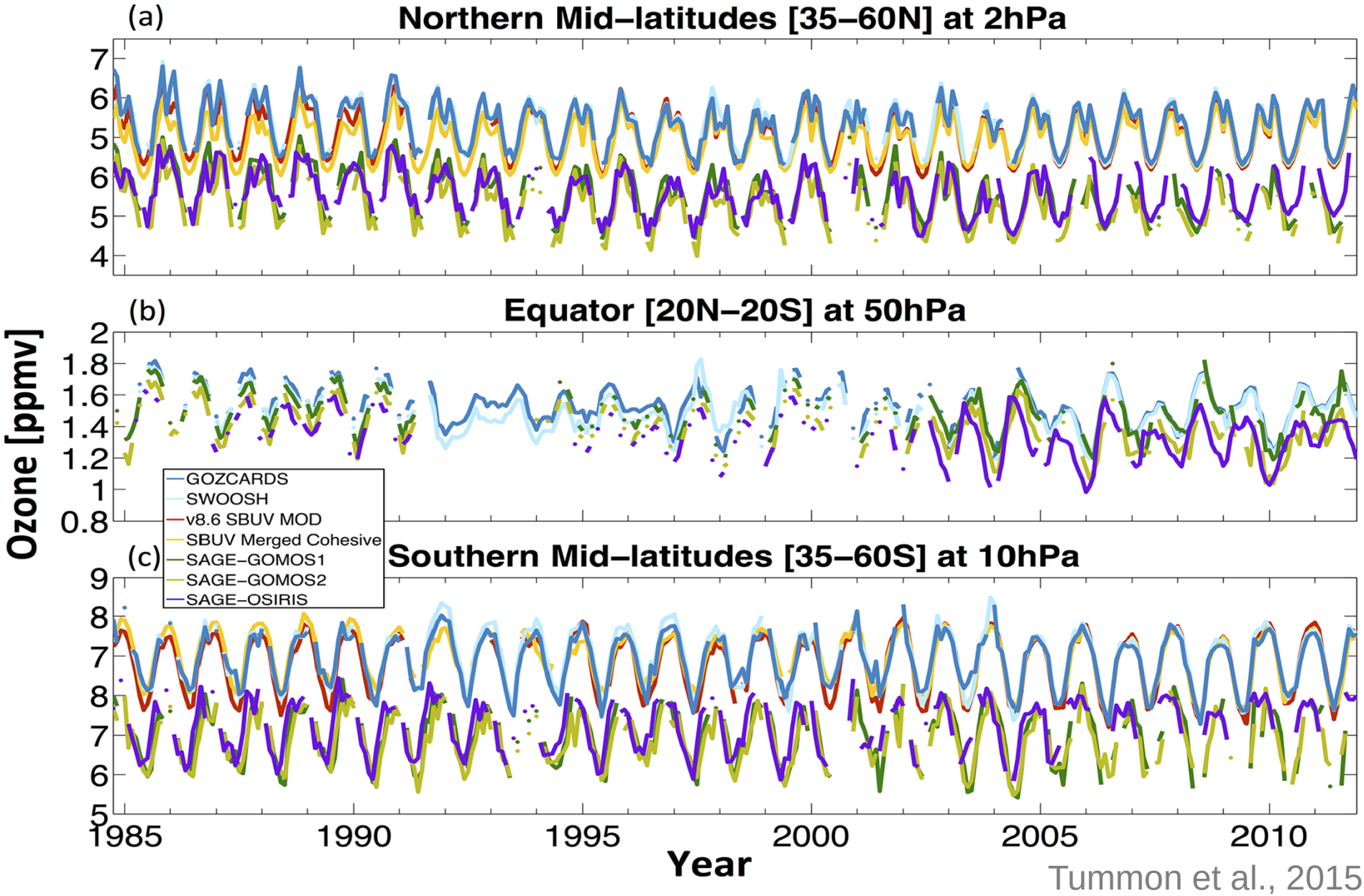
6. Outlook and Coclusions

2. Merged ozone satellite series

2005: end of SAGE and HALOE



Tummon et al., 2015



Tummon et al., 2015

For conversion of datasets from altitude to pressure: the MERRA reanalysis was used.
For comparison of individual satellite datasets see: Tegtmeier et al., J. Geophys. Res., 2013).

3. Trends: Multiple regression model

Piece-wise linear trend model (PWLT): two seperate linear trends, forced to meet at end of 1997 (except sensit. analysis)

$$\Omega(t) = A_{(NA=4)} + B_{(NB=2)} \times t + C_{(NC=2)} \times t_{(t=0)} \text{ (for t< inflection point)} + D_{(ND=2)} \times QBO(t) + E_{(NE=2)} \times QBOorthog(t) + F \times F10.7(t) + G \times Pinatubo(t) + H \times ENSO(t) + R(t)$$

Ω(t): ozone for a particular month t, altitude, latitude

(Trend component

Explanatory variables)

***A-H**: model coefficients corresp. to offset term (mean annual cycle), linear trend, and basis functions.*

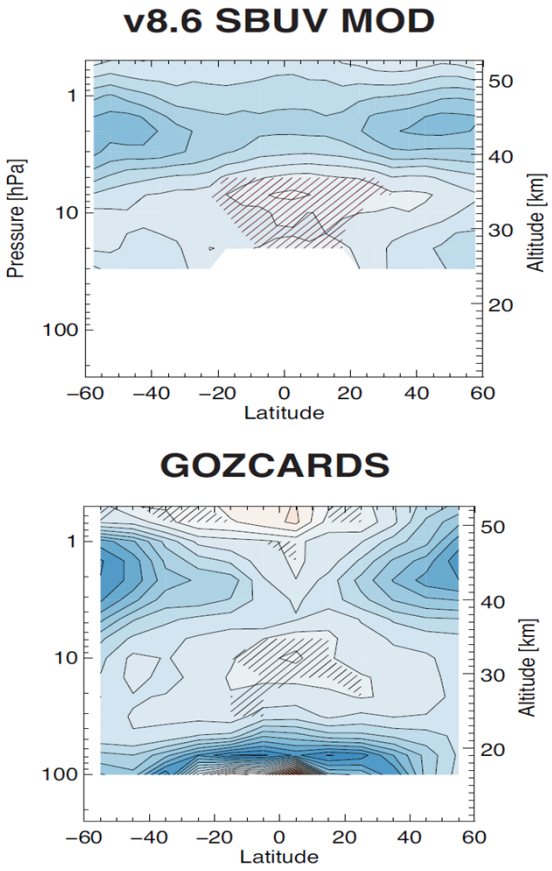
***Subscripts NA-NE**: number of Fourrier pairs used to account for seasonal dependencies.*

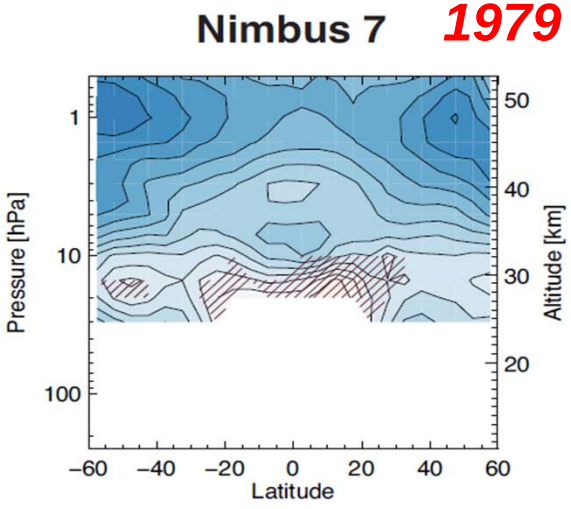
Residual term: $R(t) = \epsilon_1(t) \times R(t\text{-}1) + \epsilon_2(t) \times R(t\text{-}2) + e_t$

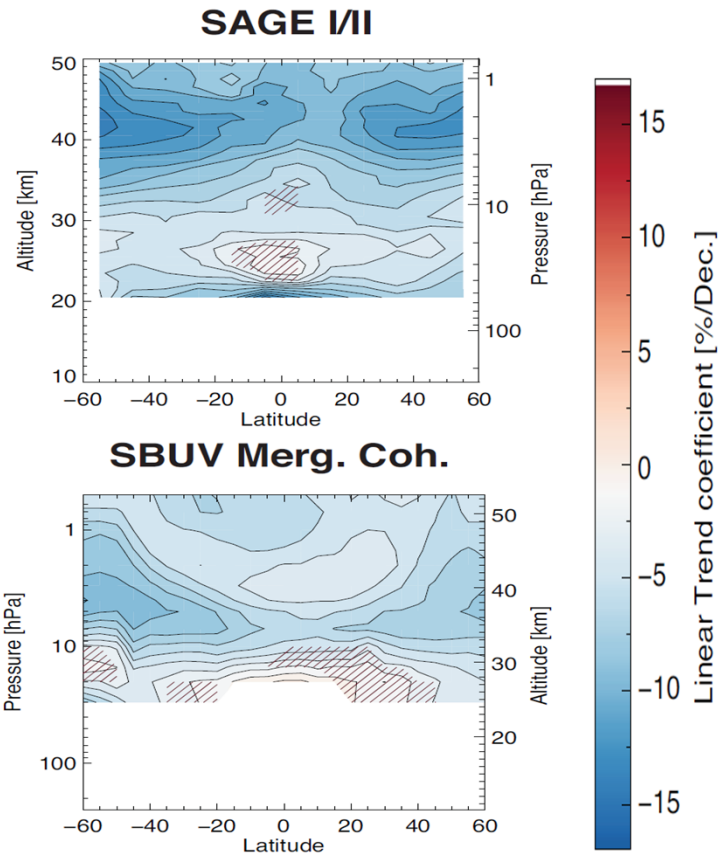
Where ϵ_1 and ϵ_2 are model coefficients, and e_t represents independent random errors

4. Trend results

1979 -1997*





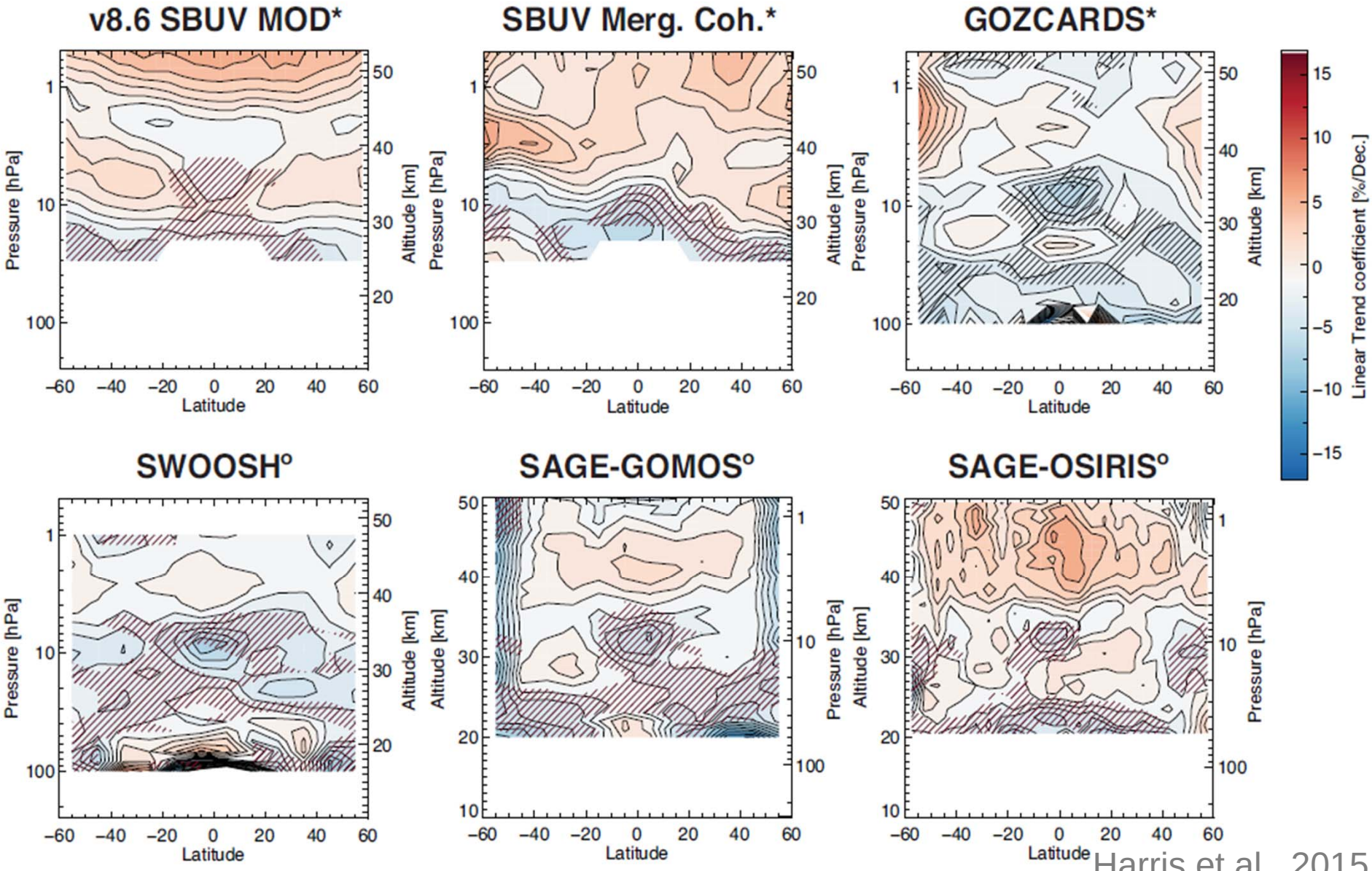


*Trends calculated with PWLT model (except SAGEI/II)

Hatched: Not significant at the 95% confidence level

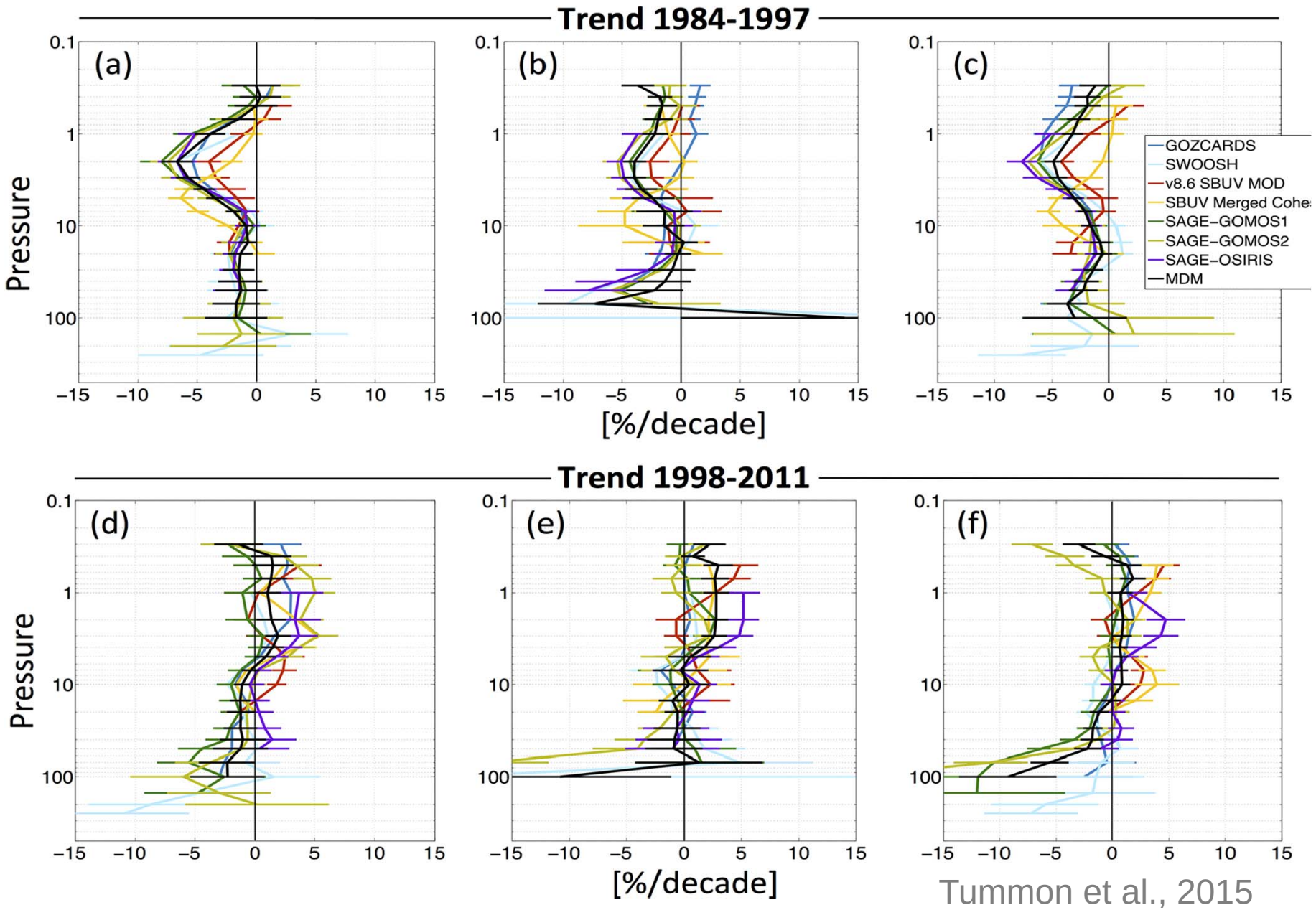
Harris et al., 2015

Trends 1998-2012: using PWLT



Harris et al., 2015

35°-60°S 20°S-20°N 35°-60°N

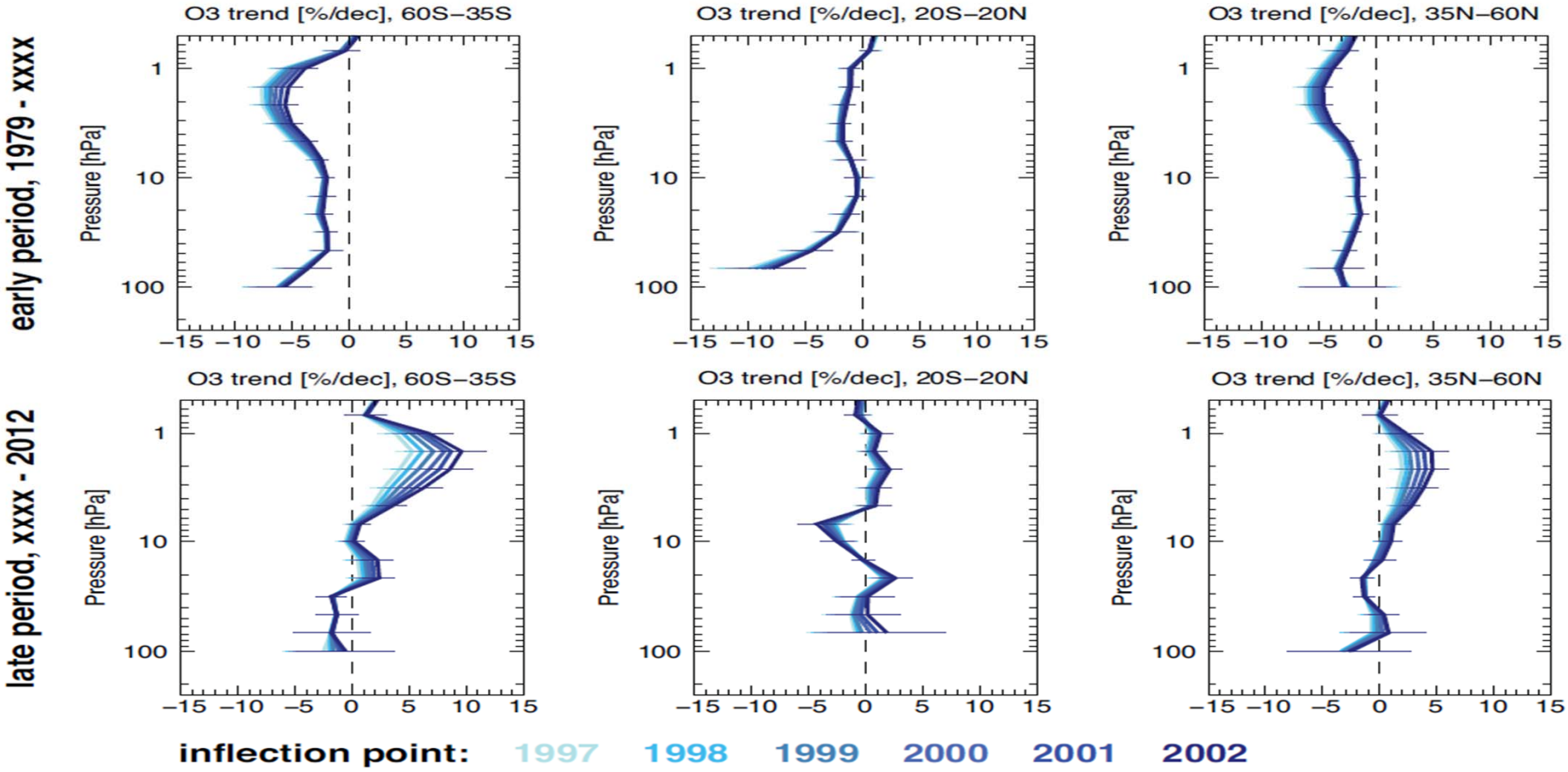


Tummon et al., 2015

5. Uncertainties and sensitivity

Sensitivity to the inflection point*: GOZCARDS*

(PWLT analysis)



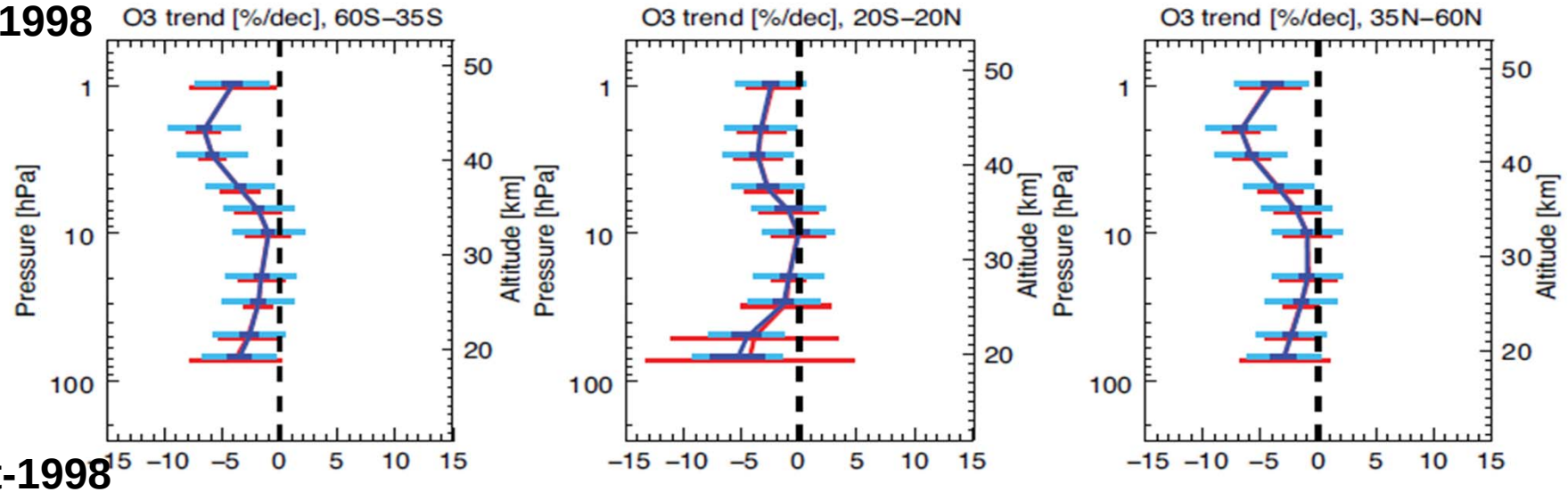
Error bars indicate the 95% confidence level.

Harris et al., 2015

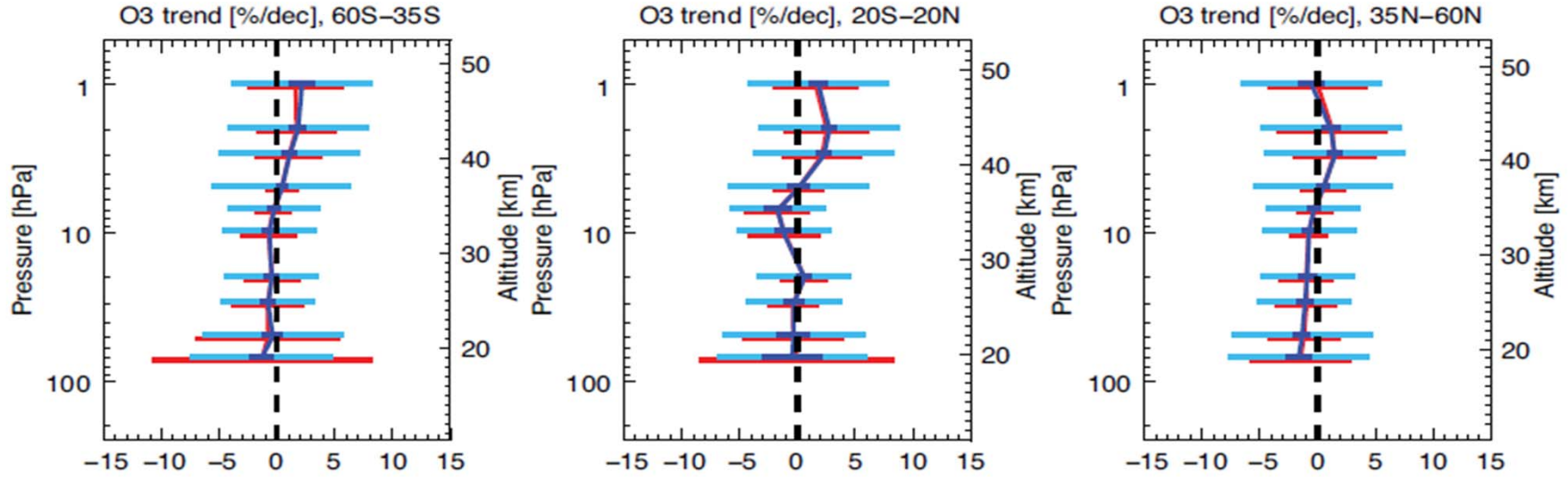
Combined trends: trends based on 7 merged satellite datasets (following approaches used in SPARC Report 6, Appendix):

- ***SWM (weighted mean) distribution:*** Trends of individual series (incl. uncertainties) treated as independent of one another.
  - Produces the 'most likely trend estimate' using the weighted mean of various datasets.
  - Uncertainty range: weighted mean of uncertainties from trends of individual merged series (however, not completely adequate since 5 merged series rely on SAGE-II as base dataset).
- ***Joint (J-) distribution:*** Different estimates combined into a single distribution and uncertainty range.
  - Corresponds to a joint distribution of individual variances and an arithmetic (unweighted) mean of all datasets.

Pre-1998



Post-1998

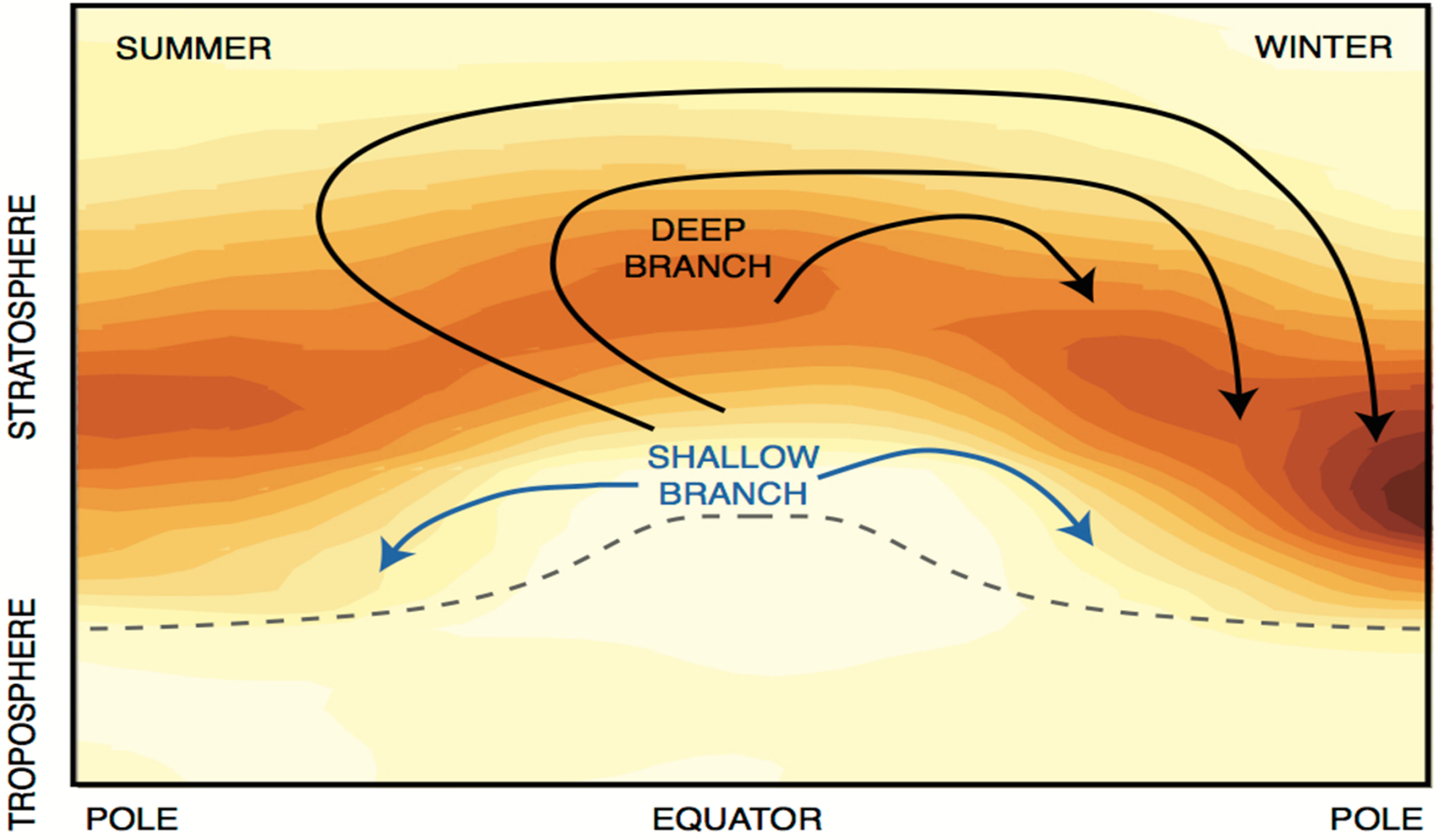


Most likely range for ozone trends (error bars show the 95% confidence level):
Thick blue lines: central estimate and associated errors assuming **SWM-distribution**.
Light blue lines: same analysis, additionally assuming possible drift of the overall observing system (Hubert et al., 2015).
Thick red lines: calculated assuming the **J-distribution**.

Harris et al., 2015

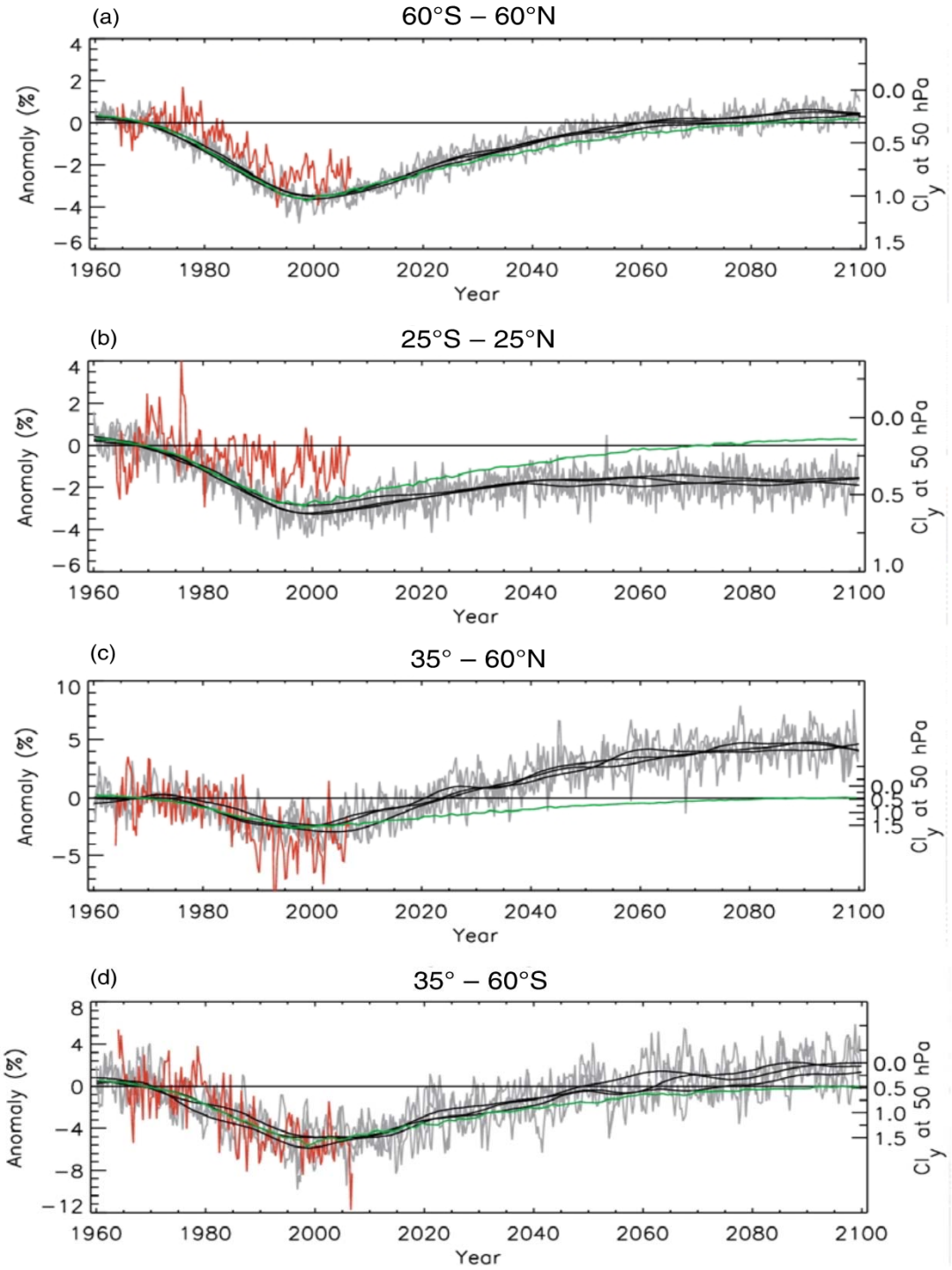
6. Outlook and Conclusions

Future: Enhancement of the ***Brewer-Dobson circulation*** projected because of *climate change* (WMO/UNEP, 2014):



Ensemble simulations using the CMAM chemistry-climate model (**black line**), ozone measurements (**red line**), and Cl_y (a measure of chemical ozone depletion by ozone depleting substances) (**green line**).

(Shepherd, 2008)



Conclusions: Satellite ozone profile trends and the Montreal Protocol

- Merged series required, producing them is challenging
- Statistical analysis shows reversal of upper stratospheric ozone trends
- Upward trends in recovery phase: strongly variable among merged series
- Combined upward trends: What is the appropriate statisitical approach? Upward trend only significant when questionable assumptions are made …
- Reliable vertical satellite data important for future (enhancement in Brewer-Dobson circulation)