Global ozone recovery trends in total ozone from observations and chemistry-climate modelling

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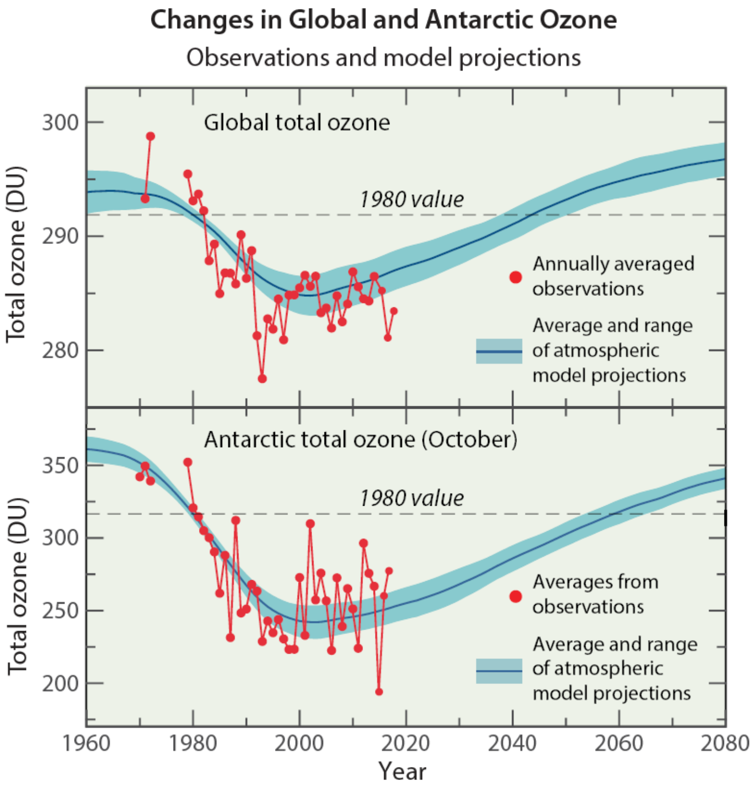
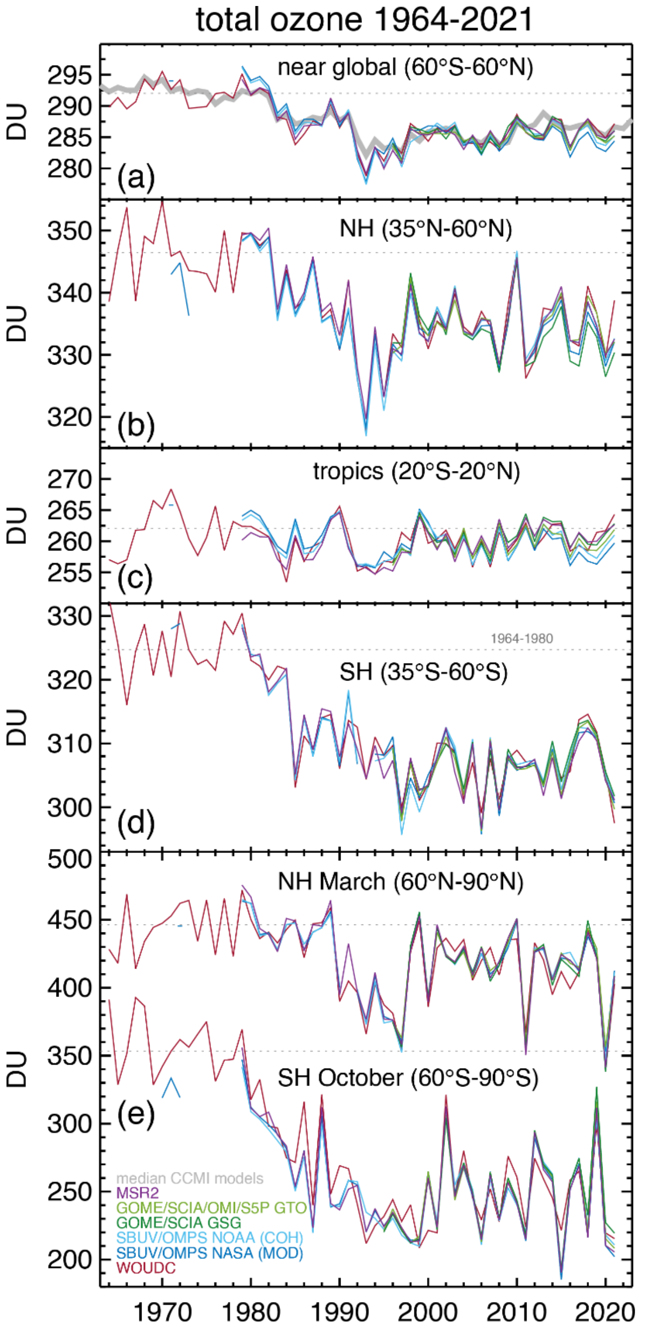
Motivation

- Update total ozone trends (Weber et al., 2018) using four more years of data up to 2020
- Current ozone levels (2017-2020) are about 2-4% below 1964-1980 levels at mid-latitudes and up to more than 20% below above Antarctica in October
- Large year-to-year variability
- Separation of atmospheric dynamics related trends linked to climate change from chemical trends related to changes in ozone-depleting substances (ODS) regulated by the Montreal-Protocol) → detection of "recovery"



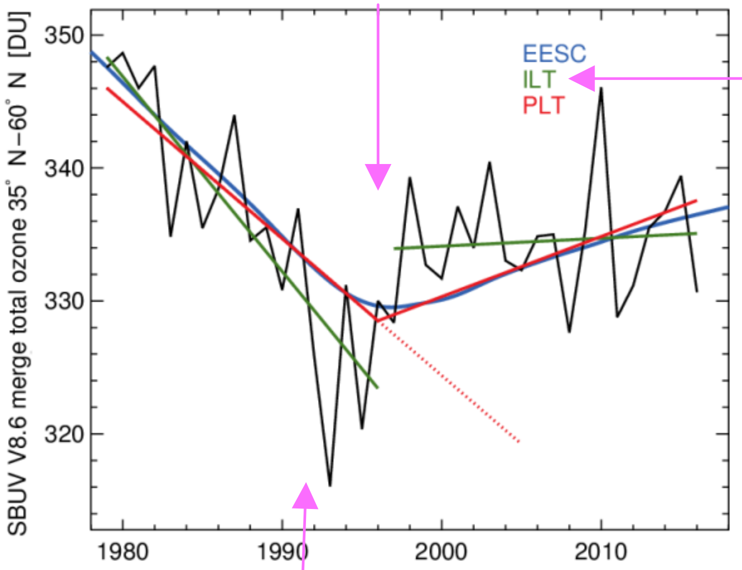
Ross J. Salawitch, R.J., et al., *Twenty Questions and Answers About the Ozone Layer: 2018 Update, Scientific Assessment of Ozone Depletion: 2018*, World Meteorological Organization, Geneva, Switzerland, 2019.



Weber et al., BAMS State of the Climate 2021 (2022)

Datasets and multiple linear regression (MLR)

- Five merged datasets (up to 2020)
  - SBUV/OMPS NASA (MOD V8.7) (Frith et al. 2014, 2017)
  - SBUV/OMPS NOAA (COH V8.6) (Wild and Long, 2021)
  - GSG (IUP Bremen) (Weber et al., 2011, 2018)
  - GTO-ECV (ESA/DLR) (Coldewey-Egbers et al., 2015; Garane et al., 2018)
  - WOUDC (Fioletov et al., 2002,2008)



Weber et al. 2018

- Multiple linear regression (MLR, Weber et al. 2018):

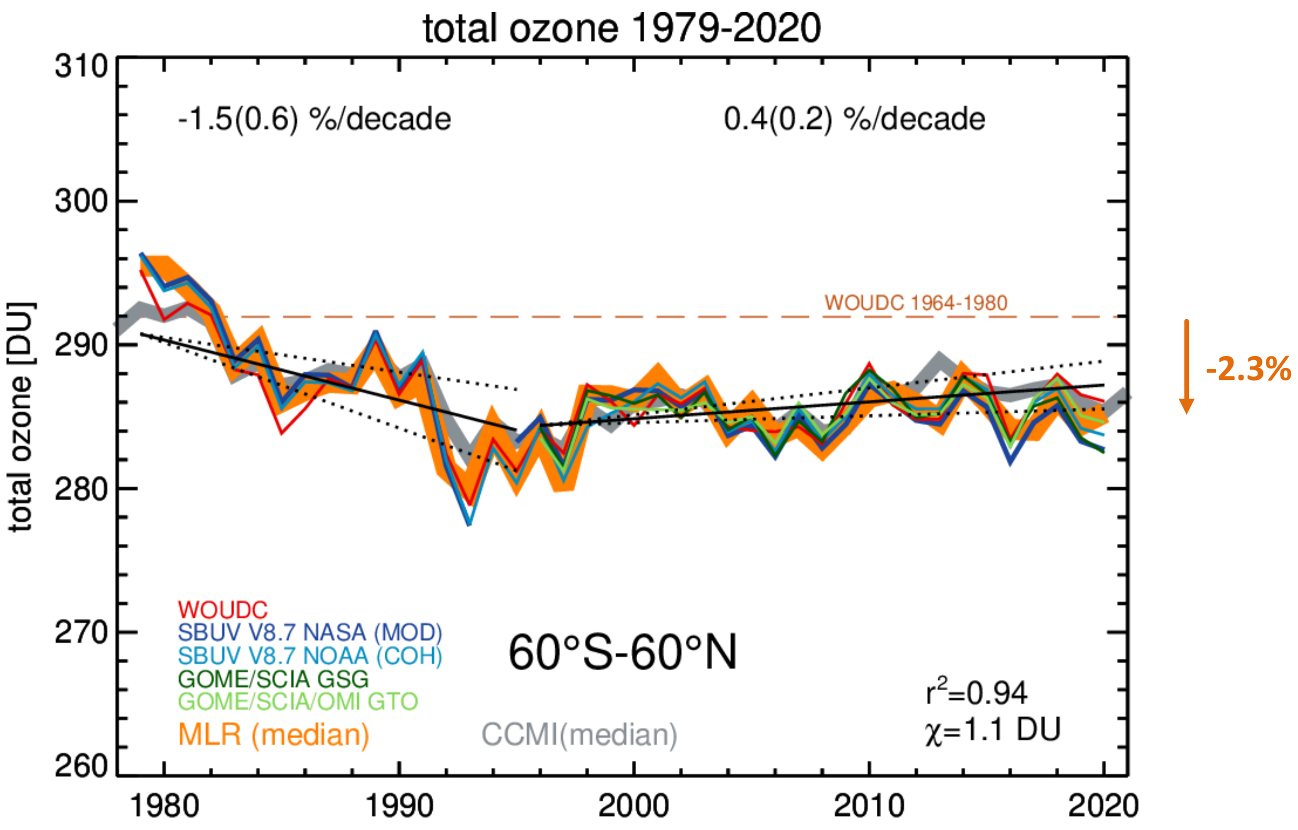
$$y(t) = [a_1 + b_1 \cdot (t_0 - t)]X_1(t) + [a_2 + b_2 \cdot (t - t_0)]X_2(t) + \alpha_{sun} \cdot S(t) + \alpha_{qbo50} \cdot Q_{50}(t) + \alpha_{qbo10} \cdot Q_{10}(t) + \alpha_{ENSO} \cdot E(t) + \alpha_{ElChichon} \cdot A_1(t) + \alpha_{Pinatubo} \cdot A_2(t) + P(t)$$

- standard ILT-MLR with P(t)=0
- $t_0 = 1996$ (2000 polar region)
- applied to annual mean zonal mean

$$P(t) = \alpha_{AO} \cdot AO(t) + \alpha_{AAO} \cdot AAO(t) + \alpha_{BDCn} \cdot B_n(t) + \alpha_{BDCs} \cdot B_s(t)$$

- additional terms needed to get ozone variability right (full ILT-MLR)
- trends more likely EESC/ODS related (recovery!)
- terms not independent (incl. QBO, ENSO)

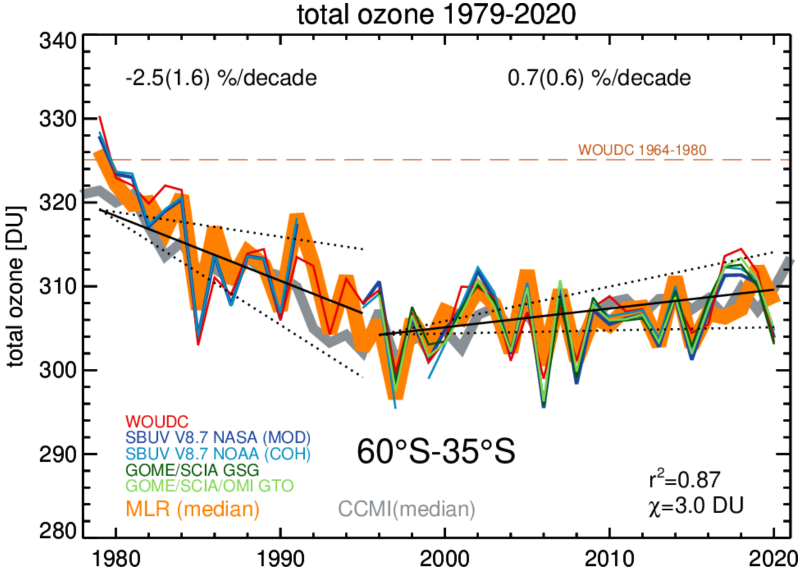
Near global trends

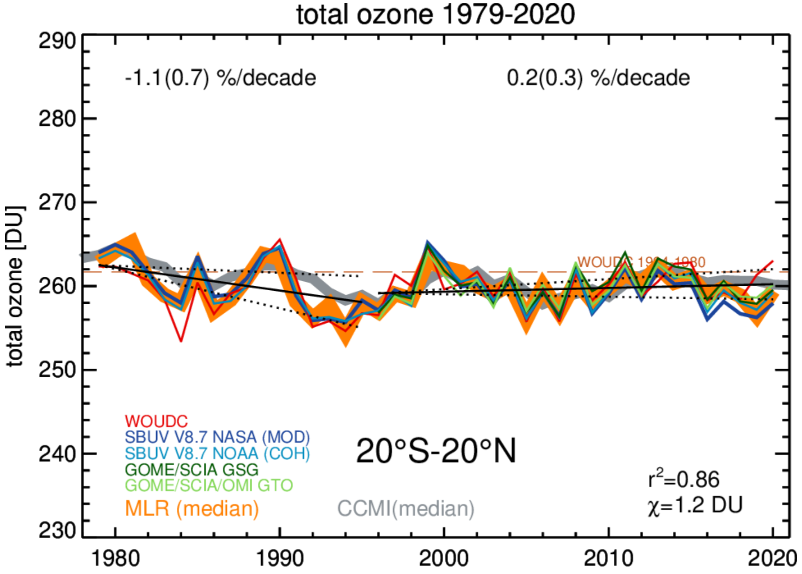


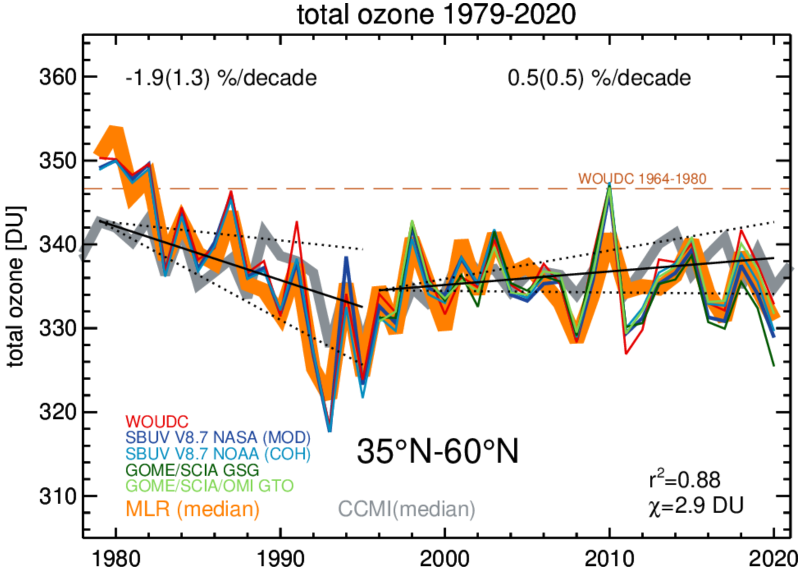
- Full MLR (..+AO+AAO+BDCs+BDCn)
- Data bias corrected using 1998-2008 as reference period

- trend of median after 1996: +0.4(2) %/decade
- Stratospheric halogens (EESC) decrease at 1/3 of the rate of its increase before 1996
  - +0.5%/decade expected (in agreement with observations)
  - Limit post-ODS period in MLR to ≥2000: (apparent zero trend) → trend of +0.5(3)%/decade (robust)
- Good agreement between observation and median of 17 chemistry climate models from CCMI phase 1 (current ODS and GHG scenarios)
  - Note: recent years may be "forecasts"

Zonal mean trends



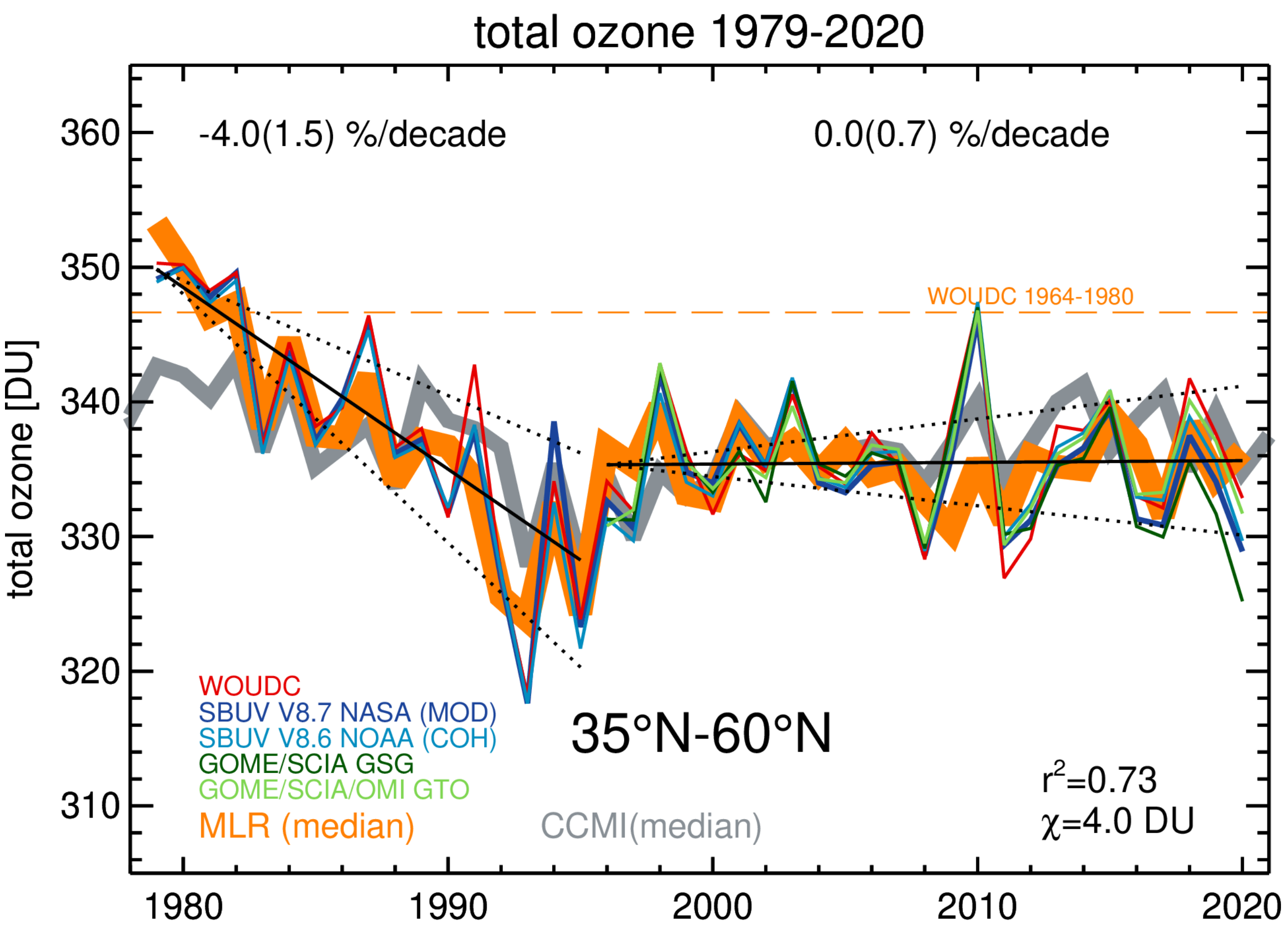




- trends after 1996:
  - mid-latitudes: about +0.5%/decade after 1996
  - SH and NH trends about -1/3 of pre-ODS peak within uncertainties (trends are likely ODS related)
  - tropics: zero trends after 1996
  - Mostly consistent with CCMI-1 median

Standard vs. full multiple linear regression (MLR) in the NH

- “Standard” MLR does not capture inter-annual variability in the NH
- Trends before and after 1995 differ significantly in the standard and full MLR
- Trends in the “standard” MLR combine chemical and dynamics related contribution → changes due to climate (GHG) and ODS
- Trends in the “full” MLR approximate the chemical (ODS related) trends → recovery due to Montreal Protocol



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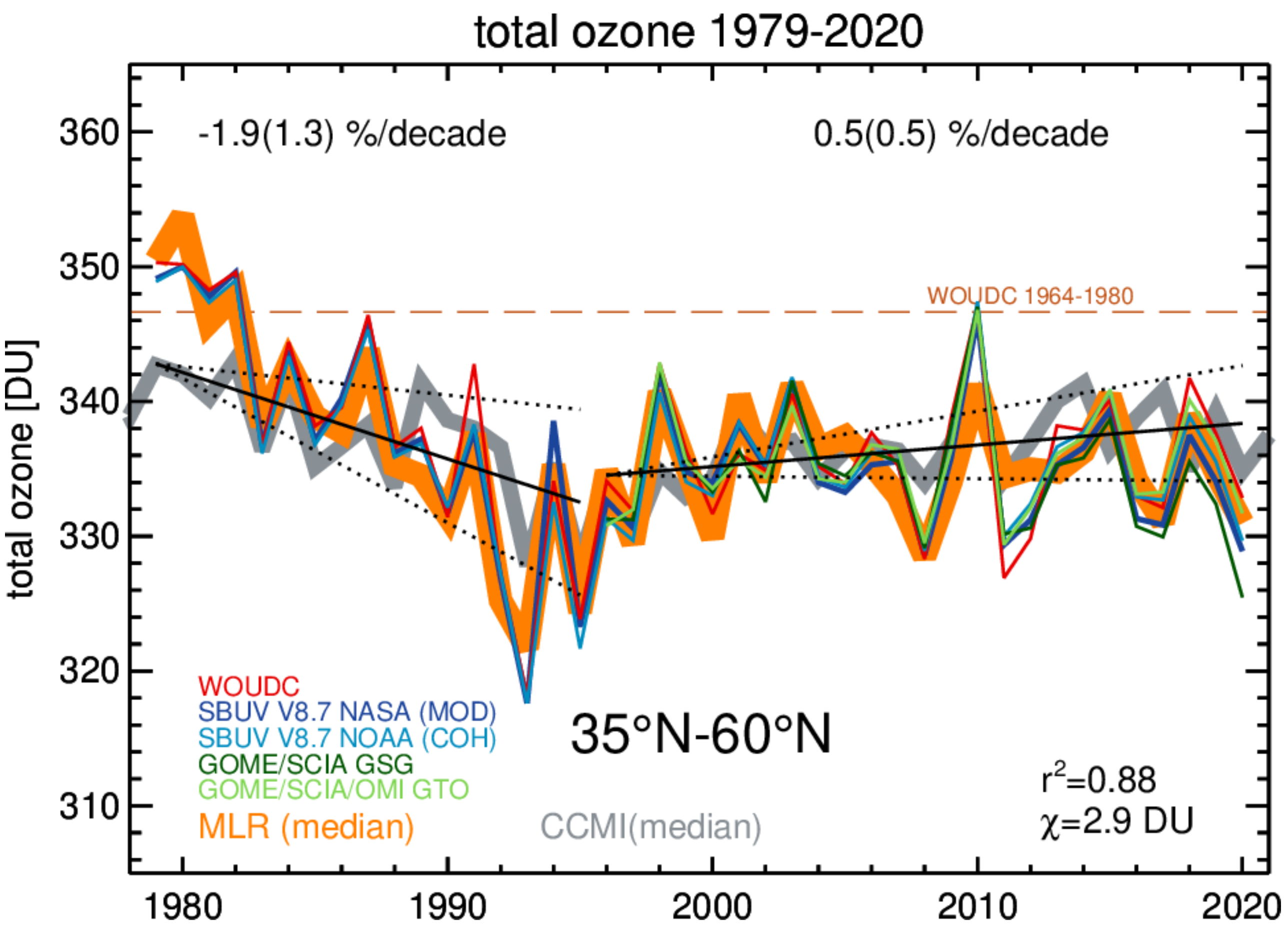

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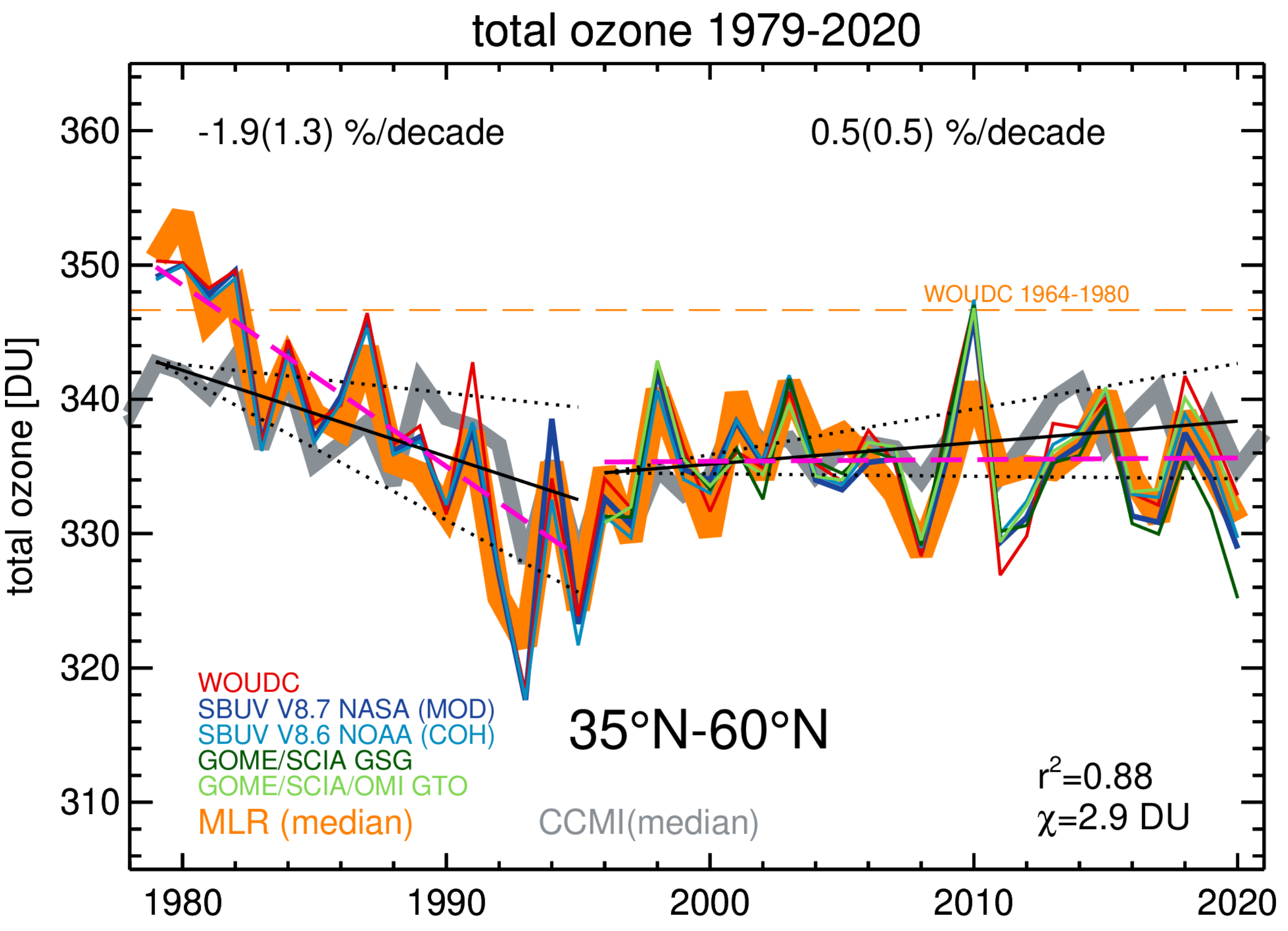
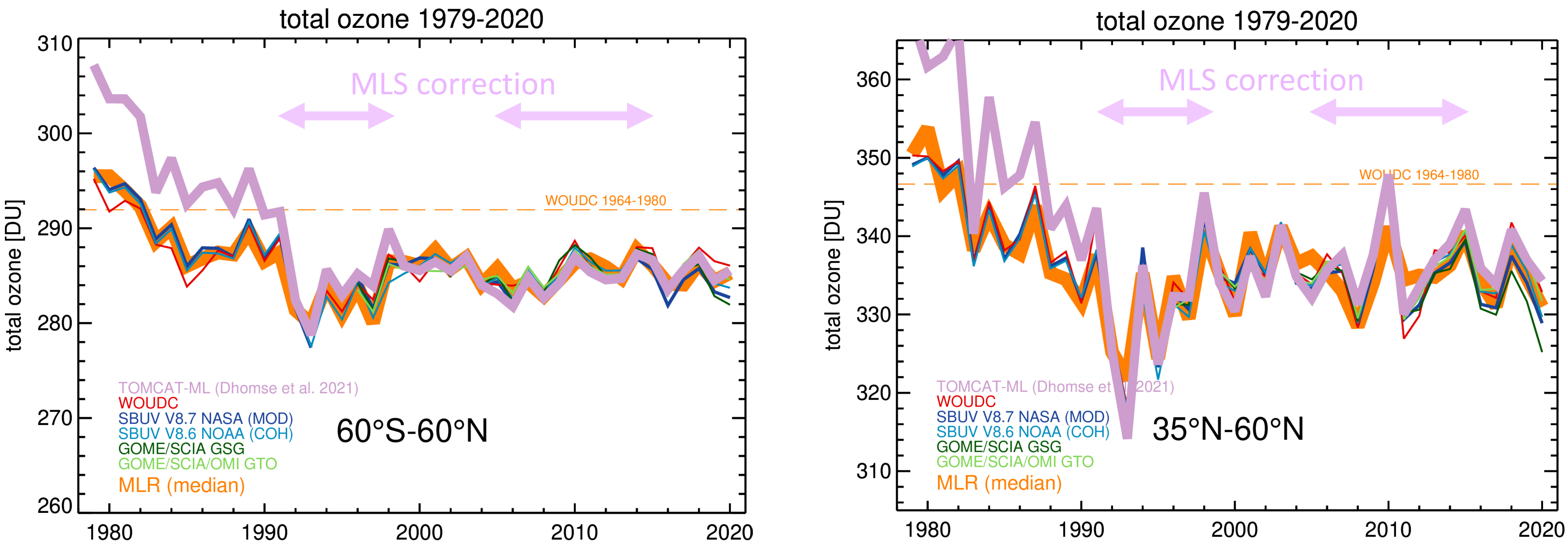
- Trends in the "standard" MLR combine chemical and dynamics related contribution → ~changes due to climate (GHG) and ODS
- Trends in the **"full"** MLR approximate the chemical (ODS related) trends → slow recovery due to Montreal Protocol

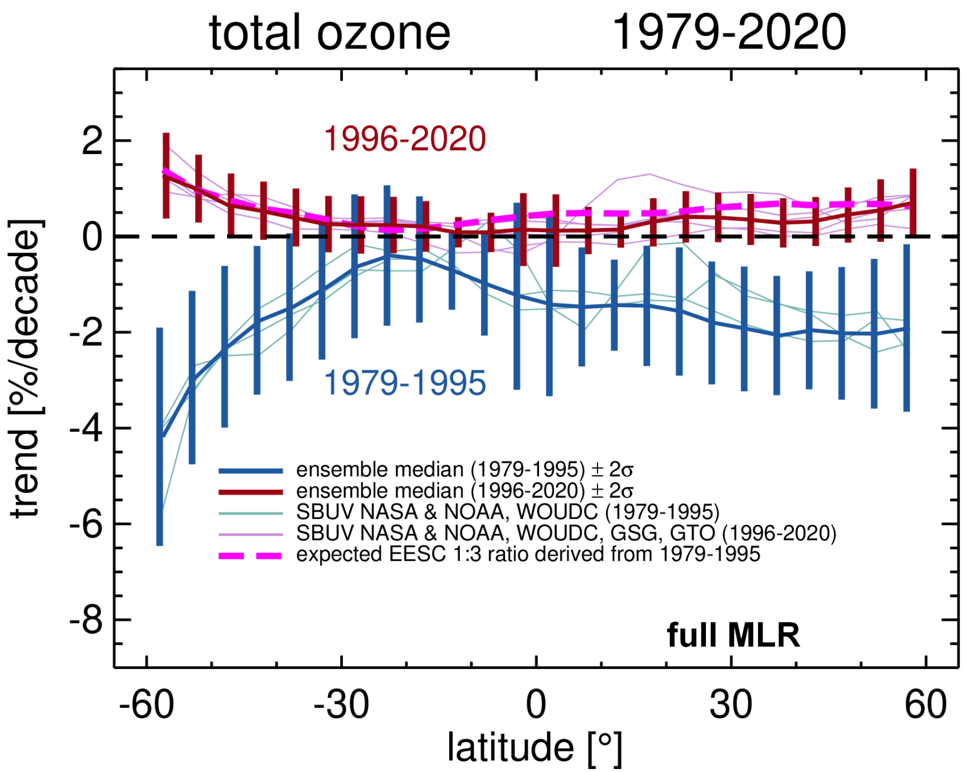


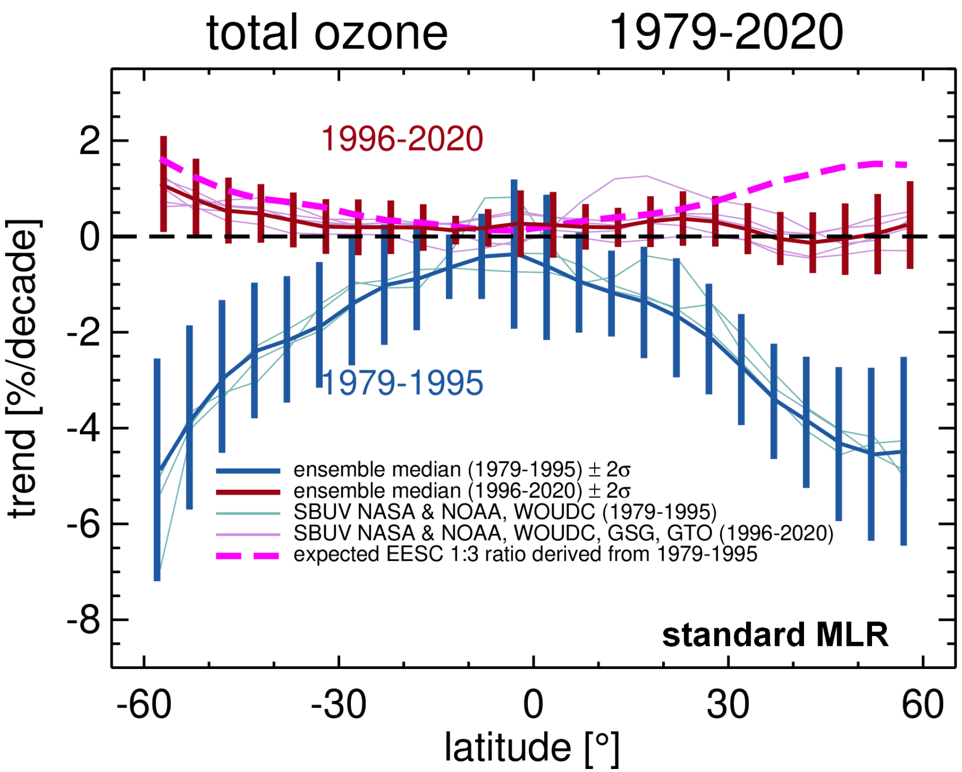
TOMCAT-CTM vs observations



- TOMCAT-ML (Dhomse et al. 2021): 3D CTM, ERA5 reanalysis, WMO2018 ODS and GHG scenarios, detailed chemistry, machine-learning-based bias-corrected using MLS ozone (1991-1998, 2005-2016)
- Some issues with transport due to ERA5 before 1991 (Li et al. 2022)

Latitude dependent total ozone trends





latitude dependent trends from full MLR

- ozone recovery at SH middle latitudes
- Non-significant small positive trend at NH mid-latitudes (~+0.5% to 1%/decade)
- (independent) trends before and after ODS peak are consistent with halogen changes –> ozone recovery

standard MLR (volc + QBO + solar + ENSO):

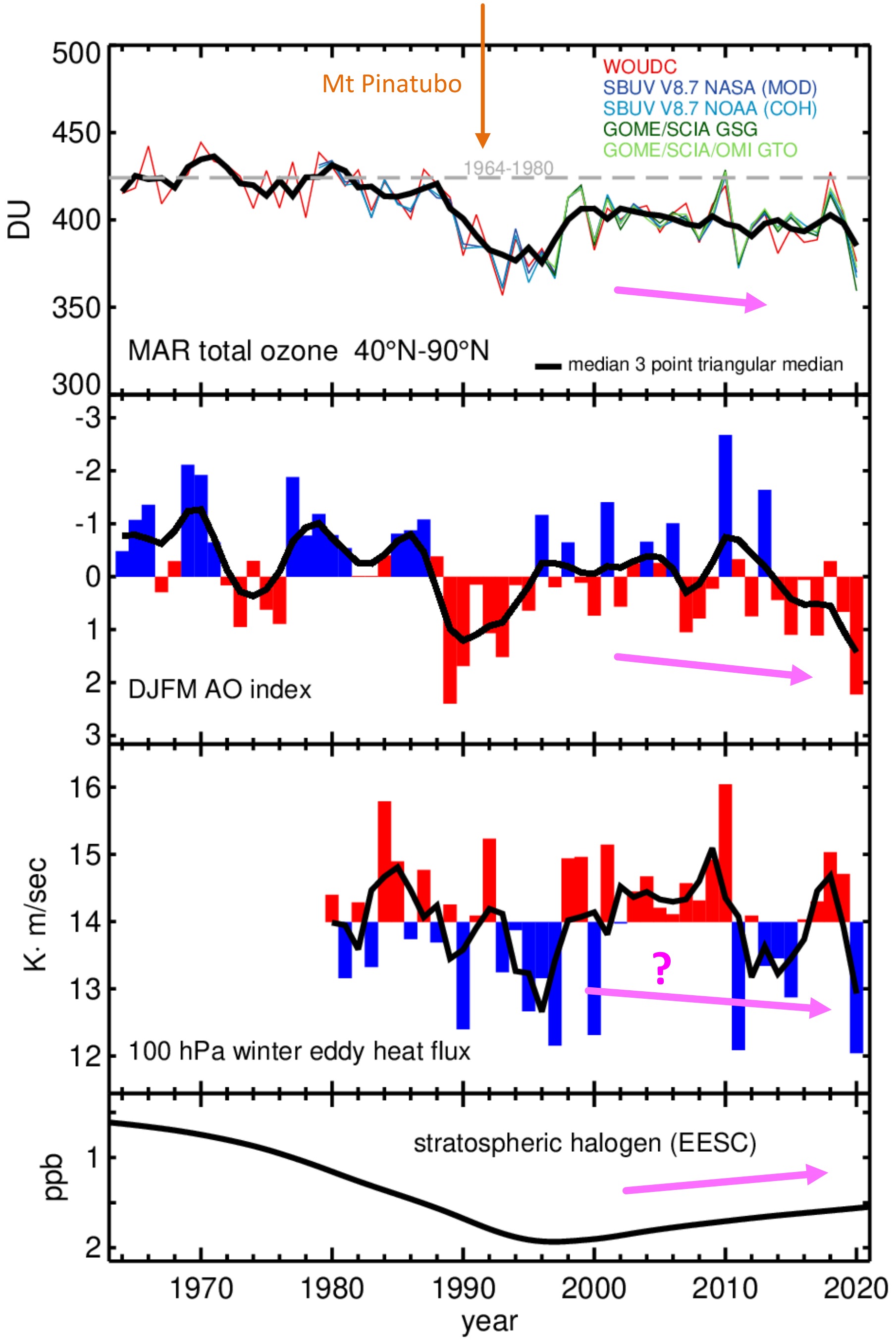
- zero trends at NH middle latitudes after 1996 (contribution from dynamics and ODS)
- Trends more negative in the NH before 1996
- overall larger uncertainties in post-1996 trends

Long-term “dynamics” trends (1964-2020)

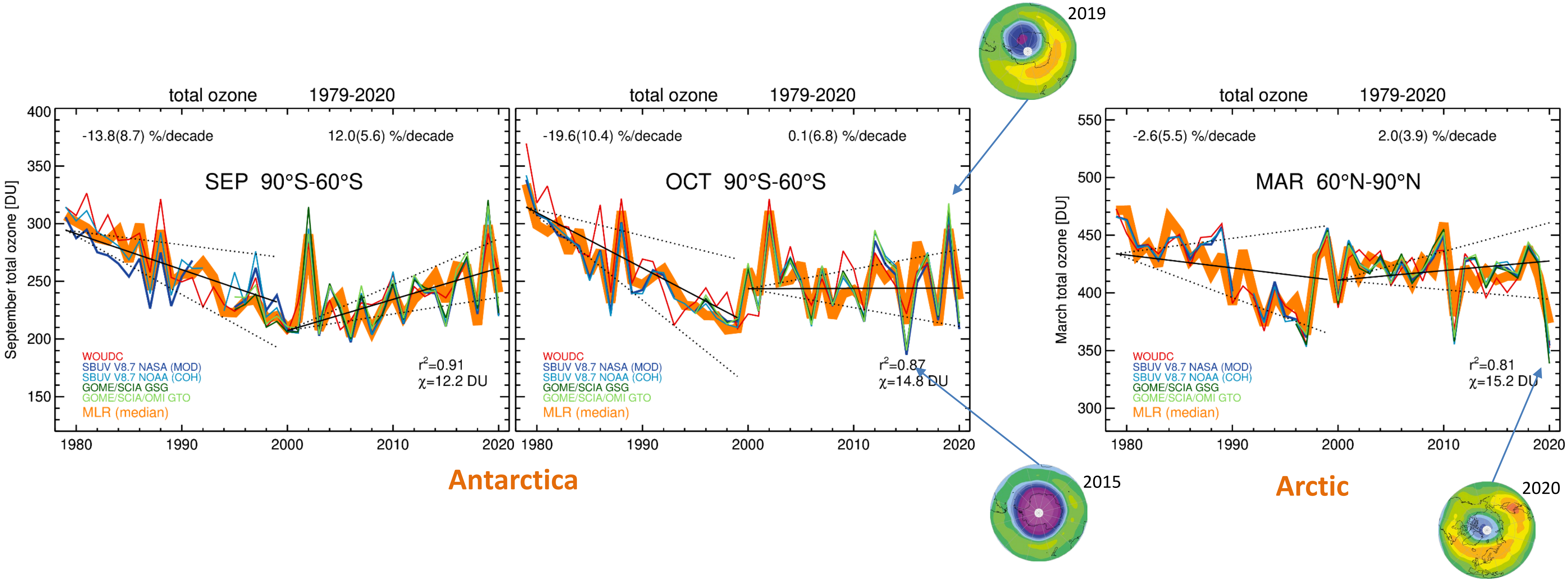
- continuous decrease in March extratropical ozone (apart from year-to-year variability and Mt Pinatubo volcanic impact)

- Apparent long-term shift to positive AO and, possibly, a weakening of BDC (winter eddy heat flux) since about 2000
  - strengthening of stratospheric Arctic vortex (e.g. Hu et al. 2018, von der Gathen et al. 2021)
  - Negative trends in extratropical lower stratospheric ozone (main contributor to total column) (Ball et al., 2018, 2020, Wargan et al., 2018)

- Atmospheric dynamics balances ODS related recovery trends in the NH after 2000



Polar ozone trends



- Robust ozone recovery above Antarctica in September ("early ozone hole period") possibly related to later onset dates of the ozone hole (Solomon et al., 2021)
- No recovery yet in October (still complete ozone depletion in lower stratosphere, larger variability)
- No clear trend in the Arctic
- Very good agreement with TOMCAT-ML

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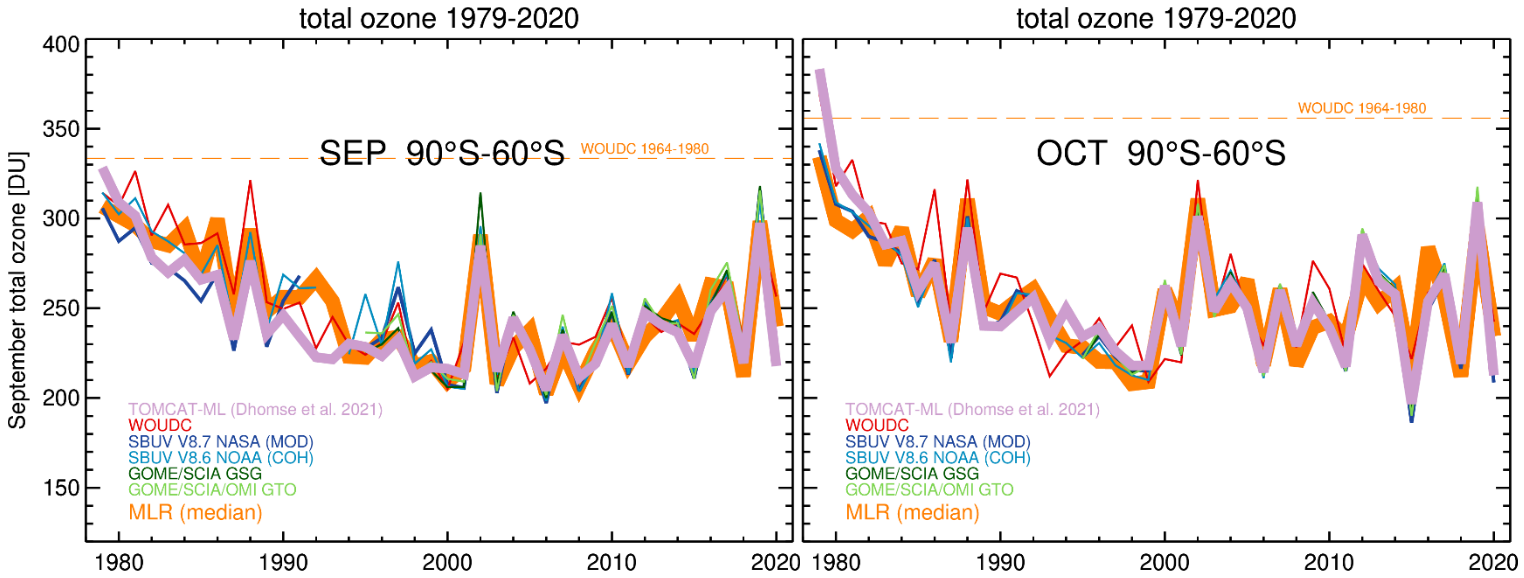
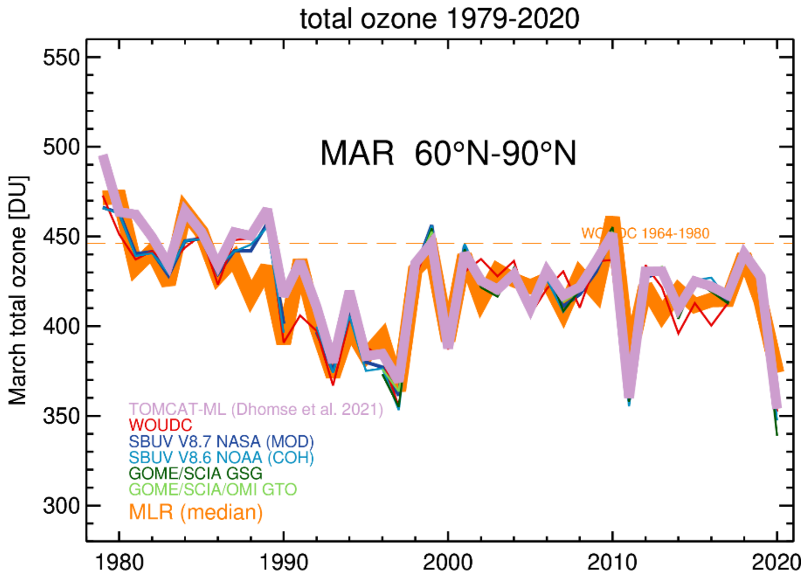


Antarctica



Arctic

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Conclusion

- Trends from MLR regression, properly accounting for dynamical ozone changes, are interpretable as ODS related ("recovery") trends
- Ozone recovery related to ODS phase out by Montreal Protocol and amendments is observed at middle latitudes in both hemispheres (about +0.5%/decade to +1%/decade) since the middle 1990 in line with the ODS/EESC/stratospheric halogen evolution
- Negative trend contribution from atmospheric circulation changes (shift towards positive AO, strengthening of stratospheric Arctic vortex) apparently balances ozone recovery leading to stable ozone levels since 2000 in the NH
- Ozone recovery in polar region is only observed in SH for September (+12%/decade), but not in October and NH March (consistent with Solomon et al., 2015, 2021)
- TOMCAT-ML CTM in good agreement with observations since the 1990s/some issues with ERA5 (and ERAI) reanalysis in the 1980s

Weber, M., Arosio, C., Coldewey-Egbers, M., Fioletov, V., Frith, S. M., Wild, J. D., Tourpali, K., Burrows, J. P., and Loyola, D.: Global total ozone recovery trends derived from five merged ozone datasets, Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2021-1058, in review, 2021. (accepted for publication in ACP)