Trends and variabilities of CO and aerosols in the upper troposphere and their connections to the Asian summer monsoon, climate variability, and surface emissions

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Asian summer monsoon (ASM) dynamic system

- The Asian summer monsoon (ASM) is a major component in the climate system. Its convective system transports aerosols and trace gases from the PBL over the most polluted regions in Asia to the upper troposphere where they spread out by the ASM anticyclone (ASMA) to regions beyond Asia and to the stratosphere

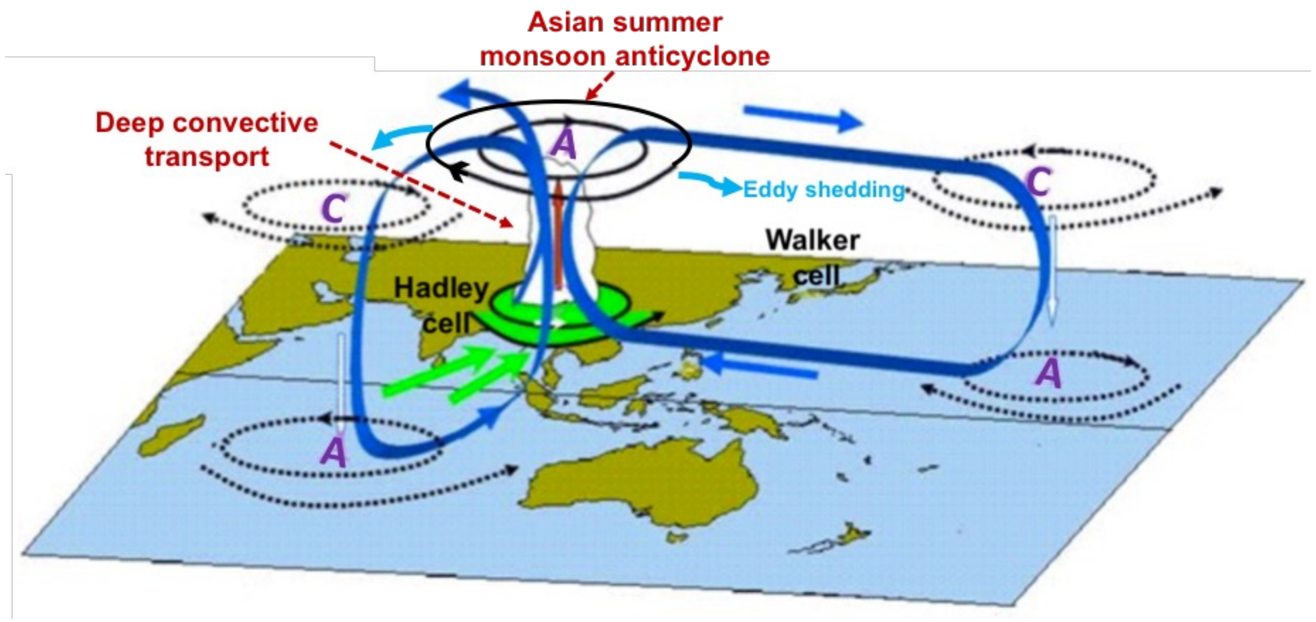
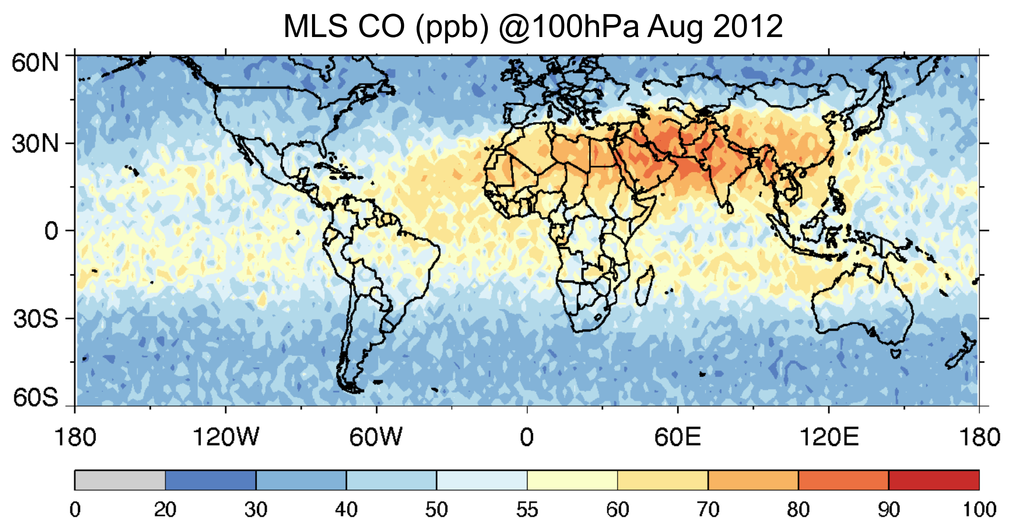
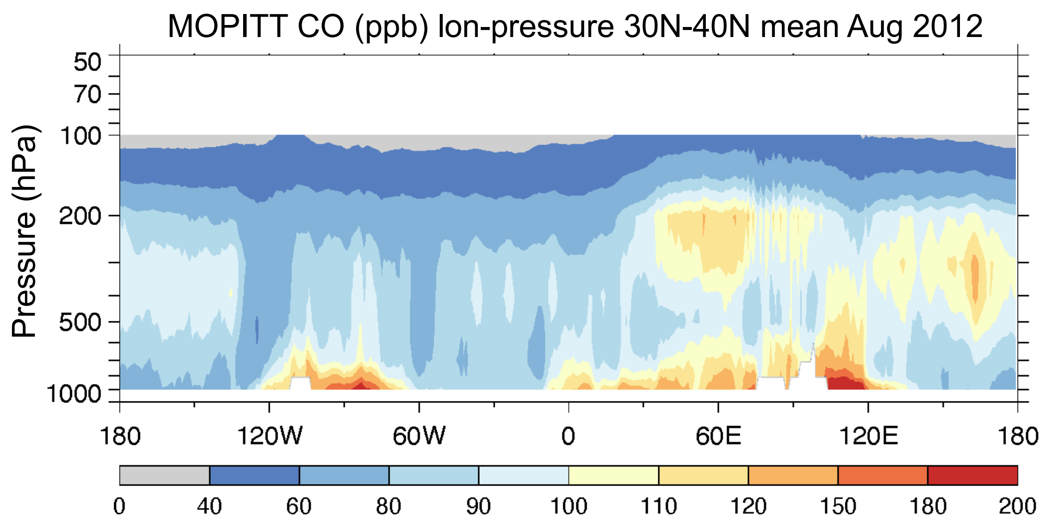


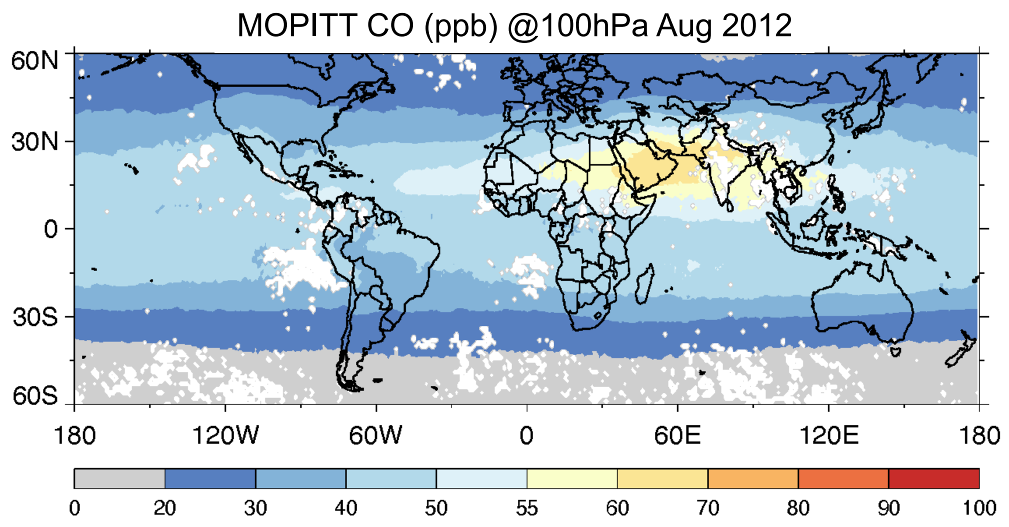
Figure adapted from: https://www.clivar.org/asian-australian-monsoon

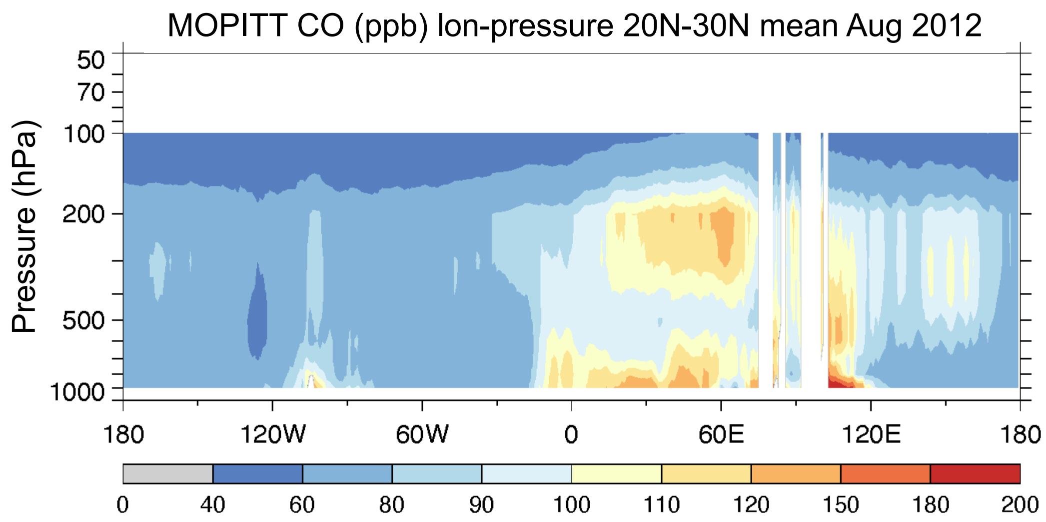
- ASM connects to other weather and climate systems, such as walker and Hadley cell circulations, with significant spatial and temporal variability ranging from weather scale to multi-year climate scale

Observational evidence of ASM transport of CO from satellite data



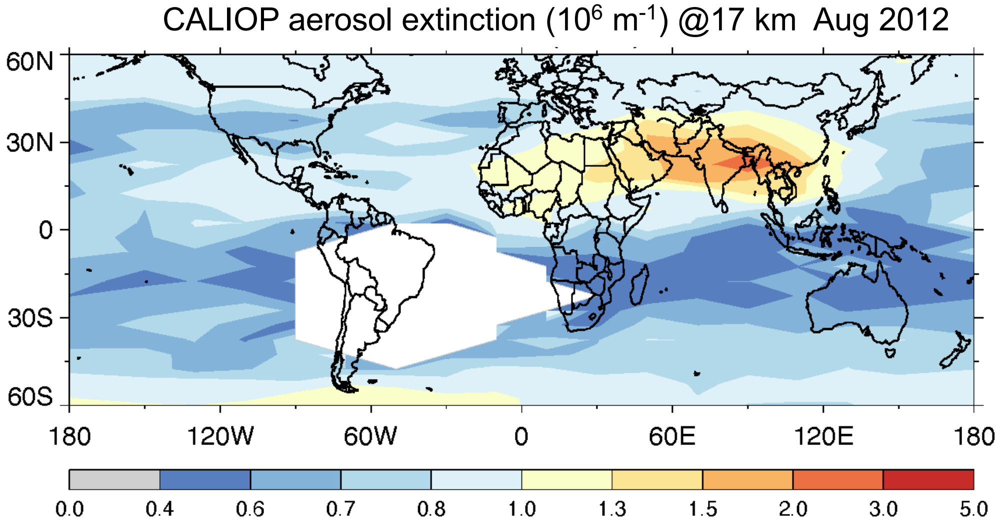


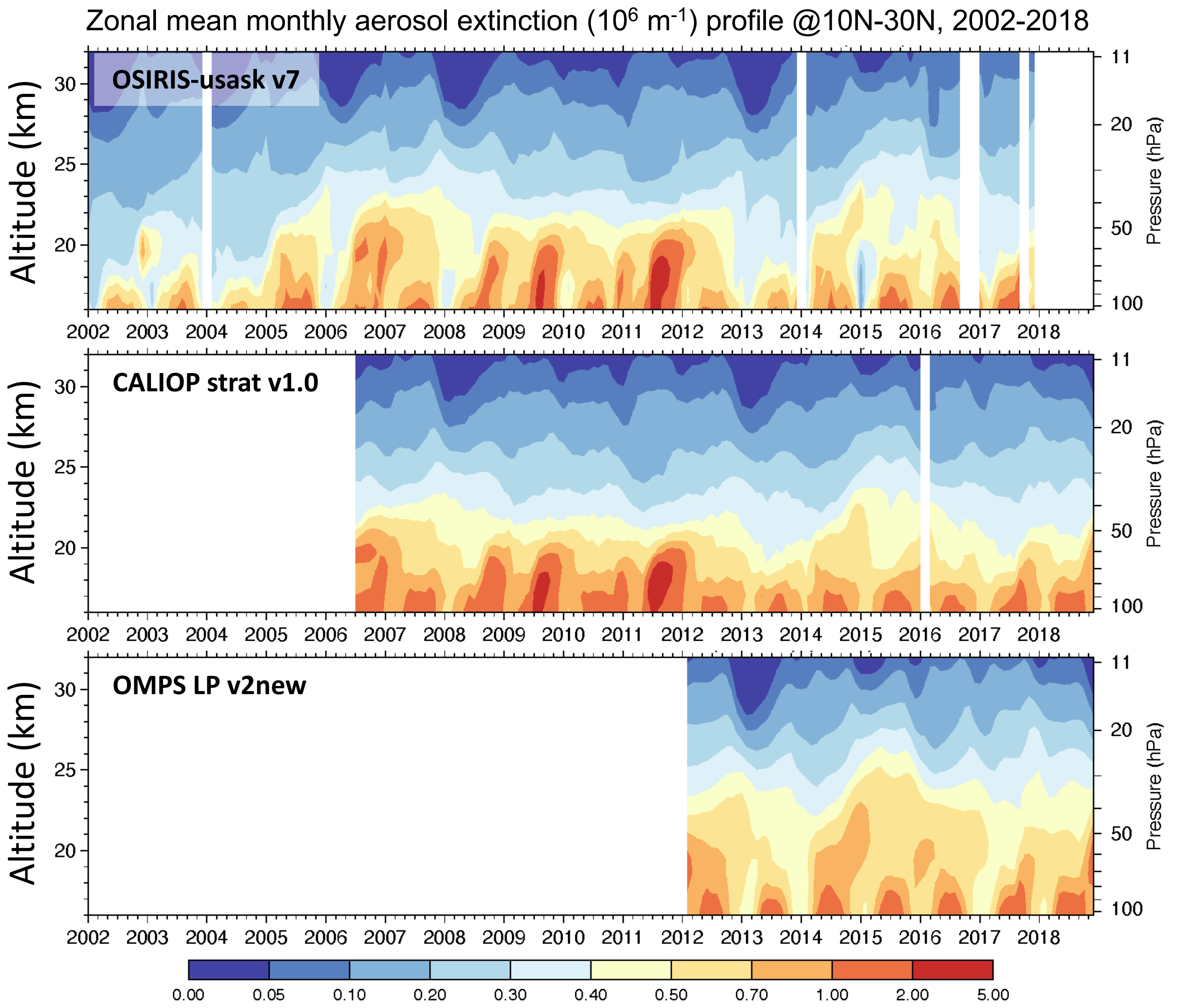




Convective transport lifts pollutants from PBL to the UT, which couples with the ASMA in the UT to spread the material around the globe

Observational evidence of ASM transport of aerosols from satellite aerosol extinction data





- Although aerosols are soluble species that can be removed by the monsoon precipitation, there are clear evidence of convective transport to the UTLS
- Satellite retrievals at the tropopause region are most difficult because the interference of the thin ice clouds

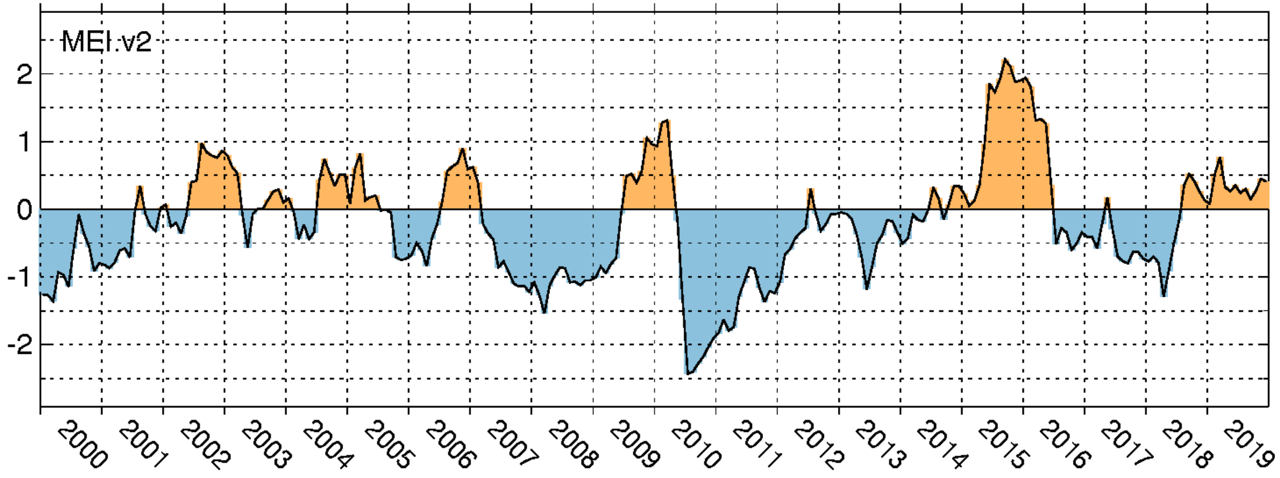
We use the NASA GEOS model together with MERRA-2 reanalysis of meteorological fields and satellite observations to examine:

1) ***Interannual variability*** of convective transport in the ASM region and large scale ASMA transport in the UT (150 hPa) and there connections to the ENSO phases
2) ***Trends*** of tropospheric pollutants of CO and aerosols in the UT and their links to the trends of surface anthropogenic emissions and concentrations

- GEOS model set up:
  - 20-year simulation (2000-2019) of aerosols and CO with time-varying emissions from anthropogenic (CEDSv1, aka CMIP6), biomass burning, and other natural sources
  - Including a transport tracer TR_{CO50} with fixed CO sources (CMIP6++, in 2010) and a fixed 50-day lifetime to attribute the pollutants interannual variability solely do to transport

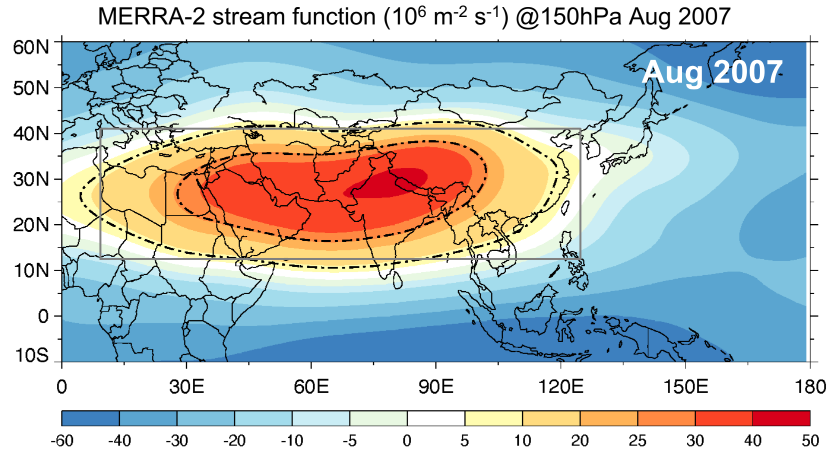
1. Interannual variability of convective transport (surface to UT) and large-scale transport by ASMA (in UT) and their connections to ENSO phases

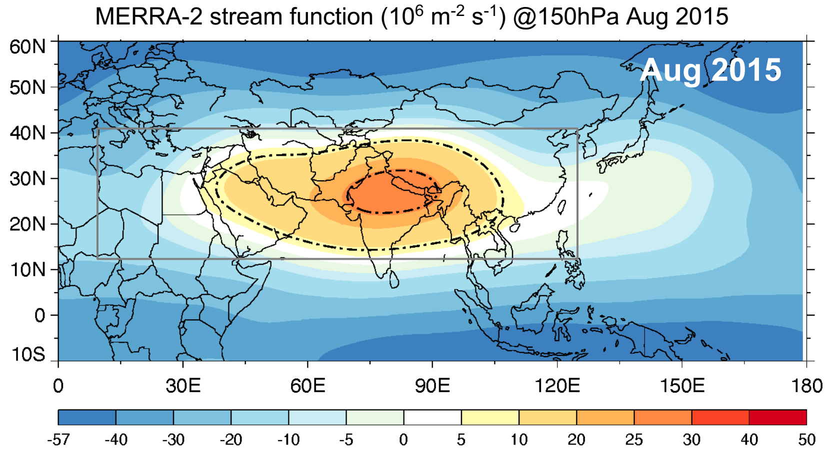
- Use the stream function (non-divergent component of the U and V winds, representing the mass transport of air in a 2-D flow in a horizontal plane (e.g., 150 hPa) as a proxy of the ASMA strength
- Use the ratio of TR_{CO50} at a UT level (e.g., 150 hPa) to that at the surface as an indicator of surface generated pollutant convective transport efficiency (CTE)
- Correlate both ASMA and CTE with the multivariate ENSO index (MEI) in boreal summer (August)



1a. Interannual variability of ASMA (defined by stream function) and correlation with MEI in August

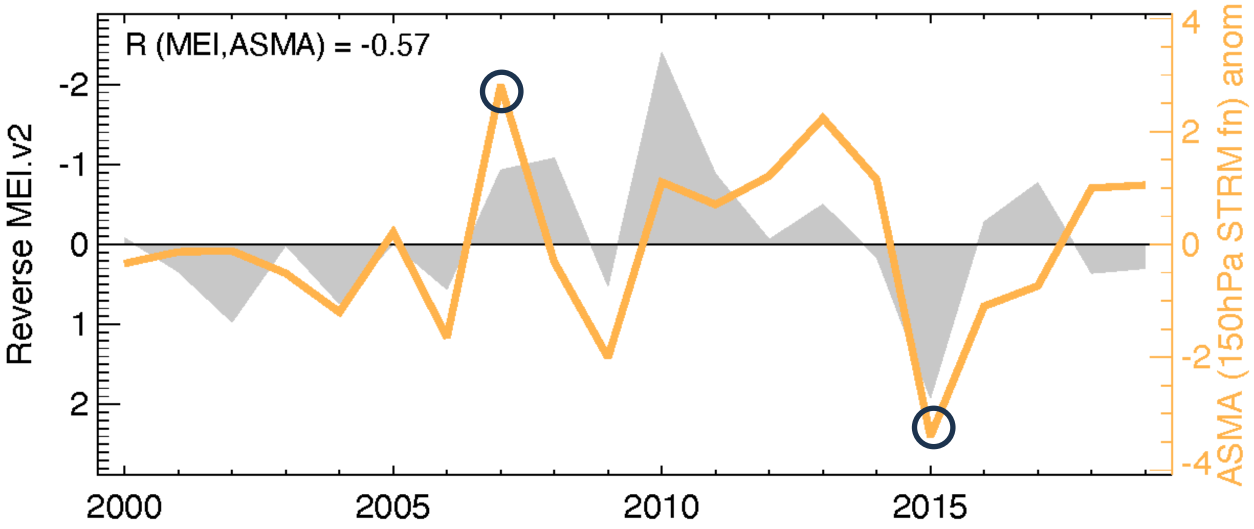
Example: differences of stream functions between Aug 2007 and Aug 2015



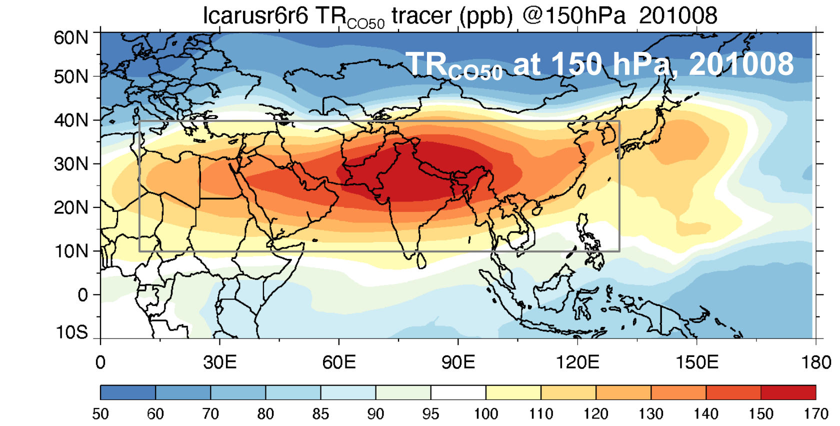


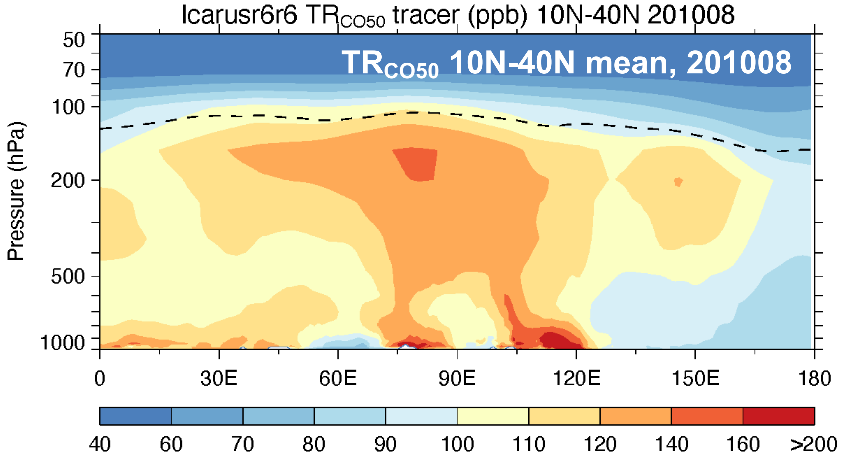
Area enclosed by inner circle with dash-dotted line: ASMA core (SF ≥ 0.75 of max of 20-year mean). Aera enclose by outer circle: range of ASMA size (SF ≥ 0.25 max of 20-year mean). Rectangular box: General ASMA area

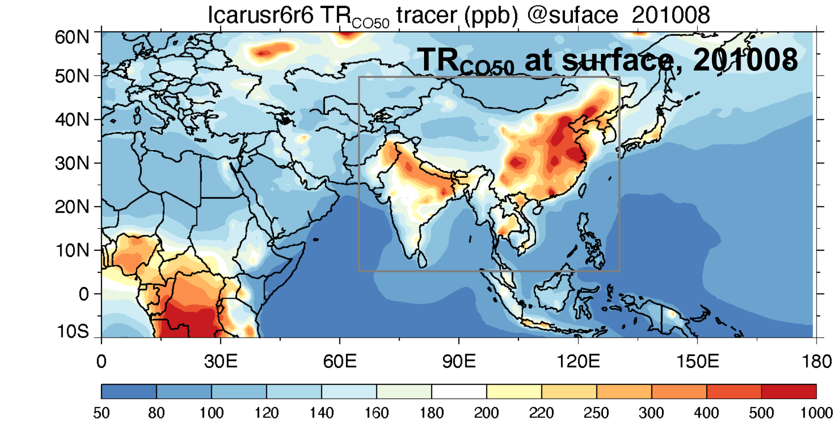
MEI and the August ASMA strength anomaly, 2000-2019



- ASMA (STRM) is negatively correlated with MEI in boreal summer
- No statistically significant trend of ASMA in 2000-2019 at 150 hPa

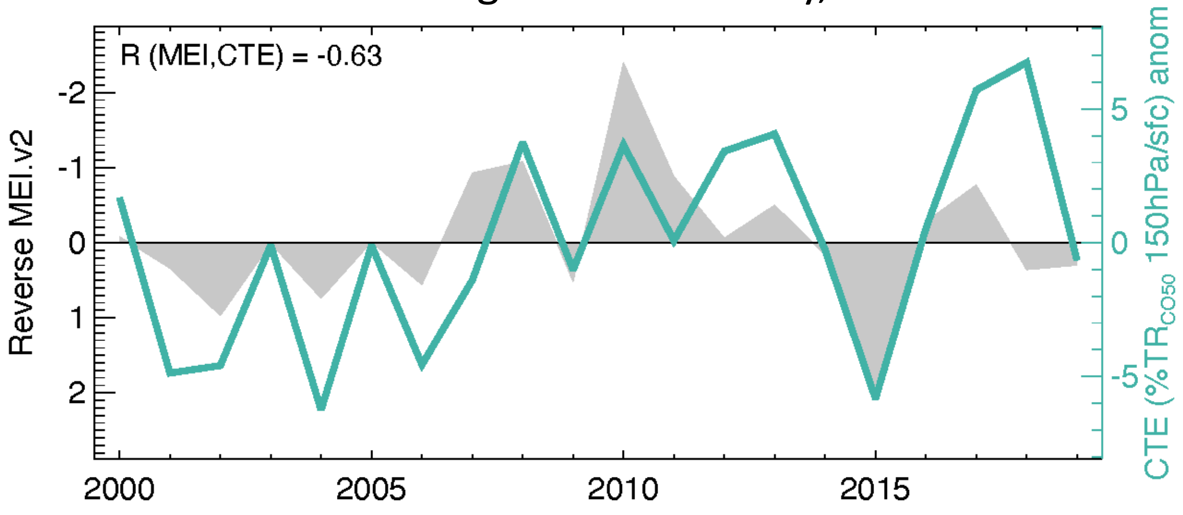






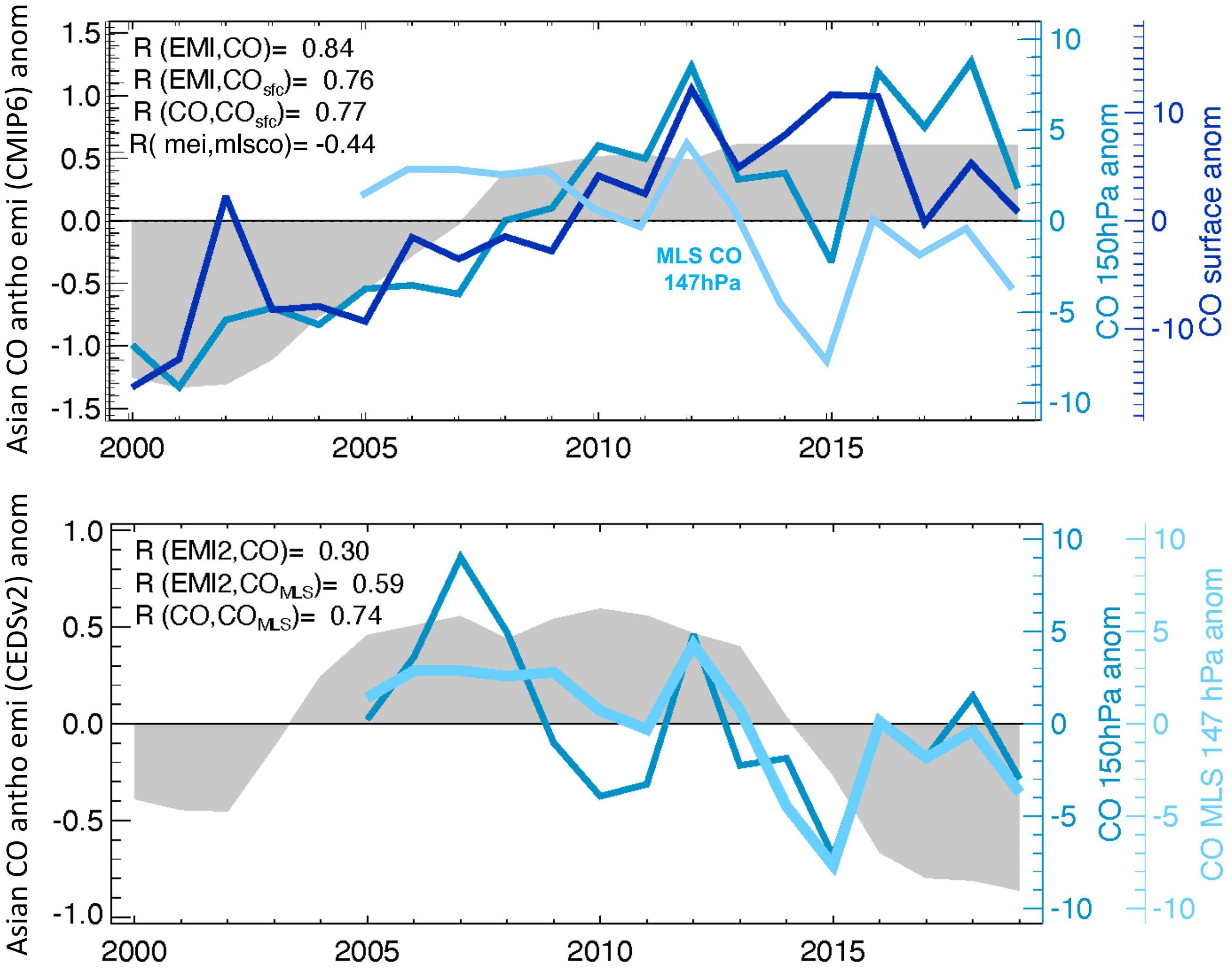
1b. Interannual variability of convective transport efficiency (CTE) as the ratio of mean TR_{CO50} at 150hPa within ASMA area to mean TR_{CO50} at surface over Asia

MEI and the August CTE anomaly, 2000-2019



- Convective transport efficiency (CTE) at 150 hPa are negatively correlated with MEI in boreal summer
- In general, CTE at 150 hPa is higher in La Niña years than in El Niño hears
- CTE show a statistically significant increasing trend at 150 hPa in 2000-2019 at 0.3/year, although the interannual variability is in a much larger magnitude

2a. Trends of CO in the UT and its connection to the trends of surface concentrations and anthropogenic emissions



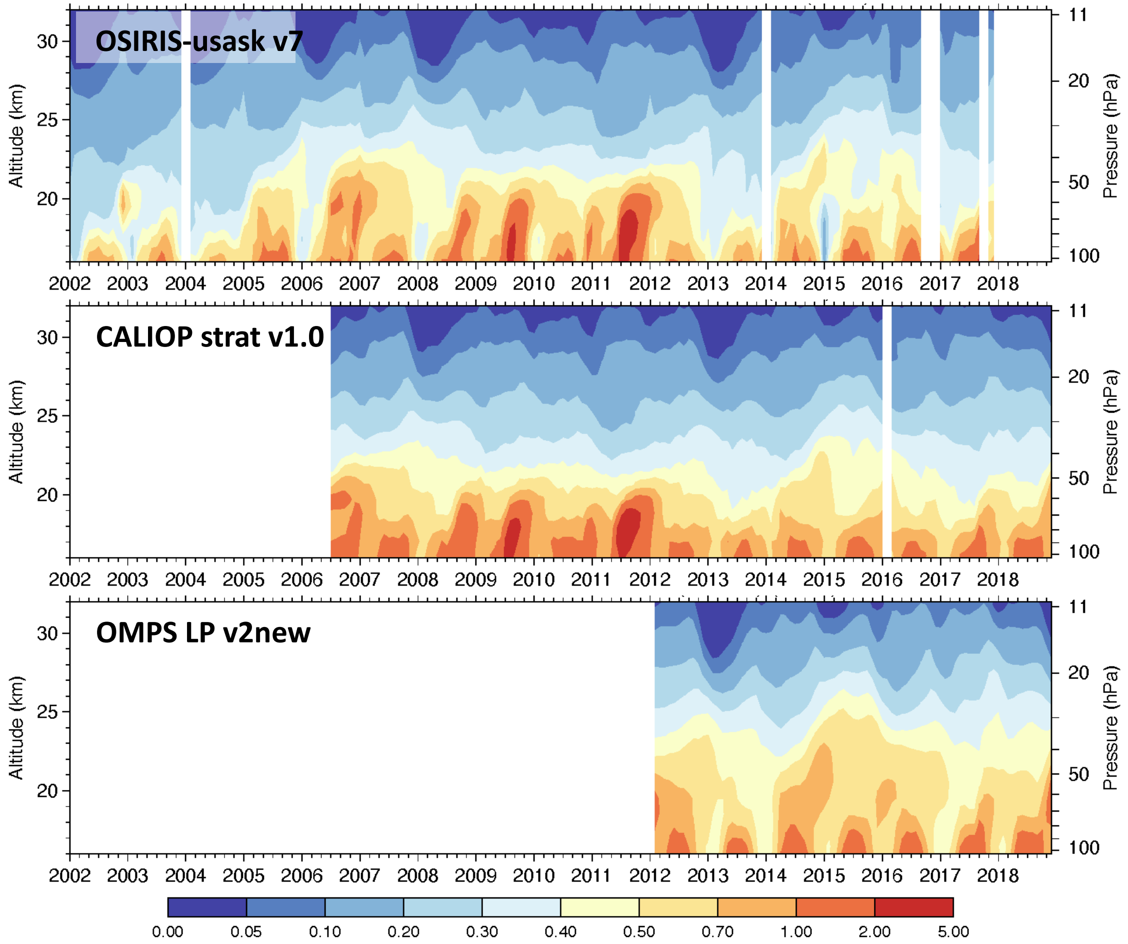
CO trends at the surface and at 150 hPa compared to the anthropogenic emission trends in Asia:

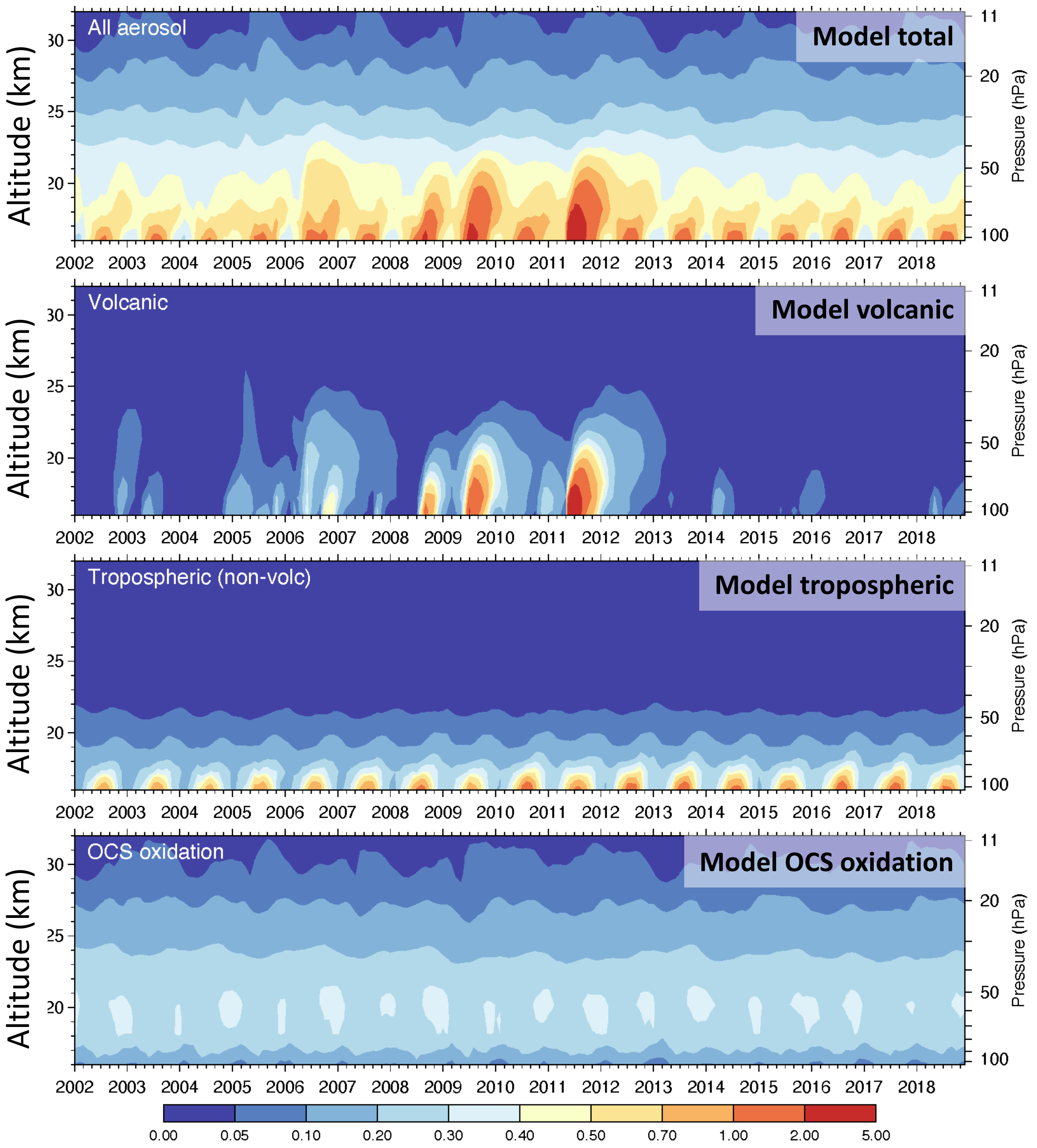
- Model simulated statistically positive trends of CO concentrations at both surface and 150 hPa follow the trend of CMIP6 (CEDS v1) anthropogenic emission used in the model
- However, MLS observed CO at 147 hPa showing an opposite temporal trend to the model trend that is statistically significant negative in 2005-2019
- The opposite trends of CO between MLS and model at ~150 hPa since 2005 can be mostly explained by the incorrect temporal trends of the Asian anthropogenic CO emission used by the model, as another simulation using the CEDS v2 (2021 release) suggested. We are currently rerun the model simulations with the CEDS v2 emissions

Two-decadal trends in the UTLS

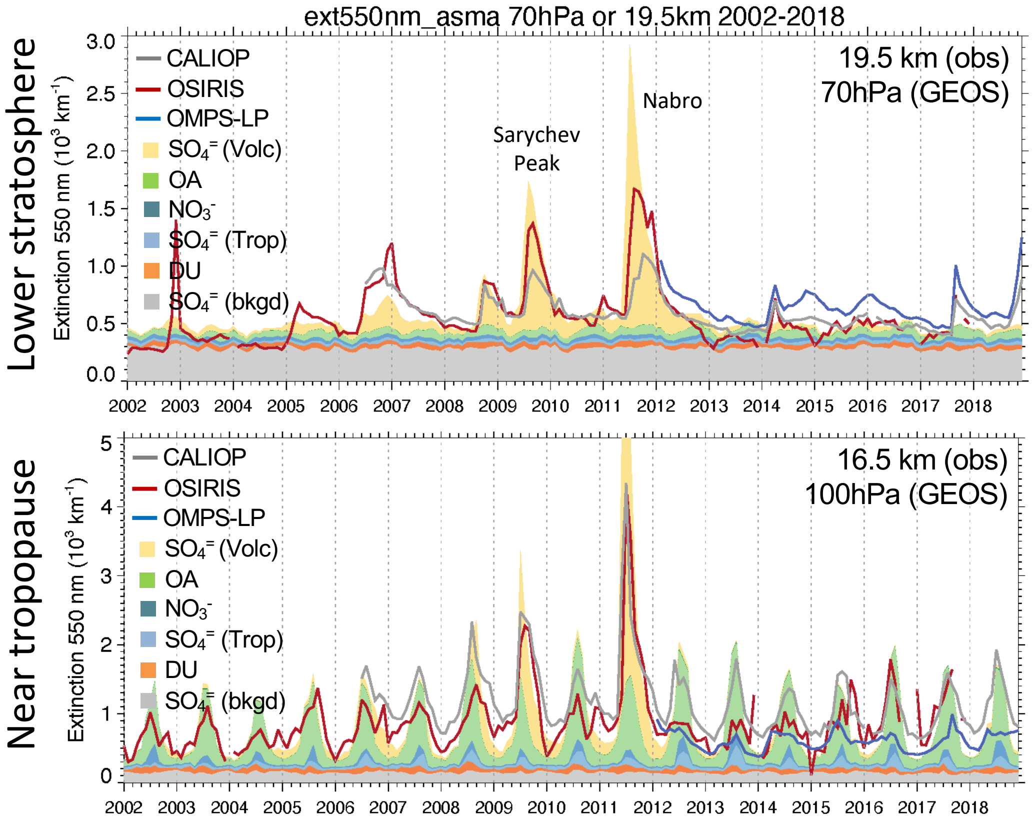
2b. Aerosol trend: Need to separate volcanic, tropospheric, and stratospheric background aerosols

Zonal mean monthly aerosol extinction (10^6 m^{-1}) @10N-30N, 2002-2018



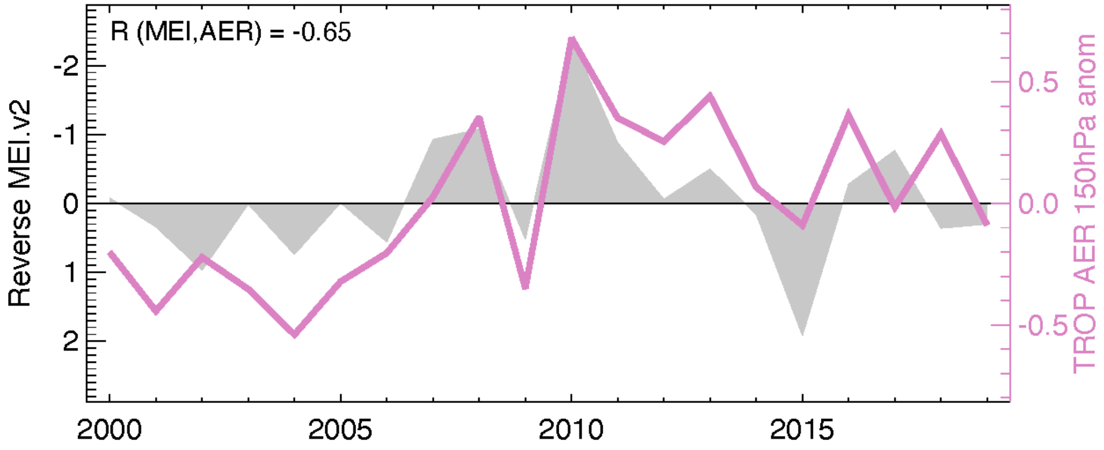


2b. Aerosol trend: extinction in UTLS over the ASMA region (10-40°N, 10-130°E)



- Model simulated aerosol extinction near the tropopause is dominated by tropospheric aerosols (mostly OA, followed by nitrate)
- In the lower stratosphere, sulfate aerosol from OCS oxidation is the dominant non-volcanic aerosol source
- Volcanic eruptions causing significant disturbance of stratospheric aerosol level

Tropospheric-origin aerosol extinction anomaly in the boreal summer (Aug) over the UT ASMA region



- The model shows the tropospheric-originated aerosol extinction in the UT negatively correlated with MEI
- Model simulated tropospheric aerosol extinction displays an increasing trend in the UT during 2000-2011 but a decreasing trend in 2011-2019, which seems to more closely follow the anthro emission trends over China

Concluding remarks

- Interannual variability over ASMA: Responding to the climate variability
  - There are significant interannual variabilities of ASMA strength/size and convective transport efficiencies in the UT, both are negatively correlated with MEI at 150 hPa (R ≈ -0.6 during 2000-2019)
  - The interannual variability of tropospheric pollutants over ASMA in the UT also responds to MEI
- Two-decadal trends of CO and aerosols in the ASMA region in response to emission and convective transport:
  - There no statistically significant trends of ASMA strength/size (indicated by the stream function) in the UT
  - There seems to be a statistically significant positive trend of convective transport efficiency to the UT
  - The two-decadal trend of CO and aerosols in the UT and near tropopause are mostly controlled by the anthropogenic emission, but not in the stratosphere (for aerosols)

In progress…

- Simulating CO and aerosols with more recent emission datasets
- Using SAGE II and III data to evaluate stratospheric aerosol simulations
- Engaging more global models in the AeroCom community for UTLS studies