National Aeronautics and Space Administration

Composition of the Asian summer monsoon anticyclone: Climatology and variability from 10 years of Aura Microwave Limb Sounder measurements

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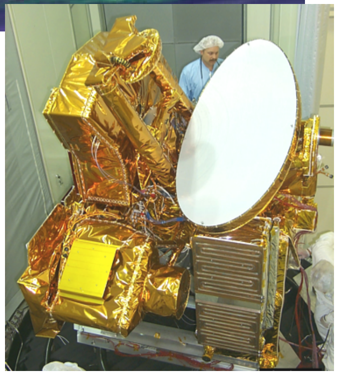
Overview

- Satellite measurements are invaluable for investigating the composition of the upper troposphere / lower stratosphere (UTLS) in the region of the Asian summer monsoon (ASM) anticyclone, which has been sparsely sampled by other means

- The Microwave Limb Sounder (MLS), launched as part of NASA's Aura satellite in July 2004, makes simultaneous co-located measurements of several trace gases and cloud ice water content (IWC, a proxy for deep convection) in the UTLS on a daily basis



- We capitalize on the dense spatial and temporal sampling, long-term (>10 years) data record, and extensive measurement suite of Aura MLS to characterize the climatological composition of the ASM region and its considerable variability

- MLS data are also used to evaluate the representation of the ASM in chemistry climate models, such as CAMChem-SD

version 4 MLS measurements

- Several previous studies have used Aura MLS measurements to investigate constituent behavior in the ASM region
- Although those studies derived many fundamental insights, none fully exploited the MLS data set; much of the earlier work was centered on:
  - A limited number of constituents (often only one)
  - A limited time period (often a single season, sometimes only a portion thereof)
  - A limited vertical domain (often a single level)
- Moreover, the latest version of the MLS data, version 4, was released in early 2015
- v4 includes several updates and refinements of particular note for ASM studies:
  - Substantially improved composition profiles in the presence of thick clouds, such as those associated with deep convection, as well as more effective identification and removal of residual cloud artifacts
  - Addition of another marker of boundary layer pollution: methanol (CH_3OH)
- Here we use v4 Aura MLS measurements of both tropospheric (H_2O, CO, CH_3Cl, CH_3CN, CH_3OH) and stratospheric (O_3, HNO_3, HCl) tracers, as well as IWC, to develop a comprehensive climatology of the composition of the ASM anticyclone

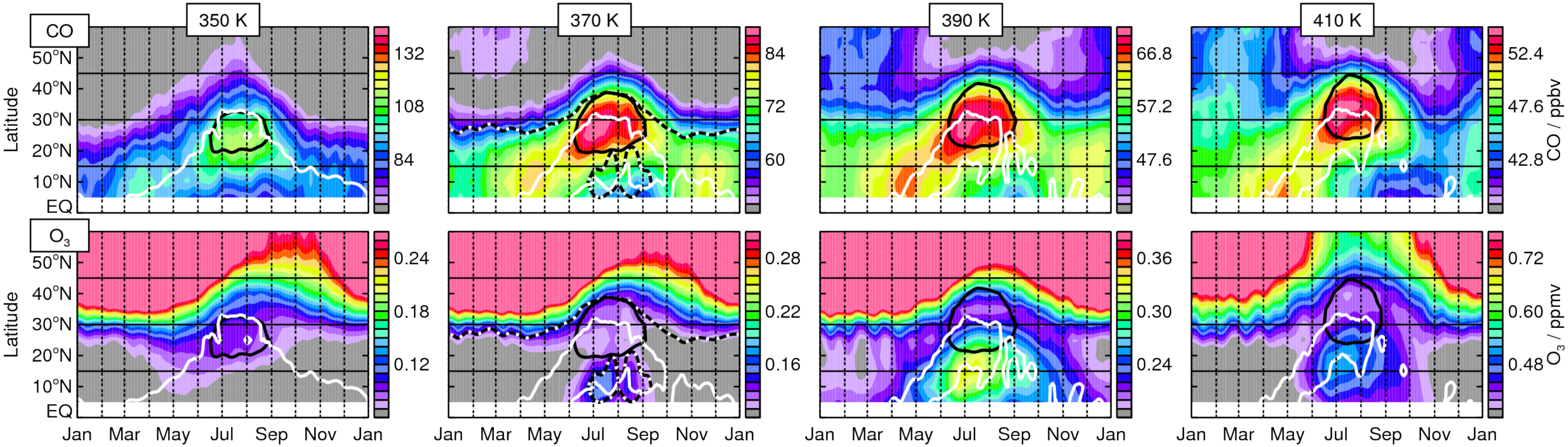
Brief summary of approach

- We focus on climatological behavior, averaged over 10 years (2005–2014)
- We define the general ASM region to lie within the 15–45°N × 10–130°E "box"
- To encompass the deep structure of the ASM circulation, MLS data are interpolated to 4 potential temperature surfaces in the UTLS, corresponding (within the box) to:

Potential Temperature Surfaces (K)	Corresponding MLS Retrieval Pressure Surfaces (hPa)	Corresponding Approximate Altitude (km)
410	100–68	16–18.5
390	121–82	14.5–17.5
370	147–100	13–16.5
350	261–177	10–13

- We use Montgomery stream function (MSF) to identify the closed circulation of the ASM anticyclone

Figure intro: Climatological (2005–2014) trace gas time series



- Time series calculated over the longitudes of the ASM box as a function of latitude and potential temperature
- The full annual cycle is shown to put the ASM in context
- MLS CO and O_3 serve as representative tropospheric and stratospheric tracers, respectively
- White contours show MLS IWC to identify regions / times of vigorous deep convection
- Dashed black-and-white contour at 370 K denotes the climatological dynamical tropopause (3 PVU)

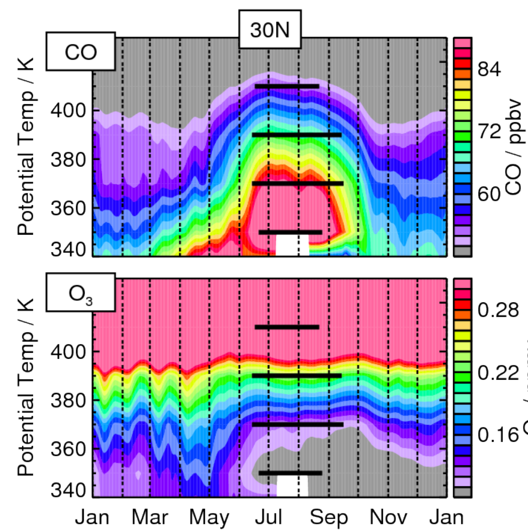
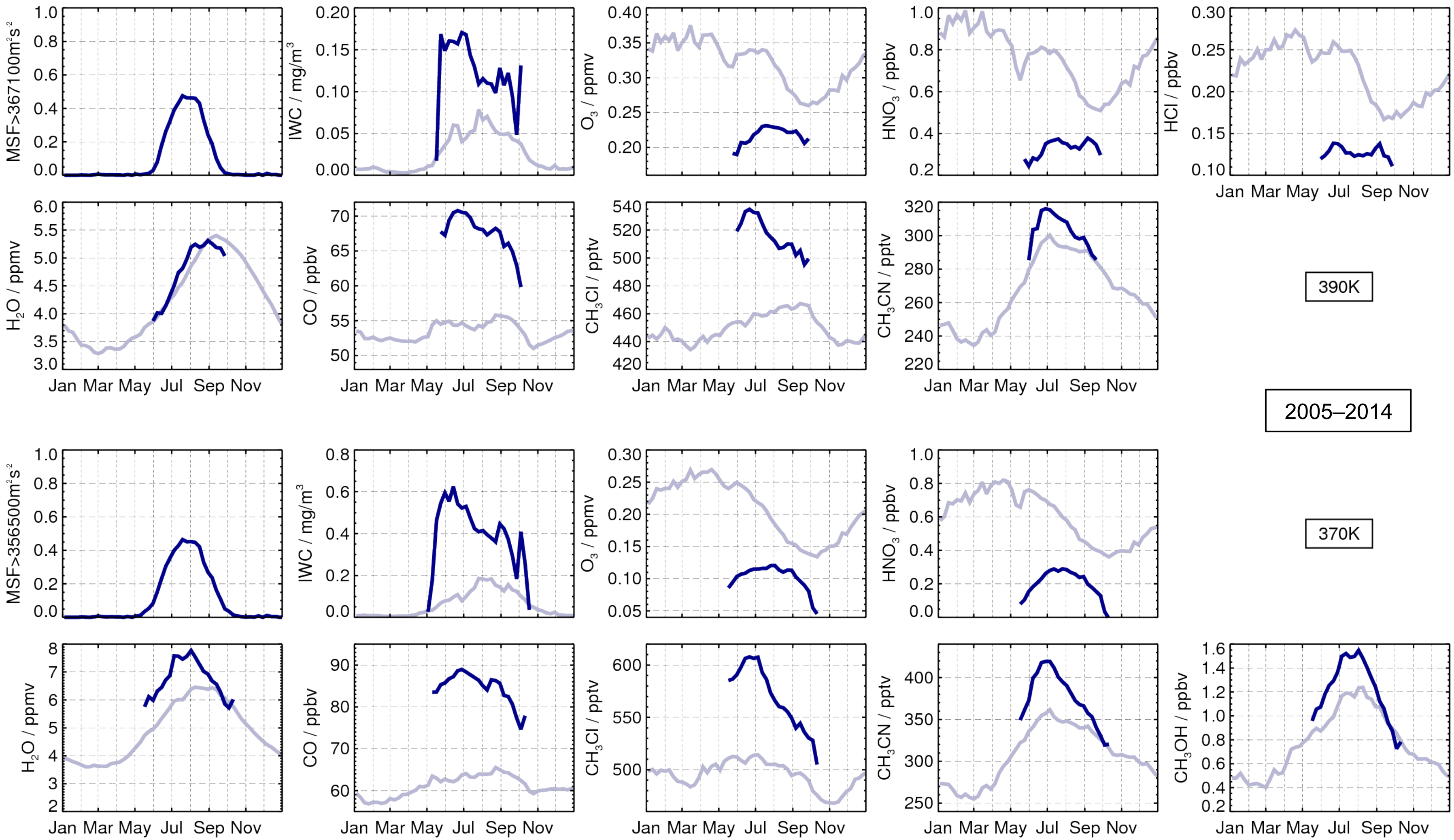
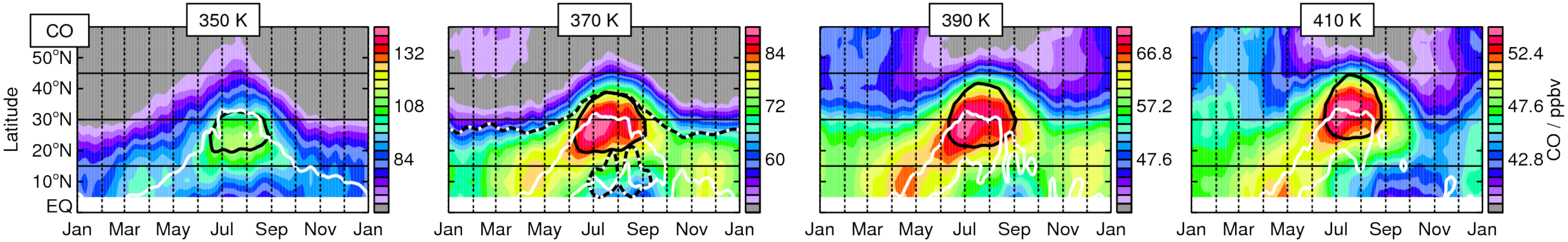


Figure intro: Climatological evolution in / out of anticyclone

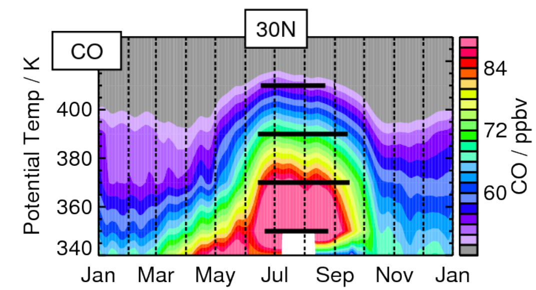


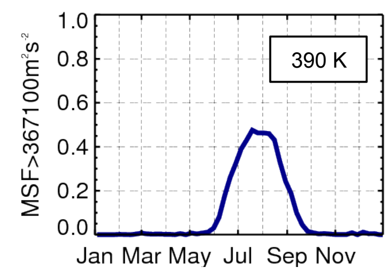
- ✦ Weekly averages of MLS measurements inside the anticyclone compared to the annual cycle observed in each species over the rest of the hemisphere (0°-180°E) outside the anticyclone but still within the latitude range of the ASM box

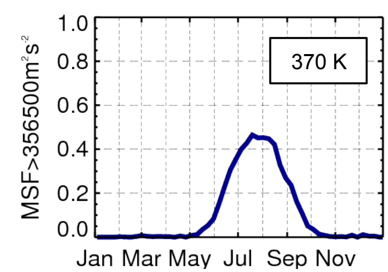
Evolution of the ASM anticyclone



- The evolution of the ASM anticyclone is marked in black
- A slight (~5°) south-to-north shift is seen between MSF contours at the lowest and the highest levels, reflecting the northward tilt of the anticyclone with altitude
- The anticyclone spins up earlier and decays later at the middle two isentropes than it does at 350 or 410 K, resulting in a difference in its climatological lifetime of about a month between the levels
- At 370 and 390 K, the anticyclone starts to occupy a sizeable fraction of the hemisphere by early June, fills nearly 50% of it in mid-July through early August, begins to decay thereafter, and dissipates completely by late September (390 K) or early October (370 K)

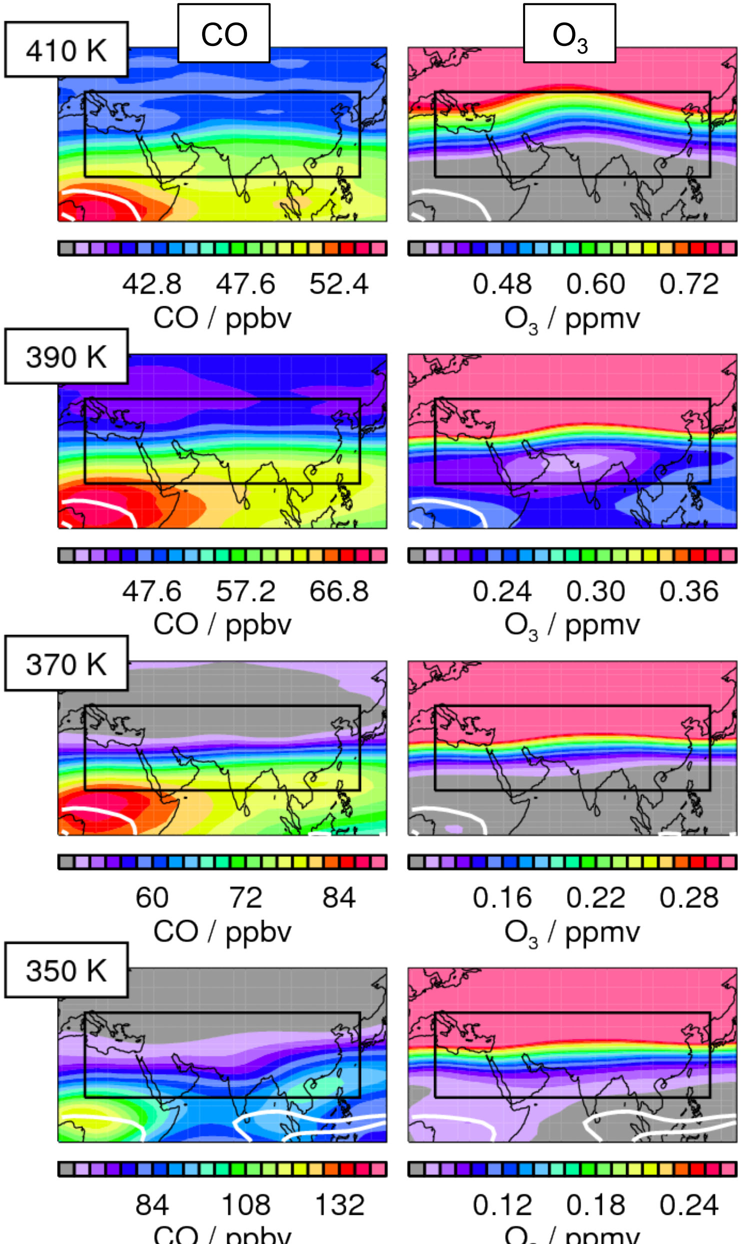




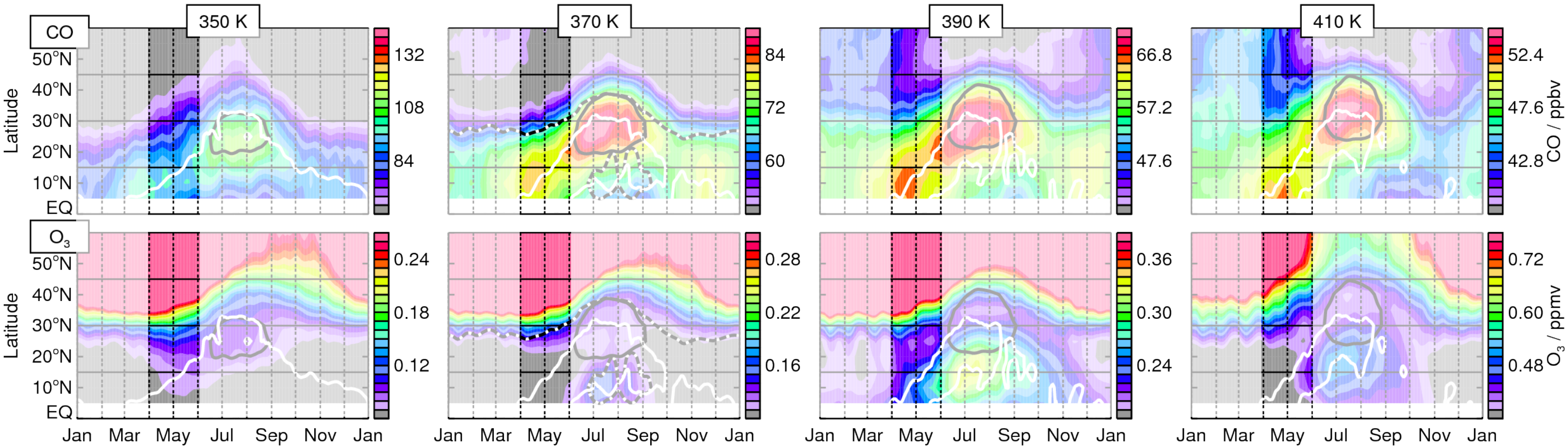


April: "Background" state prior to the influence of the ASM

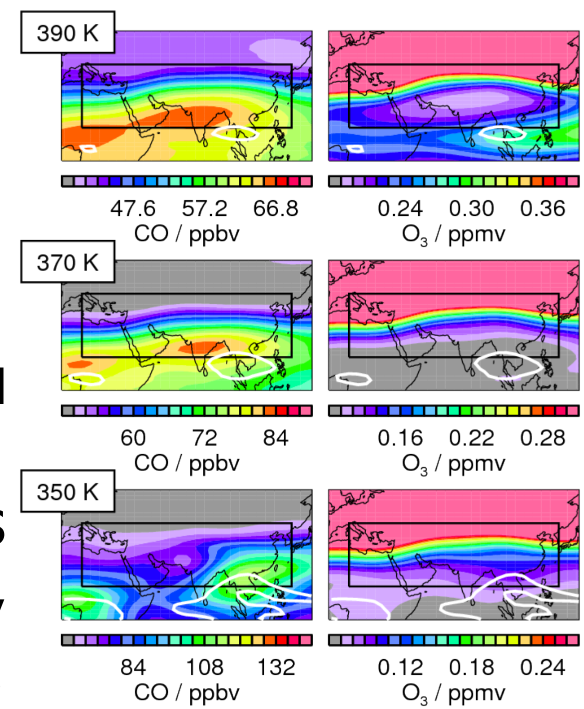
- Abundances of CO (and other markers of biomass burning pollution) reach their peak near the tropopause over central and northern Africa around this time as the fire season in that region begins to subside and vigorous seasonal convection occurs
- Within much of the ASM box, however, the distributions of these species remain relatively undisturbed at most levels
- For the most part, ozone is also unperturbed within the ASM box at this time (as are other stratospheric species)
- However, a climatological minimum is present in O_3 in this region at 390 K
- A distinct minimum in O_3 at this level is a persistent feature throughout the year



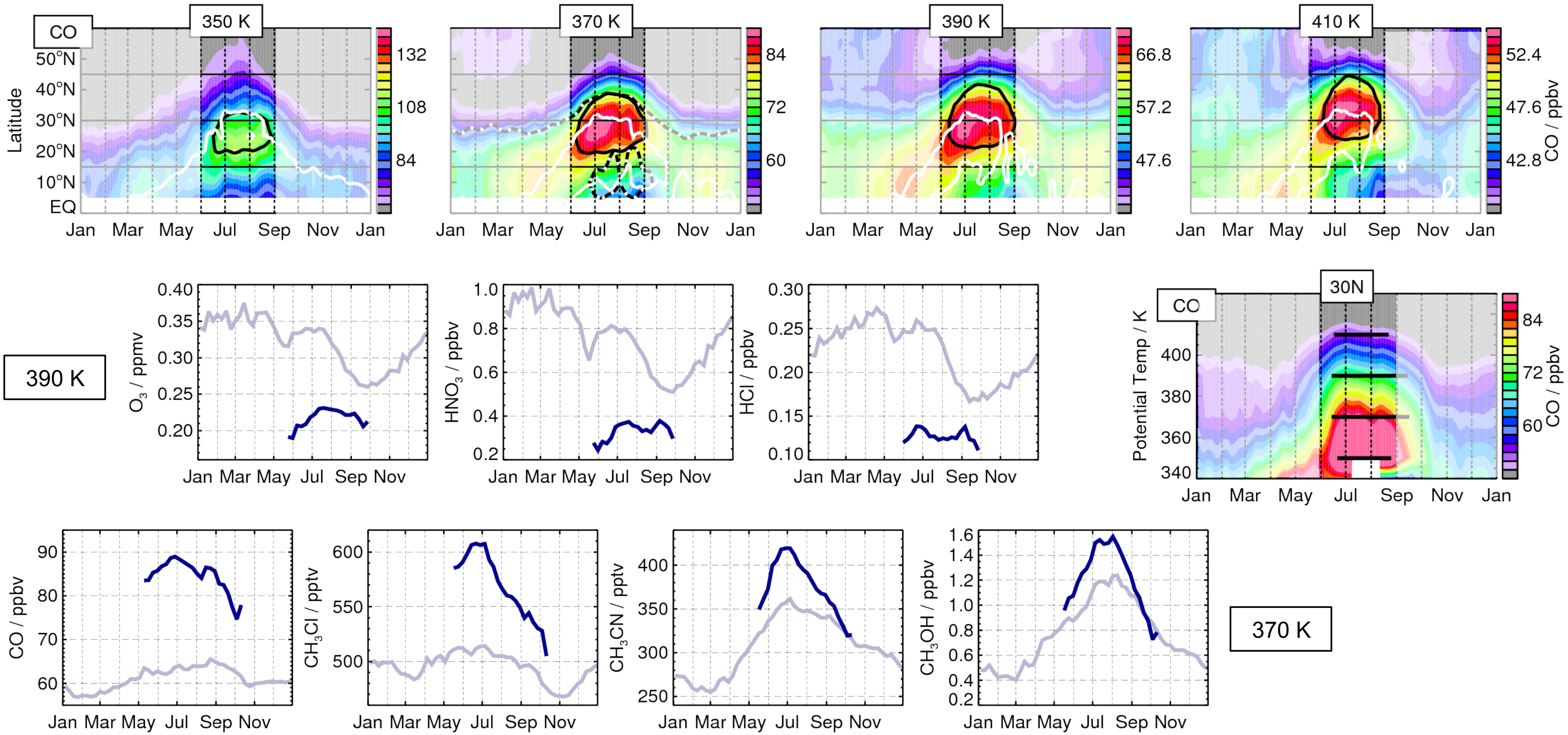
May: Onset phase of the ASM



- The anticyclone moves northward, accompanied by the poleward migration and weakening of the subtropical westerly jet, whose core coincides with the tropopause
- The summertime poleward shift of the tropopause is reflected in the characteristic “curvature” in the fields
- Although the climatological anticyclonic circulation is still weak, CO is already somewhat enhanced at 350–390 K; convection has begun to penetrate deeply into the UTLS
- Some pollution entrained into the proto-anticyclone may originate from biomass burning in Africa in prior months

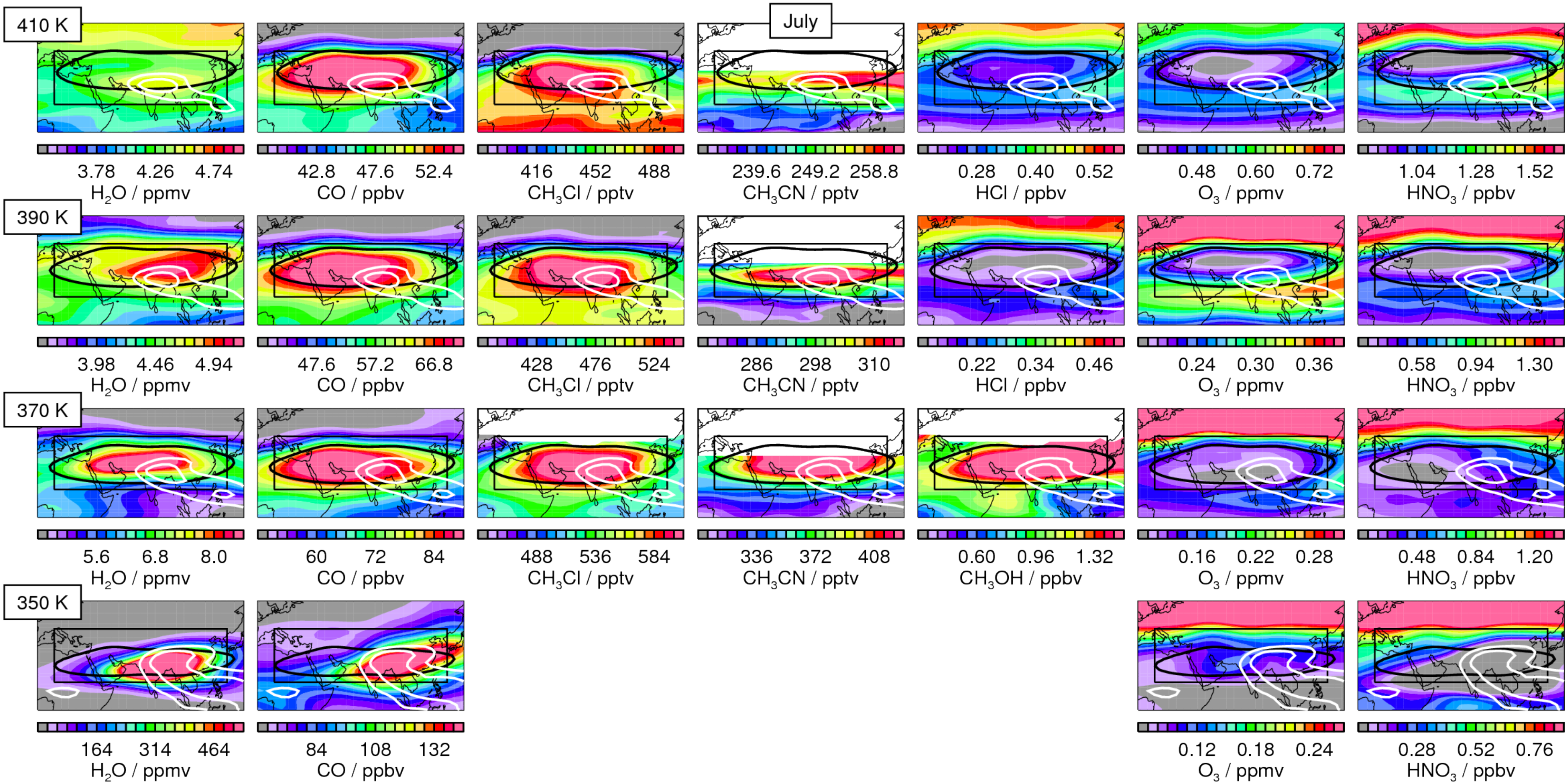


June, July, August: Mature phase of the ASM



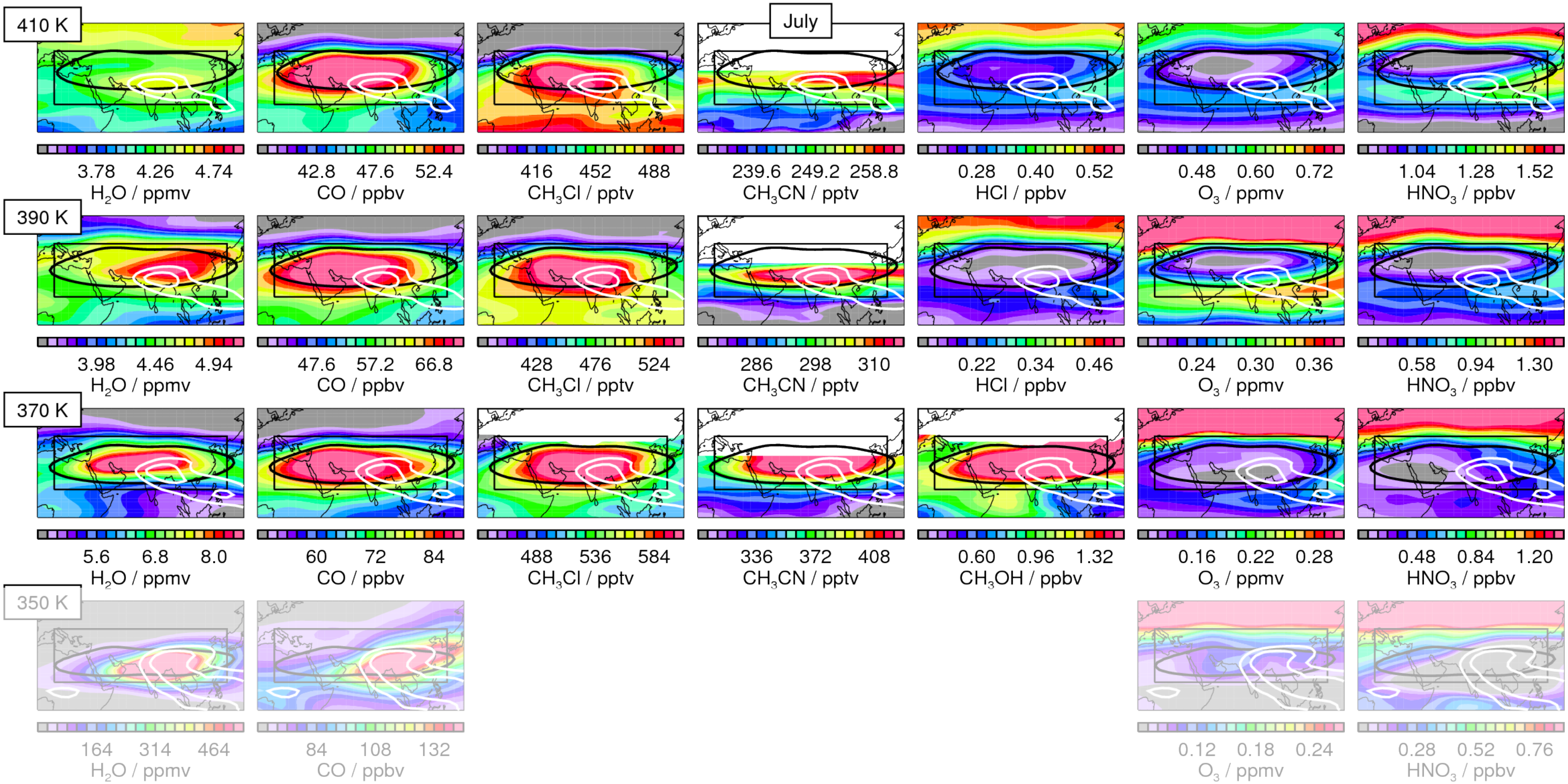
- Inside the developed anticyclone, tropospheric and stratospheric tracers exhibit substantial changes, not only from their pre-monsoon distributions in the ASM region but also from their summertime distributions in the rest of the hemisphere
- Pronounced enhancements in the tropospheric tracers extend up to 410 K
- The largest abundances of the pollution markers are seen in June and July

July: Characterization of the fully established ASM anticyclone



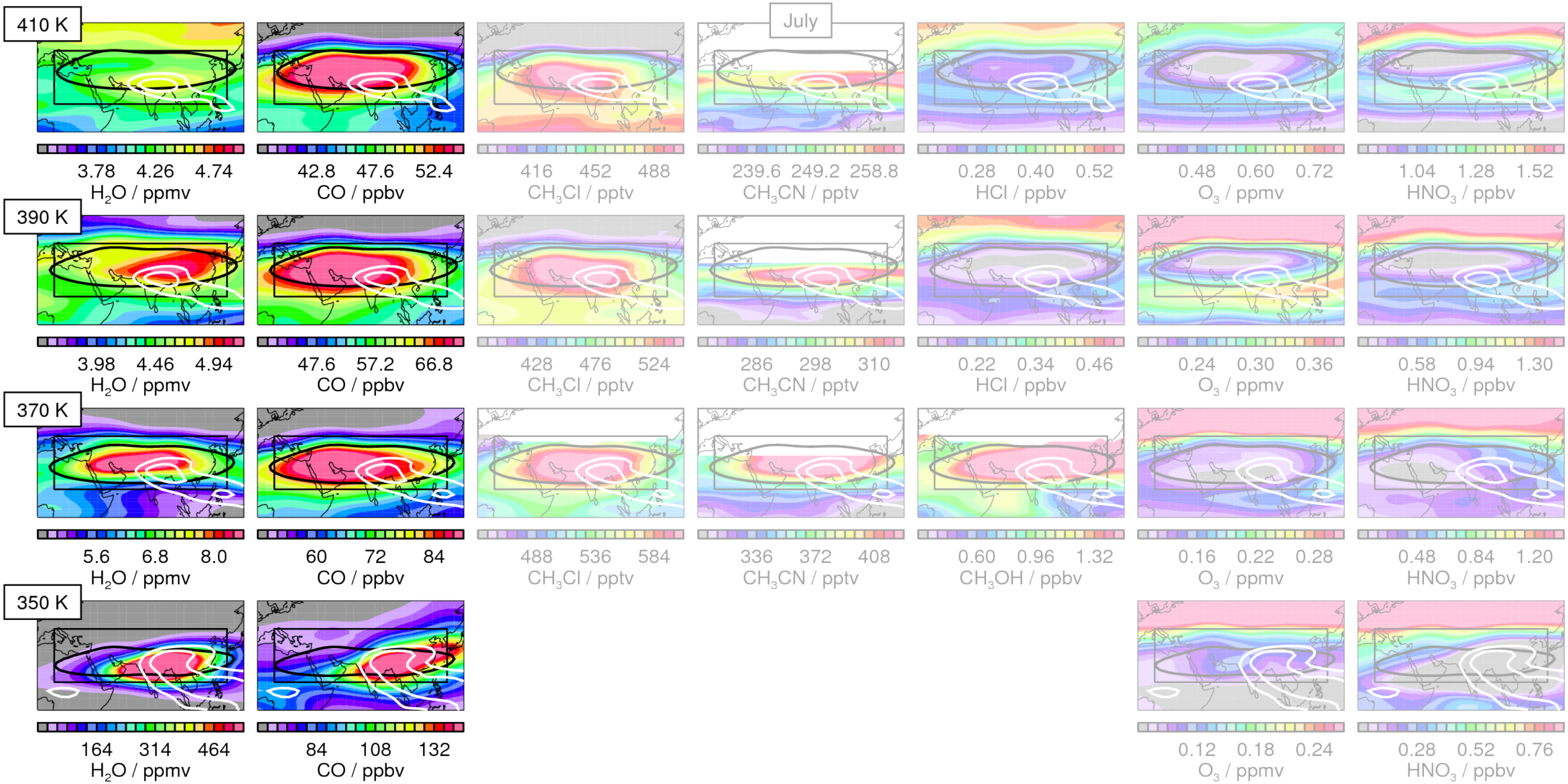
- The strong anticyclonic circulation is generally situated to the northwest of the main climatological region of intense deep convection (indicated by MLS IWC)

July: Characterization of the fully established ASM anticyclone



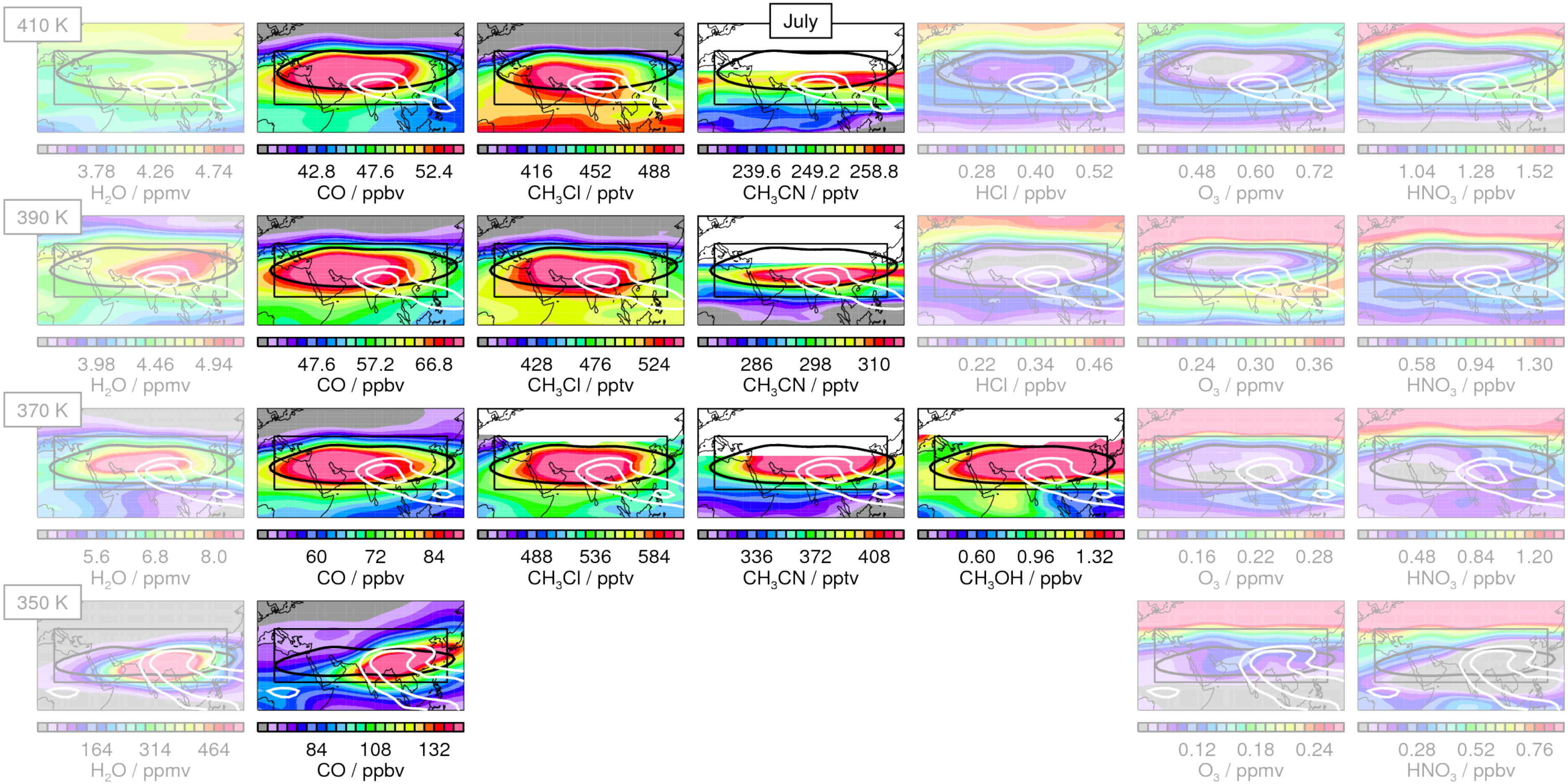
- The geographic location and exact timing of extreme values vary from species to species, but above 350 K the enhancements or depressions in the trace gases are aligned more closely with the anticyclone than with the area of convective activity

July: Characterization of the fully established ASM anticyclone



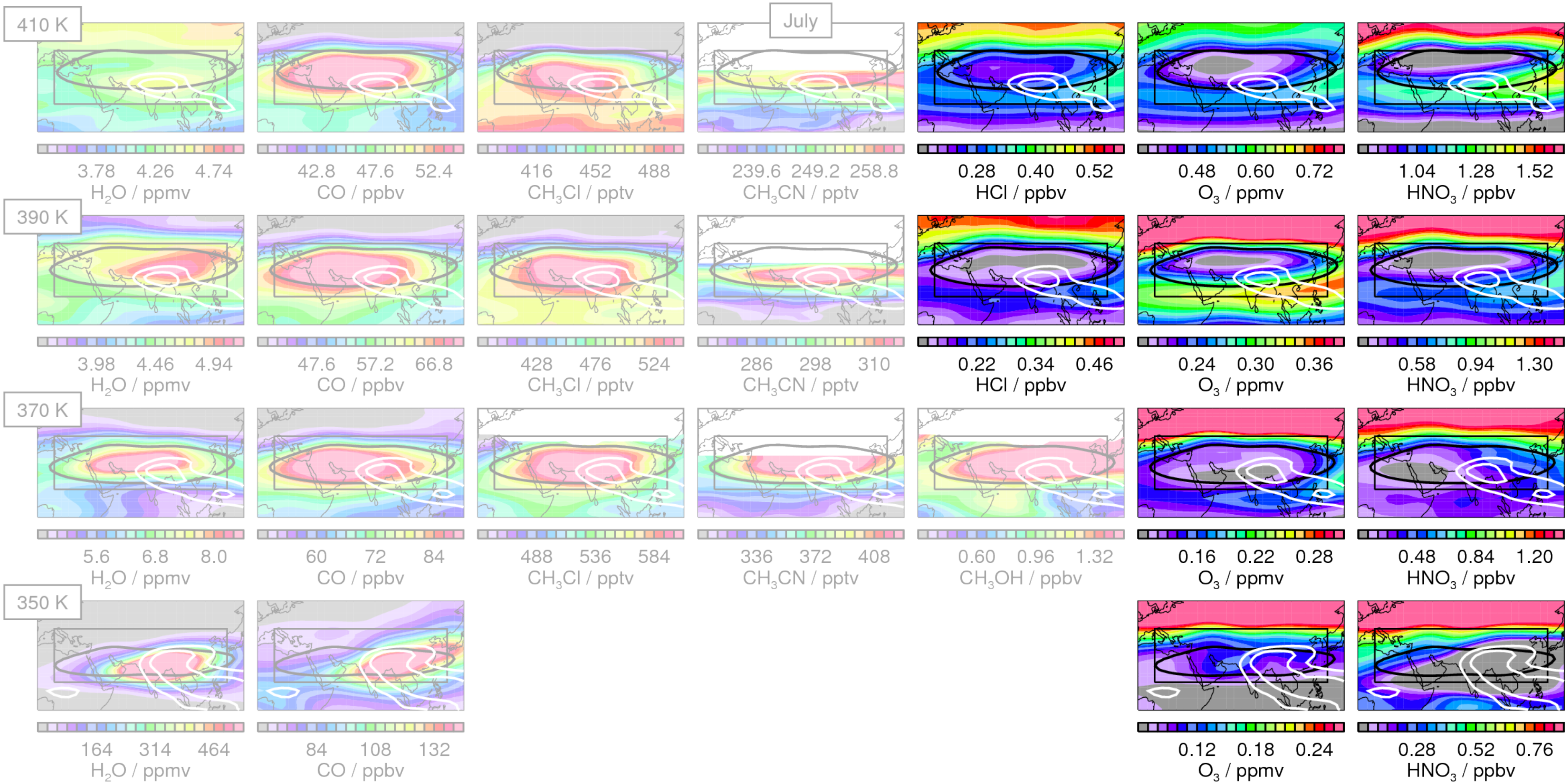
- At 350 K, the distributions of both H_2O and CO are more congruent with the broad region of intense convection than with the MSF contour, implying greater direct convective influence at this level
- Thus enhancements are persistently shifted further west at 370 K than at 350 K

July: Characterization of the fully established ASM anticyclone



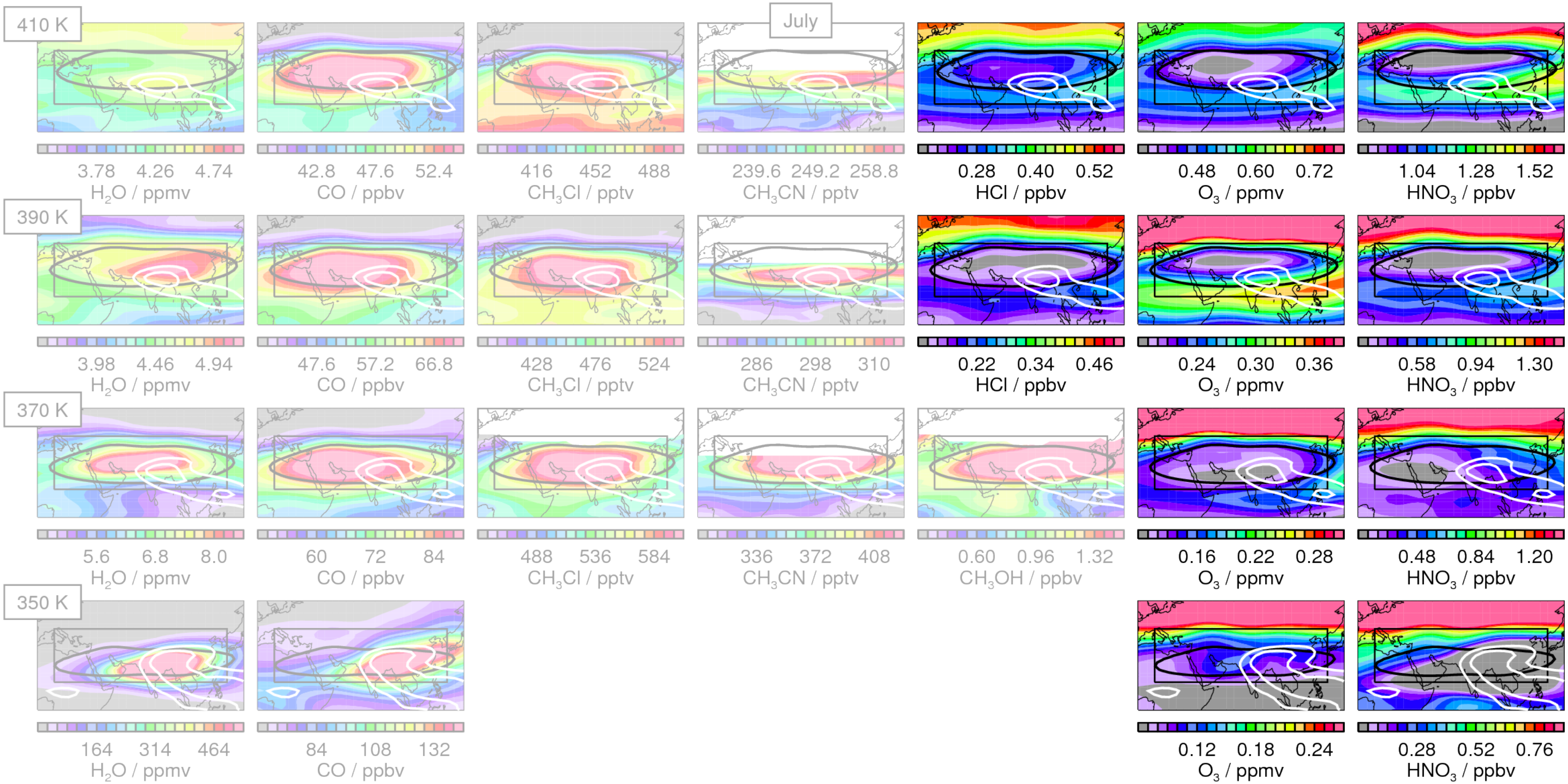
✦ In addition to CO, pronounced enhancements in the ASM anticyclone are seen in other markers of pollution measured by MLS, such as CH_3Cl, CH_3CN, and CH_3OH

July: Characterization of the fully established ASM anticyclone



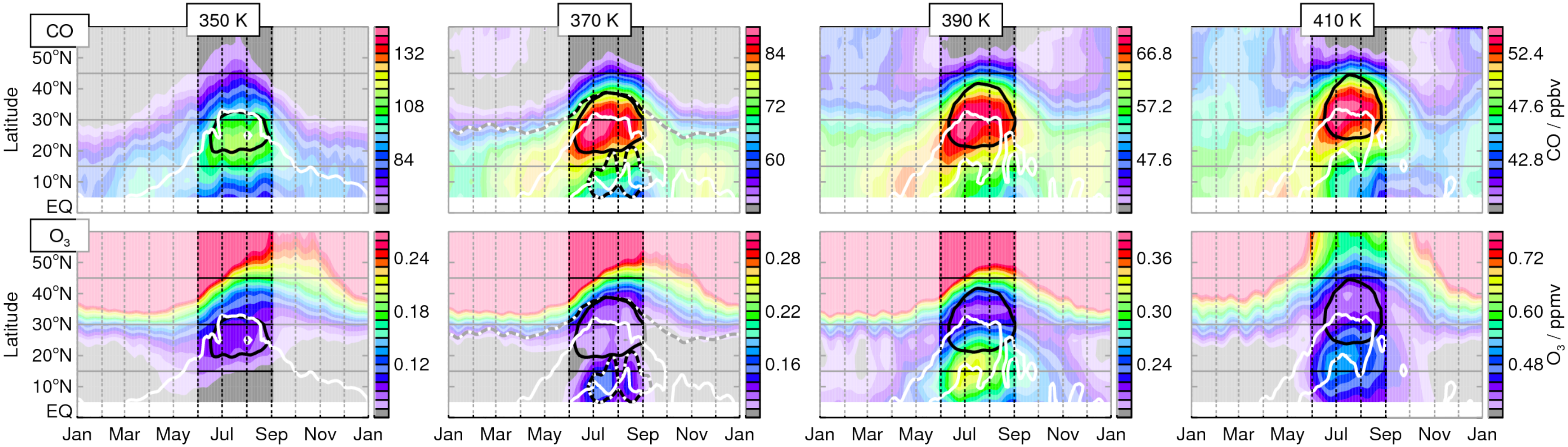
- Lofting of near-surface air generally decreases O_3 inside the anticyclone; HNO_3 abundances are also typically smaller in the upper troposphere than stratosphere
- Accordingly, minimum values of the stratospheric tracers are observed in the deep core of the anticyclone in July and August

July: Characterization of the fully established ASM anticyclone

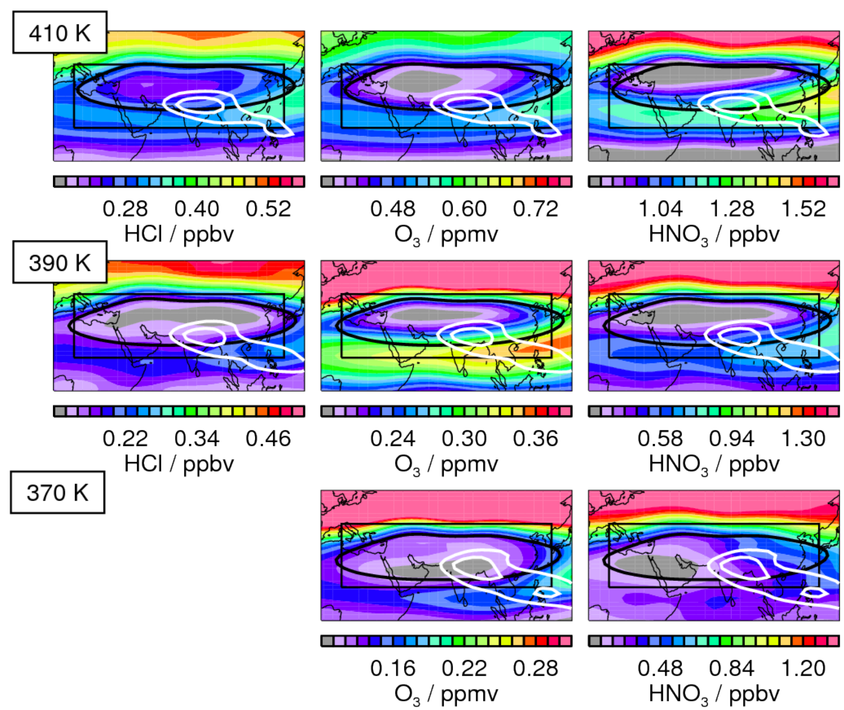


- Photochemical production can confound interpretation of O_3 in the ASM area, and local sources (e.g., lightning) and sinks (e.g., cirrus clouds) can also affect HNO_3
- In contrast, HCl has no significant sources in the upper troposphere, thus entrainment of lower-level air leads to a clear minimum in HCl in the anticyclone

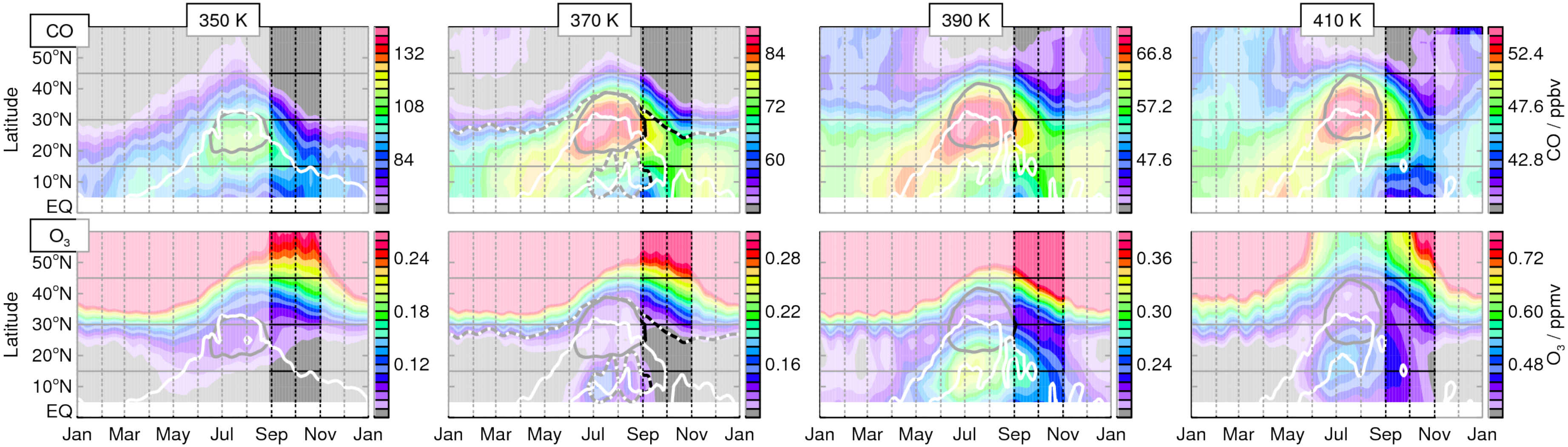
July: Characterization of the fully established ASM anticyclone



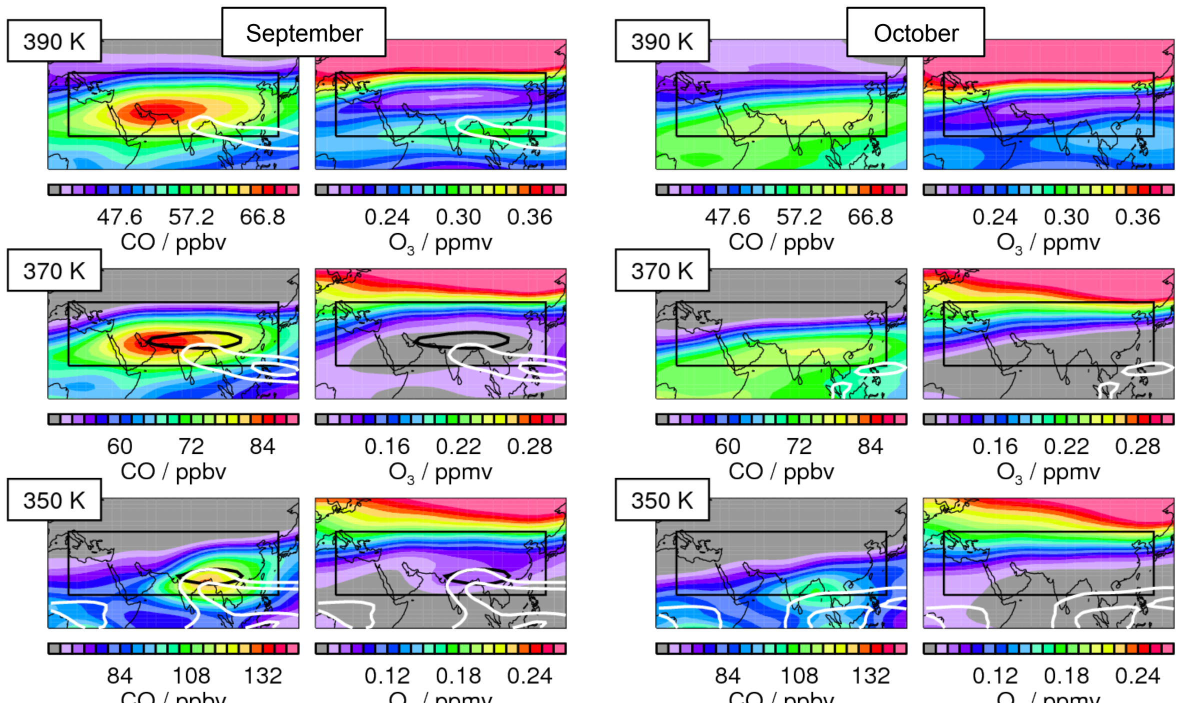
- Advection of midlatitude stratospheric air around the eastern flank of the ASM anticyclone into the tropics is clearly visible in O_3 and the other stratospheric tracers at 370 K and above
- PV overlays in the time series at 370 K indicate that the maxima in these species near the tropical tropopause reflect the presence of extratropical stratospheric air
- Tropospheric tracer signature is weaker



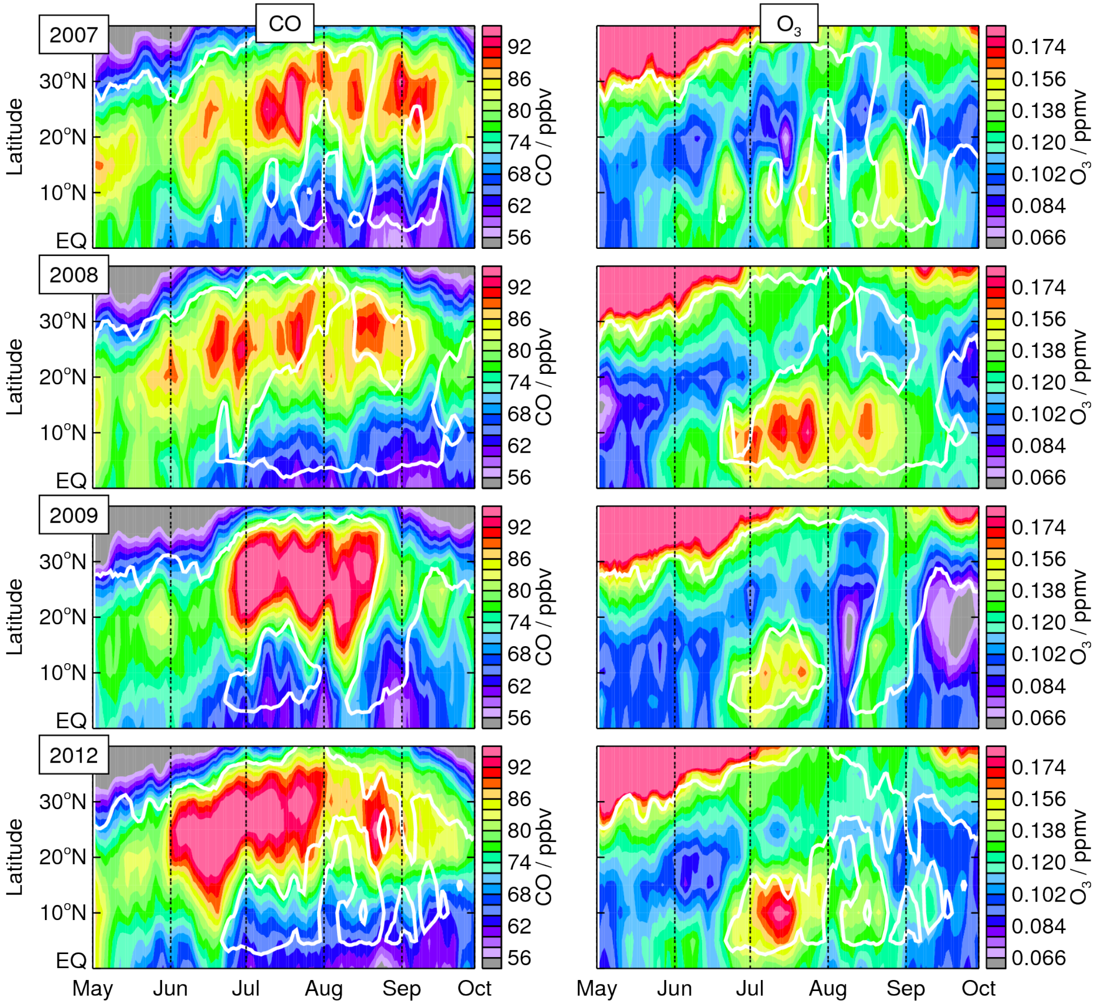
September and October: Retreat phase of the ASM



- After August, the subtropical westerly jet / tropopause gradually migrates back toward the equator
- By October, only small perturbations still linger in most of the trace gas distributions

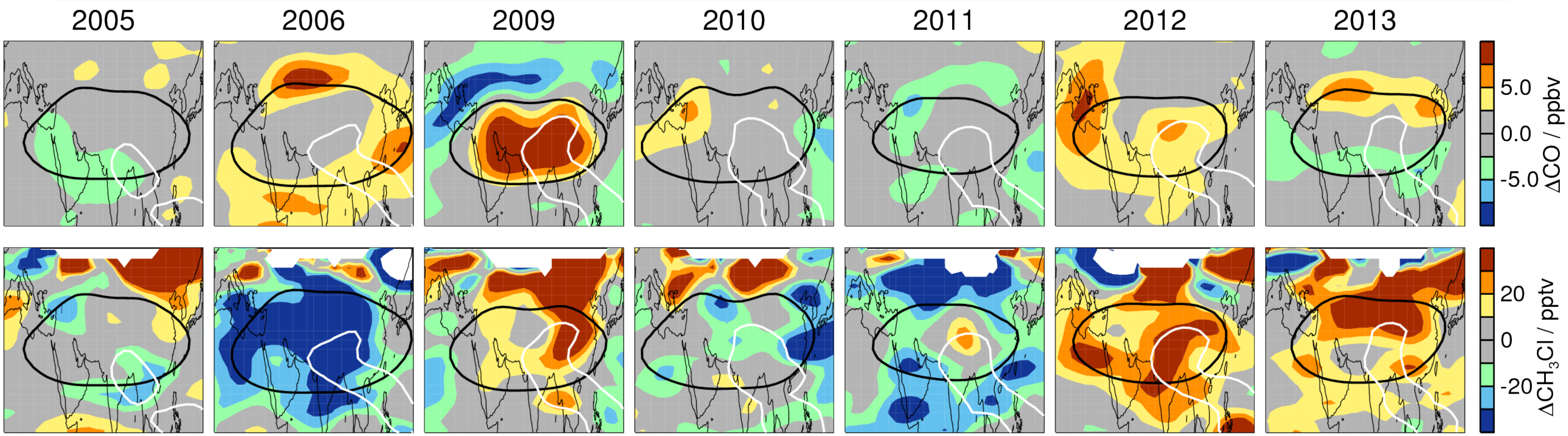


Interannual variability in the seasonal evolution at 370 K



- Although the seasonal evolution of both tropospheric and stratospheric tracers is generally similar every year, the timing and magnitude of extreme values in the ASM region display substantial interannual variability
- For example, enhancements in CO in the anticyclone were considerably greater than the climatological norm in 2009 and 2012 but weaker than typical in 2007 and 2008
- The ozone fields suggest that transport of midlatitude air around the eastern flank of the anticyclone into the tropics also varies greatly from year to year

Interannual variability in July-mean CO and CH_3Cl at 370 K

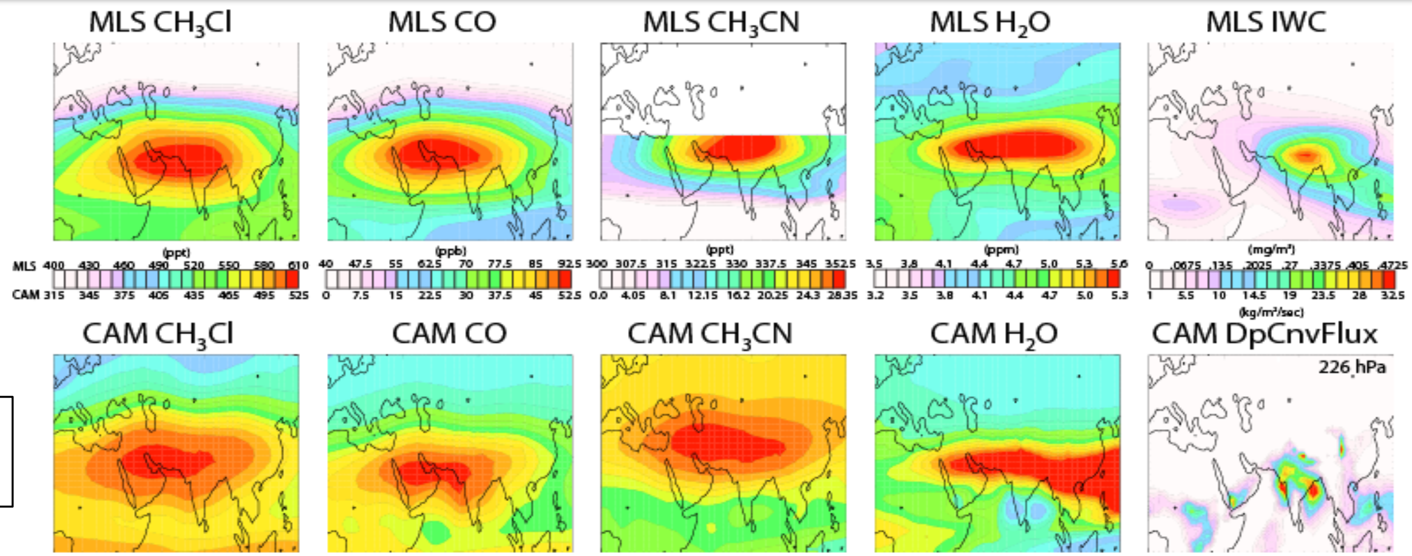


- Anomalies from 10-year climatology show that although persistent enhancements in pollution markers occur every summer in the ASM anticyclone, their magnitude and geographic extent vary considerably from year to year and between species
- In some years both species display more or less climatological behavior (2005), in other years large departures occur in both (2009, 2012); often, their monsoon signatures are highly localized (2010, 2011) or very different (2006, 2013)
- Since dynamical and meteorological conditions (large-scale vertical transport, location and intensity of convection) should affect CO and CH_3Cl similarly, these discrepancies suggest differences in the strength or location of their emissions

Model comparison: July climatology (2005–2012) at 100 hPa

v3.3 MLS

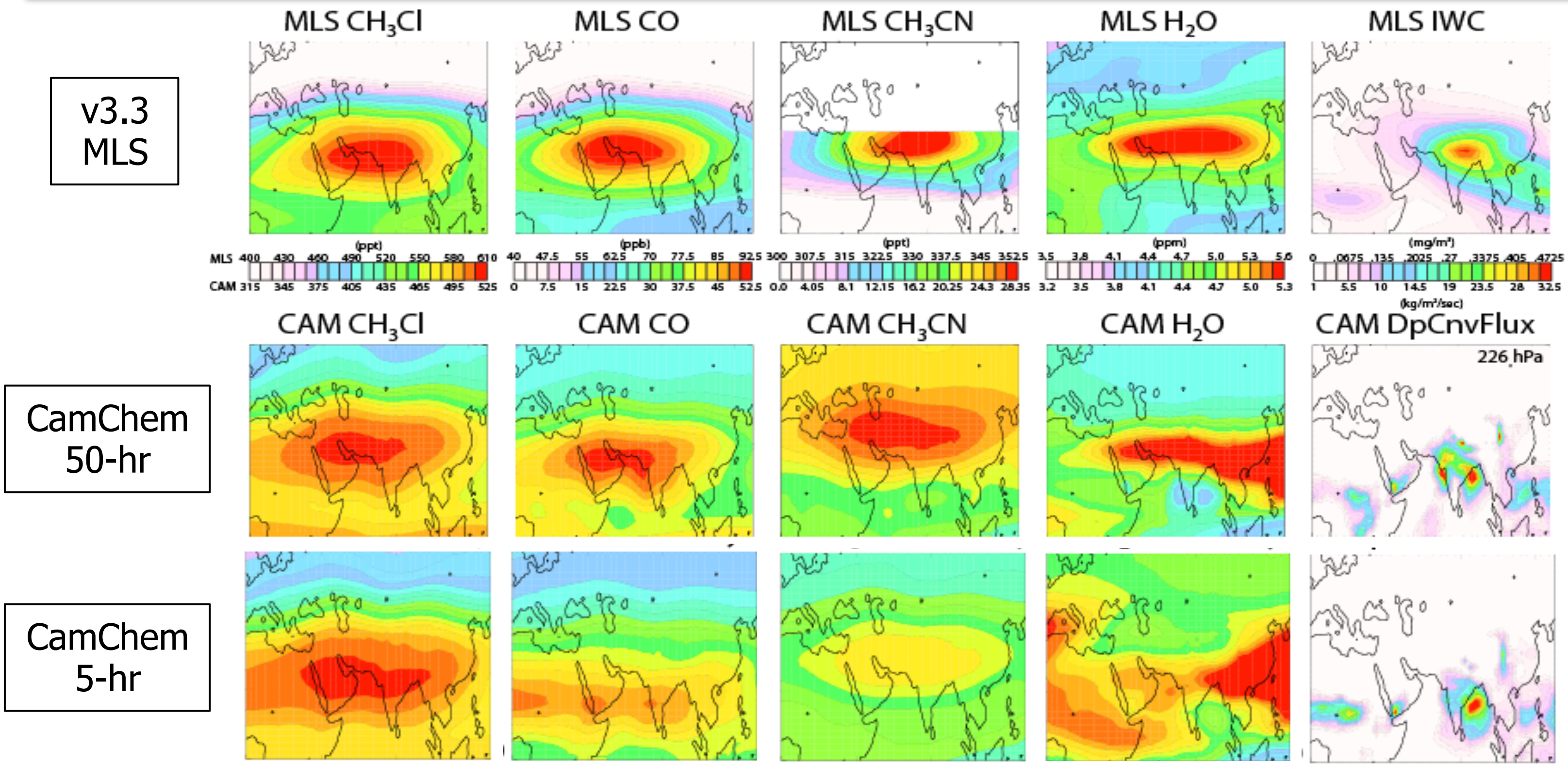
CamChem 50-hr



Note different scales for data and model

- Trace gas concentrations in the ASM anticyclone are lower in the model than those observed (in some cases considerably so) and gradients are much weaker
- Model H_2O maximum values extend too far eastward and do not show the signature of a closed circulation
- The model's deep convective mass flux has maximum values over the east and west coasts of India
- Ongoing work has shown that using 5-hr vs. 50-hr nudging timescales produces significant differences in modeled convective transport and thus UTLS composition
- 5-hr nudging improves model-measurement consistency over convective regions

Model comparison: July climatology (2005–2012) at 100 hPa



Note different scales for data and model

Figures courtesy Jessica Neu

- Use of 5-hr nudging shifts the convective region to the Bay of Bengal; comparison with OLR observations suggests that ASM convection is captured better in this run
- However, the trace gas distributions in the ASM anticyclone – especially CO and H_2O – are not as well represented with the 5-hr nudging
- The 5-hr nudging may introduce spurious dynamical variability to the system, weakening the anticyclone and increasing mixing across its boundary

Conclusions and other current work

- Summary:
  - Aura MLS provides a more than 10-year daily global data set of simultaneous and co-located measurements of an extensive suite of stratospheric and tropospheric tracers and cloud ice of great value for monsoon studies
  - We are using MLS data to characterize the climatology of UTLS trace gas distributions in the ASM region and quantify their spatial and temporal (seasonal, interannual) variability
  - MLS data are also being used to evaluate the representation of the ASM in chemistry climate models, such as CAM-Chem

- Additional studies currently ongoing:
  - Correlation of the observed trace gas behavior in the ASM region with variations in surface emissions and meteorological factors, such as existence dates, location, size, and strength of the anticyclone; the location and strength of deep convection; diagnostics of local mixing; variations in the latitude, altitude and depth, and strength of the upper tropospheric jets; ENSO and QBO indices; etc.