Update on Stratospheric Circulation Variability Driven by the QBO + Results from CESM2

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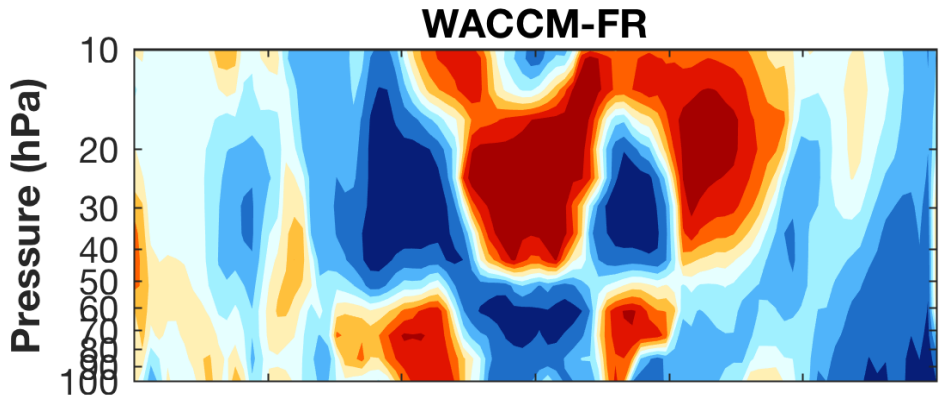

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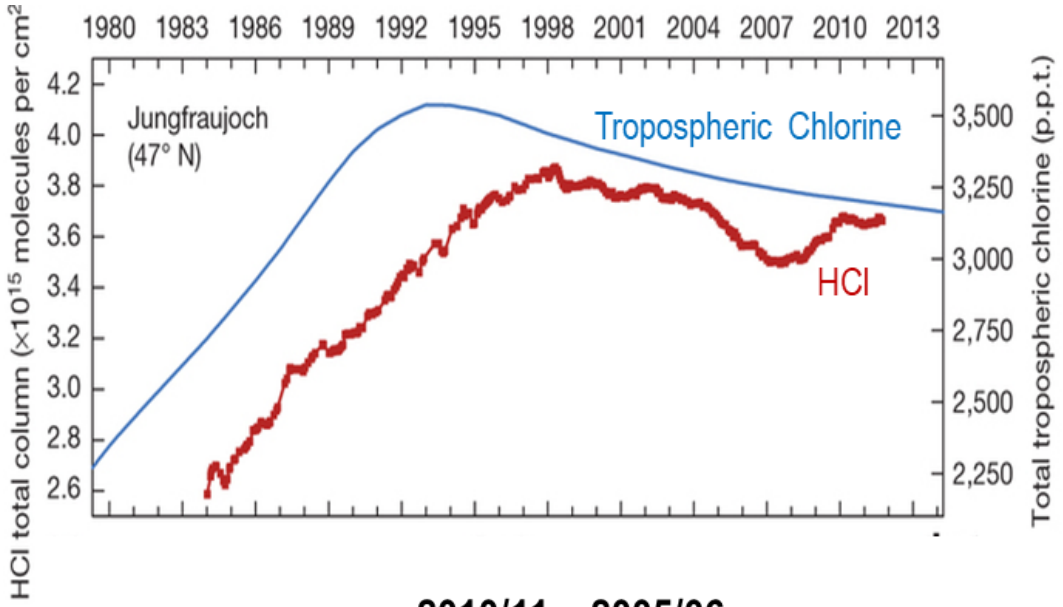
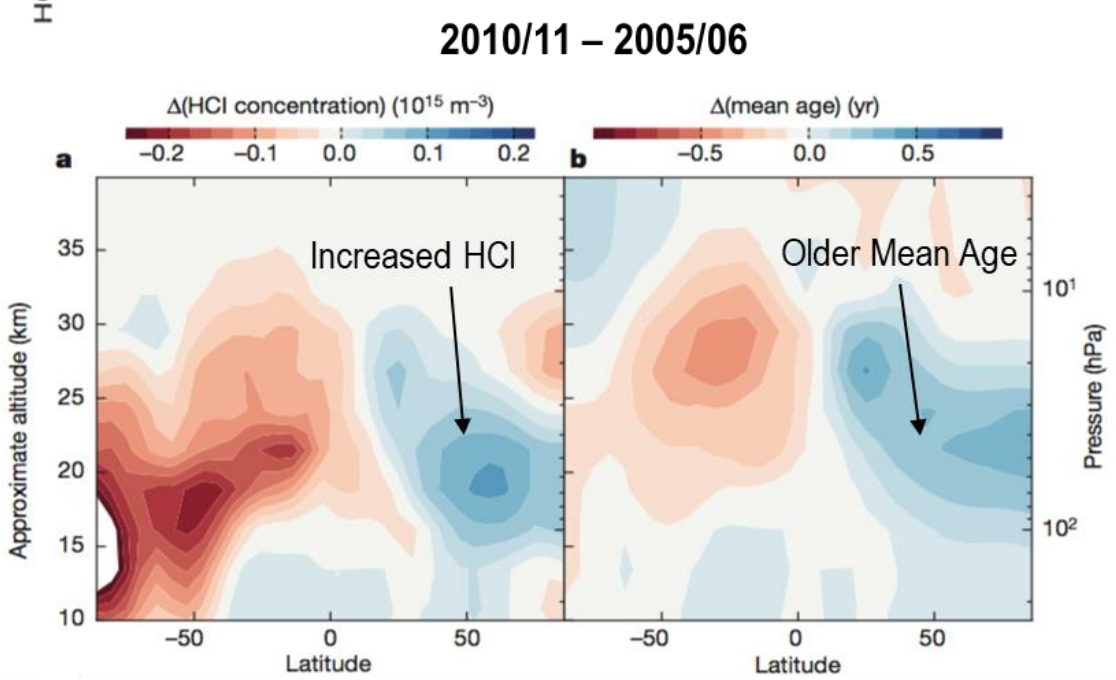
Background and Motivation

Maheiu et al. (*Nature*, 2014) reported on an increase in NH lower stratospheric HCl from 2007-2010 that was seen in multiple datasets.

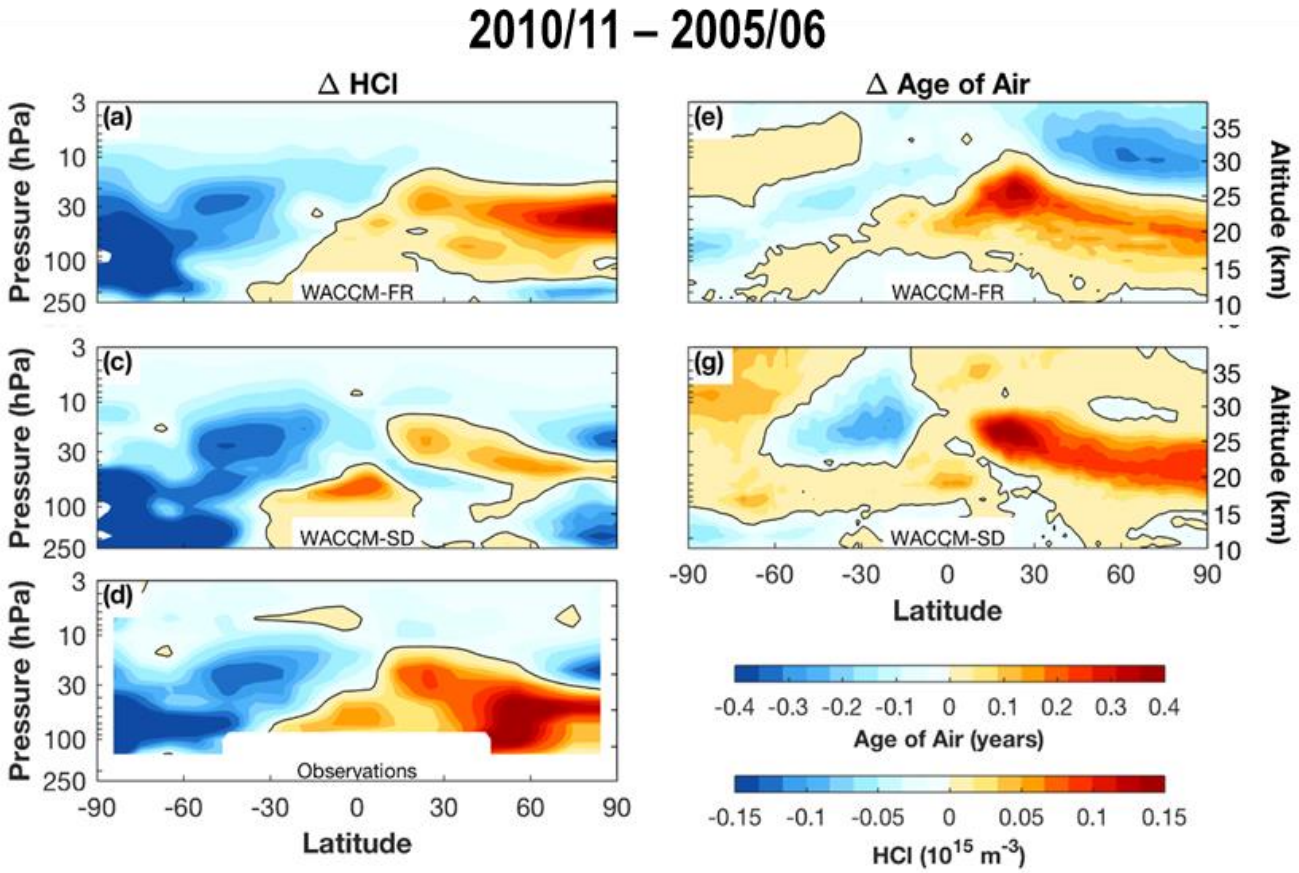
This increase was a surprise given the steady decrease in Cl_y since the early 1990s.

Using the SLIMCAT model, the authors concluded that the positive trend in HCl was driven by a **slow-down** of the stratospheric circulation between 2005 and 2010.





WACCM Simulations of HCl and Age of Air

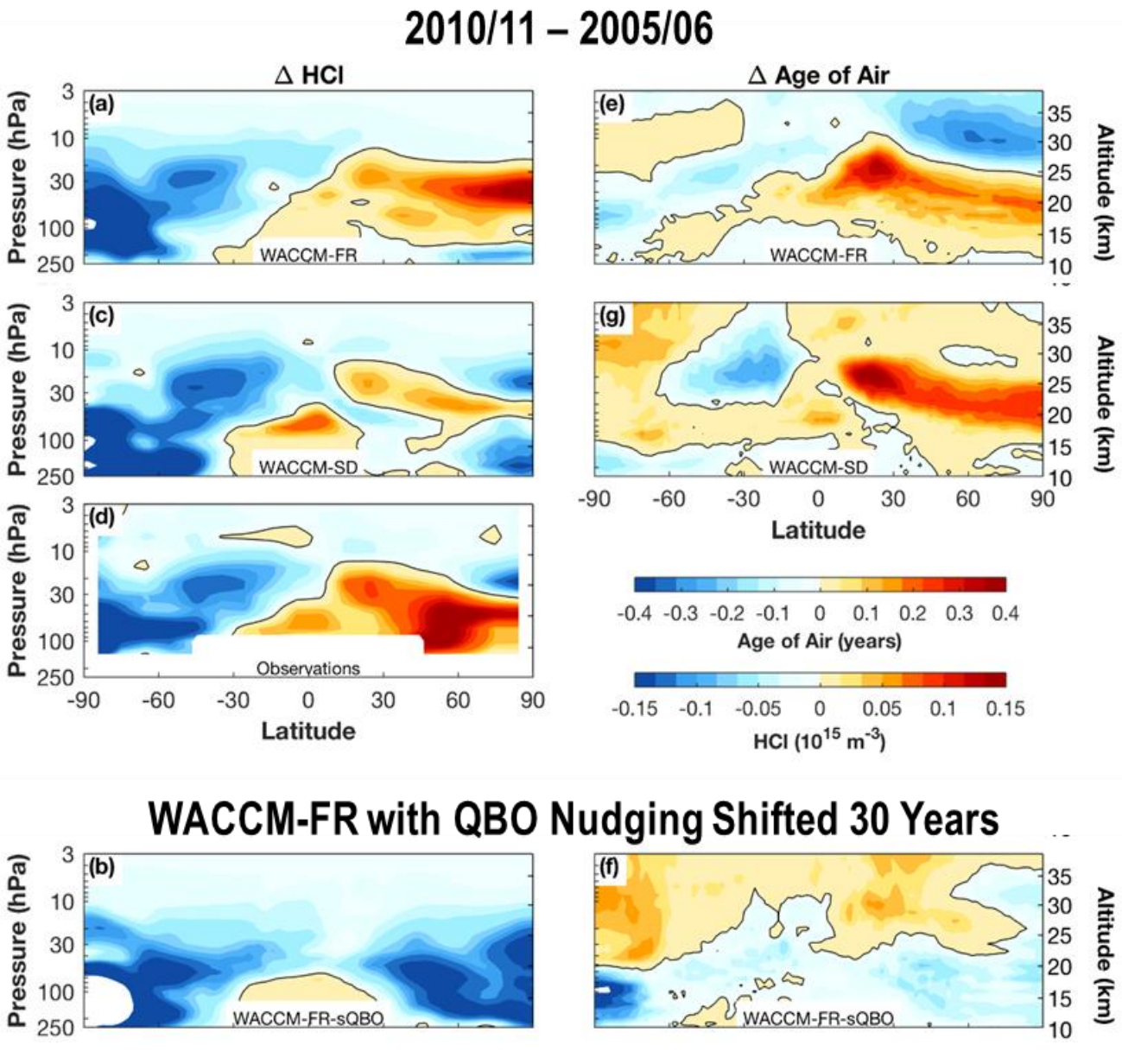


WACCM reproduces the observed change in HCl from 2005 to 2010 in both the Free Running (FR) and Specified Dynamics (SD) versions of the model.

It also reproduces the increase in Age of Air seen in the SLIMCAT model.

The QBO is nudged to Singapore winds in WACCM-FR, while all of the meteorology is nudged to MERRA in WACCM-SD.

What Would Have Happened With a Different QBO?

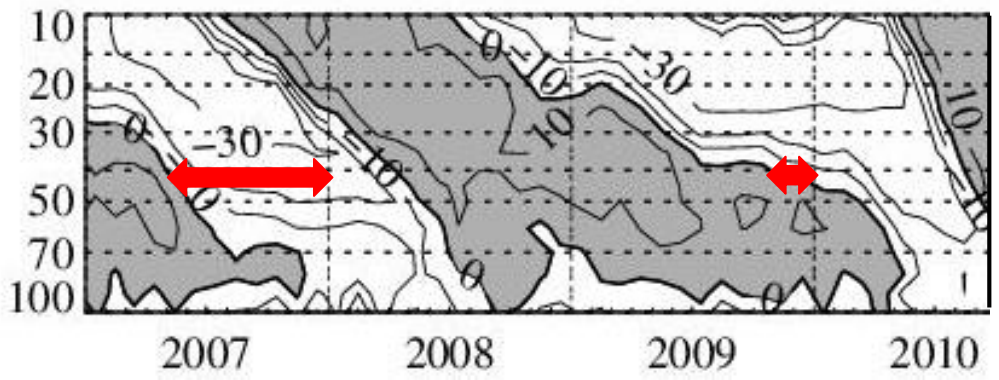


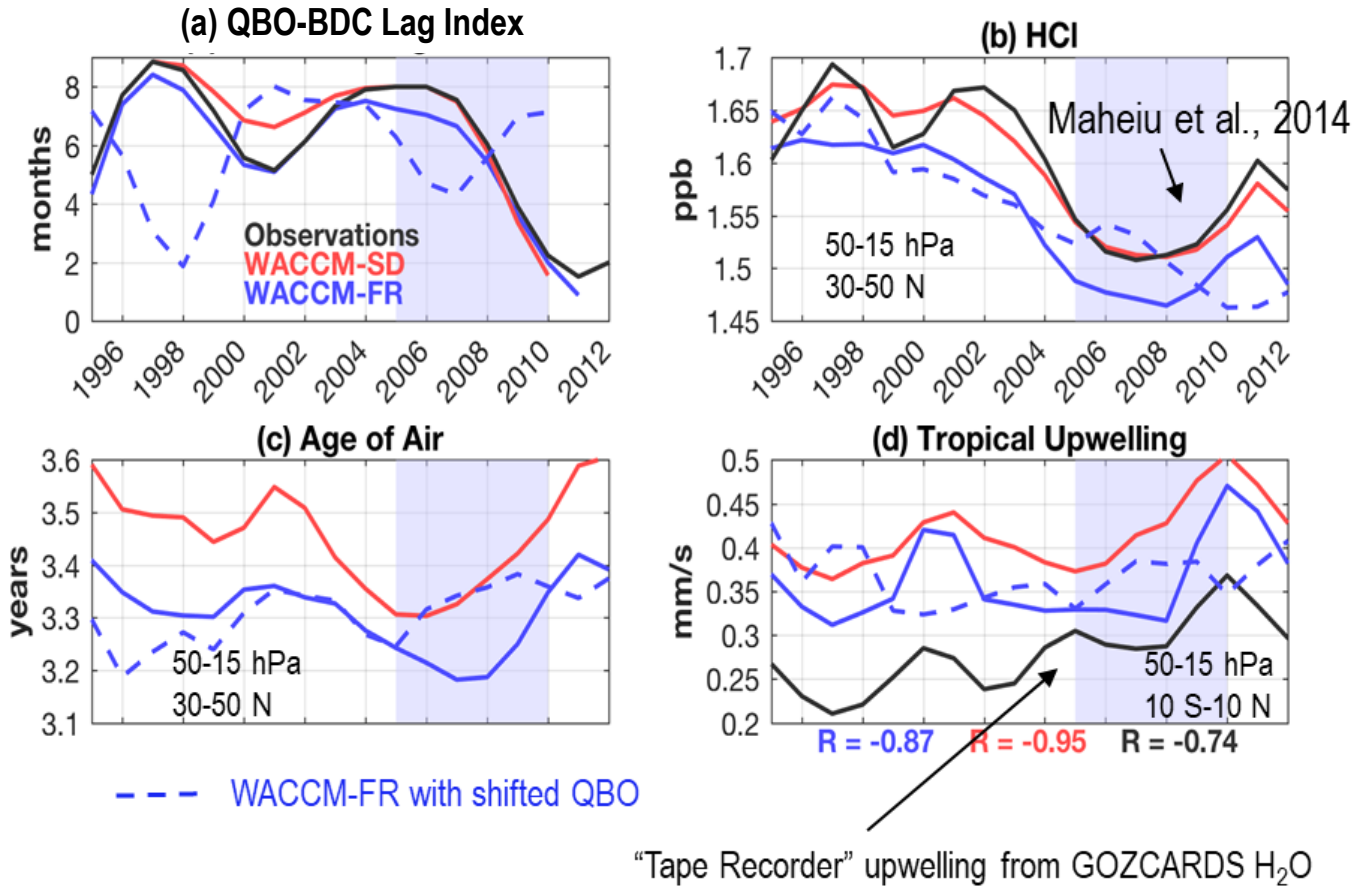
In a simulation in which the QBO nudging in WACCM-FR is shifted by 30 years (i.e. year 2005 was nudged to the 1975 QBO), the 2005-2010 HCl and Age of Air changes are of the opposite sign.

Clearly, the phase of the QBO played a critical role in the dynamically-driven increase in HCl reported by Mahieu et al. How and why?

Decadal-Scale Variability and QBO Seasonal Timing

QBO-BDC Lag Index: The difference in months between DJF and the last month of a given period during which the zonal mean zonal wind at 40 hPa is westerly. We focused on DJF because it dominates transport into the NH.

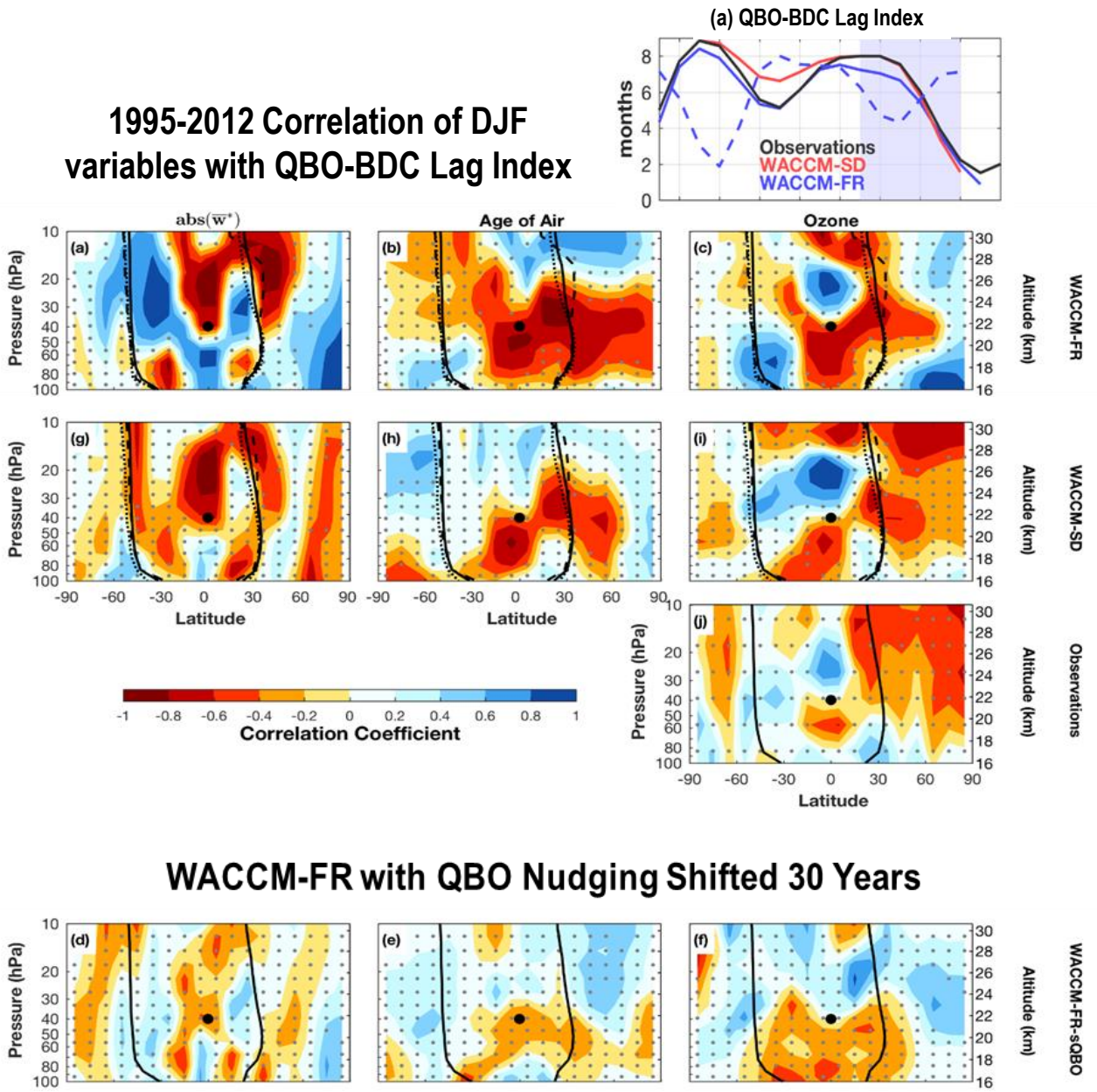




There is a strong relationship between the QBO-BDC lag index and 50-15 hPa DJF upwelling in the Tropics, with upwelling increasing as the lag index decreases.

Changes in DJF midlatitude Age of Air and HCl also correspond to changes in the lag index, though the HCl record is complicated by the ~1997 turnover in Cl_y.

Correlations with the Lag Index



At p<50 hPa, a decrease in the lag index drives a narrowing of the tropical upwelling and an increase in subtropical downwelling.

The increase in age of air results from the convergence of air in the subtropical downwelling region.

The modeled ozone fields show a similar relationship to the lag index as observations; middle stratospheric ozone decreases in the tropics and increases in midlatitudes as the lag decreases.

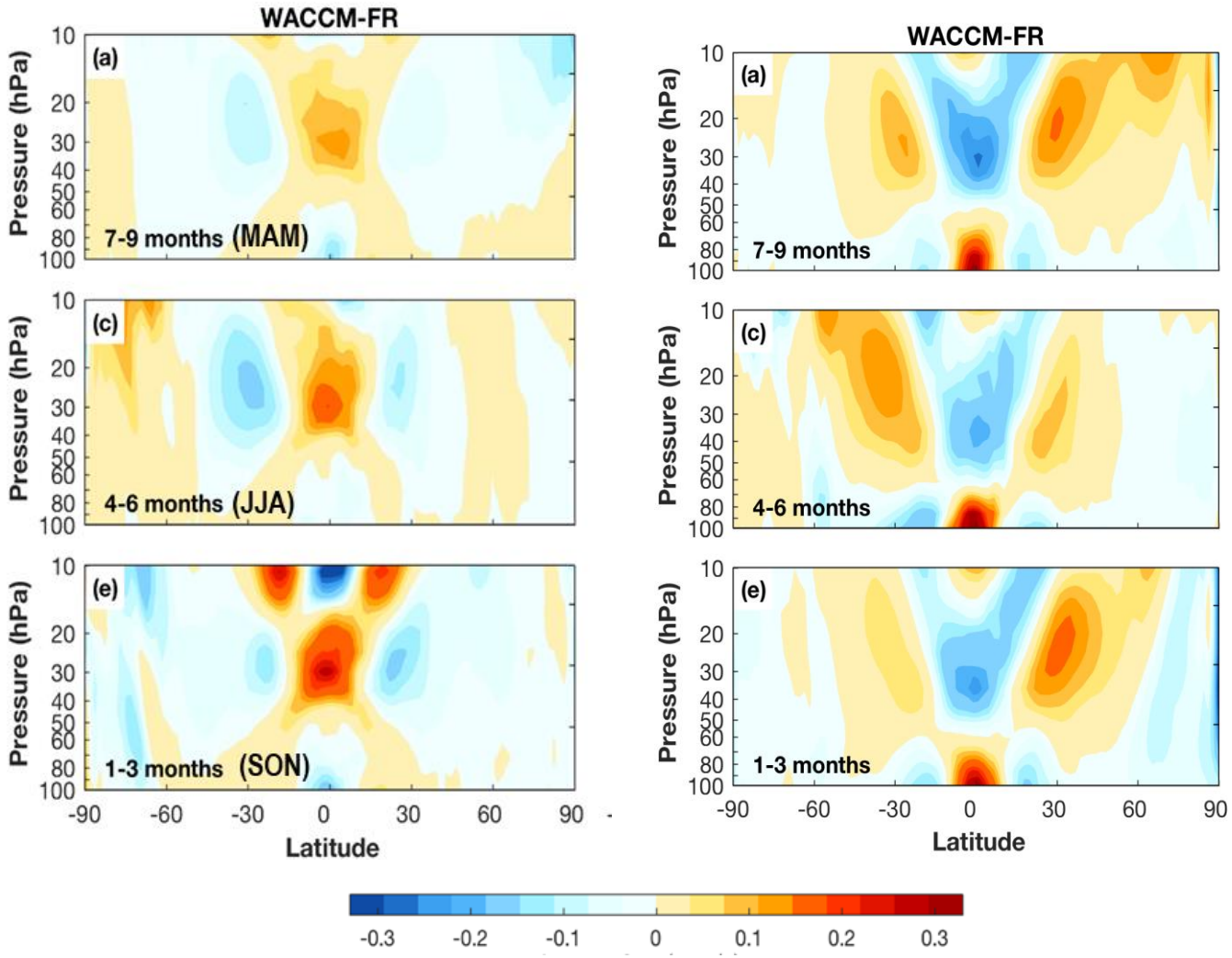
Issues with the Lag Index

We were happy with the degree of variability explained by the lag index and the relative consistency across model versions, including WACCM-FRsQBO.

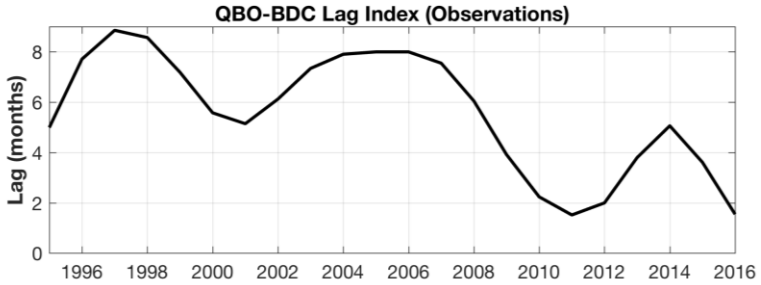
However, the lag index as we defined only has values during westerly-to-easterly transition years, and any way that we tried to include easterly-to-westerly years degraded the relationships with upwelling and the tracers.

We tried to explain this with the fact that the upwelling response to the easterly shear phase shows a strong monotonic progression with season while the response to the westerly shear phase does not, but the reviewers expressed concern with the index definition.

Composite Residual Vertical Velocity Anomalies for Easterly and Westerly Shear Phases

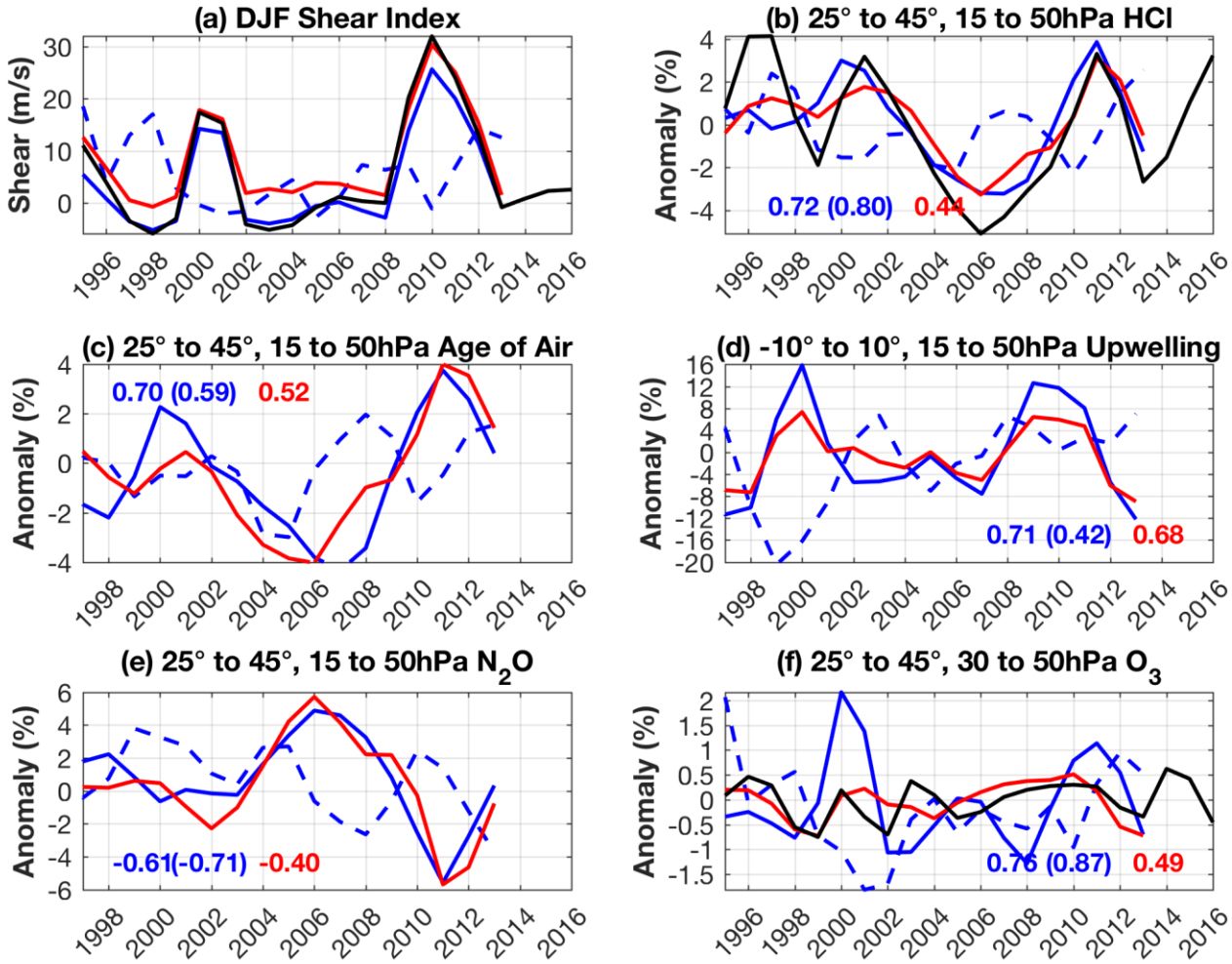


DJF Shear Index



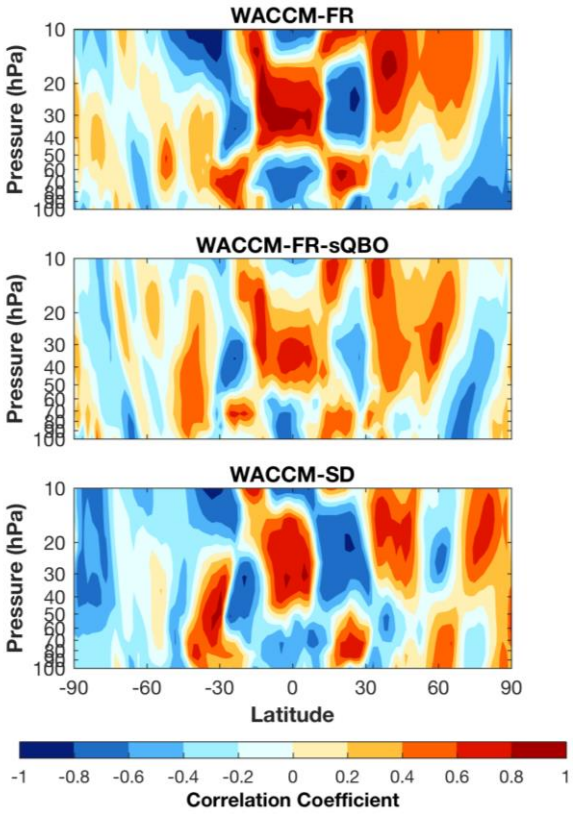
Based on a conversation at the SPARC GA, we redefined our index using the DJF shear. It shows even stronger relationships to DJF upwelling and tracers than the QBO-BDC Lag Index, with very similar correlation patterns. It also reduces the differences between WACCM-FR and WACCM-FRsQBO.

However, the relationship between DJF shear and DJF tracers was not really anything new, and so we wanted to know whether the DJF shear was particularly special with respect to annual mean upwelling and tracers.

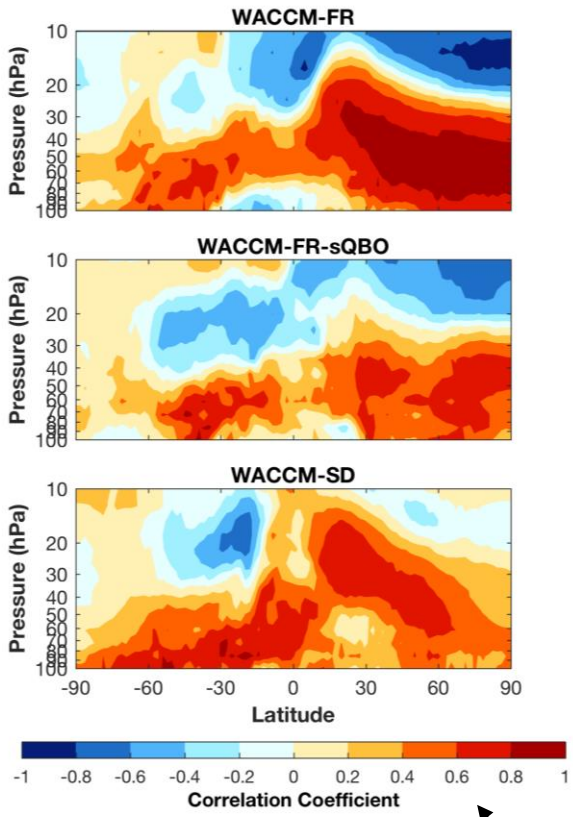


DJF Shear Index Correlation with Annual Mean Variables

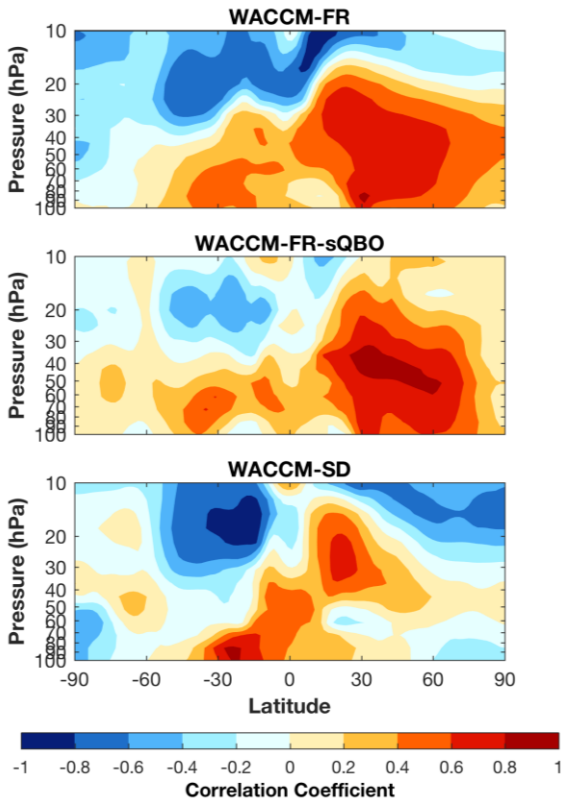
TEM $\overline{w}^*$



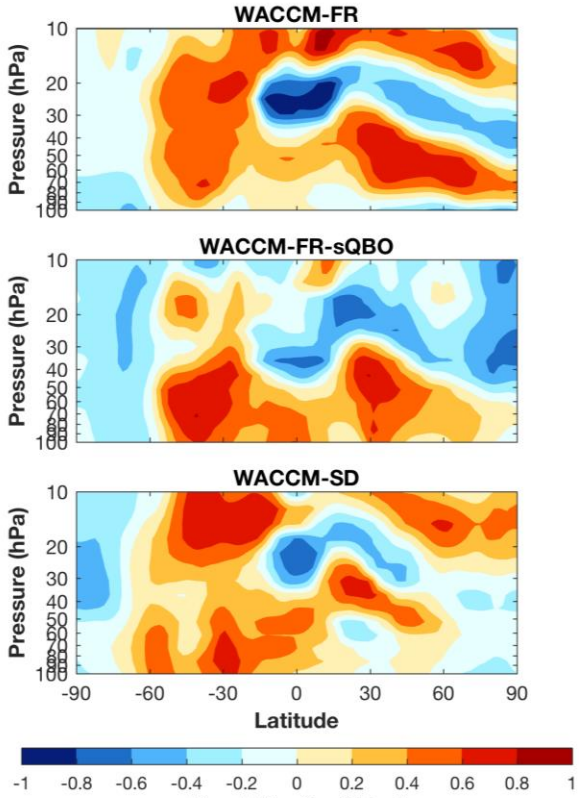
Age of Air

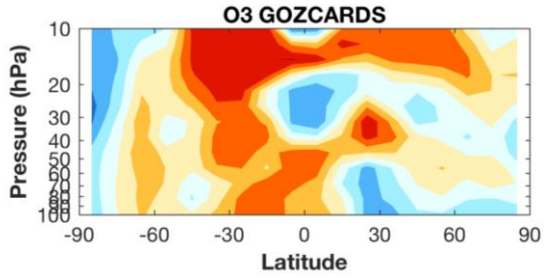


HCl



Ozone



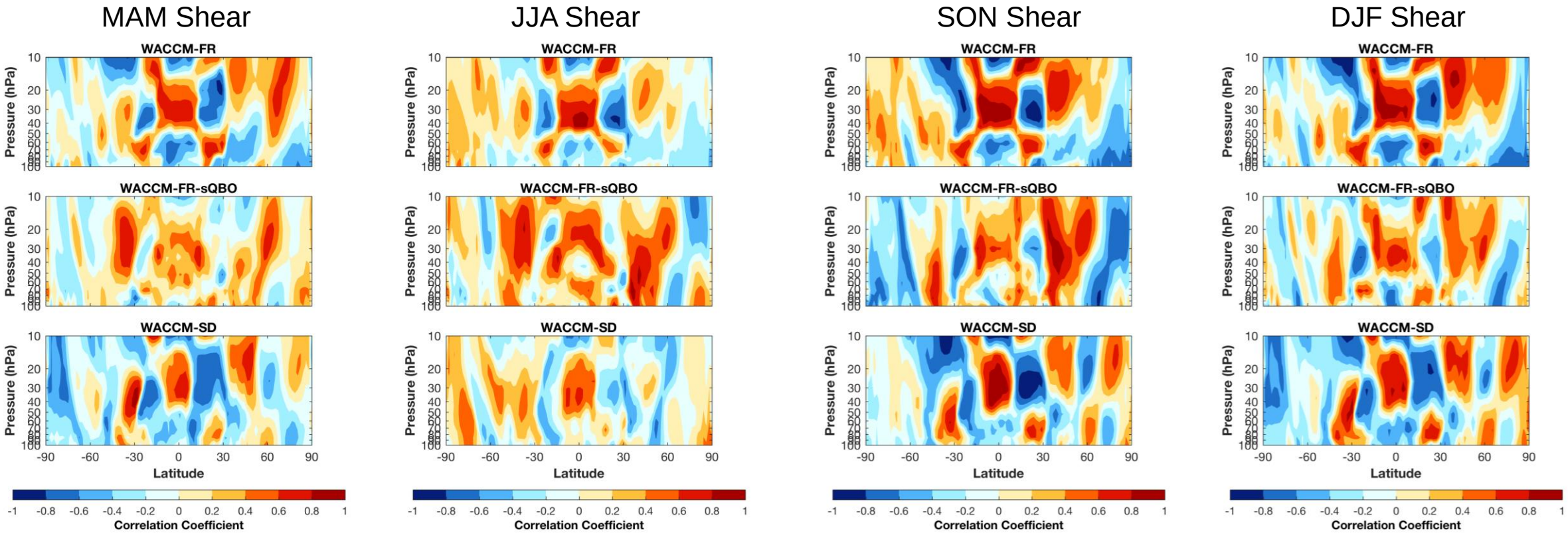


These are the same patterns as Maheiu et al. described

DJF QBO Shear vs Annual Mean X

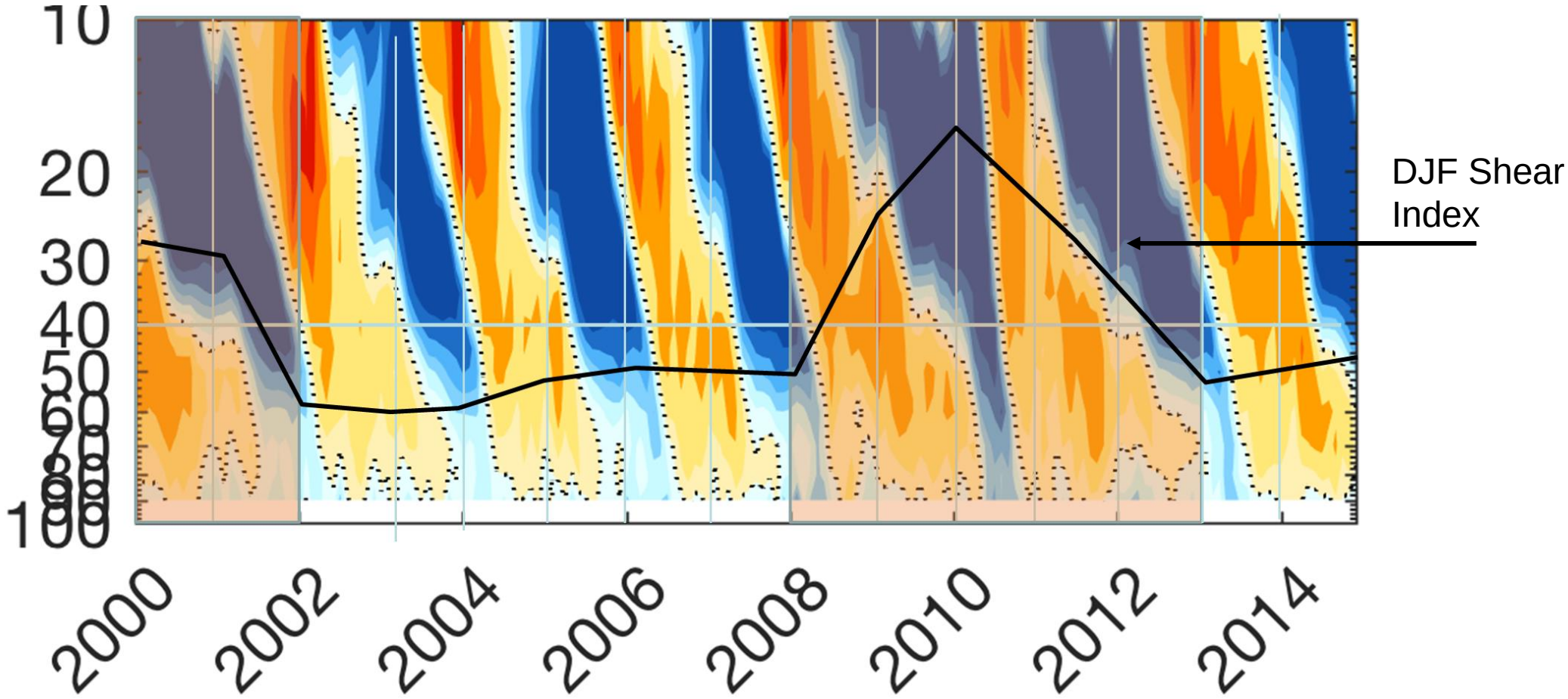
Is DJF Special (i.e. Does Seasonality Really Matter)?

Correlation of annual mean $\overline{w}^*$with:



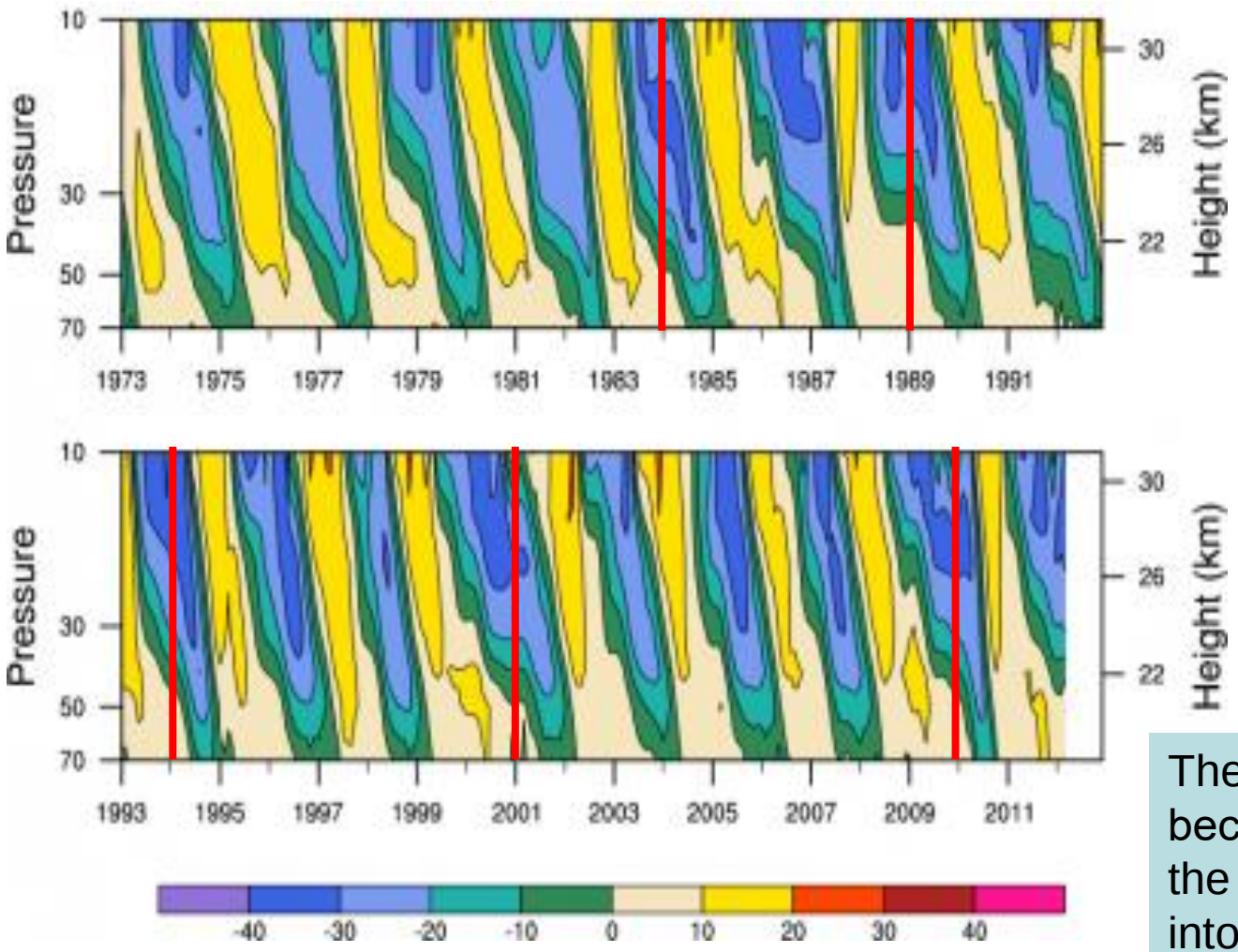
While SON and DJF clearly have stronger relationships with w* than MAM and JJA, particularly in midlatitudes, there is no “slam dunk” here – the evolution of the QBO clearly matters, but it isn’t clear that the seasonality is the reason it matters.

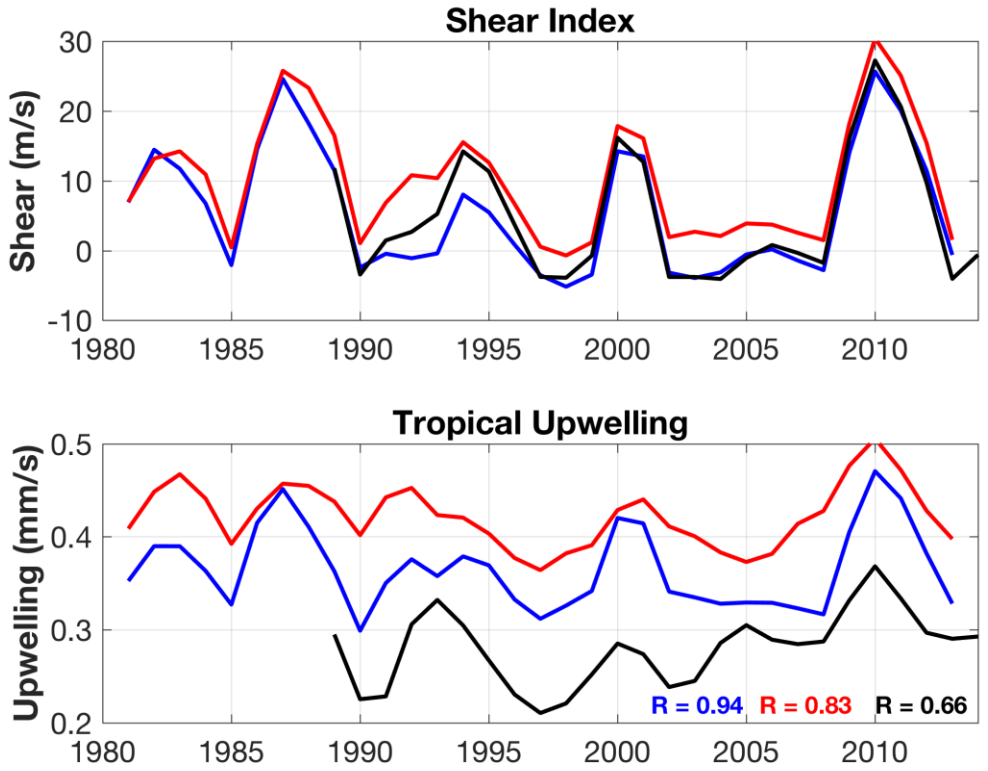
The Breakthrough?



Higher than normal westerlies at ~50 hPa + prolonged easterly phase = a delay in the westerly transition (i.e. decreasing Lag Index) and stronger easterly shear, especially in DJF (i.e. increasing DJF shear index).
It's the transitions in and out of the delayed easterly shear phases where we can expect to see short-term "trends".

Does it Hold on Longer Timescales?

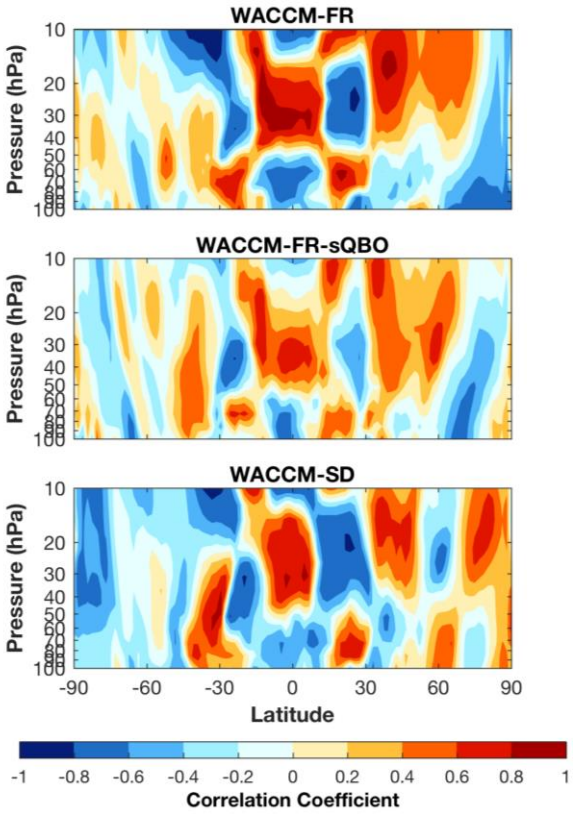




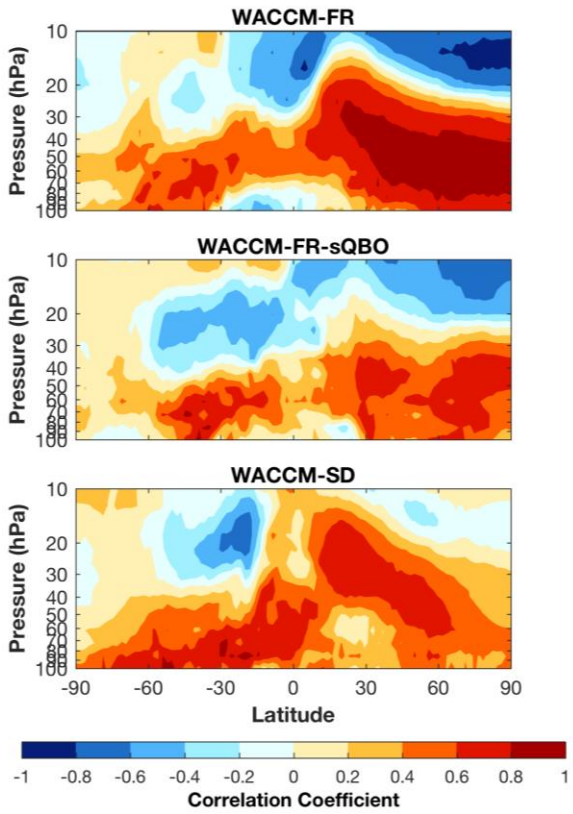
The DJF shear index and the lag index both work because the “stalling out” of the easterlies tends to push the zero wind line, and thus the strong easterly shear, into DJF. Yet these conditions also create stronger shear in other months, which explains the high correlation of annual mean variables with shear in all seasons.

Summary

TEM $\overline{w}^*$

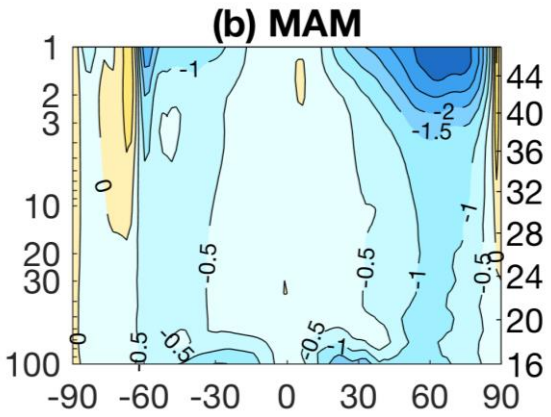


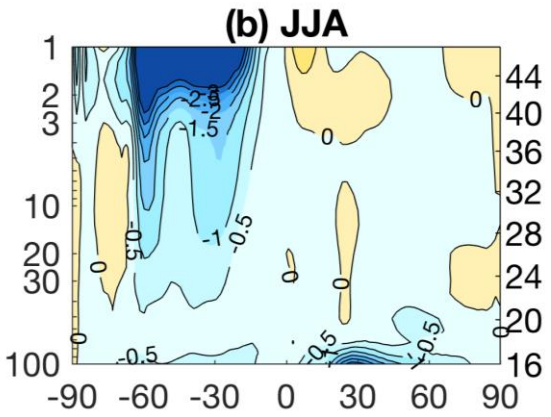
Age of Air

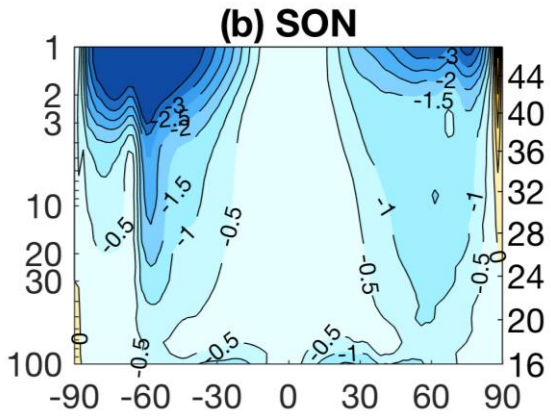


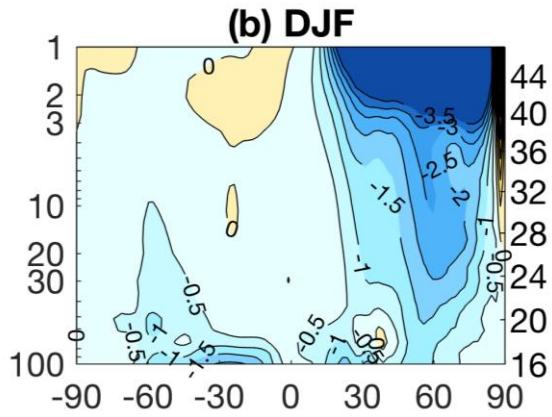
- The entire structure of the circulation is changed in response to the “stalling” of the easterly phase of the QBO, with a widening and weakening of the shallow branch and narrowing and strengthening of the deep branch.
- The increase in HCl from 2005-2010 described by Maehieu et al., which was attributed to a weaker circulation due to an association with older mean age, actually reflects stronger downwelling above 50 hPa and weaker downwelling below that level.
- The “stalling” of the easterly phase can be represented either by a Lag Index that represents the lag between the westerly to easterly transition and DJF or by a DJF Shear Index, which has the advantage of being continuous across years.
- The response of tropical upwelling, age, and long-lived trace gases to the easterly phase descent rate does not depend on the specific QBO time series.

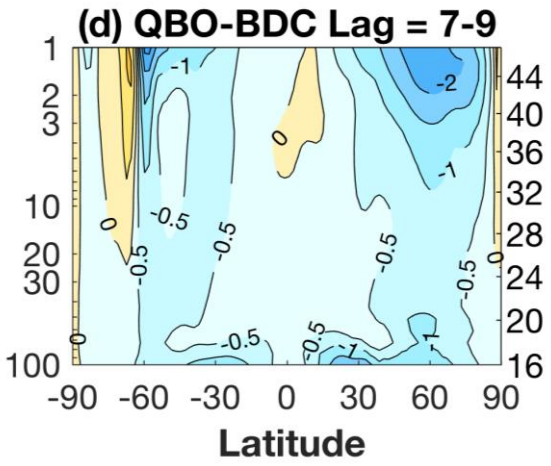
Backup


(b) MAM


(b) JJA


(b) SON


(b) DJF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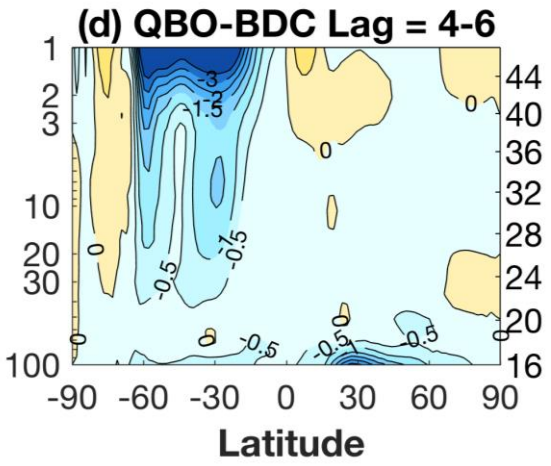
Latitude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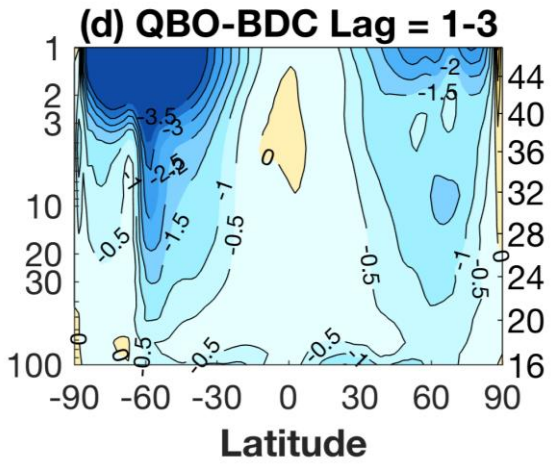
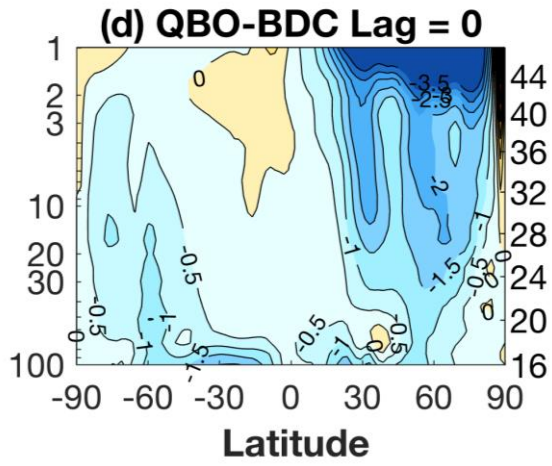
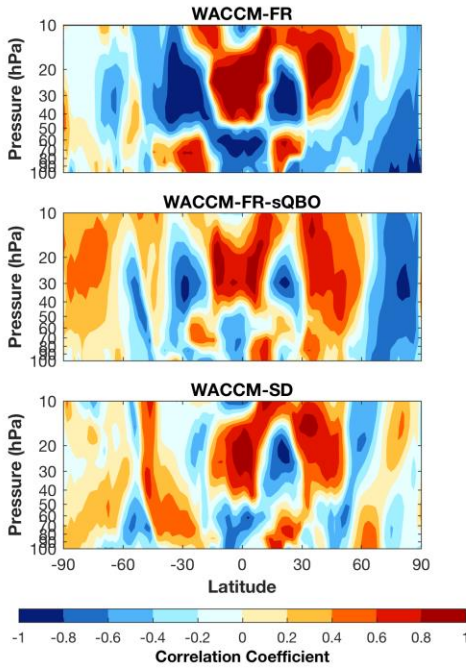
Latitude

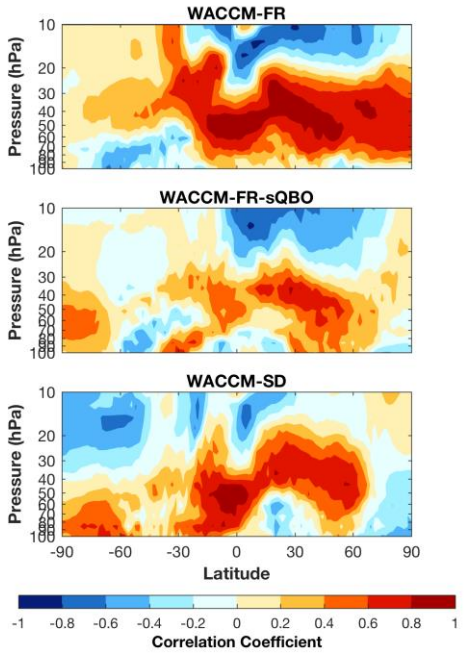

(d) QBO-BDC Lag = 1-3
Latitude


(d) QBO-BDC Lag = 0
Latitude

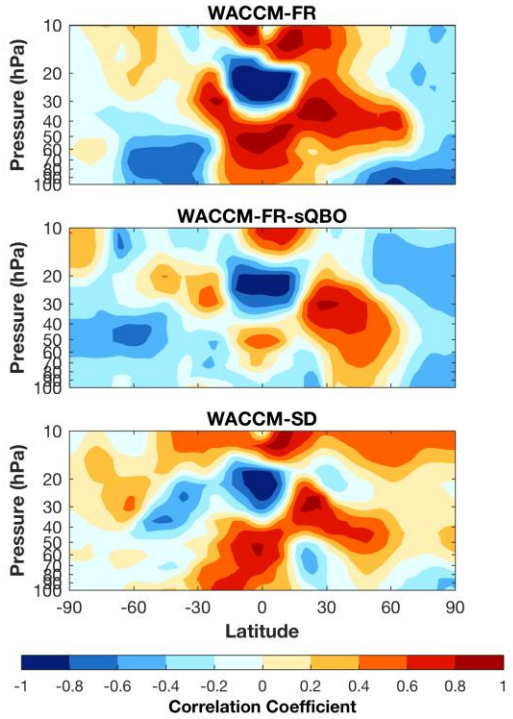
DJF wstar vs DJF shear index

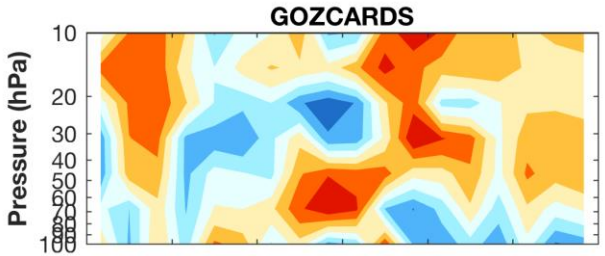


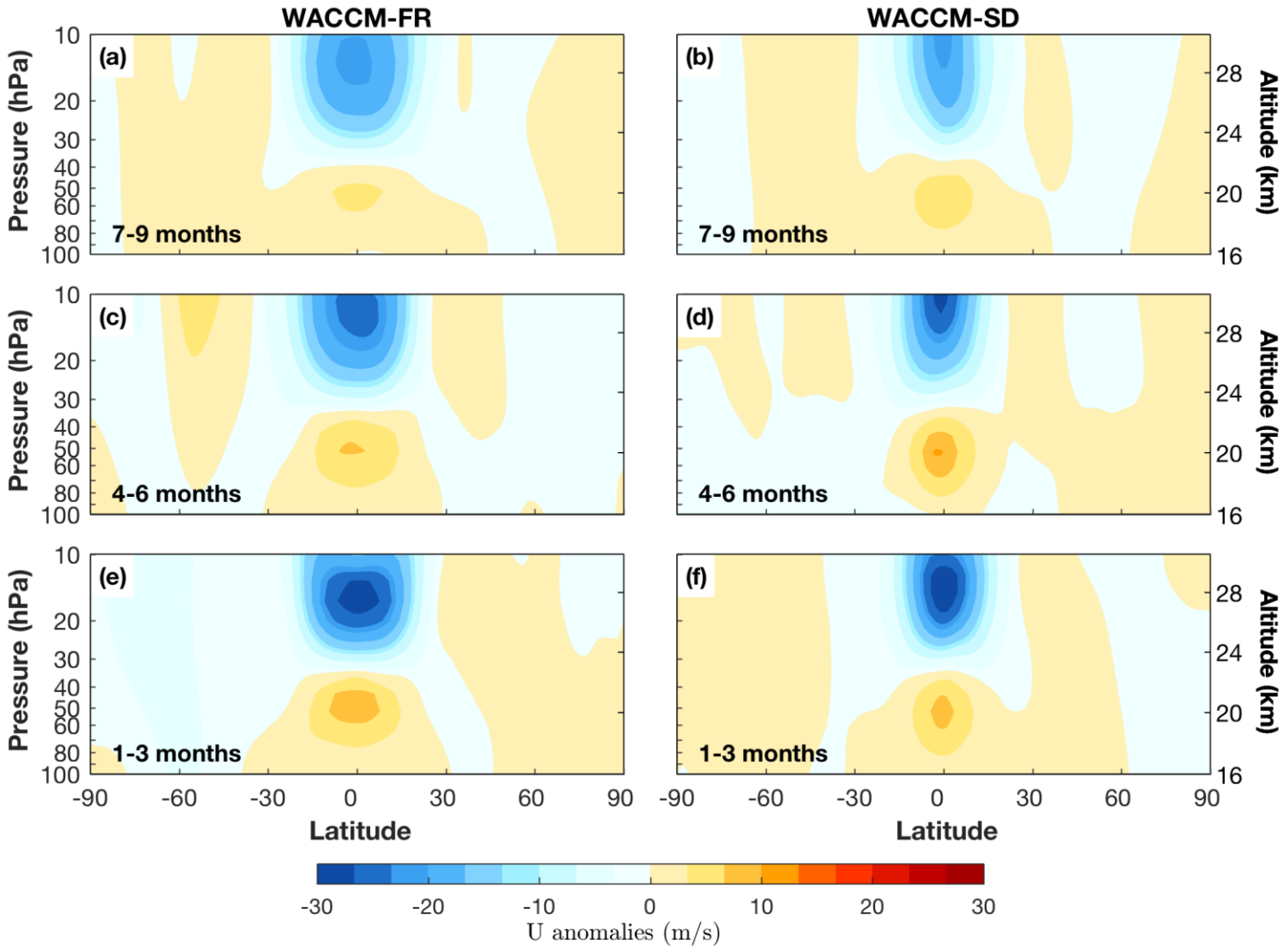
DJF AOA vs DJF shear index

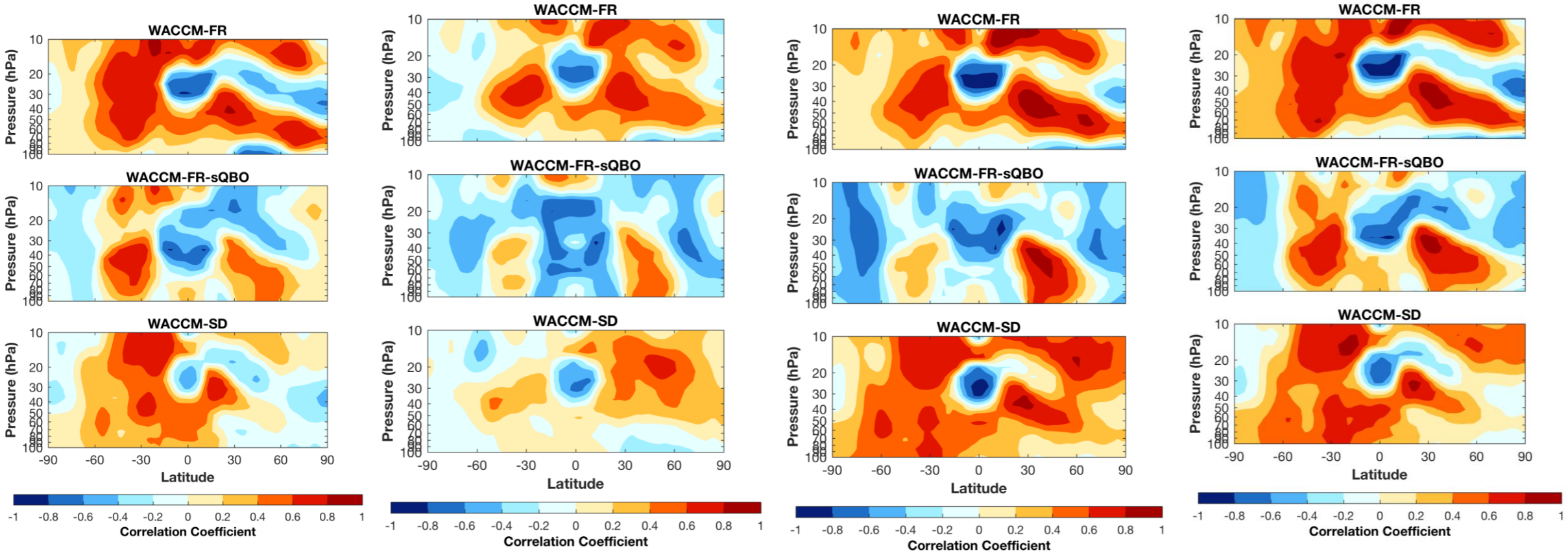


DJF ozone vs DJF shear index






WACCM-FR
WACCM-SD
(a)
(b)
(c)
(d)
(e)
(f)
7-9 months
4-6 months
1-3 months
Pressure (hPa)
Altitude (km)
Latitude
U anomalies (m/s)



Annual mean ozone vs MAM, JJA, SON, DJF shear index