Atmospheric Dynamics Presentation (10/25/24)

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Jeffrey Jonas, Tiehan Zhou, Larissa Nazarenko, Gary Russell

Outline

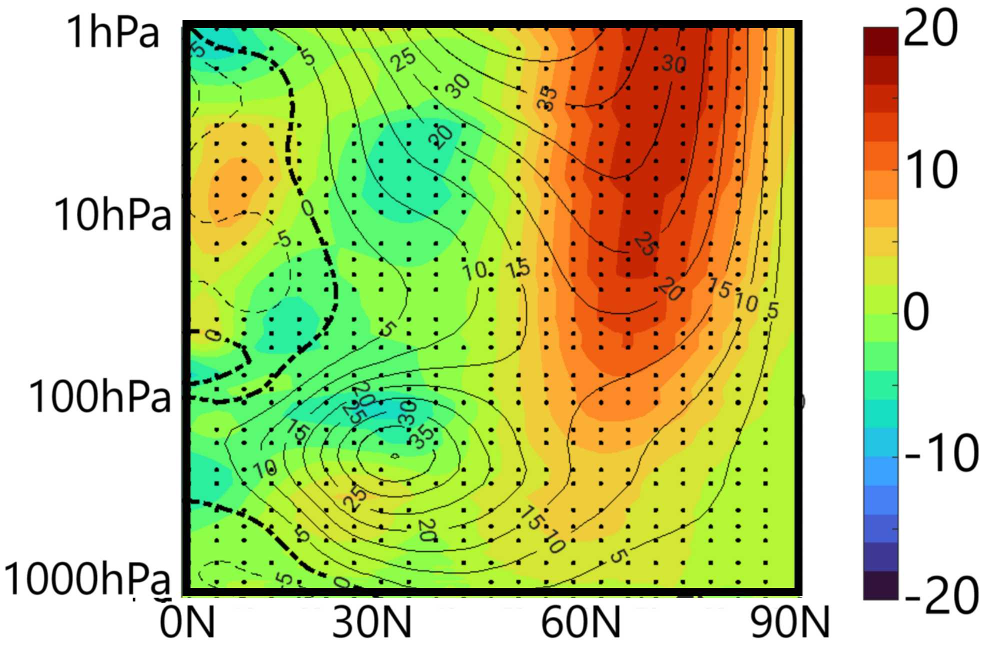
- New higher vertical resolution E2.2 runs (E2.2X) (APAM Postdoc Natasha Trencham) (12 minutes)
- Ozone feedback on the Brewer-Dobson Circulation (NPP Molly Menzel) (2 minutes)
- Sensitivities of E2.2 to Increased Mountain Drag (David Rind, Jeffrey Jonas) (8 minutes)
- Comparisons of E2.2 vs. E3 with ERA-5 (Tiehan Zhou, David Rind) (3 minutes)

Stratospheric Circulation Biases in E2.2

Problems with stratospheric dynamics in E2.2-AP (hereafter L102) as we know it:

- Strong northern hemisphere polar night jet/vortex (right)
  - Suppresses sudden stratospheric warmings (SSWs).
- Quasi-biennial oscillation (QBO) direct signal in the equatorial (lower) stratosphere is too weak
  - May be partly why we fail to see many QBO teleconnections, e.g. impact on NH polar vortex strength/SSWs in boreal winter (Holton-Tan Effect), impact on deep convection (Madden Julian Oscillation) in tropics in boreal winter.
- All of these are important, because of their impacts upon surface climate (SSTs, SLP, TSURF, etc.), mainly in the Northen Hemisphere during boreal winter.

NDJFM U
L102-MERRA2 [m/s]



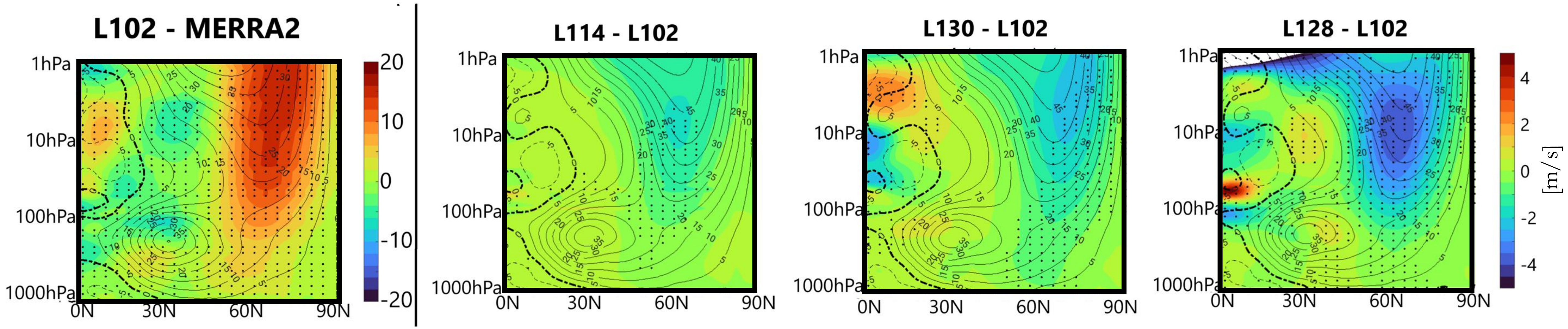
E2.2X Increased Vertical Resolution Experiments

- In an aim to decrease these biases, experiments with increased vertical resolution, mainly in the upper troposphere/lower troposphere (UTLS), were performed, as well as control simulation (**L102**):

Experiment Label	Region of increased resolution	Magnitude of resolution increase
L109	50-150hPa	2x
L114	**50-90hPa**	**3x**
L128	**50-150hPa**	**3x**
L130	**20-90hPa**	**3x**
L135	50-300hPa	2x
L156	50-150hPa	4x
L166	50-300hPa	3x

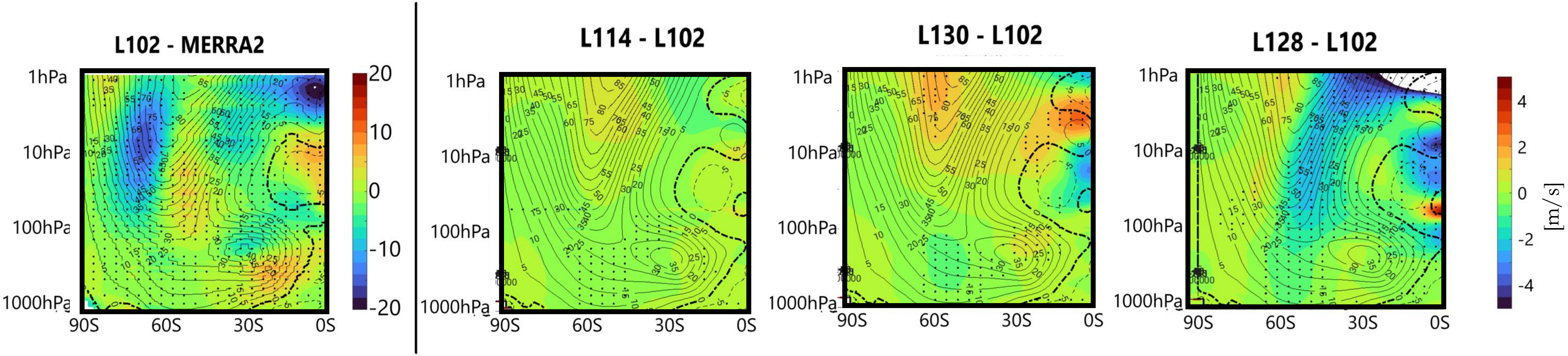
- Focus is on (100 years' worth of) coupled picontrol simulations using E2.2X (historical control simulation showed similar biases relative to MERRA2).
- Boldfaced experiment are highlighted because: (a) they all have same magnitude of resolution increase (3x) so comparison is easier, and (b) did not change resolution below UTLS region, as doing so might complicate interpretation of changes in tropospheric dynamics.

Results: Climatological Zonal Wind Changes (NH, NDJFM)



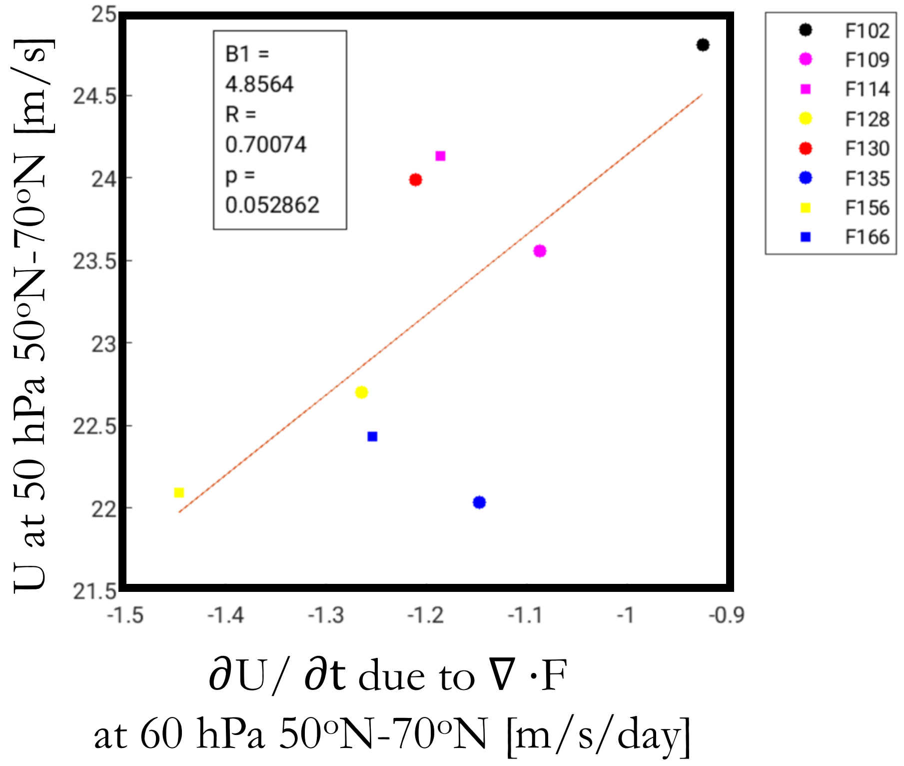
- Higher resolution simulations help to reduce climatological NDJFM biases of zonal winds, managing to:
  - Reduce polar vortex strength (all);
  - Reduced midlatitude jet strength (L130, L128);
  - Increased strength of subtropical jet around core (L130, L128).
  - Strongest response in L128, which had resolution changes extending into upper troposphere.

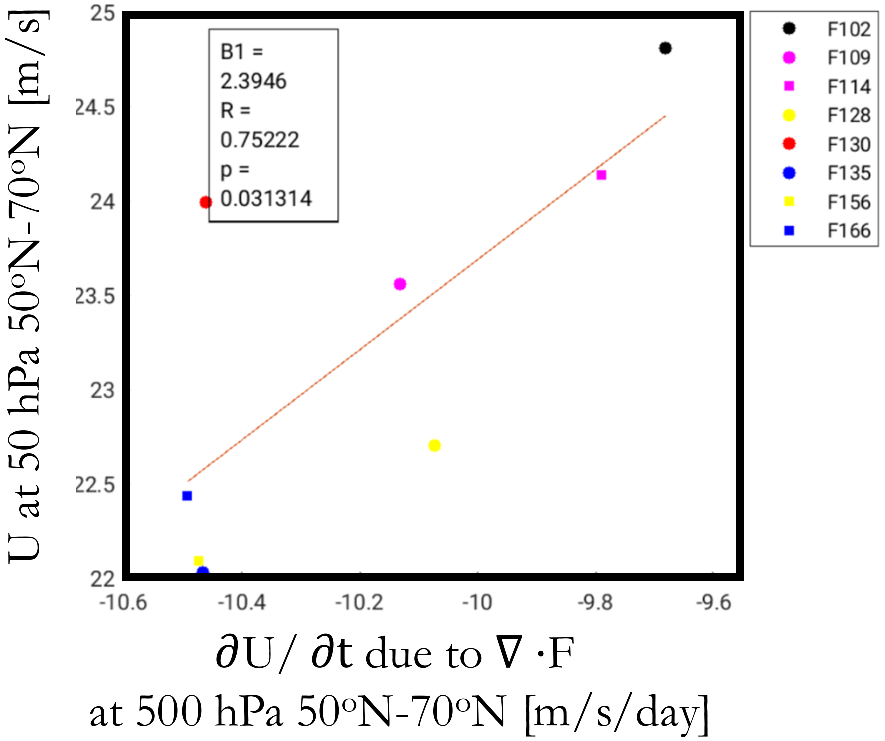
Results: Climatological Zonal Wind Changes (SH, JJA)



- Left: SH vortex shows almost opposite bias in L102 relative to MERRA2, showing a weakening and equatorward-shift. Similar weak, downward-shifted subtropical jet bias. Midlatitude tropospheric bias as big.
- L130 and, especially L128, help to reduce this bias in vortex. Explanation seems similar to NH winter (i.e. stronger wave midlatitude convergences, stratosphere + troposphere).

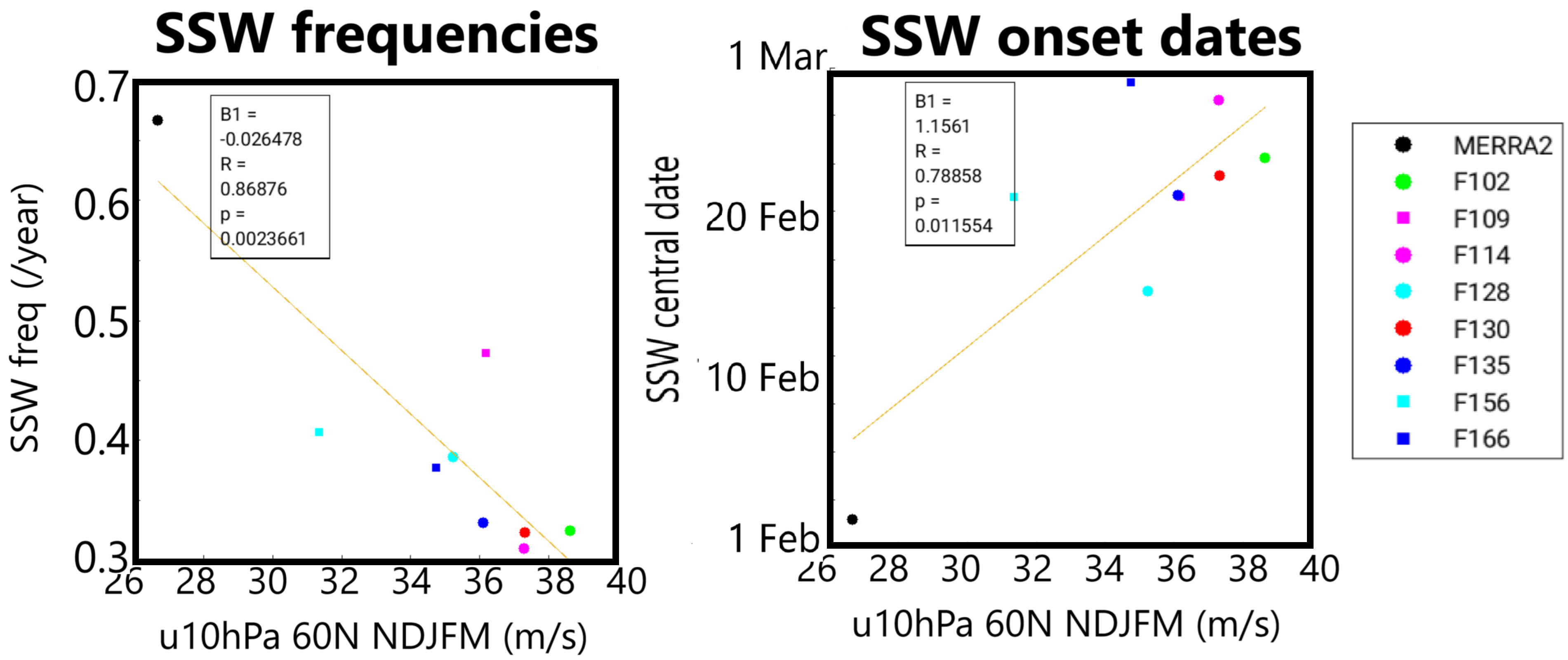
Results: Drivers of NH Vortex Strength Changes





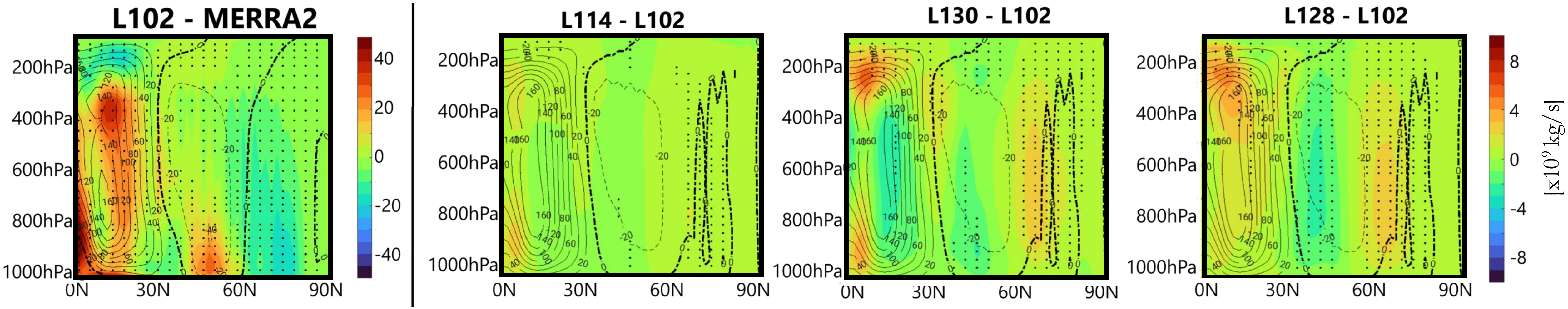
- Changes appears driven by stronger planetary waves (measured by Eliassen Palm (EP) flux convergence) around the vortex (left), extending down into the troposphere (right), driving easterly anomalies in midlatitudes.
  - Wave convergence is stronger in models with vertical resolution changes extending into the troposphere (L128, L135, L156, L166).
- Eddy-mean flow feedbacks then drive anomalous westerlies in subtropics to compensate/preserve angular momentum.

Results: Climatological SSW Frequencies & Timings



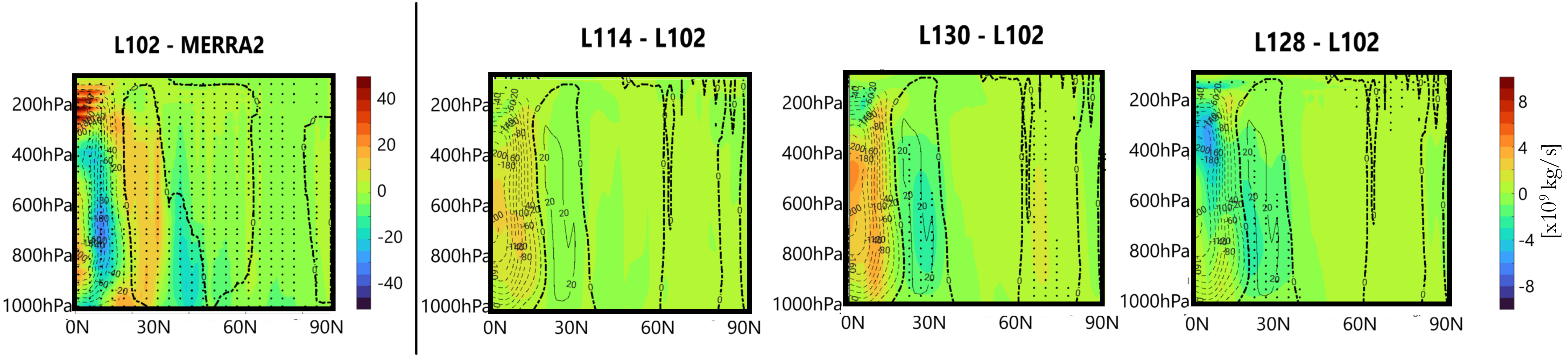
- F102 vs MERRA2 (green vs black dots): Due to strong NH vortex, SSWs much less frequent and later in season;
- HR models: Reduced vortex strengths cause more frequent, earlier SSWs. Greatest changes in F128/F156 (enhanced resolution in UTLS region).
  - Note: this is in spite of these models showing *reductions* in midlatitude eddy activity.

Results: Tropospheric Impacts – Mass Streamfunction (NH, NDJFM)



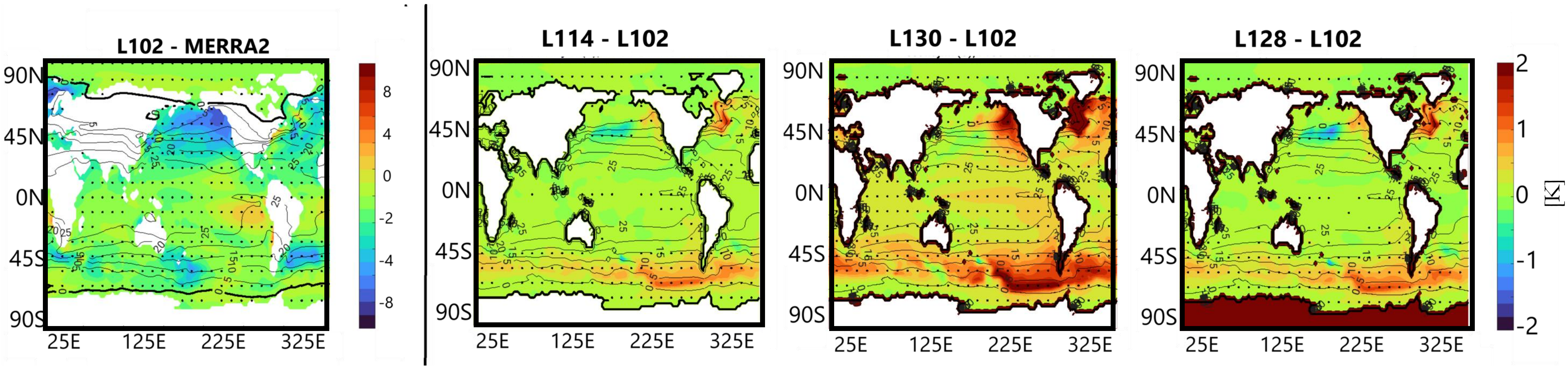
- Left panel: relative to MERRA2, L102 features an anomalously strong NH Hadley cell in boreal winter, and poleward-shifted and weakened Ferrel cell, in-line with poleward-shifted and weakened midlatitude jet.
- L114 shows no change, in line with lack of tropospheric zonal wind response.
- L130/L128 both show reduced bias in Ferrel cell, in-line with reduced bias in midlatitude jet.
- Different responses in Hadley cell, with L130 showing weakening of poleward flank (better), L128 a strengthening (worse). Correlate with different zonal wind anomalies in tropics.

Results: Tropospheric Impacts – Mass Streamfunction (NH, JJA)



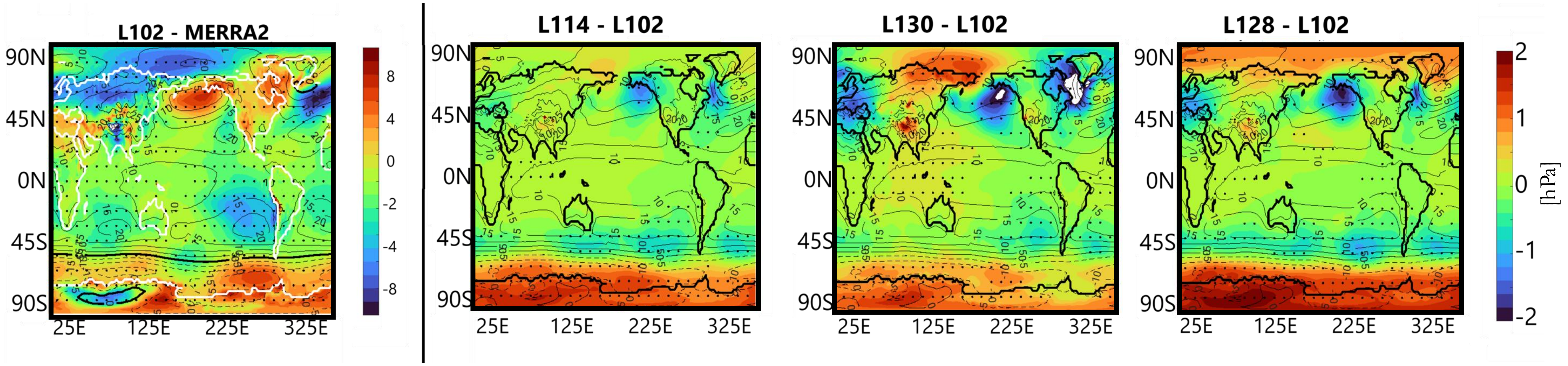
- Left panel: in NH Hadley cell appears anomalously strong and equatorward-contracted relative to MERRA2.
- L130/128 appear to help poleward-expand summer Hadley cell. Don't really help with bias in Hadley cell strength.

Results: Climatological Surface Impacts – Sea Surface Temperatures (NDJFM)



- Left: L102 exhibits cold biases in midlatitudes, maximizing around boundary currents, where dSST/dx large. Warm/Cold bias in tropical East/West pacific.
- Higher resolution runs improve extratropical cold biases (largest in L130). No detectable improvement in tropical east/west bias.
- Annual mean picture similar.

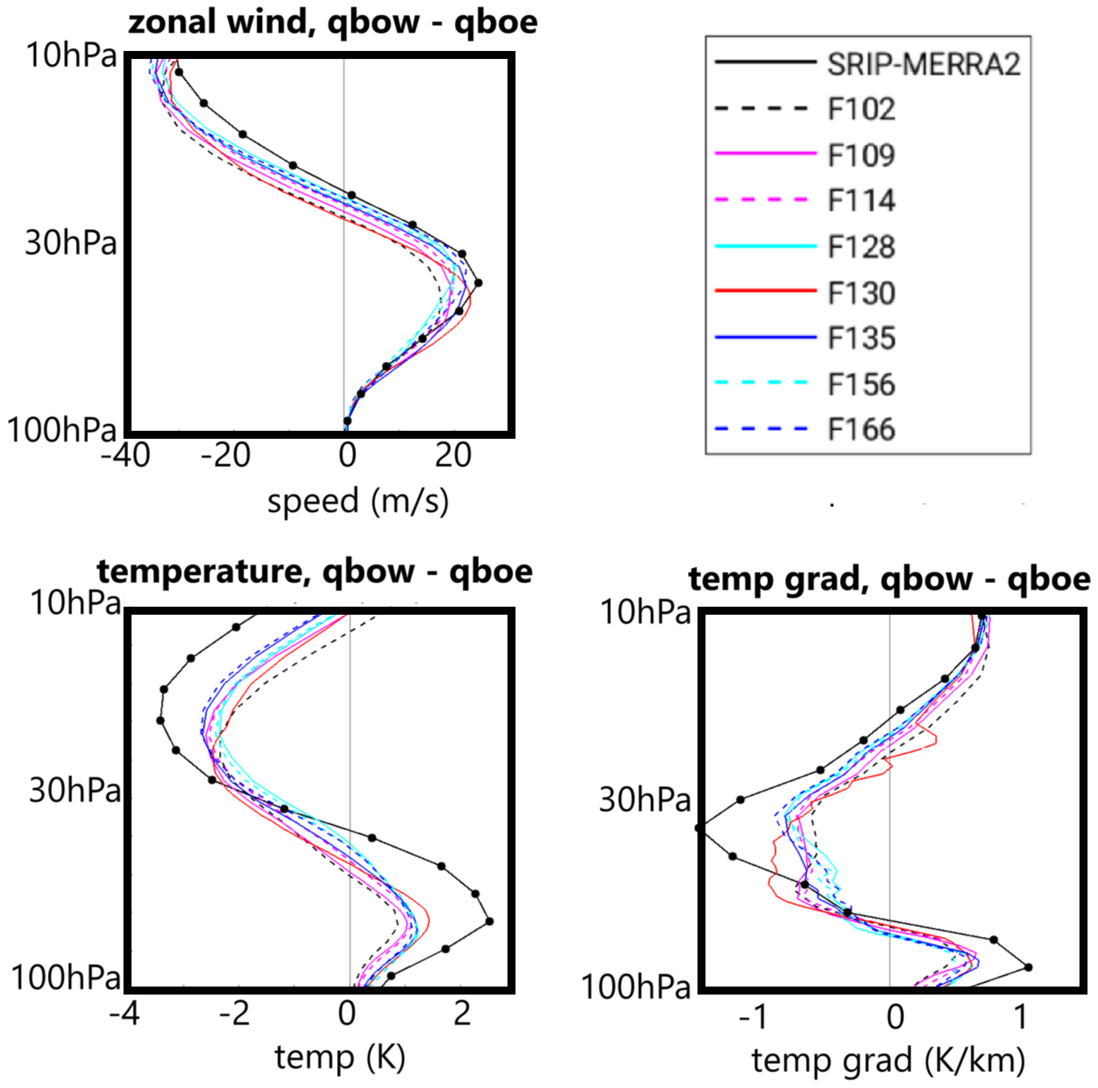
Results: Climatological Surface Impacts – Sea Level Pressures (NDJFM)



- Left: L102 shows a weakened Aleutian low/Siberian + Arctic high, and weakened zonal SLP gradient in East/West Pacific. All in agreement with SST biases.
- Similar to SST biases, higher resolution runs do reduce the NH extratropical SLP biases, probably greatest improvement in L130. Slight further degradation of tropical pacific East/West SLP gradient bias.
- Annual mean shows similar picture with weakened anomalies in NH extratropics.

Changes in QBO structure

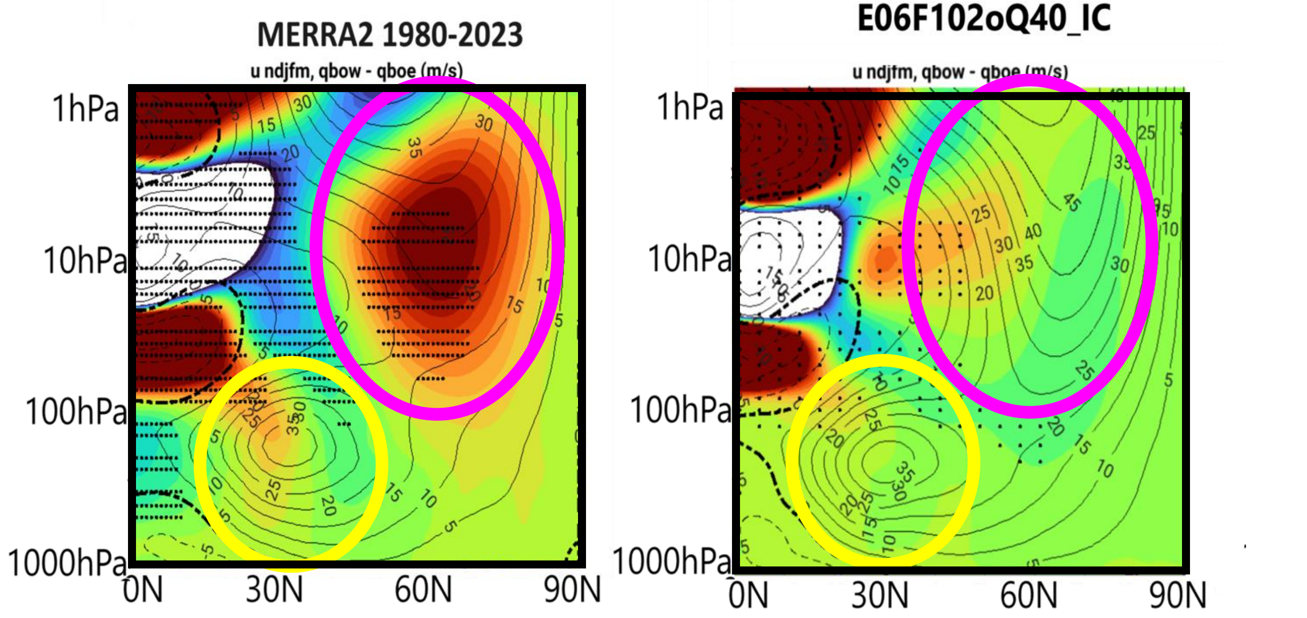
- F102 vs MERRA2 (black dashed vs solid lines): underrepresents zonal wind anomalies 20-50hPa, and temperature and dT/dz anomalies throughout stratosphere;
- HR models:
  - Improve zonal wind anomalies, mainly 20-50hPa;
  - Struggle to impact T and dT/dz anomalies in lower stratosphere.
    - Interactive ozone configurations (OMA, LINOZ) are more effective at this (DallaSanta et al. (2021)).
    - This may partly explain apparent lack of QBO modulation of tropical convection (e.g. MJO) in these models.

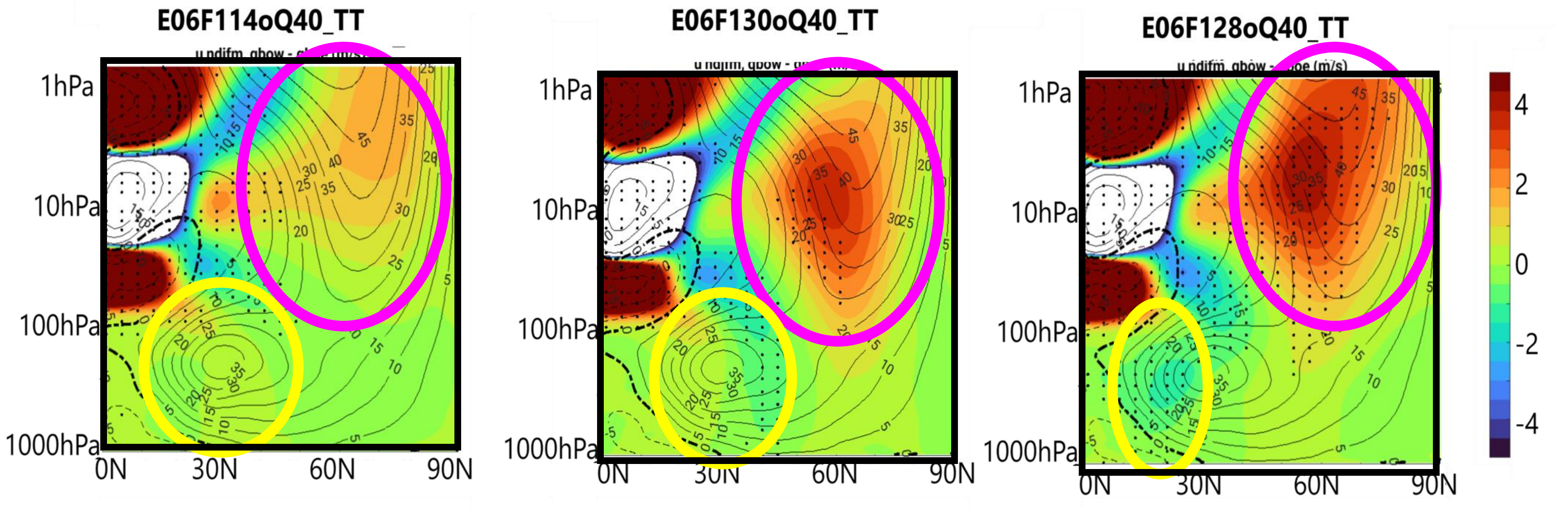


Result: QBO Impacts – Zonal Winds

- MERRA2: NH polar vortex strengthened and subtropical jet (STJ) equatorward-shifted during QBOW vs QBOE;
- F102: STJ slightly stronger, but not the vortex, during QBOW;

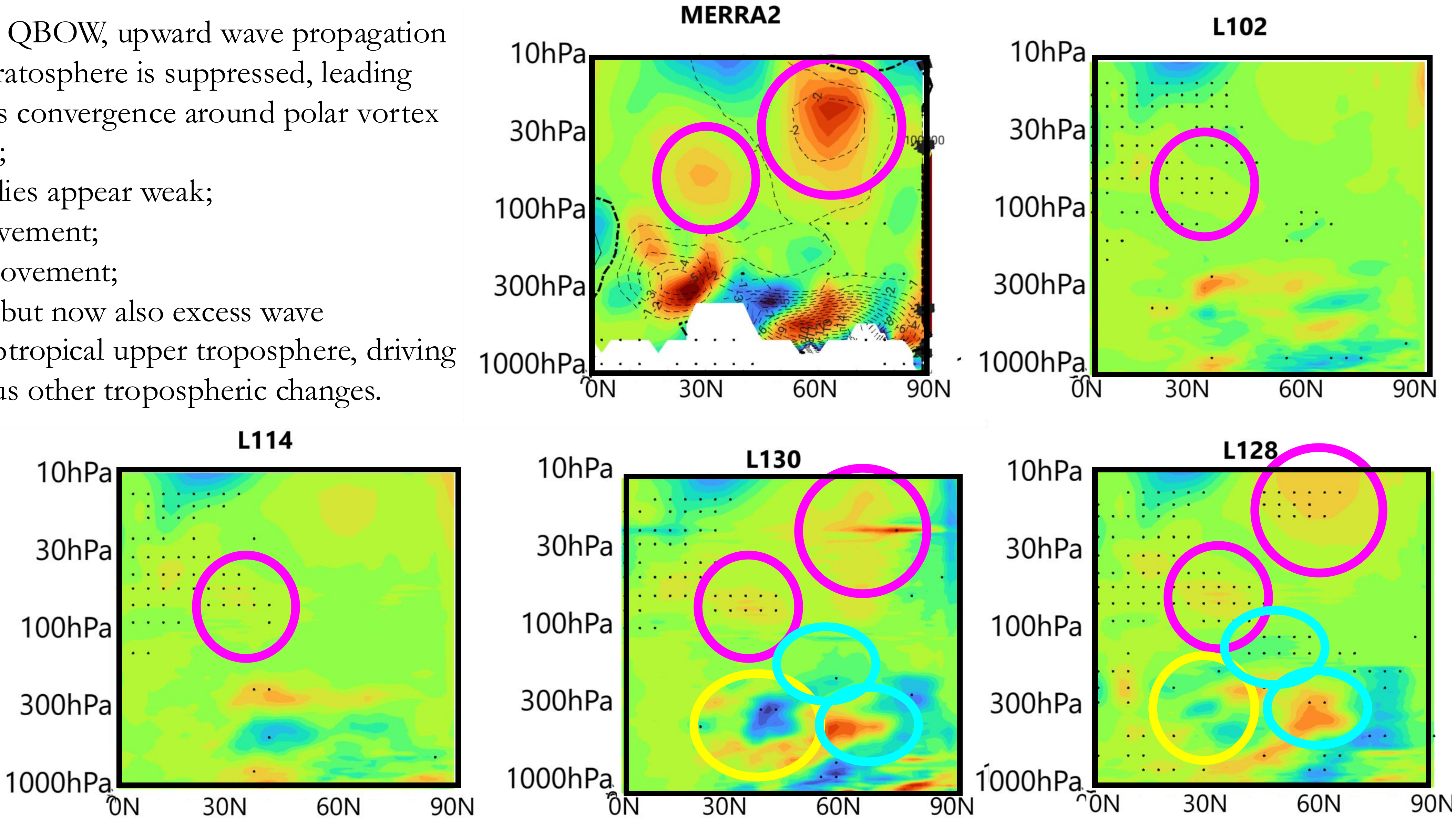
- HR models:
  - F114: No change
  - F130: Vortex stronger, slightly improved STJ equatorward-shift;
  - F128: Vortex even stronger BUT STJ now weaker.





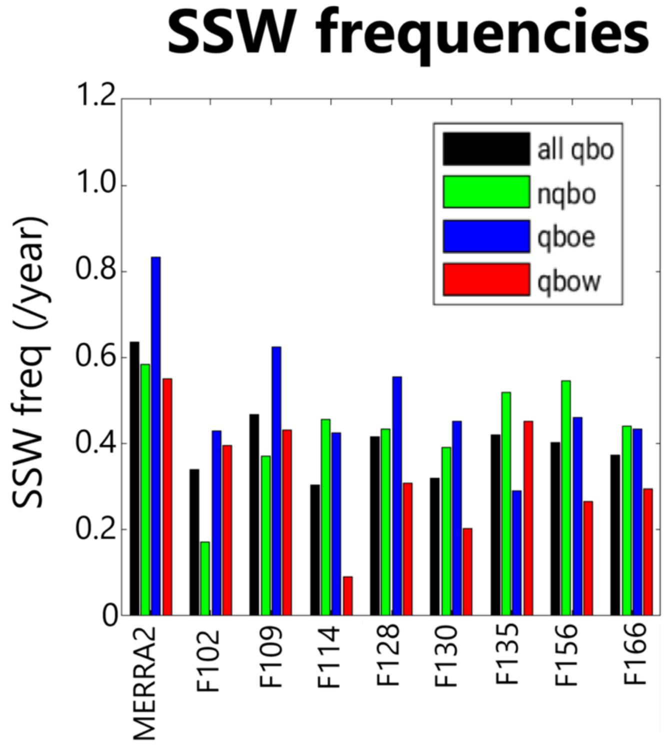
Drivers of Holton-Tan Changes

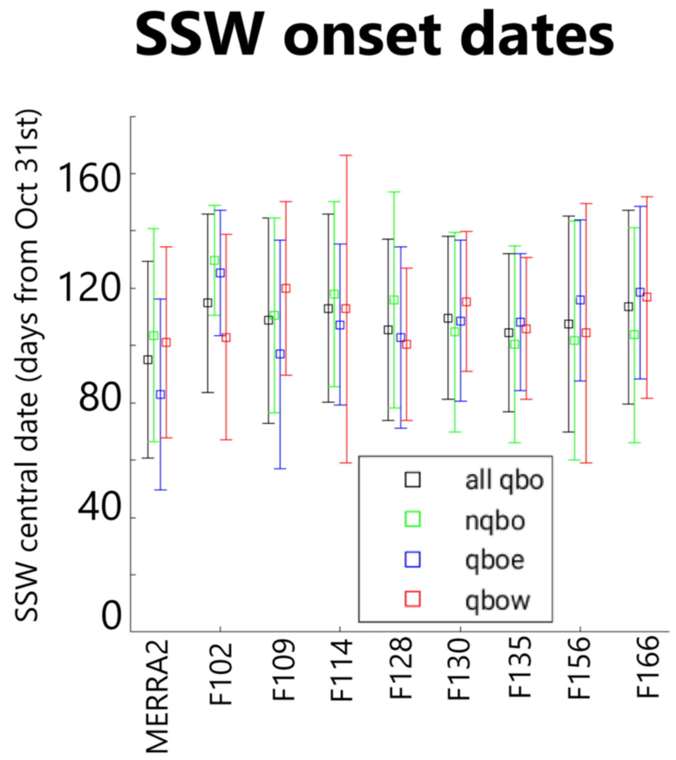
- MERRA2: During QBOW, upward wave propagation into subtropical stratosphere is suppressed, leading downstream to less convergence around polar vortex so net acceleration;
- F102: both anomalies appear weak;
- F114: some improvement;
- F130: greater improvement;
- F128: even better, but now also excess wave convergence in subtropical upper troposphere, driving STJ weakening, plus other tropospheric changes.



Results: QBO Impacts - SSW frequencies & Timings

- MERRA2: more frequent and earlier SSWs on average during QBOE vs QBOW;
- F102: No real difference in SSW frequencies, earlier onset during QBOW;





- HR models: Most (all but F135) show enhanced frequency during QBOE vs QBOW; no real difference in timings.
  - QBOI nudging experiments found similar results;
  - Frequencies often greatly amplified during QBOE/ENINO, so even greater improvement in frequencies vs. QBOW/ENINO.

Key Points: Higher Vertical Resolution (HR) Experiments

- HR runs help to improve the following model biases/discrepancies in E2.2:
  - Too strong/weak polar vortex in NH/SH wintertime;
  - Too infrequent, late SSWs in NH;
  - Poleward-displaced NH midlatitude jet and circulation during wintertime;
  - Cold extratropical SSTs;
  - Weak sea level pressure anomalies in NH extratropics;
  - QBO zonal wind anomalies down to ~50hPa;
  - Lacking QBO modulation of NH polar vortex strength and SSW frequencies.

- Some HR runs do help with the following model biases:
  - Insufficient QBO modulation of NH subtropical jet position (F130).

- HR runs do not generally help with the following model biases:
  - A Hadley circulation which is too strong/weak in boreal wintertime/summertime;
  - Weak QBO anomalies in temperature, dT/dz and vertical velocity in UTLS region;
  - QBO modulation of SSW timings.

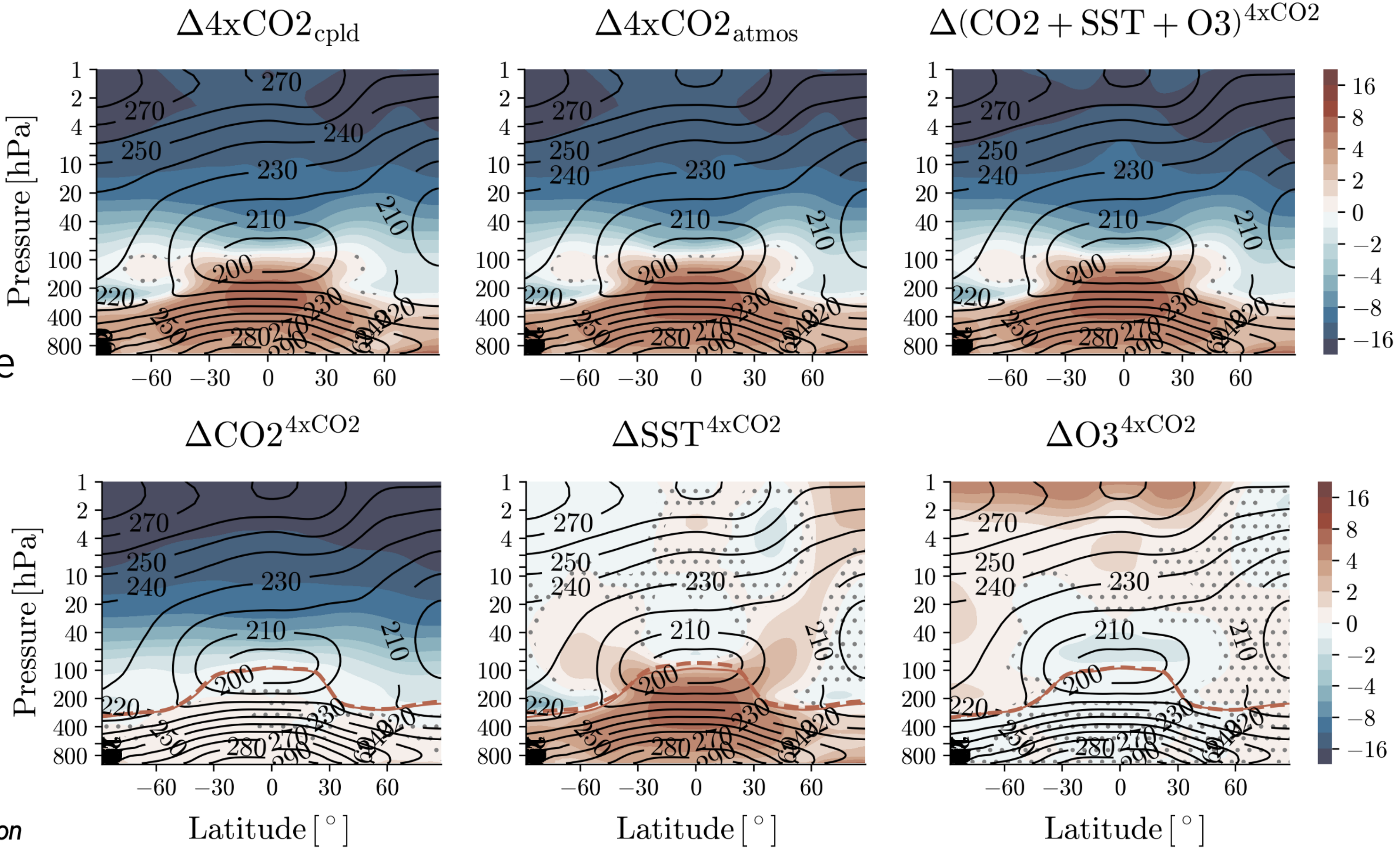
Decomposing the Coupled Response to 4xCO2

Idealized simulations isolate the impact of warming and composition responses to 4xCO2.

Validation of Decomposition

Coupled =
Direct CO2 Radiative
+ Surface Warming
+ Interactive Ozone

Isolated Perturbation Simulations



Menzel et al. *in preparation*

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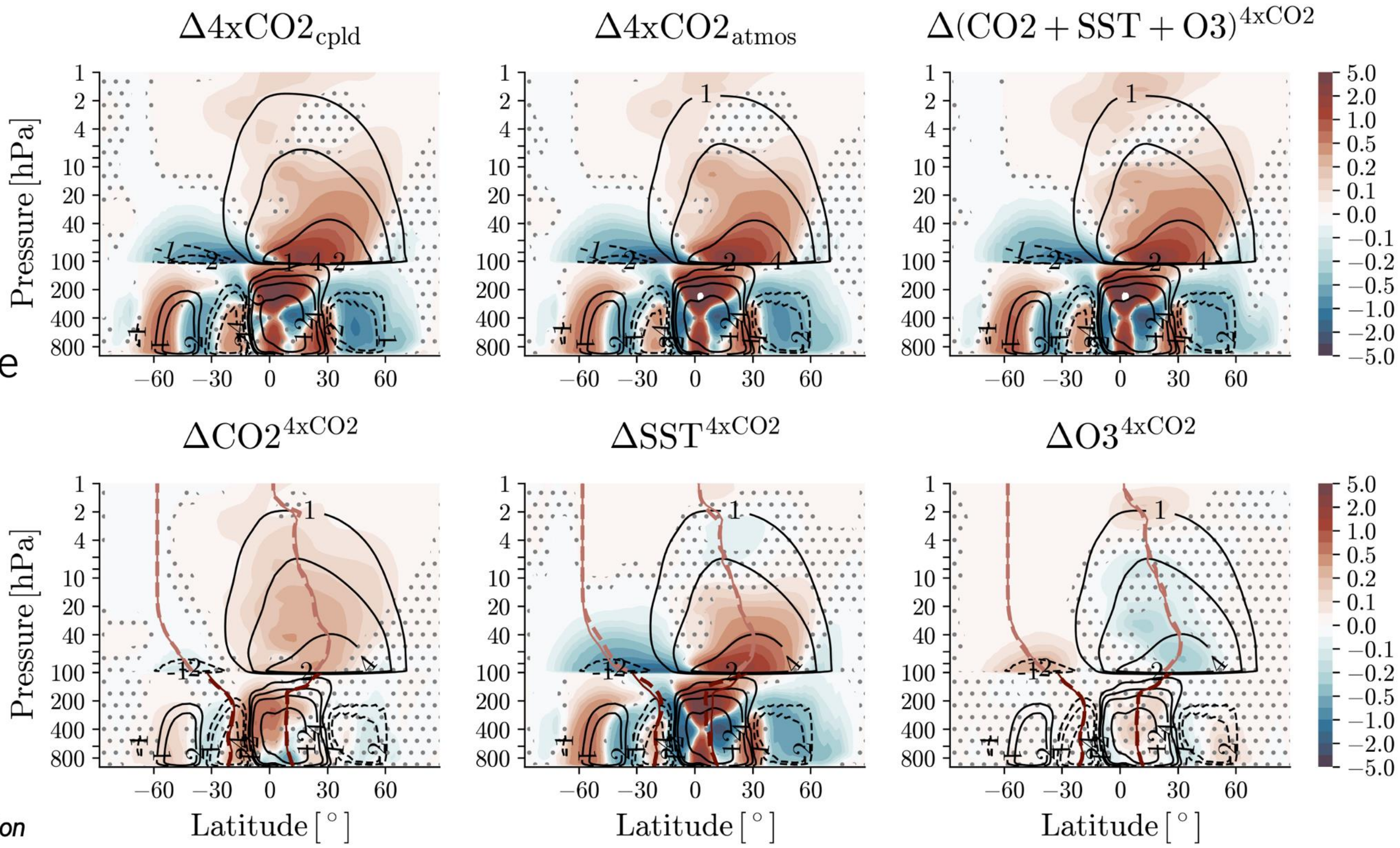

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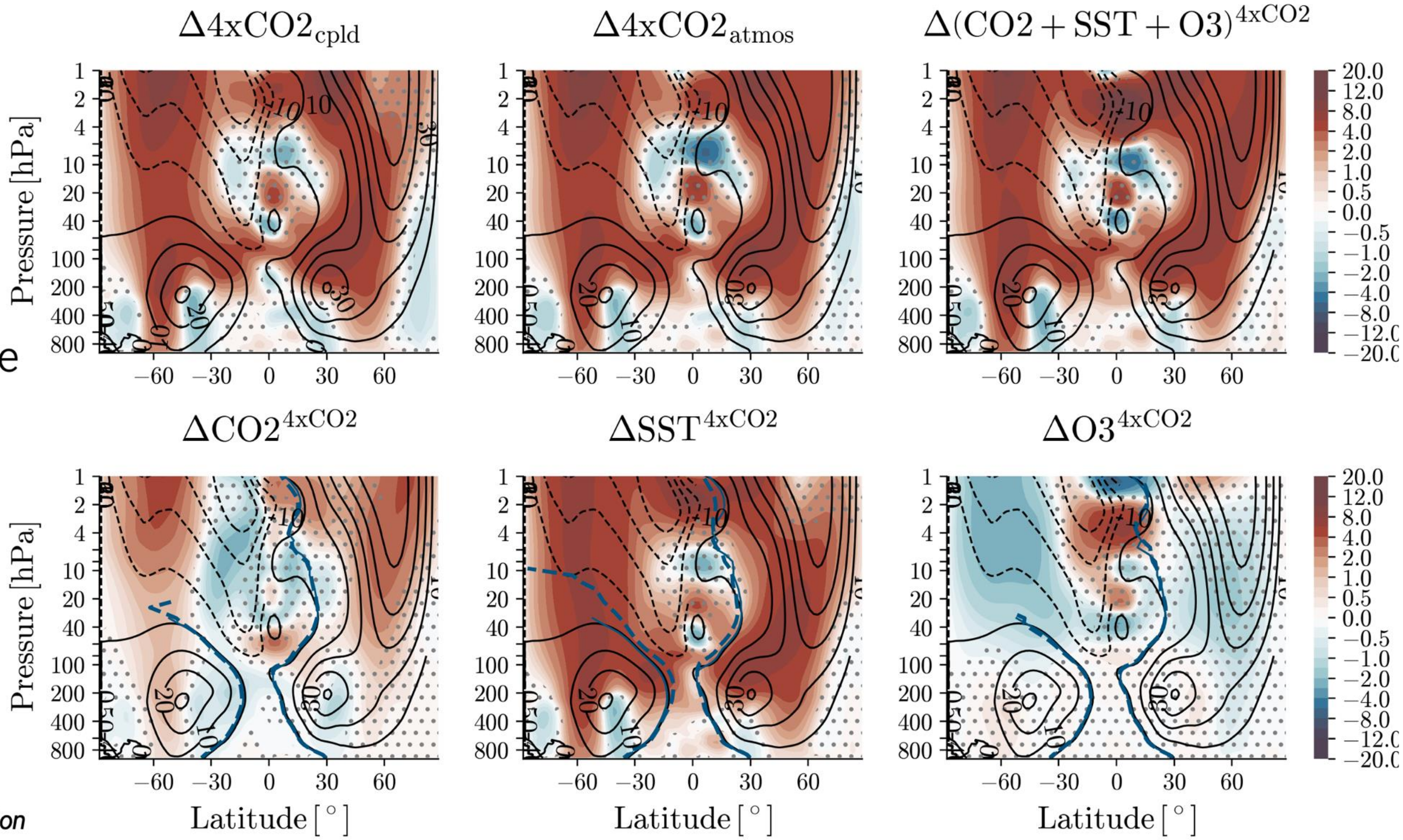
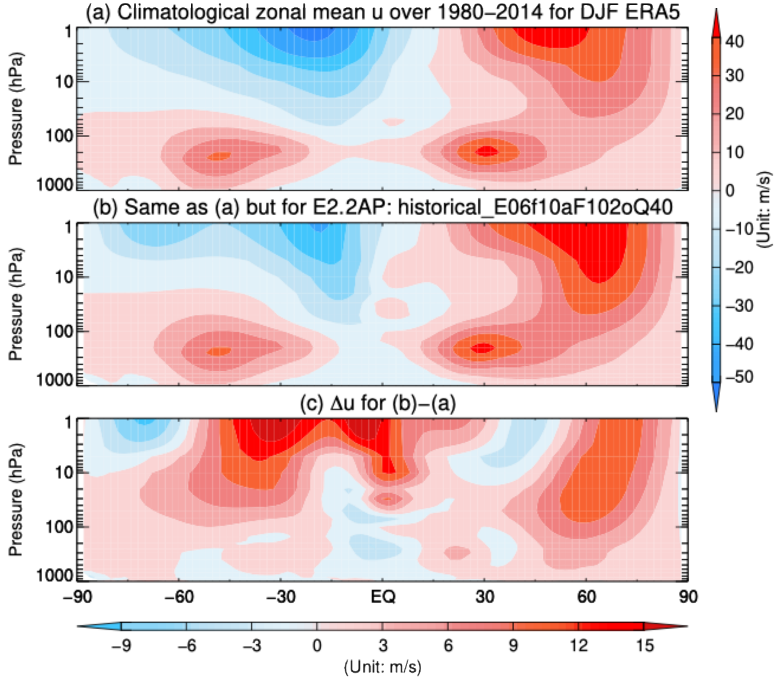


Menzel et al. *in preparation*

Strat Warmings and Tropospheric Response

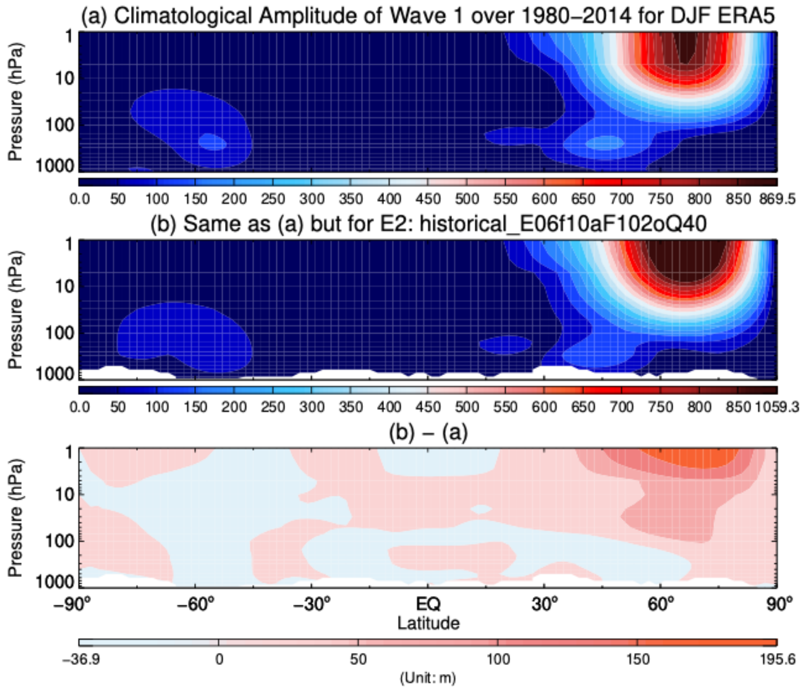
Also (eventually) Change with Climate

- Goal is to assess how SSWs influence the troposphere, i.e., ‘cold air outbreaks in winter, and how it changes as climate changes.
- First requirement is that one gets the proper number of SSWs, and also that they propagate downward sufficiently in the stratosphere to influence the troposphere.
- Number of SSWs, defined as occurrence of east winds at 10 hPa and 60°N during November through March, depends on the strength of the polar vortex; if it is too strong westerly, harder to get winds reduced to east.
- Comparison to ERA5 shows model west winds too strong by ~12 m/s

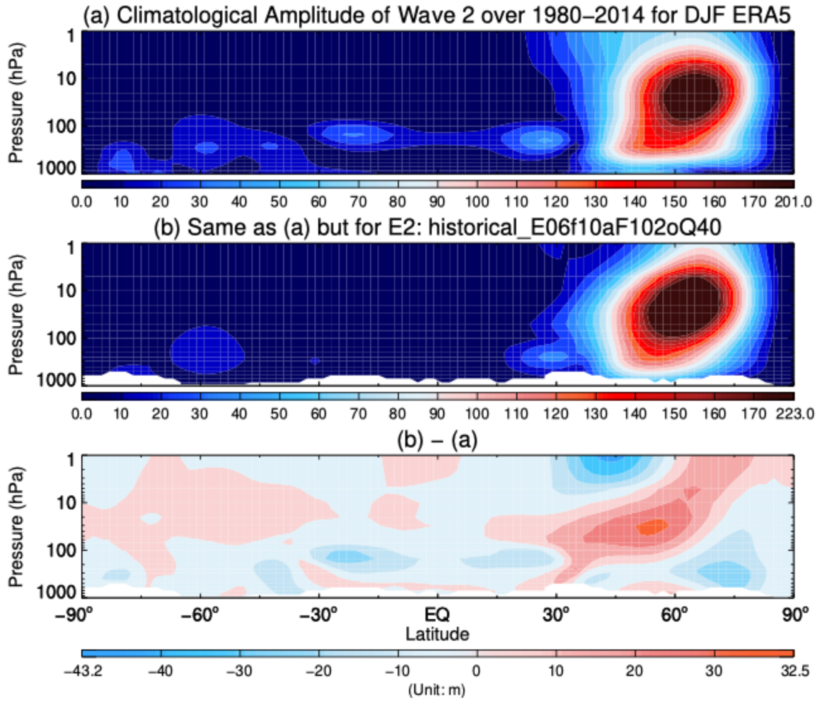


WHY ARE THE ZONAL WINDS TOO STRONG?

- One possibility is that the planetary longwave amplitudes, particularly wave #s 1 and 2, are too weak.
- Comparison with ERA5 shows they are not too small in the region above 100 hPa



WAVE #1

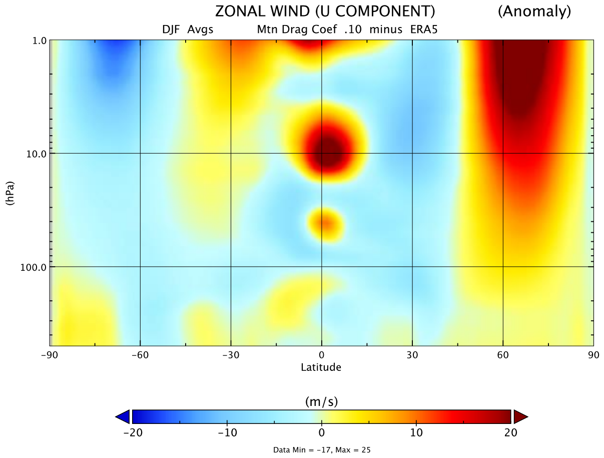


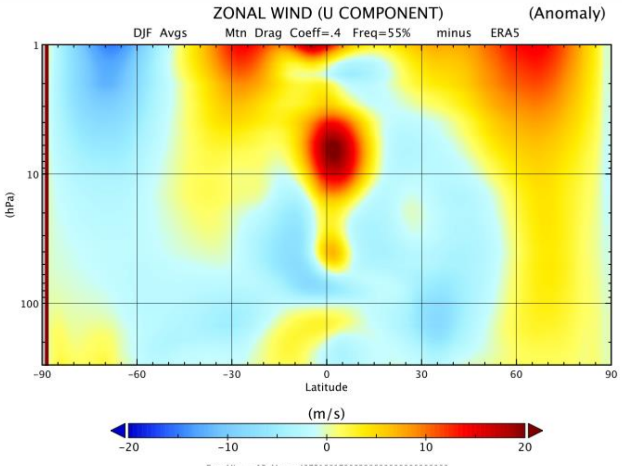
WAVE #2

- Andrews and McIntyre (1976) Non-interaction theorem suggests that for waves to affect the mean flow there needs to be dissipation or transience. Maybe there is not enough dissipation.
- The mountain drag was increased to ‘optimum’ levels (by increasing their frequency and strengthening their drag coefficient), to produce a weaker polar vortex. It does this by acting directly on zonal winds and by allowing planetary waves to act on them also.
- It did reduce zonal winds, although they are still a little too strong (~5 m/s) as is the polar vortex strength

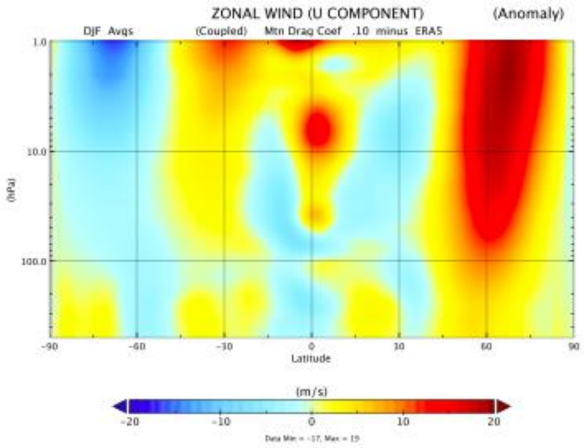
CONTROL

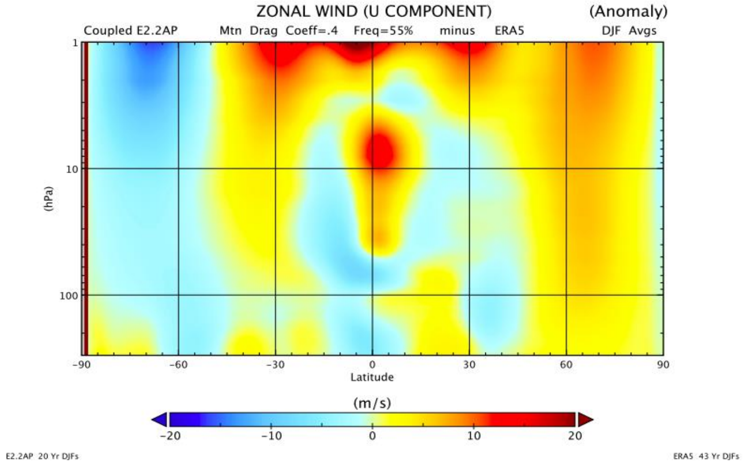
OPTIMIZED





AMIP





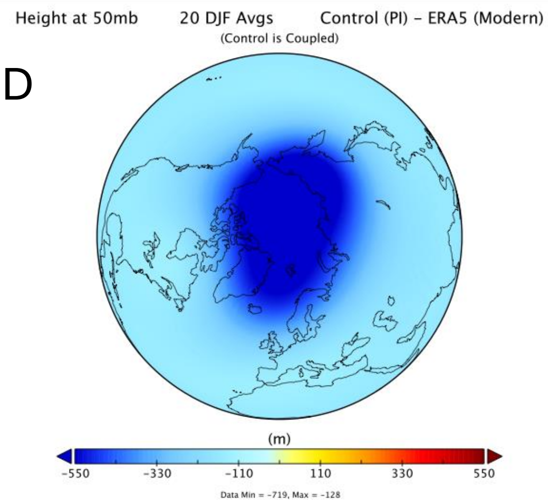
COUPLED

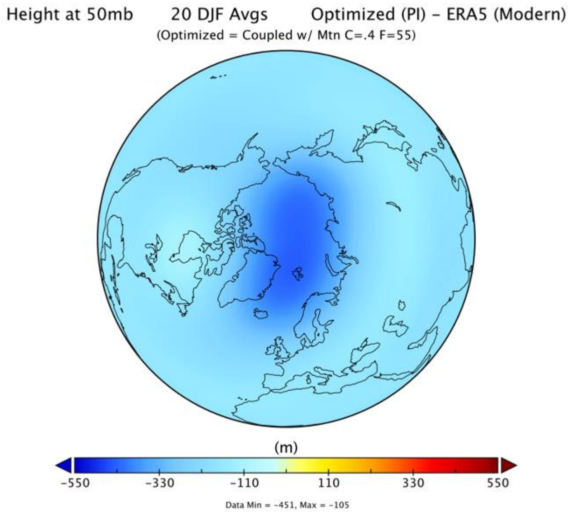
Other experiments, particularly removing the UV filter on the winds, seems to help further, as seen in the 50 hPa polar vortex

CONTROL

OPTIMIZED

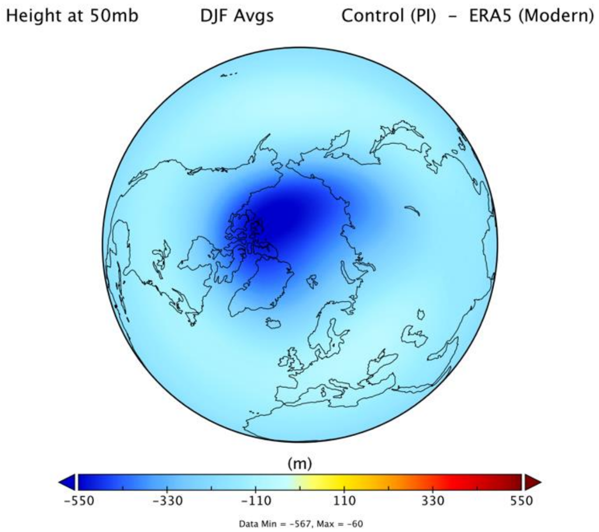
COUPLED

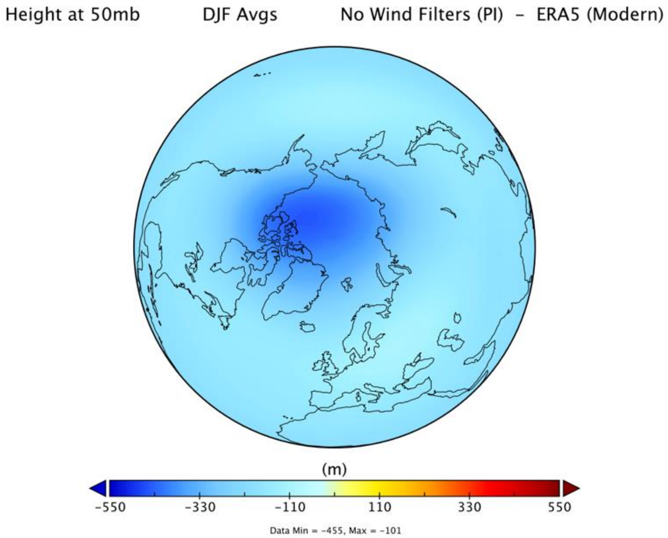


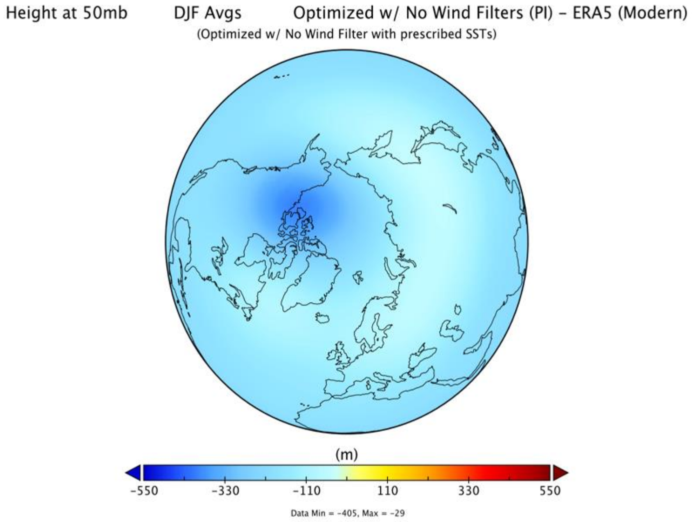


OPTIMIZED + NO UV FILTER

AMIP

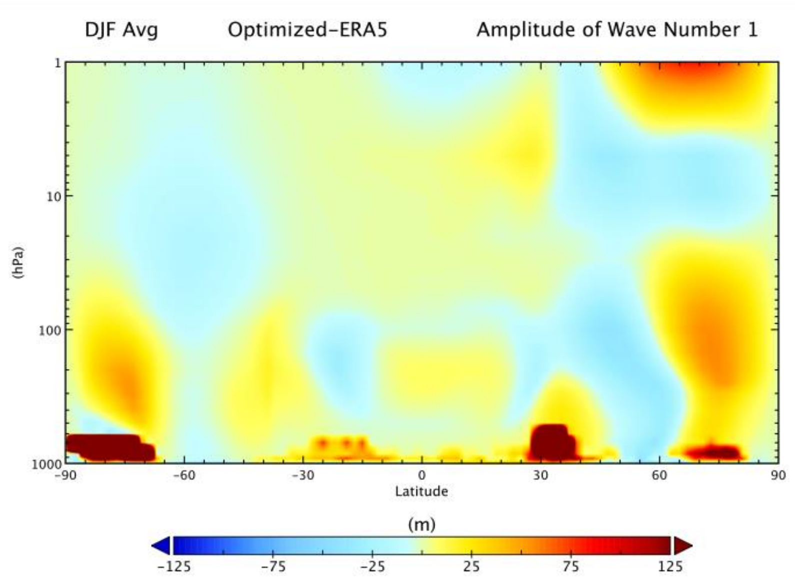


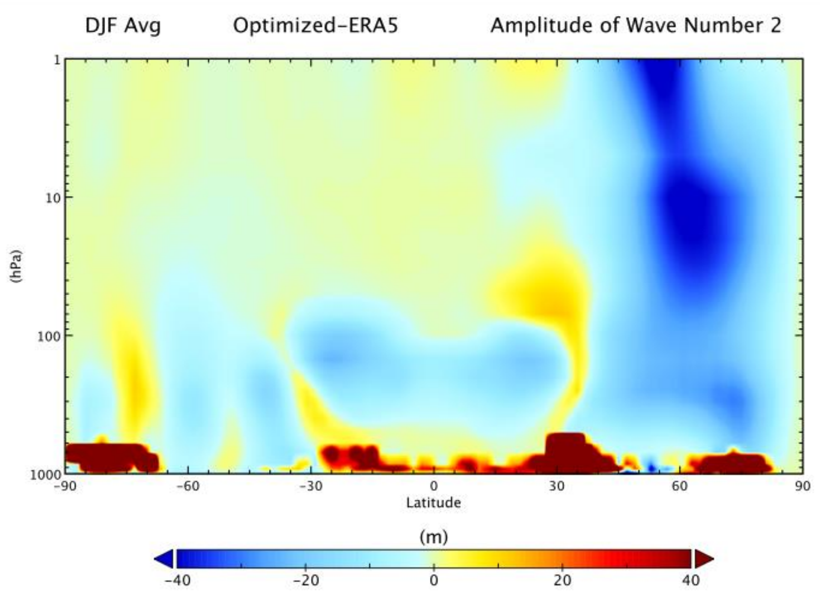




HAVE WE MADE ANY PROGRESS?

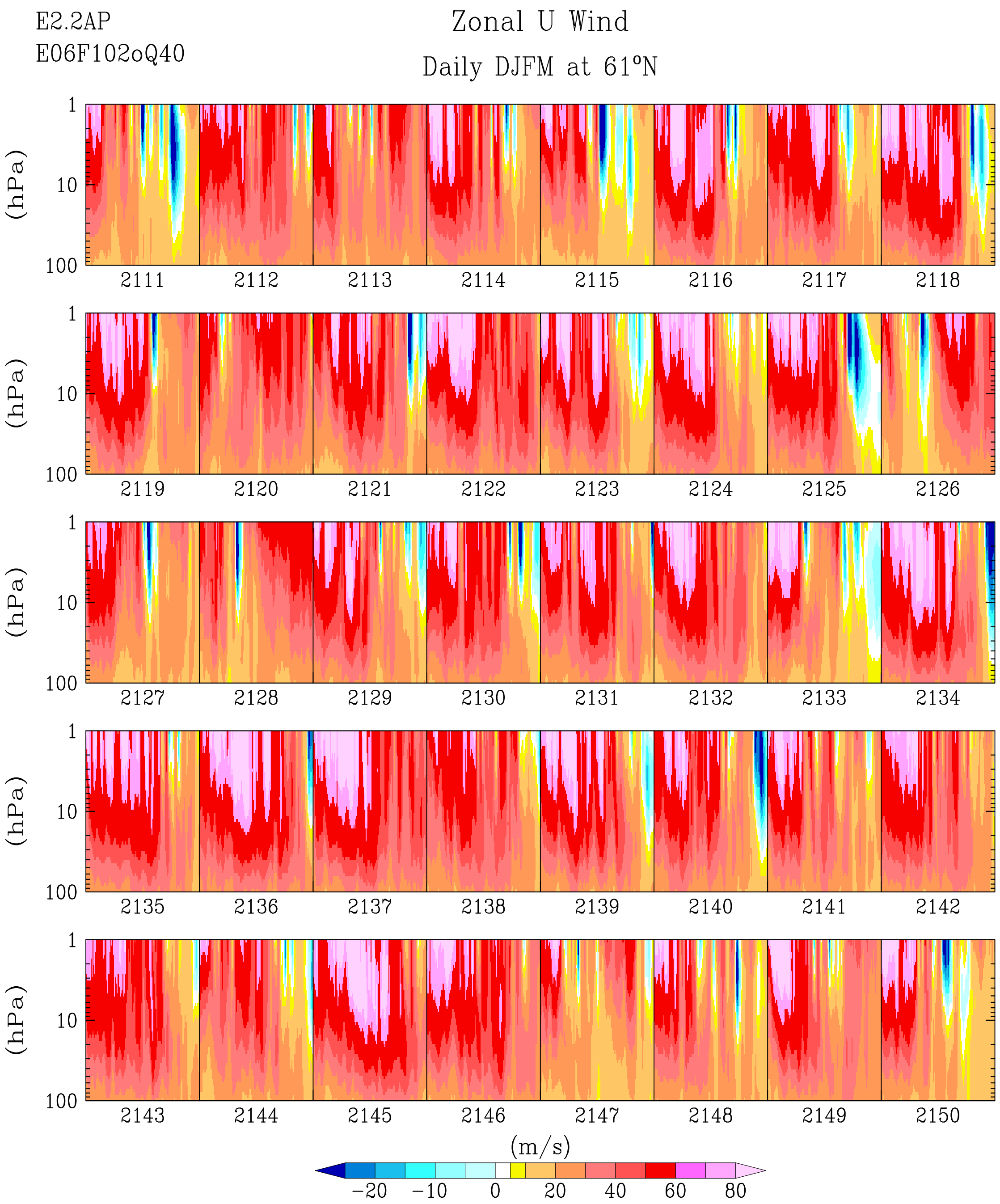
- Standard model is deficient in number of SSWs
  Observed: 62% of winters; Model: 49%
- Optimized model is better – 65% of winters
- Optimized Model does seem to have more downward propagating events, as can be seen in zonal wind record and by using Polar Cap Height anomalies
- Greater mountain drag does reduce planetary wave amplitudes, especially wave #2 (wave #1 was too large before).



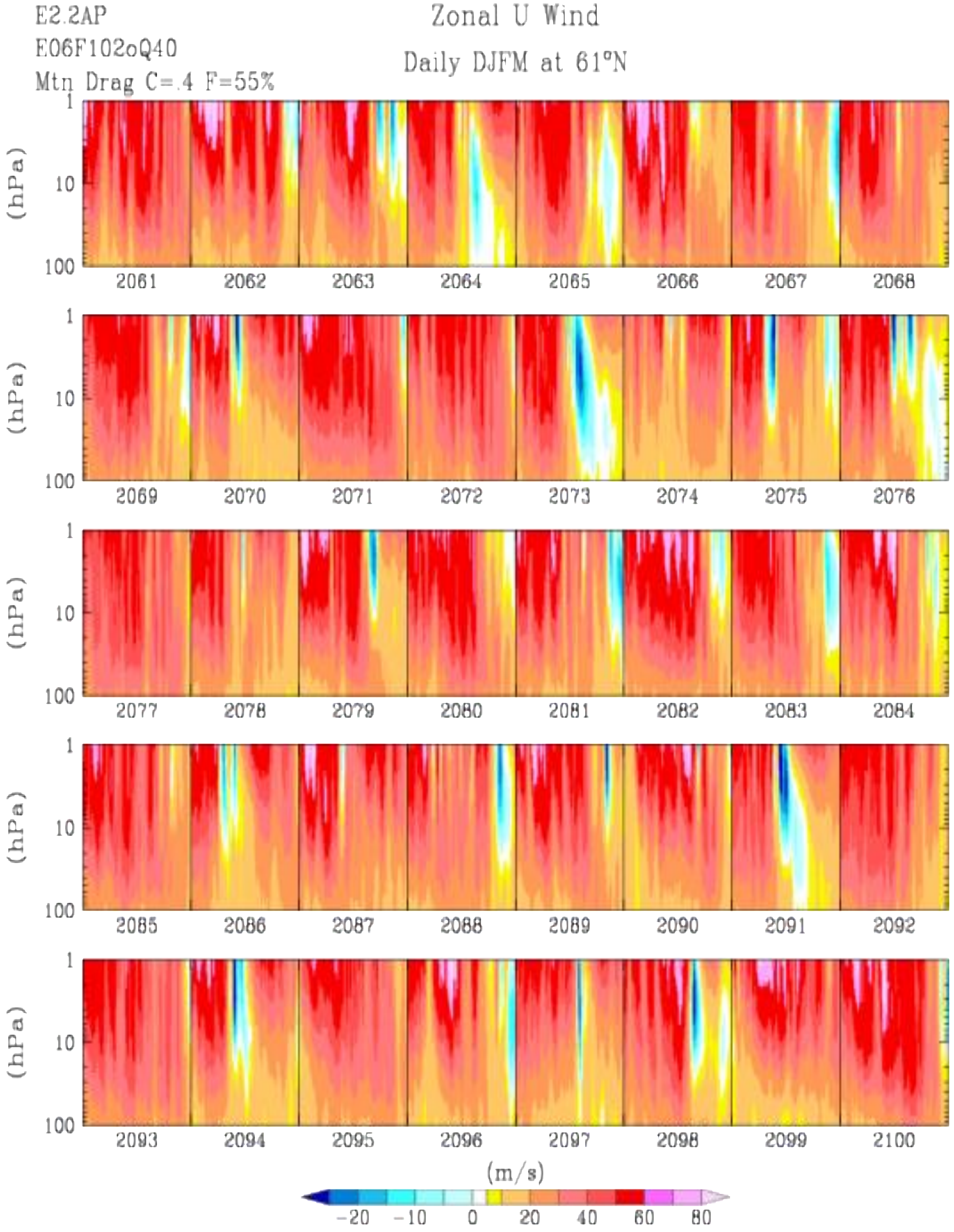


Now 20% below observations

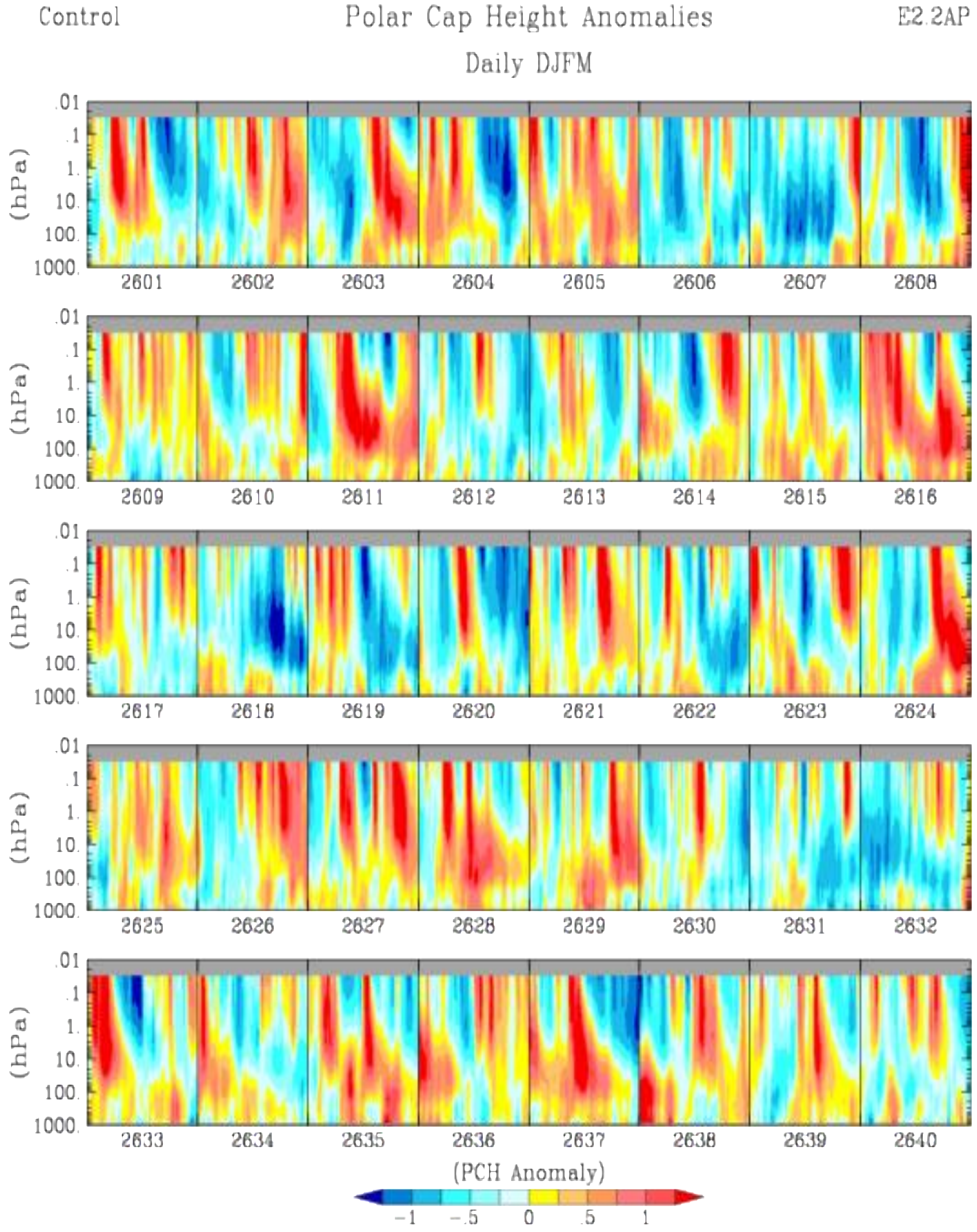
CONTROL



OPTIMIZED



CONTROL



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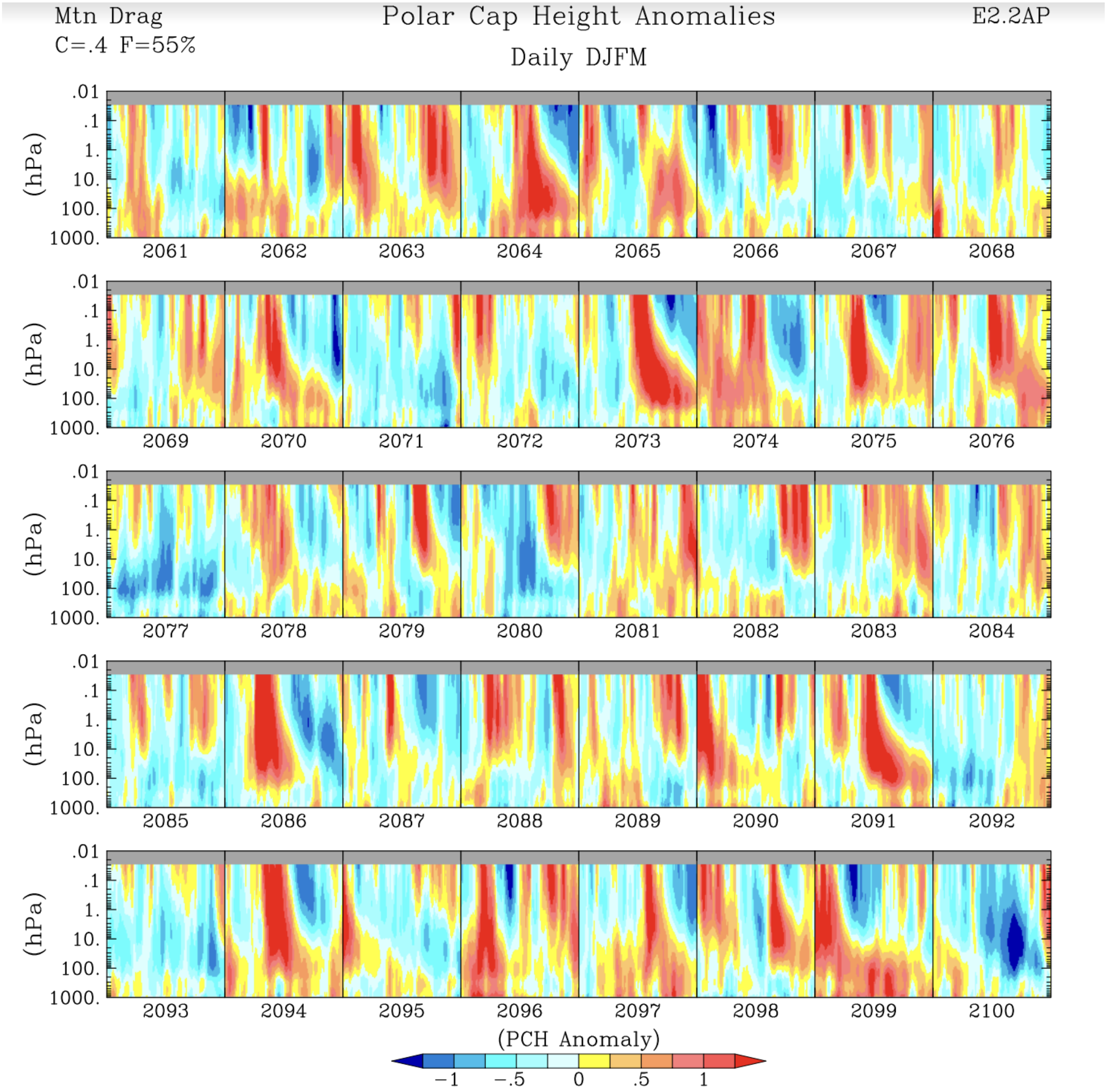
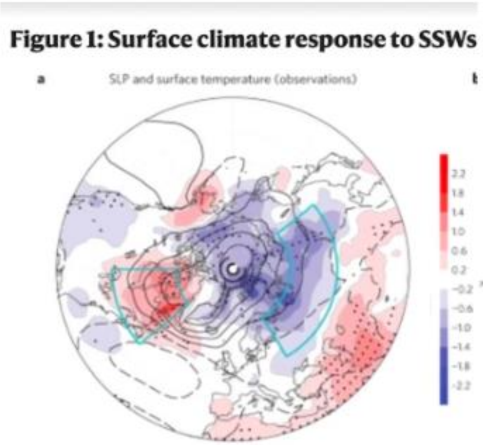
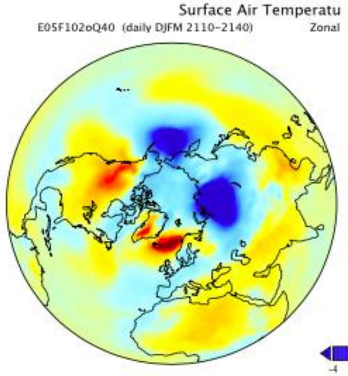


Both Standard and Optimized produce the proper Surface Air Temperature and SLP responses



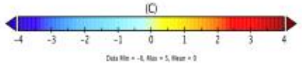
Sigmond et al., 2013
Contours show SLP
Colors show SAT

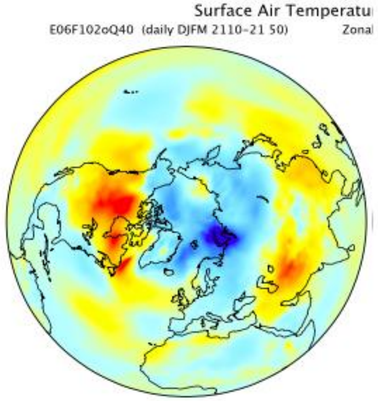
SURF AIR TEMPERATURE



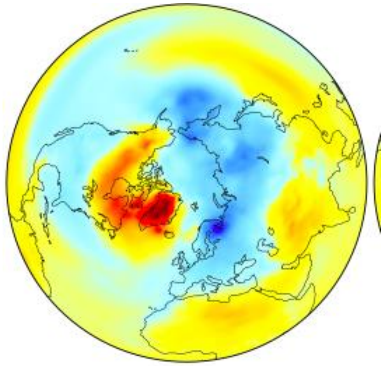
E2.2SP

Following 15-60 day anomalies from climatology



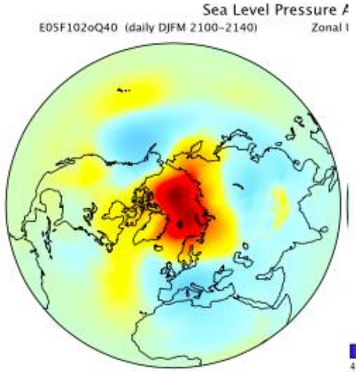


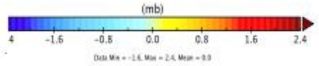
E2.2AP

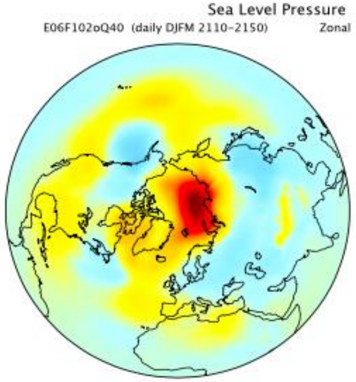


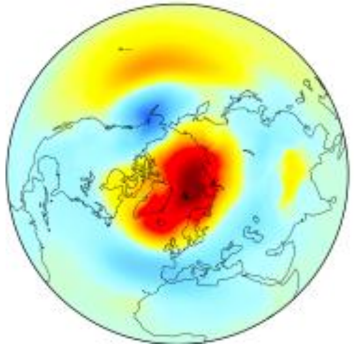
OPTIMIZED

SEA LEVEL PRESSURE







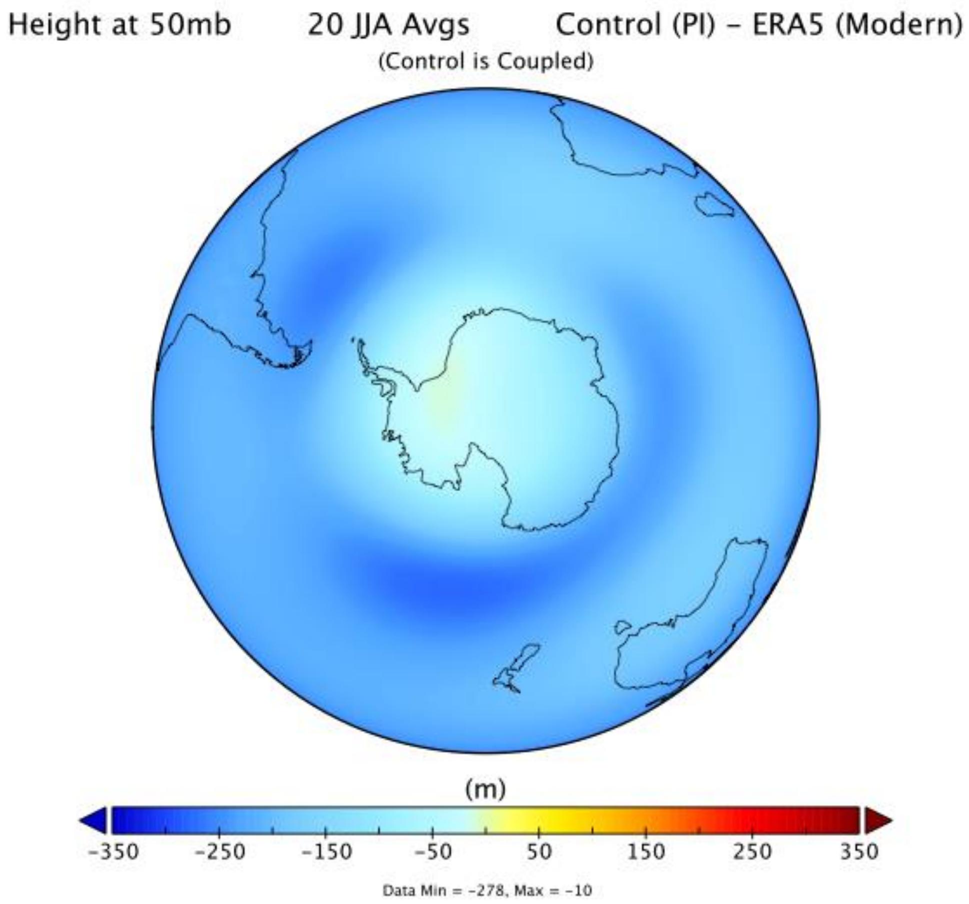


CONTINUING WORK

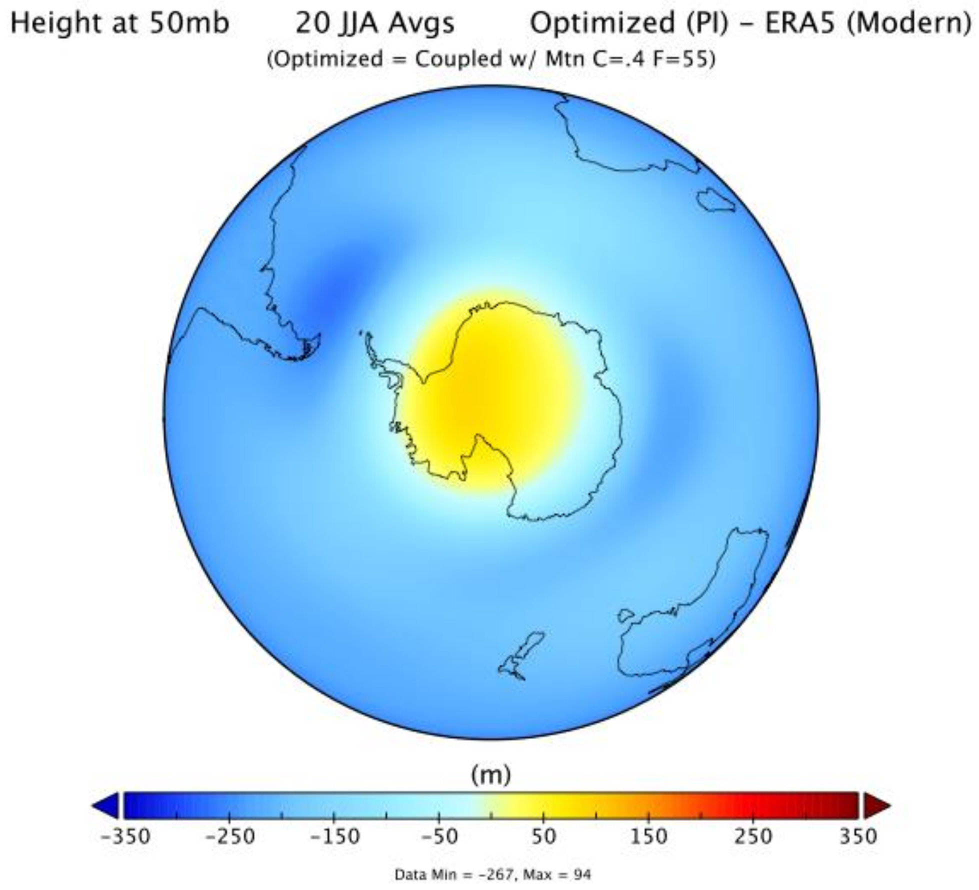
- Continue experiments to reduce polar vortex strength a little more
- Investigate impact of transient EKE in stratosphere – in the model, there is more energy in transient waves than in the standing waves
- Produce daily vertical energy flows (EP fluxes) to discriminate between energy propagation up vs. down between troposphere and stratosphere
- See if 'Optimized' version run with higher vertical resolution produces changes in SSWs and their downward propagation
- See if warmer model (currently being run) can impact polar vortex
- Ultimately see how the events which influence the troposphere change with a warming climate

SH issues for Optimized run…

CONTROL



OPTIMIZED



COMPARISON E3, E2.2 OBS

Part 1: Protocol

E3: 1°x1.25°

E2.2: 2°X2.5°

OBS: ERA5, NOAA

(GENERAL FORMAT)

P101

ERA 5
MODEL
MODEL-ERA5

P102

ERA 5
MODEL
MODEL-ERA5

VARIABLE

ANN OR SEASON

P103

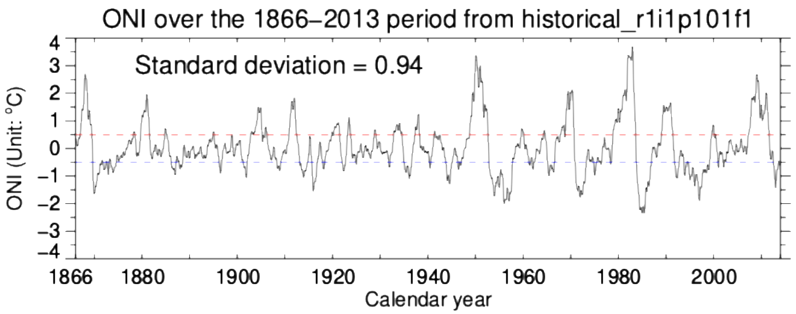
ERA 5
MODEL
MODEL-ERA5

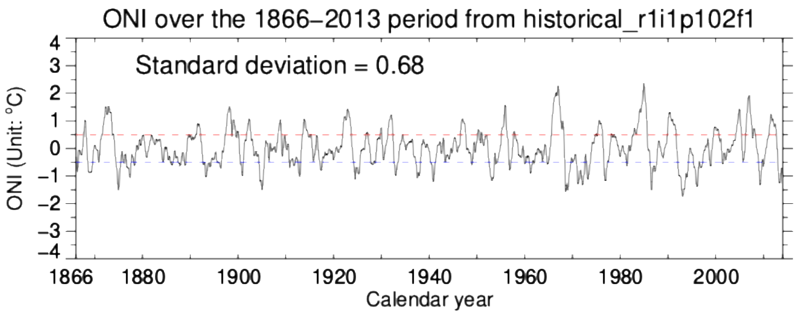
E2.2AP

ERA 5
MODEL
MODEL-ERA5

FIVE TAKEAWAYS FROM MODEL E3 COMPARISONS
Areas for Improvement

1. ENSO : Period too long, extends too far west
2. Tropical Moisture/Circulations: Indian Ocean & Indonesia
3. Atmospheric Planetary Waves (Deficient longwave energy #s 1-3)
4. Regions of Importance for Stratospheric Ozone (Too warm – JJA BD too weak)
5. QBO (Too weak, reduced variability); Semi-annual Oscillation too weak





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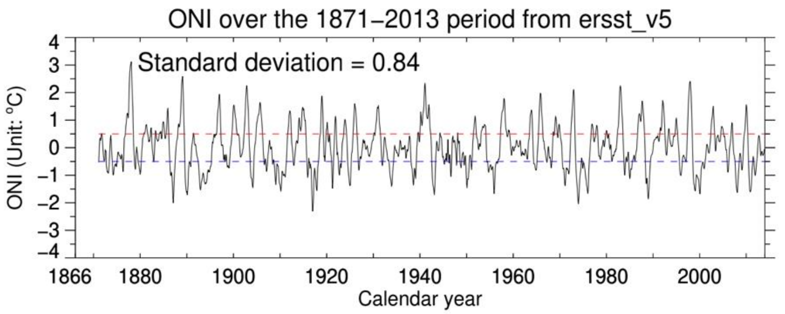
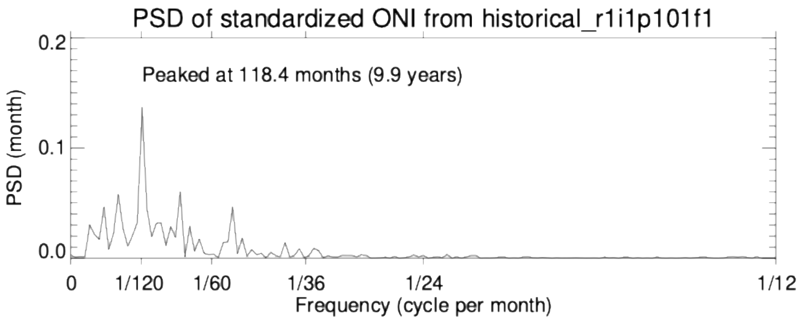
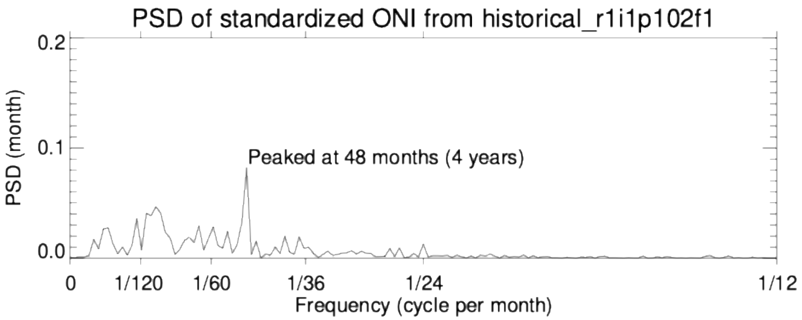
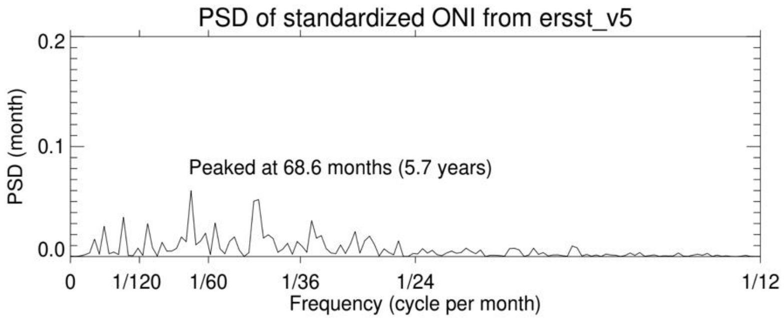
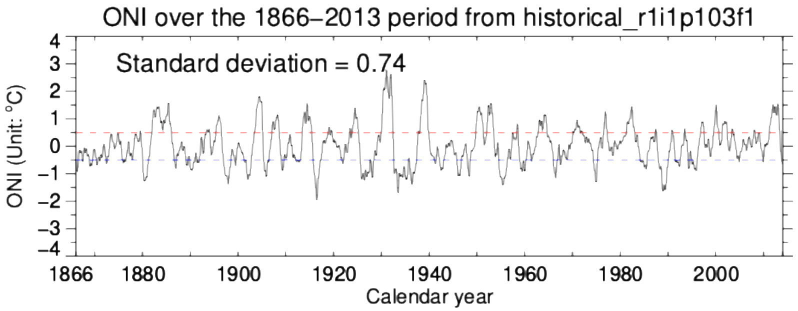
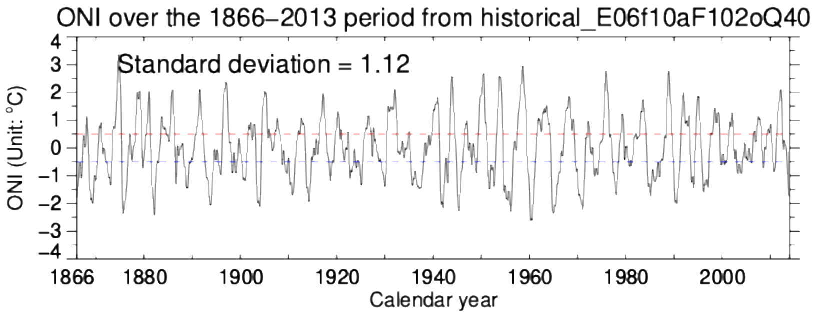






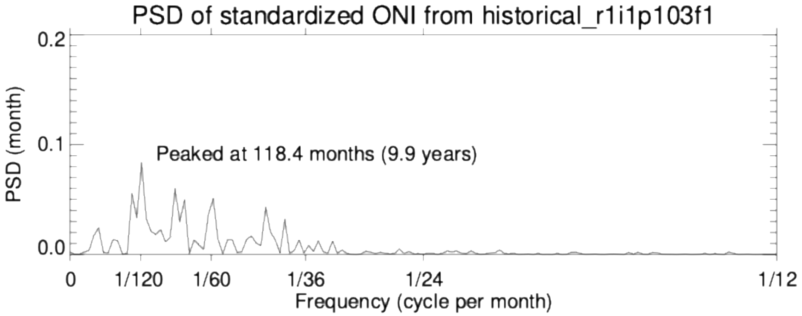


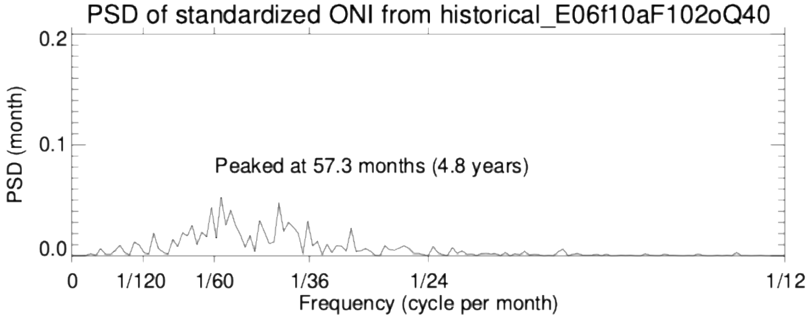




#1

ENSO

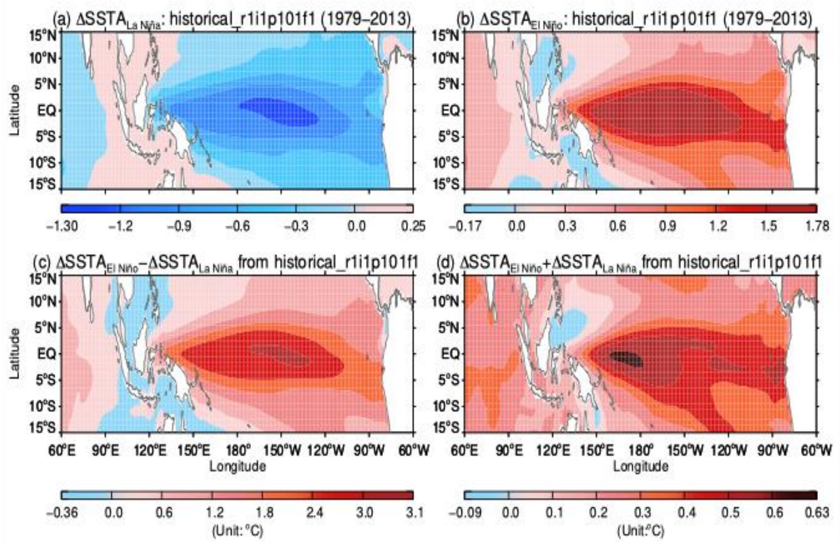


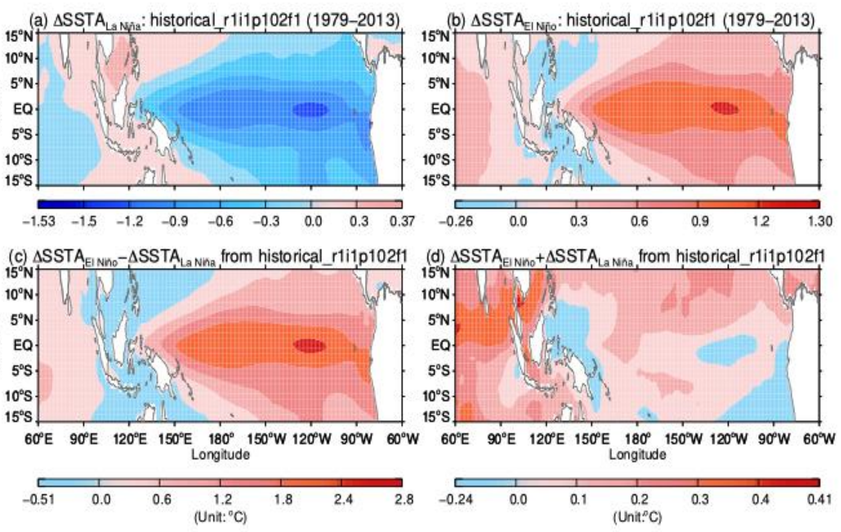


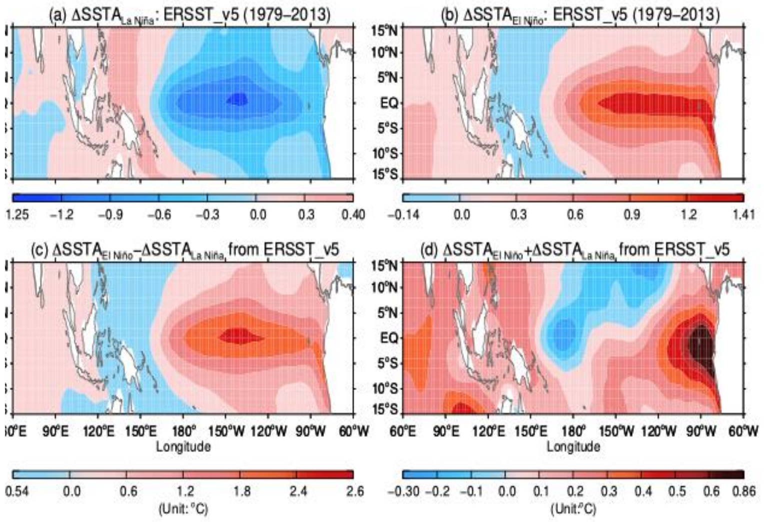
AMP and PERIOD

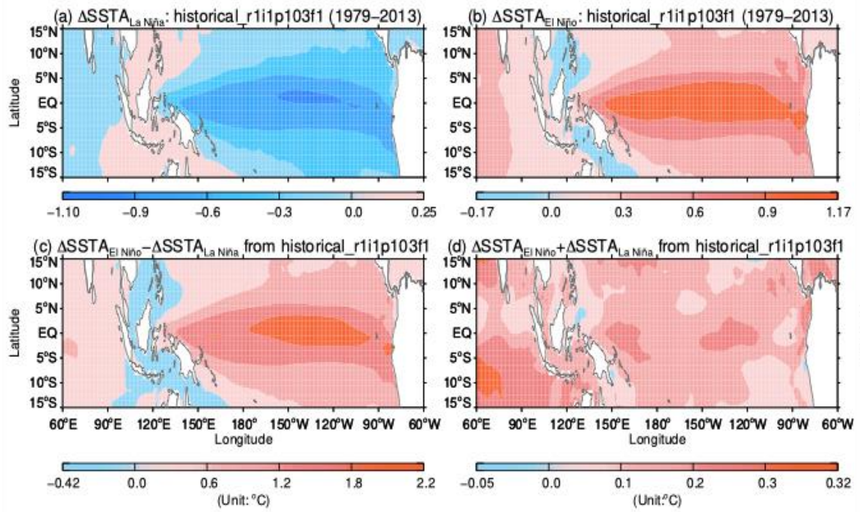
*

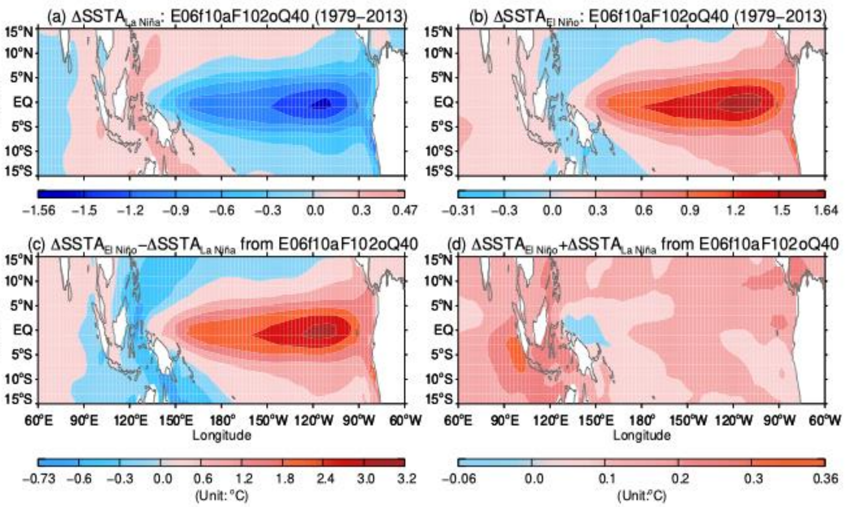
OBSERVED







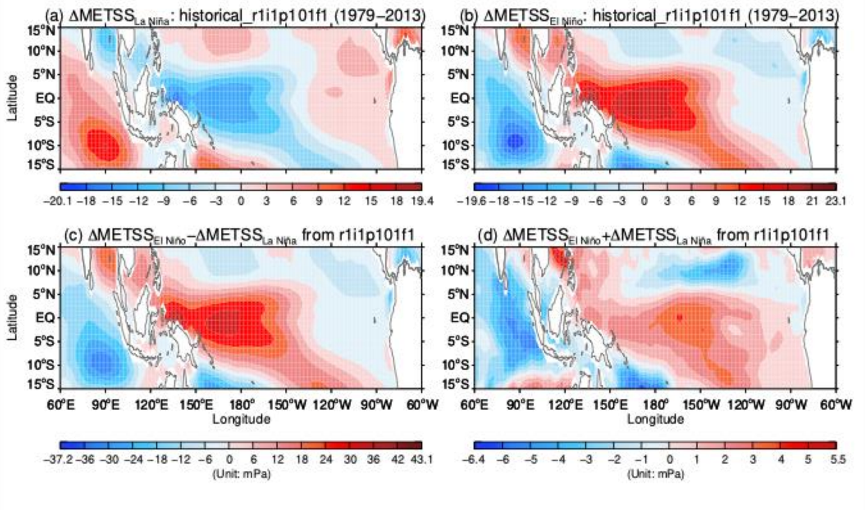


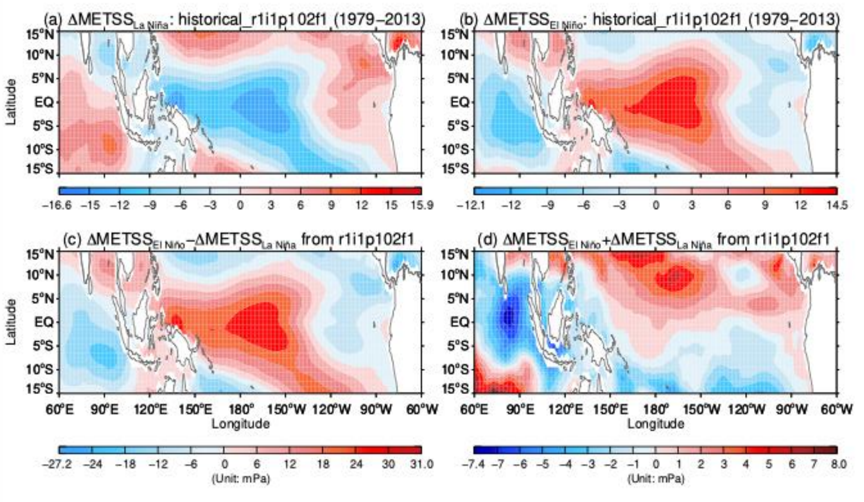


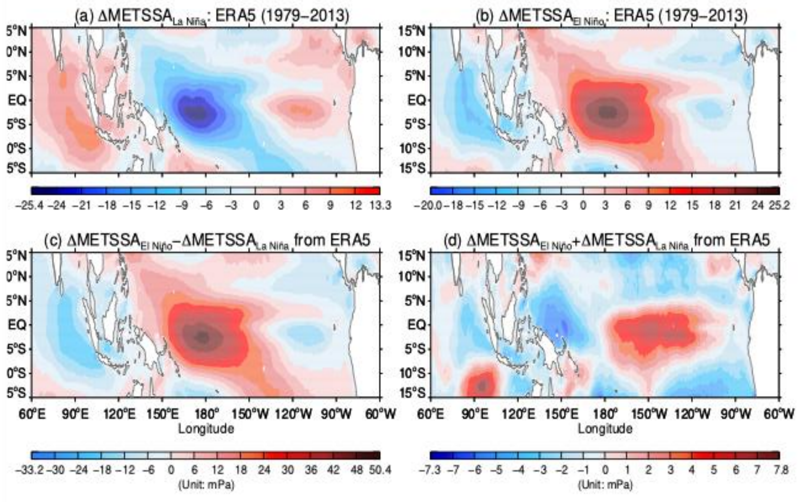
ENSO SSTs

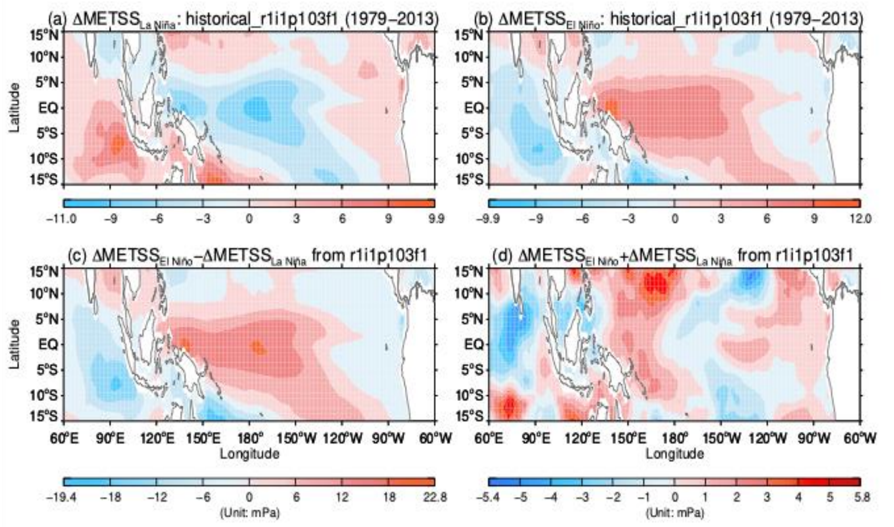
*

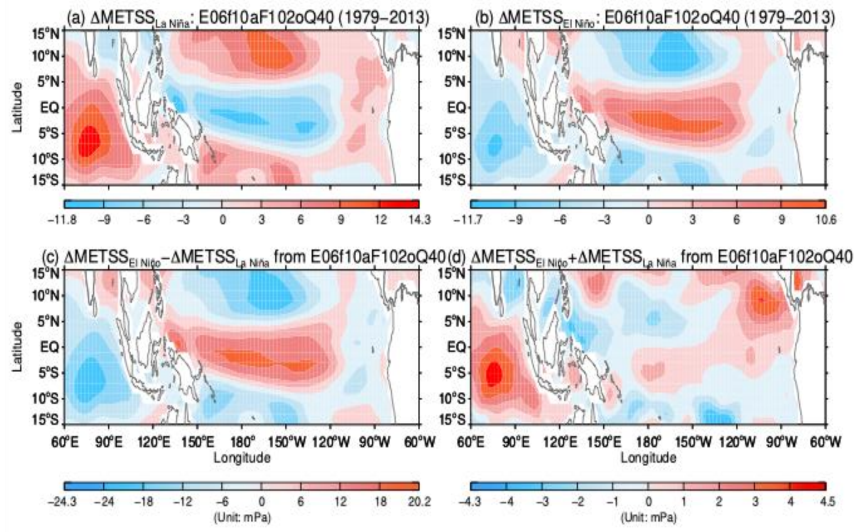
OBSERVED



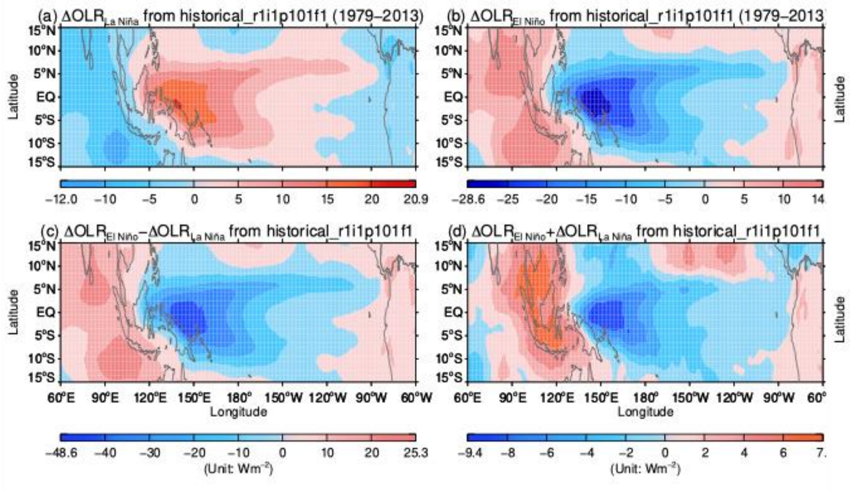


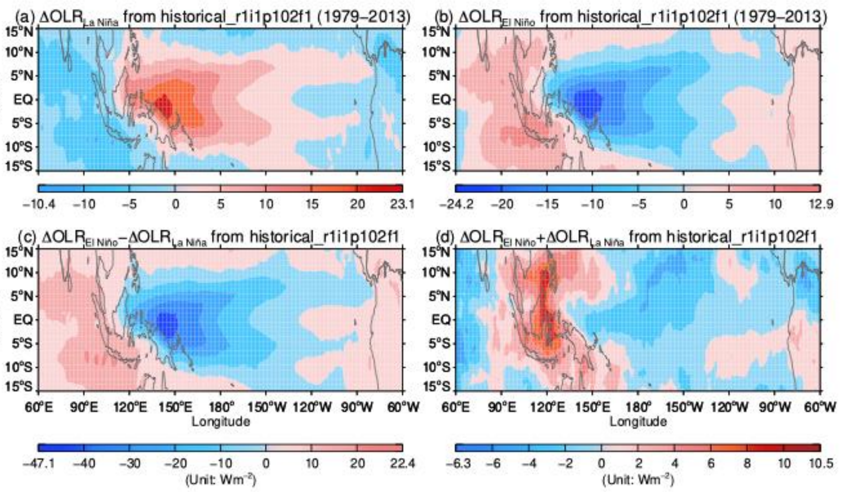






EASTWARD SURFACE WIND STRESS DURING ENSO





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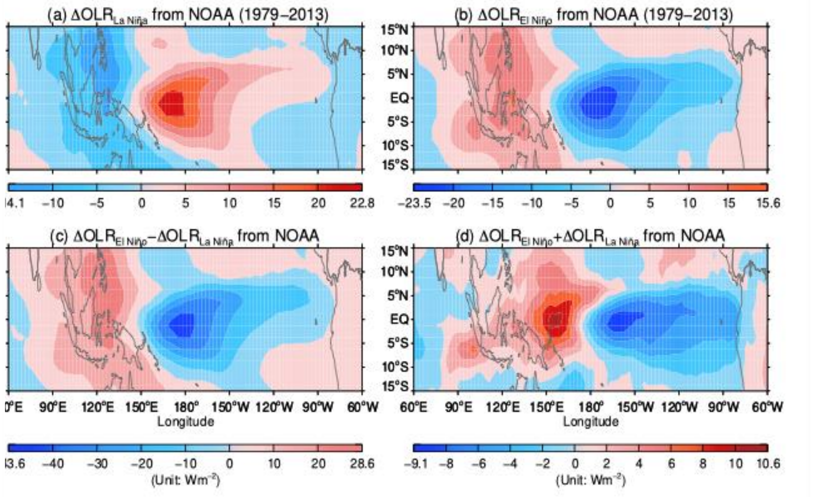
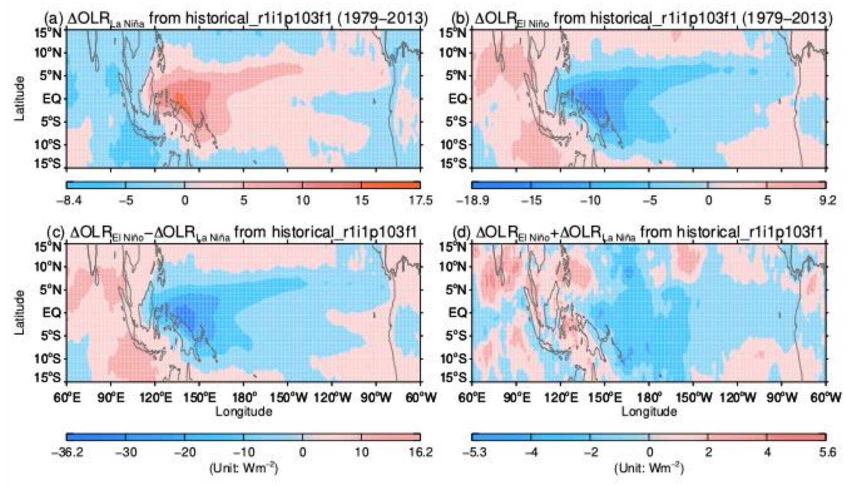
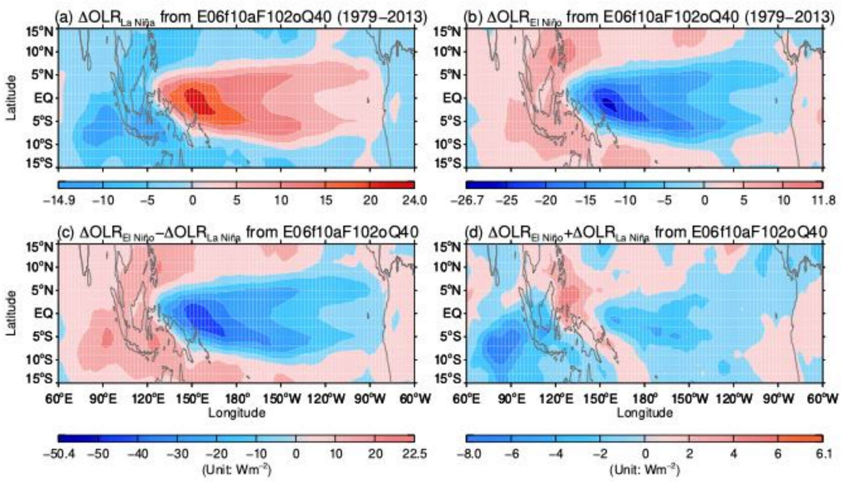
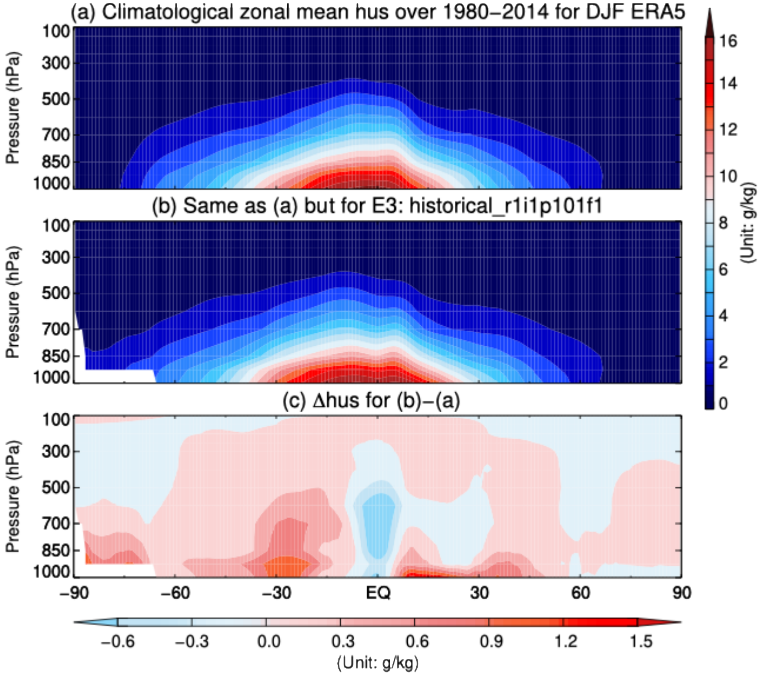


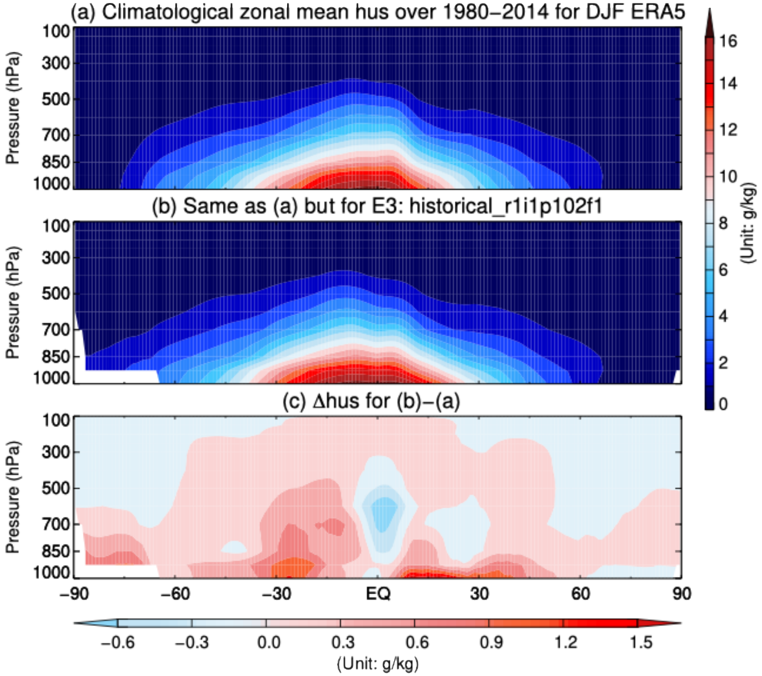




TOP OF ATM. LONG WAVE RADIATION
DURING ENSO

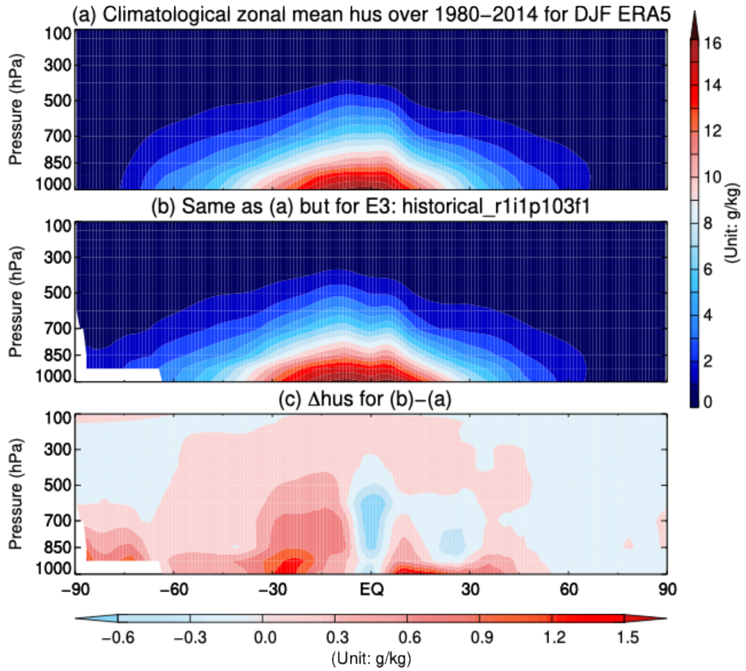
*

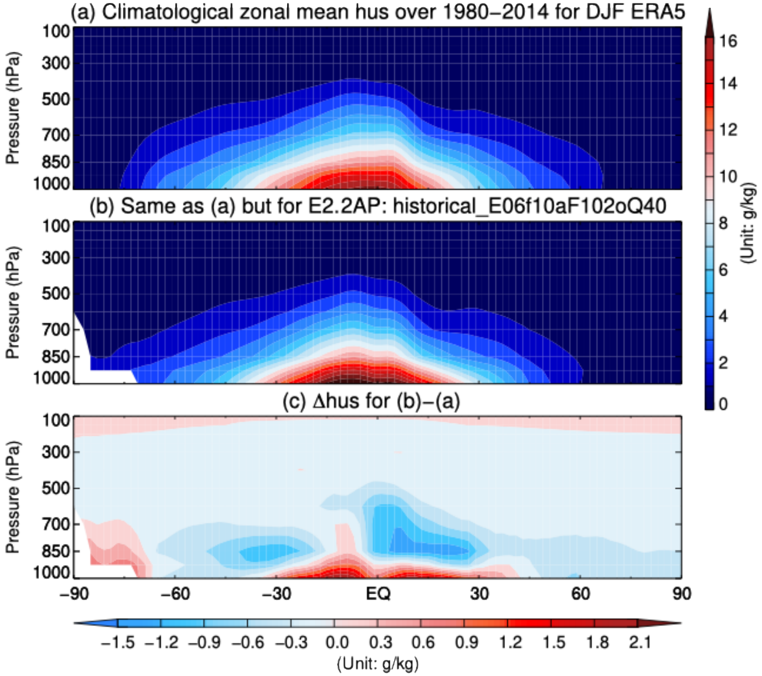




#2 TROPICAL MOISTURE/CIRCULATIONS

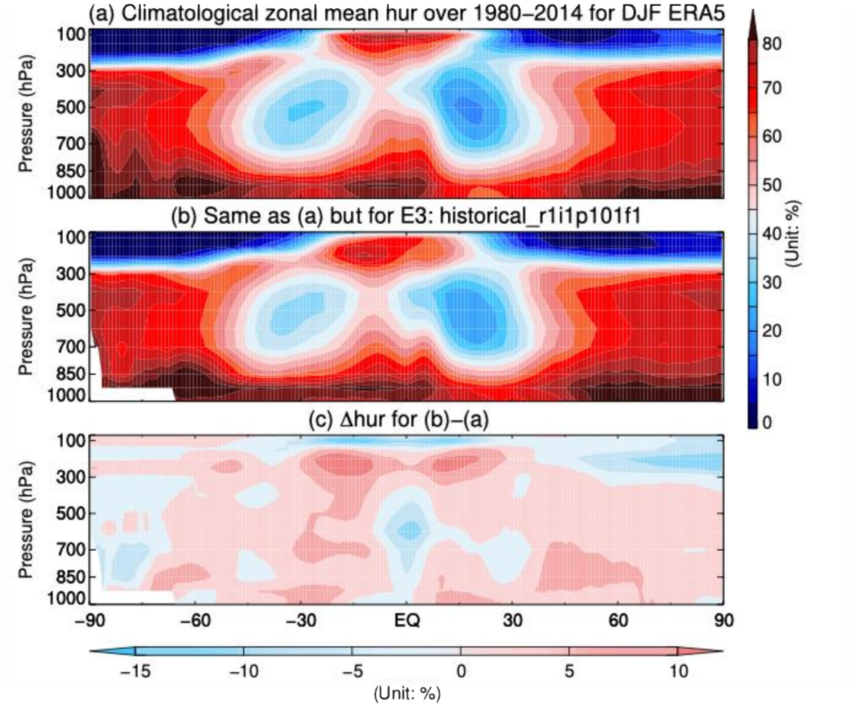
SPECIFIC HUMIDITY
DEC-FEB

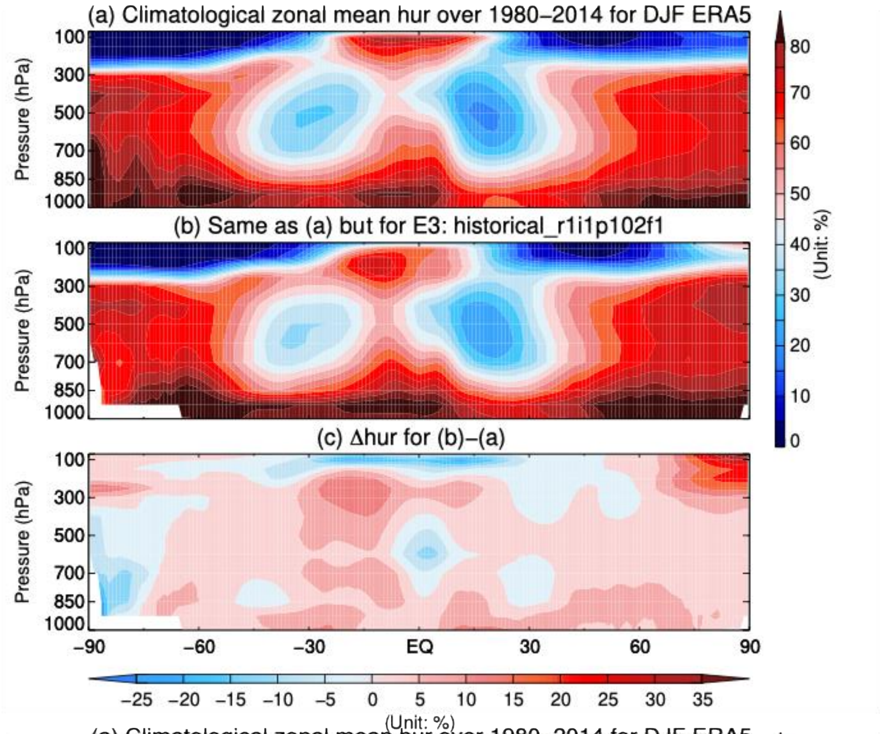


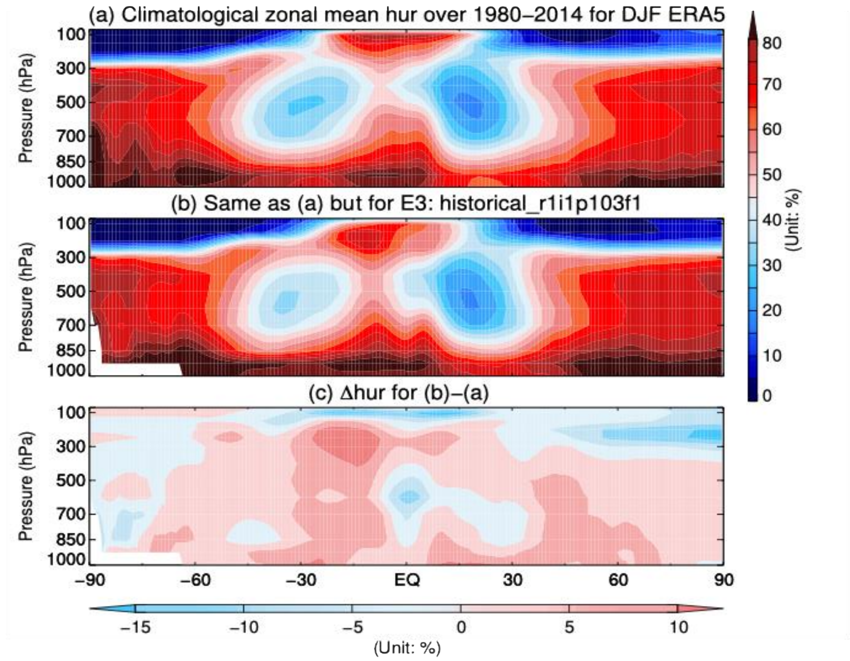


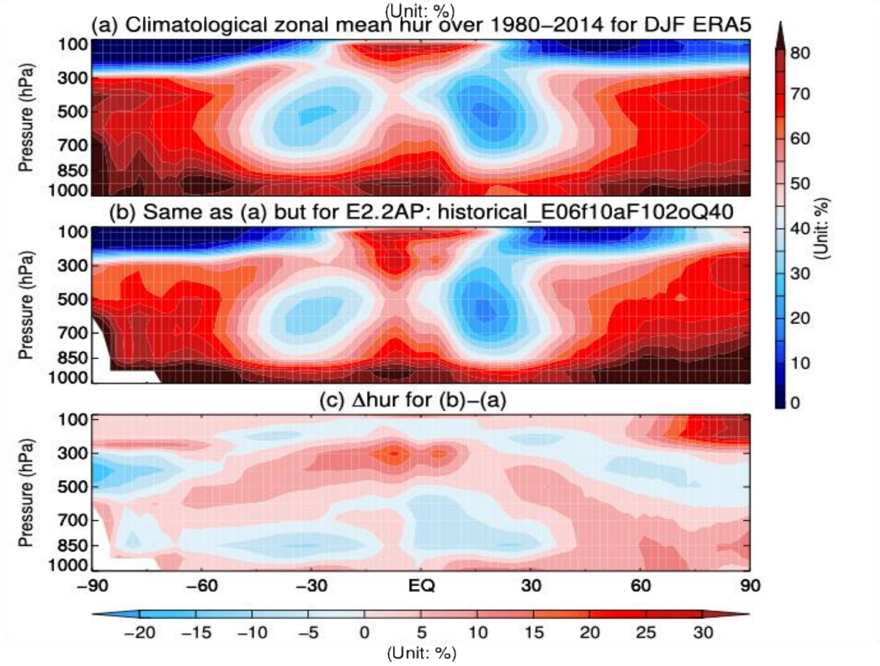
Anomalies O(15%)

*



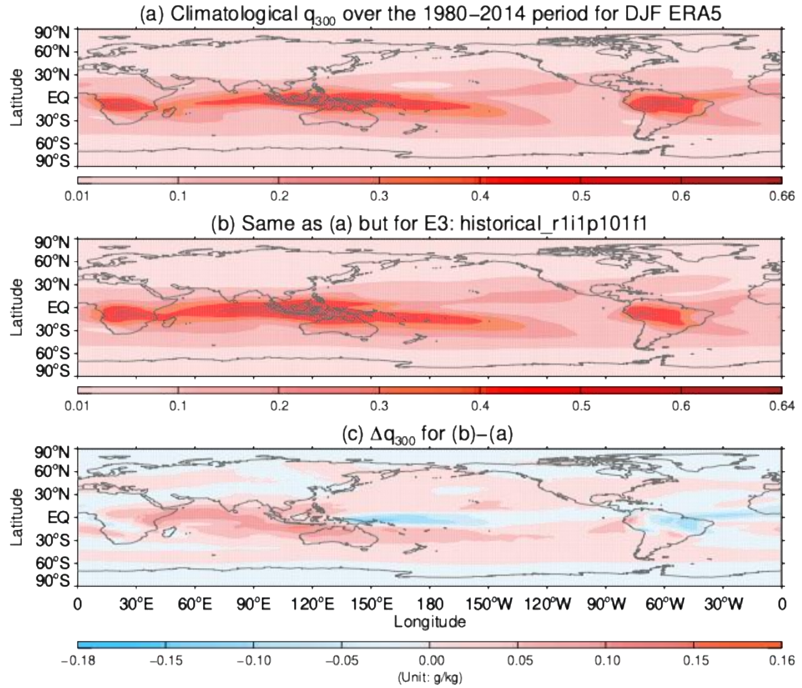


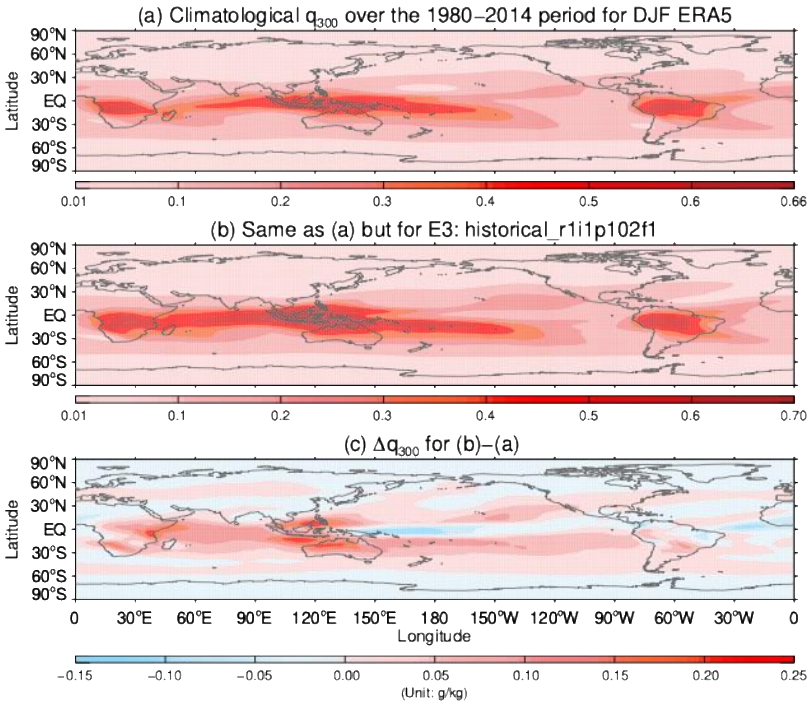


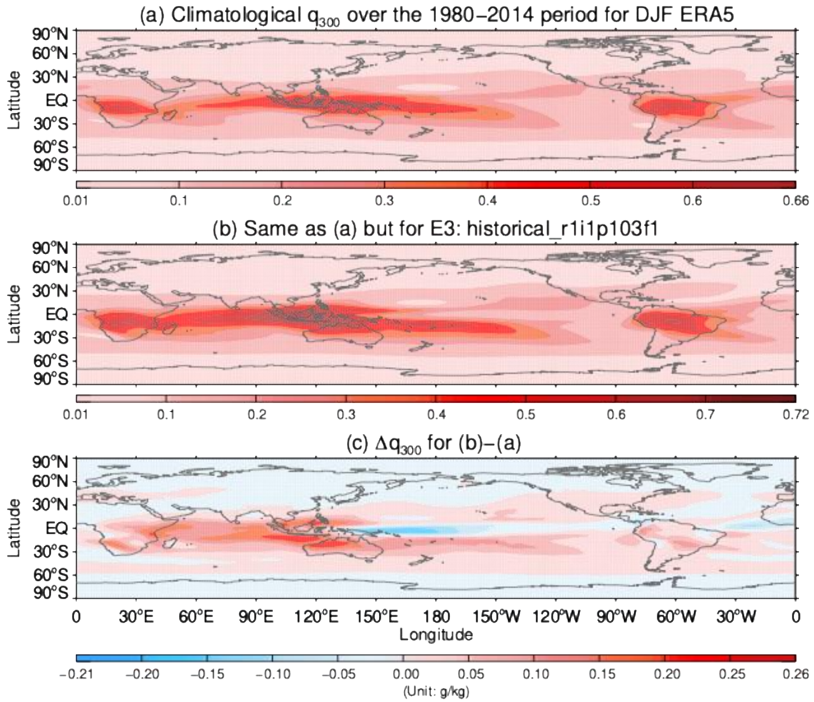


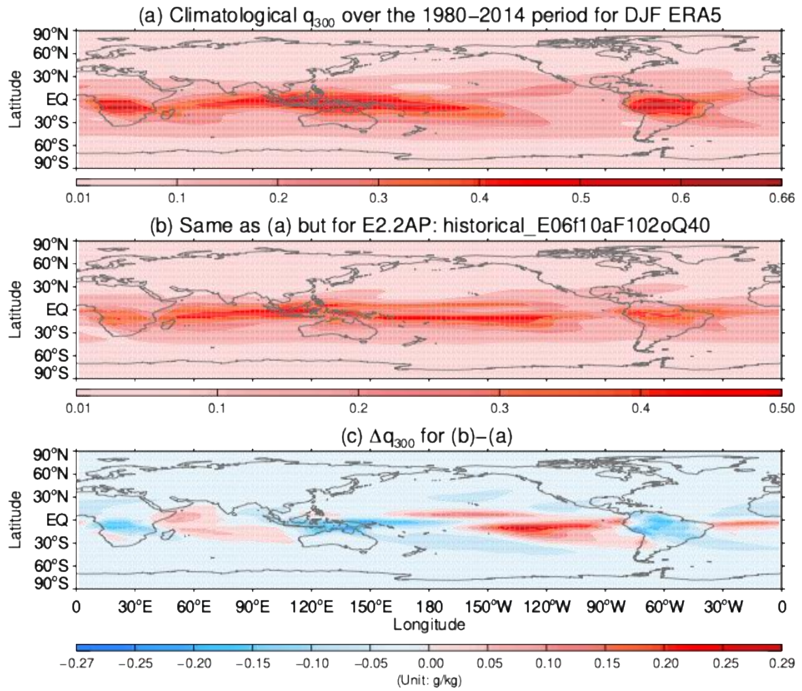
RELATIVE HUMIDITY
DEC-FEB

Anomalies 5-15% absolute



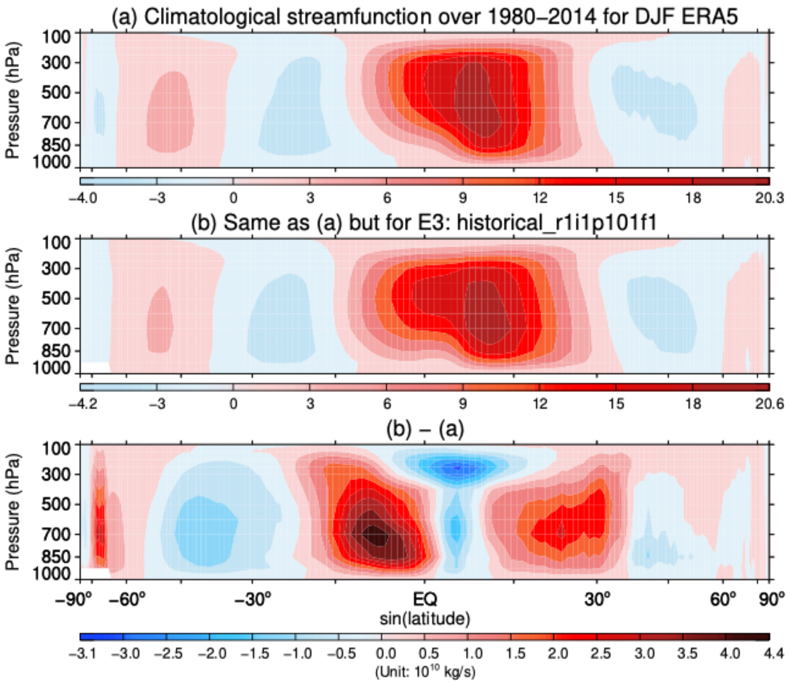


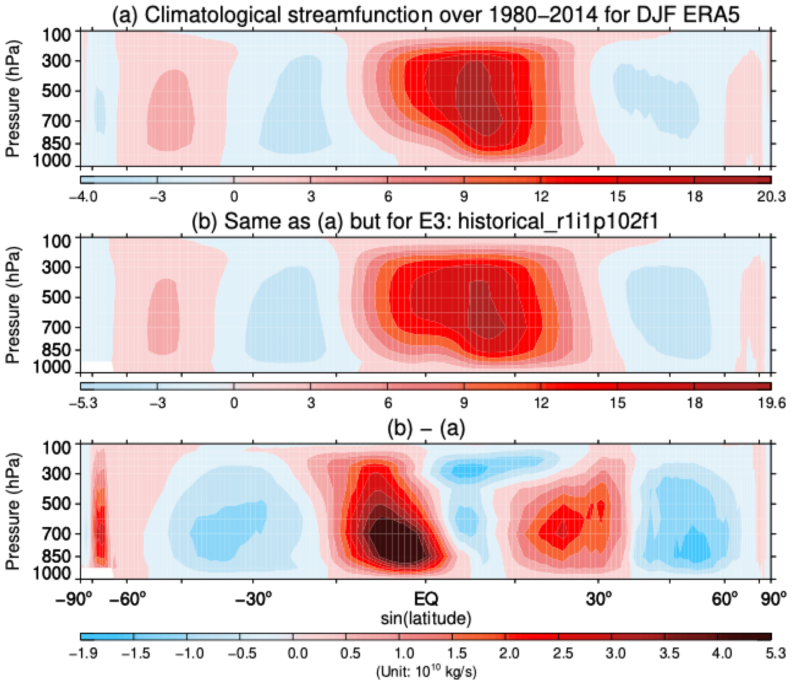


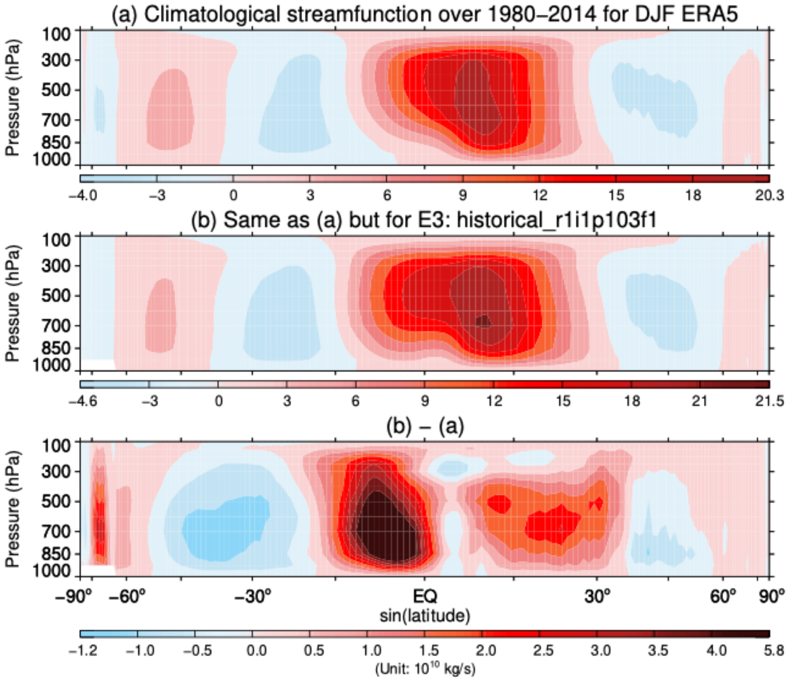


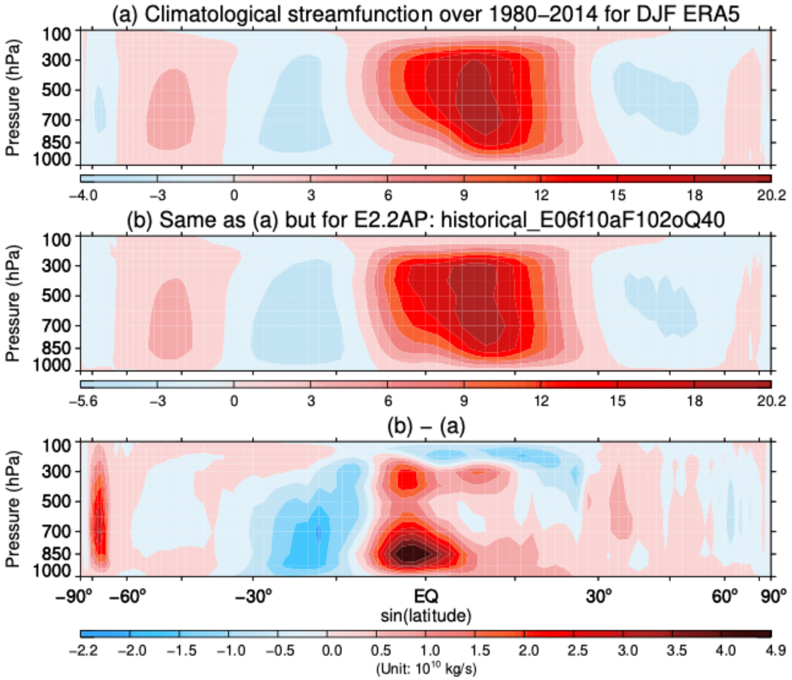
SPECIFIC HUMIDITY 300 hPa
DEC-FEB

Anomalies O(20%)





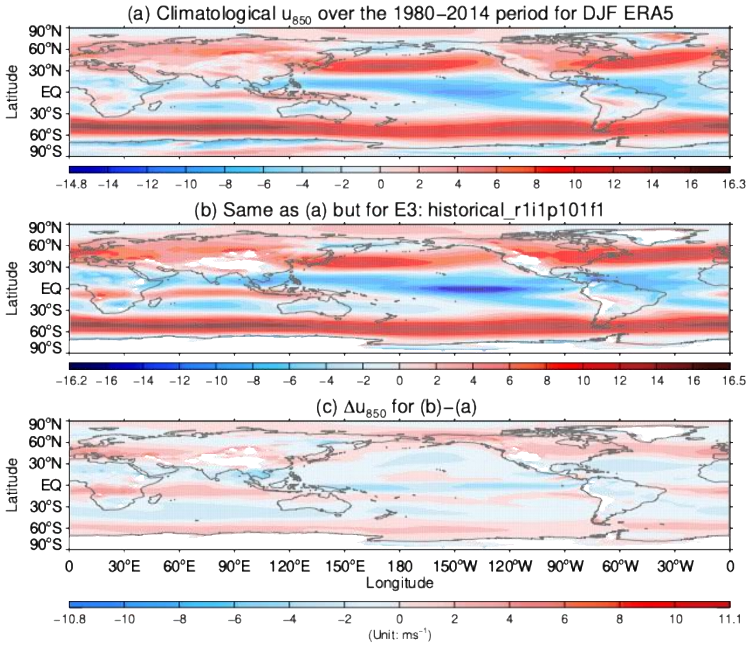


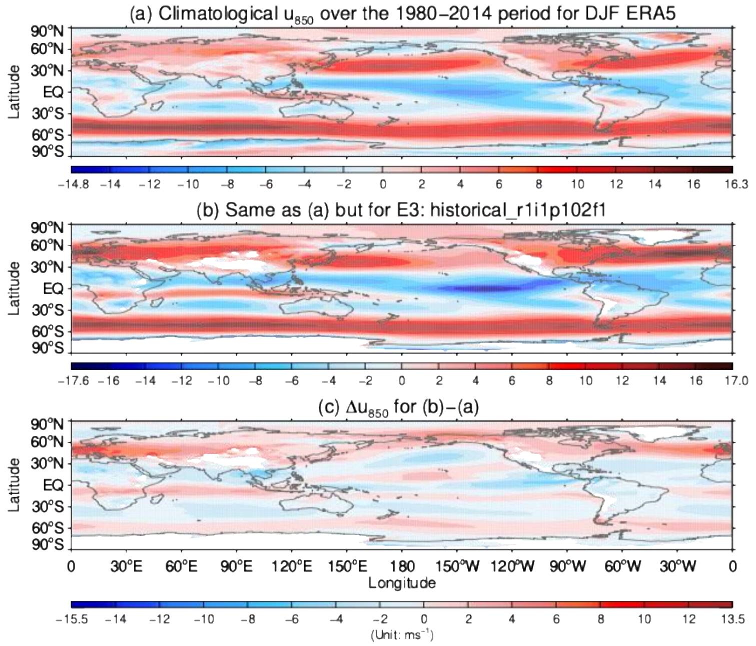


STREAMFUNCTION
DEC-FEB

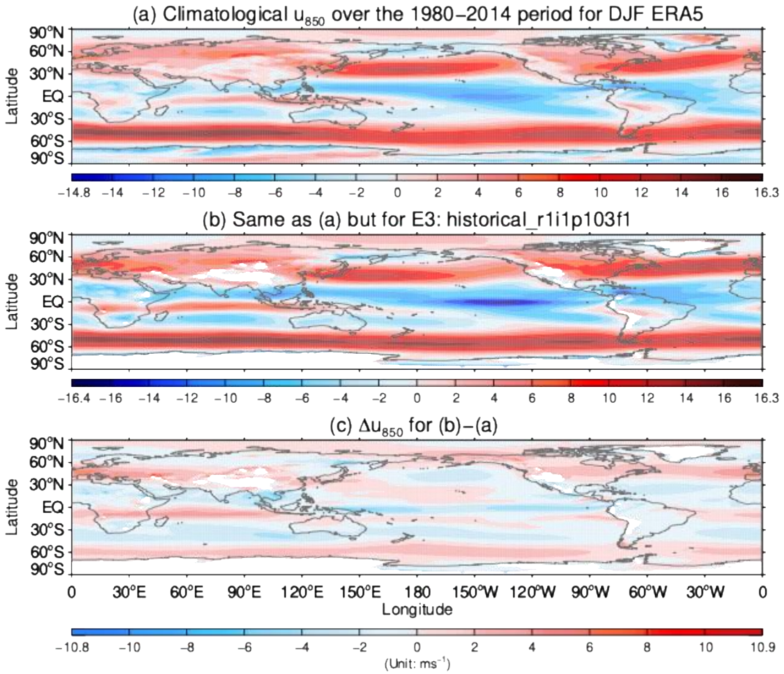
Anomalies 20-100%

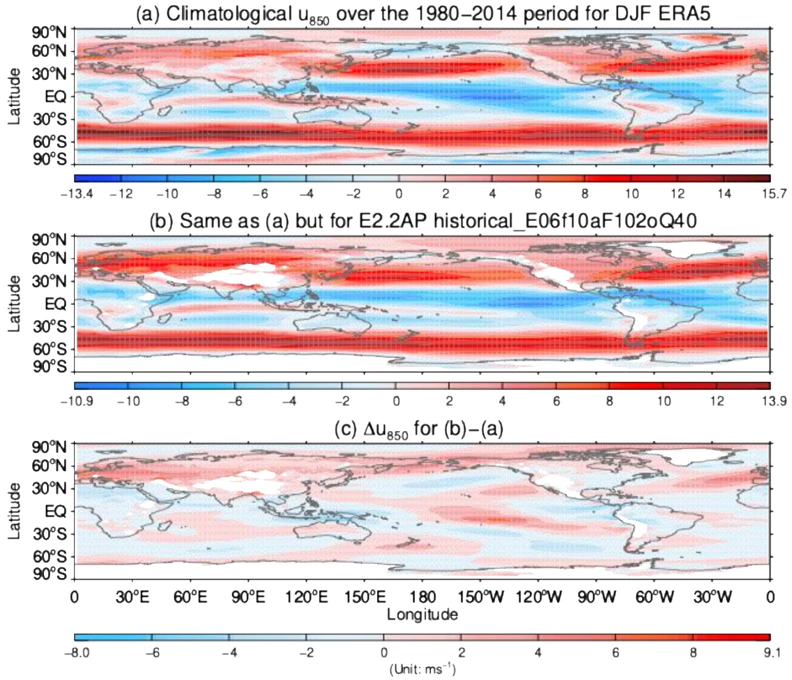
*



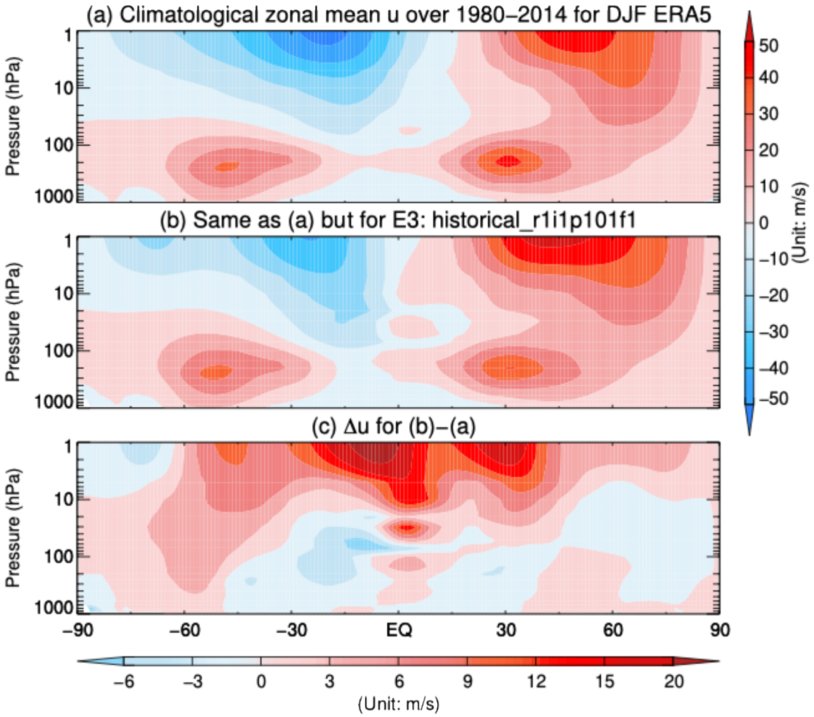


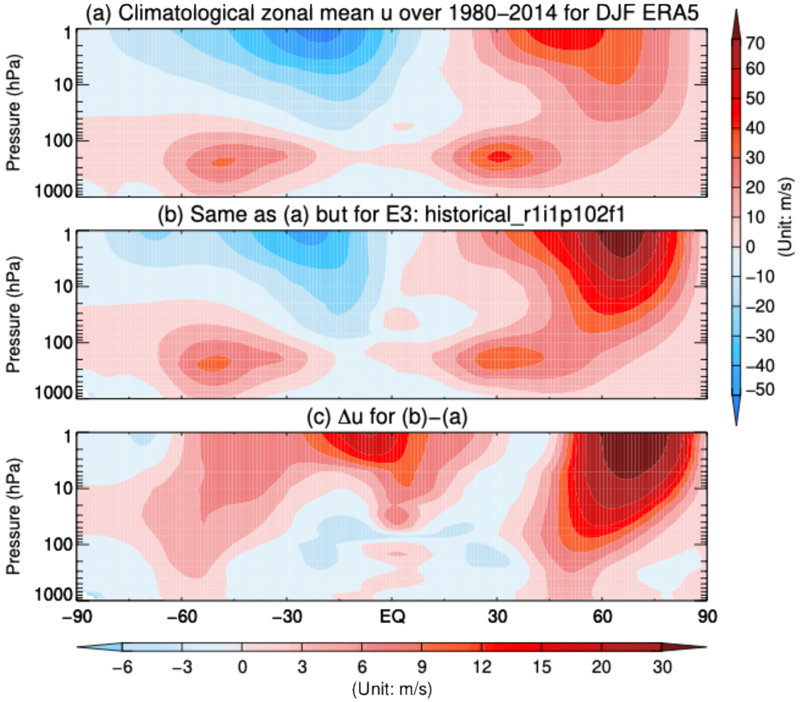
U 850 hPa
DEC-FEB





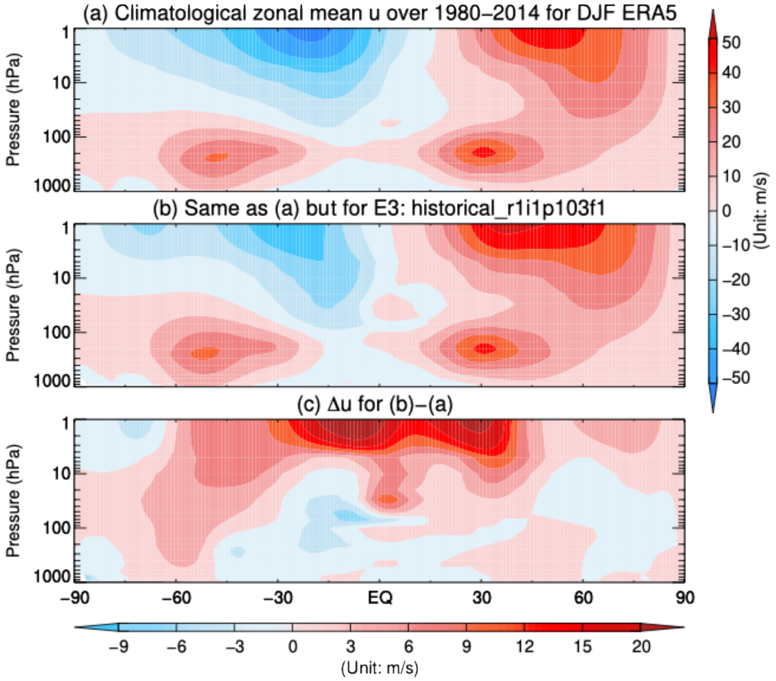
Anomalies O(20%)

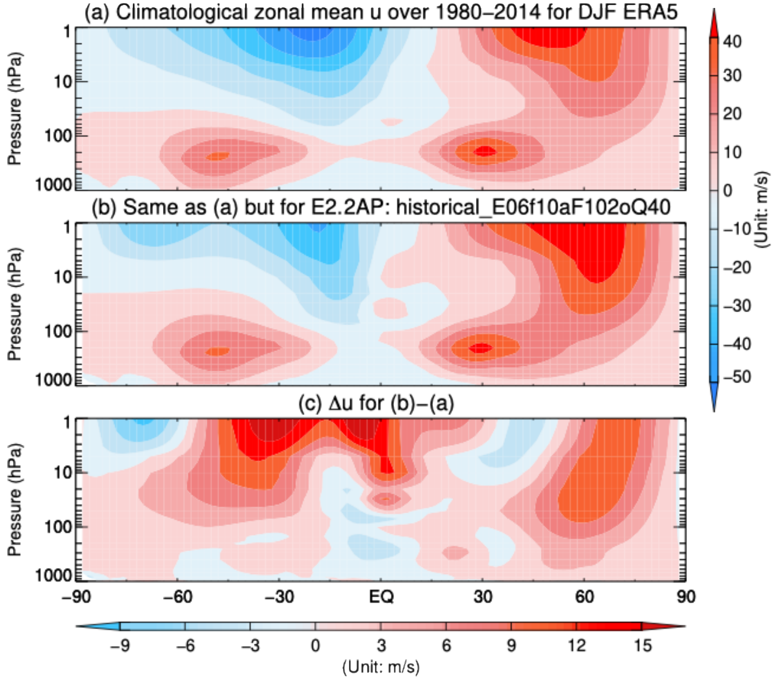




#3 PLANETARY WAVES

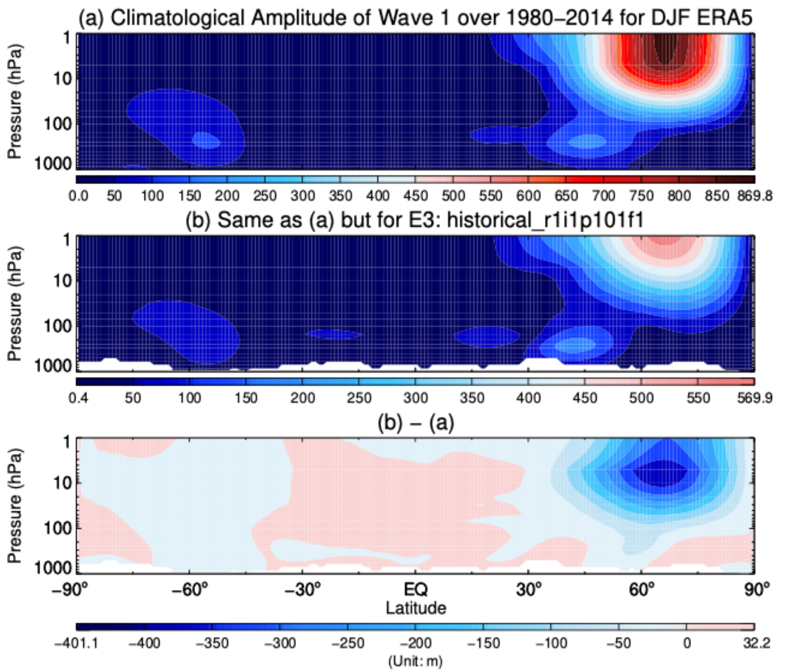
ZONAL WIND
DEC-FEB

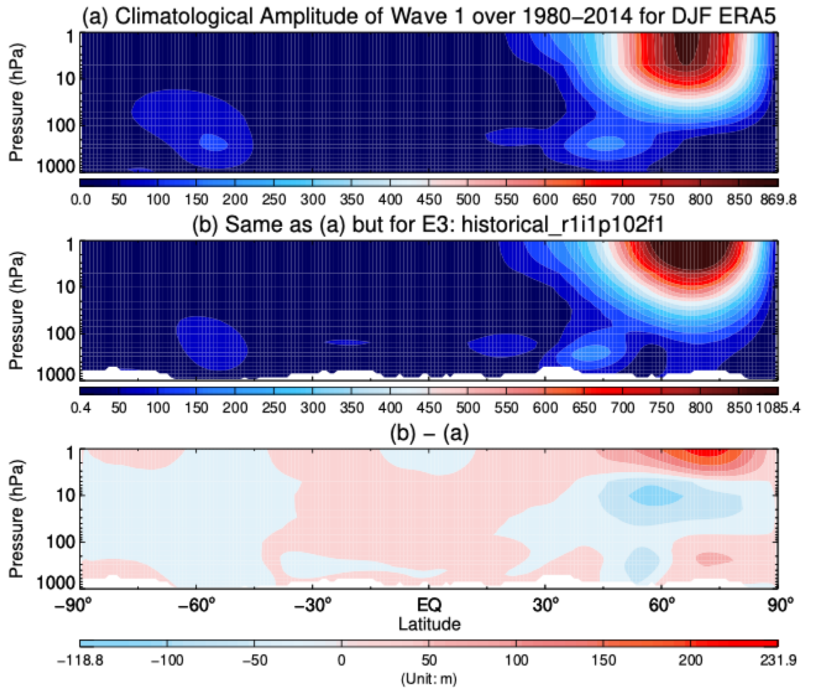


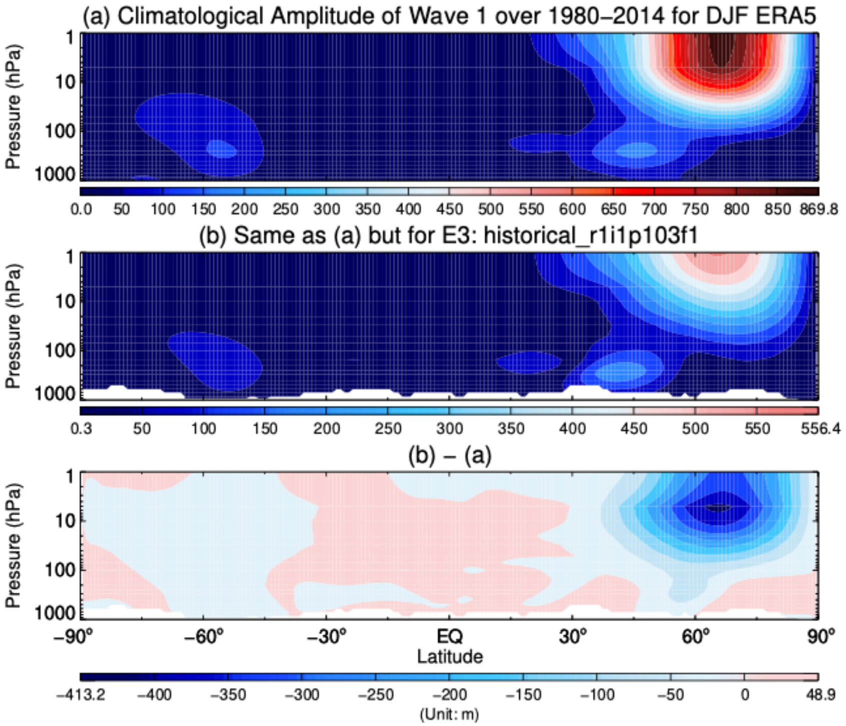


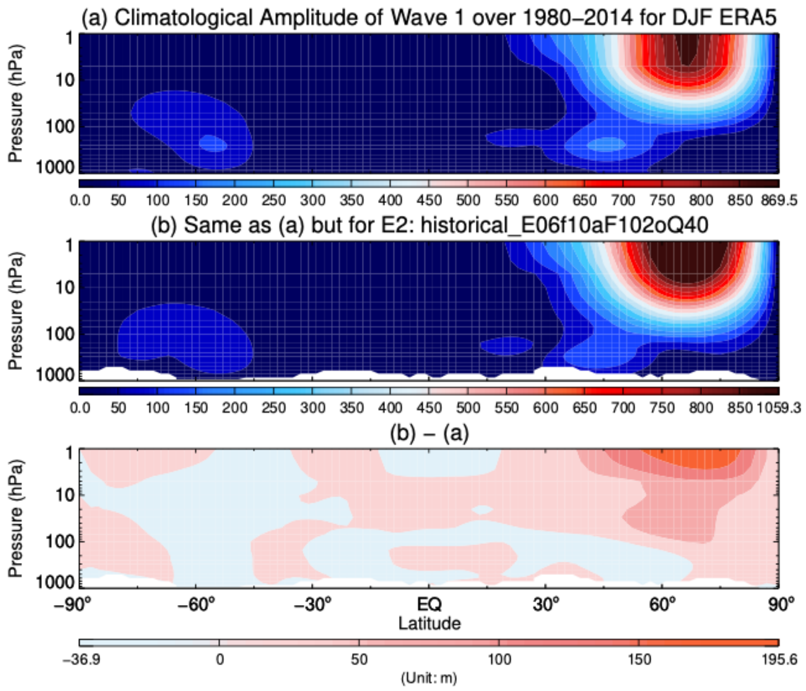
Anomalies 10-15 m/s

*





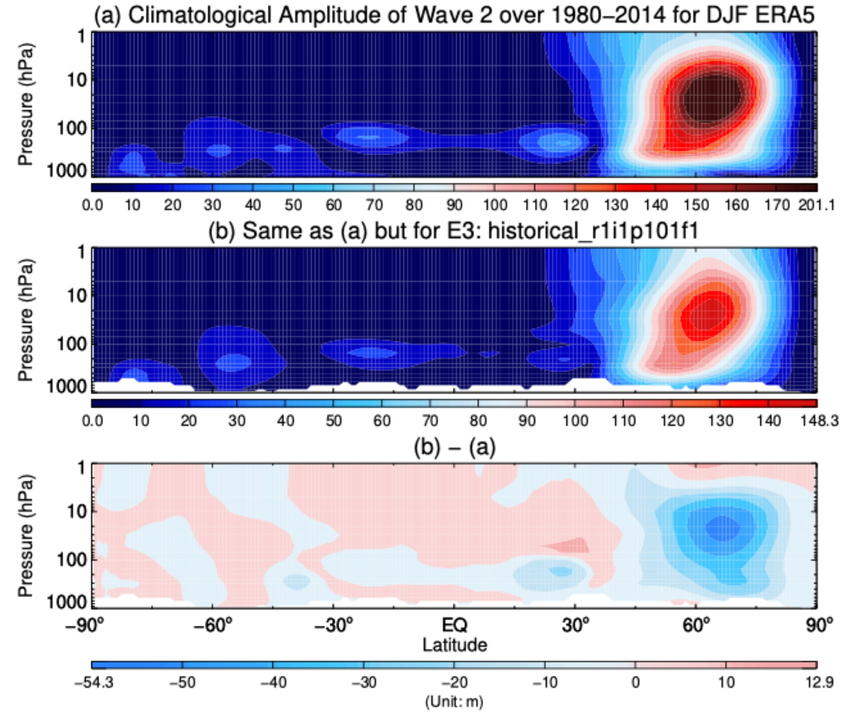


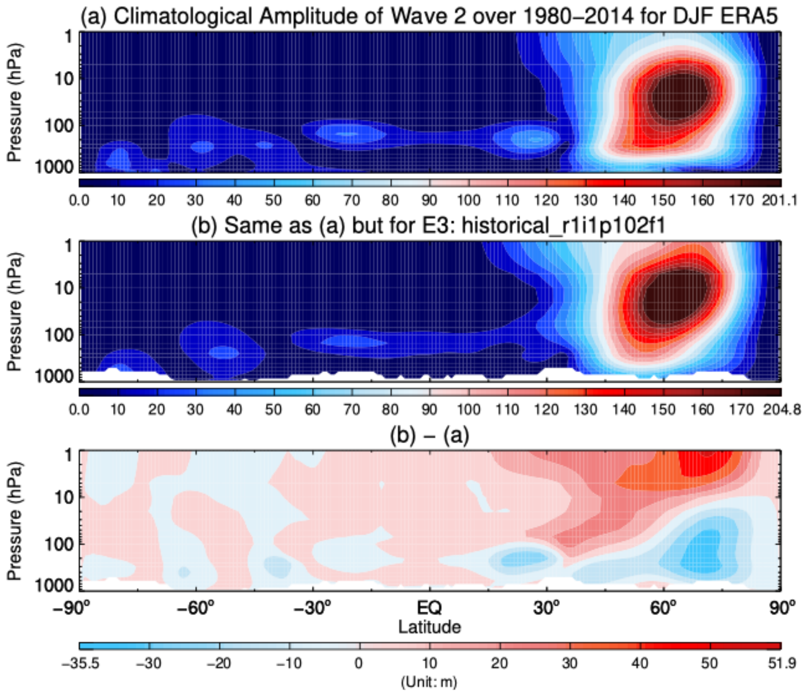


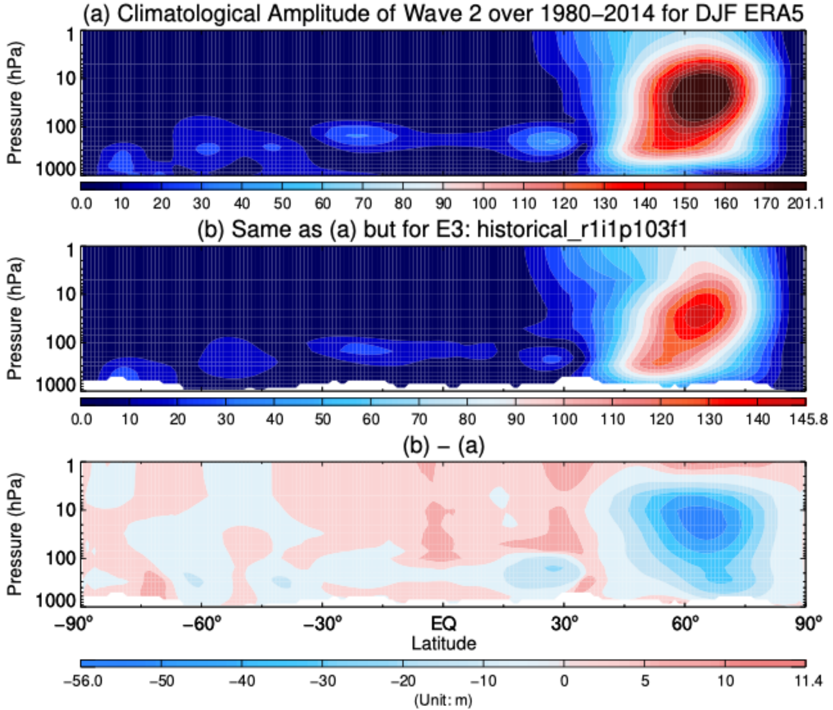
WAVE #1
AMPLTIUDE
DEC-FEB

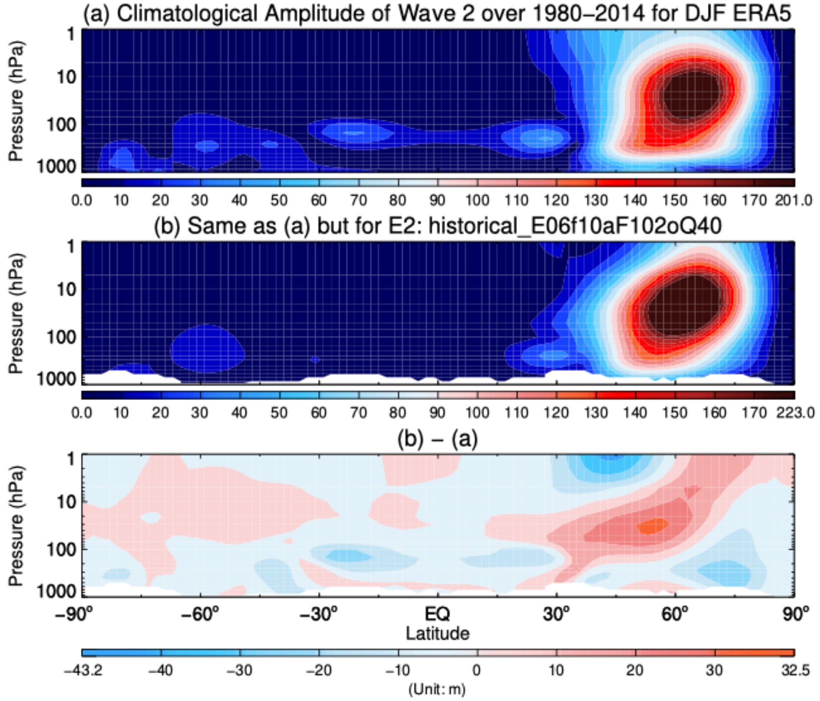
Anomalies O(40%)

*



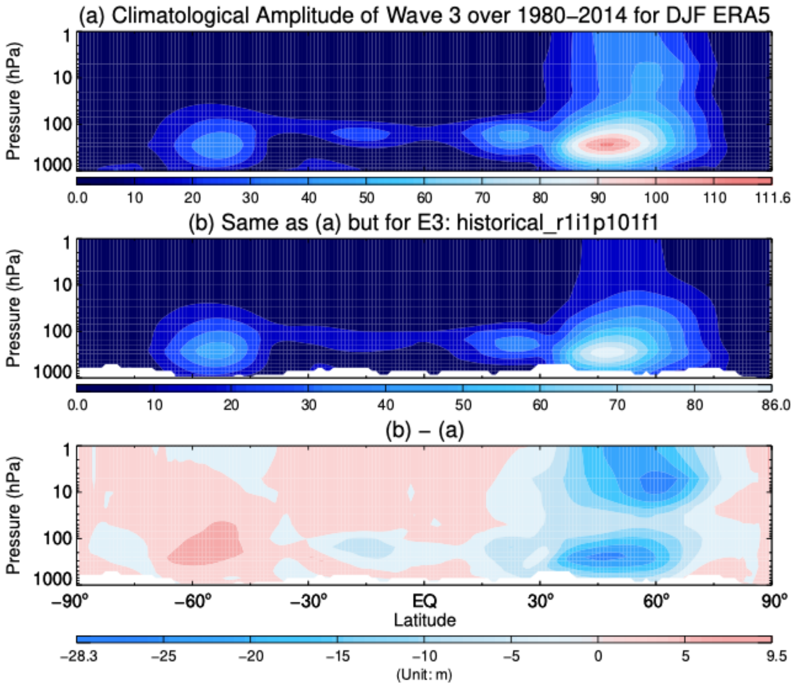


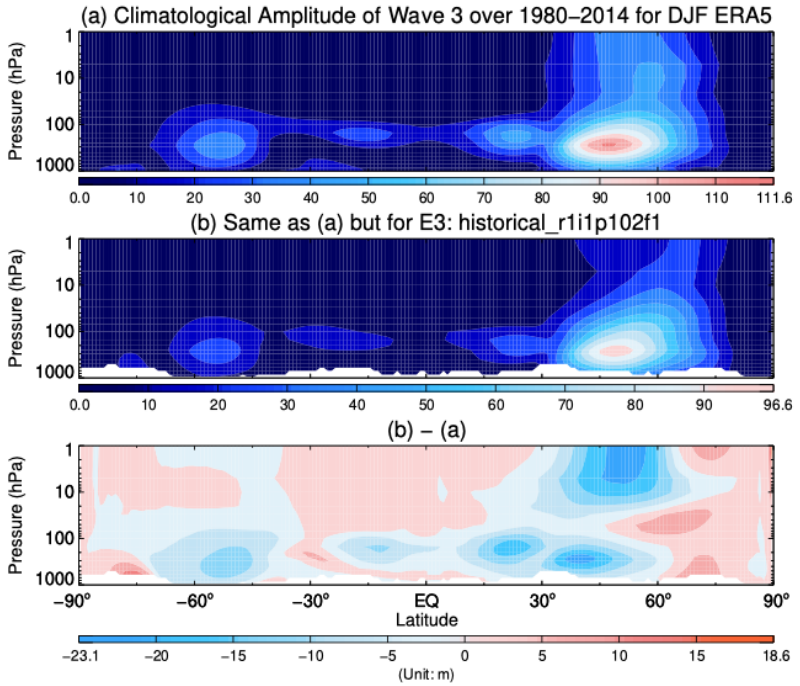


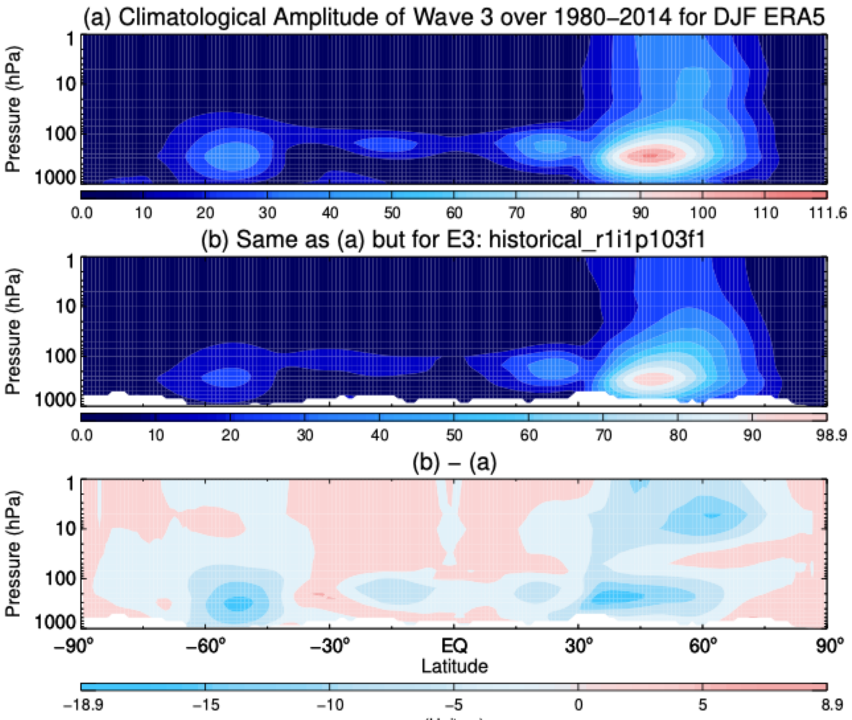


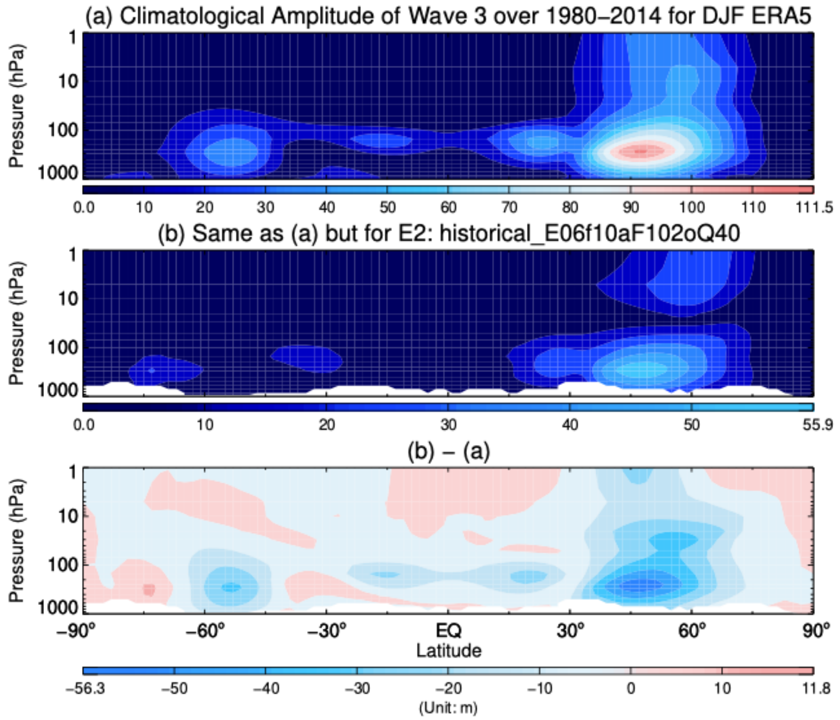
WAVE #2
AMPLTIUDE
DEC - FEB

Anomalies O(40%)



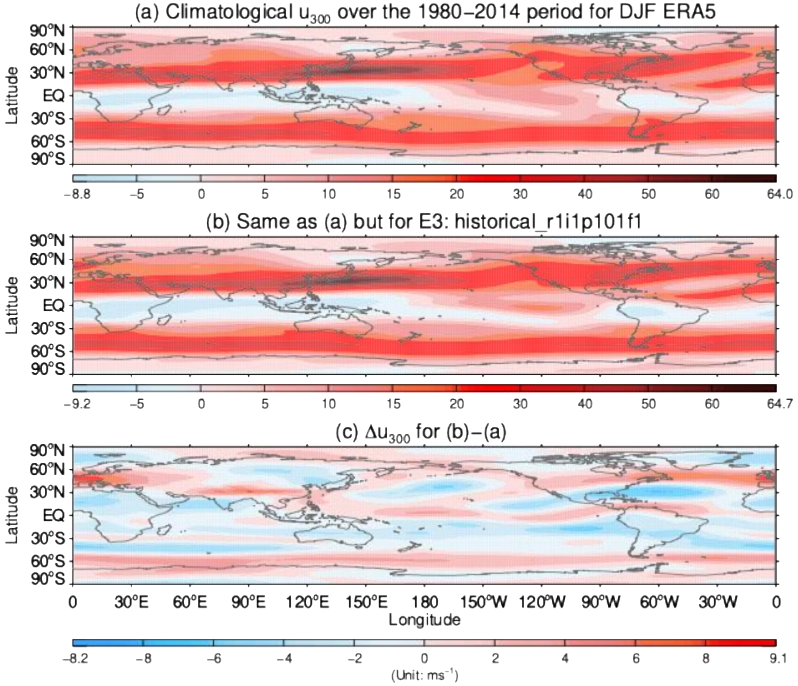


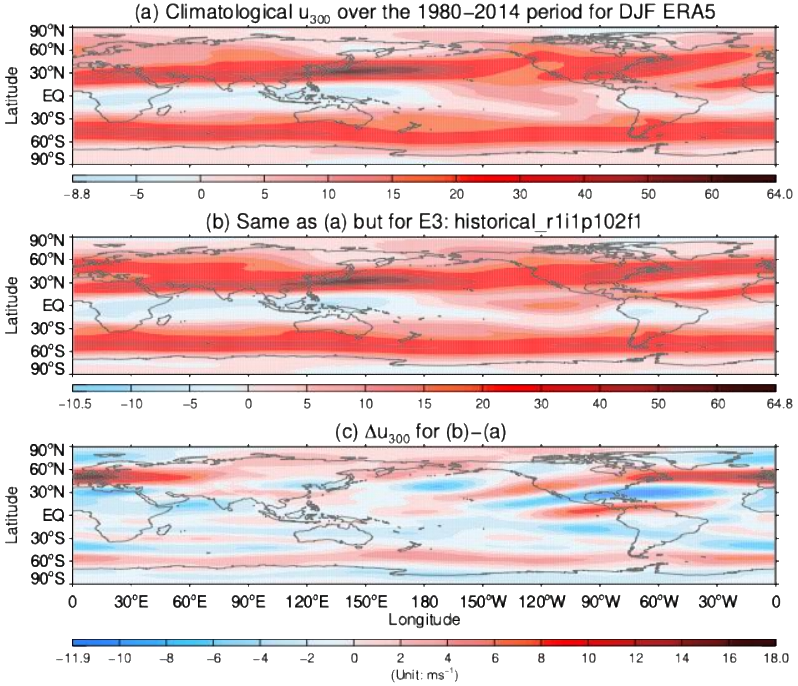


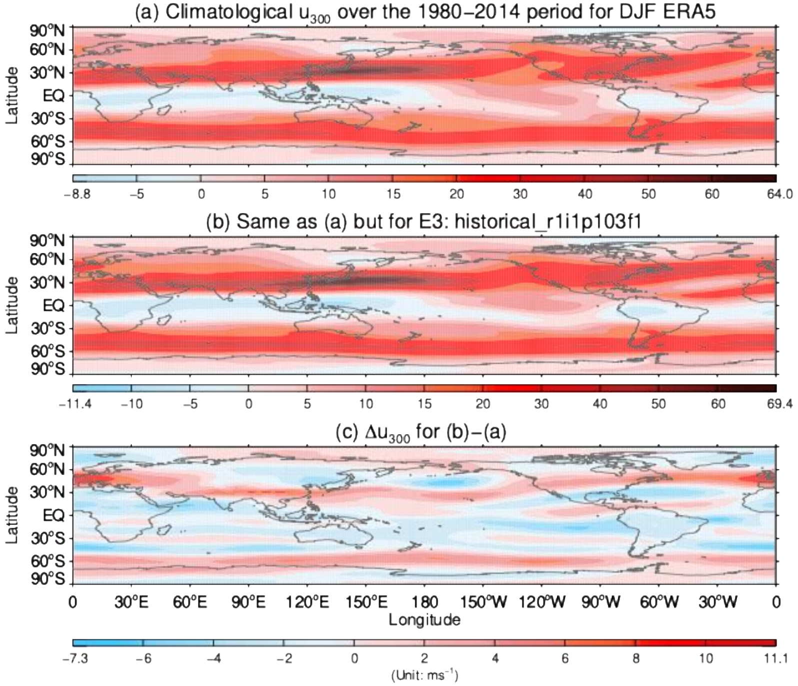


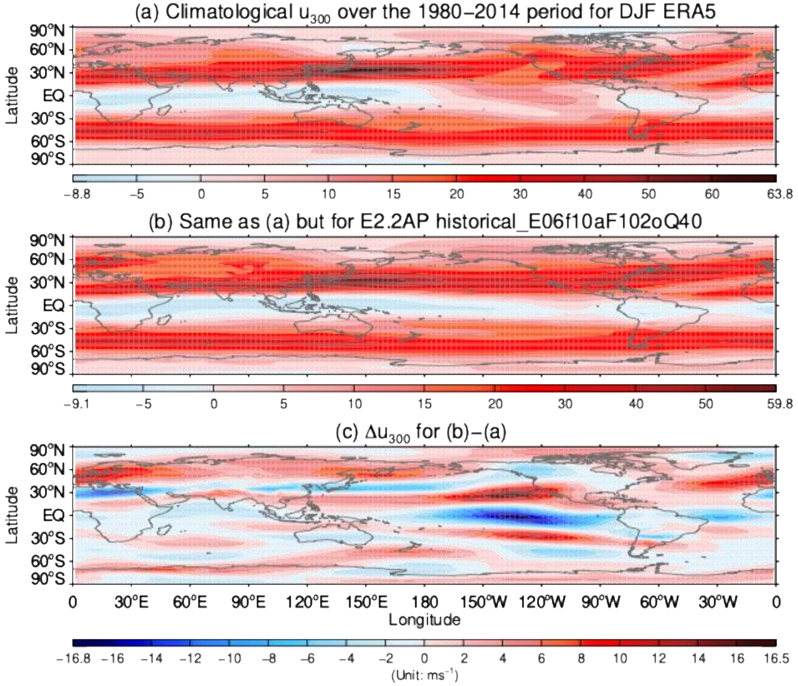
WAVE #3 AMPLITUDE
DEC - FEB

Anomalies 20-30%



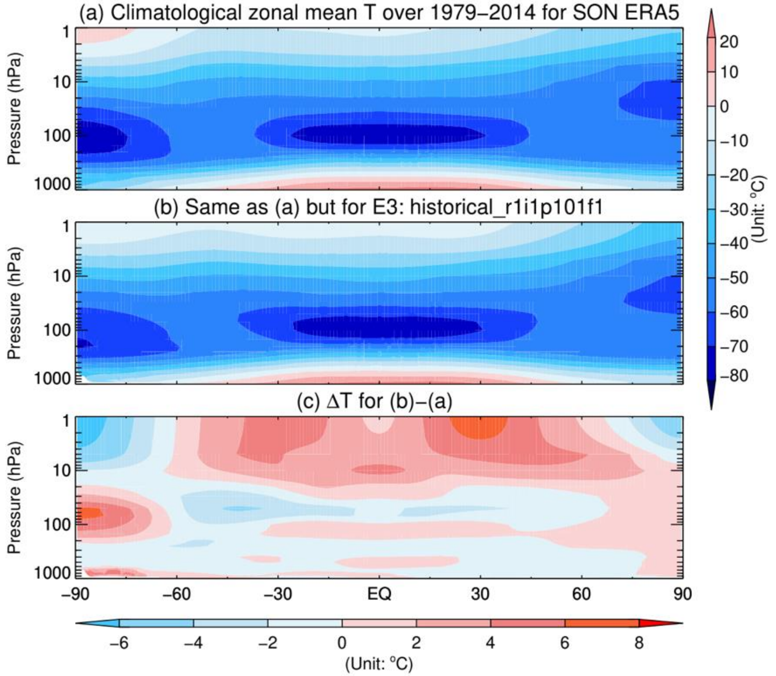


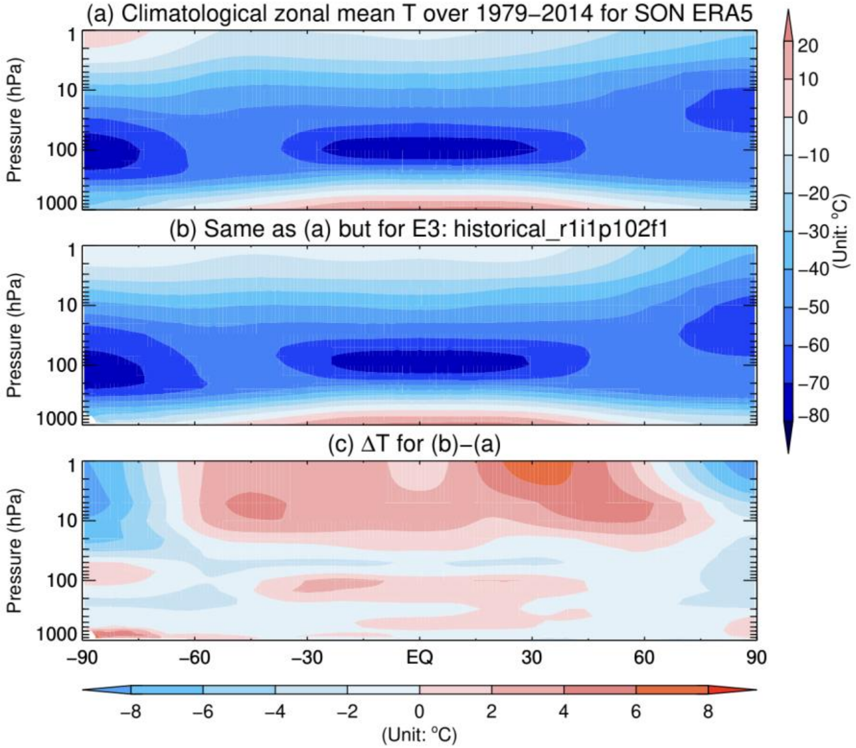


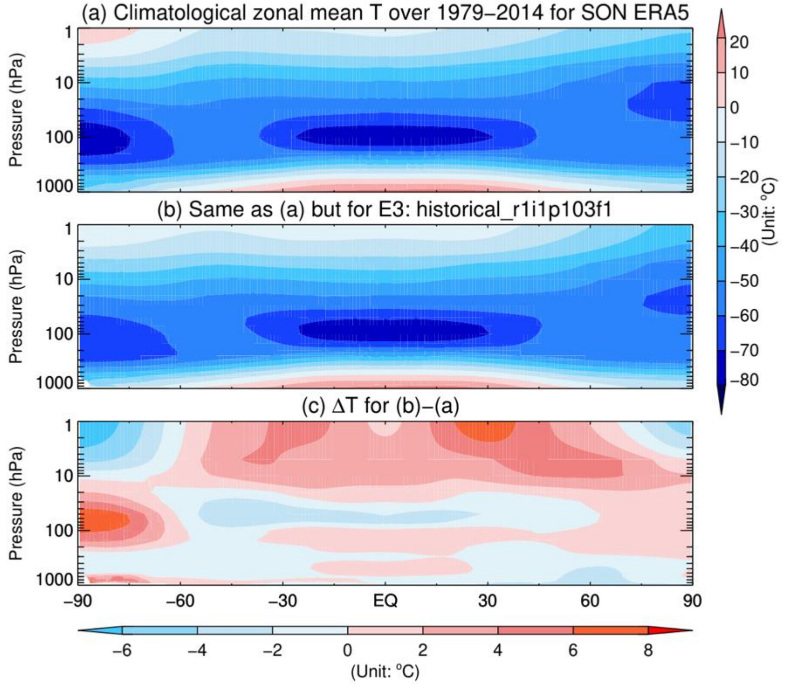


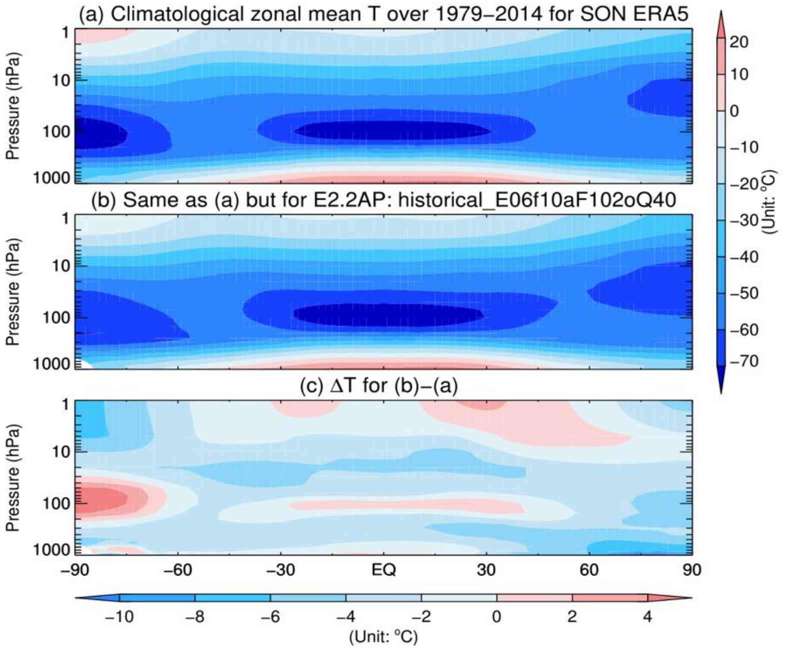
U 300 hPa
DEC-FEB

Anomalies 10 m/s









#4
STRATOSPHERIC OZONE
REGIONS OF
IMPORTANCE

TEMPERATUR
E
SEPT-NOV

Anomalies 5-
10°C

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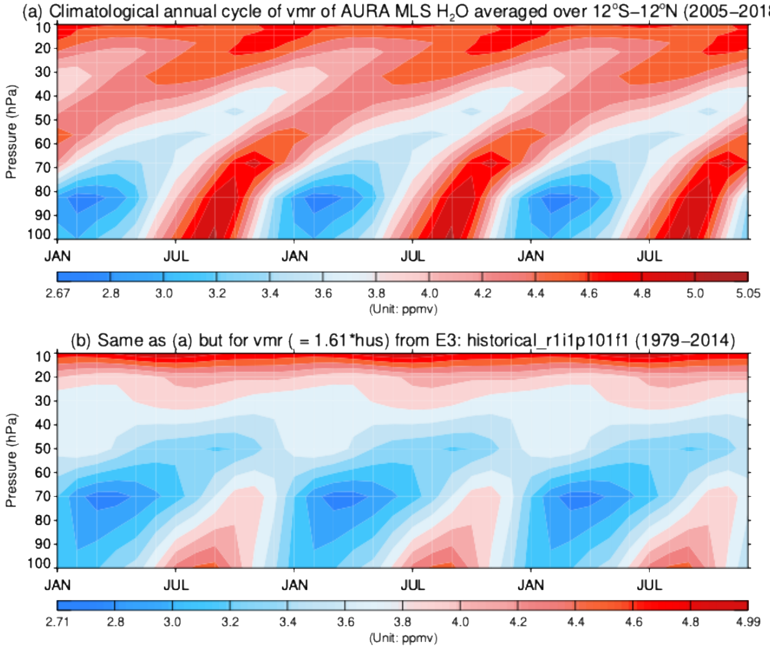
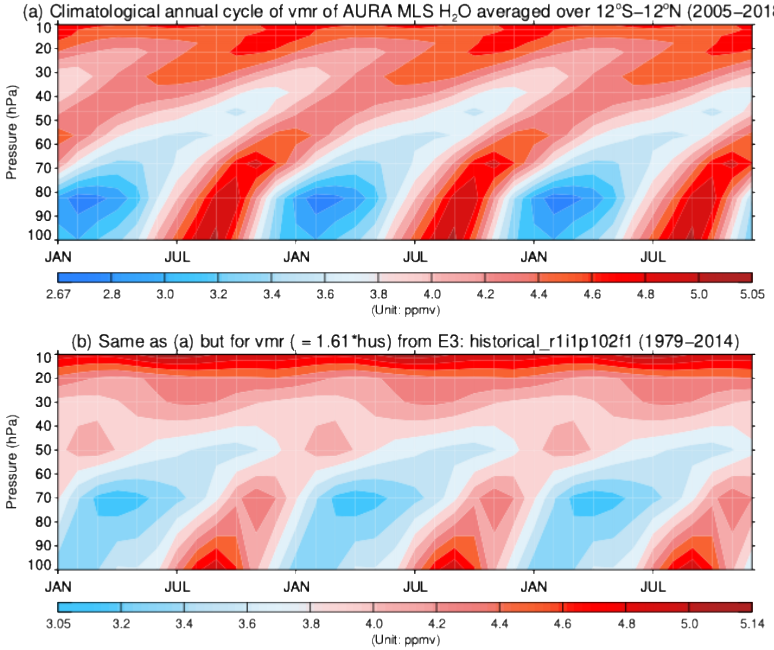
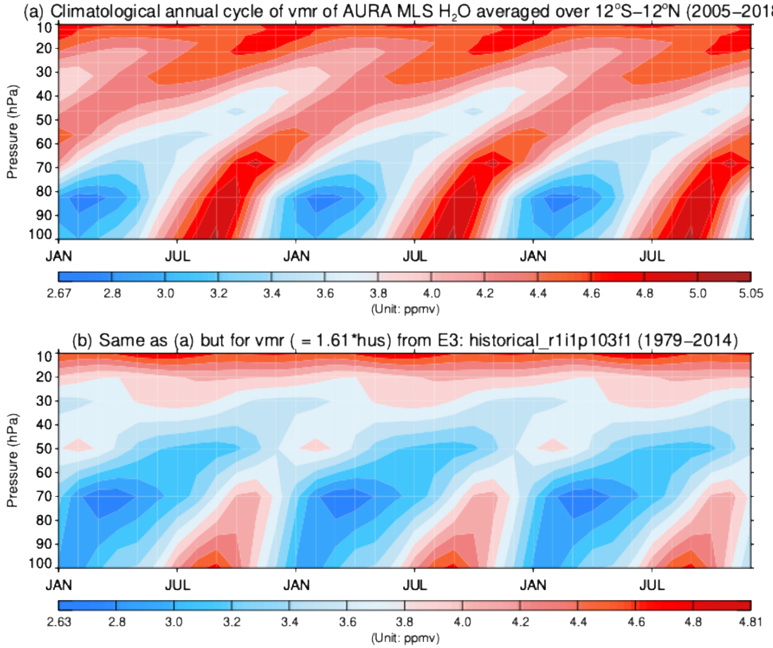
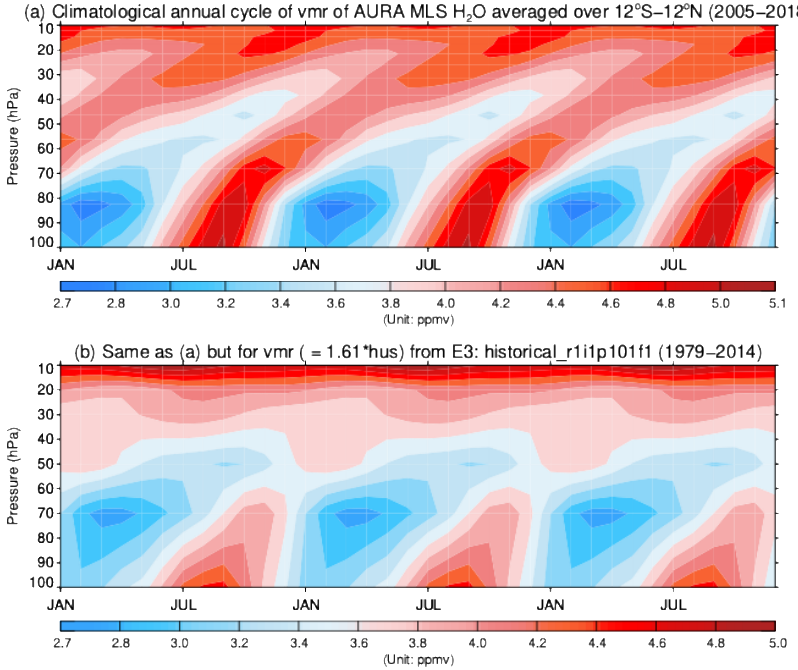
WATER VAPOR TAPE RECORDER









E2.2AP magnitude ‘corrected’

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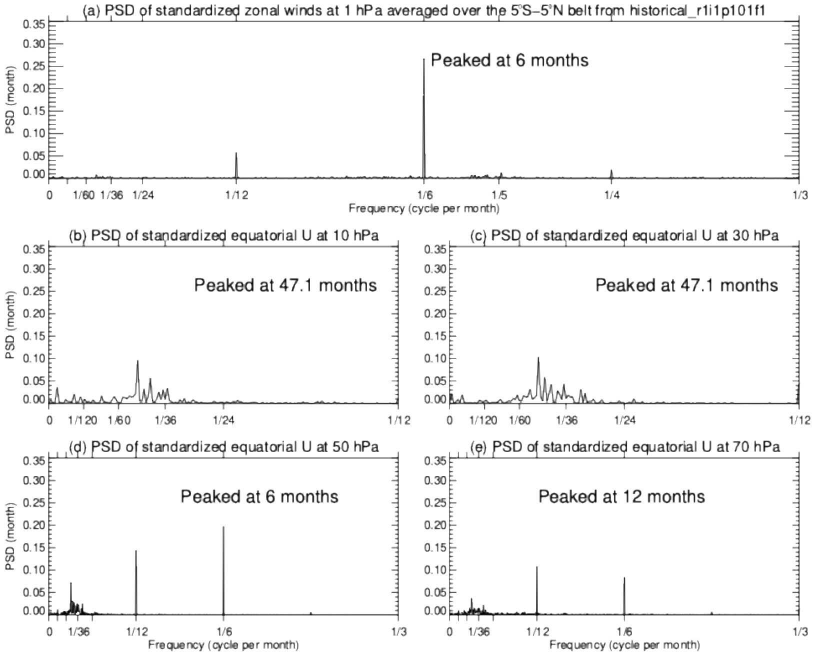
r1I1P101F1



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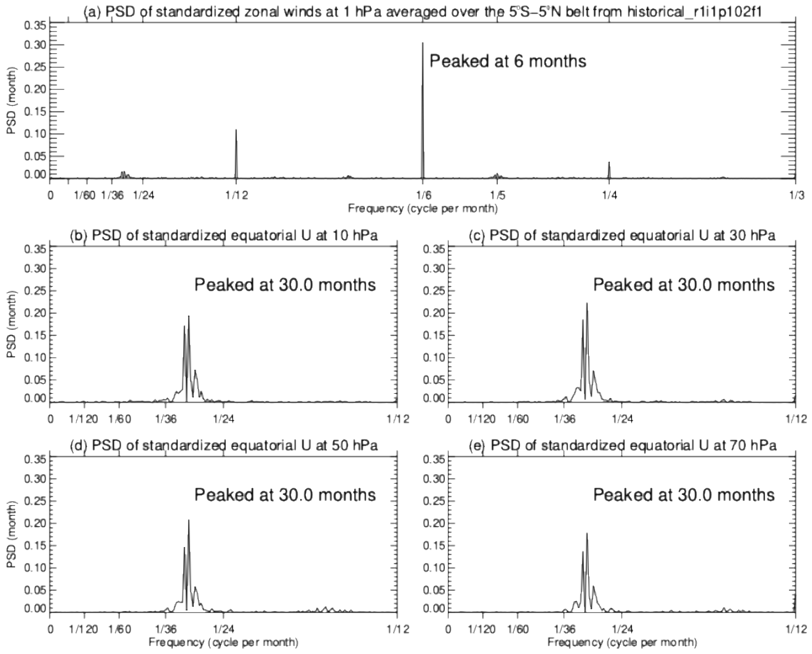
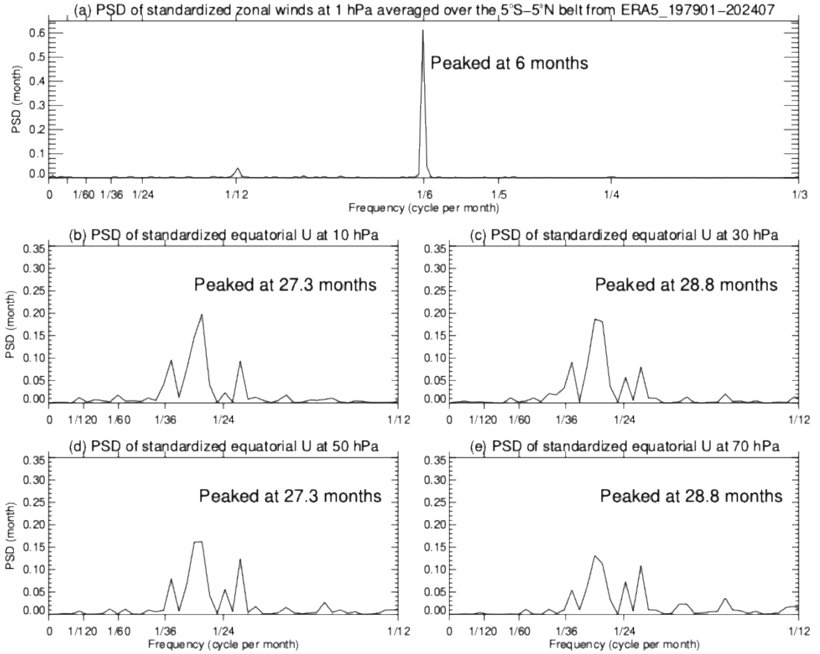


ERA5



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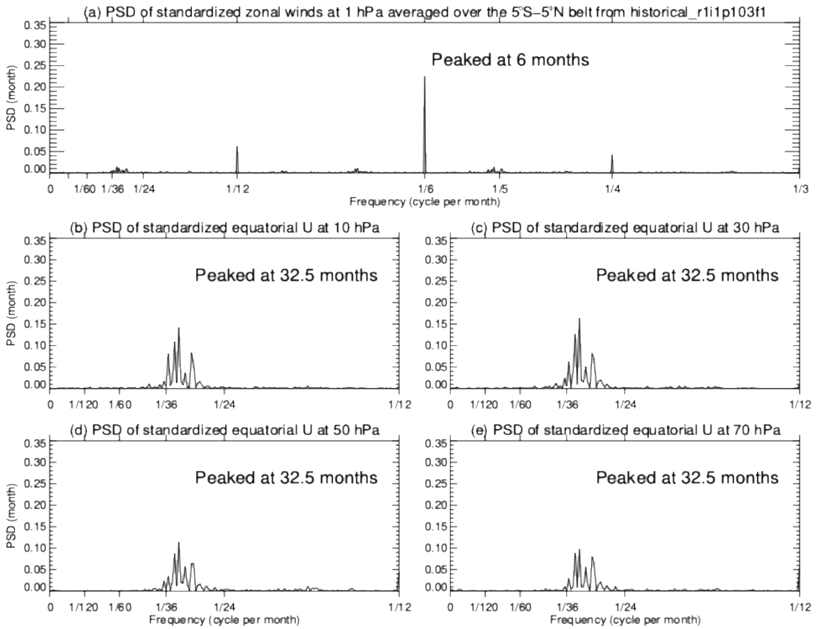
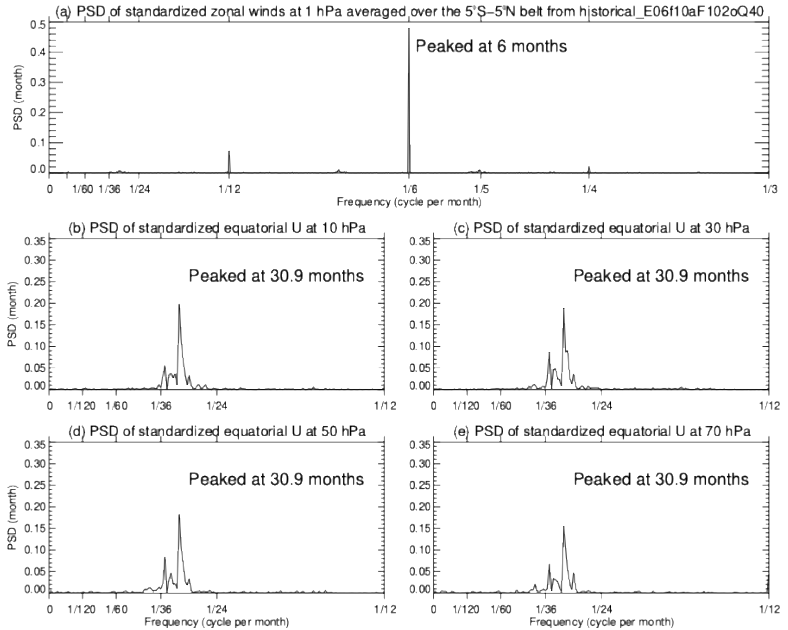


E2.2AP



#5
QBO

NOTE: 1 hPa scales differ

Semiannual wind anomaly 50-100%

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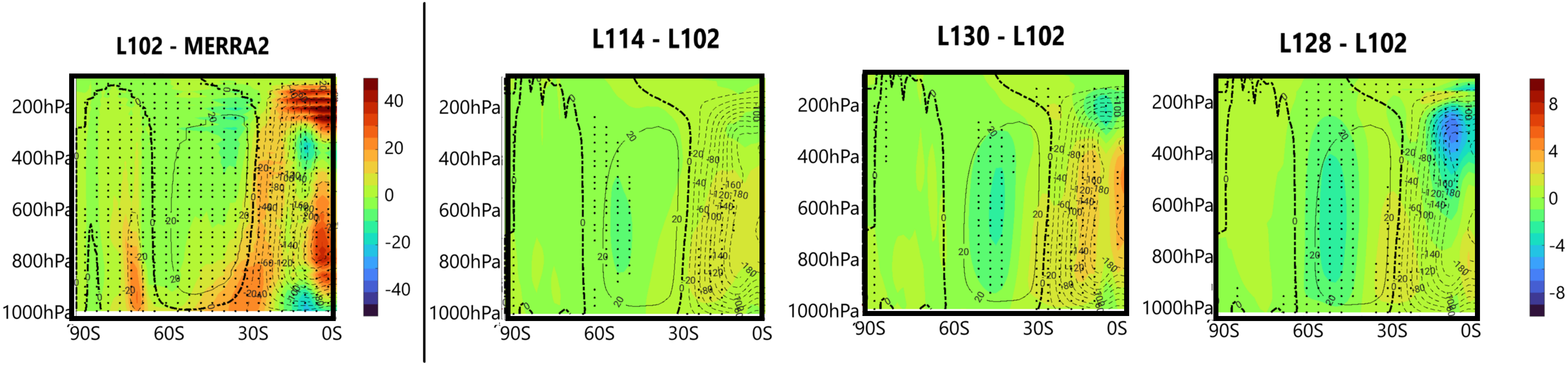
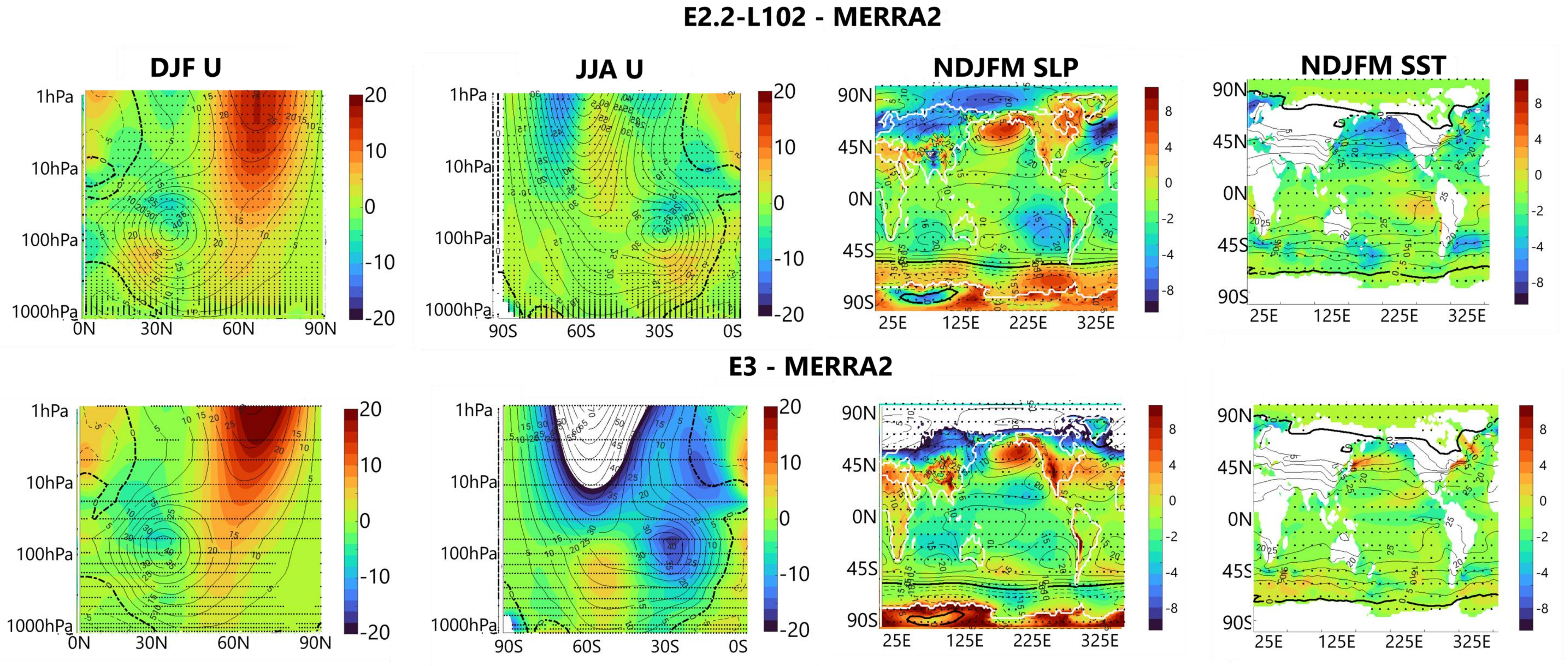
Extra Slides

Results: Tropospheric Impacts – Mass Streamfunction (SH, JJA)



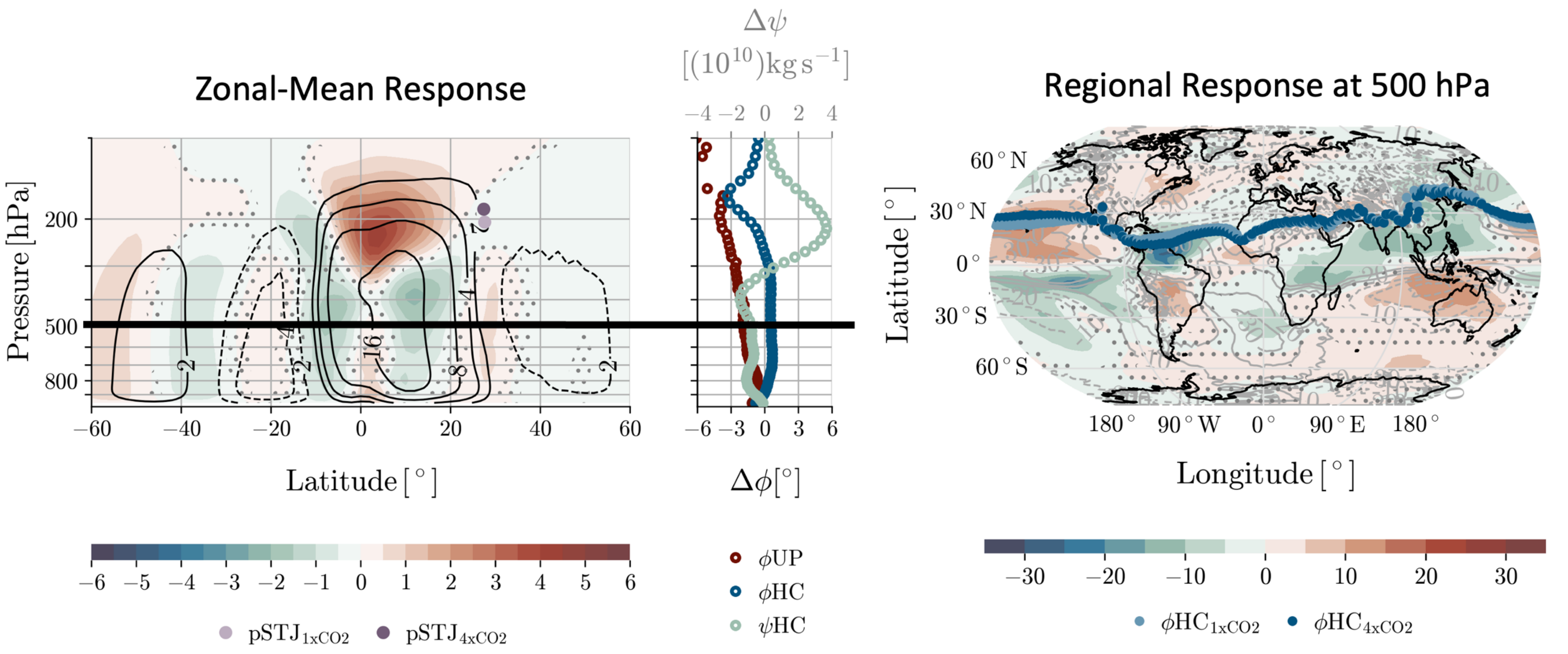
- Left panel: in contrast to NH wintertime, SH winter Hadley cell appears too weak and equatorward-contracted in F102. Slight equatorward-contraction of Ferrel cell in upper-tropospheric midlaitutdes, in-line with lower-stratospheric zonal wind anomalies.
- L114/L130 show no change/slight worsening of Hadley and Ferrel cell anomalies. L128 also slightly exacerbates Ferrel cell anomalies, although upper branch of Hadley cell shows slight improvement.

Results: Climatological Biases – E2.2 vs E3



Regional Hadley Cell Response to 4xCO2

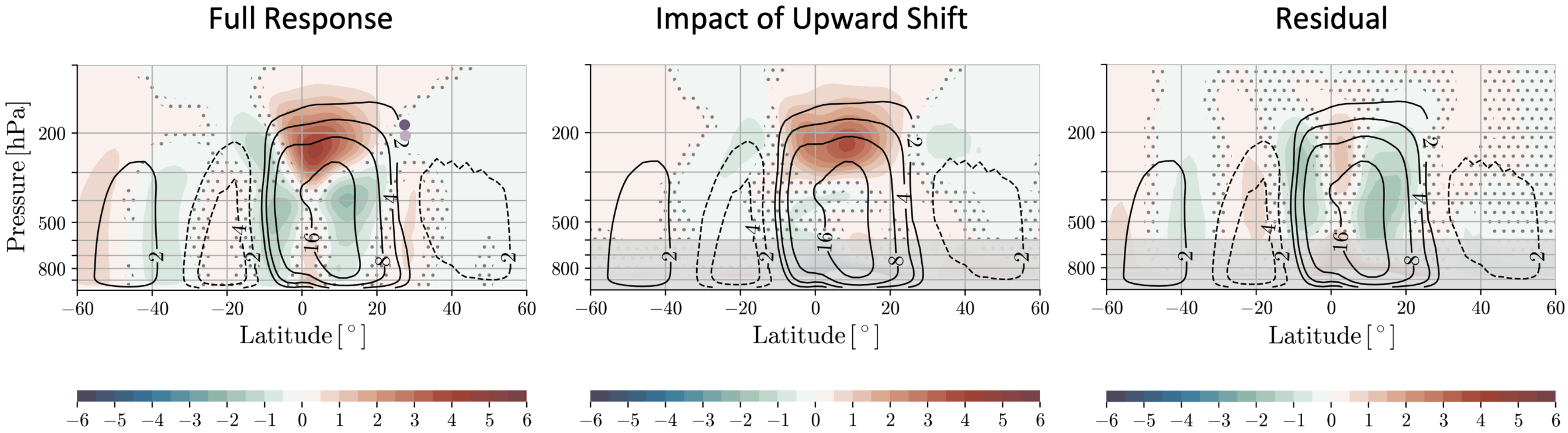
Regionally, the Hadley Cell expands where it strengthens (and vice versa), opposing the well-known and robust zonal-mean response of Hadley Cell expansion and weakening.



Menzel and Orbe (2024) ***submitted to Journal of Climate***

Hadley Cell Response to 4xCO2

While the upper tropospheric response largely reflects a zonally uniform upward extension of the troposphere, the mid-to-lower tropospheric response features strong regional variations.



Menzel and Orbe (2024) ***submitted to Journal of Climate***