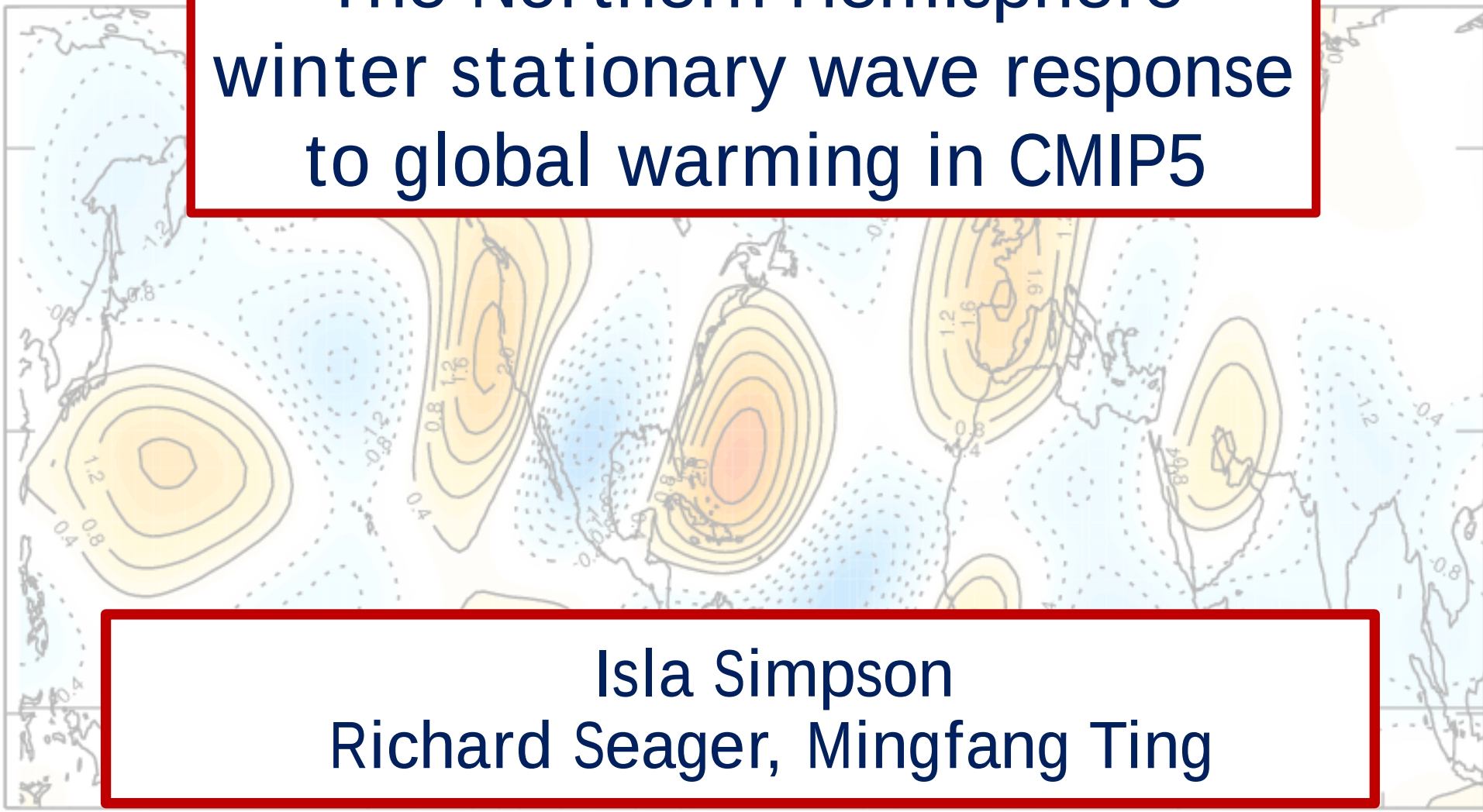
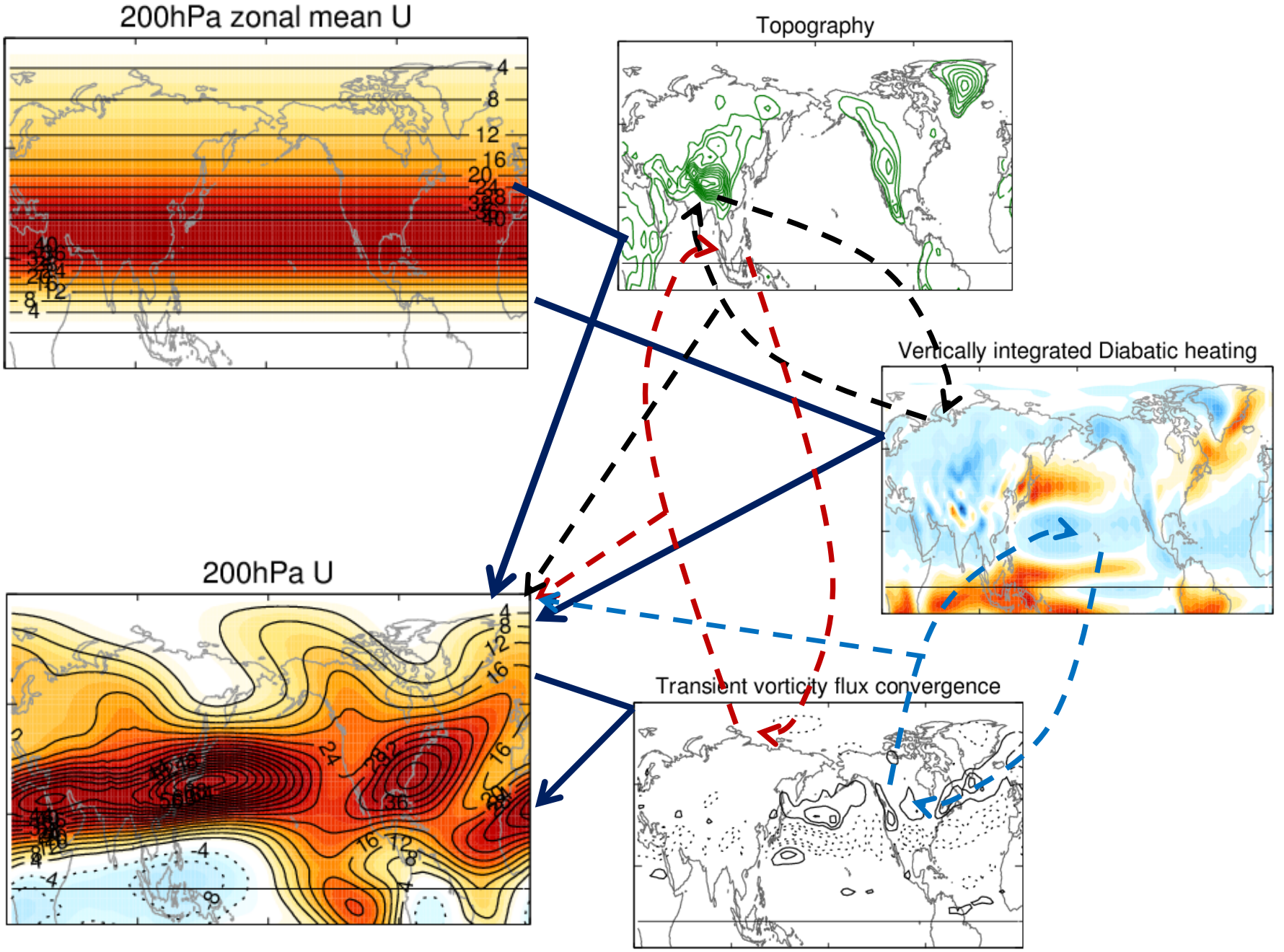
The Northern Hemisphere winter stationary wave response to global warming in CMIP5



Isla Simpson
Richard Seager, Mingfang Ting

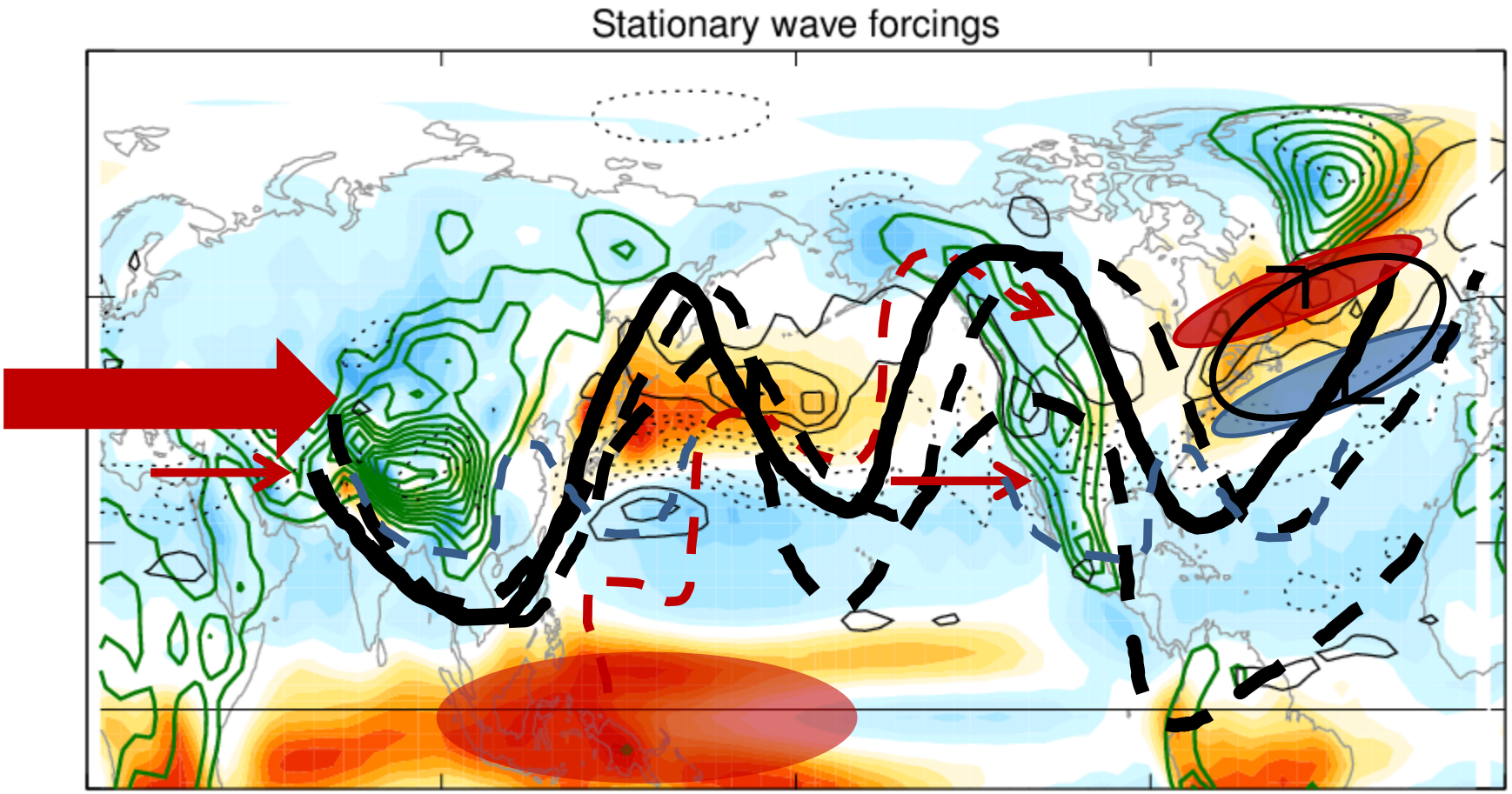
Lamont-Doherty Earth Observatory, Columbia University



ERA-Interim DJF climatology

see e.g. Held et al (2002)

Will the stationary waves change? How?



topography

Transient vorticity flux convergence (200hPa)

Shading=vertically integrated diabatic heating

Previous Studies

- ## Single Model Studies

  Stephenson and Held (1993), GFDL

  Joseph et al (2004), GFDL

  Wang and Kushner (2011), CMAM

  Selten et al (2004), Branstator and Selten (2009) CCSM1.4

- ## CMIP-3

  Brandefelt and Körnich (2008)

  Haarsma and Selten (2012)

Previous Studies

- Single Model Studies

  Stephenson and Held (1993), GFDL

  Joseph et al (2004), GFDL

  Wang and Kushner (2011), CMAM

  Selten et al (2004), Branstator and Selten (2009) CCSM1.4

- CMIP-3

  Brandefelt and Körnich (2008)

  Haarsma and Selten (2012)

Altered tropically forced waves

Altered zonal mean basic state

CMIP-5 data

- 35 models, all available ensemble members

  PAST: 1979-2005 of the historical run

  FUTURE: 2070-2099 of the RCP8.5 scenario

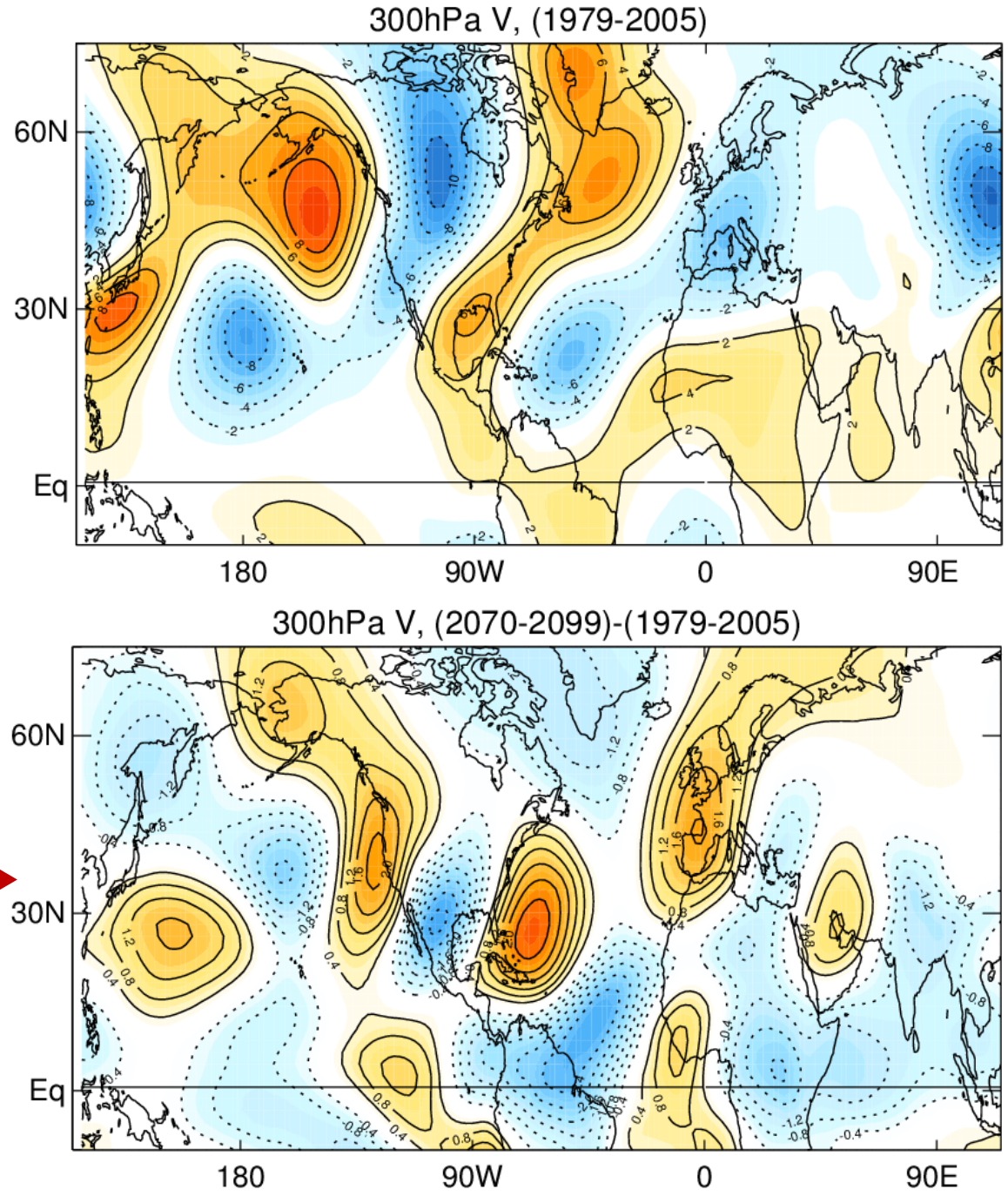
- DJF season

- Compare with variability in 200y of piControl

Past,
contour=2m/s

300hPa V
Multi-model mean
(35 models)

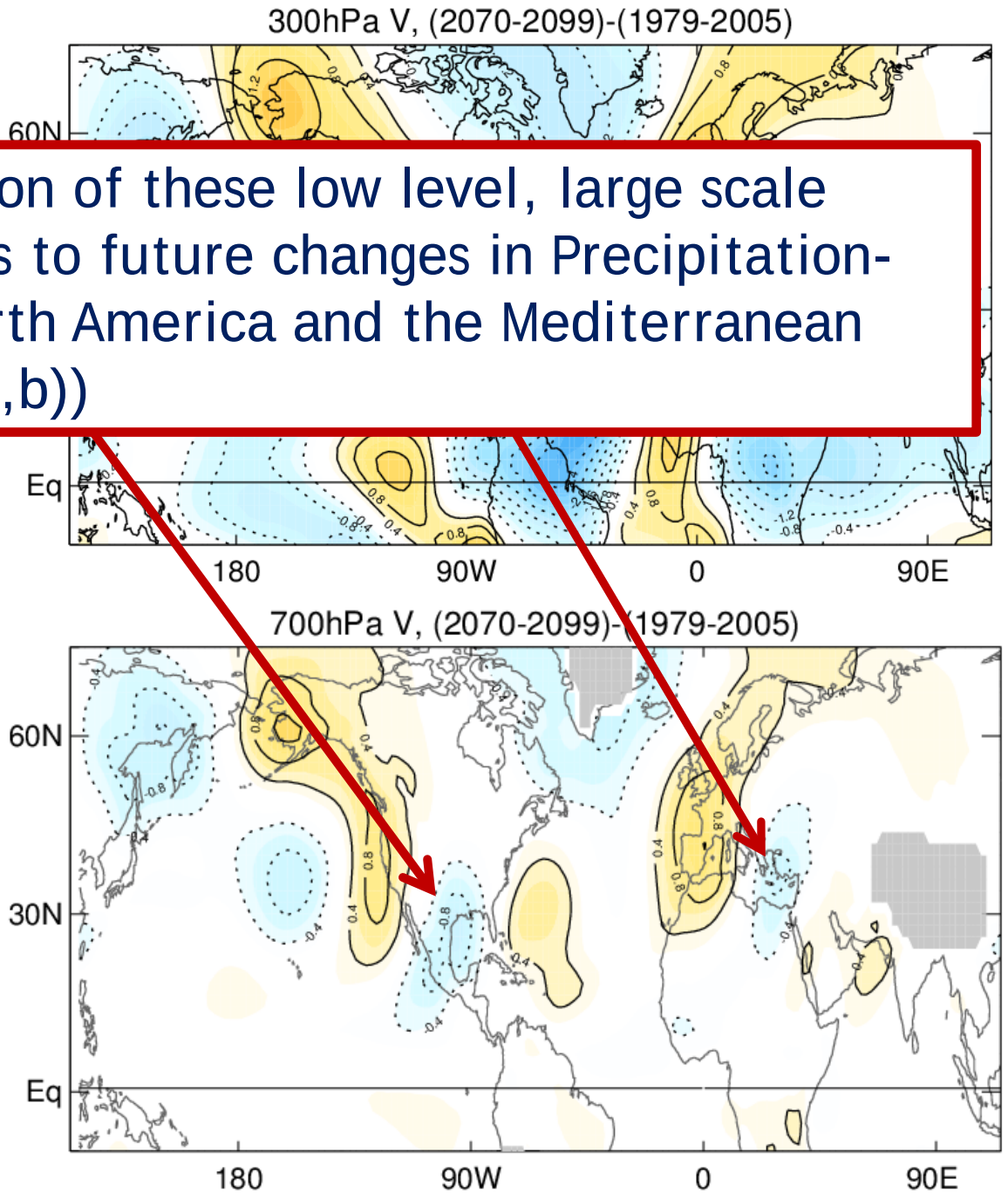
Future-Past
contour=0.4m/s



Important Contribution of these low level, large scale circulation anomalies to future changes in Precipitation-Evaporation over North America and the Mediterranean (Seager et al (2014 a,b))

V, Multi-model mean (35 models)

700hPa contour=0.4m/s



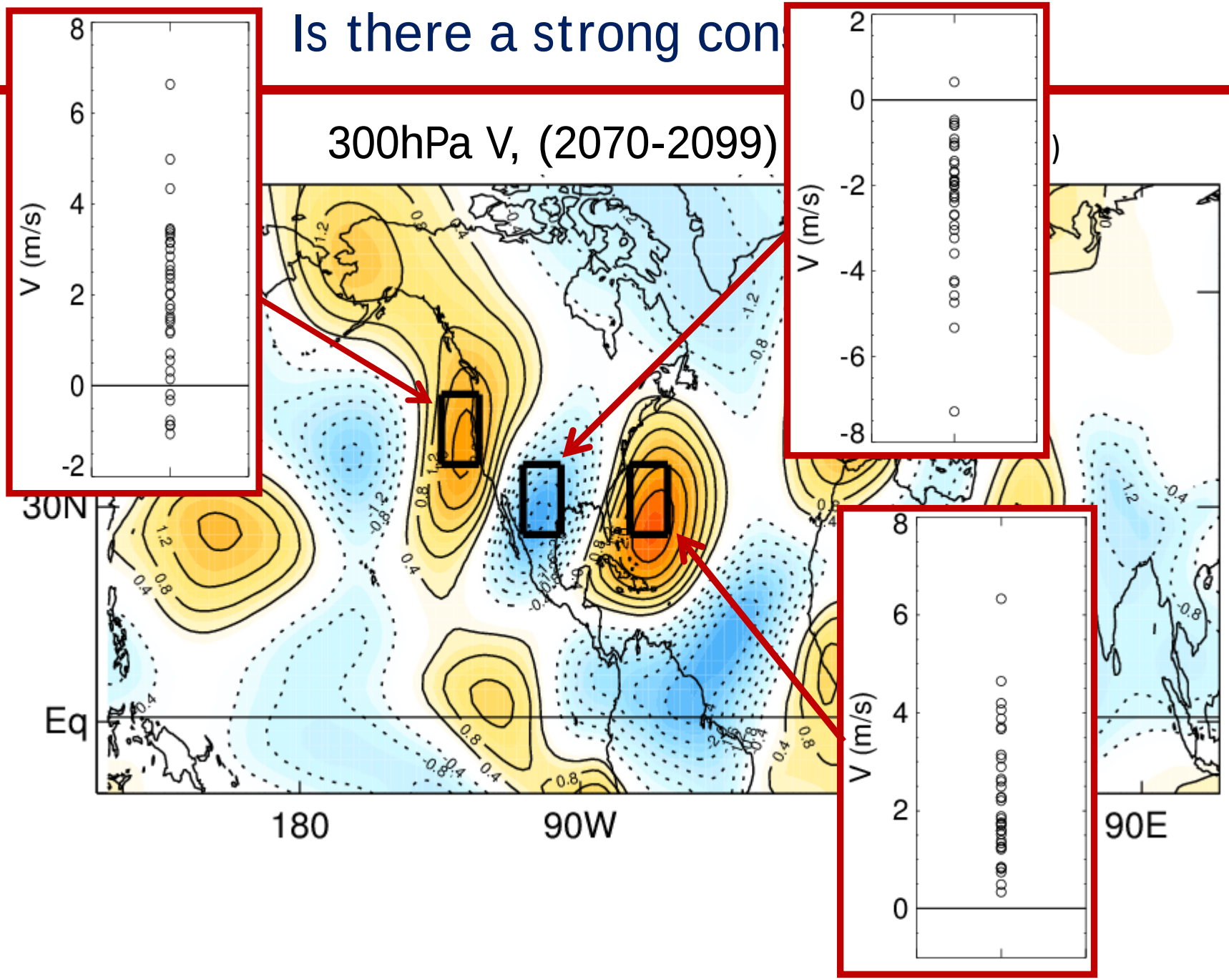
Should we expect the real world to behave this way?

Does the multi-model mean represent a strong consensus response among the models?

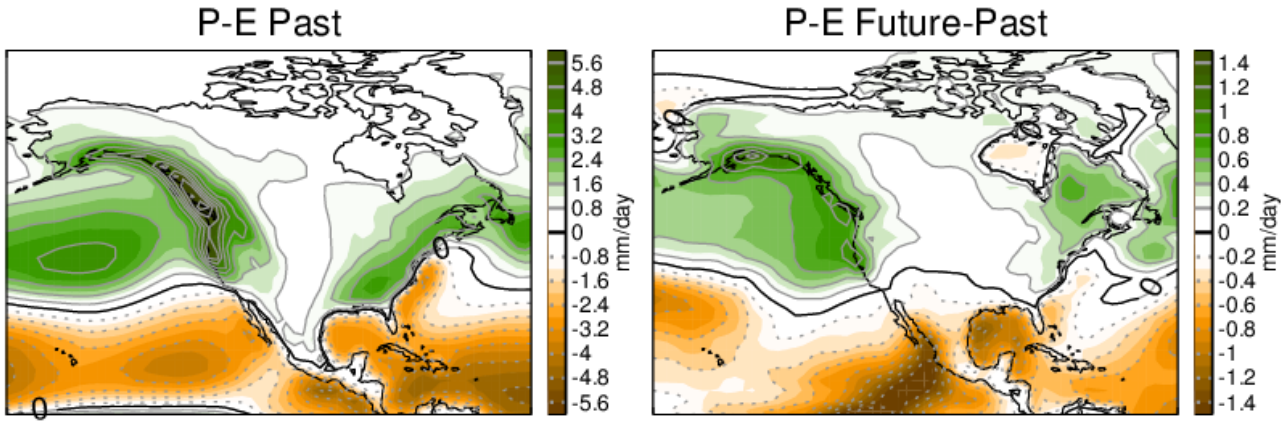
Is it a signal that can be seen to emerge outside of the natural variability in a single realization?

Can we understand it and does it depend on something that we have confidence in our abilities to model?

Is there a strong con

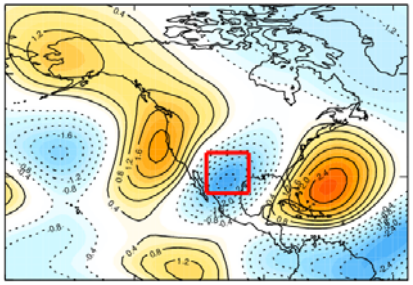


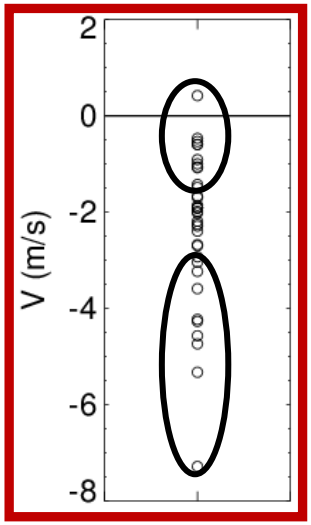
Large Scale Circulation influence on P-E

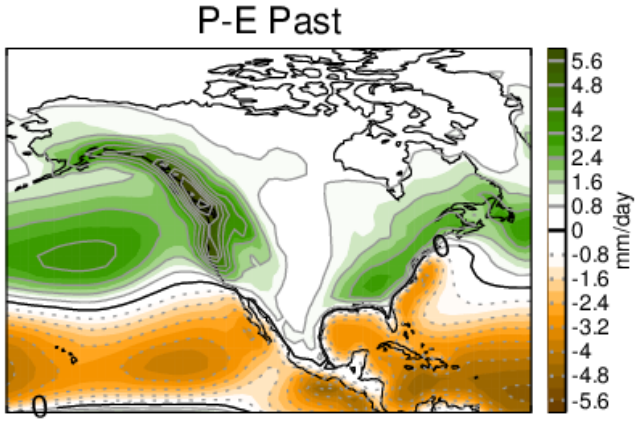


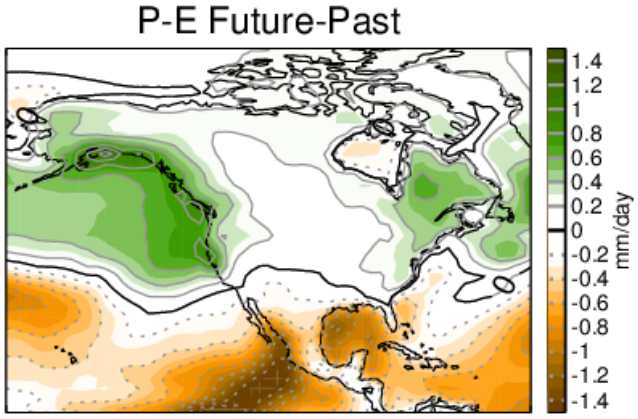
See also Seager et al (2014)

Large Scale Circulation influence on P-E



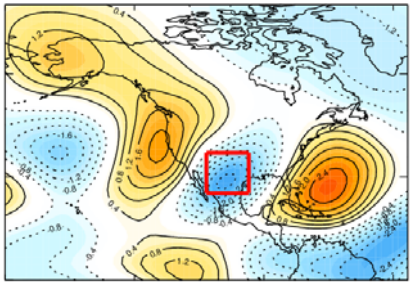


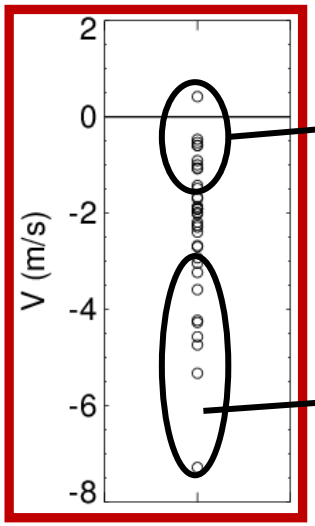




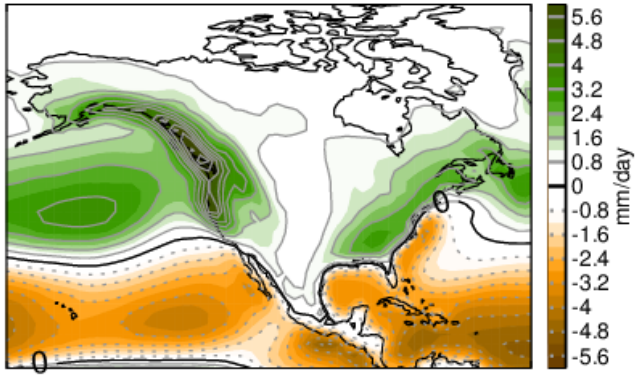
See also Seager et al (2014)

Large Scale Circulation influence on P-E

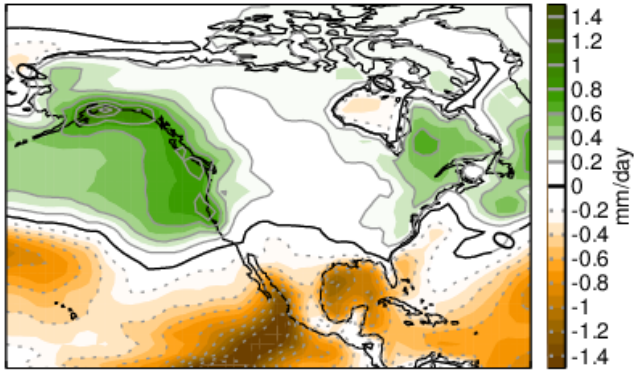




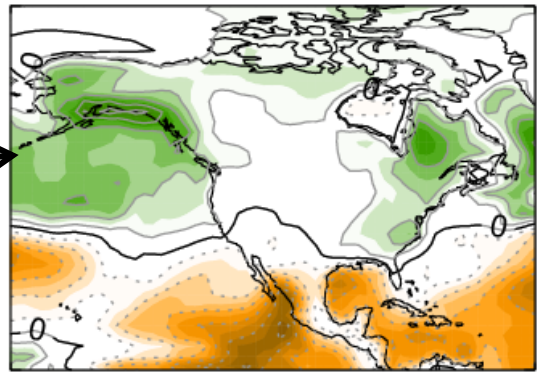
P-E Past



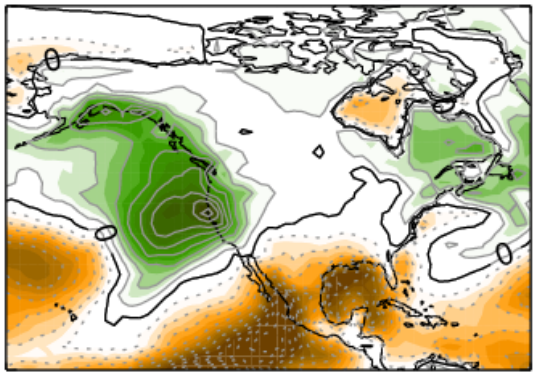
P-E Future-Past



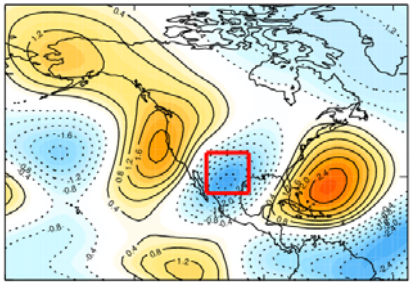
P-E Future-Past, Weakest 25%

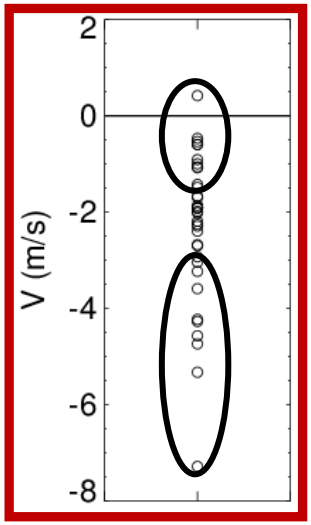


P-E Future-Past, Strongest 25%

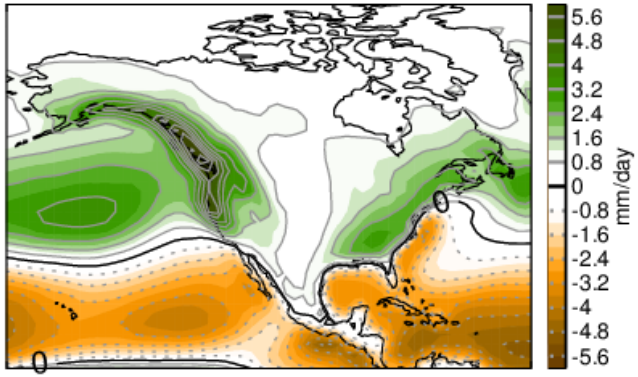


Large Scale Circulation influence on P-E

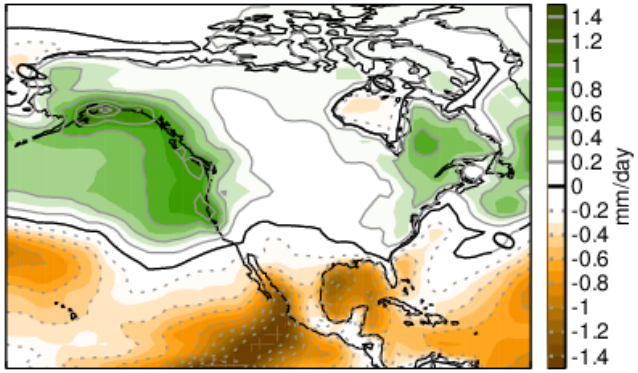




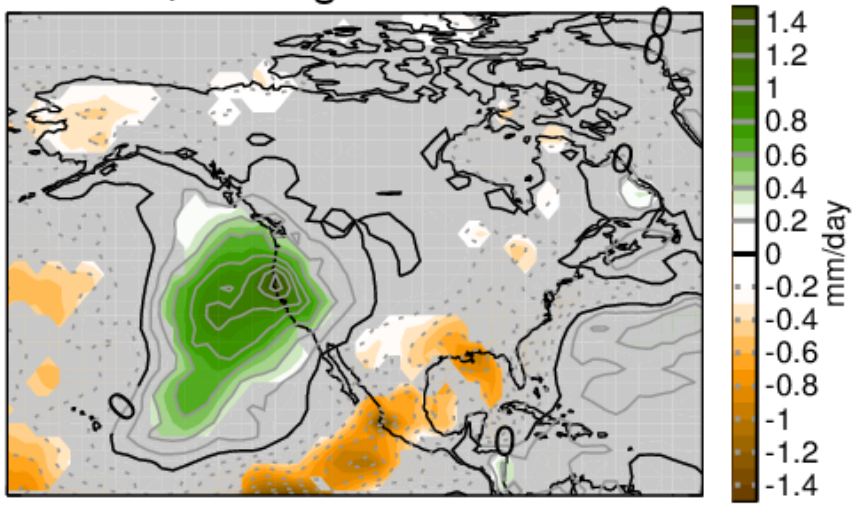
P-E Past



P-E Future-Past



P-E, Strongest -Weakest



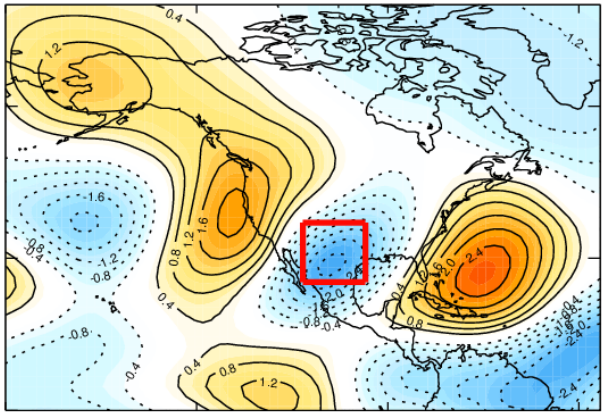
Should we expect the real world to behave this way?

Does the multi-model mean represent a strong consensus response among the models?

Yes, but with spread in the magnitude

Is it a signal that can be seen to emerge outside of the natural variability in a single realization?

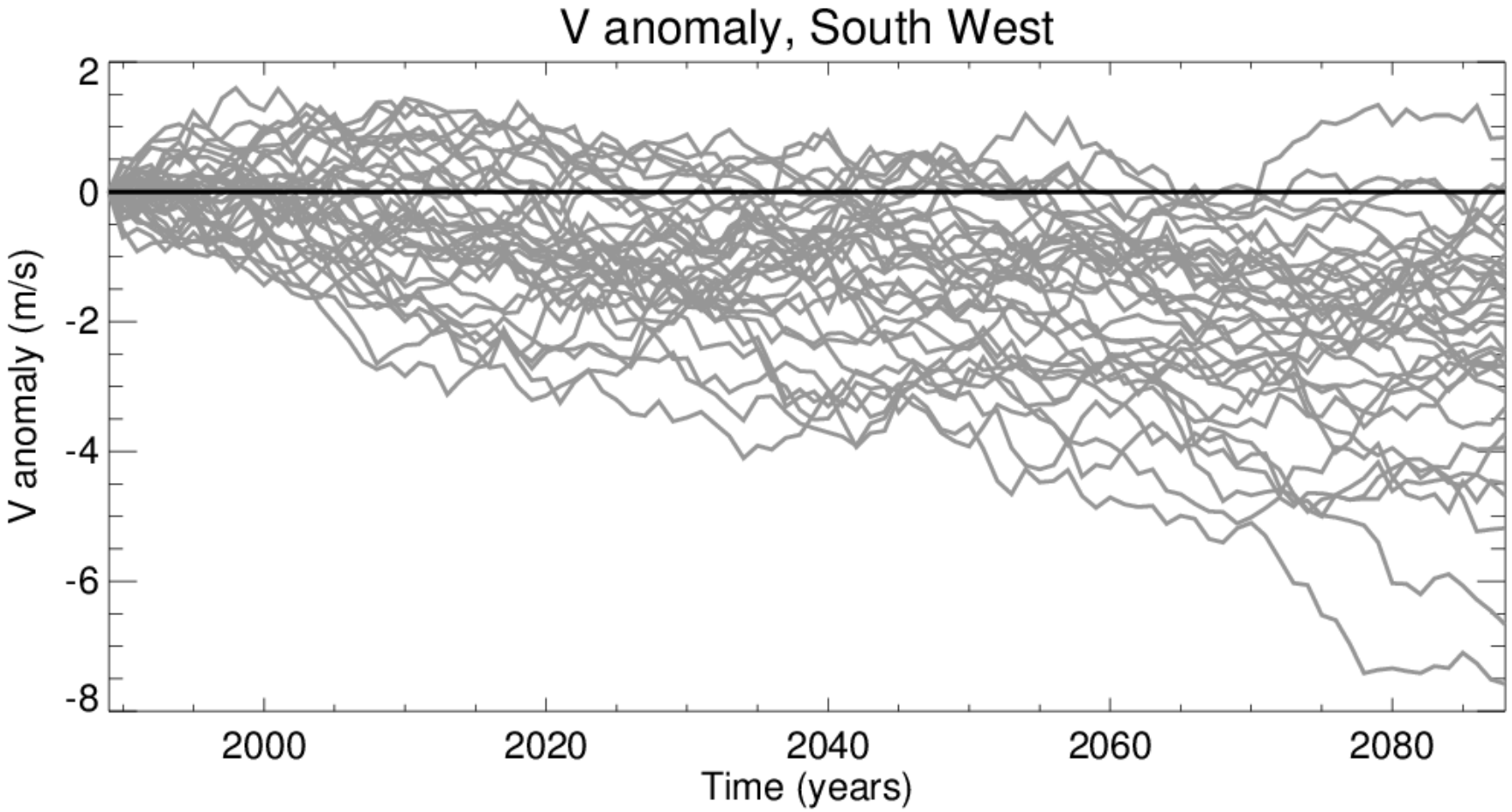
Can we understand it and does it depend on something that we have confidence in our abilities to model?

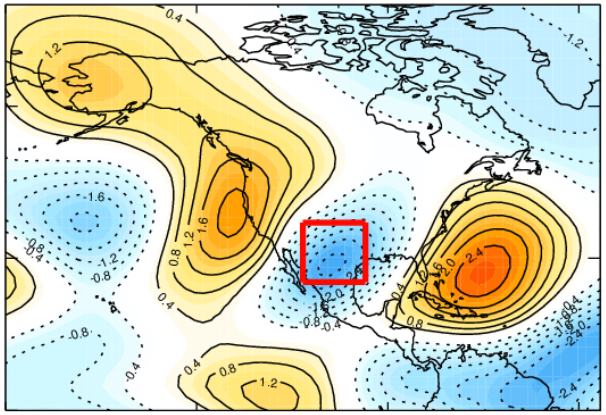


The South West

21 year running means, 1 member

Does the *v* anomaly become larger than the 5-95% confidence interval of the distribution of variability in 21 years means in the piControl ?

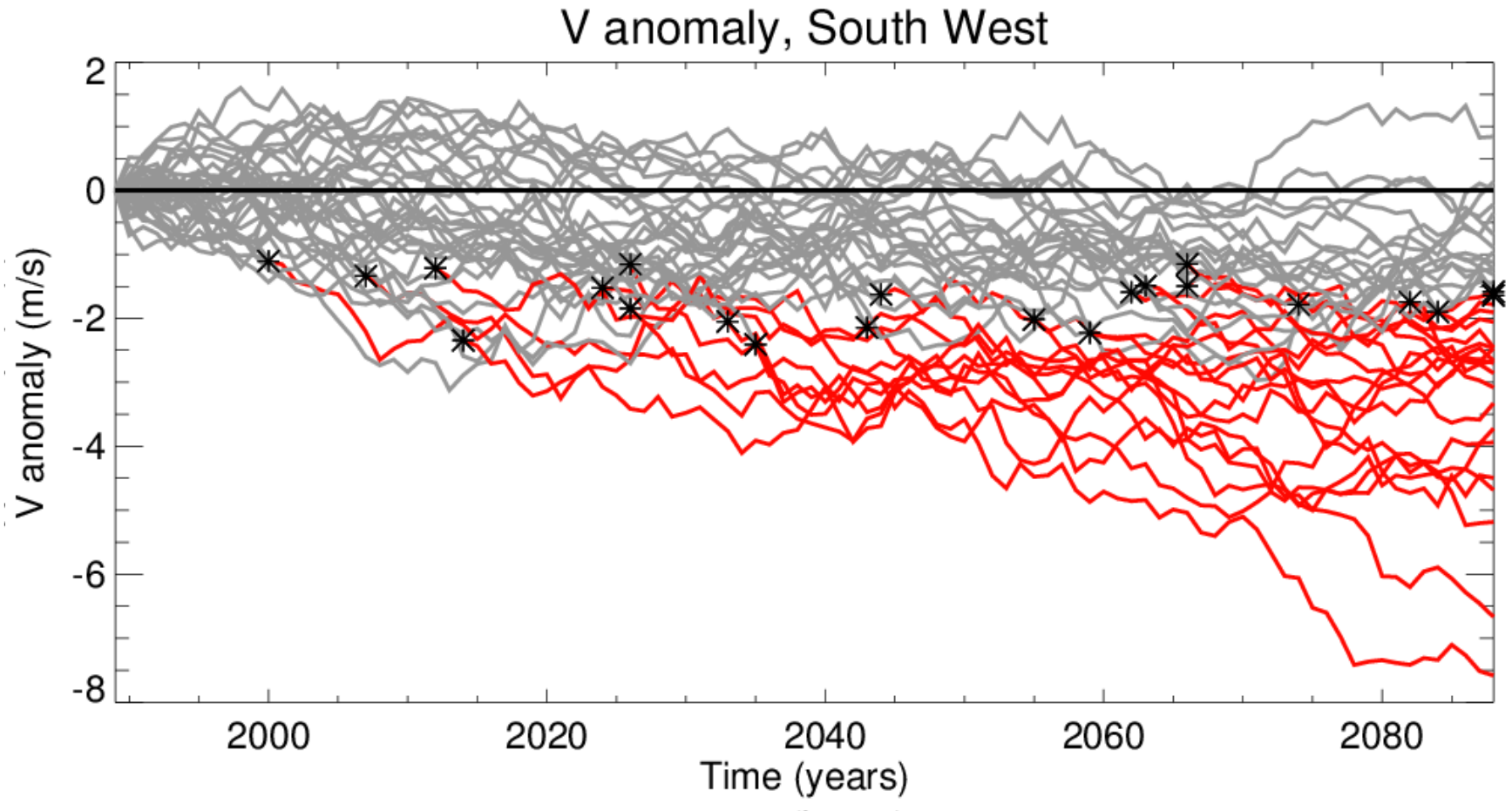


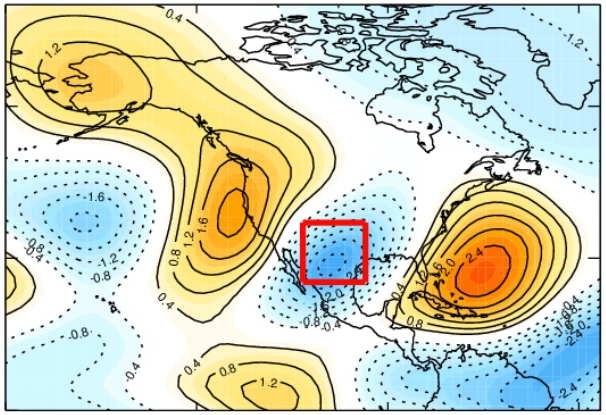


The South West

21 year running means, 1 member

Yes, in 22/35 models





The South West

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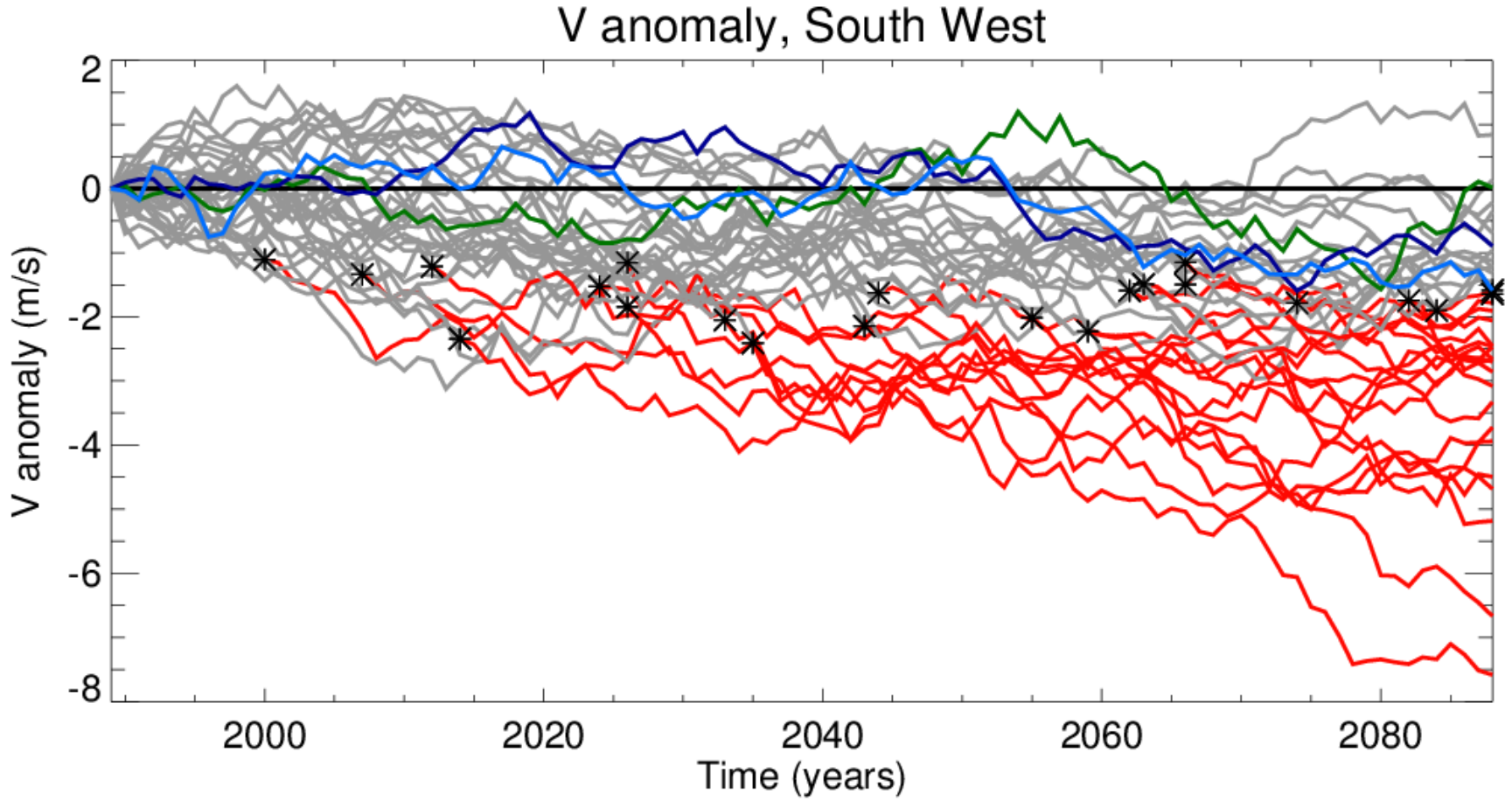
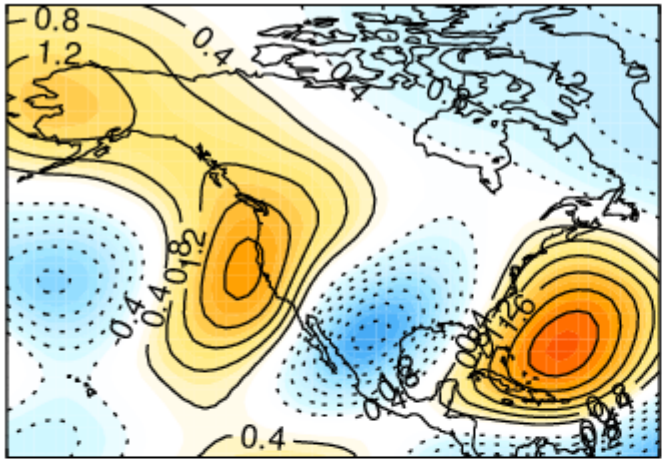
CCSM4 — CESM1-CAM5 — CESM1-WACCM



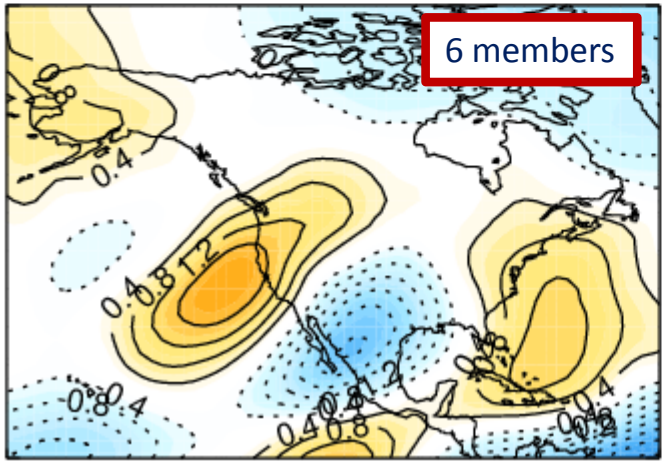
The NCAR models over North America

(2070-2099)-(1979-2005), ensemble mean

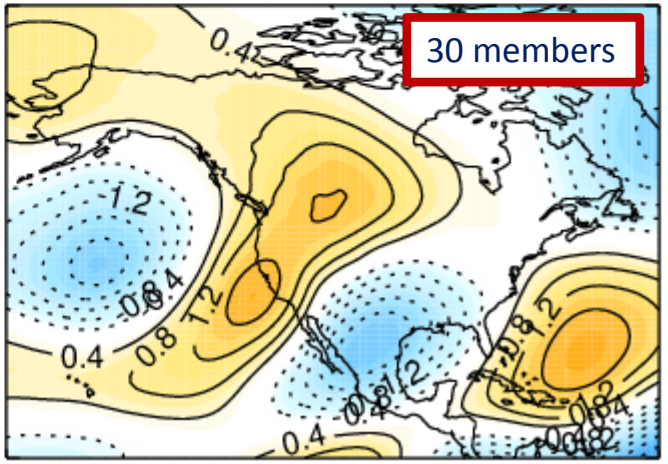
Multi-model mean

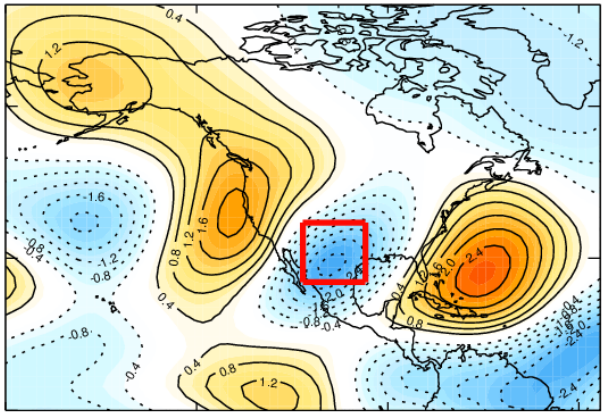


CCSM4



CESM1-CAM5





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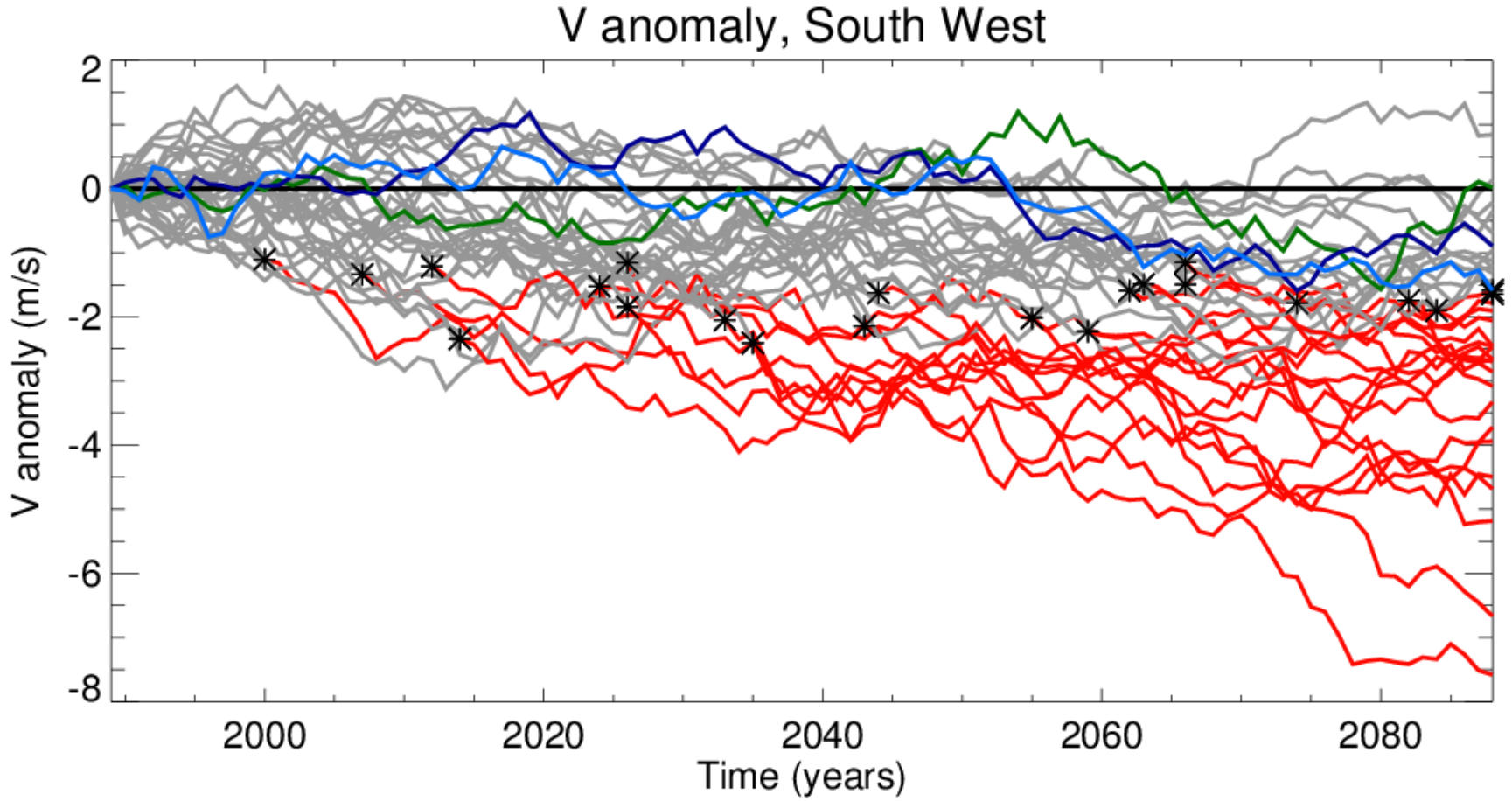
CCSM4 — CESM1-CAM5 — CESM1-WACCM



Should we expect the real world to behave this way?

Does the multi-model mean represent a strong consensus response among the models?

Yes, but with spread in the magnitude

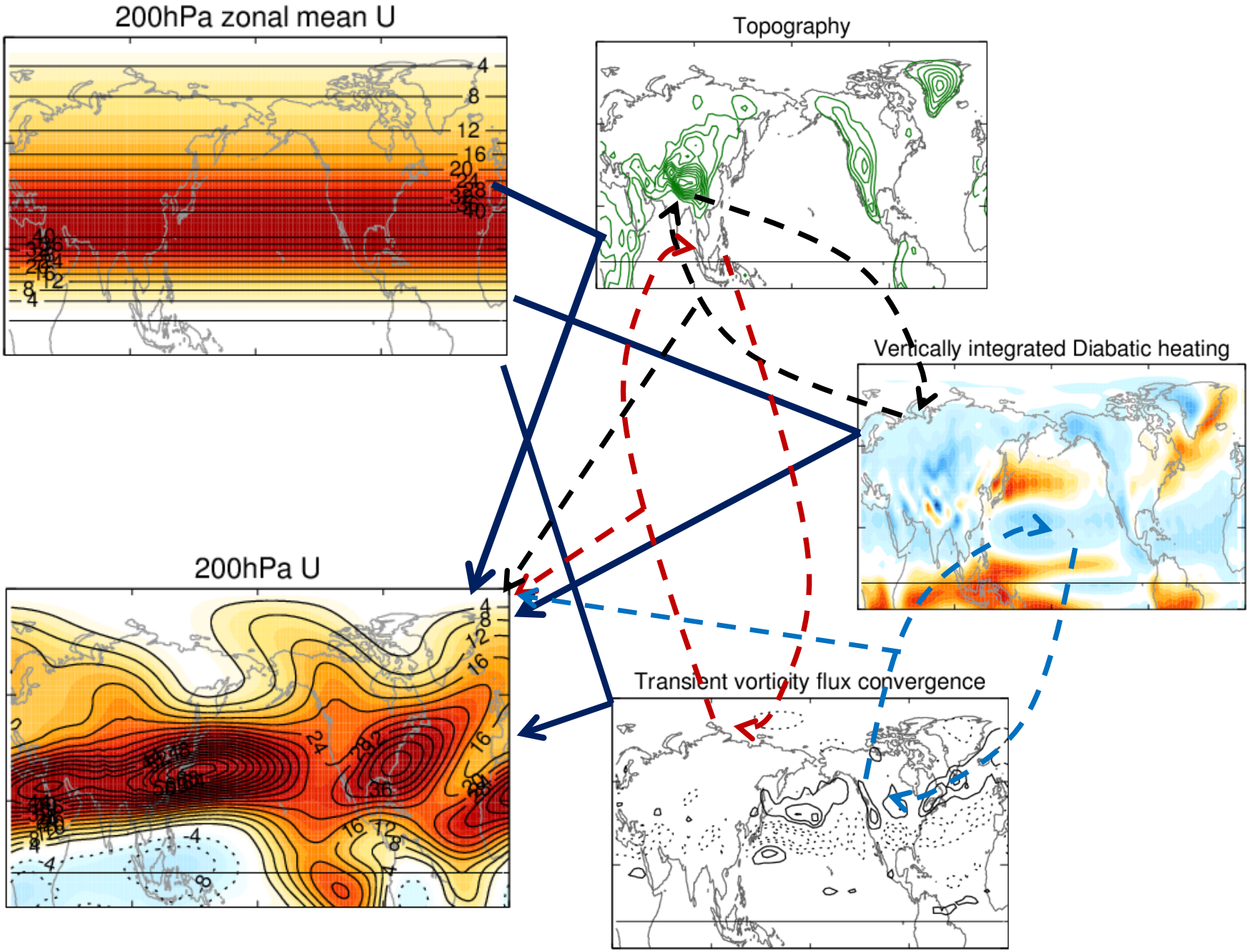
Is it a signal that can be seen to emerge outside of the natural variability in a single realization?

Yes, in a large number of the models

Can we understand it and does it depend on something that we have confidence in our abilities to model?

Stationary wave modelling

- Stationary wave model described in detail in Ting and Yu (1998)
- Solving the non-linear primitive equations for the anomalies from a prescribed basic state in the presence of zonally asymmetric forcings
- R30L24, σ coordinate
- No Physics, Idealized dampings
- Time integration to 80 days. Quasi-steady state after about day 20. Average days 30-80.



ERA-Interim DJF climatology

see e.g. Held et al (2002)

Can we reproduce the Future-Past difference with the stationary wave model?

$$v_P = F(\overline{BS}_P + Q_P + O + TR_P)$$

- v_P: Stationary waves
- $\overline{BS}_P$: Zonal mean basic state
- Q_P: Diabatic Heating
- O: Orography
- TR_P: Transient momentum fluxes

Multi-model mean forcings/basic state calculated from all available models

Can we reproduce the Future-Past difference with the stationary wave model?

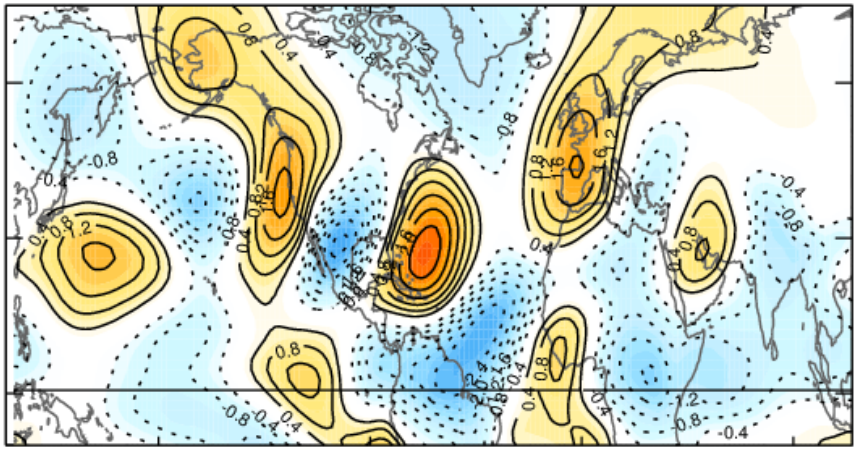
$$v_P = F(\overline{BS}_P + Q_P + O + TR_P)$$

$$v_F = F(\overline{BS}_F + Q_F + O + TR_F)$$

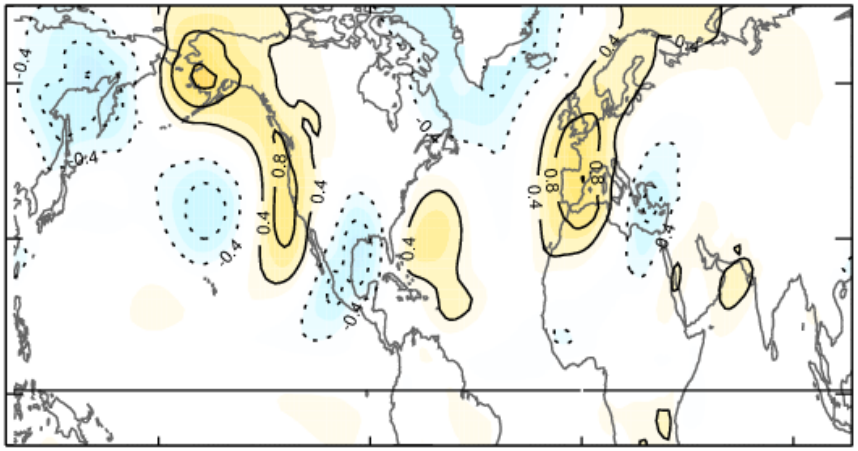
$$\Delta v = v_F - v_P$$

CMIP5 multi-model mean

CMIP5, 300hPa V, Future-Past



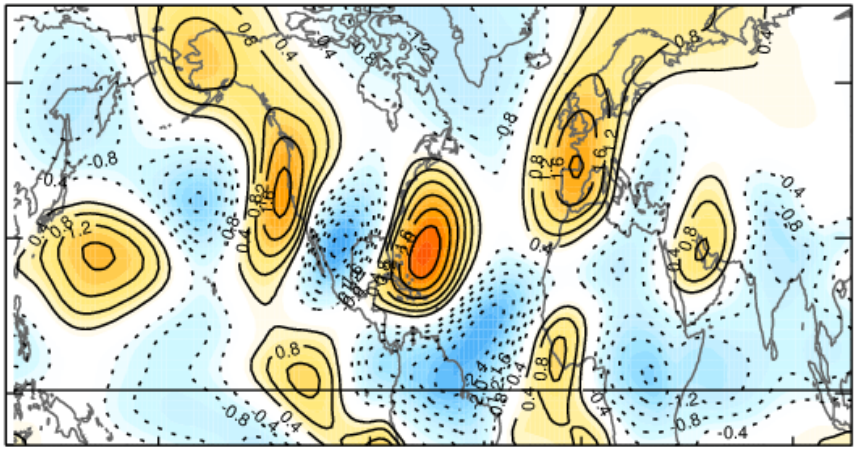
CMIP5, 700hPa V, Future-Past



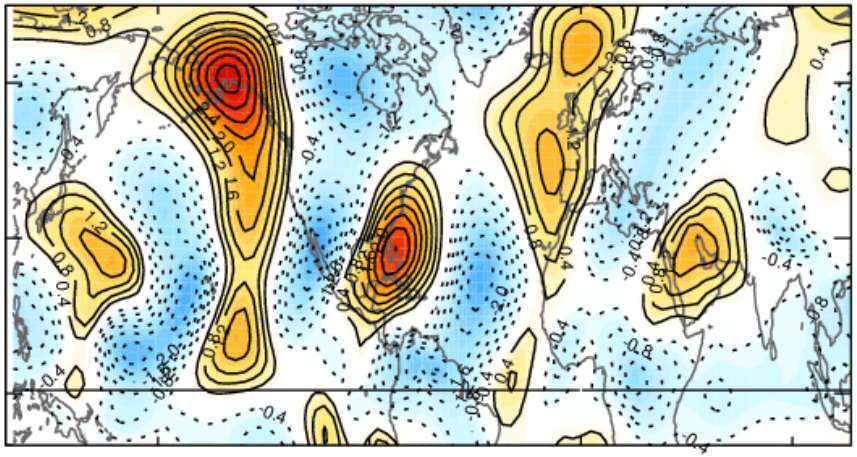
CMIP5 multi-model mean

Stationary wave model

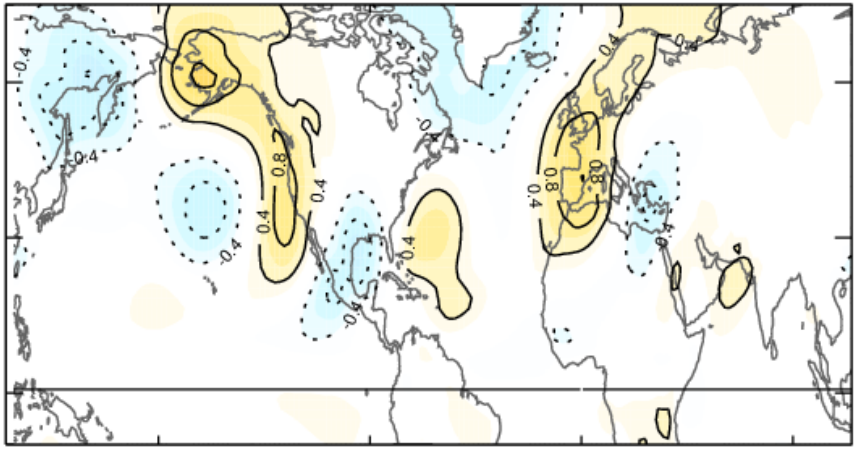
CMIP5, 300hPa V, Future-Past



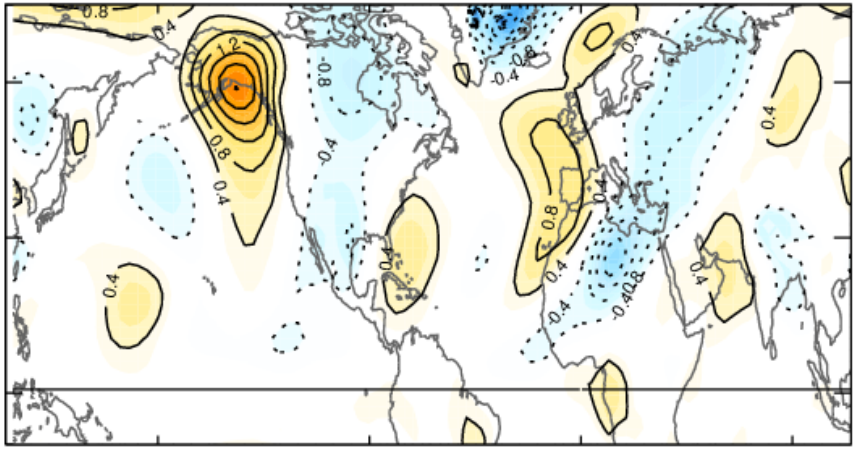
SW model, 300hPa V, Future-Past



CMIP5, 700hPa V, Future-Past



SW model, 700hPa V, Future-Past



Decomposing the response into 4 contributions:

Basic State Influence:

$$\Delta v_{BS} = F(\overline{BS}_F + Q_P + O + TR_P) - F(\overline{BS}_P + Q_P + O + TR_P)$$

Diabatic Heating Influence:

$$\Delta v_{Q} = F(\overline{BS}_P + Q_F + O + TR_P) - F(\overline{BS}_P + Q_P + O + TR_P)$$

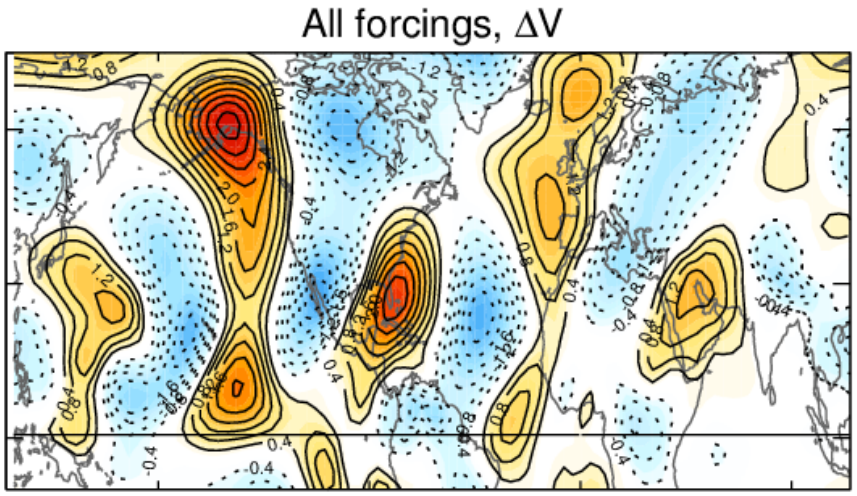
Transient Momentum Forcing Influence:

$$\Delta v_{TR} = F(\overline{BS}_P + Q_P + O + TR_F) - F(\overline{BS}_P + Q_P + O + TR_P)$$

Residual:

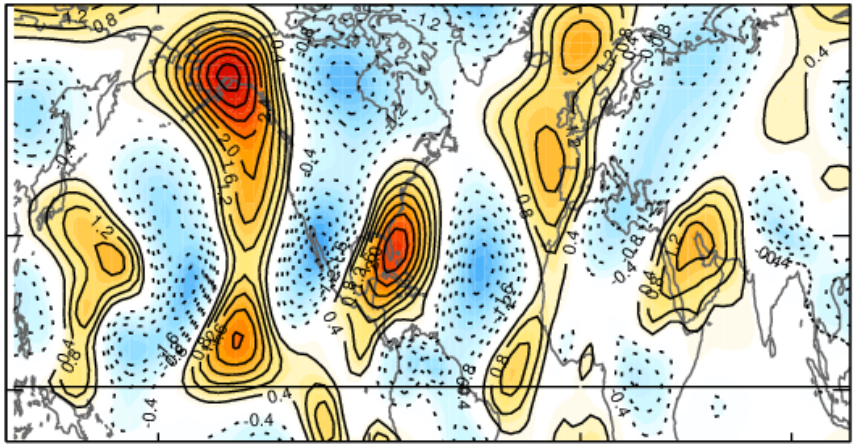
$$\Delta v_{RES} = \Delta v - (\Delta v_{BS} + \Delta v_{Q} + \Delta v_{TR})$$

Decomposing the response

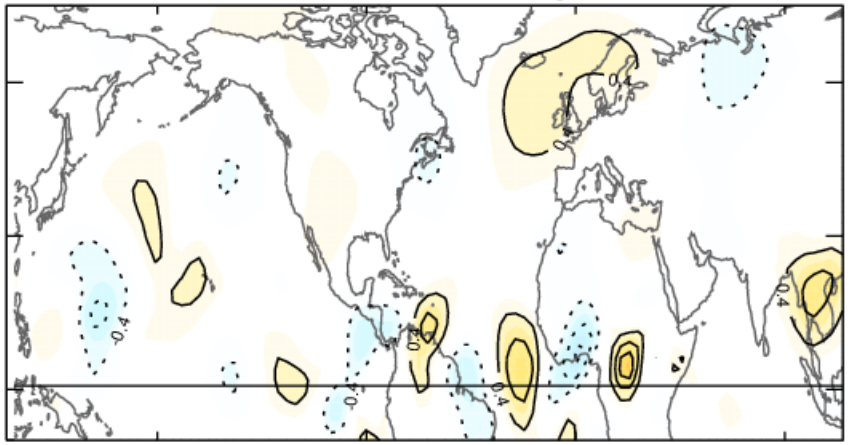


Decomposing the response

All forcings, ΔV

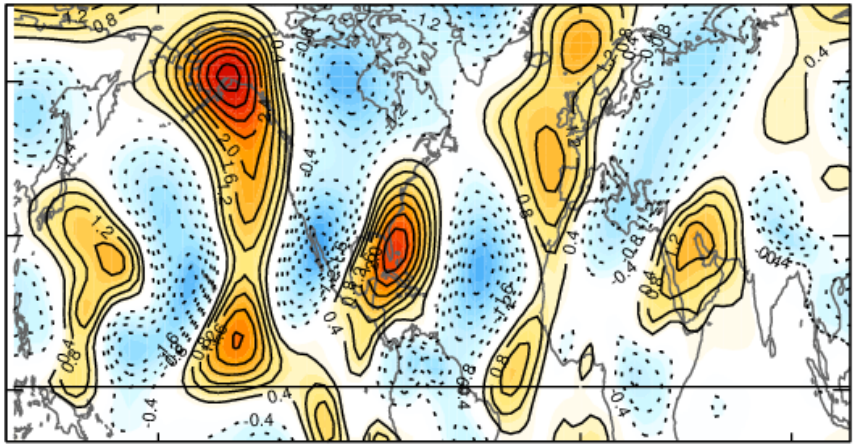


Residual, ΔV_{RES}

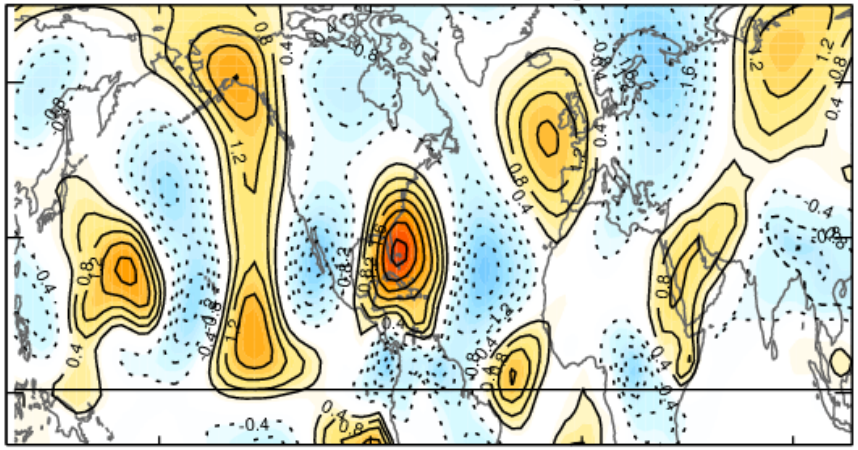


Decomposing the response

All forcings, ΔV

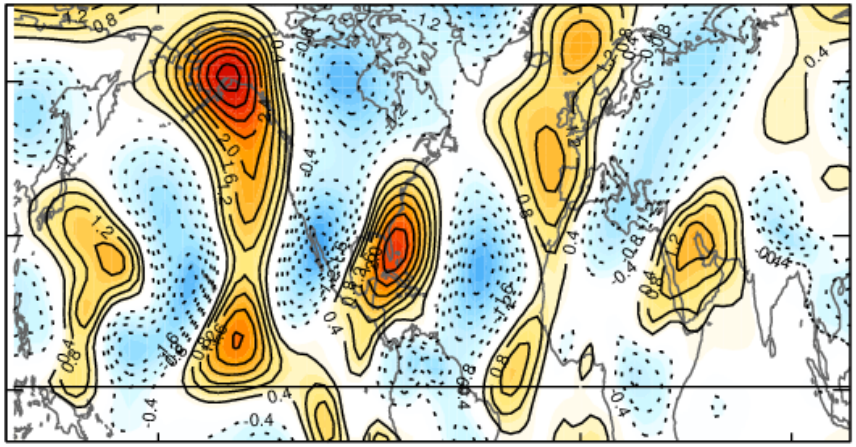


Basic State, ΔV_{BS}

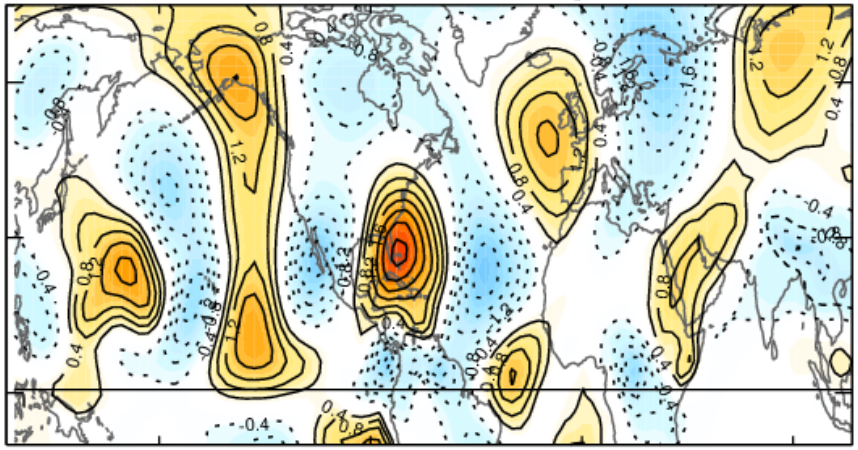


Decomposing the response

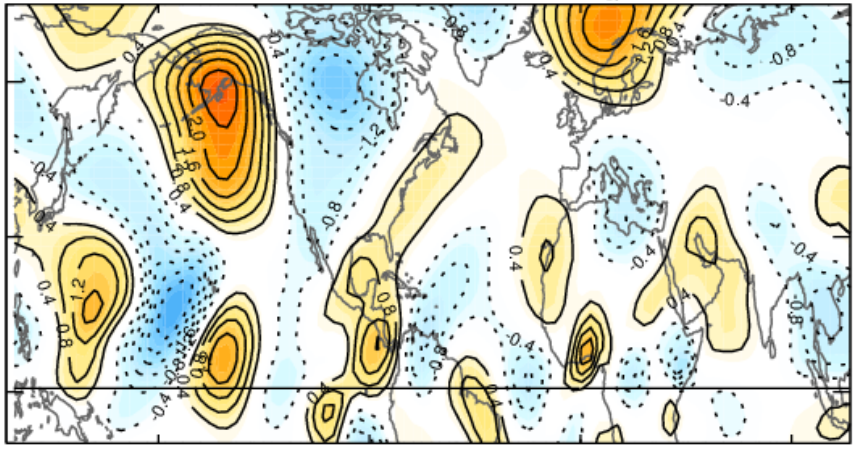
All forcings, ΔV



Basic State, ΔV_{BS}

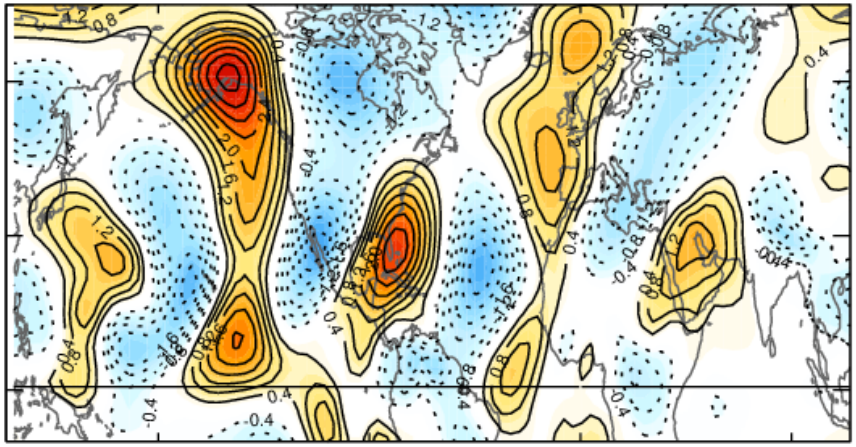


Diabatic heating, ΔV_Q

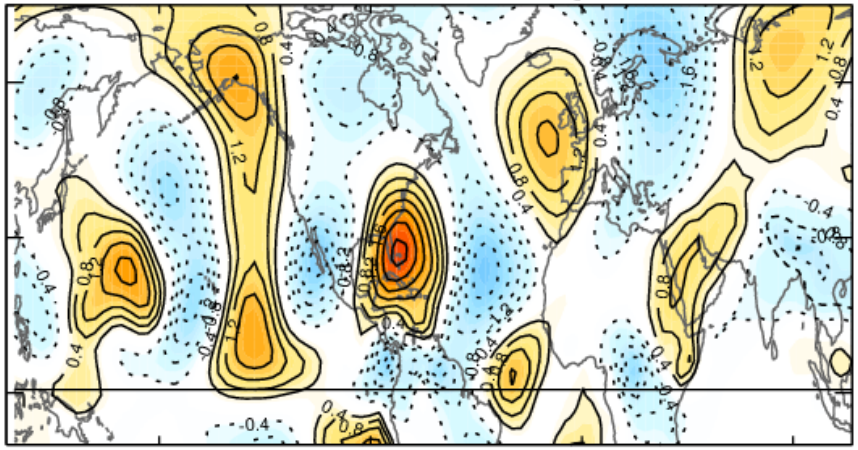


Decomposing the response

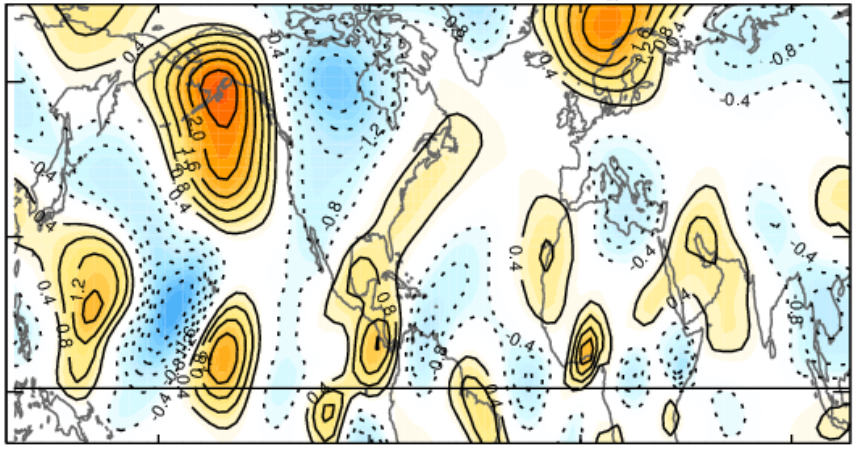
All forcings, ΔV



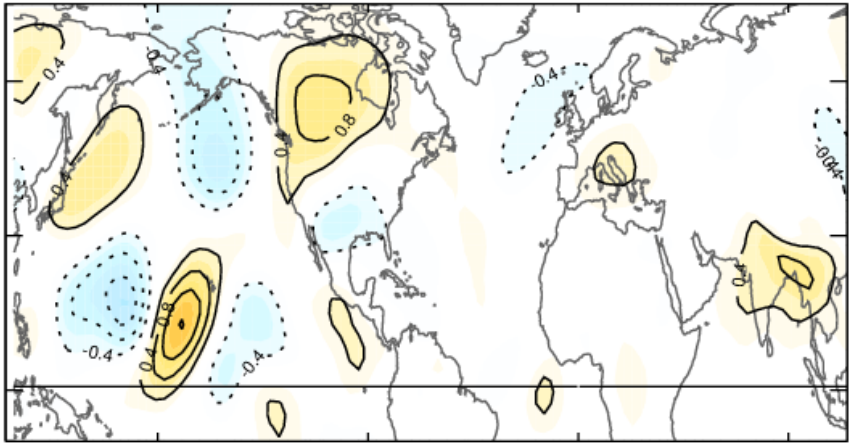
Basic State, ΔV_{BS}



Diabatic heating, ΔV_Q

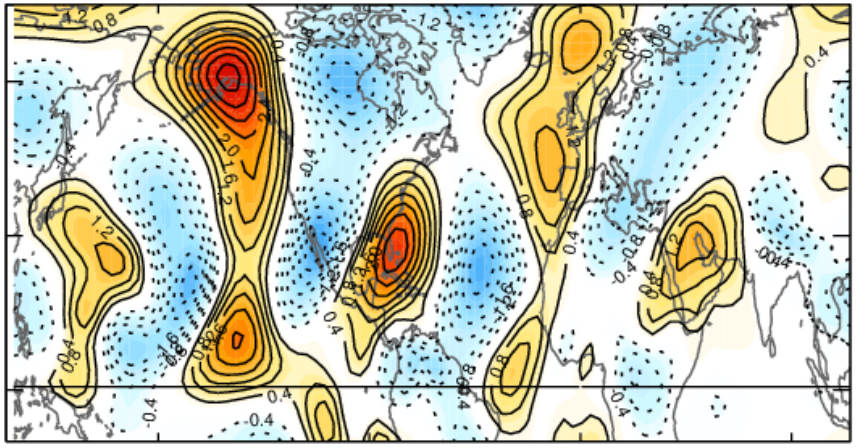


Transient momentum forcing, ΔV_{TR}

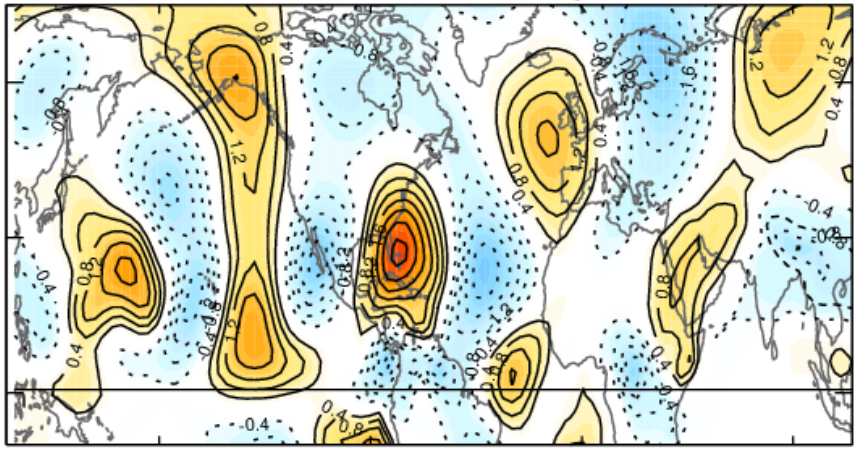


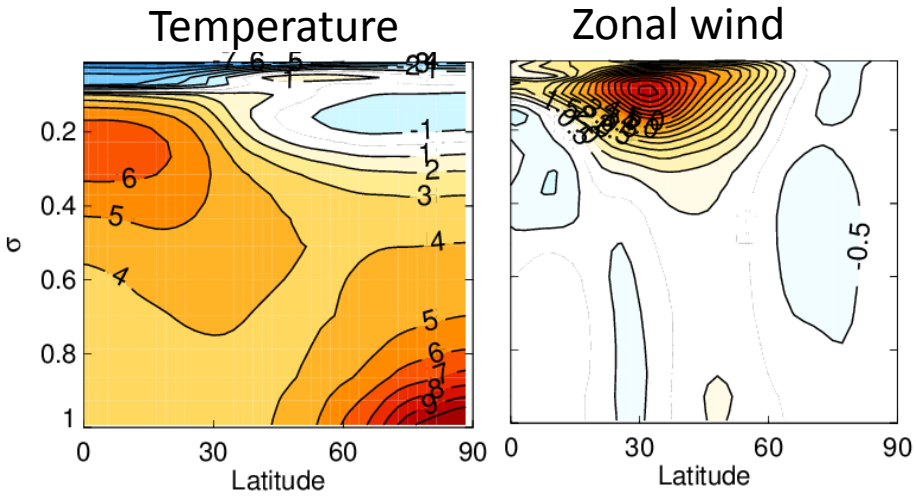
Decomposing the response

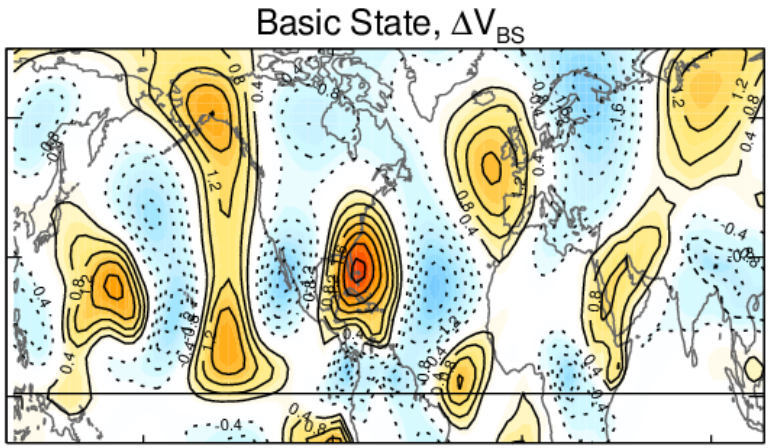
All forcings, ΔV



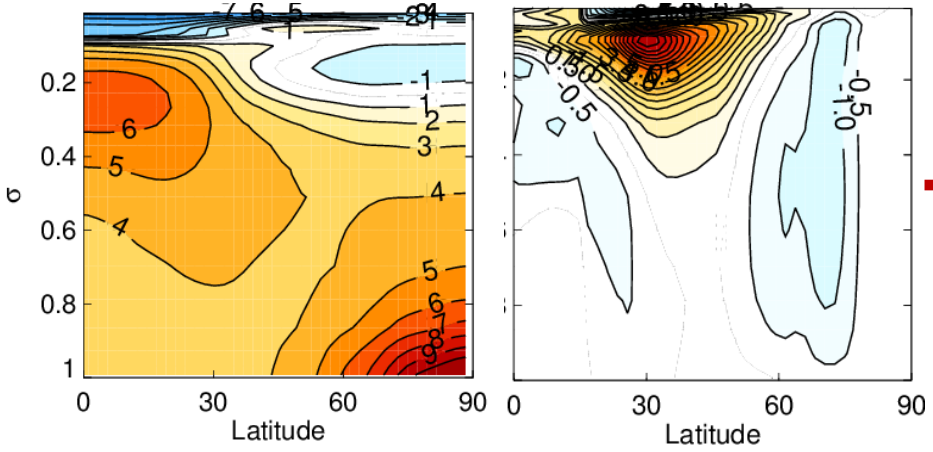
Basic State, ΔV_{BS}

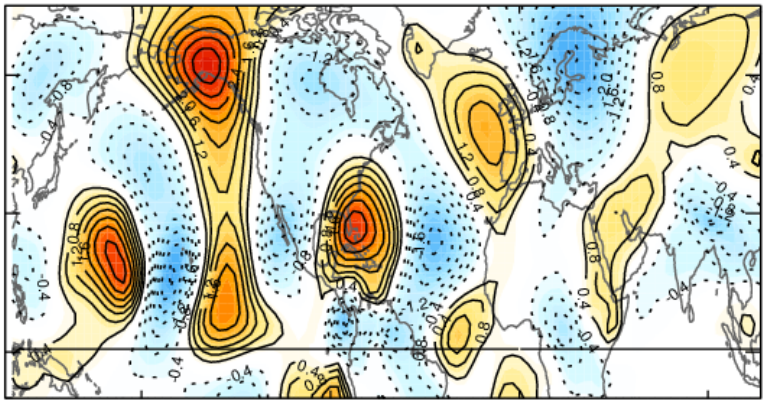




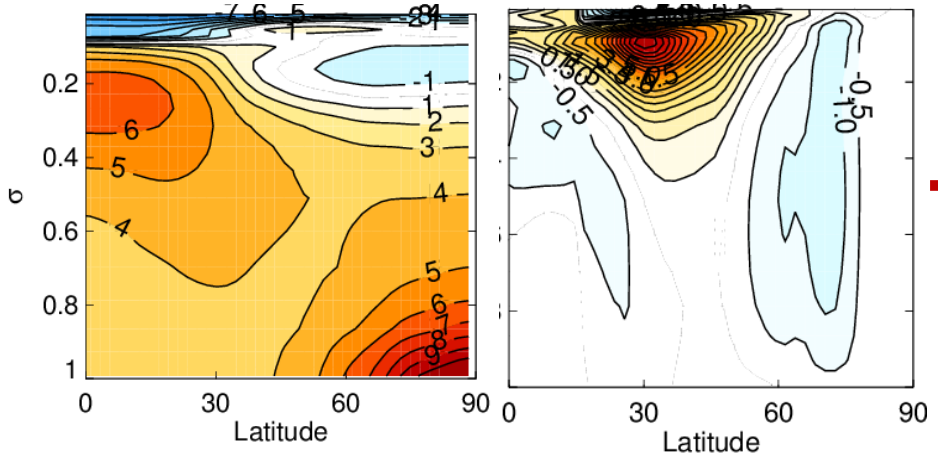


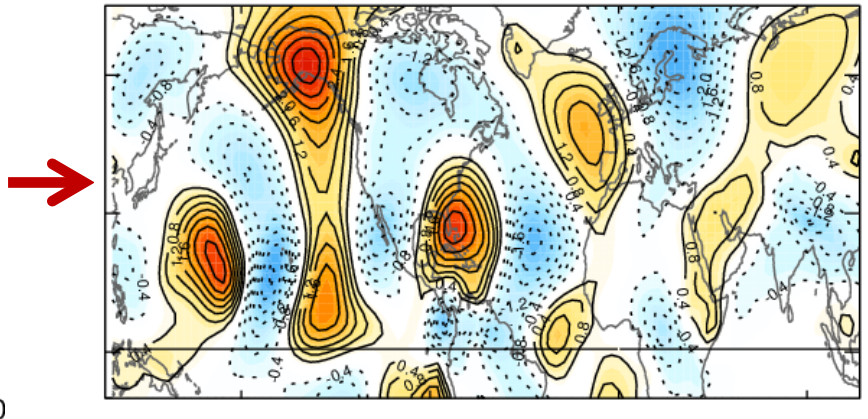
Thermal Wind Balanced State



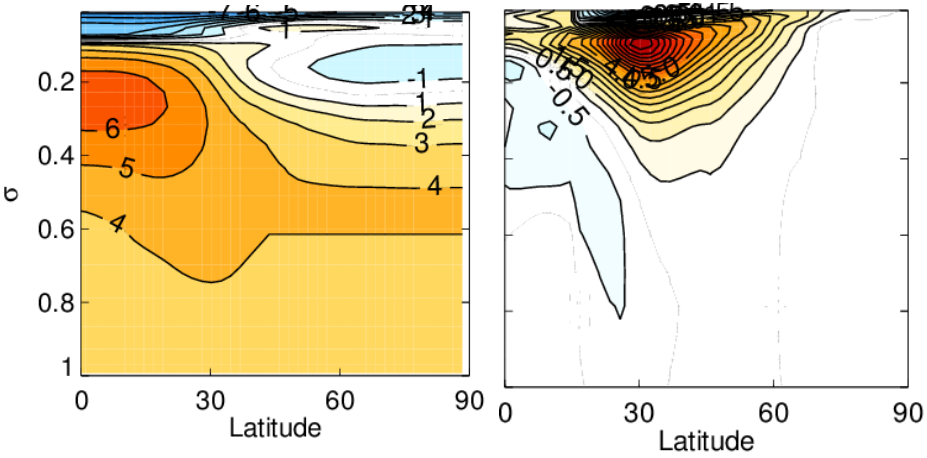


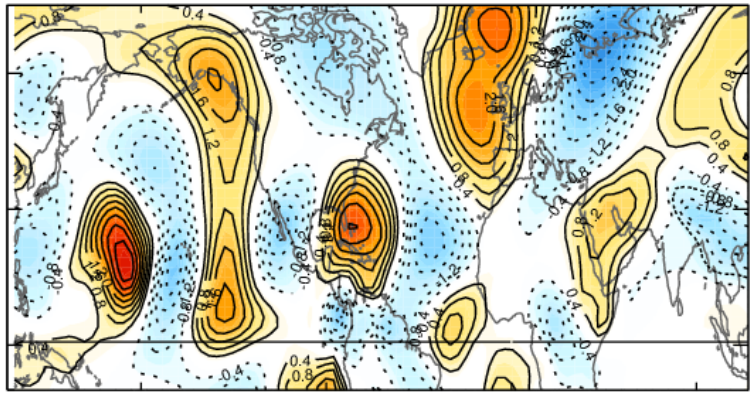
Thermal Wind Balanced State



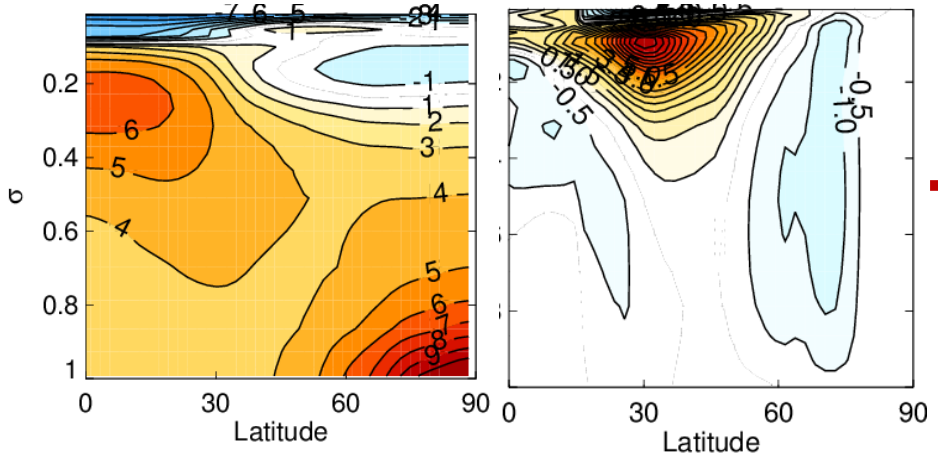


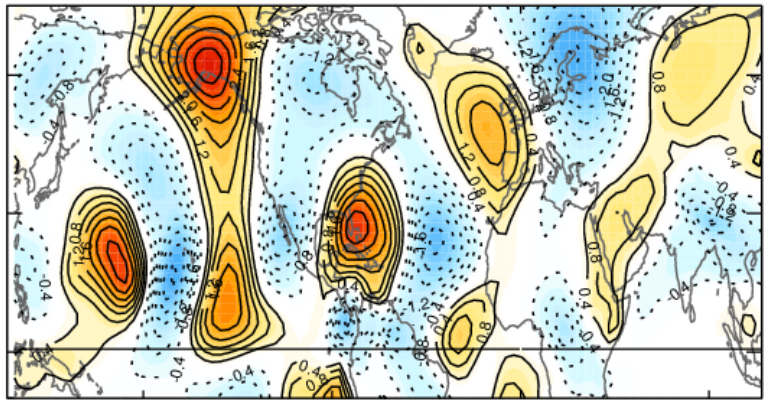
No Arctic Amplification



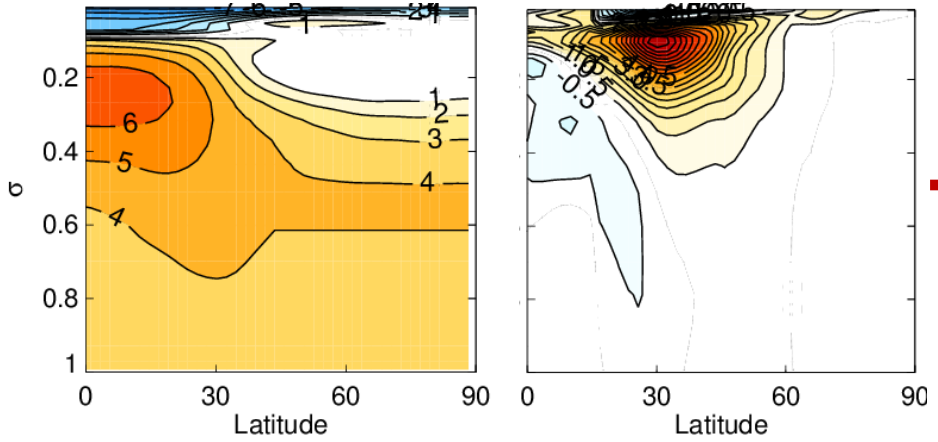


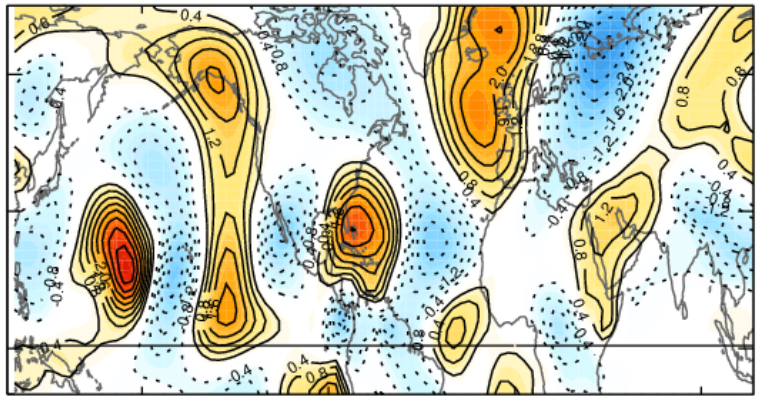
Thermal Wind Balanced State



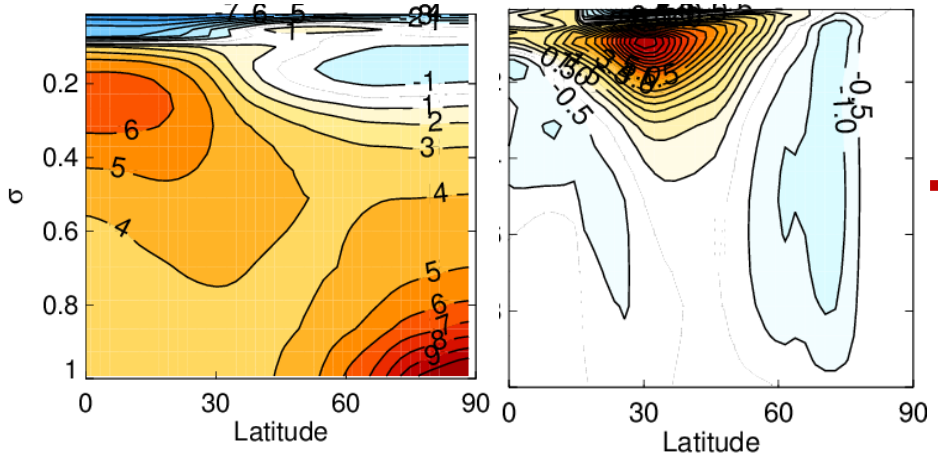


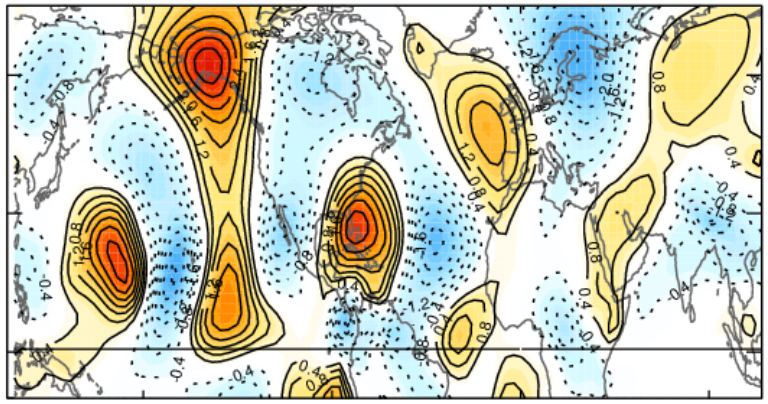
No Arctic Amplification or polar stratospheric cooling



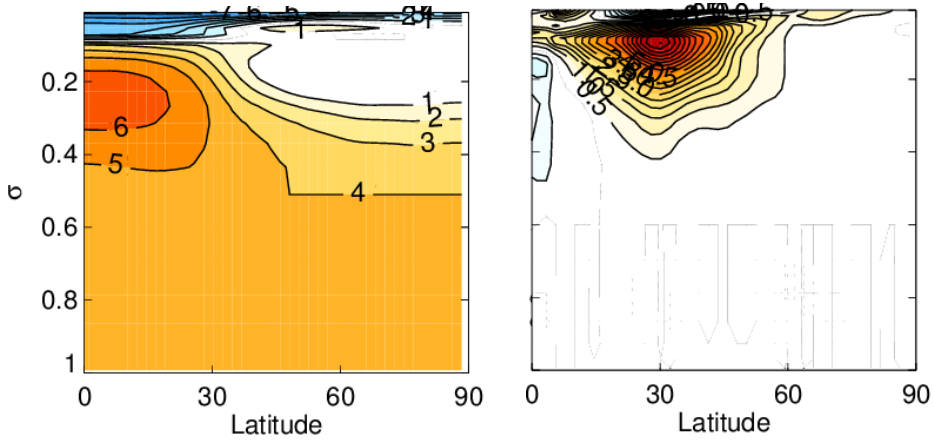


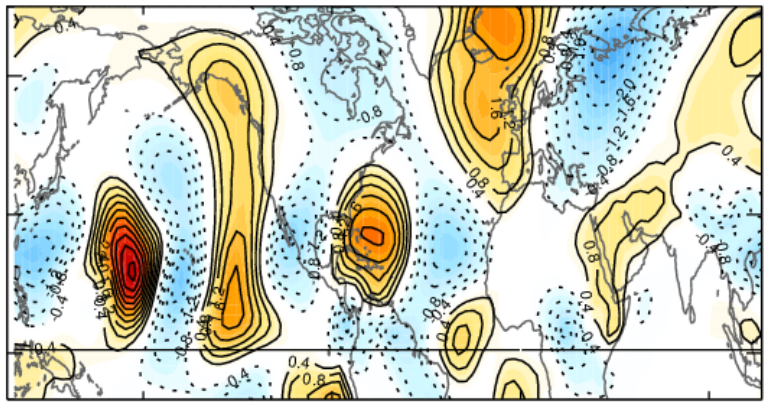
Thermal Wind Balanced State



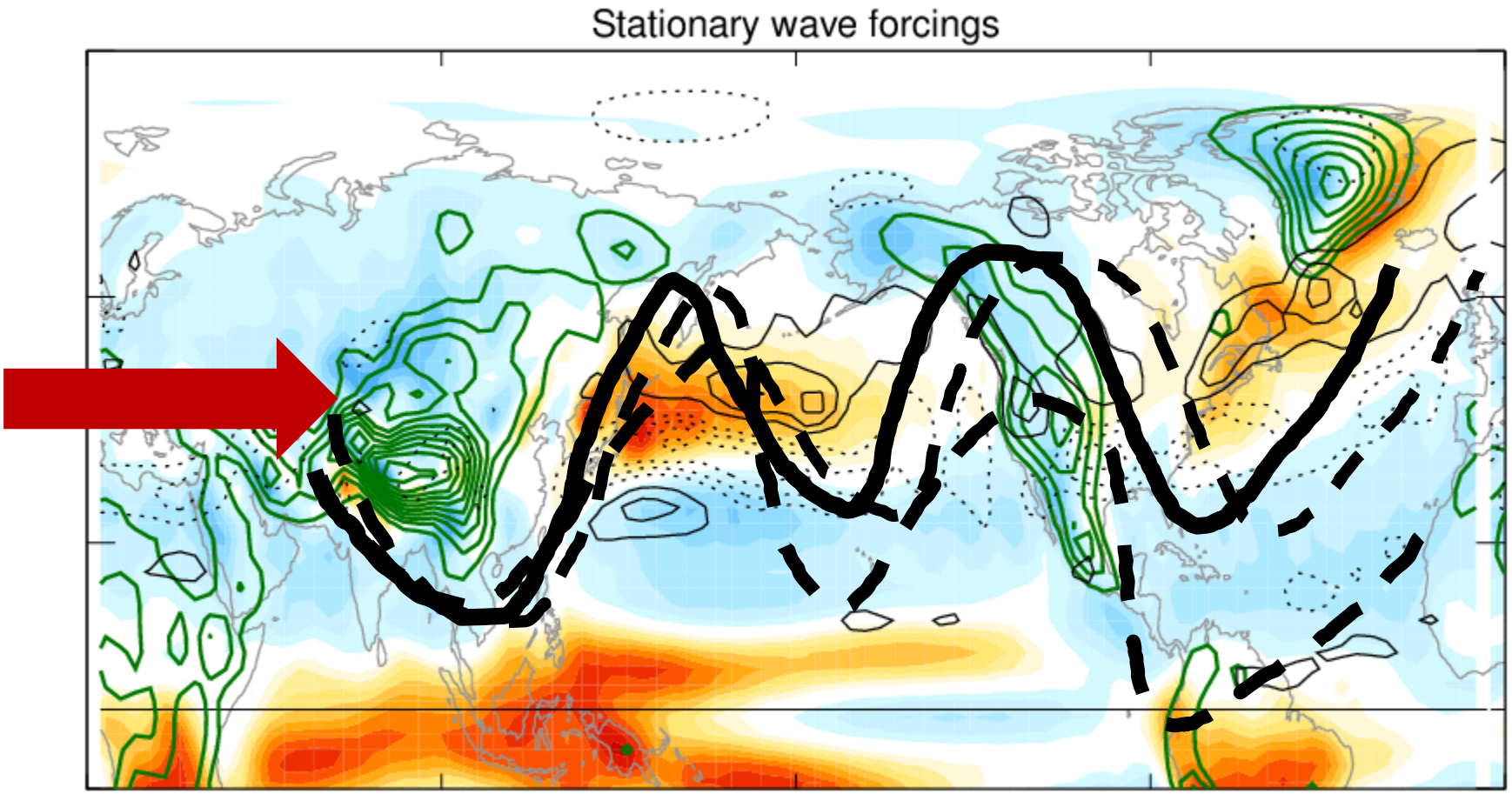


No Arctic Amplification or polar stratospheric cooling or tropospheric wind anomalies below σ=0.5



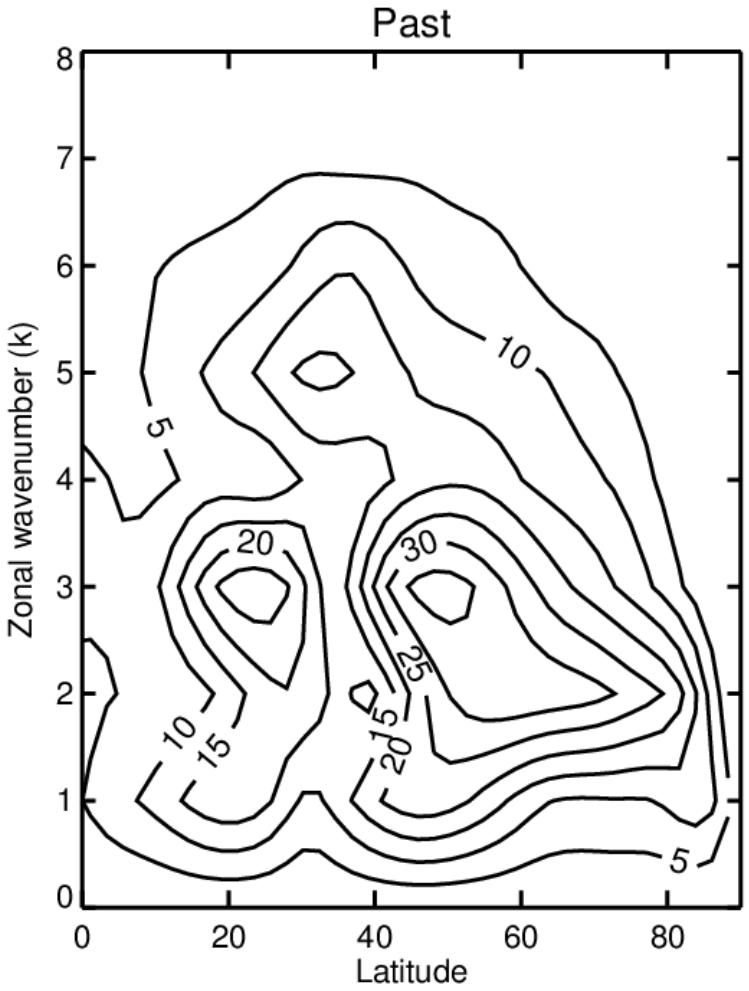


How does the basic state have this influence?



Zonal wavenumber decomposition, Past

Root mean square v amplitude

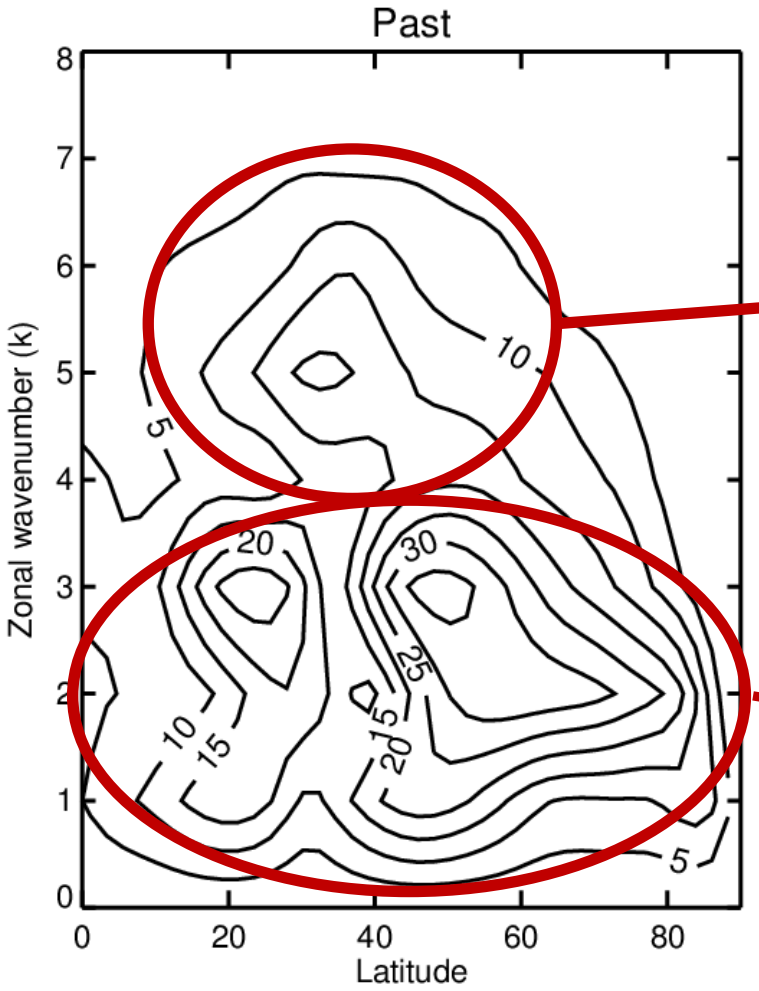


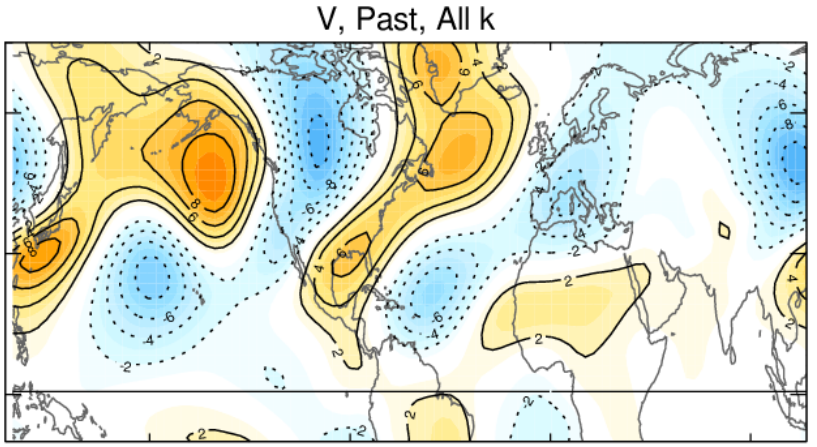
Smaller zonal scales

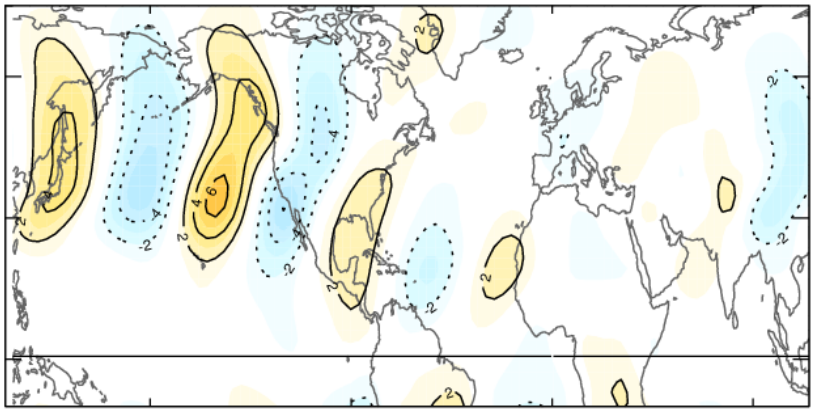
Larger zonal scales

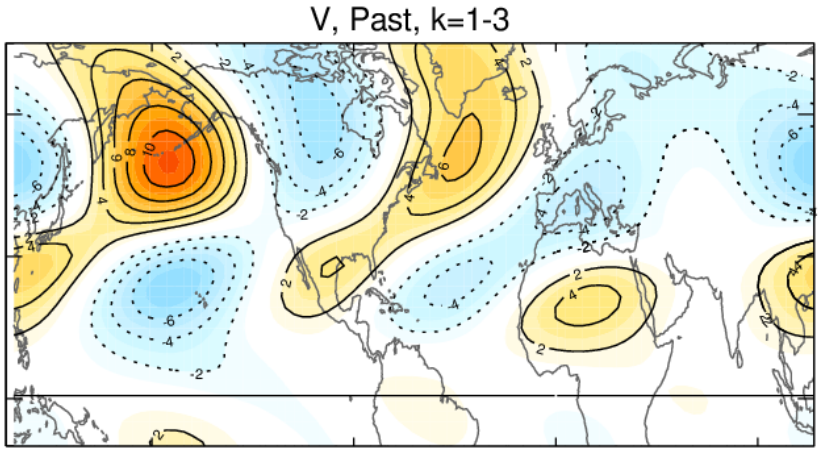
Zonal wavenumber decomposition, Past

Root mean square v amplitude

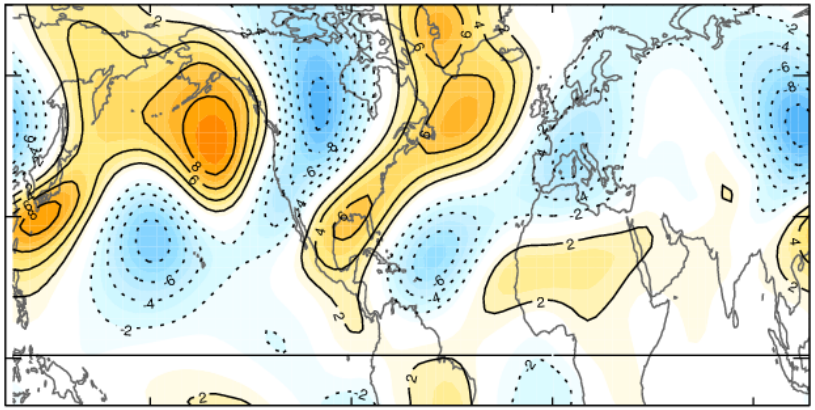




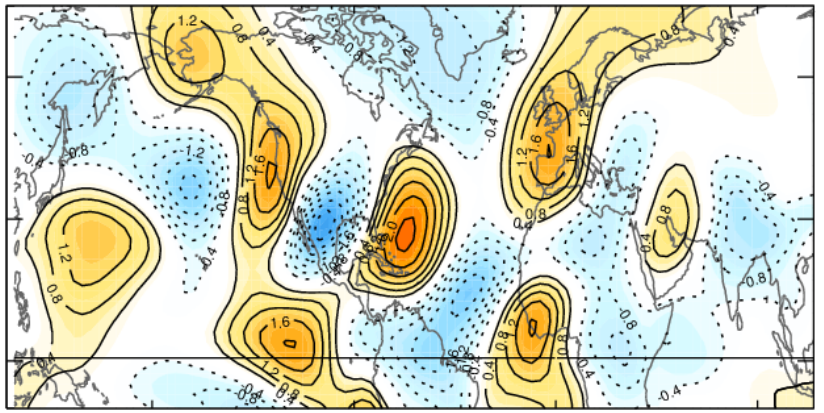




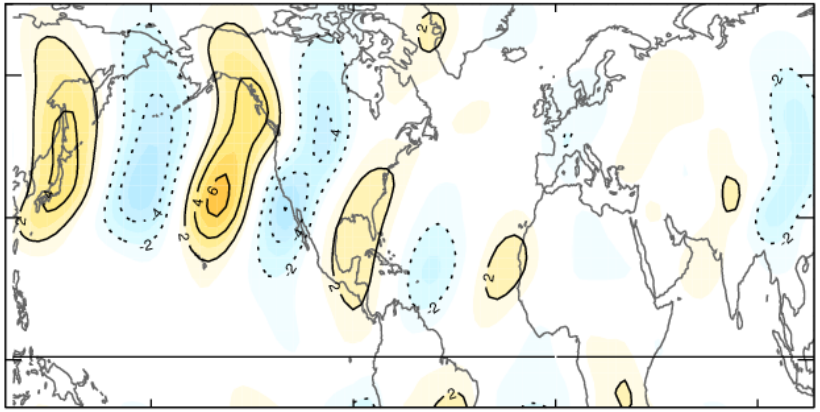
V, Past, All k



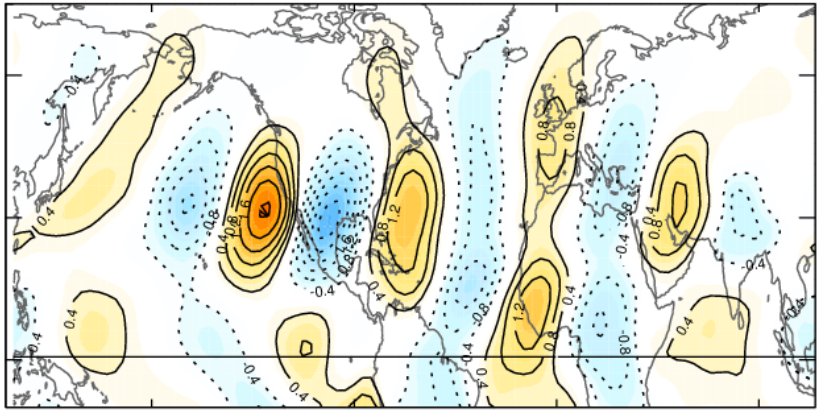
V, Future-Past, All k



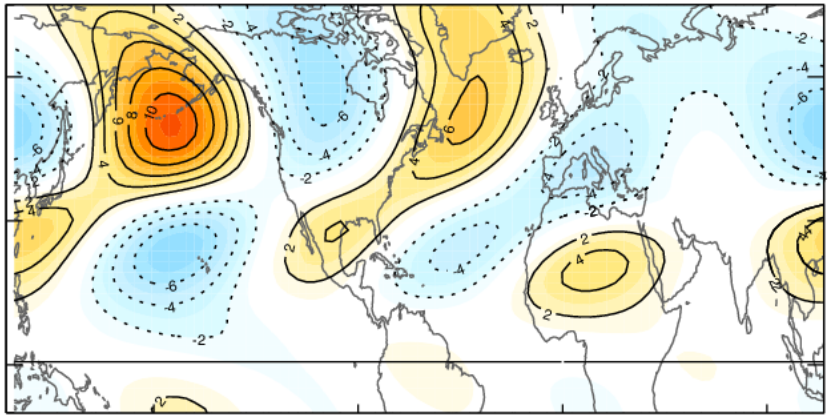
V, Past, ≥4



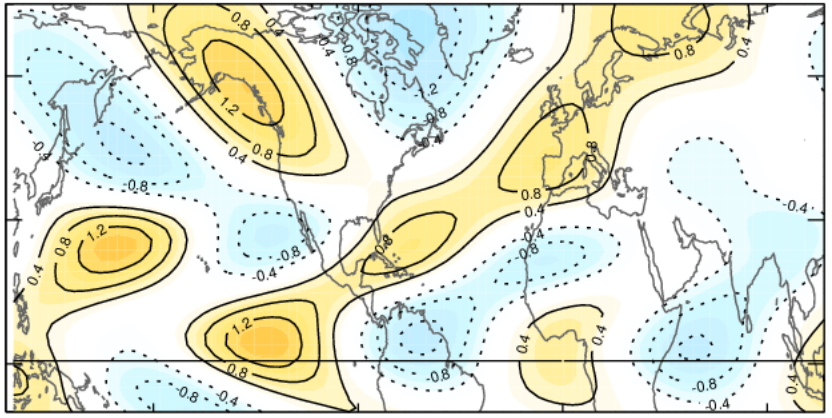
V, Future-Past, ≥4



V, Past, k=1-3

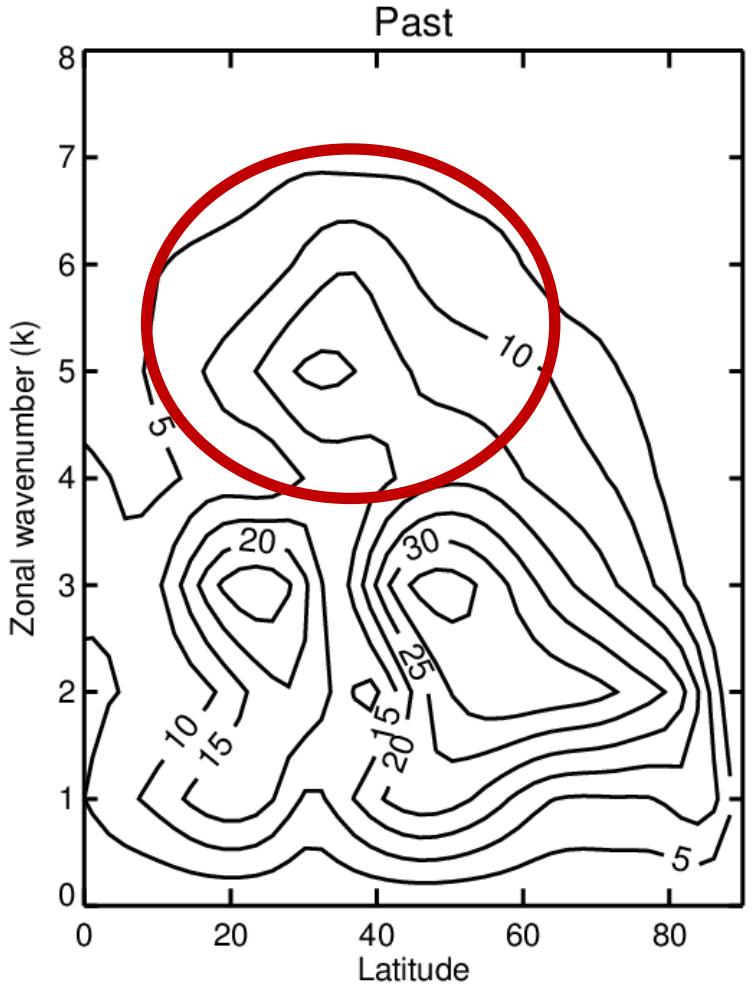


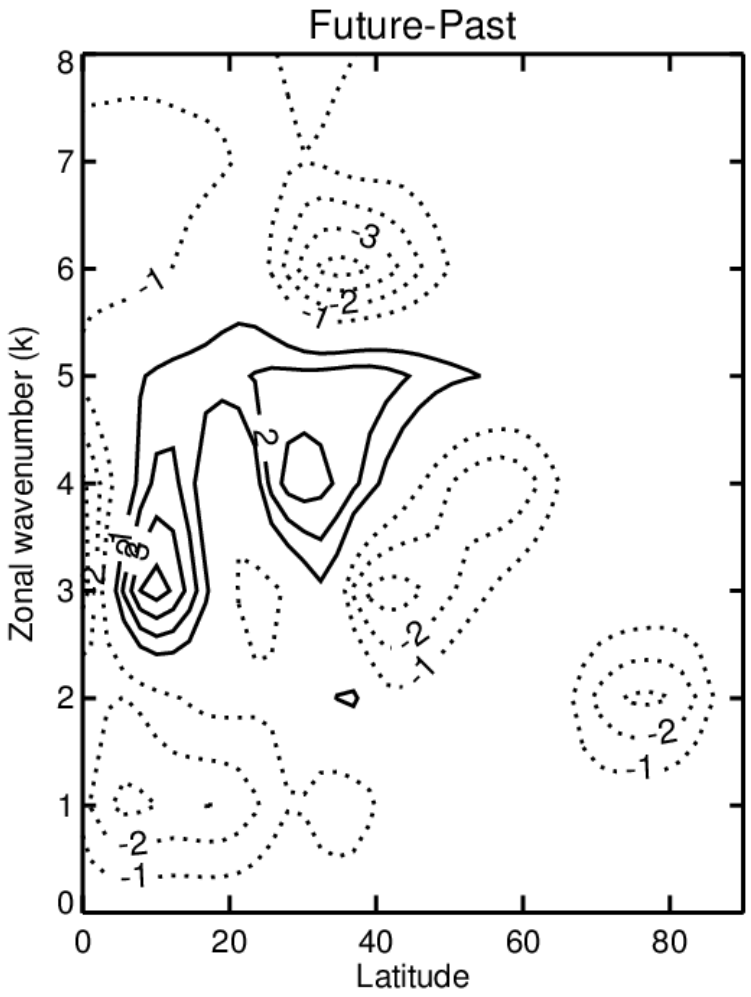
V, Future-Past, k=1-3



Zonal wavenumber decomposition, Past

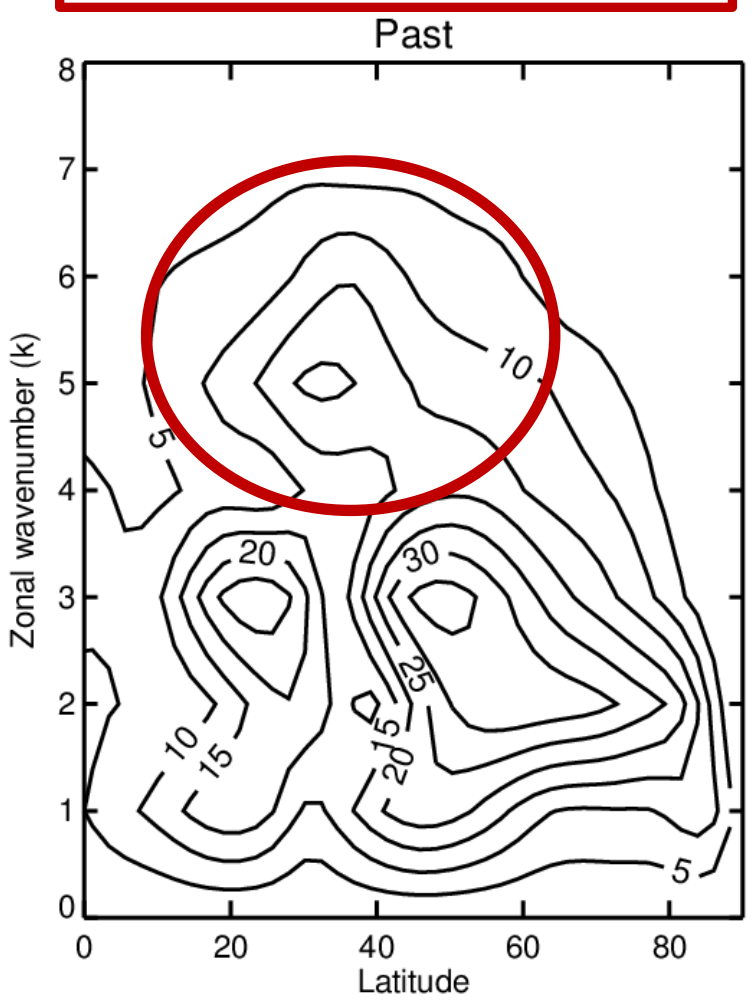
Root mean square v amplitude

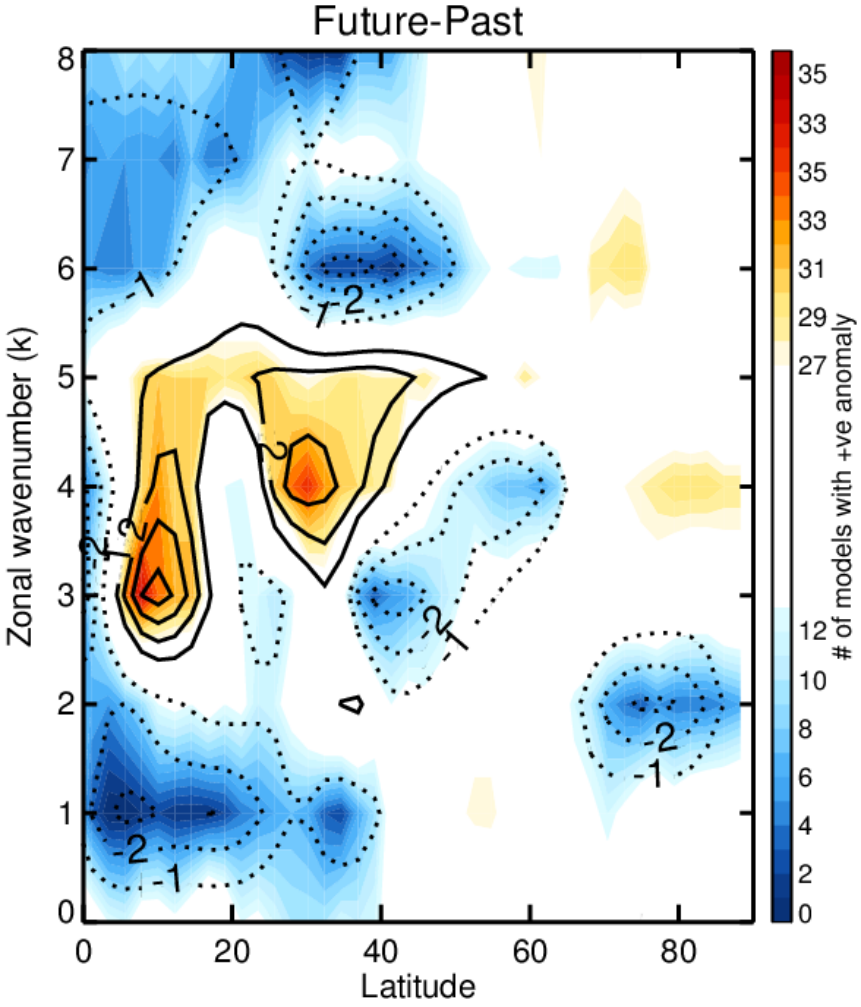




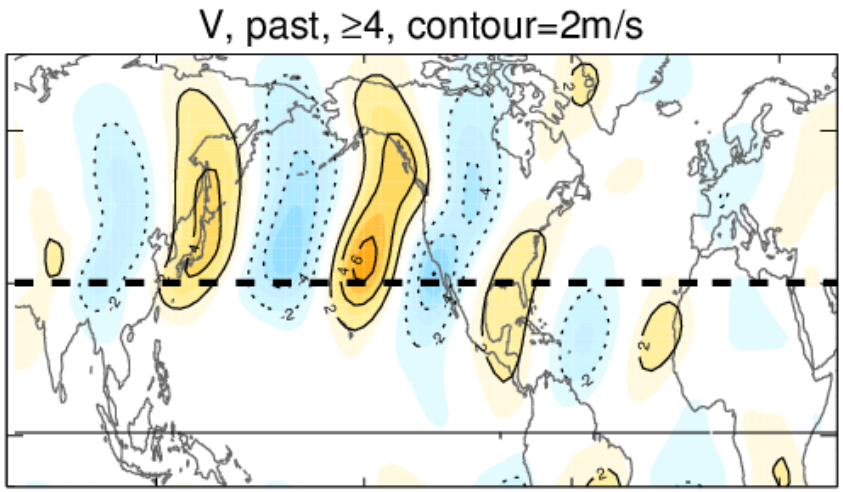
Zonal wavenumber decomposition, Past

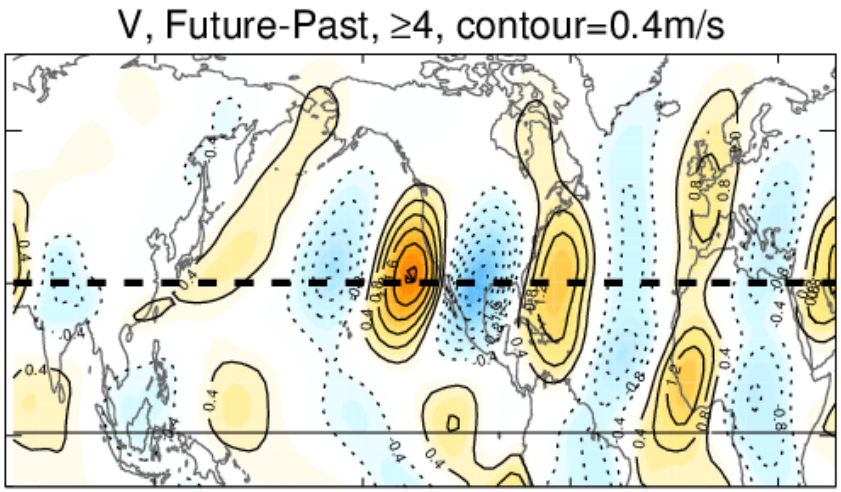
Root mean square v amplitude



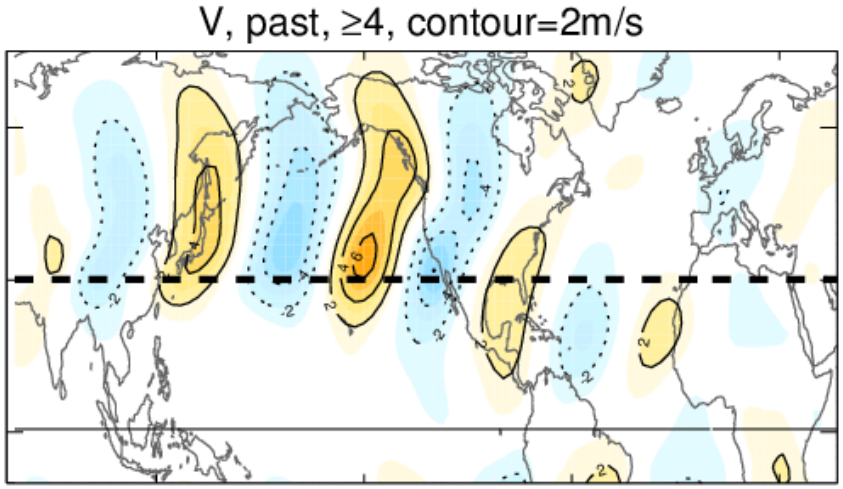


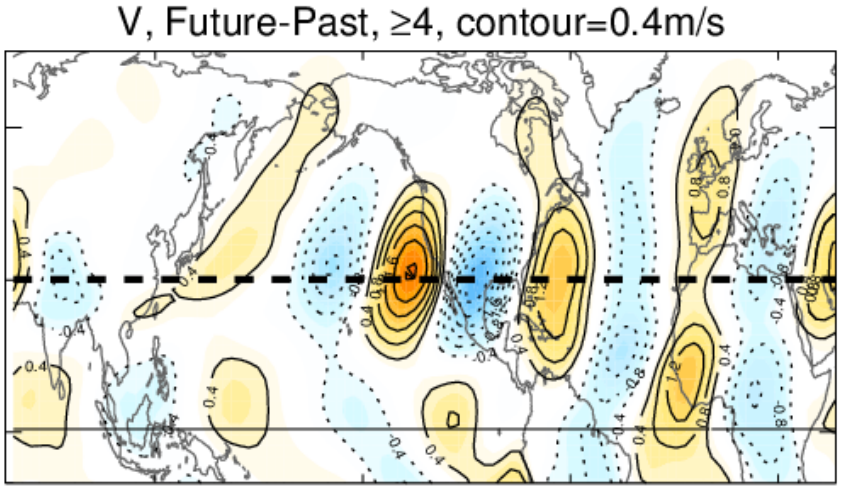
Lengthening of the scale of high wavenumber, meridionally trapped, zonally propagating stationary waves

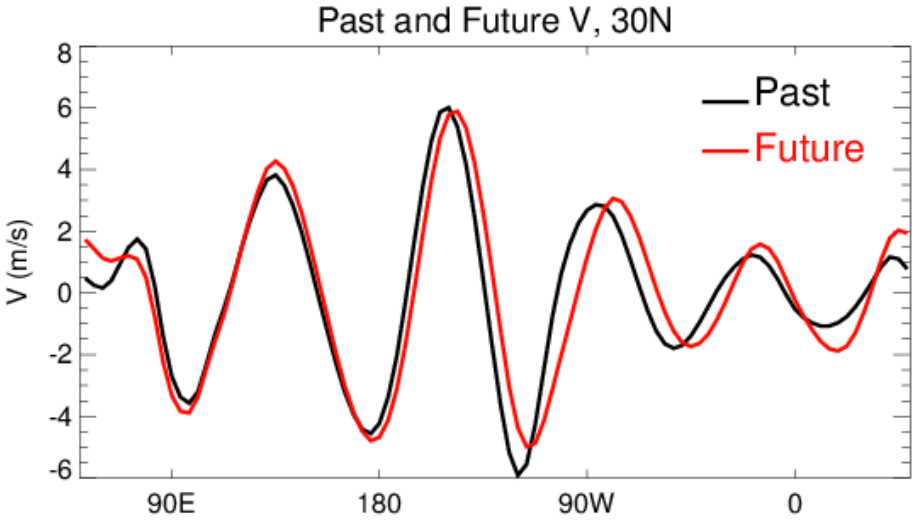


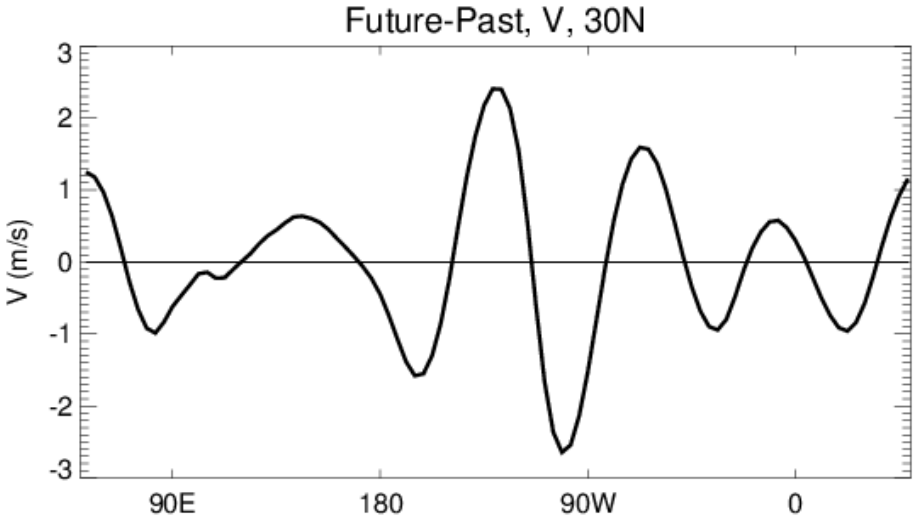


Lengthening of the scale of high wavenumber, meridionally trapped, zonally propagating stationary waves







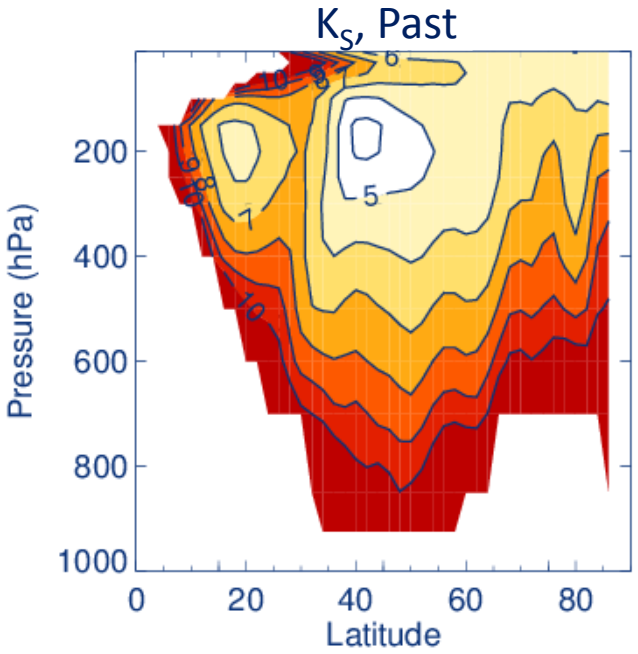


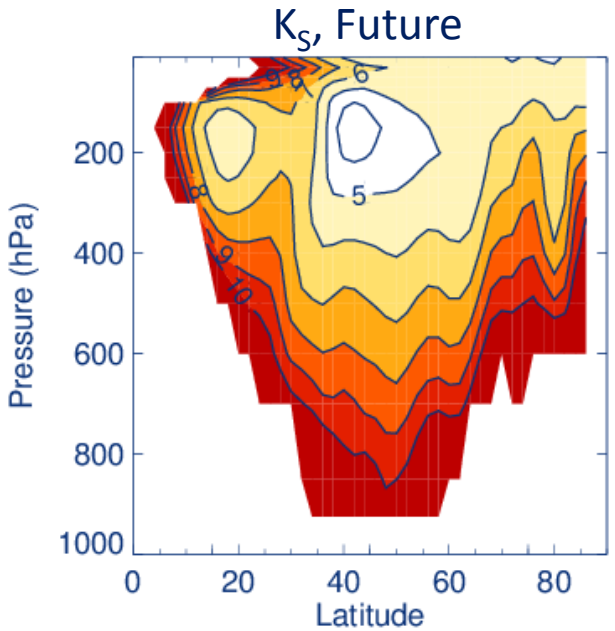
Linear barotropic stationary wave theory

The atmosphere can only support stationary waves with $K < K_S$

$$(K = \sqrt{k^2 + l^2})$$

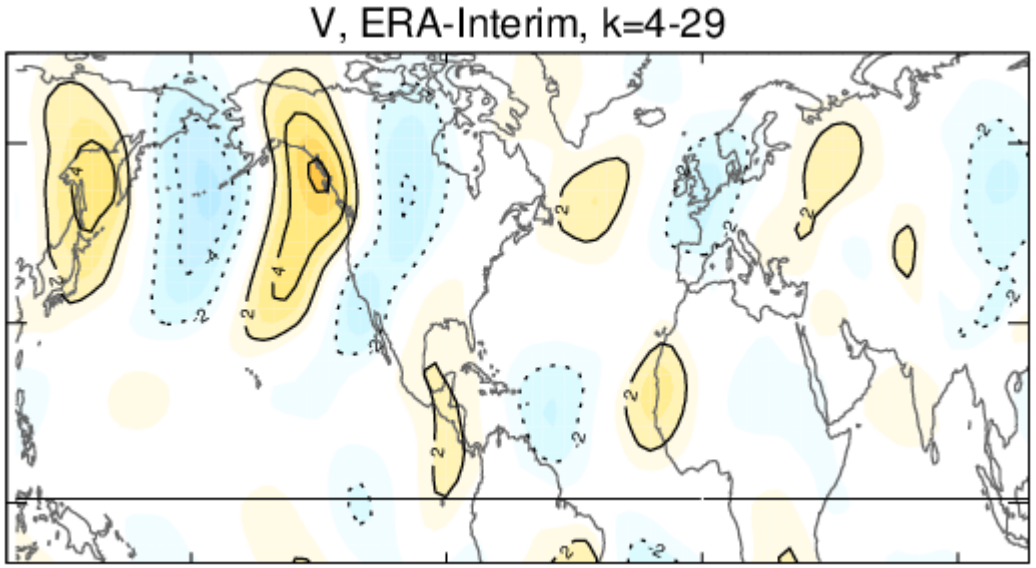
$$K_S = \sqrt{\frac{\beta - \bar{u}_{yy}}{\bar{u}}}$$





Group Velocities: $c_x = \frac{2\bar{u}k^2}{(k^2 + l^2)}$ $c_y = \frac{2\bar{u}kl}{(k^2 + l^2)}$

If these intermediate scale stationary waves exist in the real atmosphere……



and we have an acceleration of the sub-tropical upper tropospheric zonal winds in the future, then it seems likely that this stationary wave response will occur, to some degree.

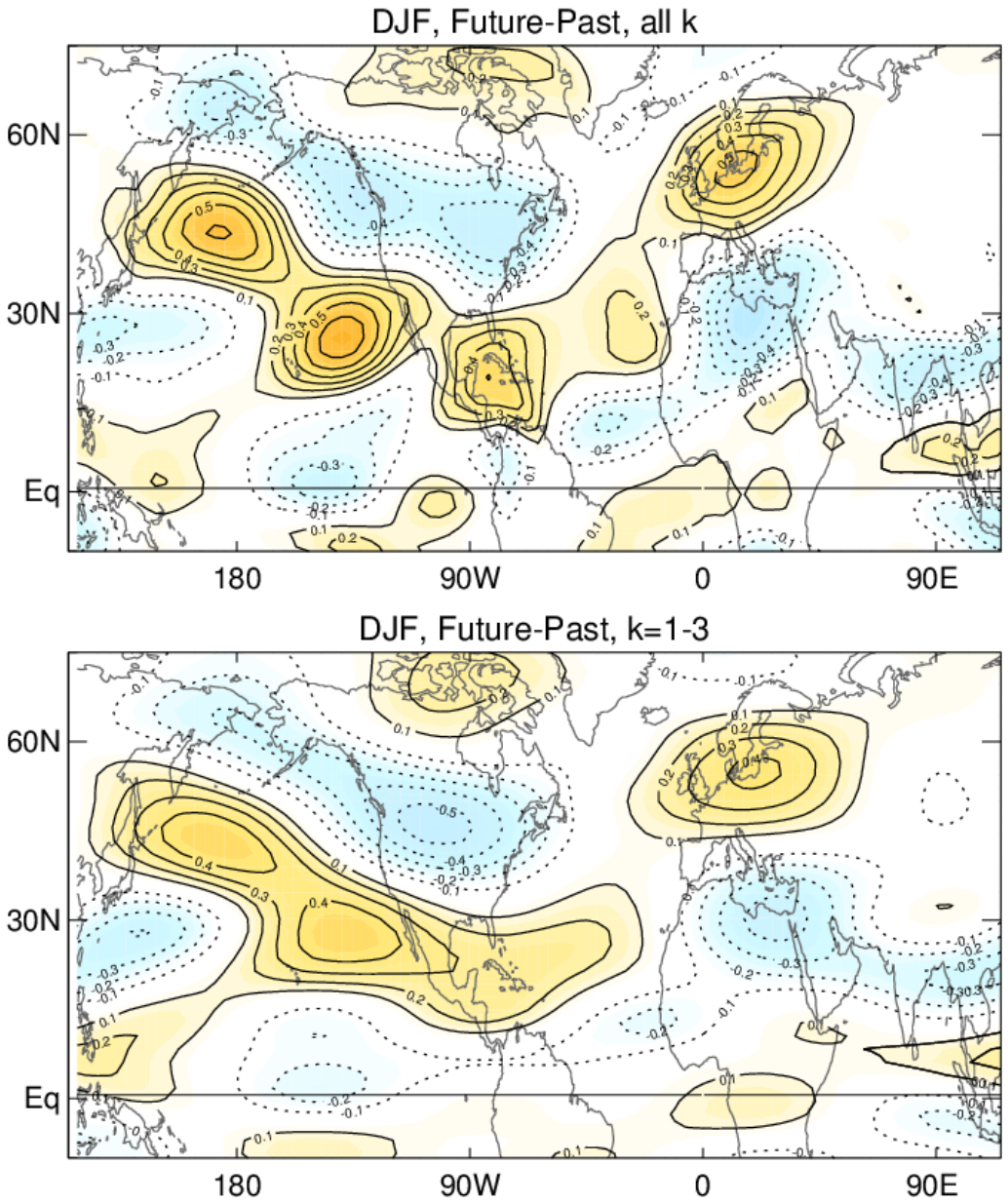
Other aspects of NH winter stationary wave changes

The larger scales are more important for the zonal wind response

All zonal wavenumbers →

700hPa U, Future-Past Multi-model mean

Zonal wavenumbers 1-3 →



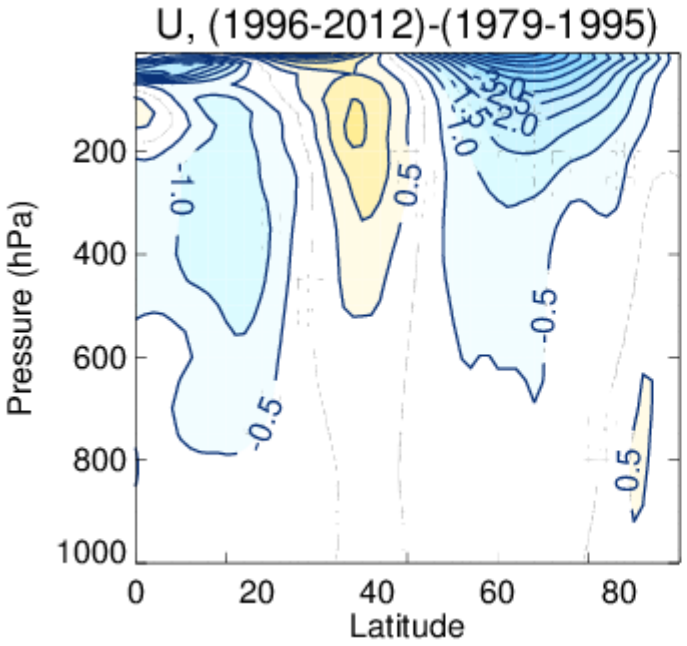
Conclusions

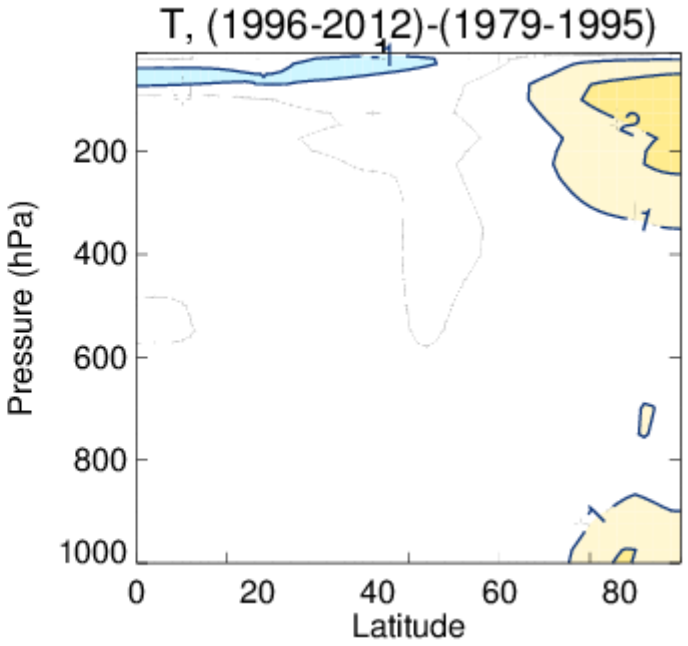
- The CMIP-5 models exhibit future changes in the mid-latitude meridional wind, with a strong consensus.
- These circulation changes have a substantial influence on the future hydroclimate of North America and the Mediterranean
- Stationary wave modelling suggests that this response is primarily induced by the acceleration of the sub-tropical upper tropospheric zonal wind in association with a warming of the tropical upper troposphere.
- The acceleration of the zonal wind lengthens the dominant scale if the intermediate wavenumber meridionally trapped, zonally propagating waves in the mid-latitudes.
- We need to understand the spread in the magnitude of this response among the models.

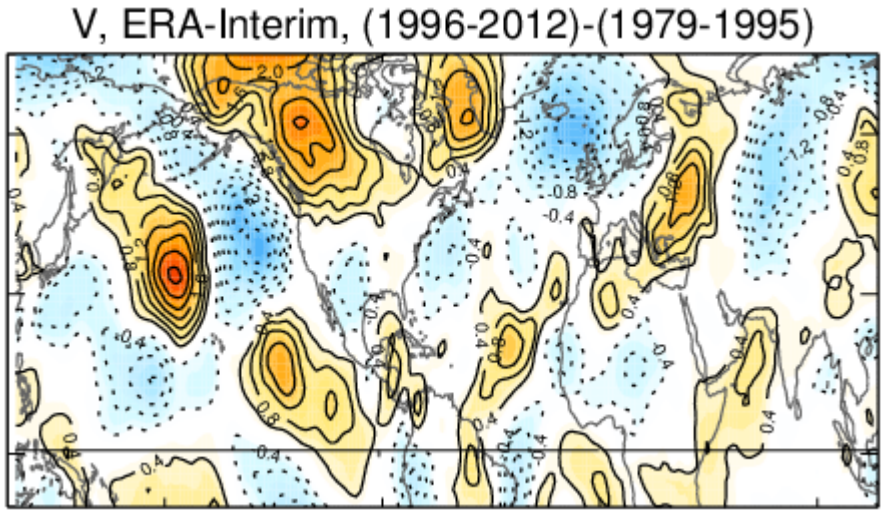
Extra Slides

Comparison with ERA-Interim

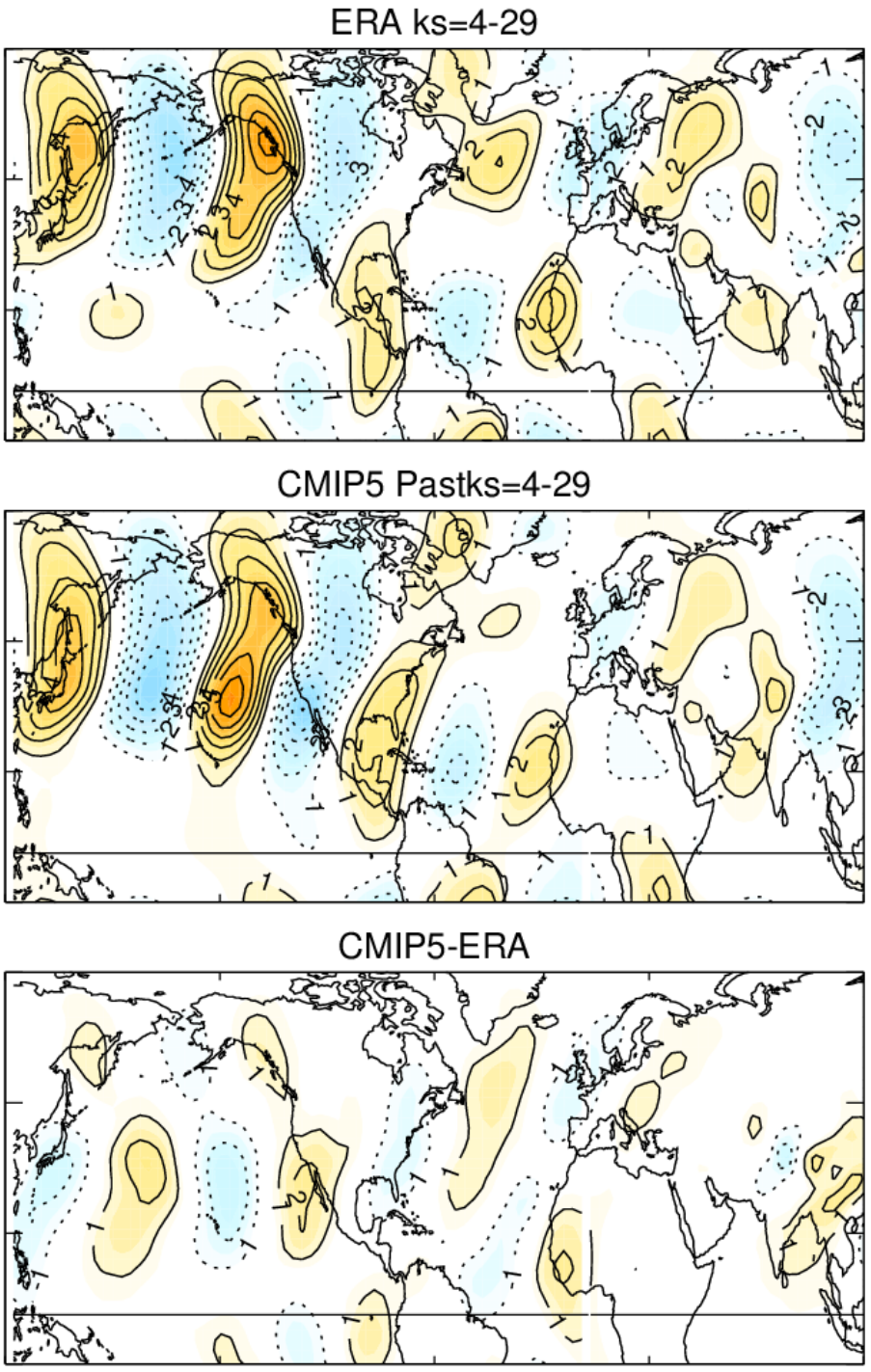
ERA-Interim (1996-2012)-(1979-1995) differences

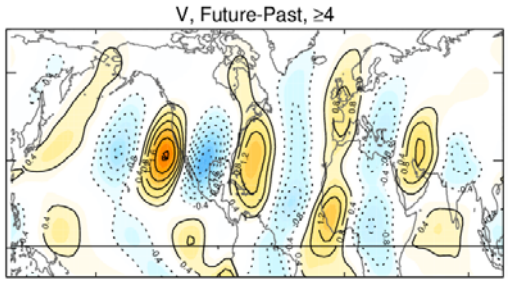




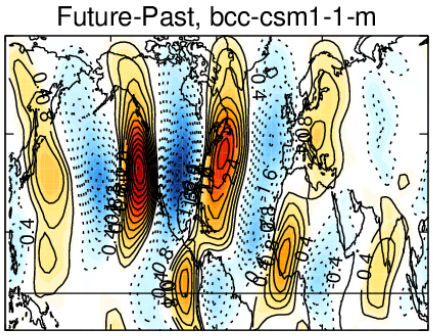


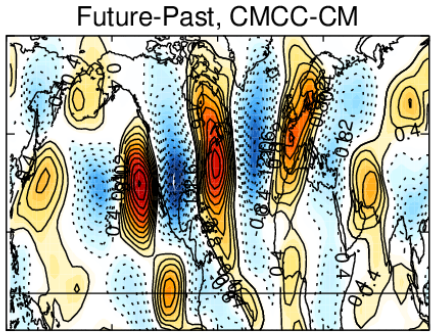
K>=4

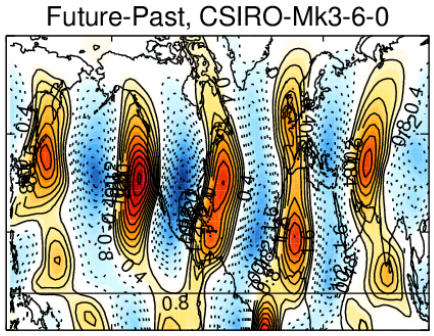


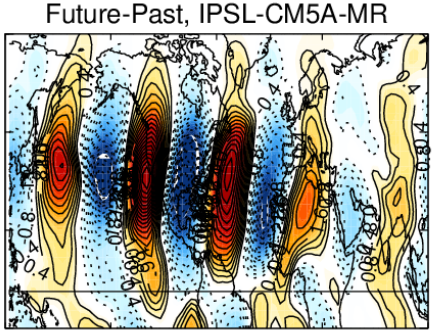


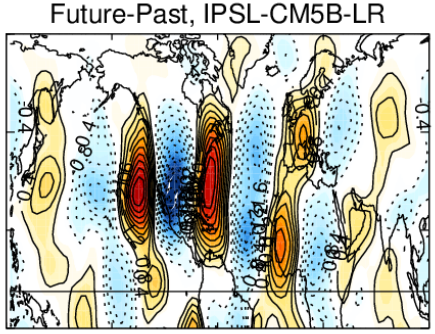
K>=4 difference in 300hPa V for models with a large response over North America

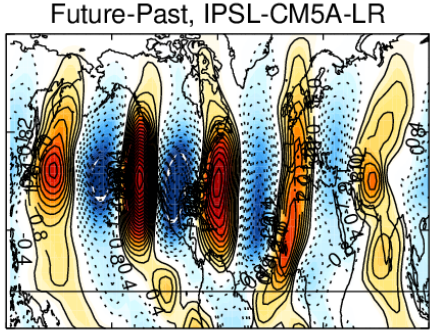


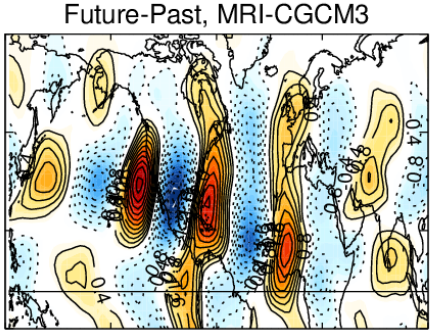




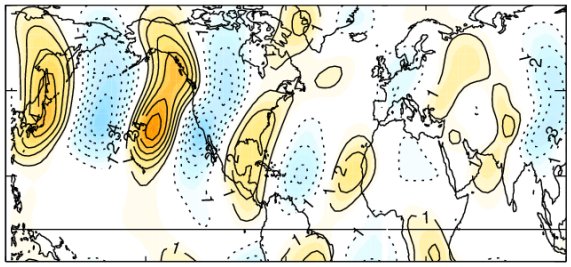






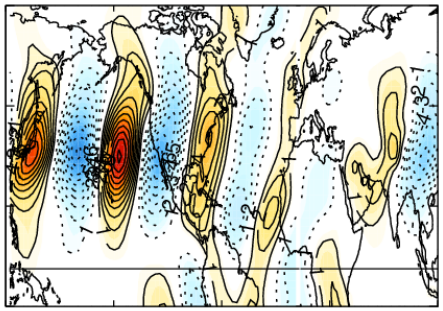


CMIP5 Pastks=4-29

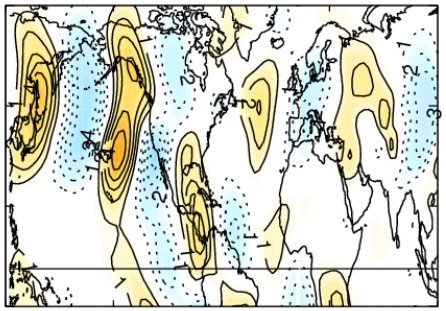


K>=4 difference in 300hPa V for models with a large response over North America

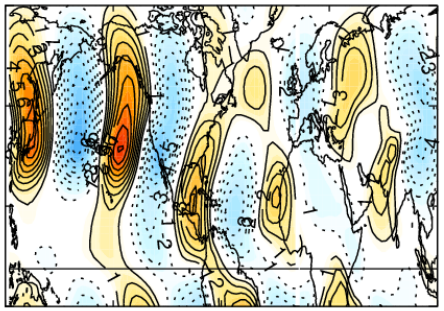
Past, bcc-csm1-1-m



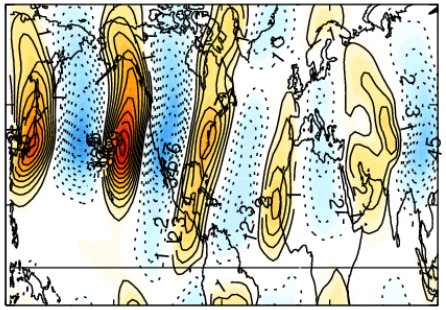
Past, CMCC-CM



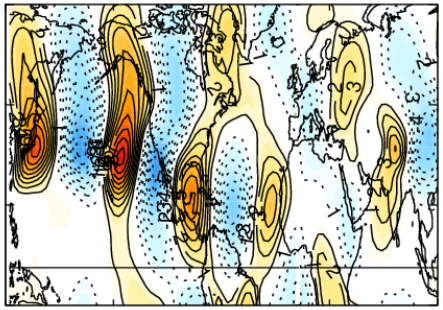
Past, CSIRO-Mk3-6-0



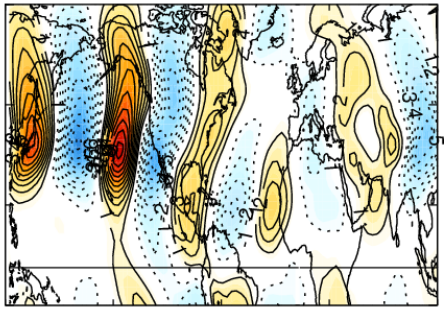
Past, IPSL-CM5A-MR



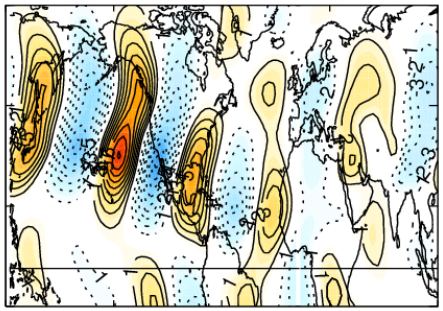
Past, IPSL-CM5B-LR



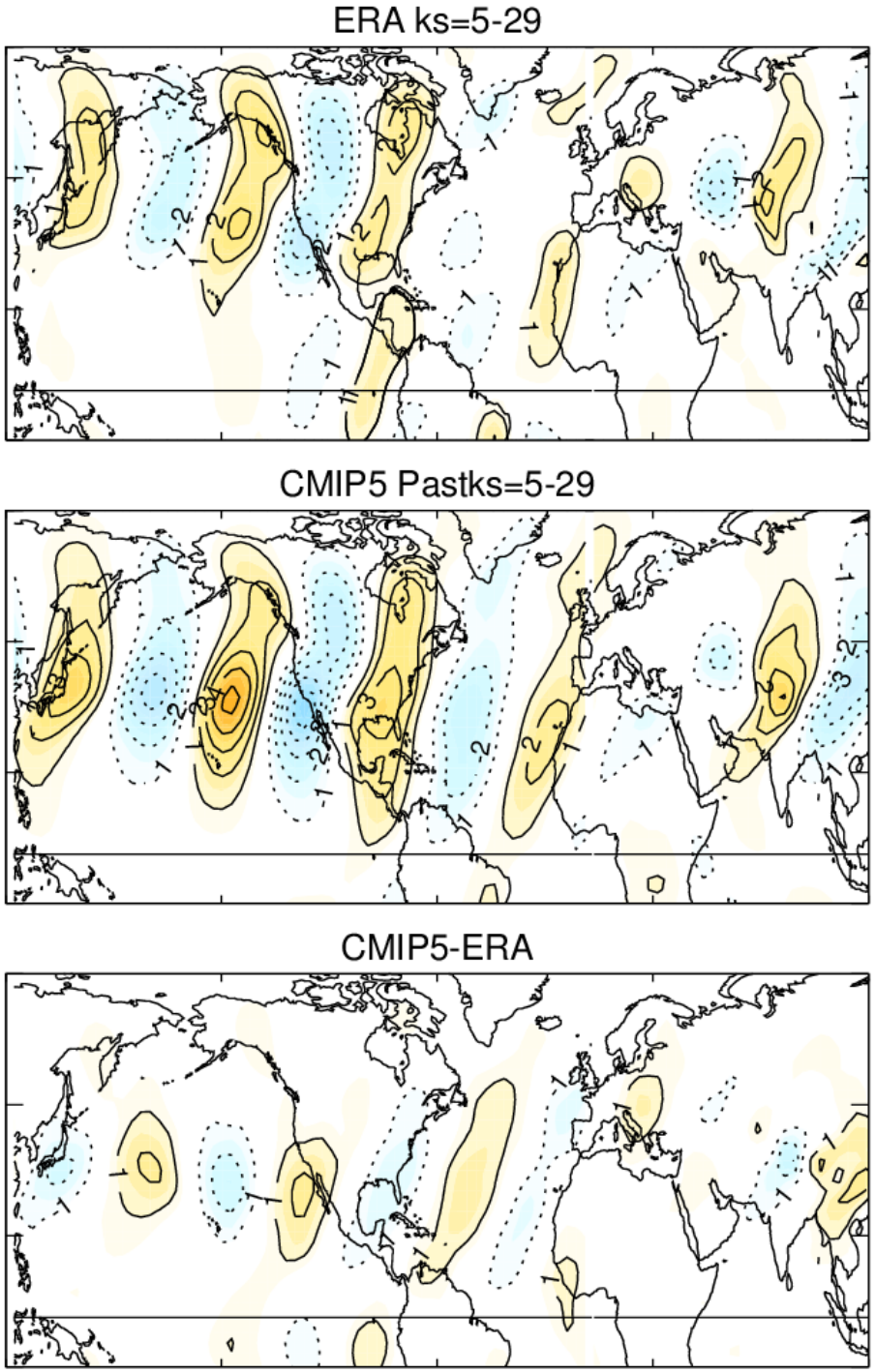
Past, IPSL-CM5A-LR



Past, MRI-CGCM3

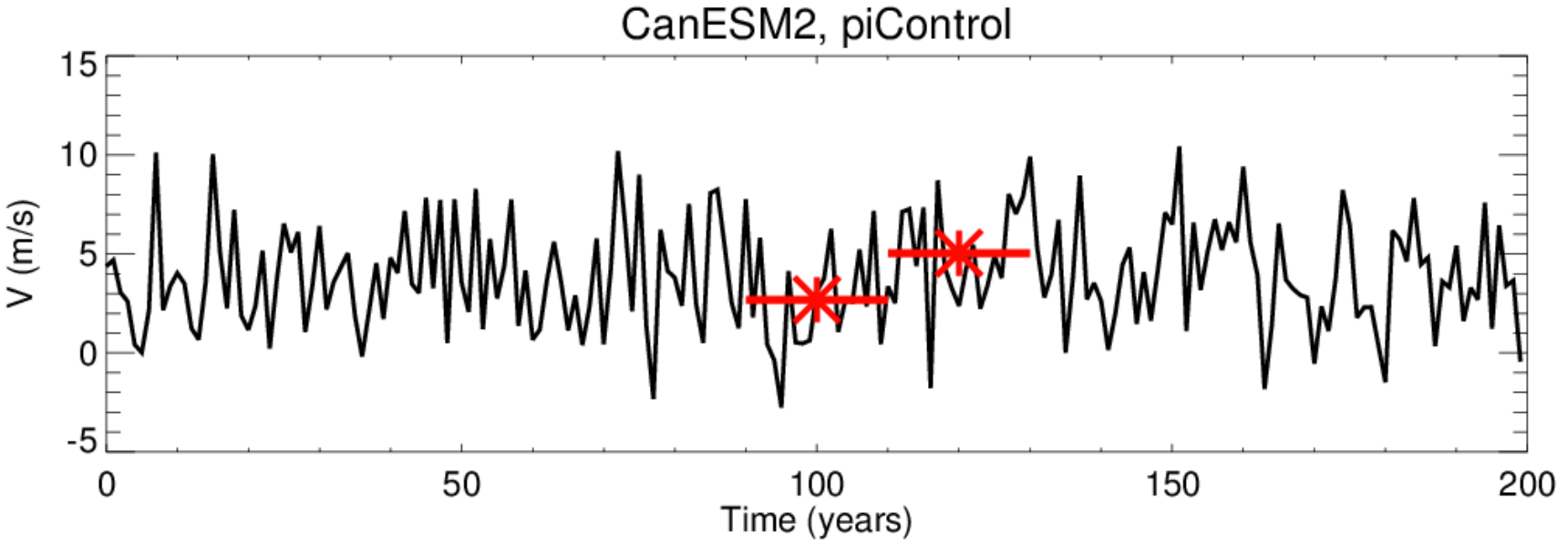


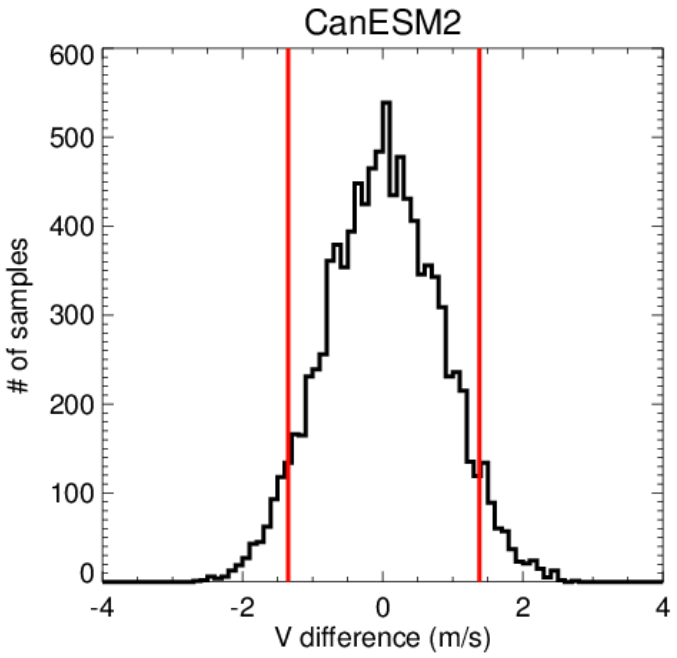
k>=5

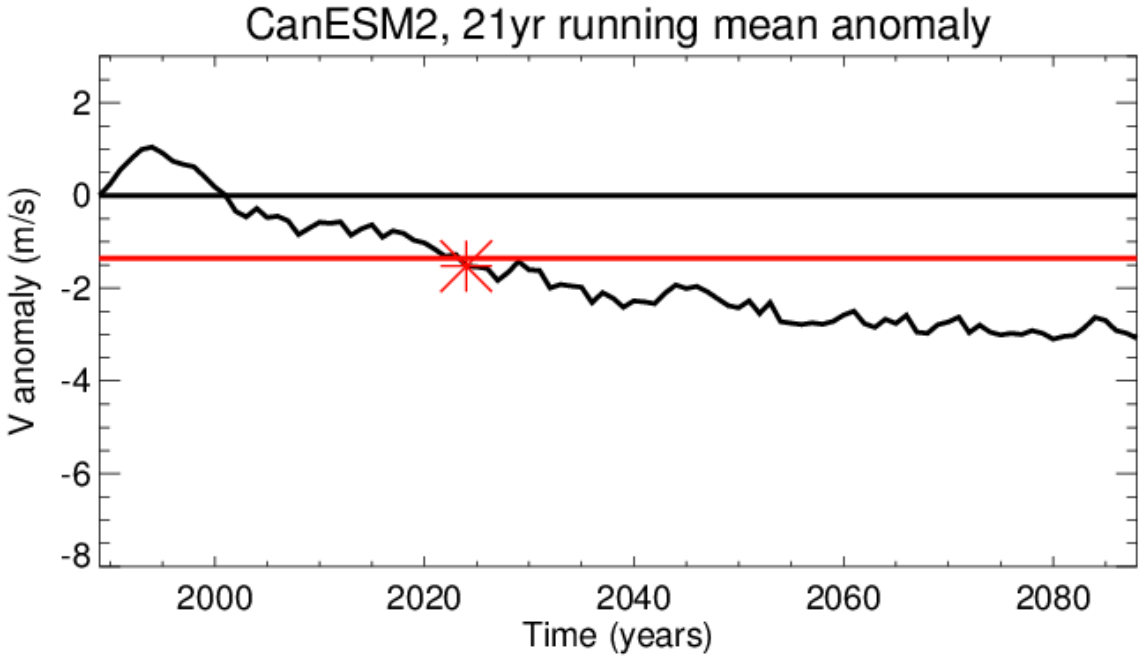


Comparing with piControl

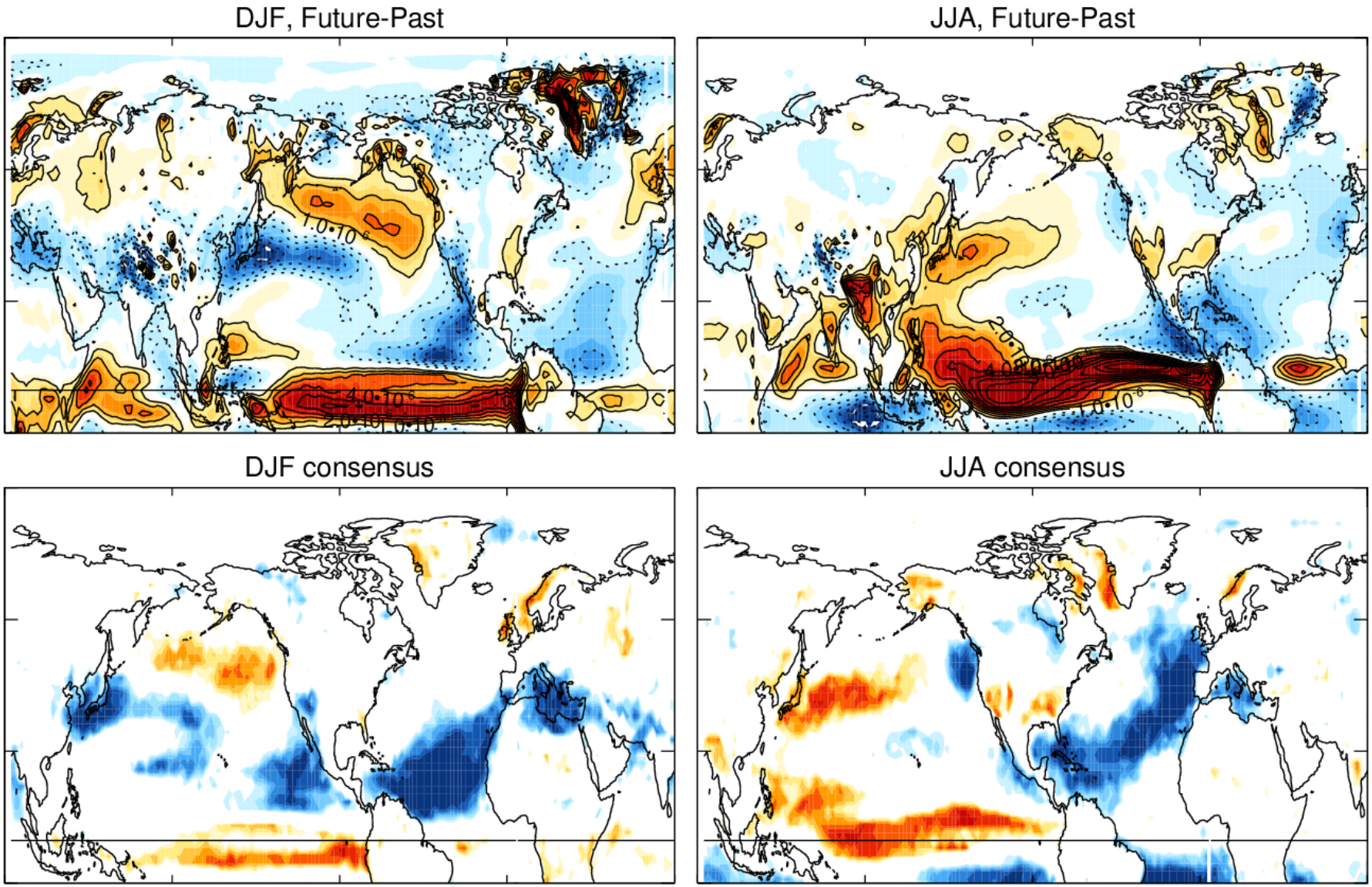
Assessing significance for an individual member





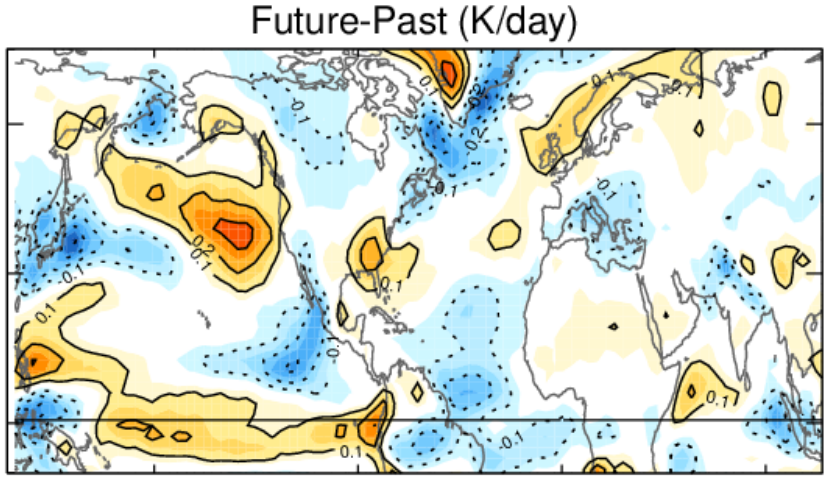


Diabatic Heating

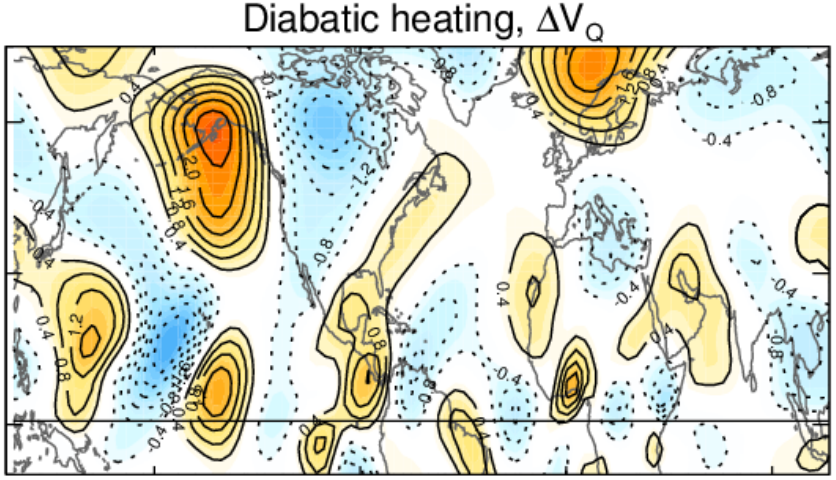


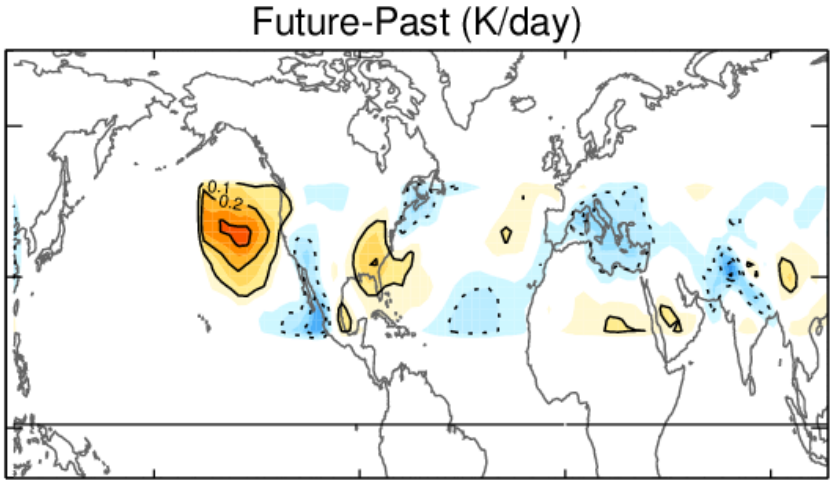
Diabatic Heating, Forcing or Feedback?

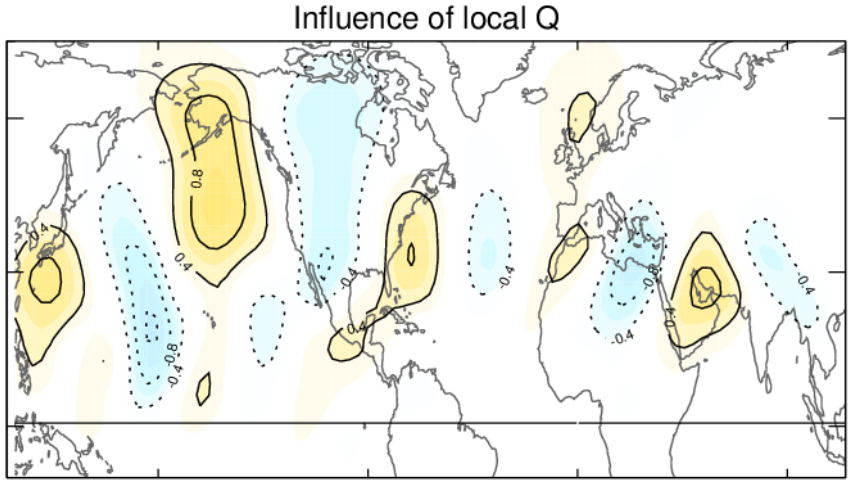
Zonally asymmetric diabatic heating



Influence on 300hPa v

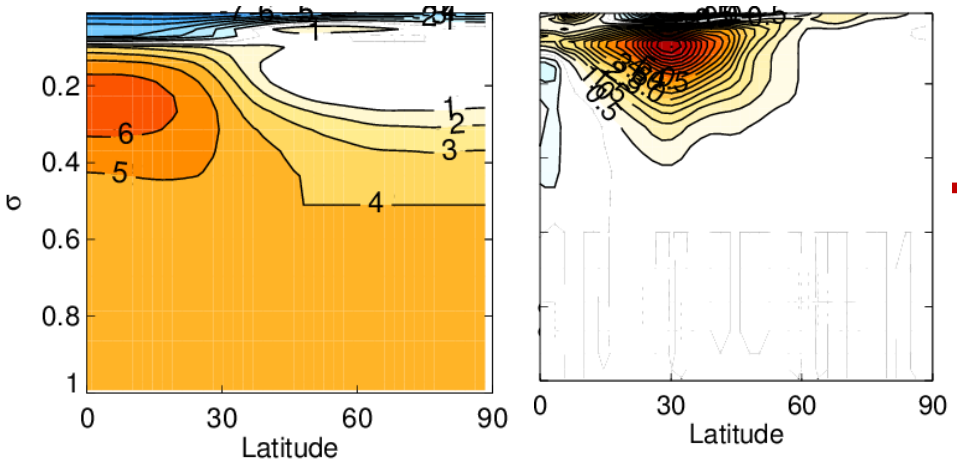


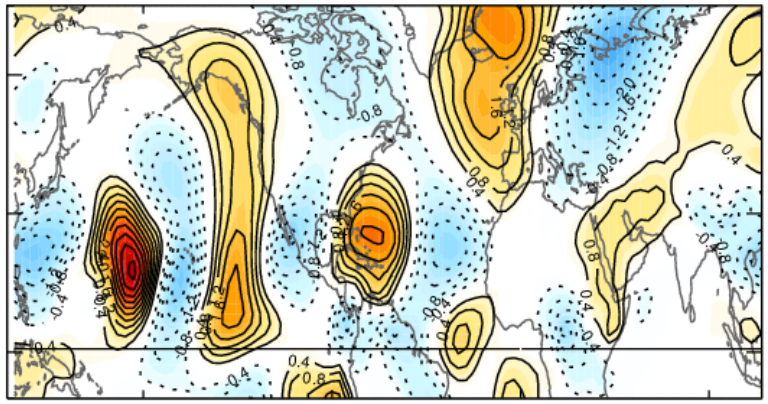




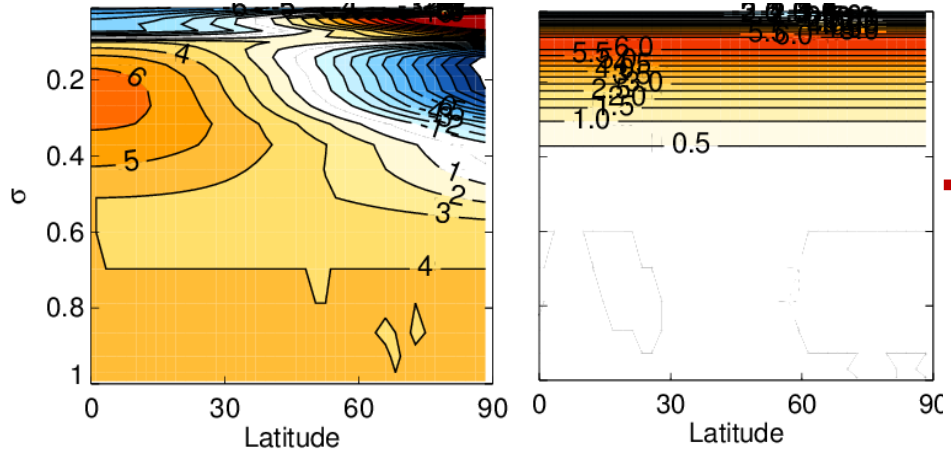
Other Idealized basic states

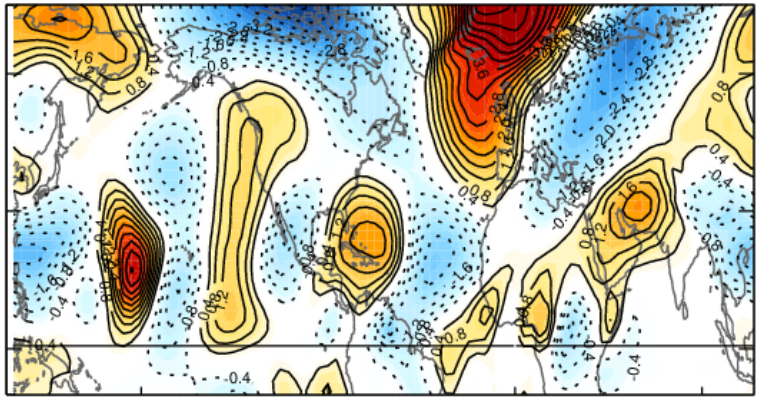
No Arctic Amplification or polar stratospheric cooling or tropospheric wind anomalies below σ=0.5



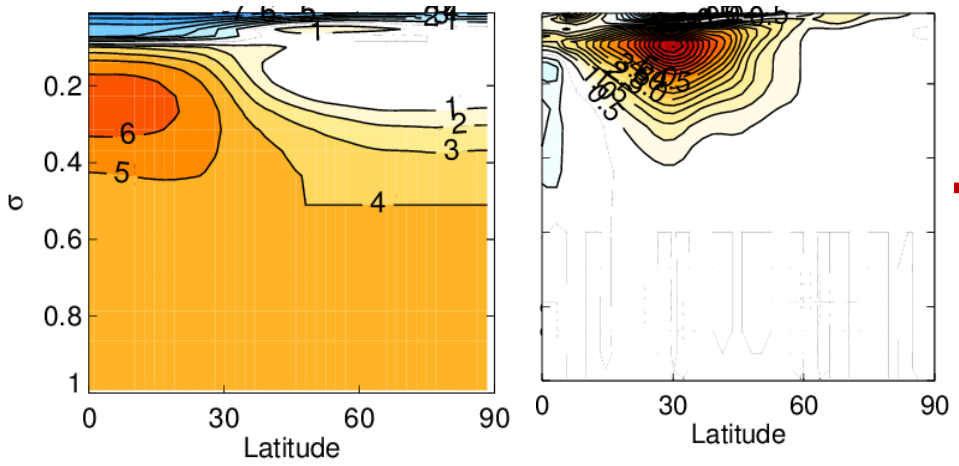


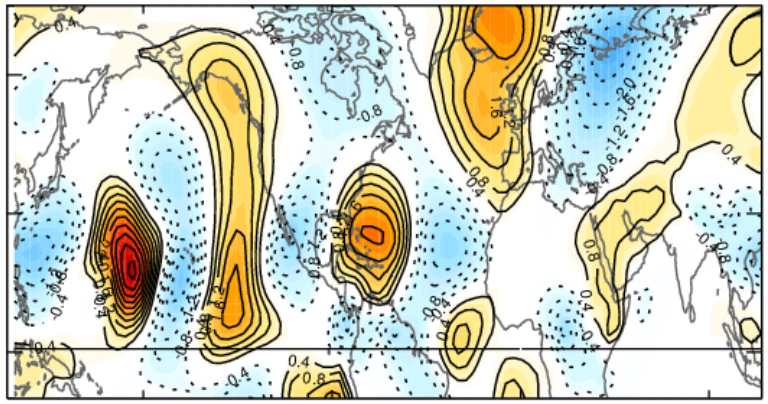
Only change the zonal wind speed, no altered structure



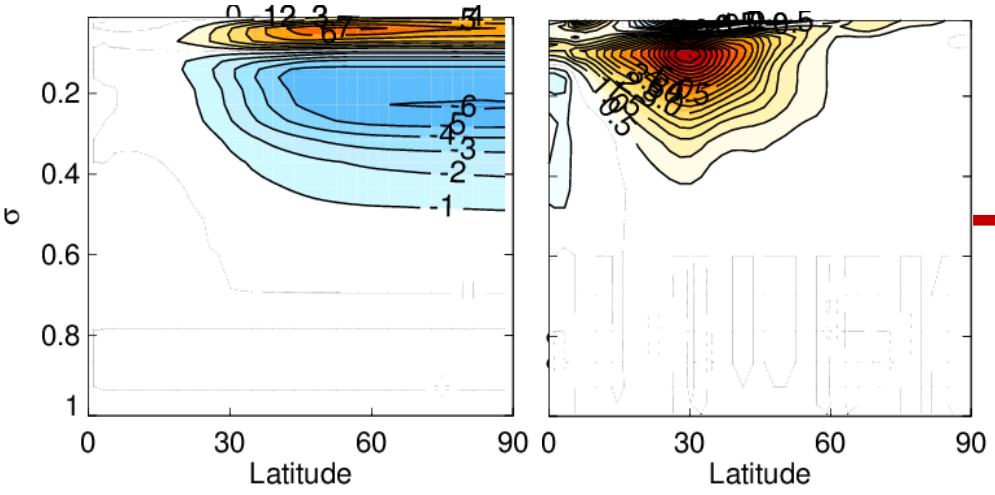


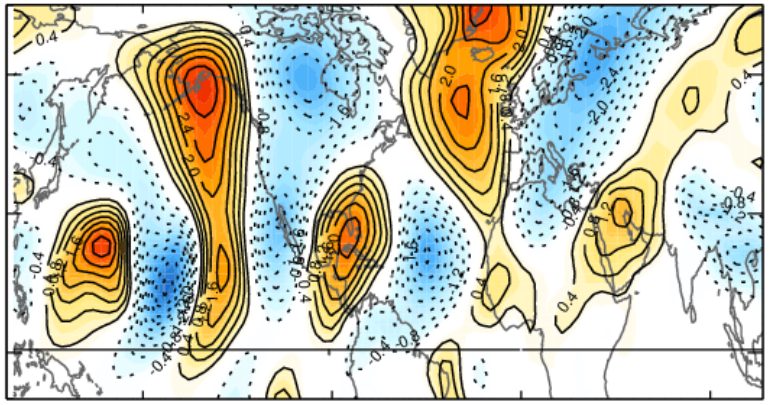
No Arctic Amplification or polar stratospheric cooling or tropospheric wind anomalies below σ=0.5





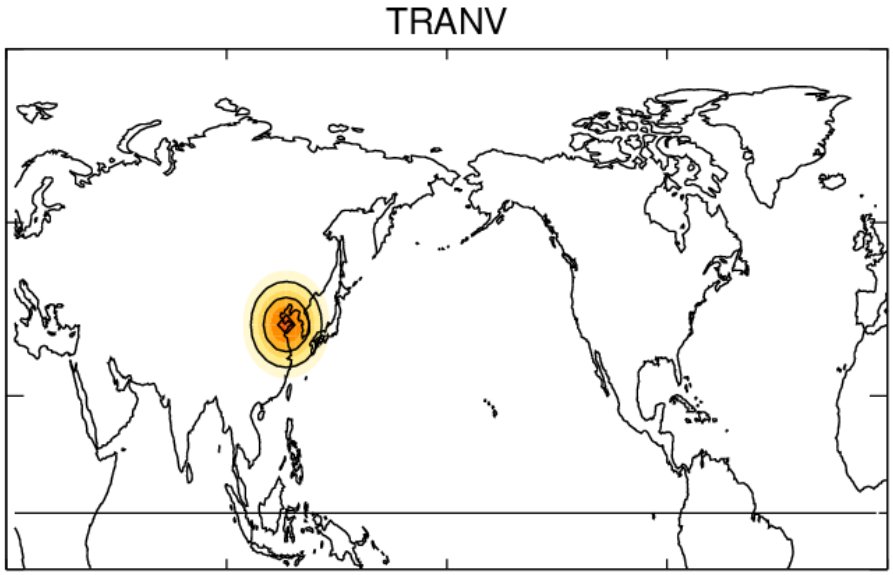
Remove the change in tropical upper tropospheric stability

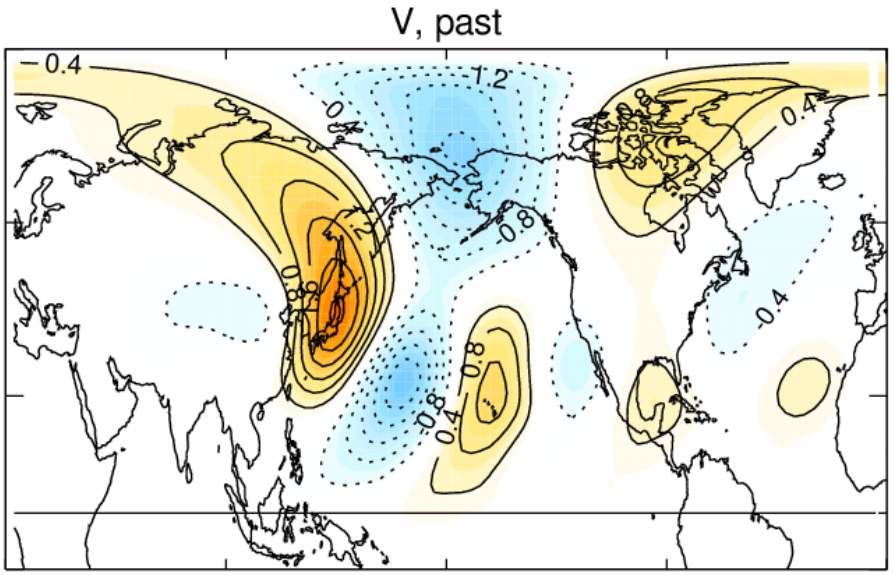


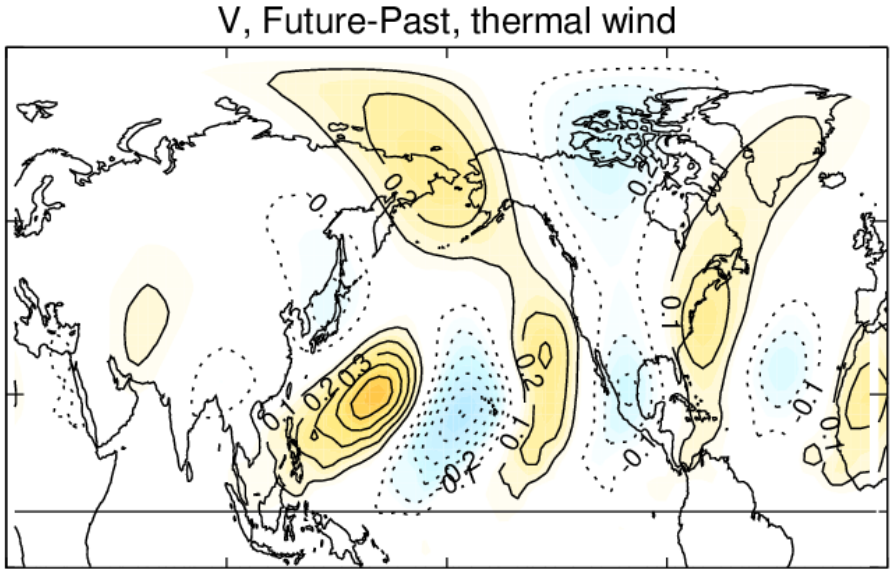


Idealized Vorticity Source

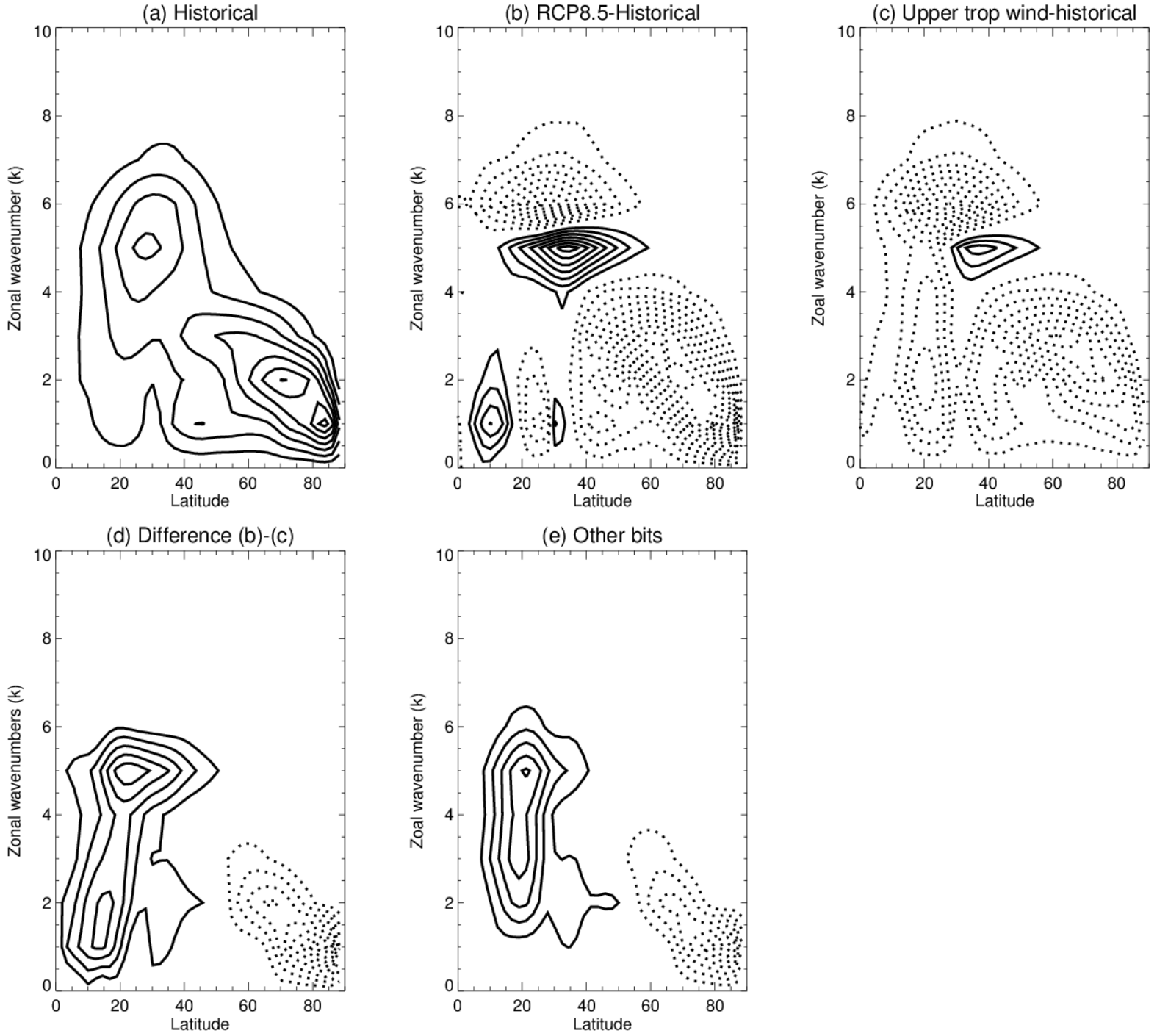
Idealized vorticity source.



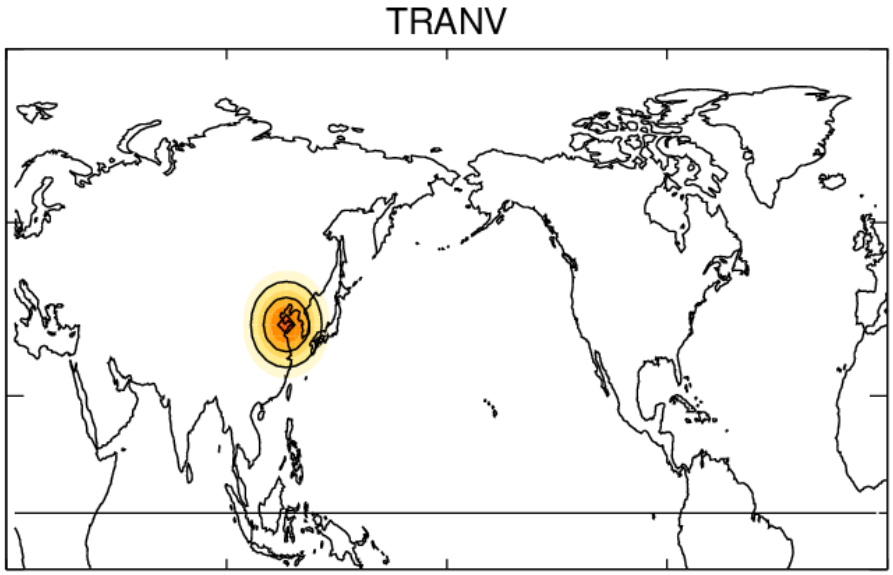


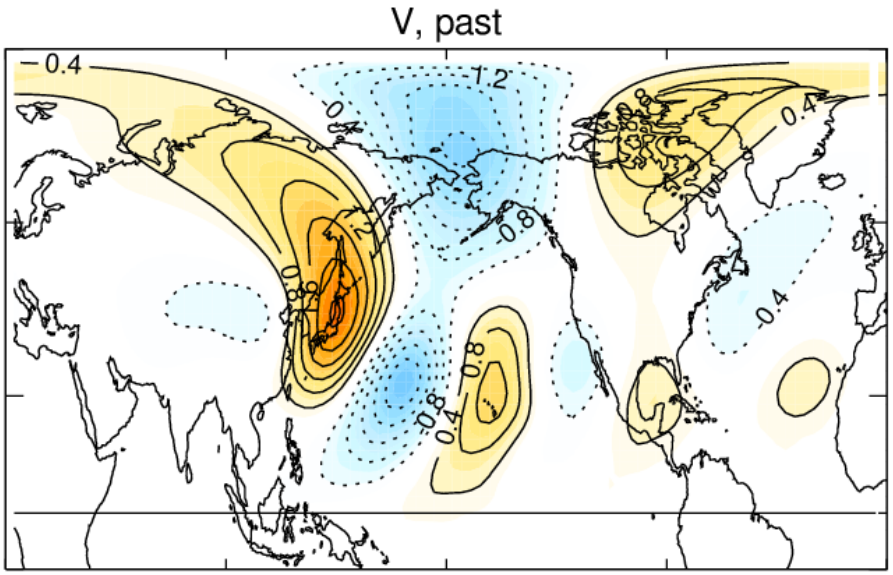


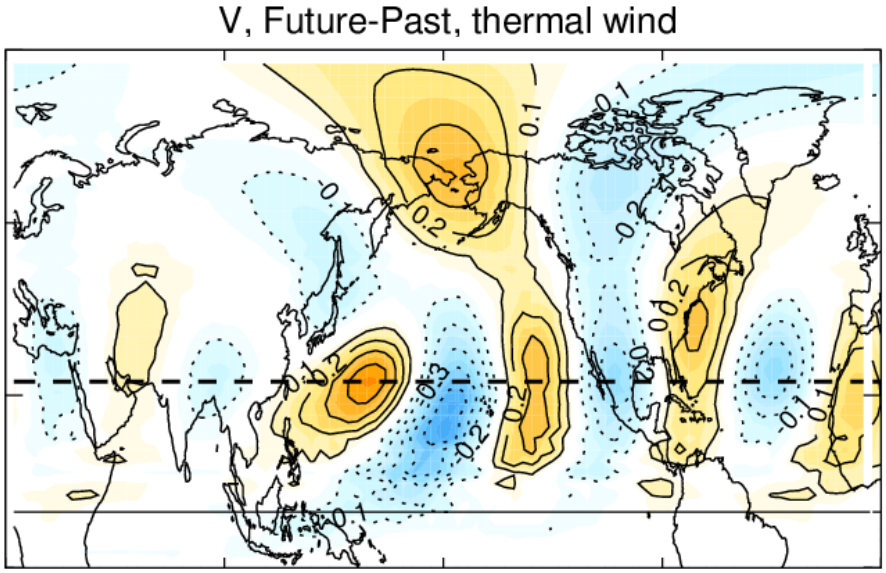
/home/isla/IDL/programs/swpaper/spectral/klksdecomp/kdecomp/idealvort

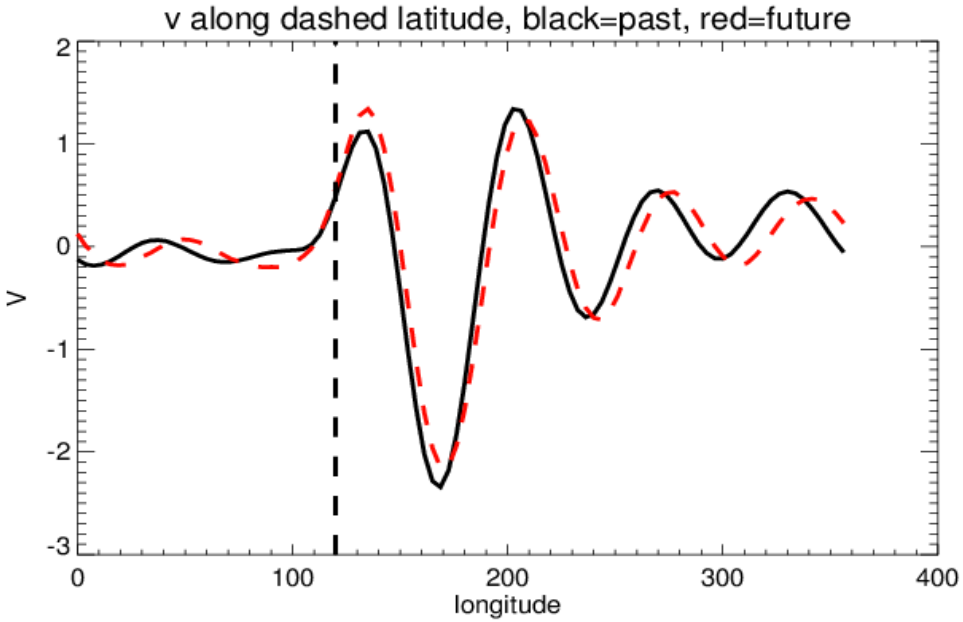

(a) Historical
(b) RCP8.5-Historical
(c) Upper trop wind-historical
(d) Difference (b)-(c)
(e) Other bits
Zonal wavenumber (k)
Zonal wavenumbers (k)
Zoal wavenumber (k)
Latitude
0
2
4
6
8
10
0
20
40
60
80

Idealized vorticity source.









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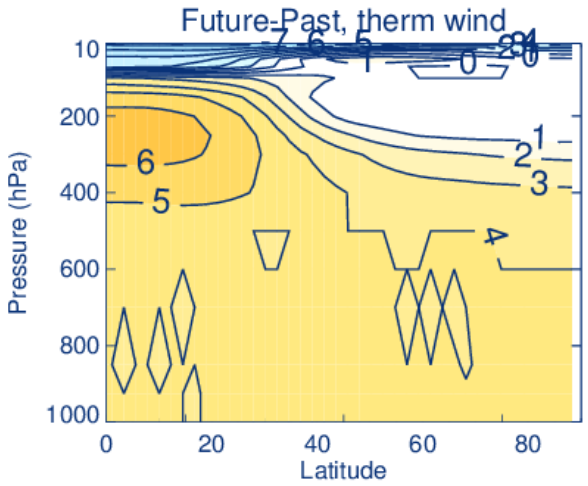

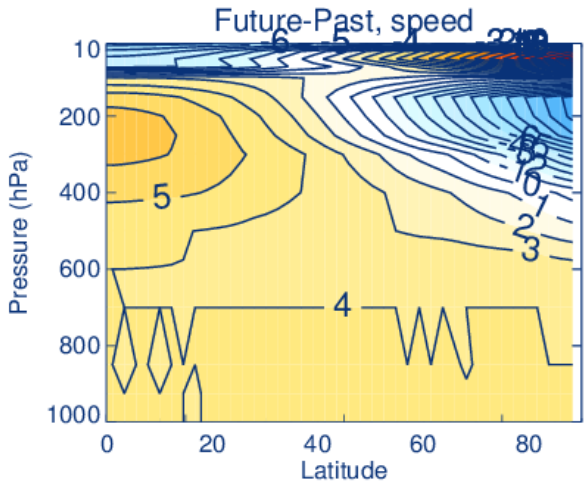

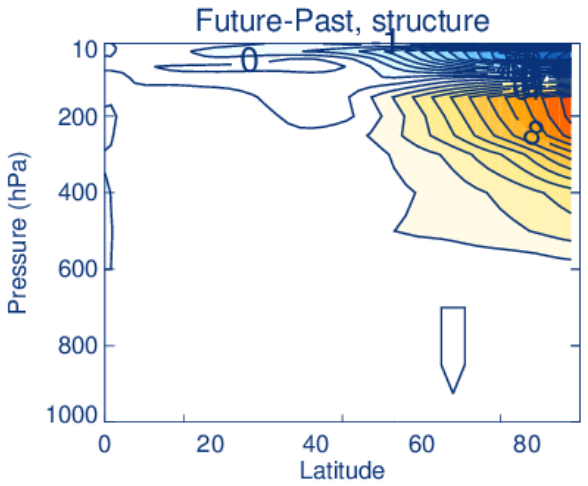

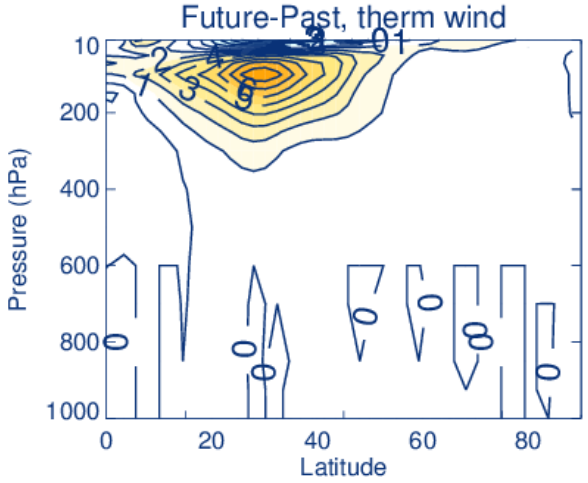

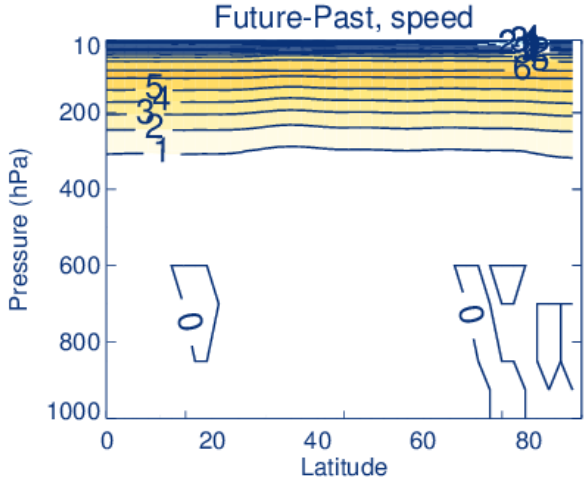

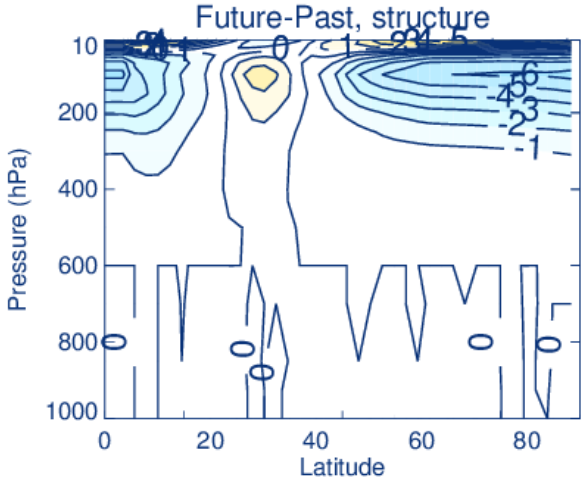

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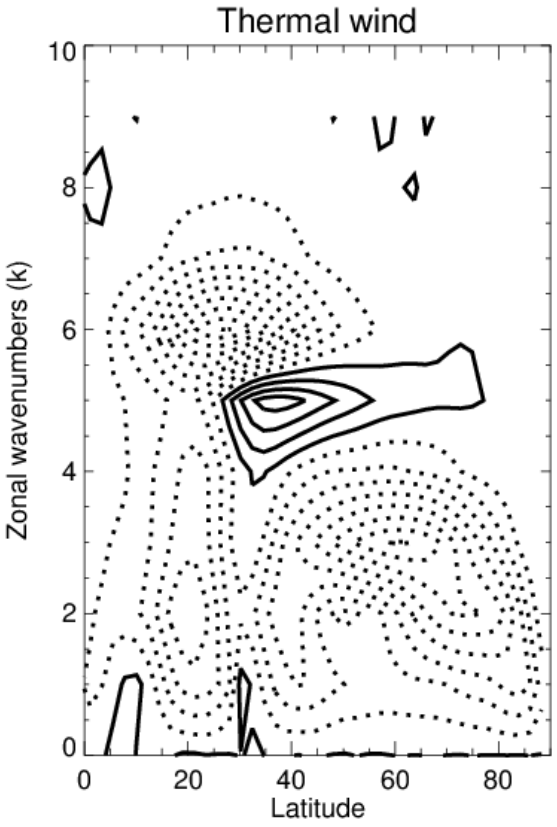

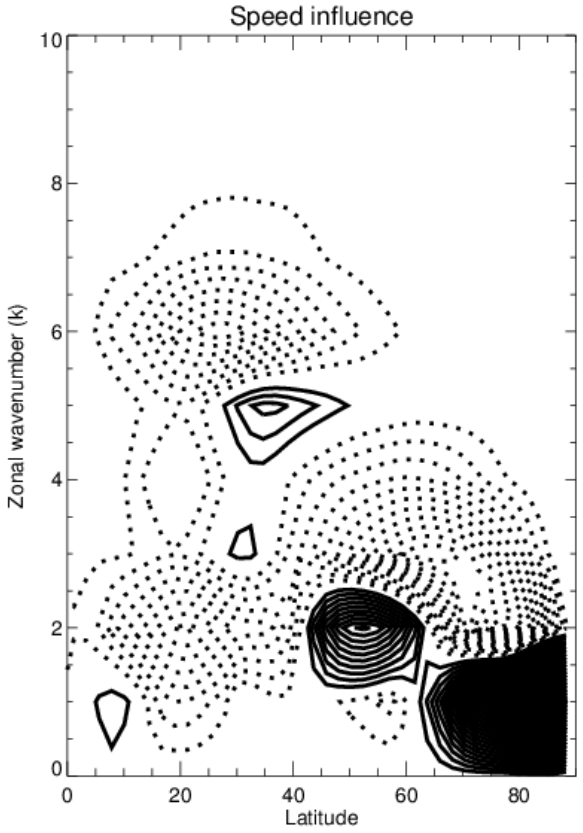

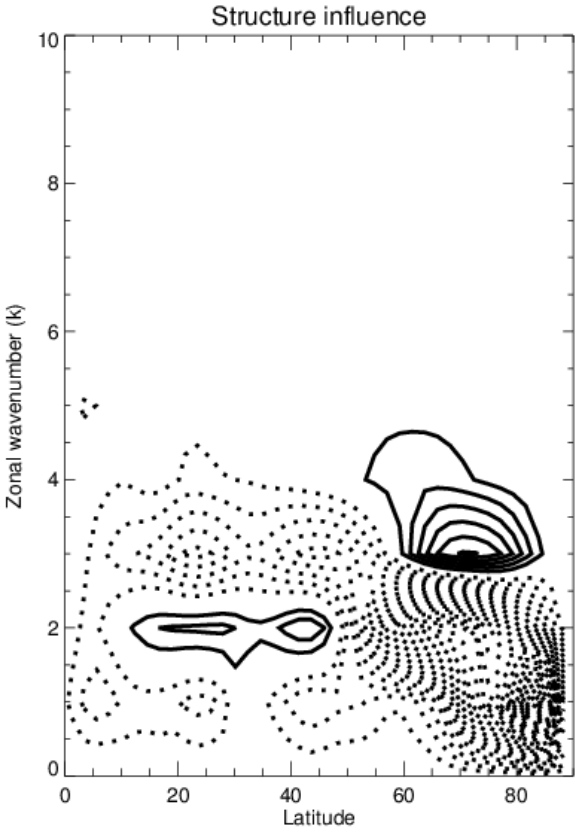

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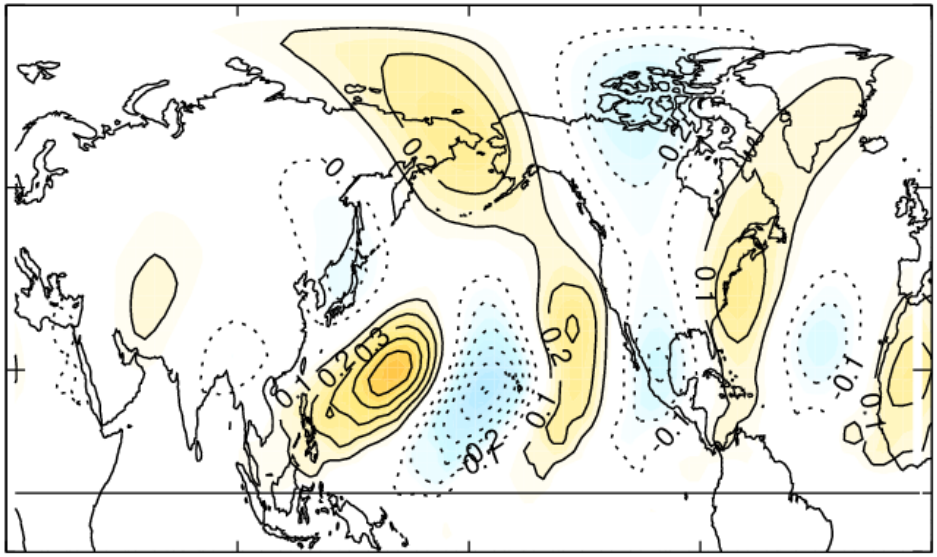
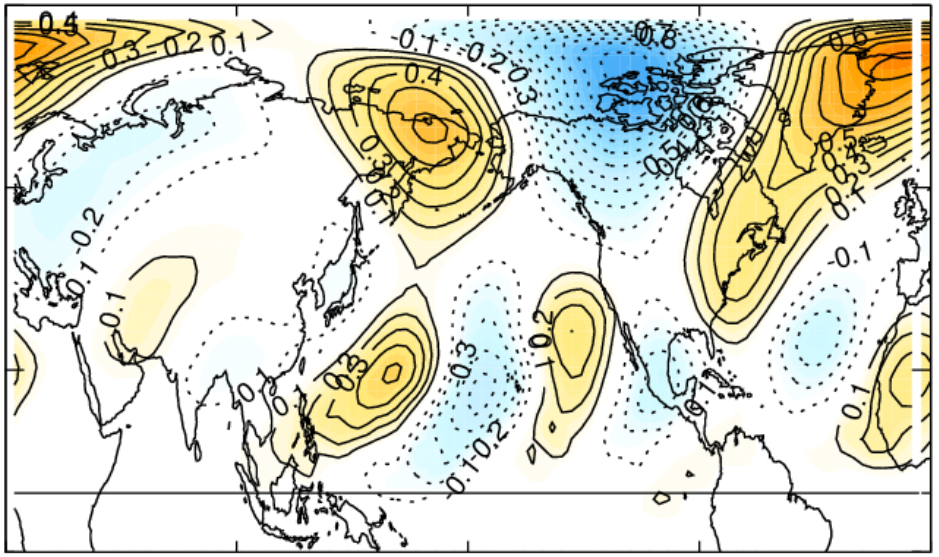
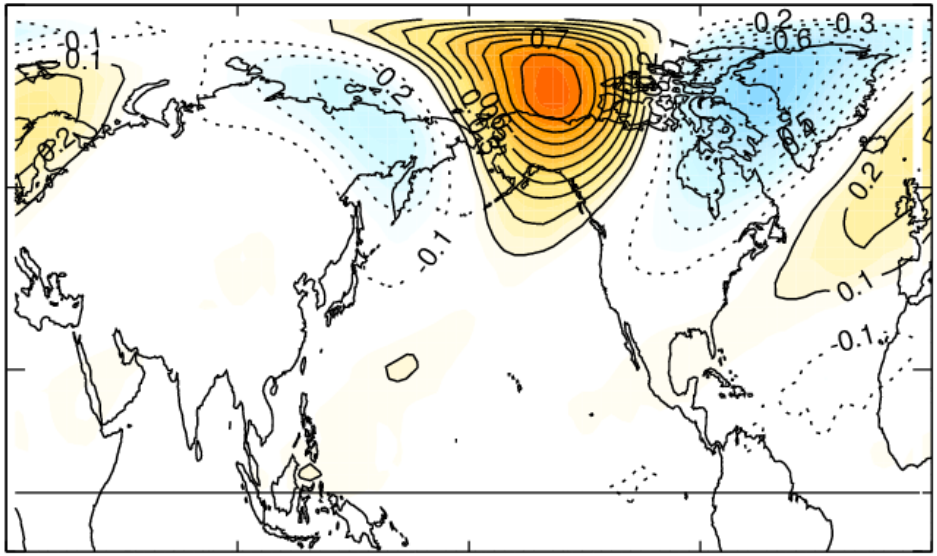
V, Future-Past, thermal wind



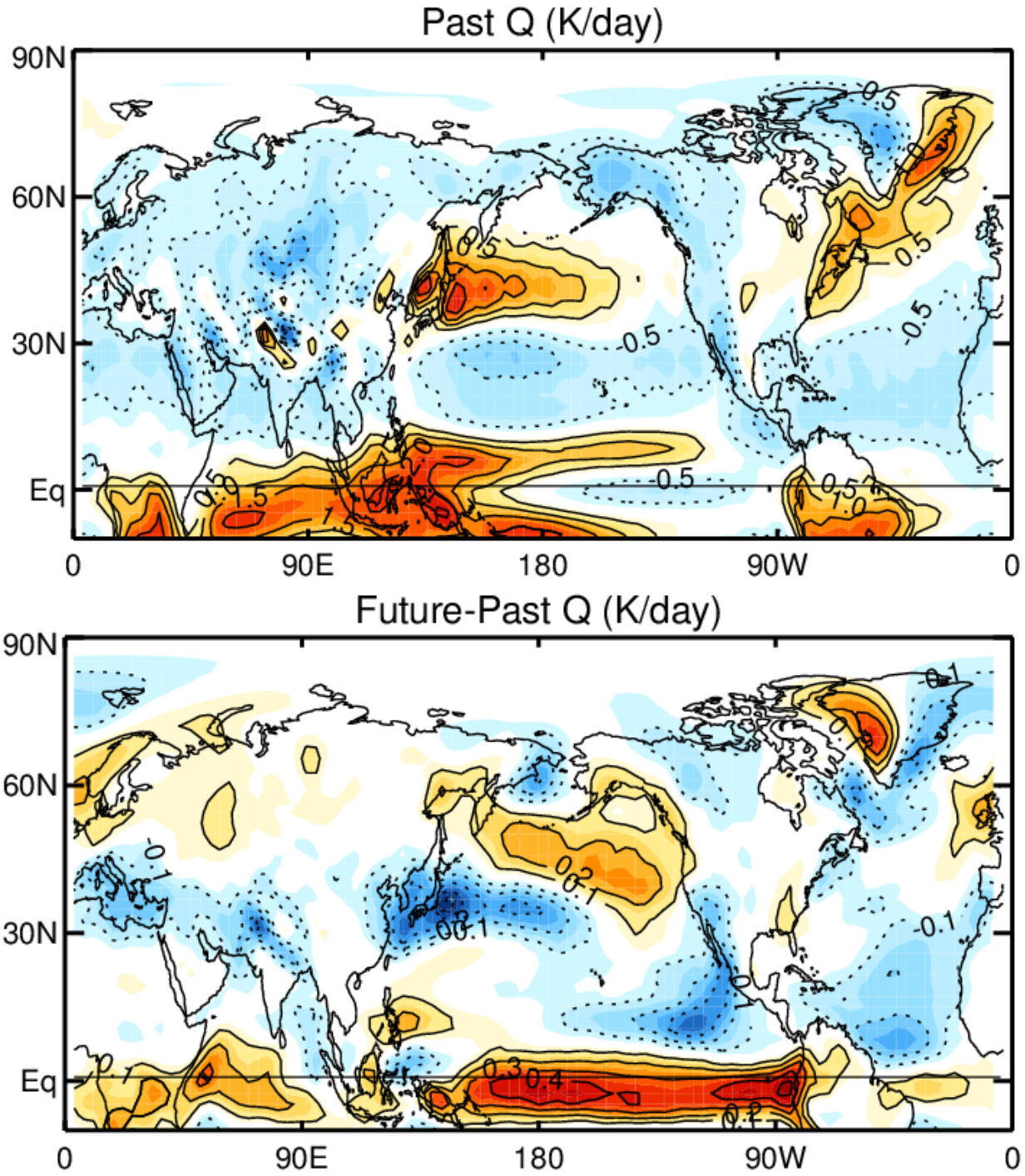
V, Future-Past, Speed



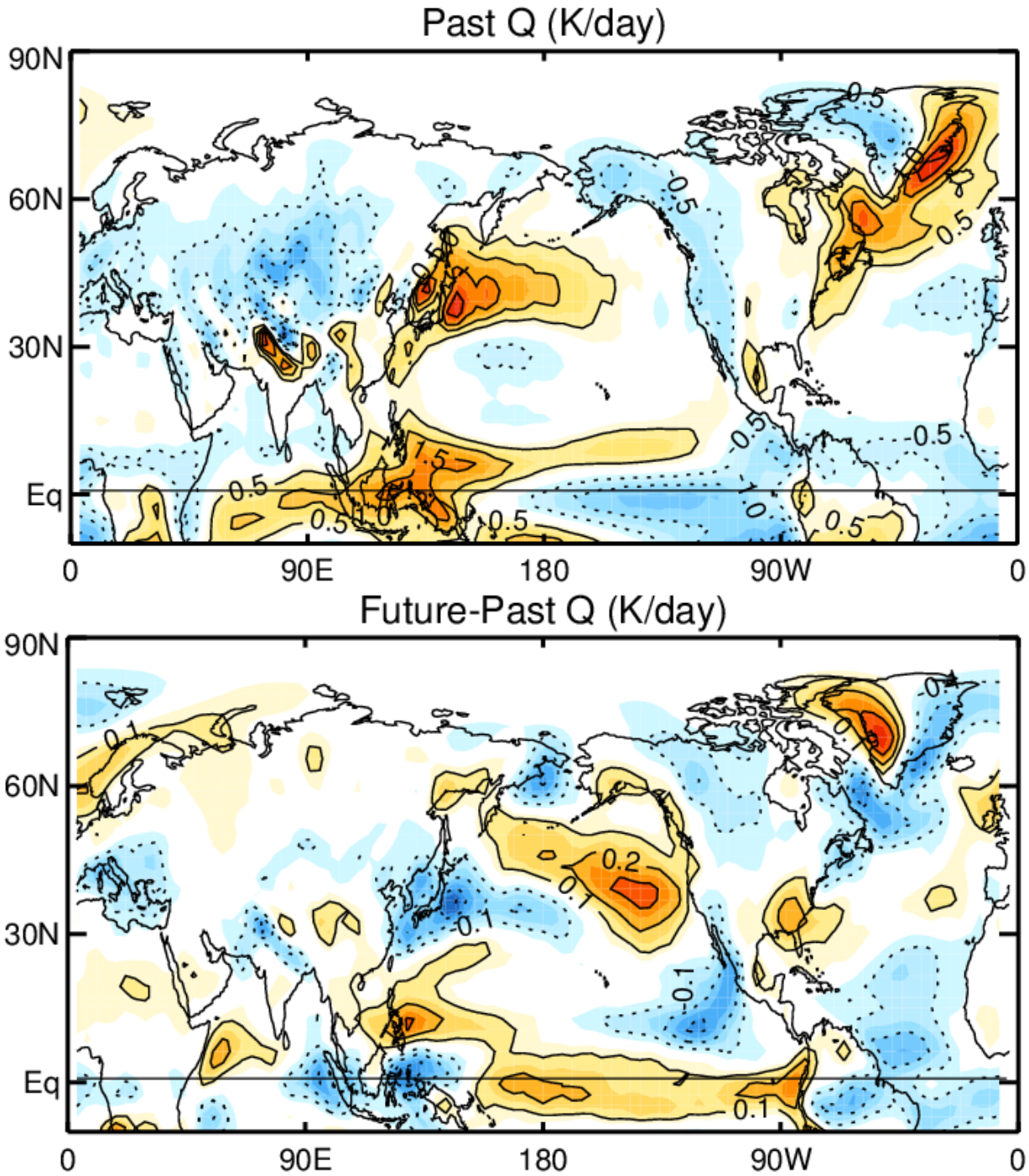
V, Future-Past, structure



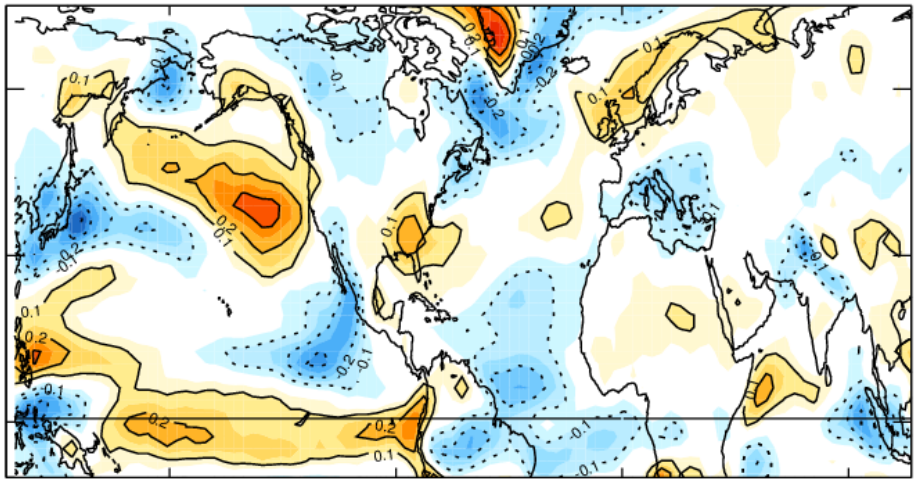
Diabatic Heating



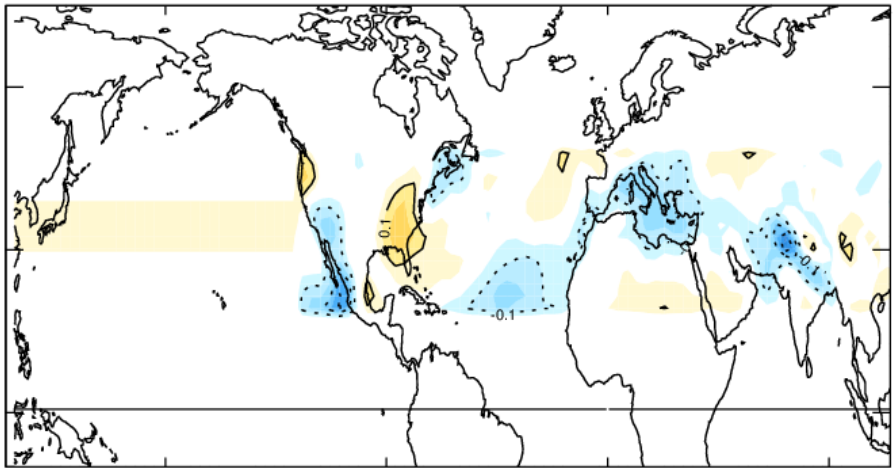
Zonally Asymmetric Diabatic Heating



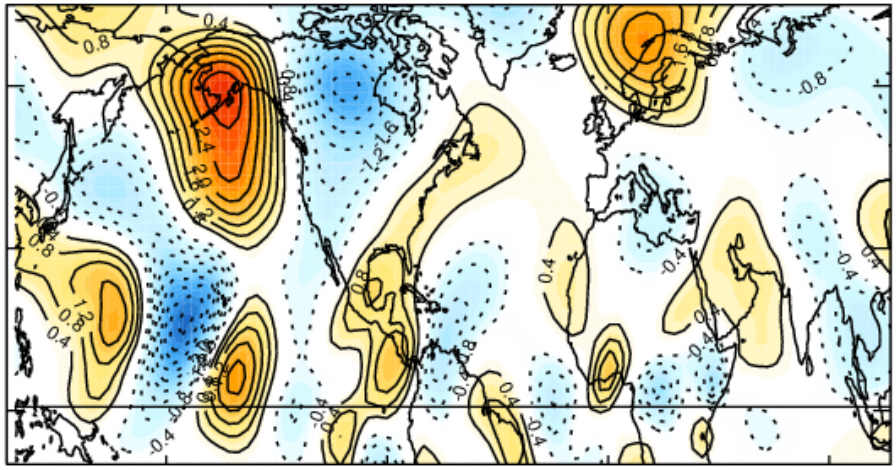
Future-Past Q (K/day)



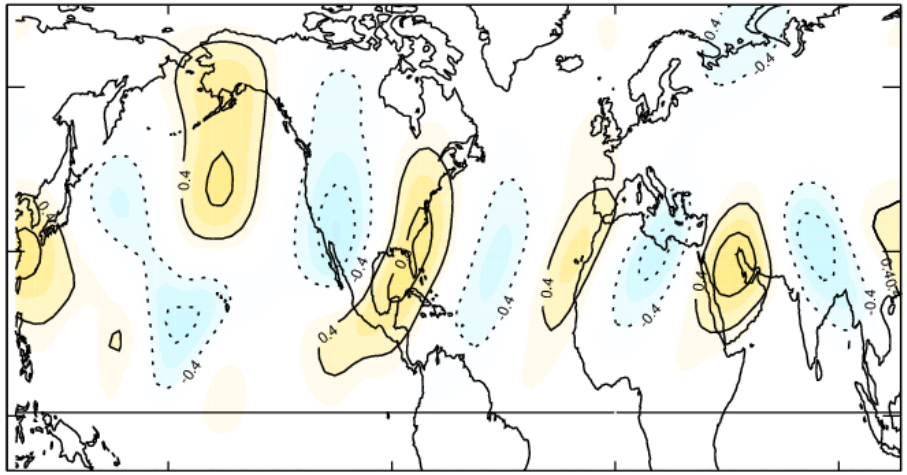
Future-Past Q (K/day)



Diabatic heating, ΔV_Q

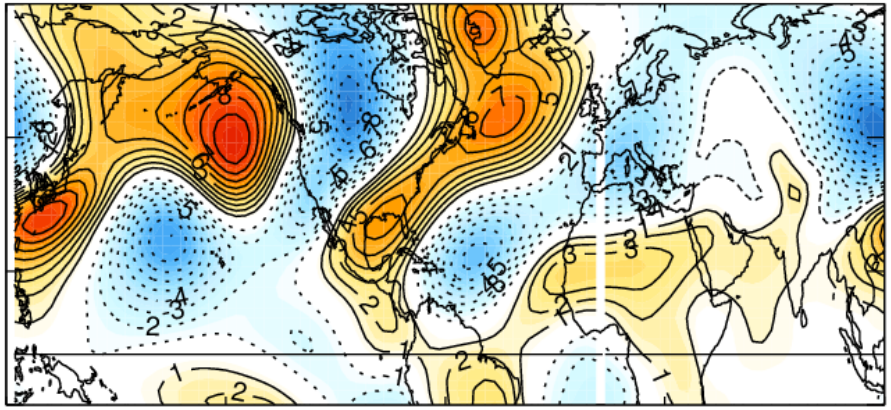


Influence of local Q

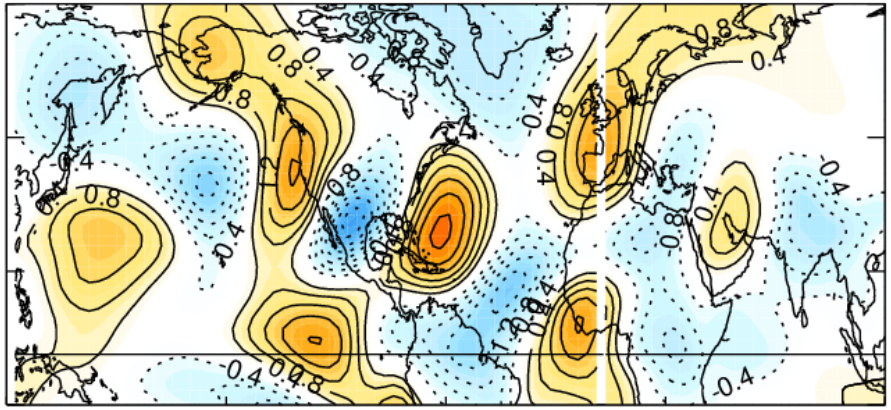


Wavenumber Decomposition

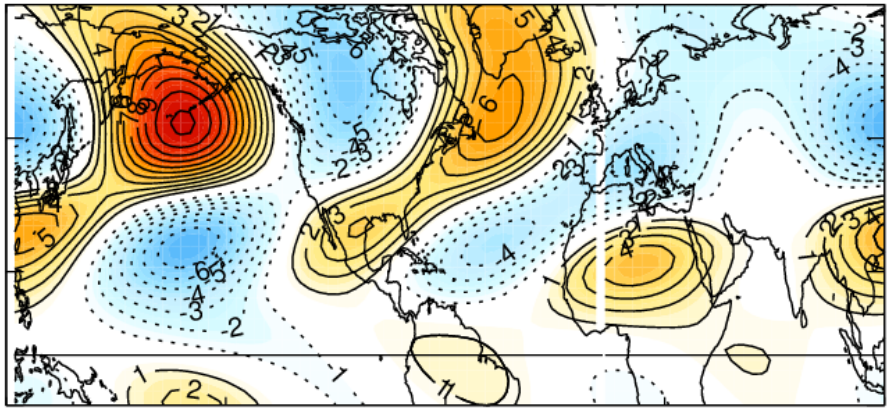
Past, ks=0-29



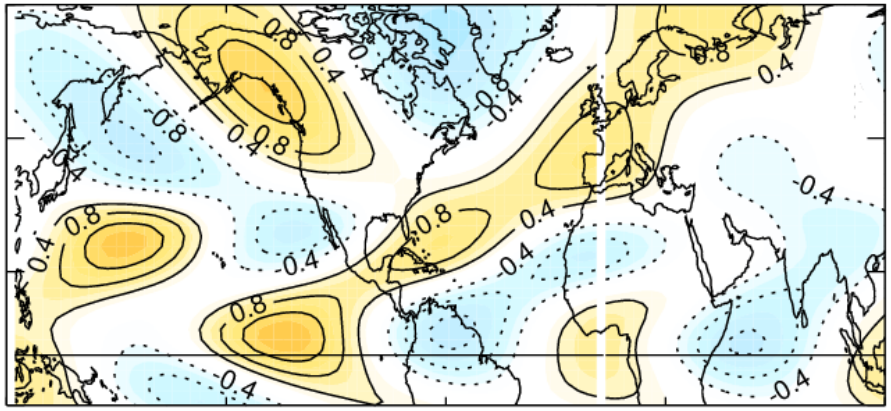
Future-Past, ks=0-29



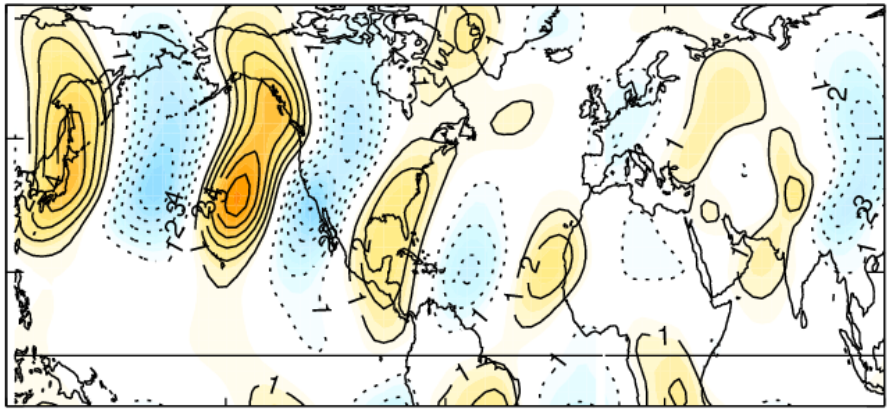
Past, ks=0-3



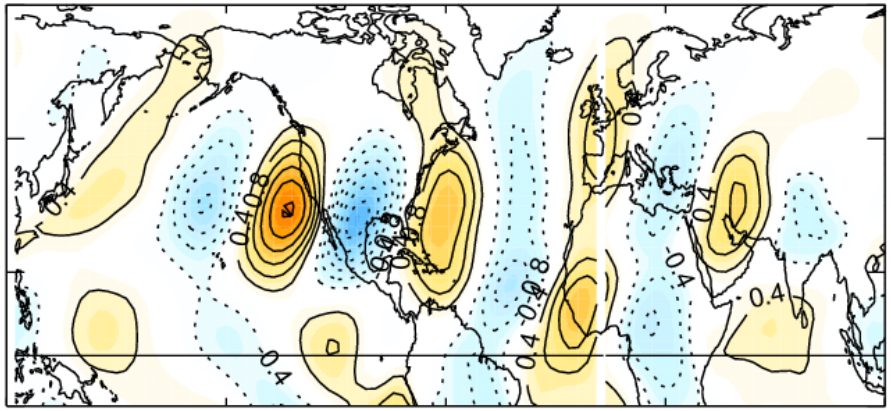
Future-Past, ks=0-3



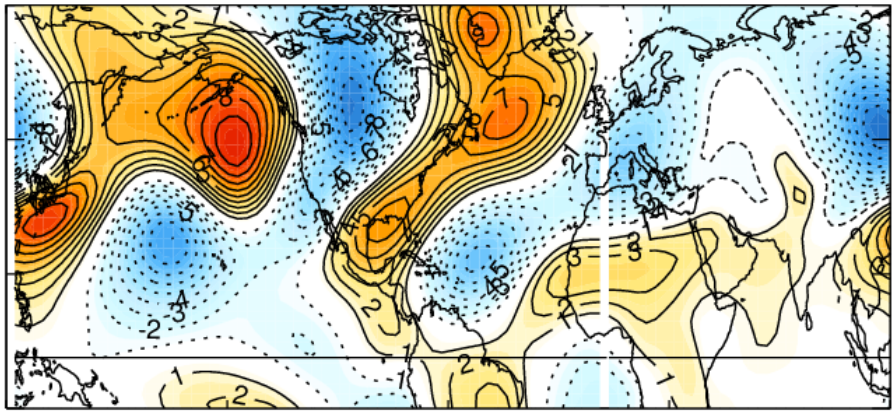
Past, ks=4-29



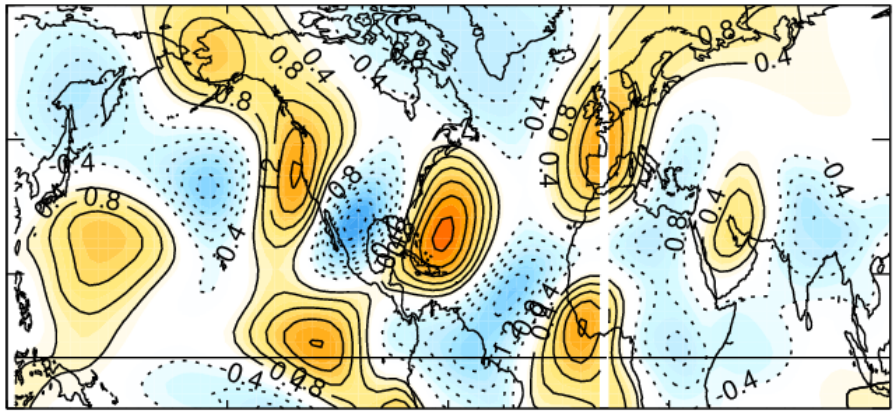
Future-Past, ks=4-29



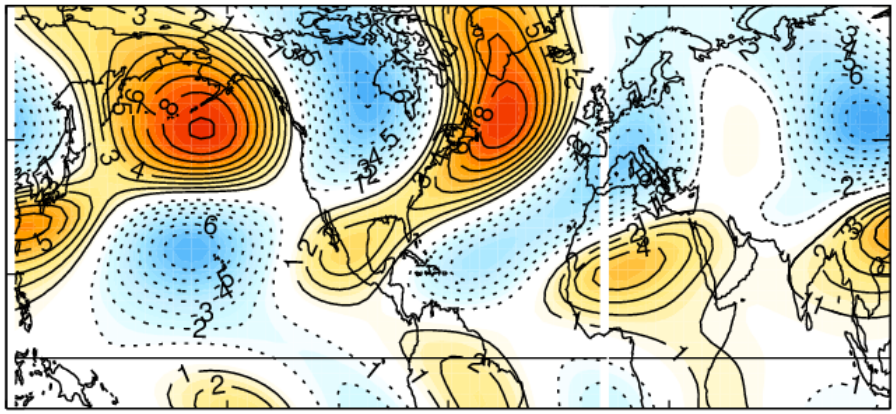
Past, ks=0-29



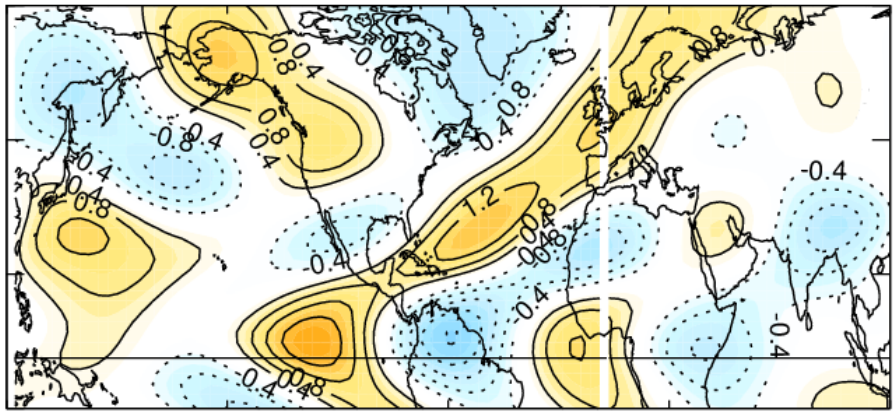
Future-Past, ks=0-29



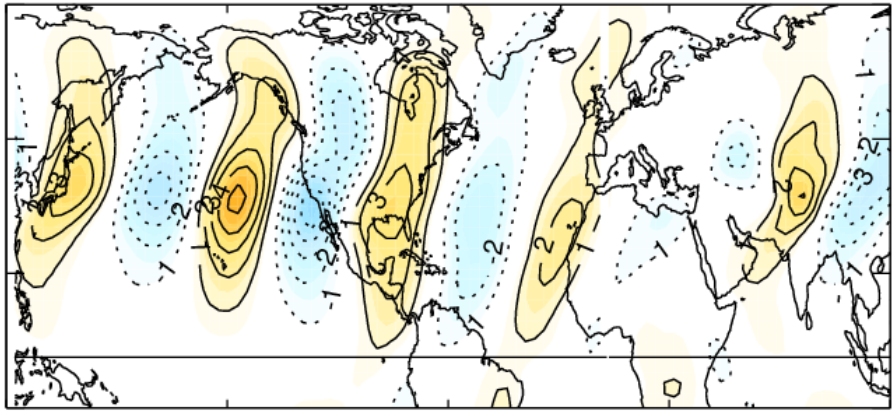
Past, ks=0-4



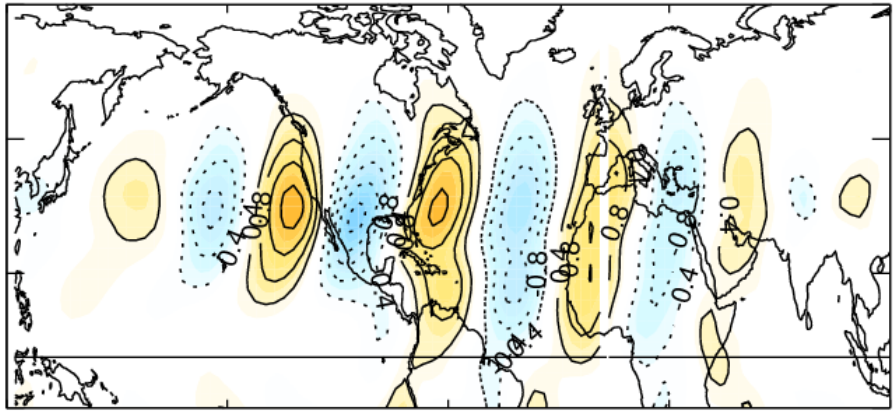
Future-Past, ks=0-4



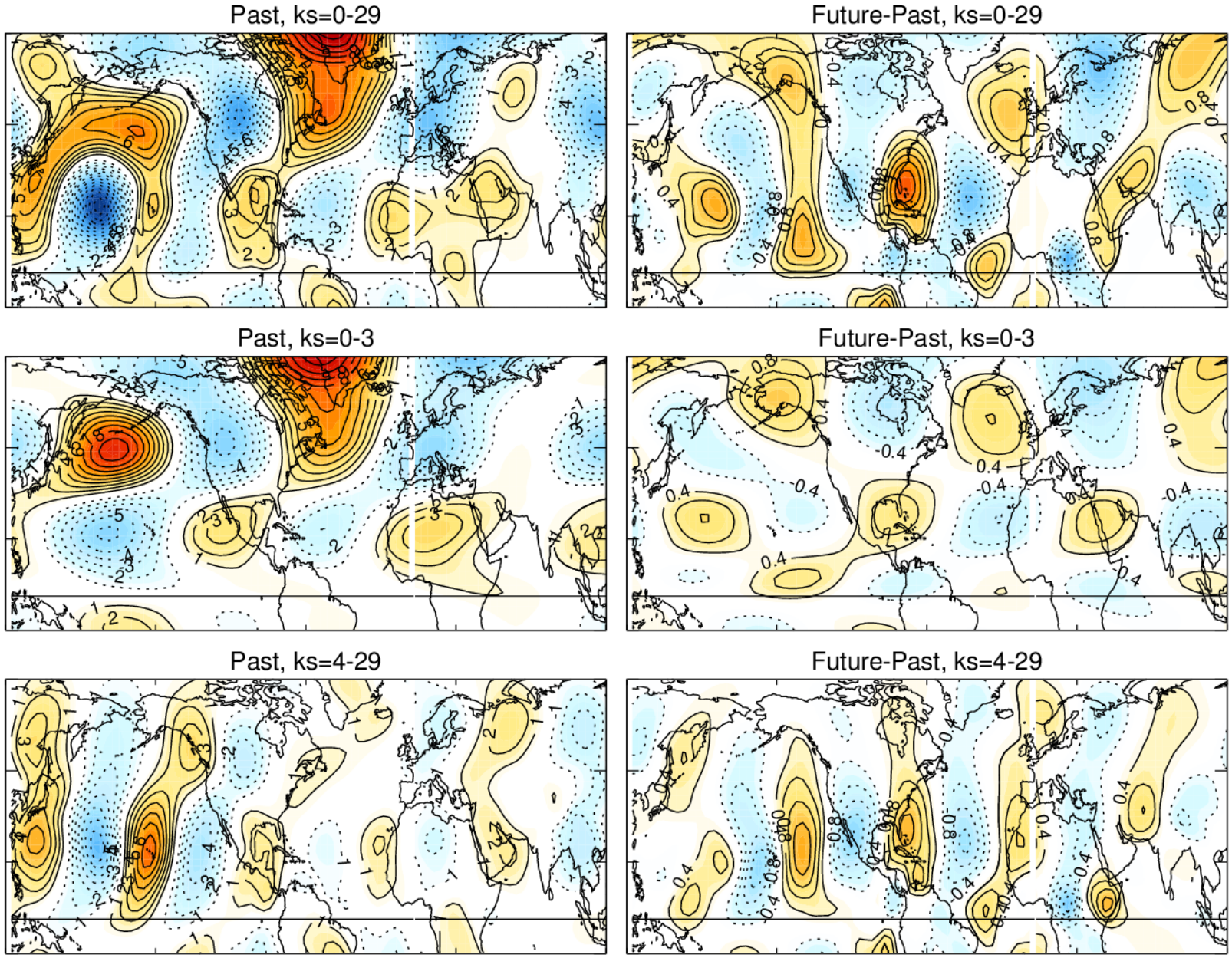
Past, ks=5-29



Future-Past, ks=5-29

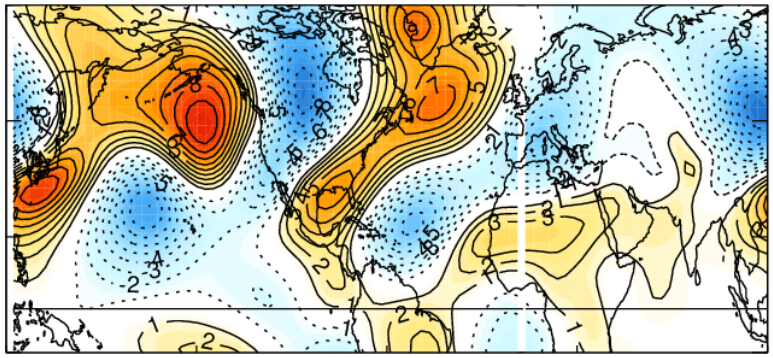


SW model, wavenumber decomposition

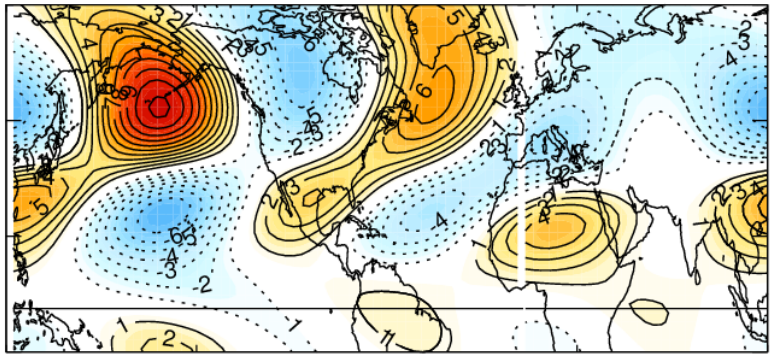


CMIP-5

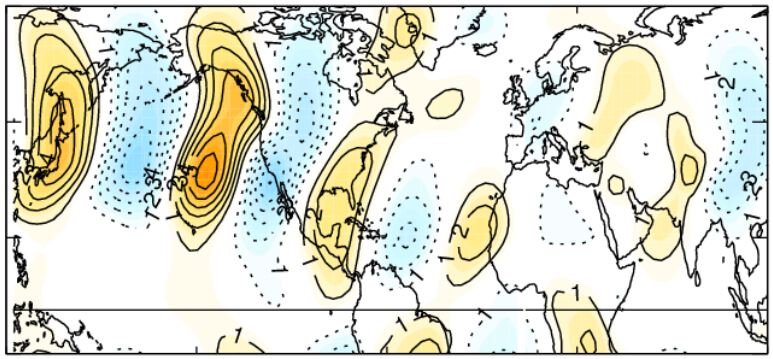
Past, ks=0-29



Past, ks=0-3

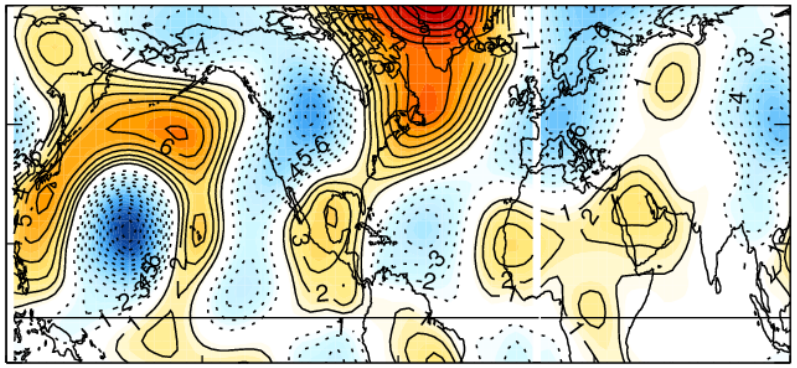


Past, ks=4-29

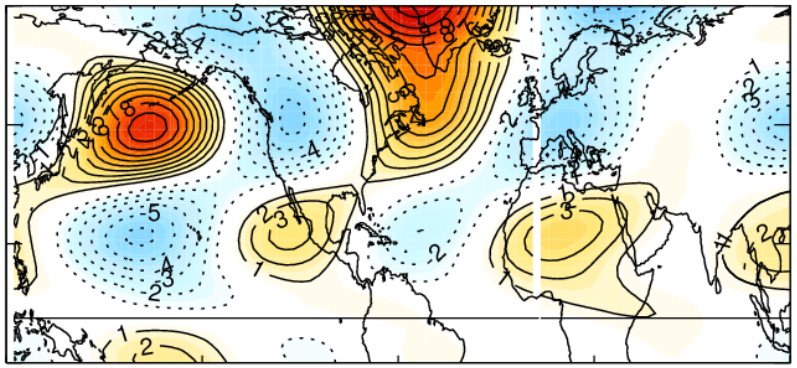


SW model

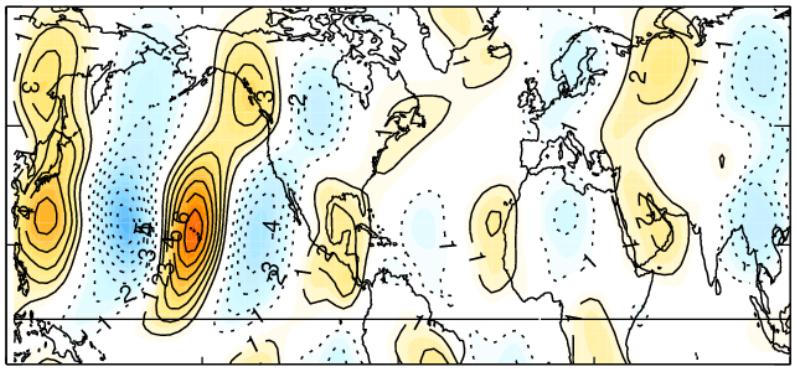
Past, ks=0-29



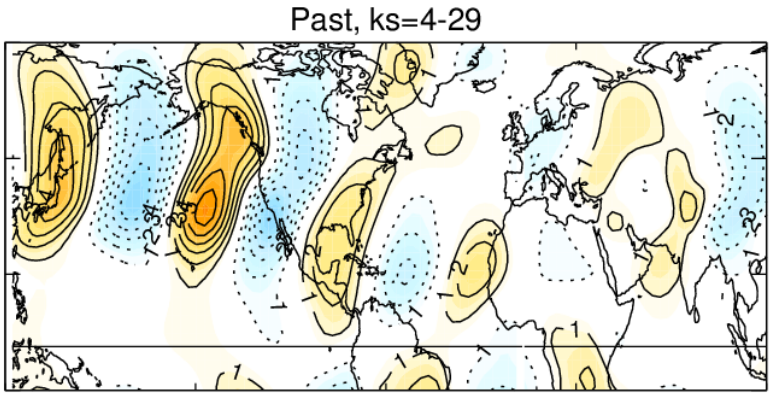
Past, ks=0-3

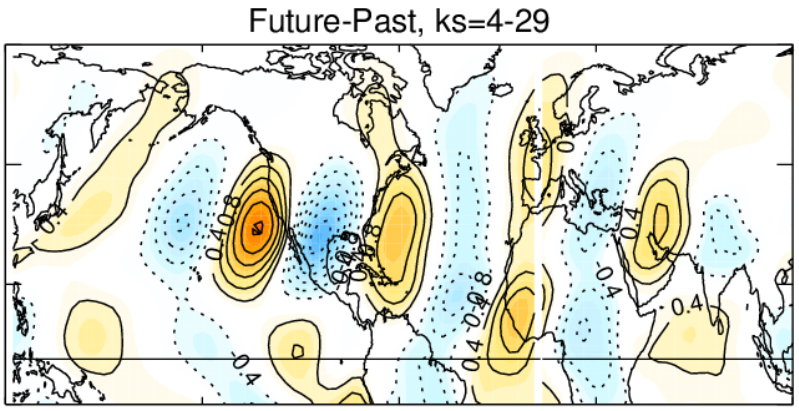


Past, ks=4-29

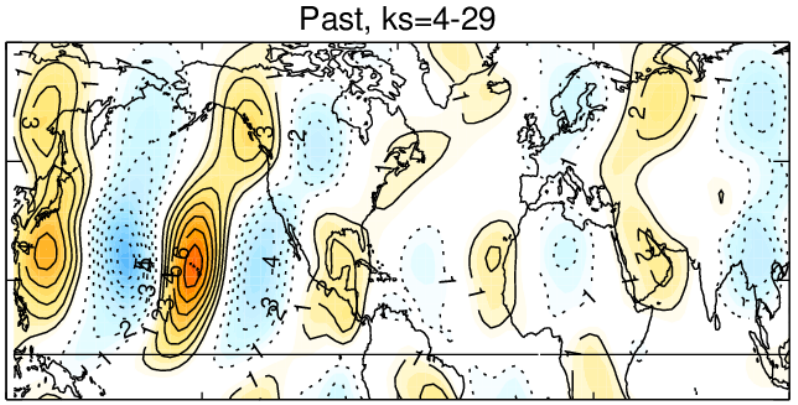


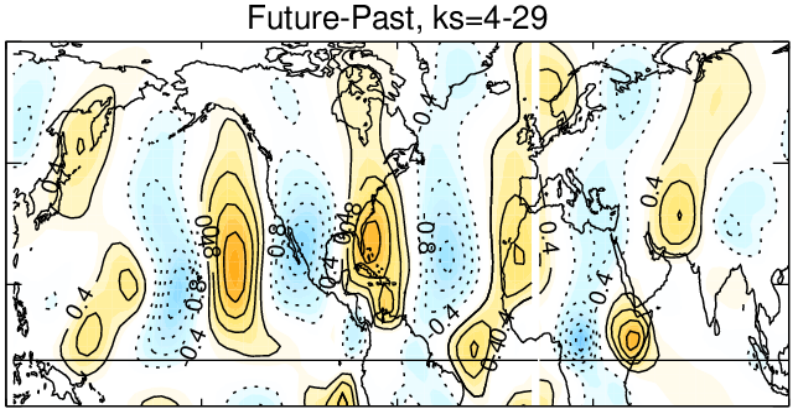
CMIP5





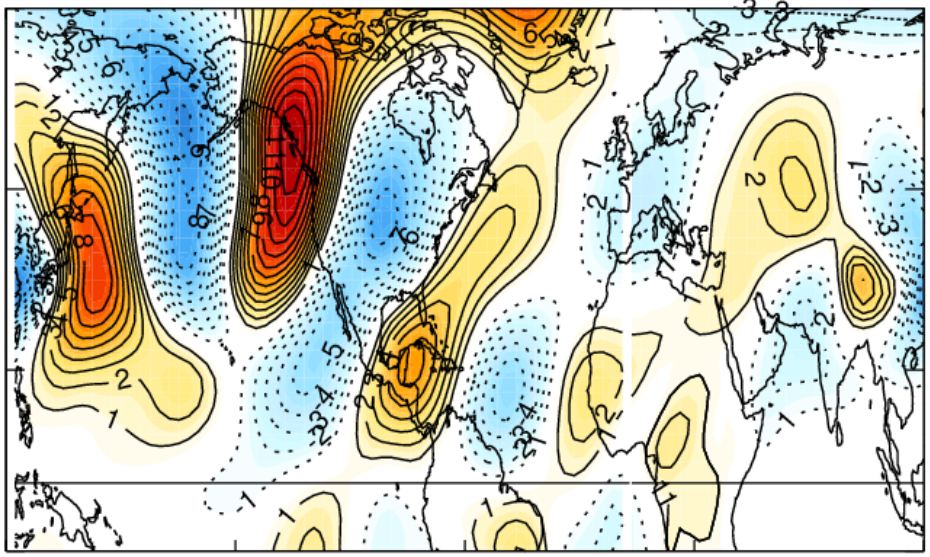
SW model



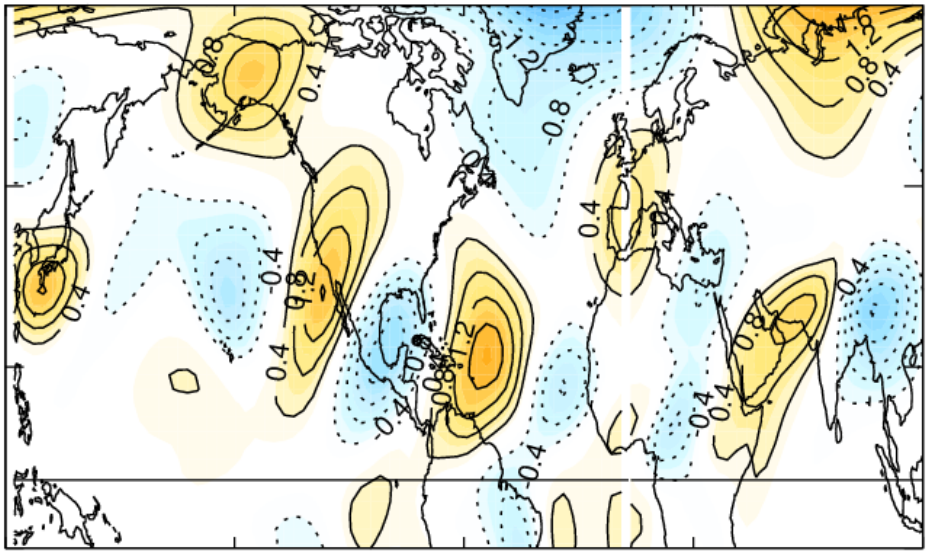


Putting only k ge 4 forcings in k lt 4 BS

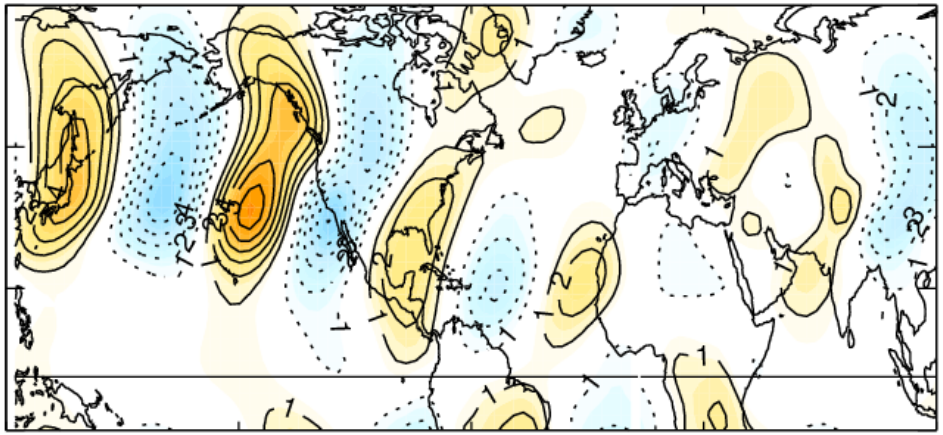
V, Past



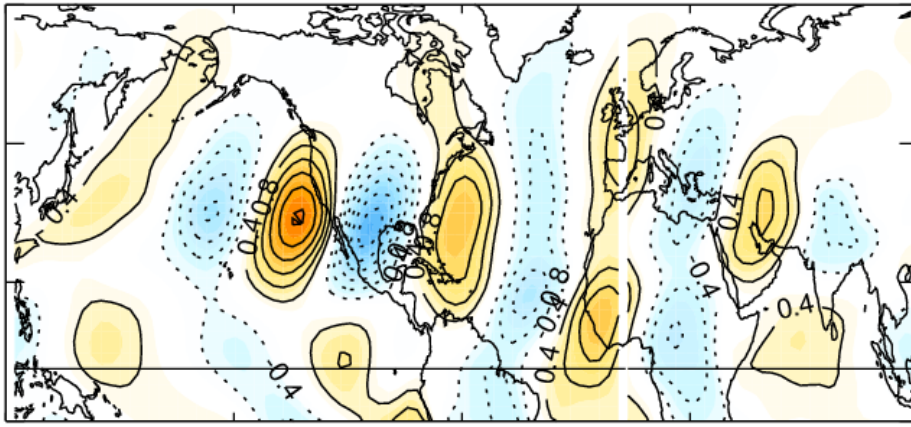
V, Future-Past



Past, ks=4-29

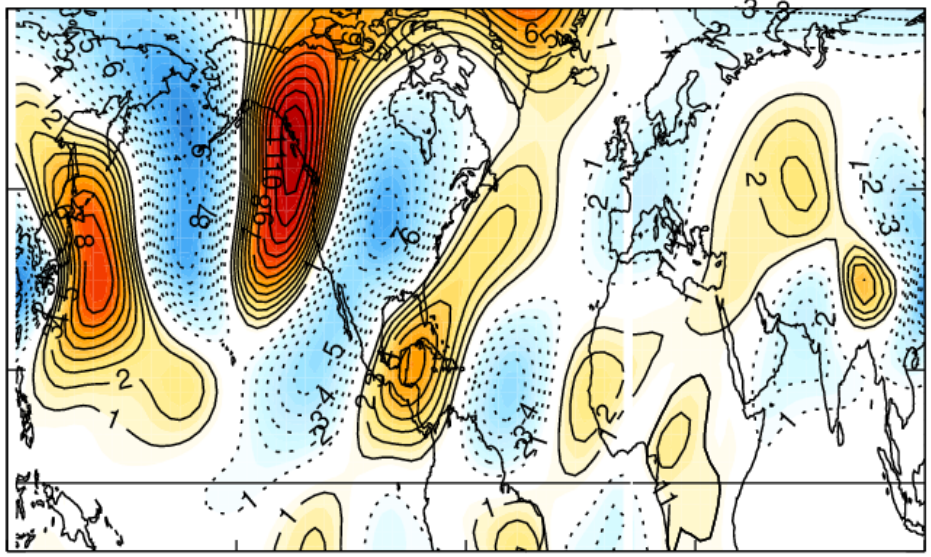


Future-Past, ks=4-29

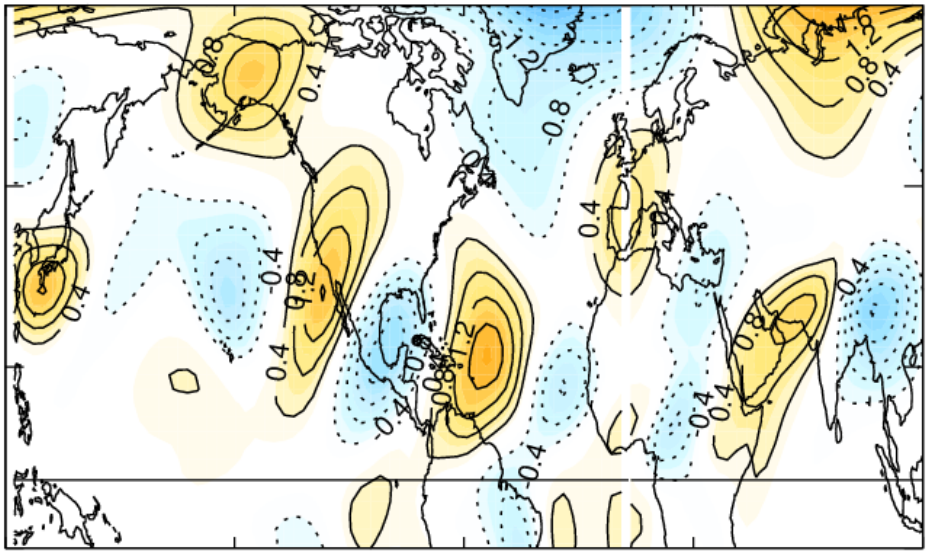


Putting only k ge 4 forcings in k lt 4 BS

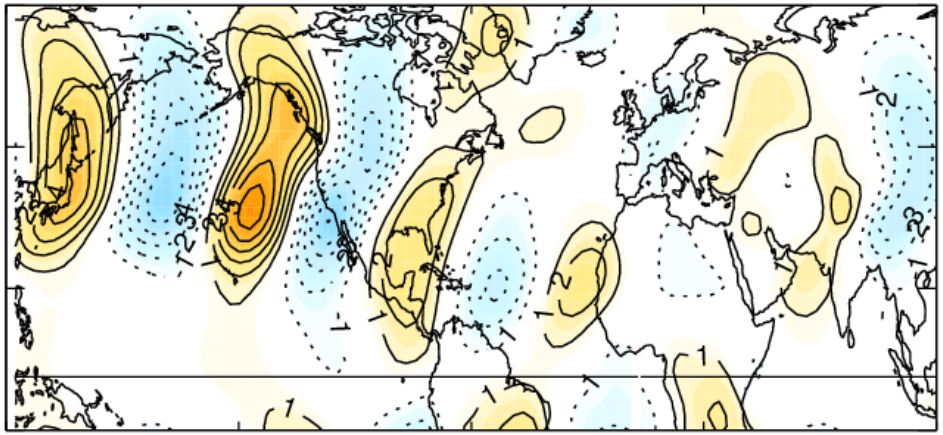
V, Past



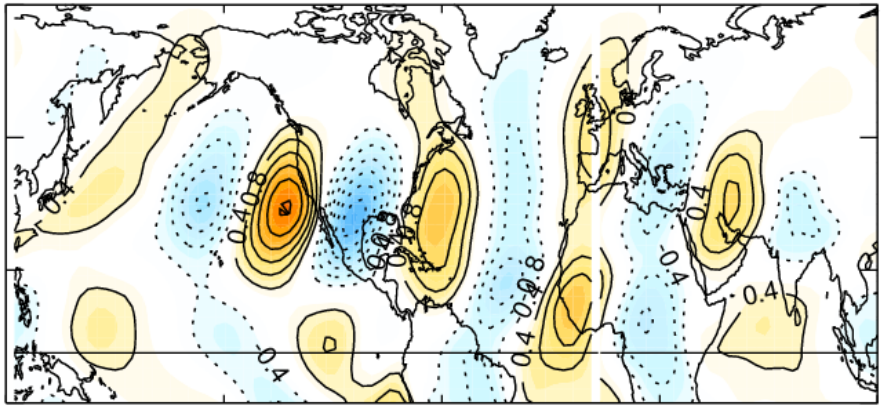
V, Future-Past



Past, ks=4-29



Future-Past, ks=4-29

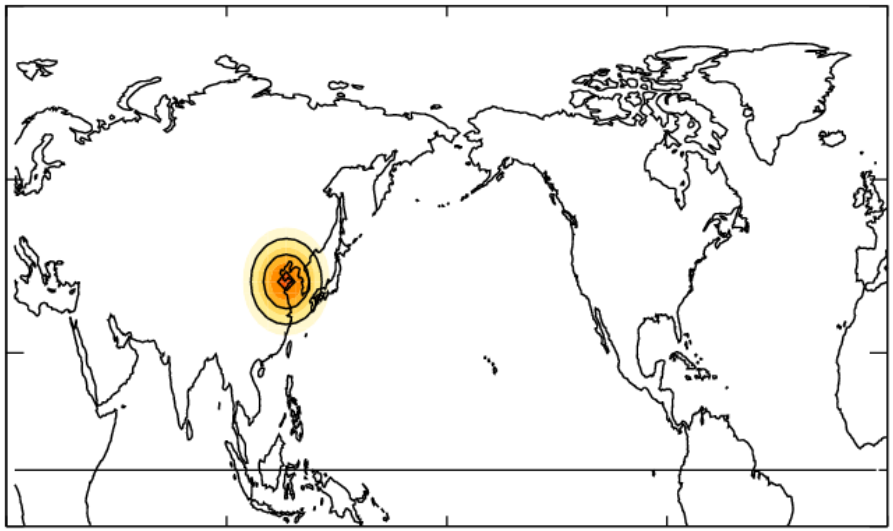


With non-linear forcings

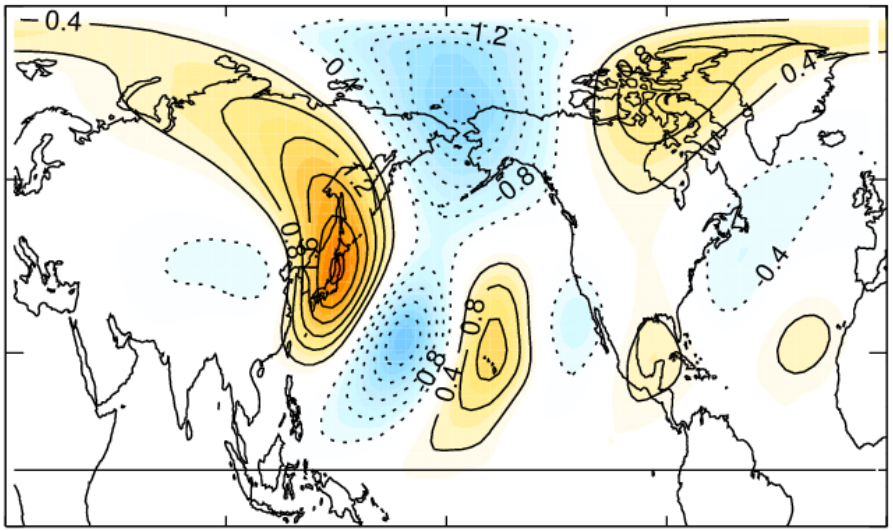
Idealized Vorticity Source

Idealized vorticity source.

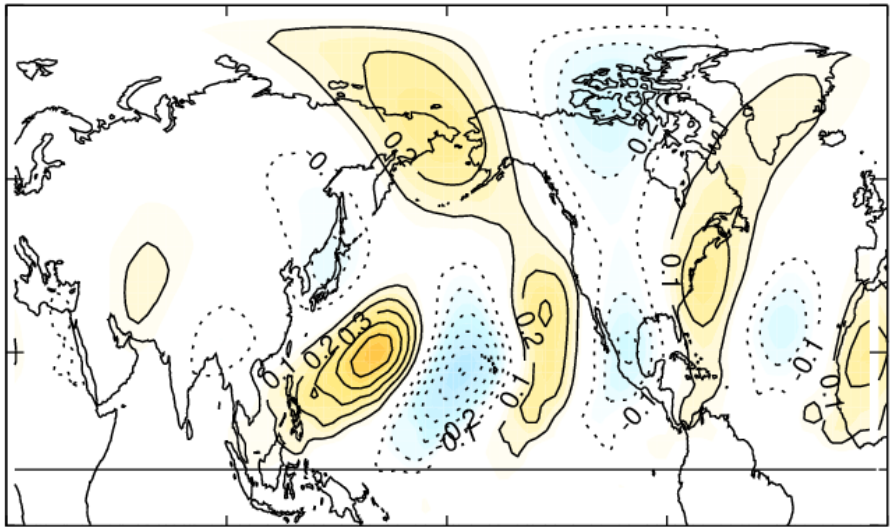
TRANV

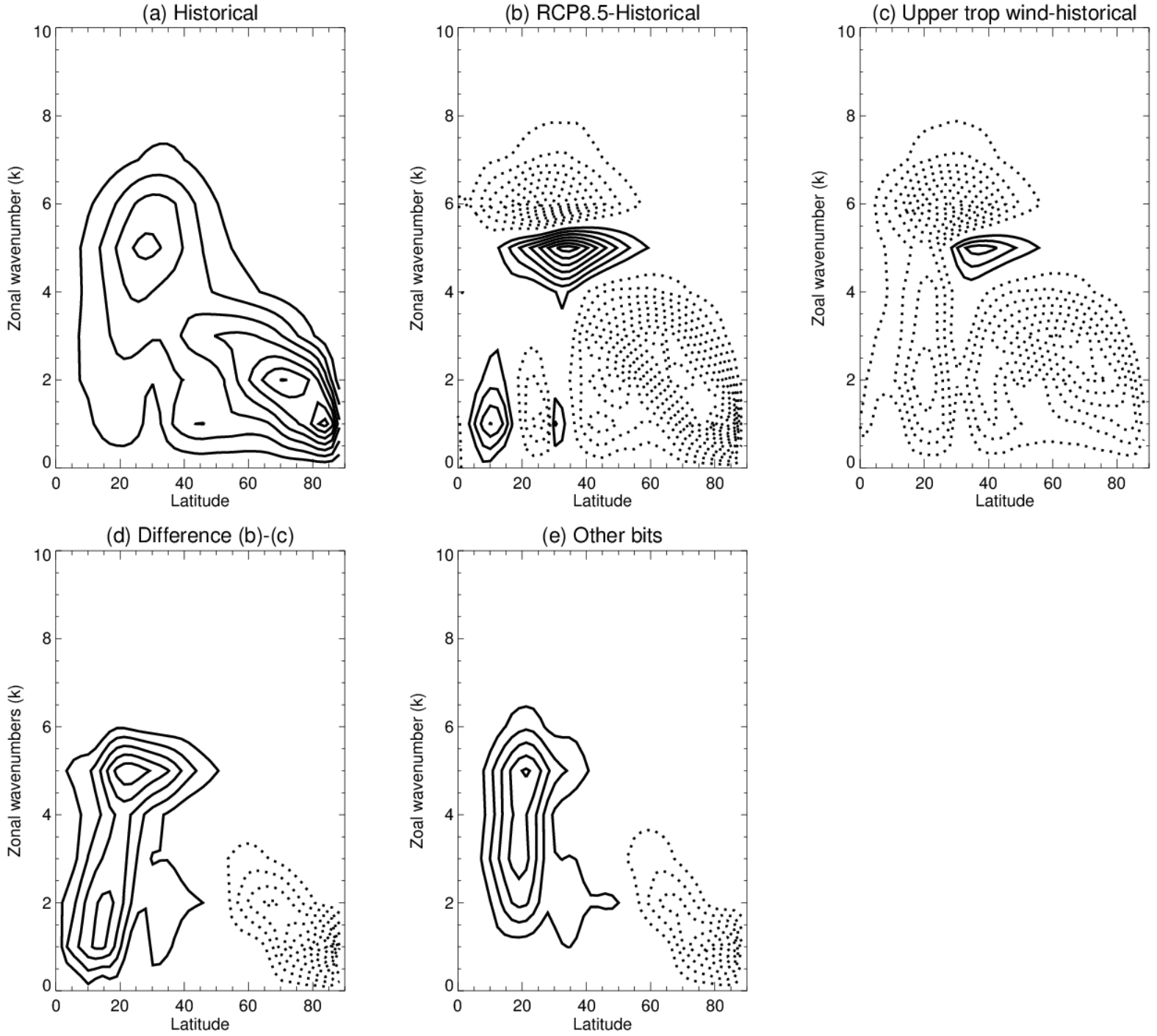


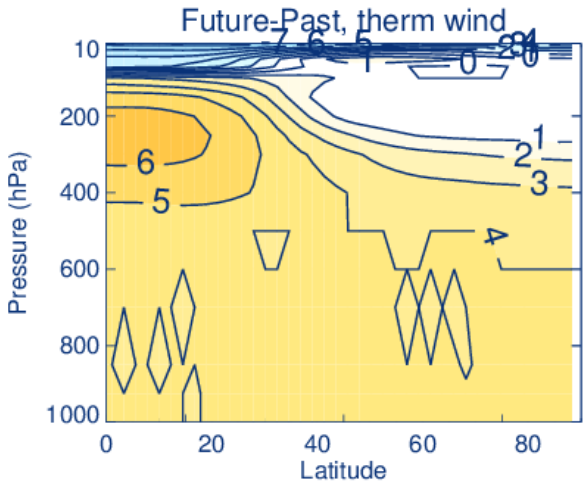
V, past

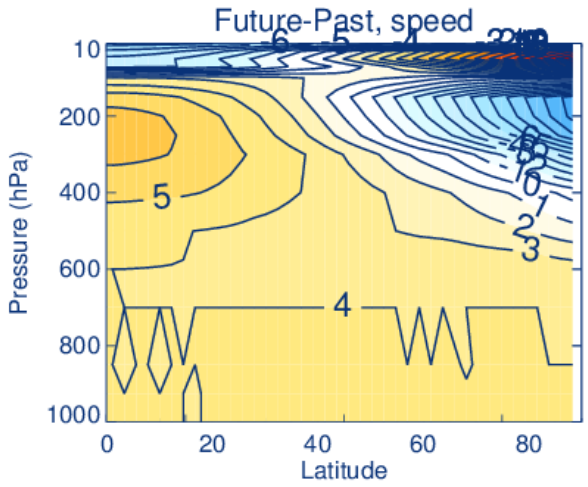


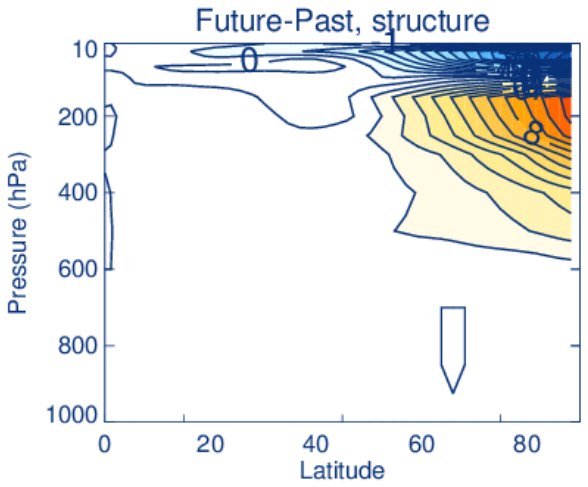
V, Future-Past, thermal wind

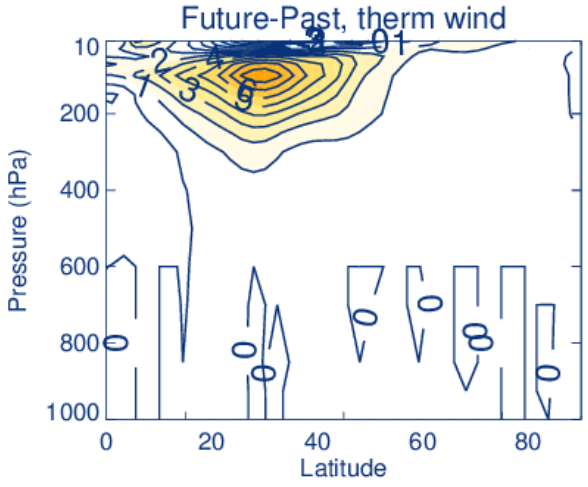


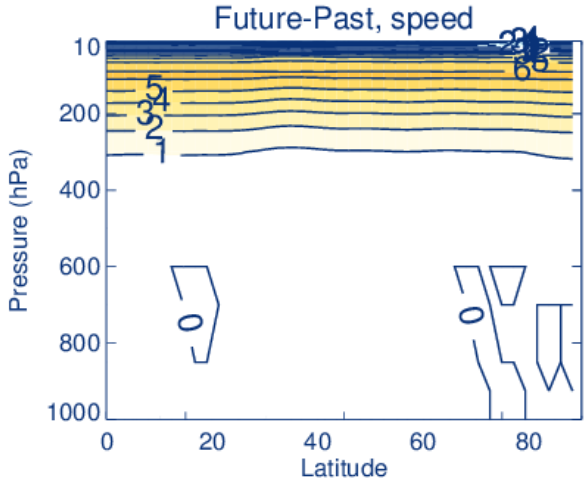

(a) Historical
(b) RCP8.5-Historical
(c) Upper trop wind-historical
(d) Difference (b)-(c)
(e) Other bits
Zonal wavenumber (k)
Zonal wavenumbers (k)
Zoal wavenumber (k)
Latitude
0
2
4
6
8
10
0
20
40
60
80

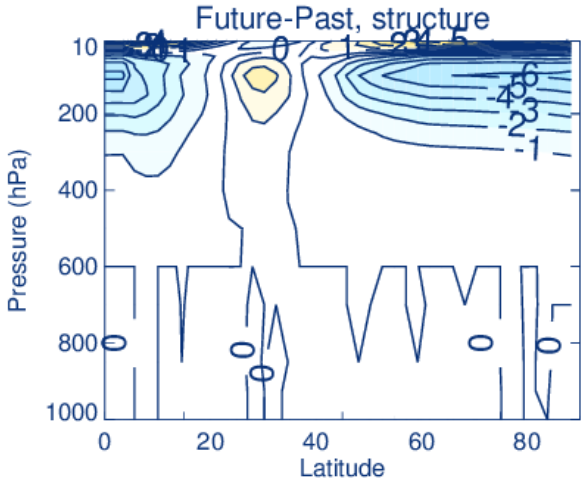

Future-Past, therm wind
Pressure (hPa)
Latitude
10
200
400
600
800
1000
0
20
40
60
80

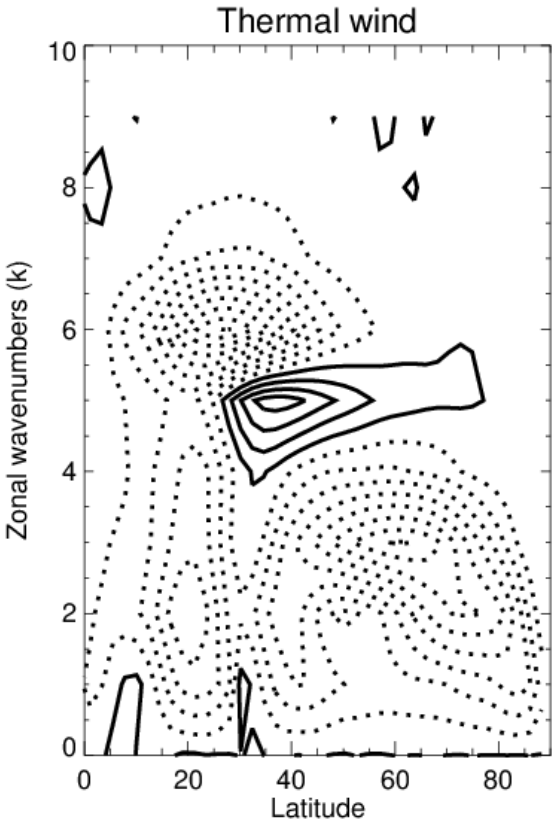

Future-Past, speed
Pressure (hPa)
Latitude
10
200
400
600
800
1000
0
20
40
60
80

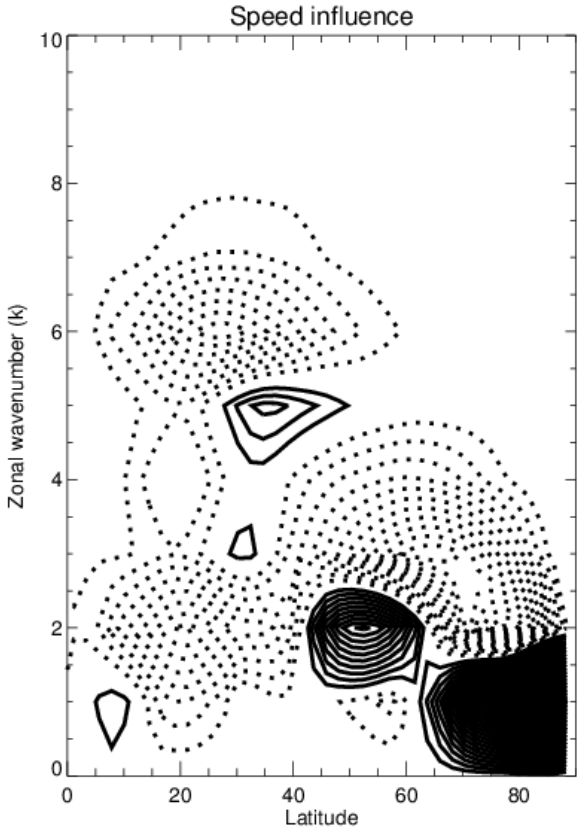

Future-Past, structure
Pressure (hPa)
Latitude
10
200
400
600
800
1000
0
20
40
60
80

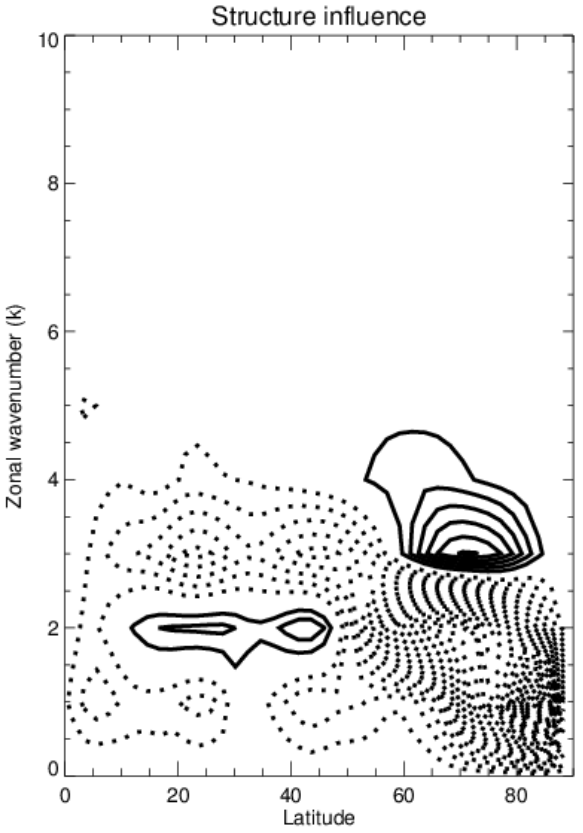

Future-Past, therm wind
Pressure (hPa)
Latitude
10
200
400
600
800
1000
0
20
40
60
80


Future-Past, speed
Pressure (hPa)
Latitude
10
200
400
600
800
1000
0
20
40
60
80


Future-Past, structure
Pressure (hPa)
Latitude
10
200
400
600
800
1000
0
20
40
60
80







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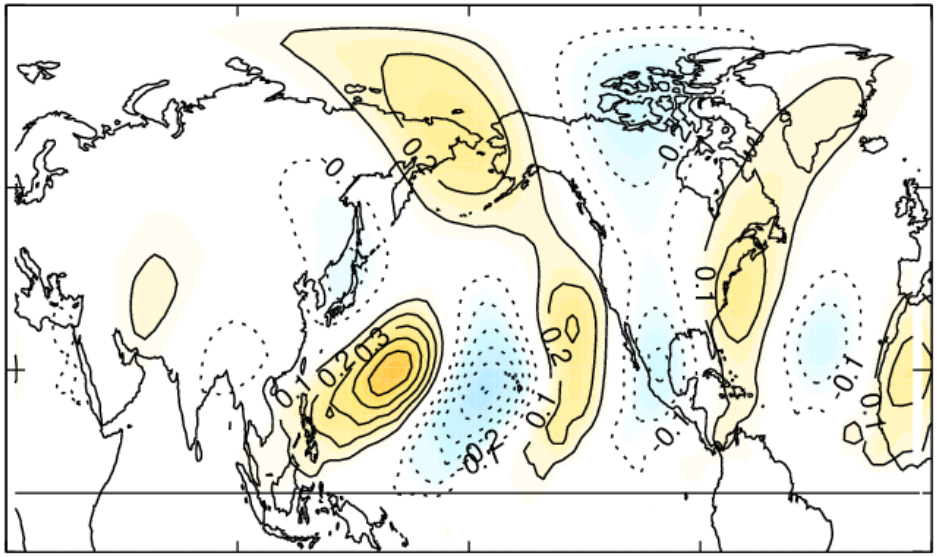
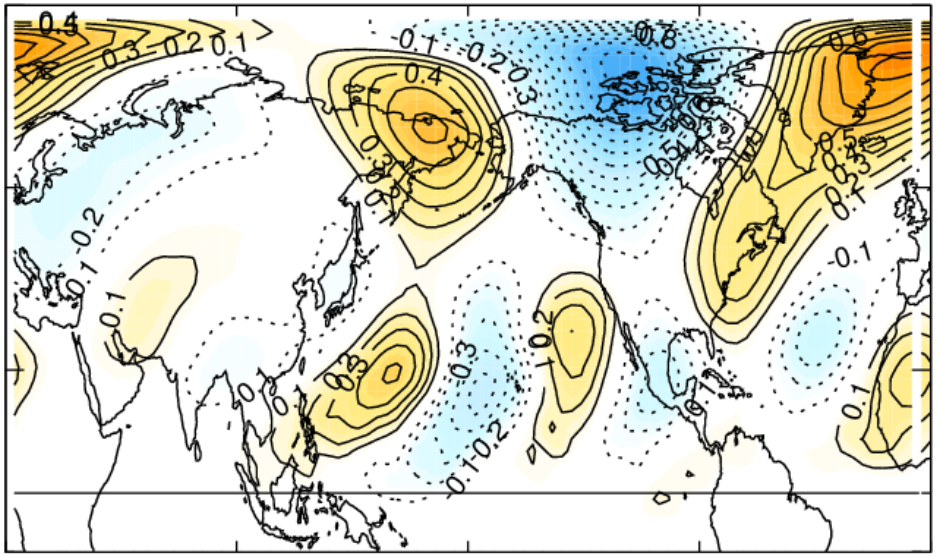
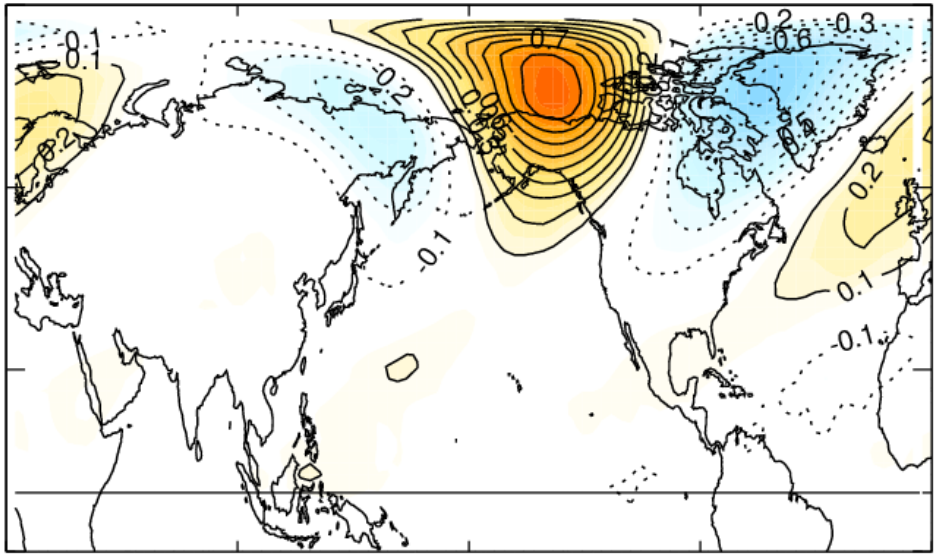
V, Future-Past, thermal wind

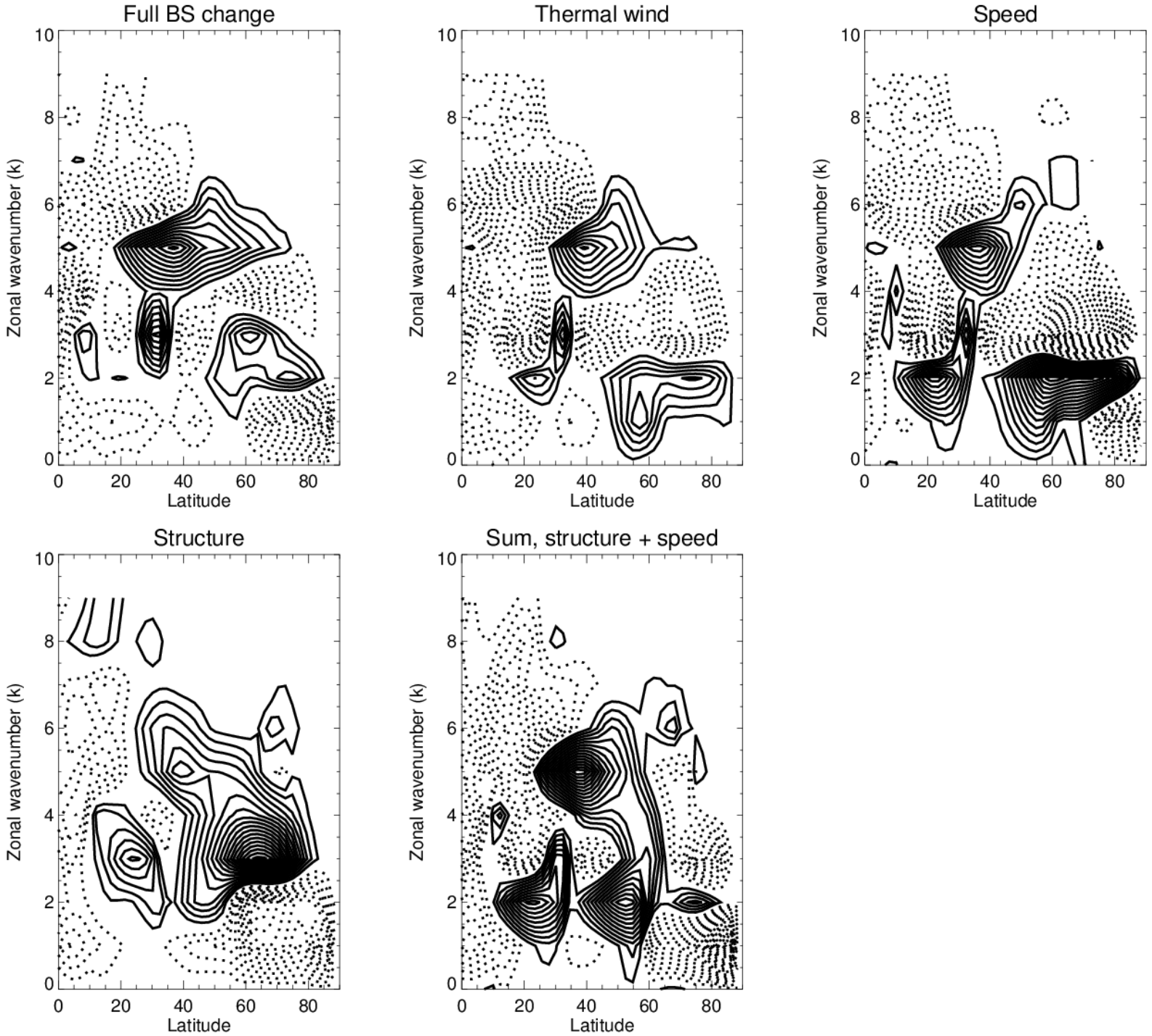


V, Future-Past, Speed

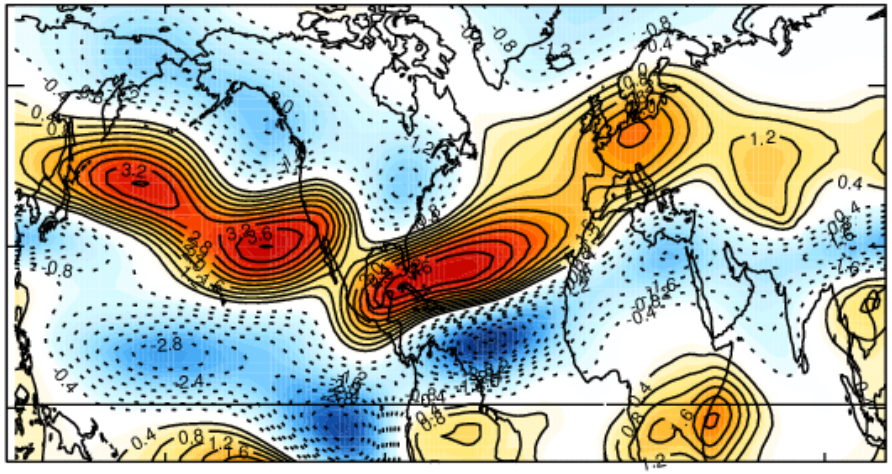


V, Future-Past, structure

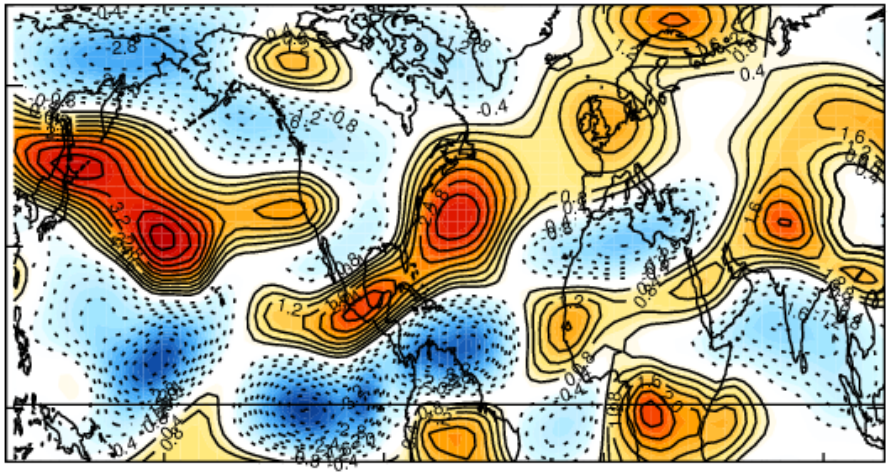



Full BS change
Thermal wind
Speed
Structure
Sum, structure + speed
Zonal wavenumber (k)
Latitude
0
2
4
6
8
10
0
20
40
60
80

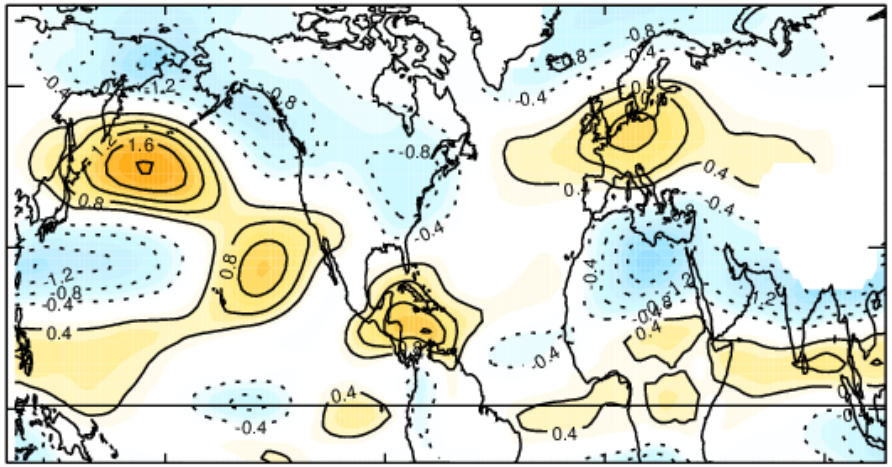
CMIP5, 300hPa U, Future-Past



SW model, 300hPa U, Future-Past



CMIP5, 700hPa U, Future-Past



SW model, 700hPa U, Future-Past