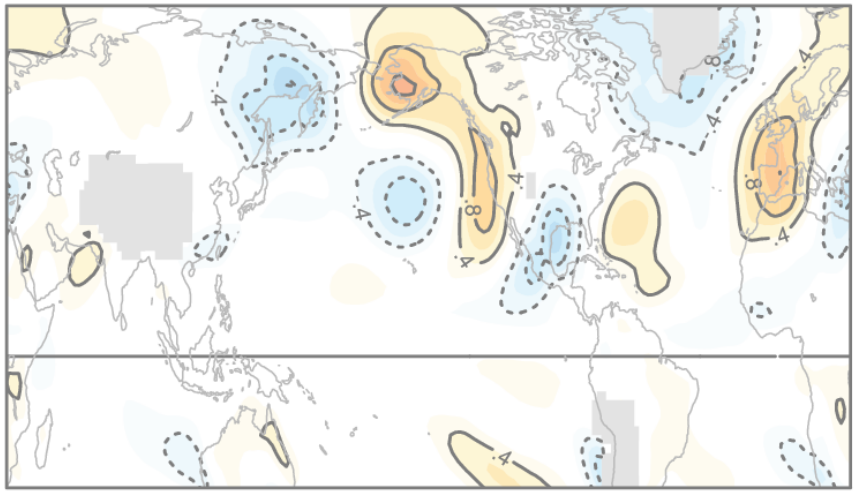
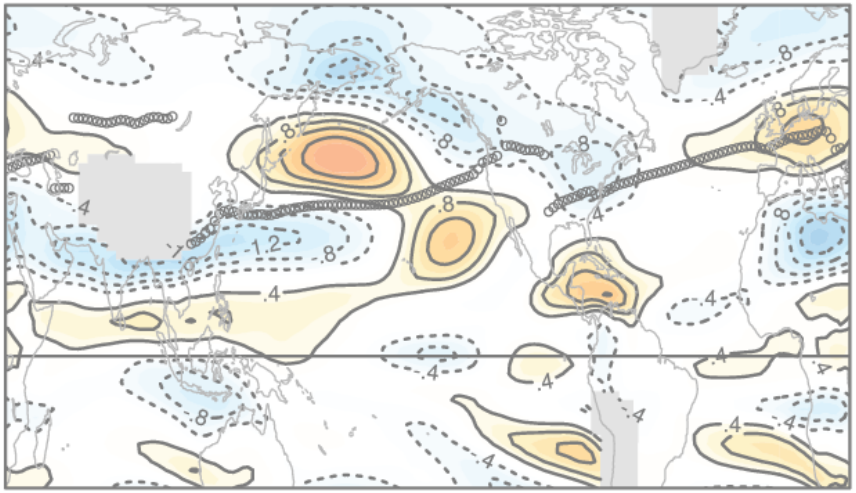
Tropospheric circulation change in the CMIPs





Isla Simpson
Climate and Global Dynamics Laboratory, NCAR

Outline

Part 1: Methods for analyzing circulation change in the CMIPs

Part 2: An example – the meridional wind response to climate change and impacts on North American hydroclimate.

Outline

Part 1: Methods for analyzing circulation change in the CMIPs

Part 2: An example – the meridional wind response to climate change and impacts on North American hydroclimate.

Methods

- Dealing with calendars
- Assessing significance of differences
- Exploiting model spread
- Making use of available scenarios

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- Assessing significance of differences
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Dealing with Calendars

```
        double time(time) ;
                time:bounds = "time_bnds" ;
                time:units = "days since 1850-1-1 00:00:00" ;
                time:calendar = "proleptic_gregorian" ;
                time:axis = "T" ;
                time:long_name = "time" ;
                time:standard_name = "time" ;
```

Example netcdf meta-data

MPI-ESM-LR

Dealing with Calendars

```
double time(time) ;
        time:bounds = "time_bnds" ;
        time:units = "days since 1850-1-1 00:00:00" ;
        time:calendar = "proleptic_gregorian" ;
        time:axis = "T" ;
        time:long_name = "time" ;
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```

Example netcdf meta-data

MPI-ESM-LR

```
double time(time) ;
        time:bounds = "time_bnds" ;
        time:units = "days since 1850-1-1" ;
        time:calendar = "365_day" ;
        time:axis = "T" ;
        time:long_name = "time" ;
        time:standard_name = "time" ;
```

CanESM2

Dealing with Calendars

```
double time(time) ;
        time:bounds = "time_bnds" ;
        time:units = "days since 1850-1-1 00:00:00" ;
        time:calendar = "proleptic_gregorian" ;
        time:axis = "T" ;
        time:long_name = "time" ;
        time:standard_name = "time" ;
```

Example netcdf meta-data

MPI-ESM-LR

```
double time(time) ;
        time:bounds = "time_bnds" ;
        time:units = "days since 1850-1-1" ;
        time:calendar = "365_day" ;
        time:axis = "T" ;
        time:long_name = "time" ;
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```

CanESM2

HadGEM2-ES

```
double time(time) ;
        time:bounds = "time_bnds" ;
        time:units = "days since 1859-12-01" ;
        time:calendar = "360_day" ;
        time:axis = "T" ;
        time:long_name = "time" ;
        time:standard_name = "time" ;
```

Dealing with Calendars

```
        double time(time) ;
                time:bounds = "time_bnds" ;
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                time:calendar = "360_day" ;
                time:axis = "T" ;
                time:long_name = "time" ;
                time:standard_name = "time" ;
```

HadGEM2-ES

```
time = 15, 45, 75, 105, 135, 165, 195, 225, 255, 285, 315, 345, 375, 405,
   435, 465, 495, 525, 555, 585, 615, 645, 675, 705, 735, 765, 795, 825,
   855, 885, 915, 945, 975, 1005, 1035, 1065, 1095, 1125, 1155, 1185, 1215,
   1245, 1275, 1305, 1335, 1365, 1395, 1425, 1455, 1485, 1515, 1545, 1575,
   1605, 1635, 1665, 1695, 1725, 1755, 1785, 1815, 1845, 1875, 1905, 1935,
   1965, 1995, 2025, 2055, 2085, 2115, 2145, 2175, 2205, 2235, 2265, 2295,
   2325, 2355, 2385, 2415, 2445, 2475, 2505, 2535, 2565, 2595, 2625, 2655,
   2685, 2715, 2745, 2775, 2805, 2835, 2865, 2895, 2925, 2955, 2985, 3015,
   3045, 3075, 3105, 3135, 3165, 3195, 3225, 3255, 3285, 3315, 3345, 3375,
   3405, 3435, 3465, 3495, 3525, 3555, 3585, 3615, 3645, 3675, 3705, 3735,
```

Dealing with Calendars

```
double time(time) ;
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```

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```
time = 15, 45, 75, 105, 135, 165, 195, 225, 255, 285, 315, 345, 375, 405,
   435, 465, 495, 525, 555, 585, 615, 645, 675, 705, 735, 765, 795, 825,
   855, 885, 915, 945, 975, 1005, 1035, 1065, 1095, 1125, 1155, 1185, 1215,
   1245, 1275, 1305, 1335, 1365, 1395, 1425, 1455, 1485, 1515, 1545, 1575,
   1605, 1635, 1665, 1695, 1725, 1755, 1785, 1815, 1845, 1875, 1905, 1935,
   1965, 1995, 2025, 2055, 2085, 2115, 2145, 2175, 2205, 2235, 2265, 2295,
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   3045, 3075, 3105, 3135, 3165, 3195, 3225, 3255, 3285, 3315, 3345, 3375,
   3405, 3435, 3465, 3495, 3525, 3555, 3585, 3615, 3645, 3675, 3705, 3735,
```

How to grab out the time period you want e.g., 1979 – 2005?

In an automated way that works for all models with different calendars, simulations with different start dates etc?

Solution: ncl and cd_calendar

```
begin
  ystart = 1979
  mstart = 1
  yend = 2005
  mend = 12
```

Solution: ncl and cd_calendar

e.g., var is an array of size (nlon,nlat,ntime)

```
begin
  ystart = 1979
  mstart = 1
  yend = 2005
  mend = 12

  in=addfile("fname","r")
  time=in->time
  var=in->var
```

Solution: ncl and cd_calendar

```
begin
  ystart = 1979
  mstart = 1
  yend = 2005
  mend = 12

  in=addfile("fname","r")
  time=in->time
  var=in->var

  date=cd_calendar(time,1)
```

e.g., var is an array of size (nlon,nlat,ntime)

e.g., with
time:units = "days since 1859-12-01"
time:calendar = "360_day"

time= 15, 45, 75,…

date = 185912, 186001, 186002

Solution: ncl and cd_calendar

```
begin
  ystart = 1979
  mstart = 1
  yend = 2005
  mend = 12

  in=addfile("fname","r")
  time=in->time
  var=in->var

  date=cd_calendar(time,1)

  ystartv = ystart*100 + mstart
  yendv = yend*100 + mend
```

e.g., var is an array of size (nlon,nlat,ntime)

e.g., with
time:units = "days since 1859-12-01"
time:calendar = "360_day"

time= 15, 45, 75,…

date = 185912, 186001, 186002

→ ystartv=197901

Solution: ncl and cd_calendar

```
begin
  ystart = 1979
  mstart = 1
  yend = 2005
  mend = 12

  in=addfile("fname","r")
  time=in->time
  var=in->var

  date=cd_calendar(time,1)

  ystartv = ystart*100 + mstart
  yendv = yend*100 + mend

  ibeg = ind(date.eq.ystartv)
  iend = ind(date.eq.yendv)
```

e.g., var is an array of size (nlon,nlat,ntime)

e.g., with
time:units = "days since 1859-12-01"
time:calendar = "360_day"

time= 15, 45, 75,…

date = 185912, 186001, 186002

→ ystartv=197901

Find where date is equal to your start and end dates

Solution: ncl and cd_calendar

```
begin
  ystart = 1979
  mstart = 1
  yend = 2005
  mend = 12

  in=addfile("fname","r")
  time=in->time
  var=in->var

  date=cd_calendar(time,1)

  ystartv = ystart*100 + mstart
  yendv = yend*100 + mend

  ibeg = ind(date.eq.ystartv)
  iend = ind(date.eq.yendv)

  ntimeuse = iend-ibeg+1
  datuse = reshape(dat(ibeg:iend,:,:),(/ntimeuse,nlat,nlon/) )
```

e.g., var is an array of size (nlon,nlat,ntime)

e.g., with
time:units = "days since 1859-12-01"
time:calendar = "360_day"

time= 15, 45, 75,…

date = 185912, 186001, 186002

→ ystartv=197901

Find where date is equal to your start and end dates

grab out the part of the array that you want e.g. here, the data between Jan 1979 and Dec 2005

Solution: ncl and cd_calendar

```
begin
  ystart = 1979
  mstart = 1
  yend = 2005
  mend = 12

  in=addfile("fname","r")
  t
  v

  d

  y
  y

  i
  iend = ind(date.eq.yendv)

  ntimeuse = iend-ibeg+1
  datuse = reshape(dat(ibeg:iend,:,:),(/ntimeuse,nlat,nlon/) )
```

e.g., var is an array of size (nlon,nlat,ntime)

e.g., with
time:units = "days since 1859-12-01"
time:calendar = "360_day"

2

r start
and end dates

Check out:

www.ncl.ucar.edu/Document/Functions/Built-in/cd_calendar.shtml

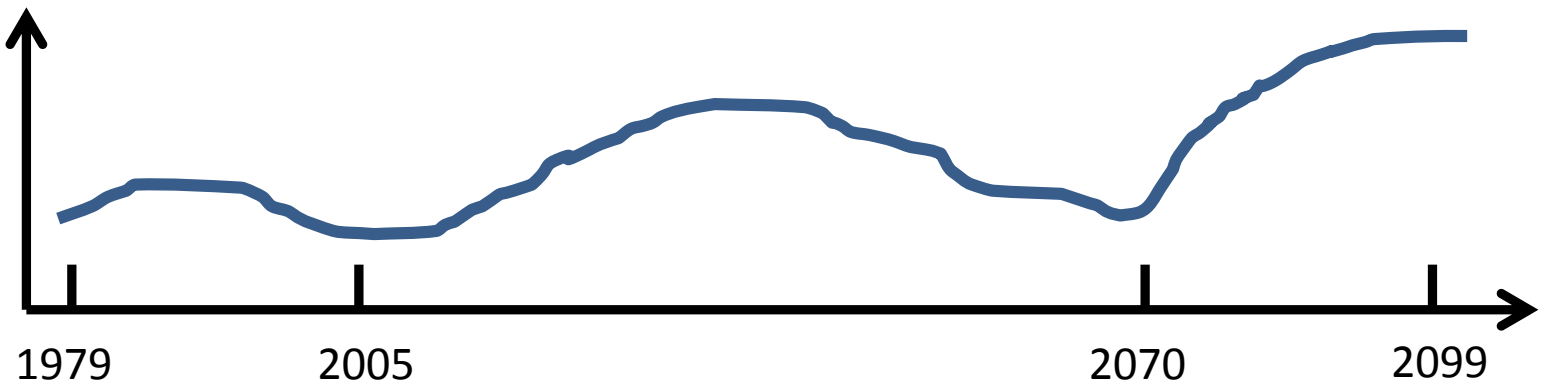
Example script on yellowstone:
/glade/u/home/islas/cmiptutorial/output_time_level_var.ncl

grab out the part of the array that you want e.g. here, the data between Jan 1979 and Dec 2005

Methods

- Dealing with calendars
- Assessing significance of differences
- Exploiting model spread
- Making use of available scenarios

Assessing significance of differences



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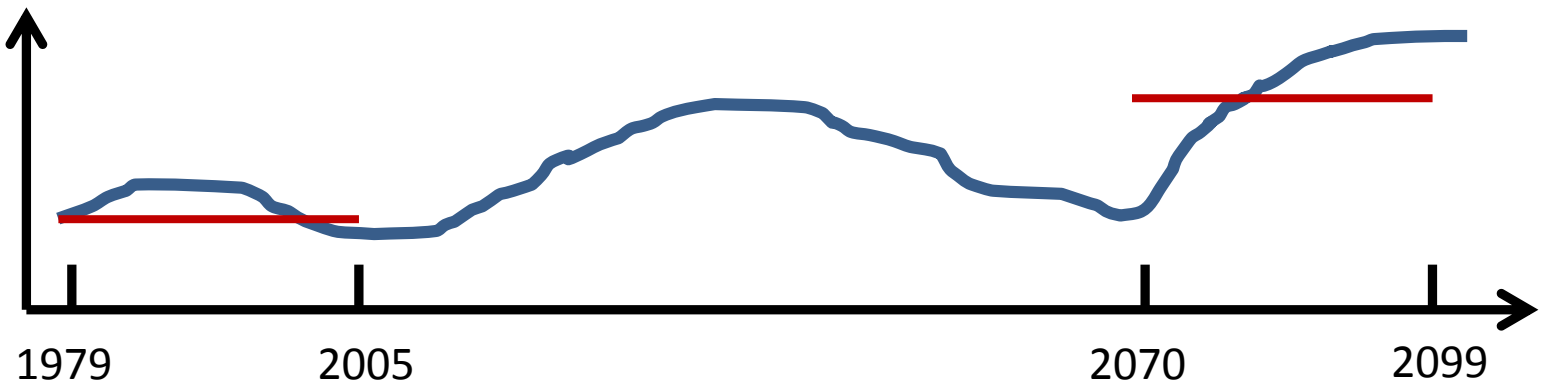

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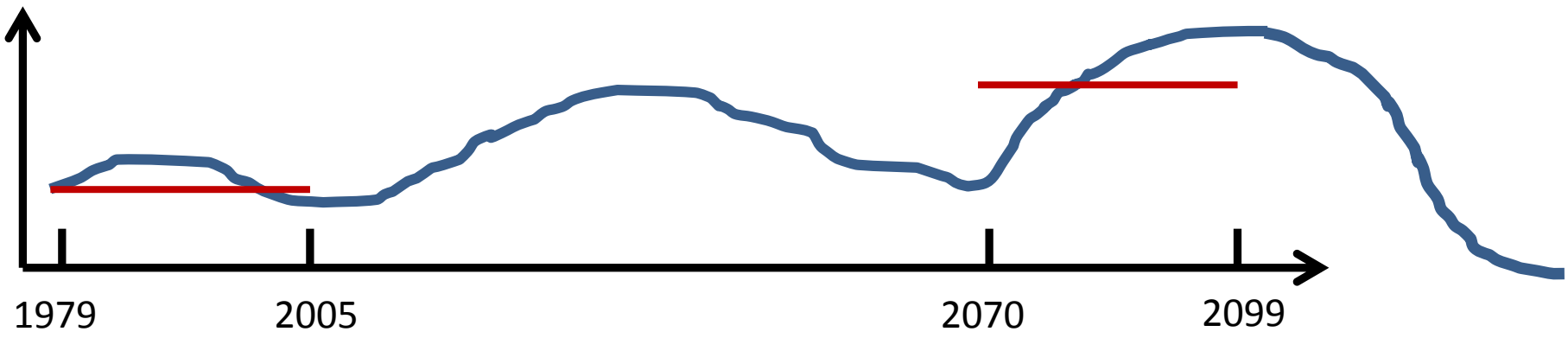

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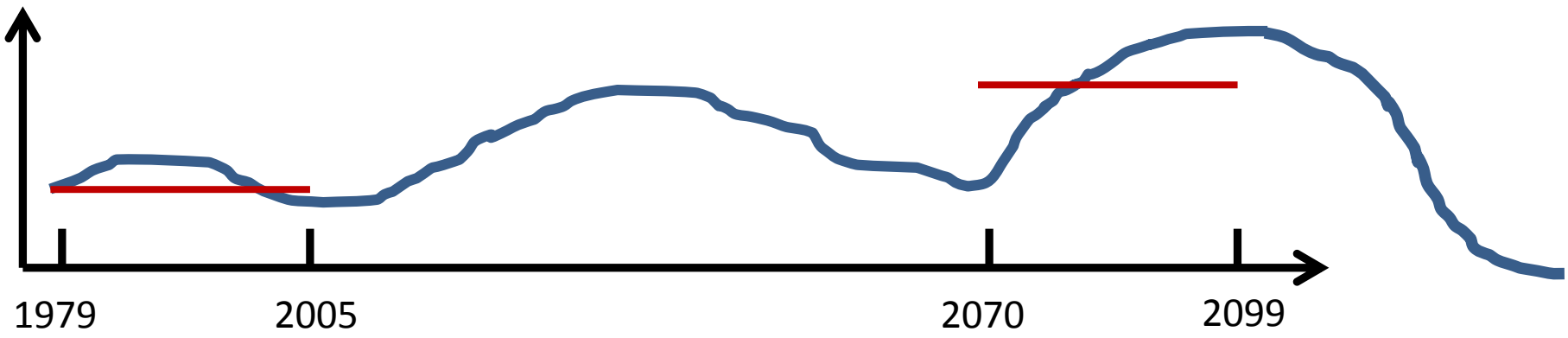
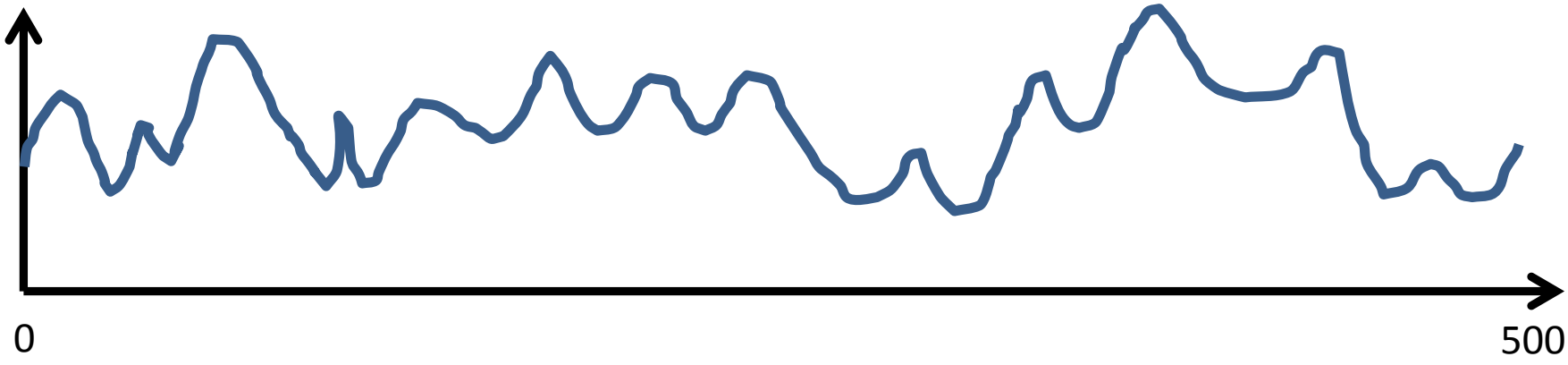


Make use of the long pre-industrial control simulations for each model to assess whether your signal is outside anything you might expect to arise from natural variability



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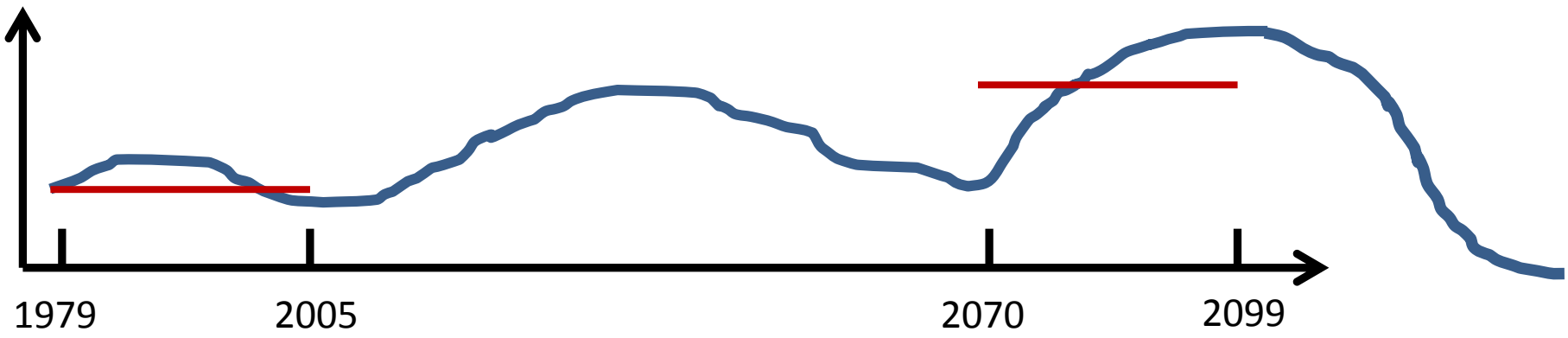

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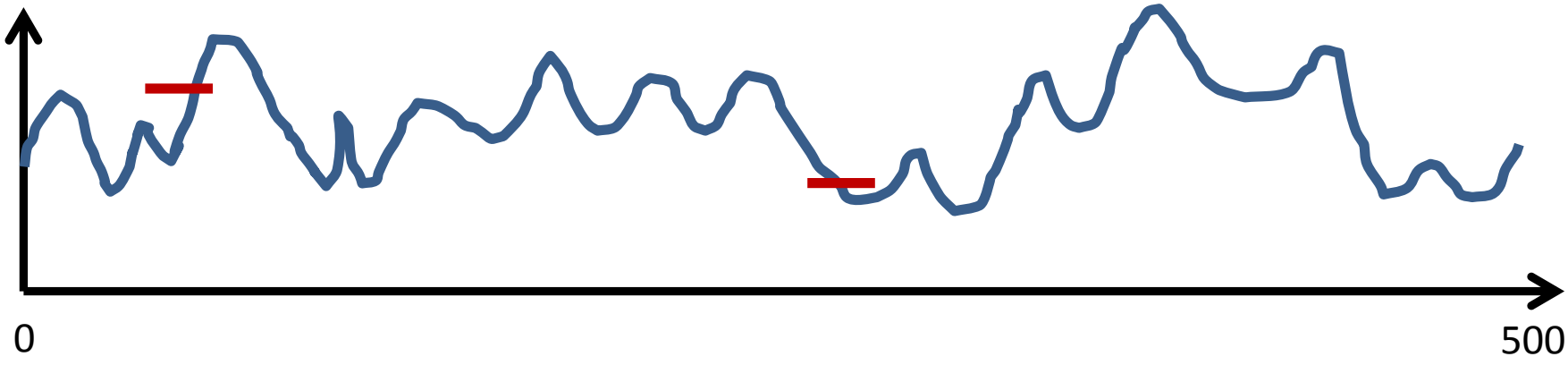

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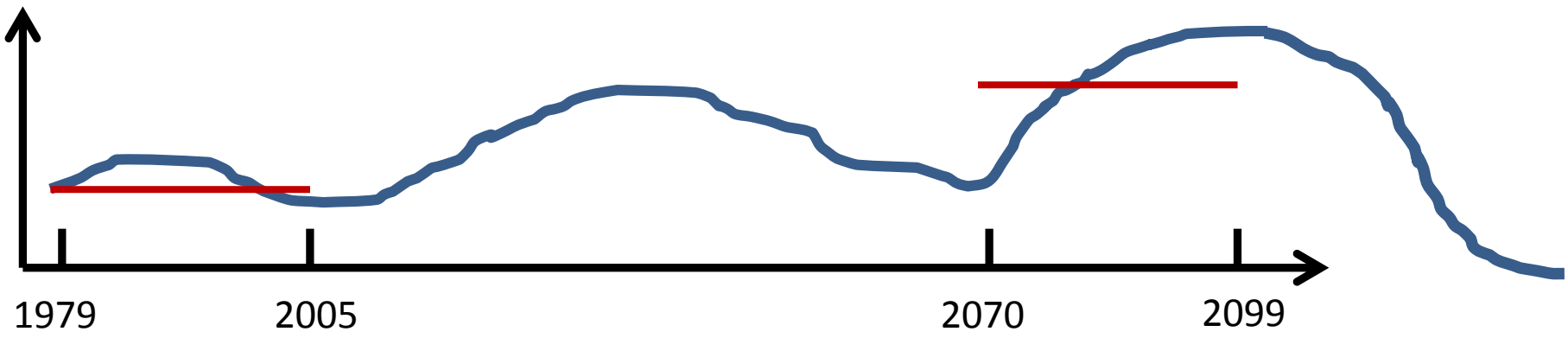

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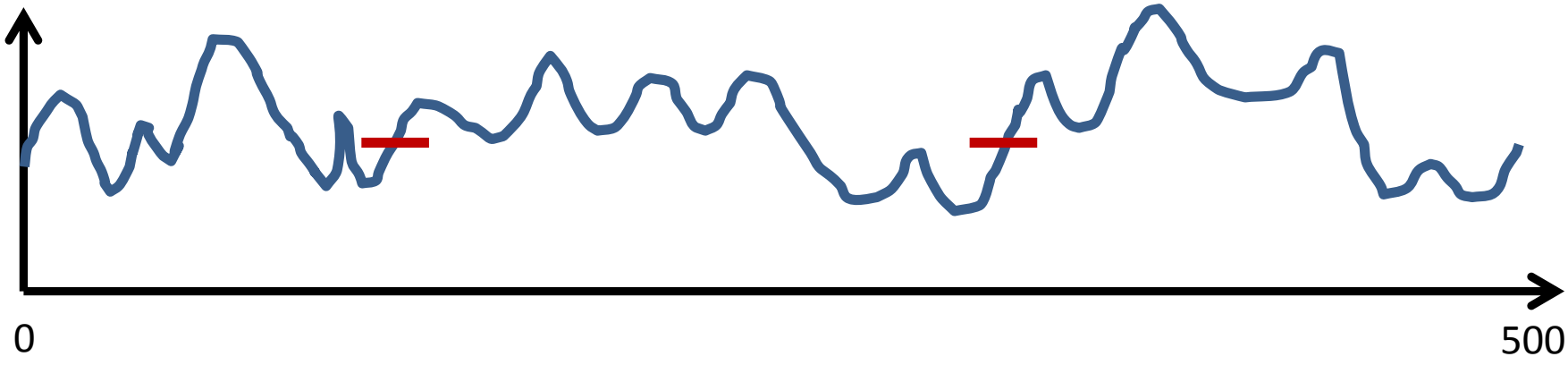

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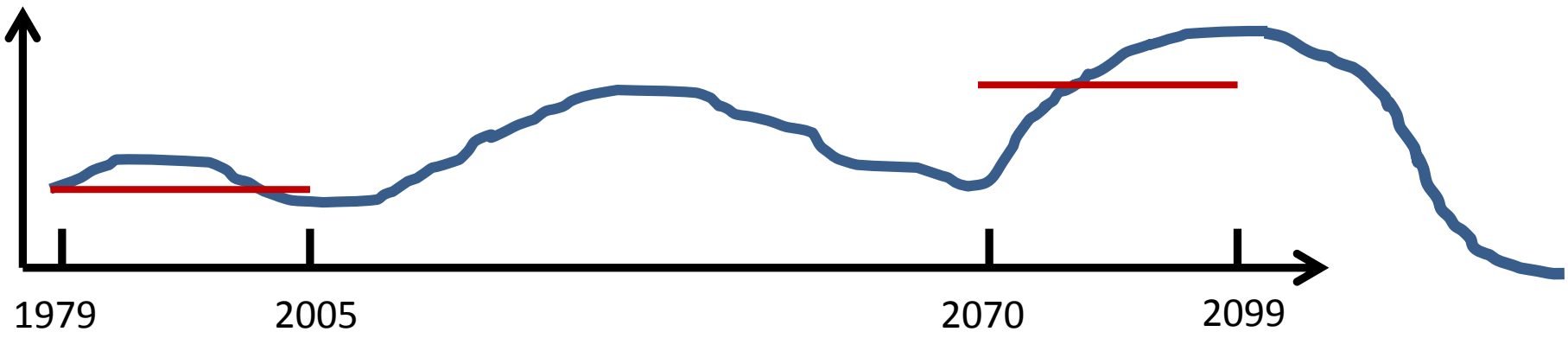

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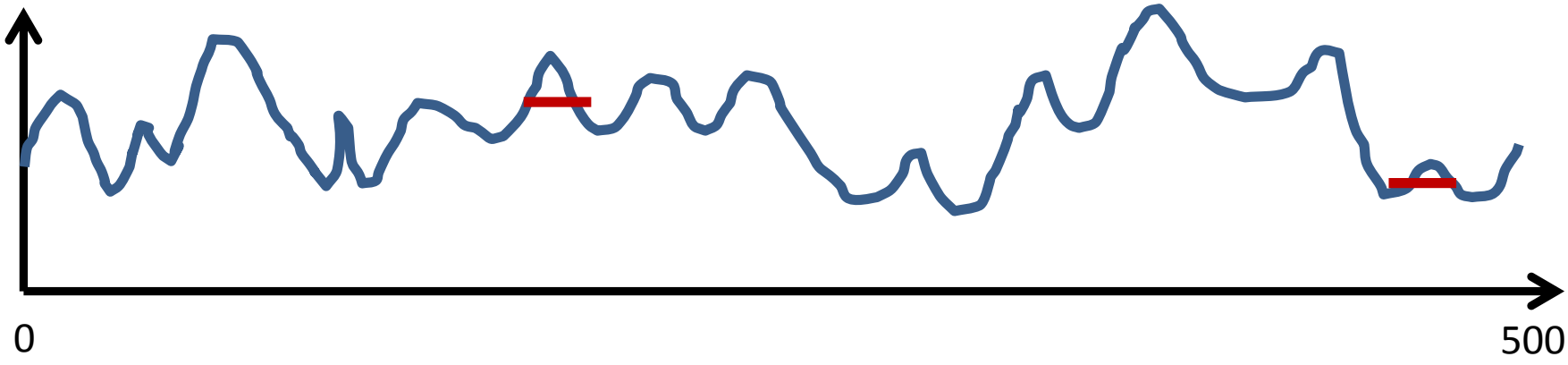

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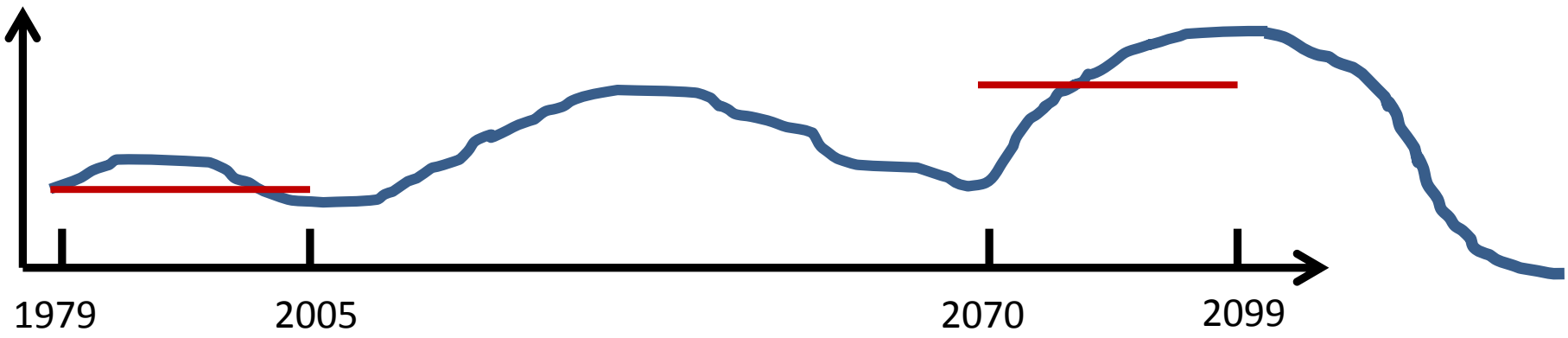

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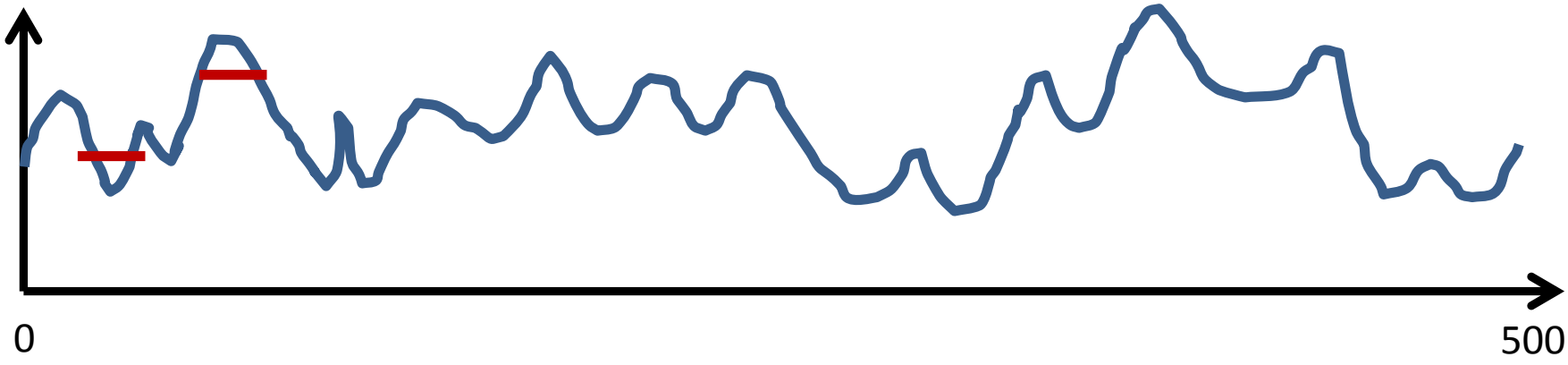
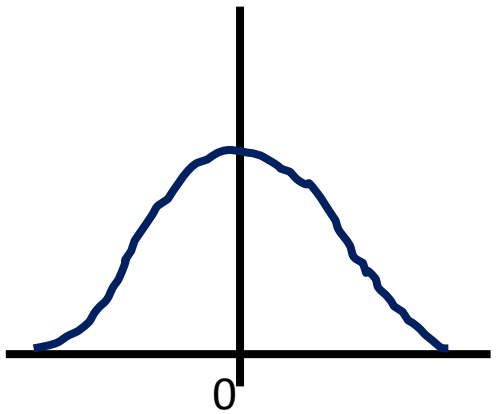
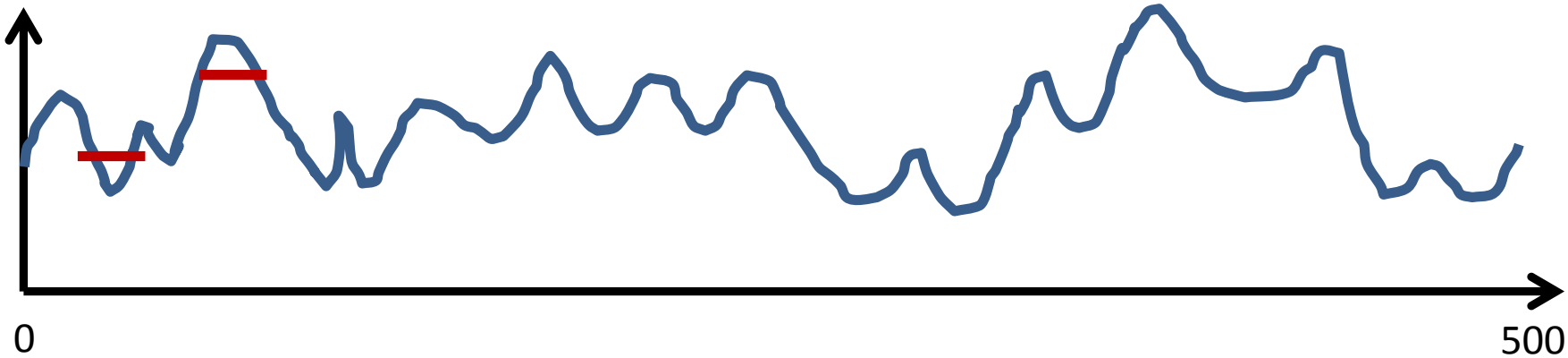


Assessing significance of differences

Build up the distribution of possible differences you could expect just from natural variability by randomly sampling a 27 year chunk and a 30 year chunk



Make use of th
each model to
you might expe
g



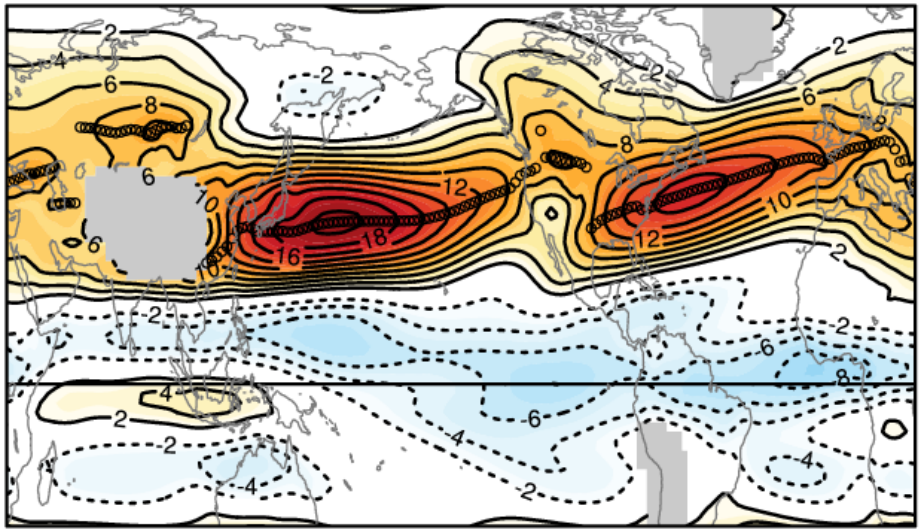
An example: the poleward shift of the westerlies in the extra-tropical pacific during DJF

Past Climatology

(1979-2005) hist

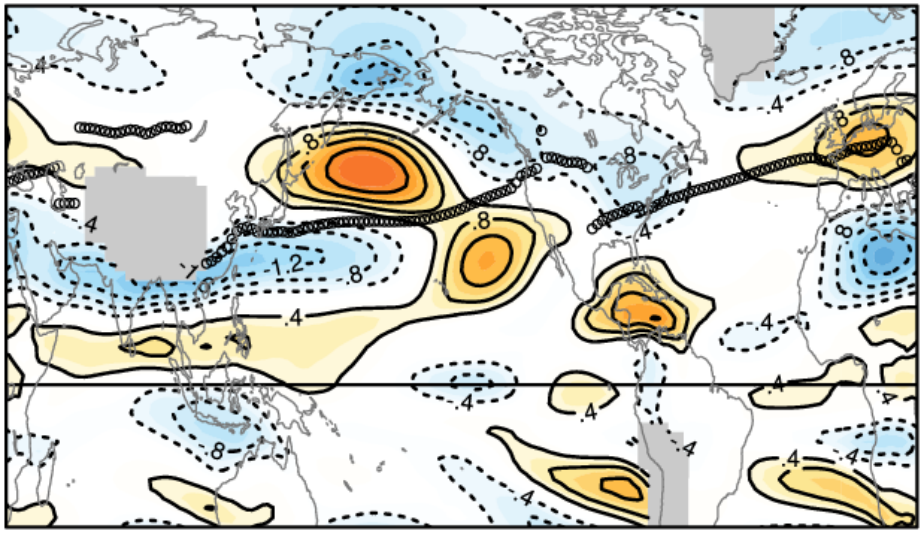
700hPa zonal wind
35 model mean

- Local Jet Maximum



Future-Past difference

(2070-2099) RCP8.5 – (1979-2005) hist



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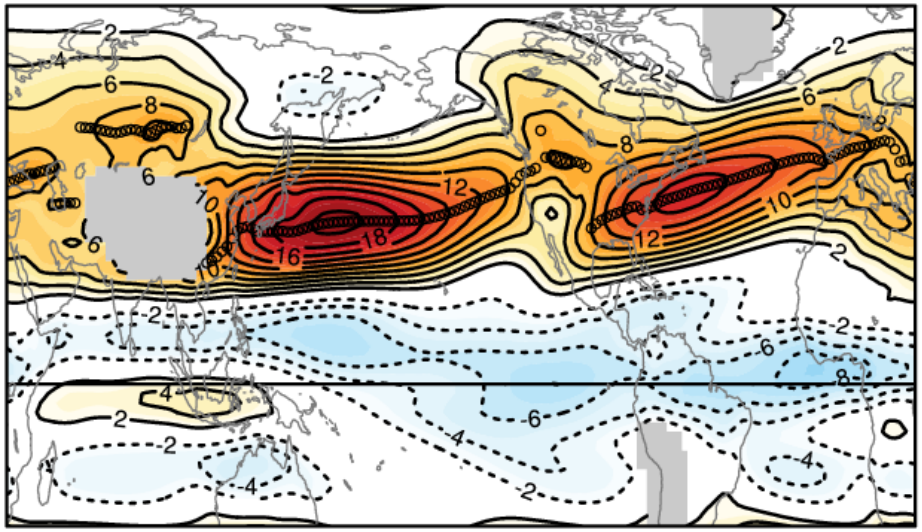

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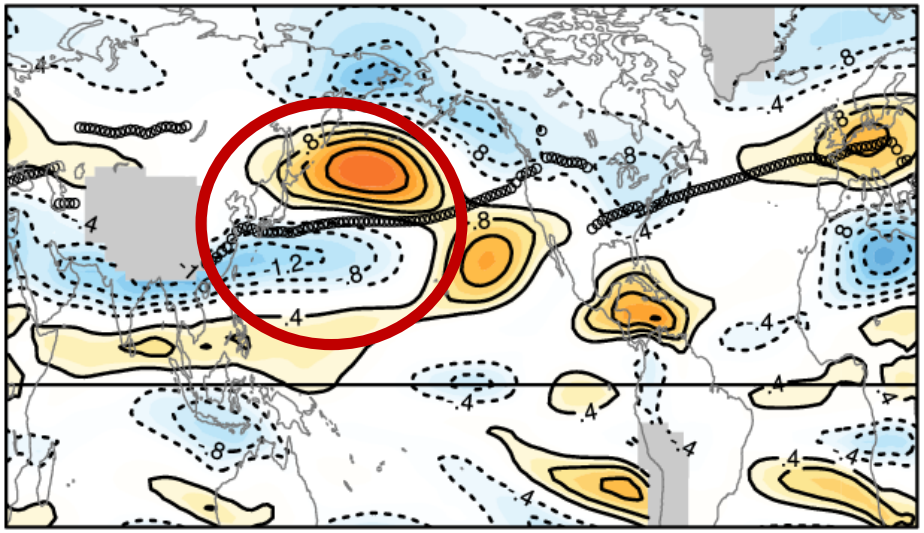
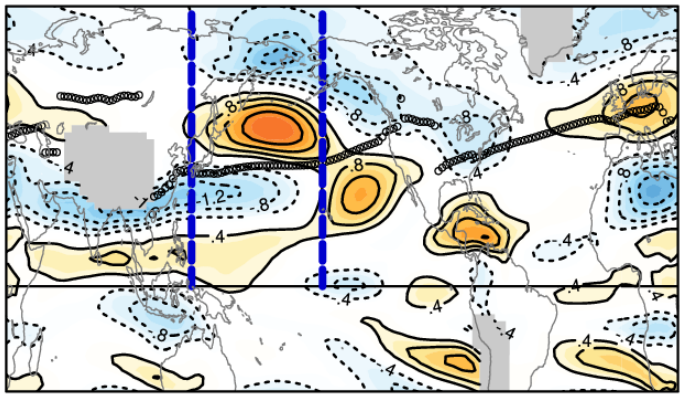
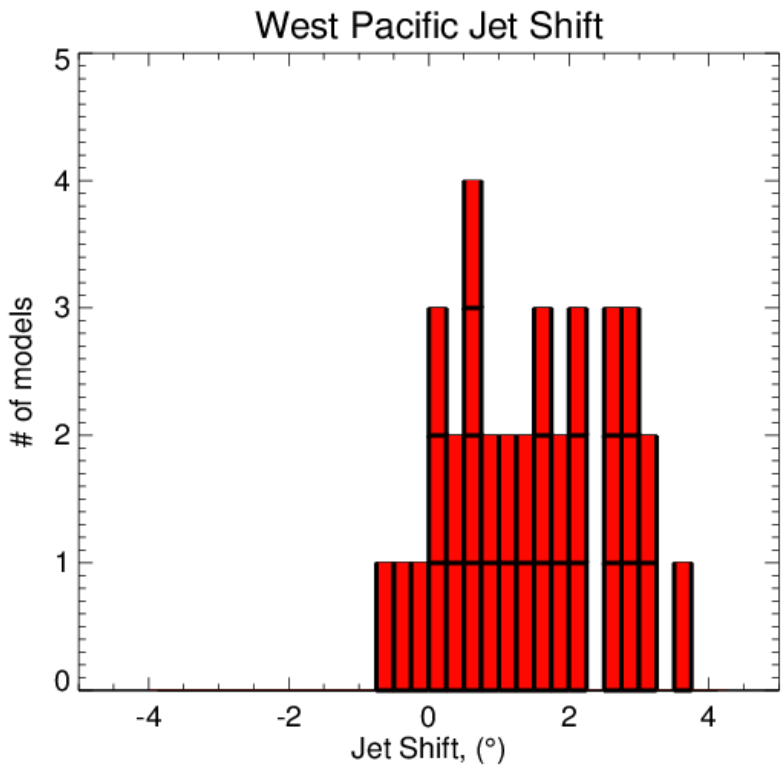
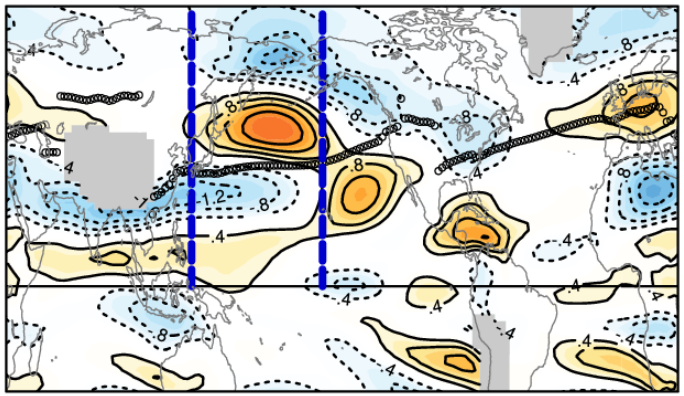
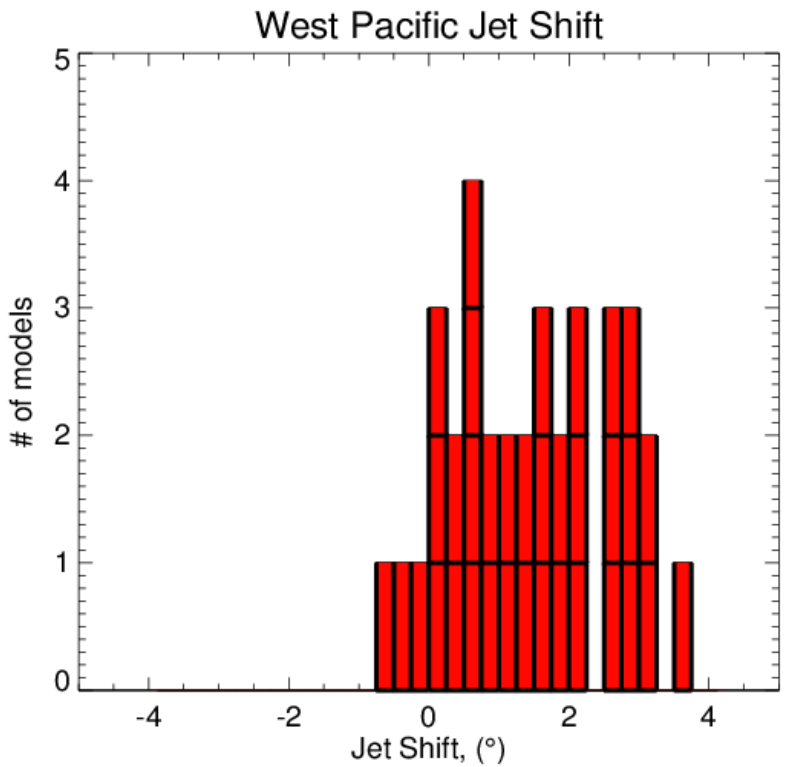




West Pacific Jet Shifts

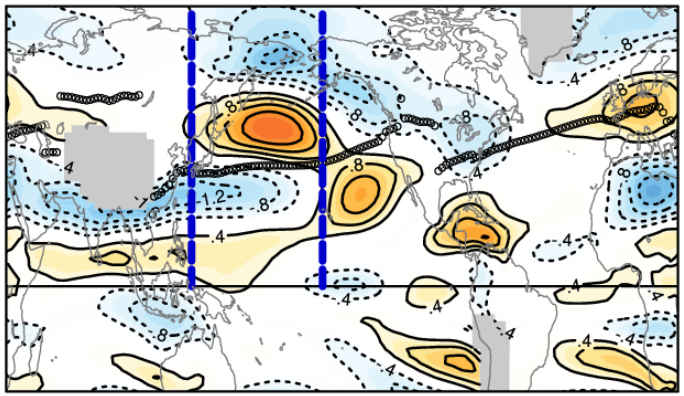


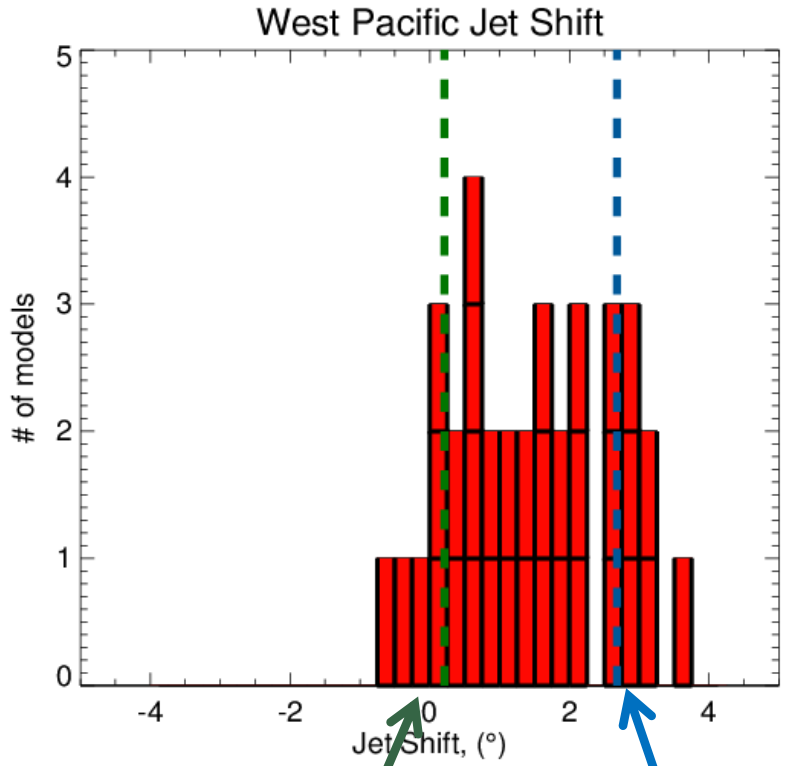




West Pacific Jet Shifts

Are any of these jet shifts significant? Are they a forced response or an artefact of the limited sampling of the natural variability?





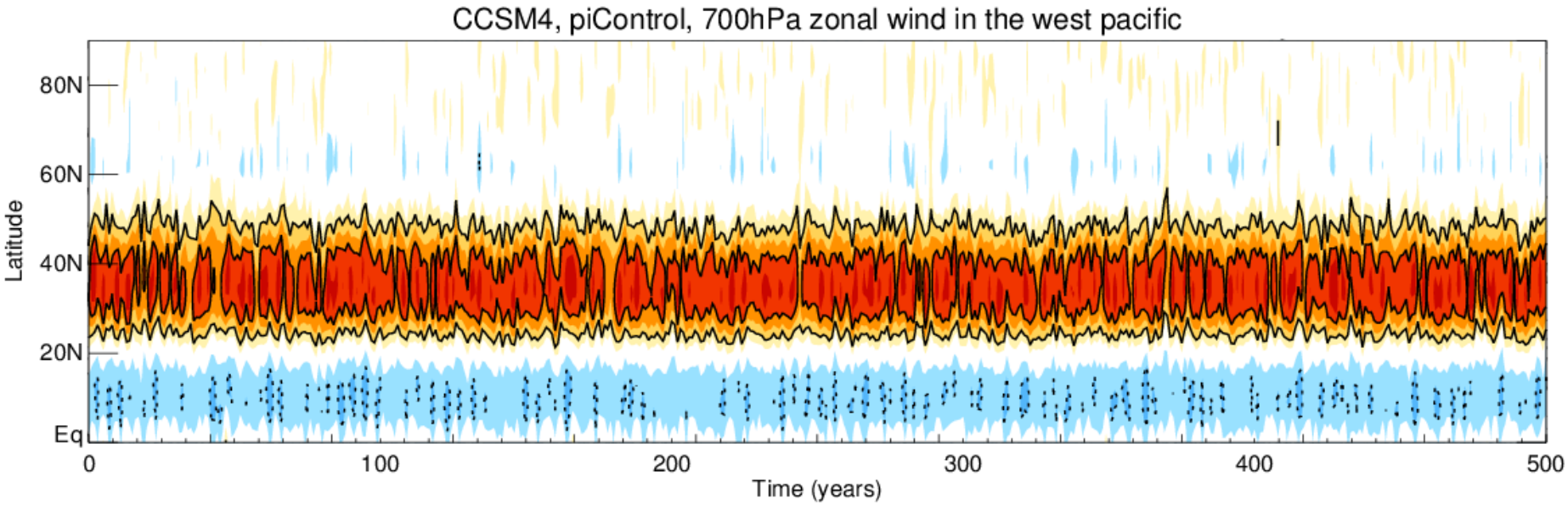
West Pacific Jet Shifts

CCSM4

MPI-ESM-LR

Are any of these jet shifts significant? Are they a forced response or an artefact of the limited sampling of the natural variability?

Zonal wind time series in the west Pacific for the CCSM4 piControl simulation



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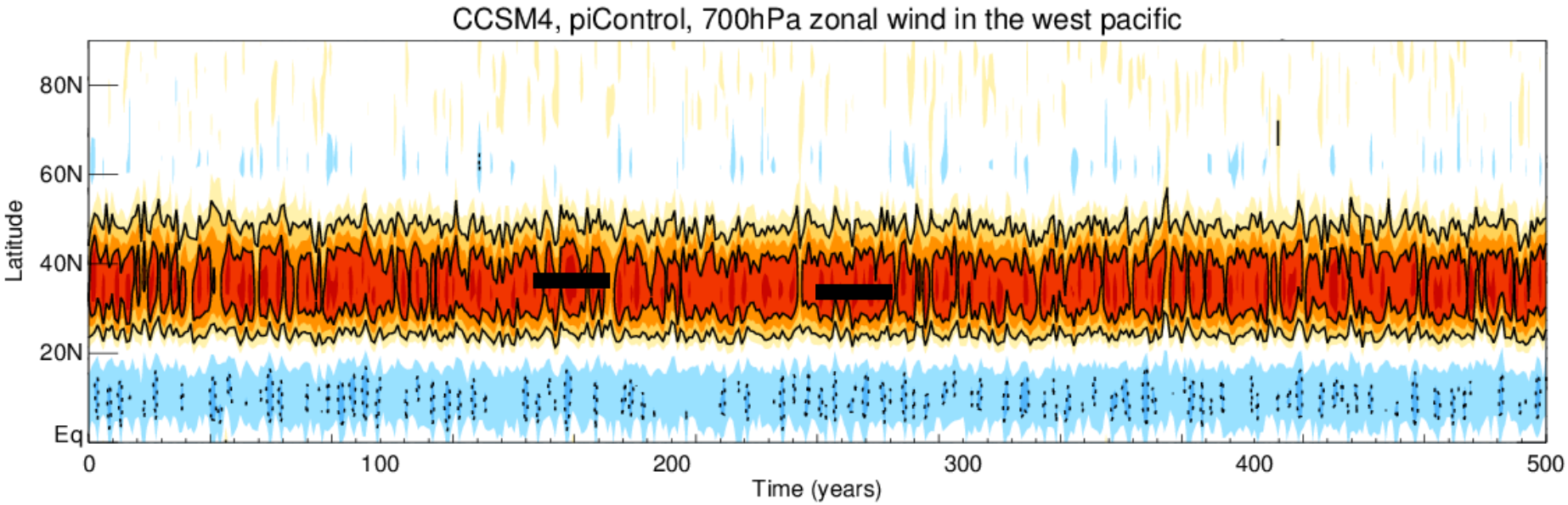

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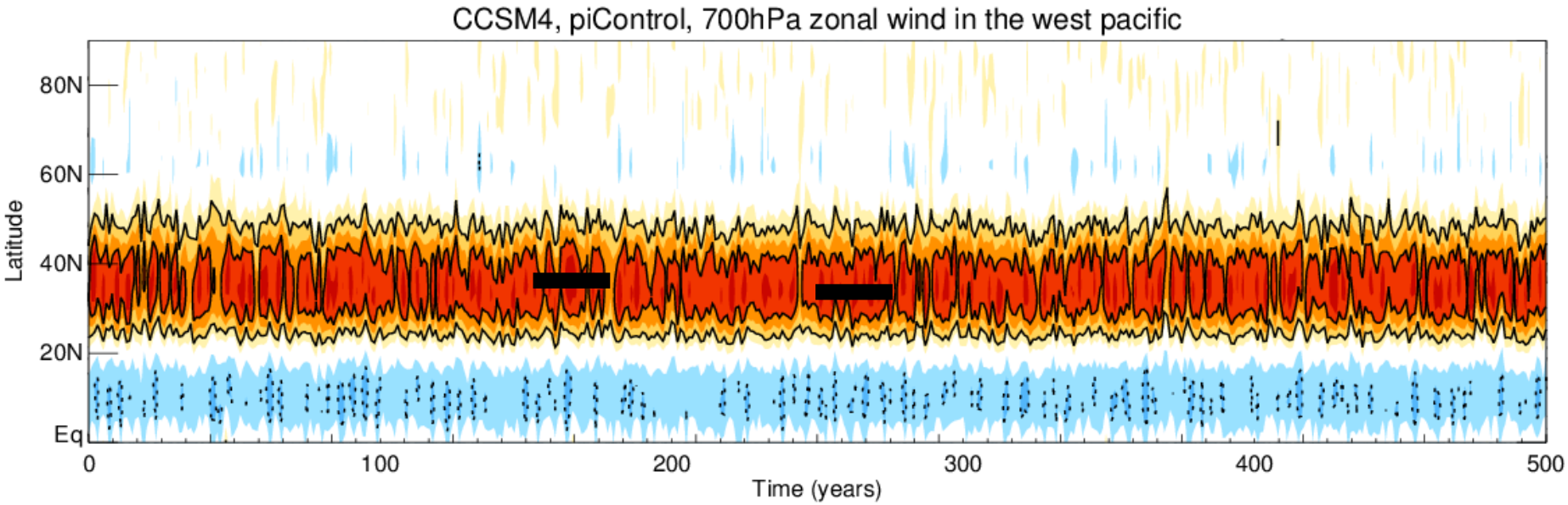

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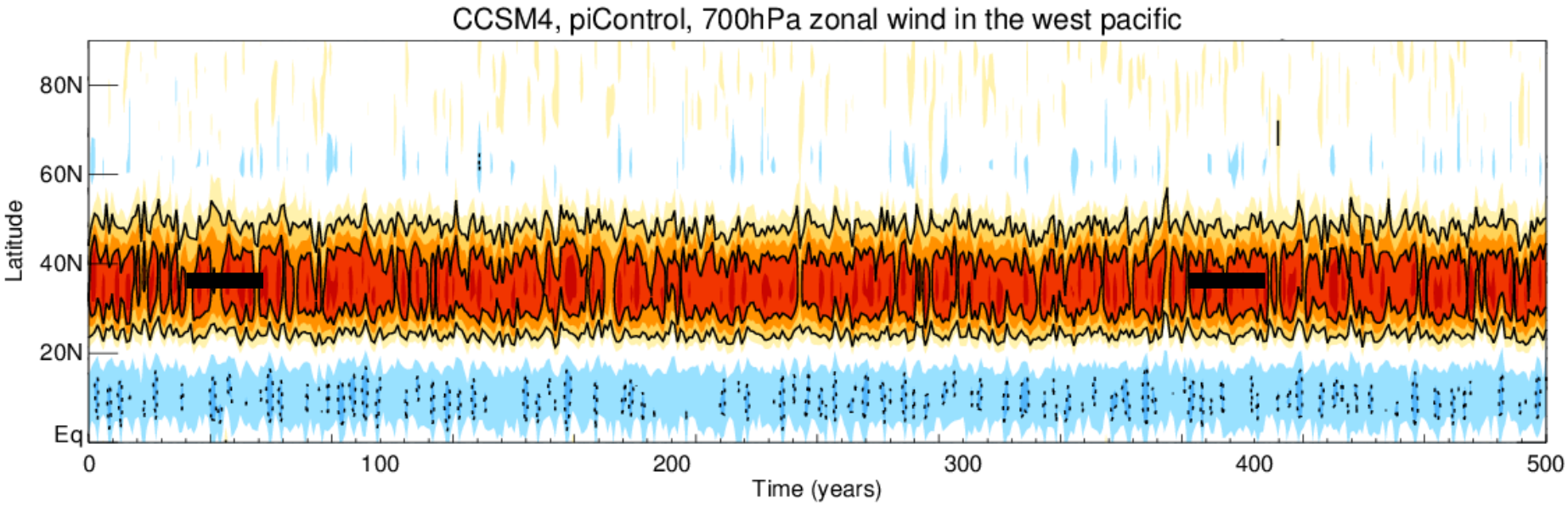

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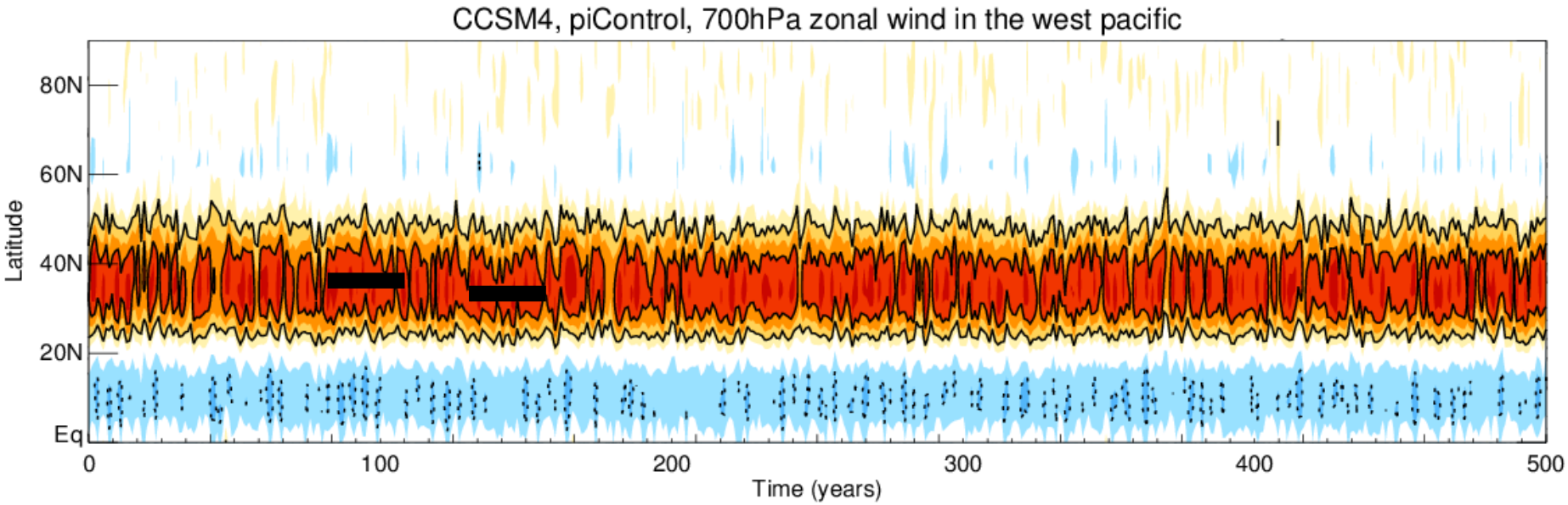
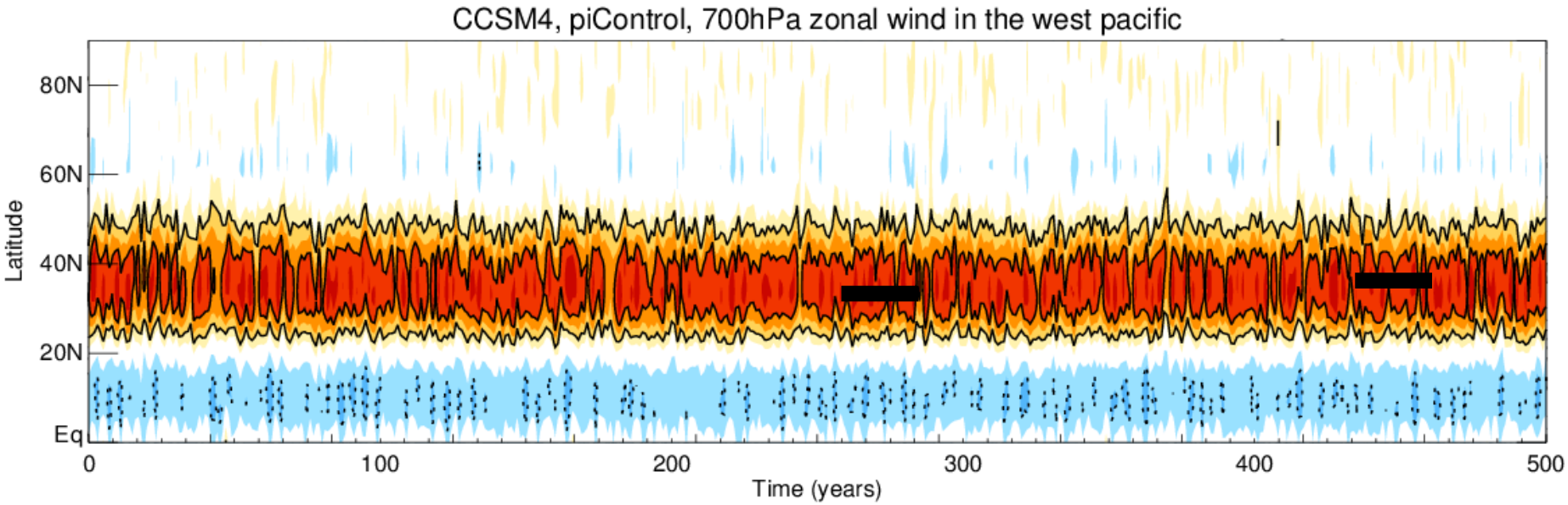


Zonal wind time series in the west Pacific for the CCSM4 piControl simulation



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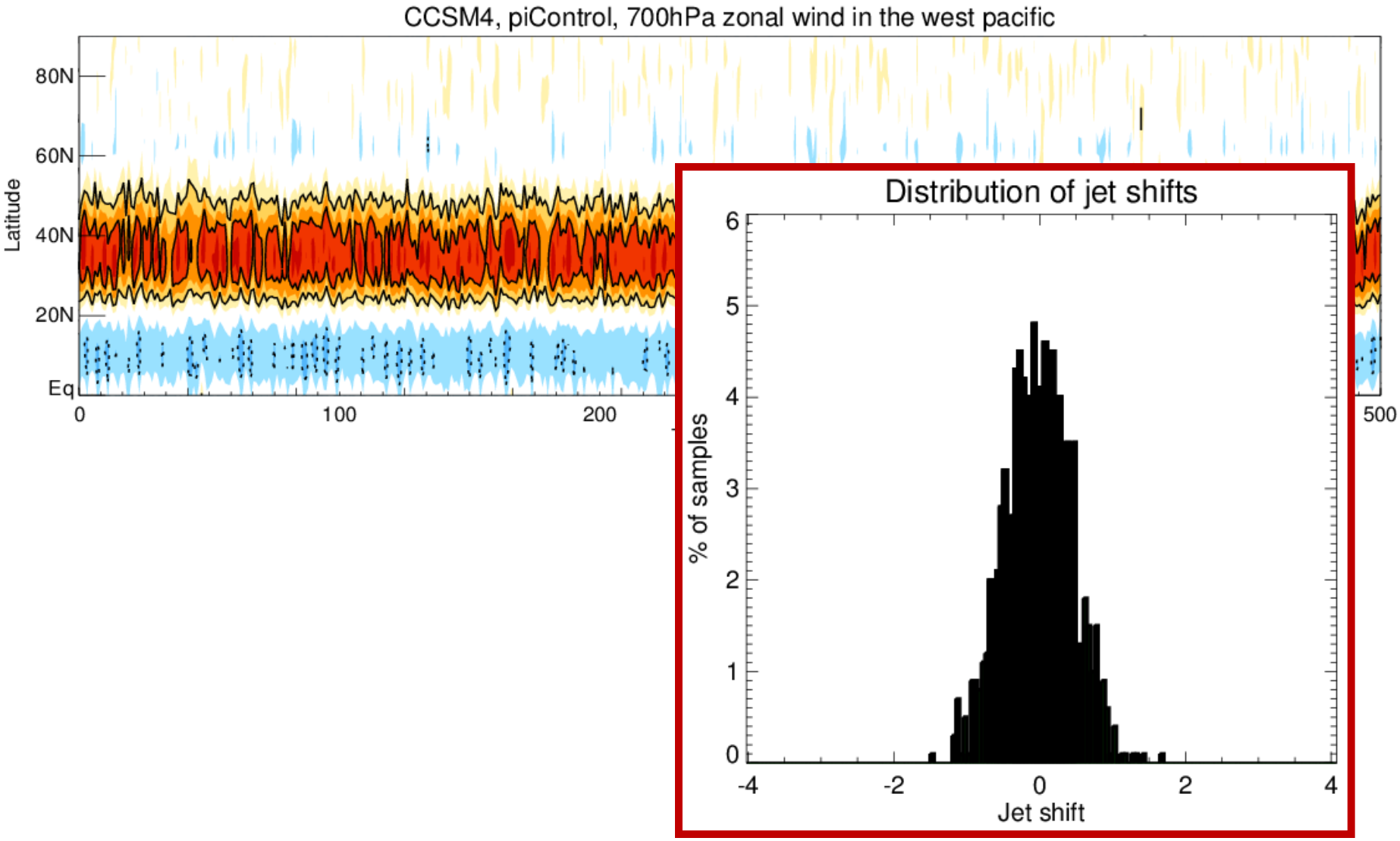

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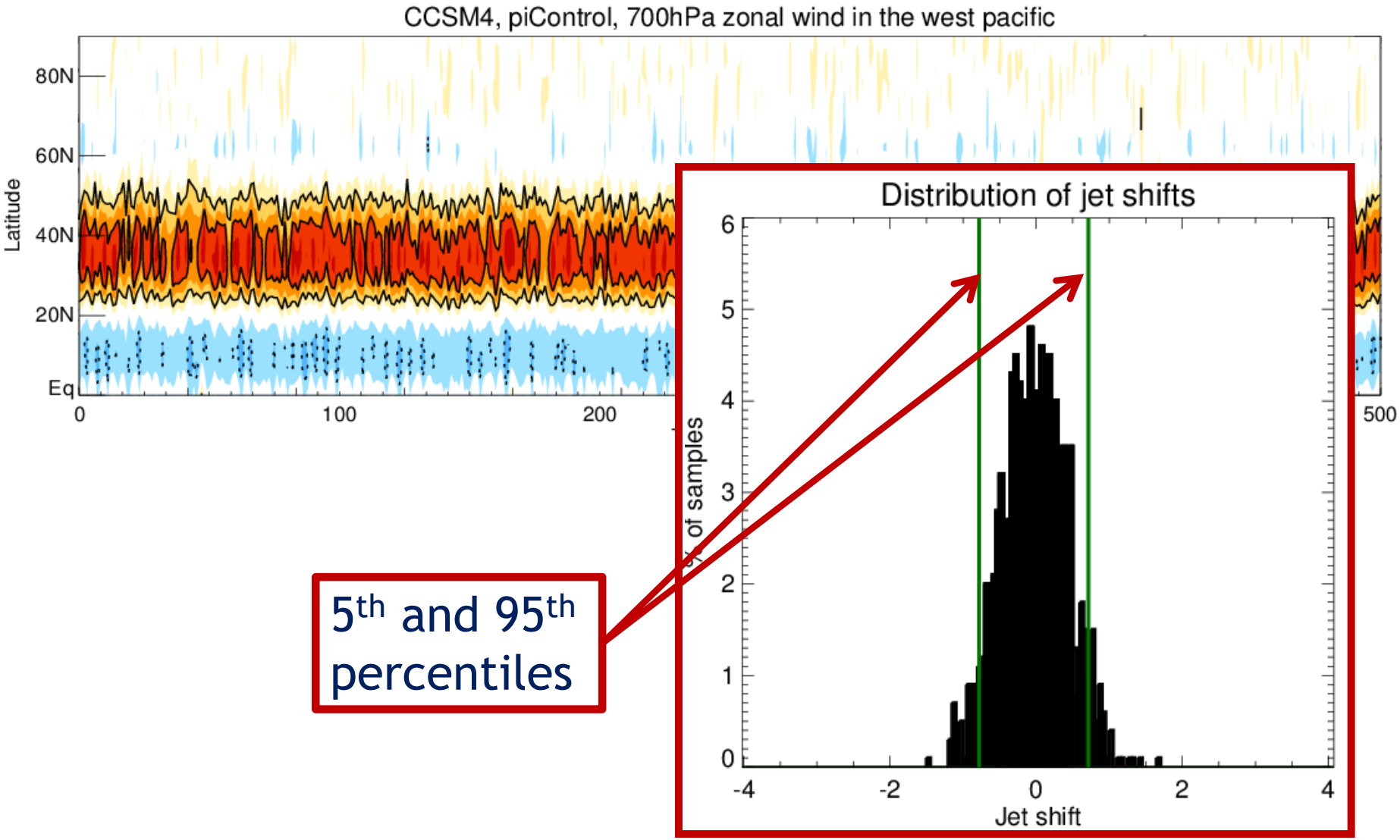
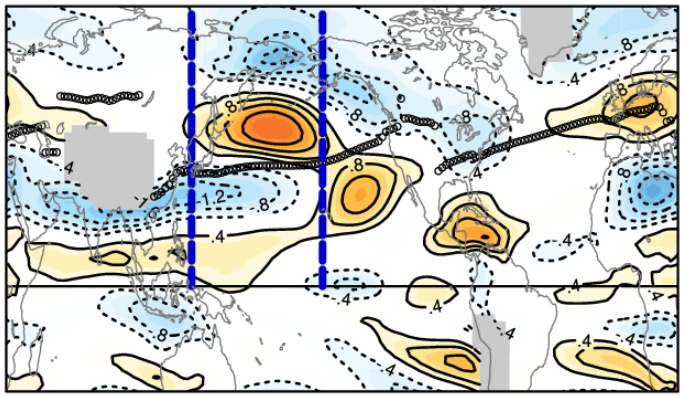
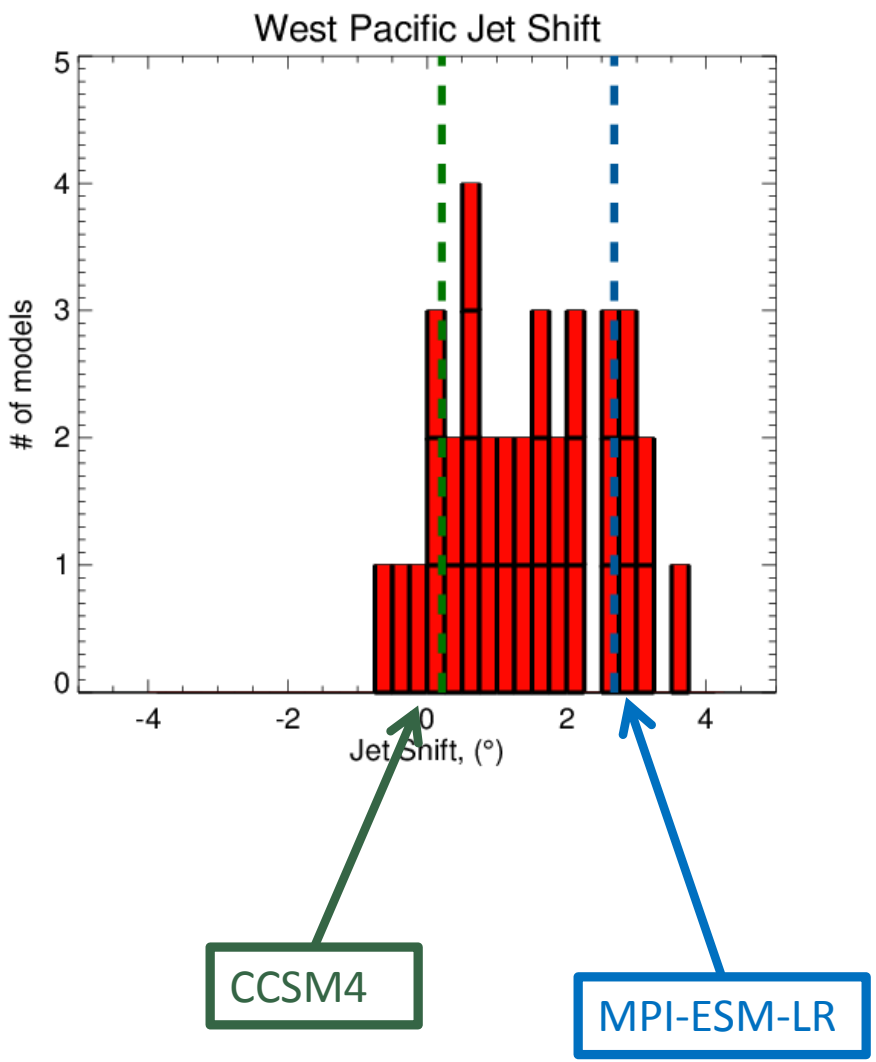
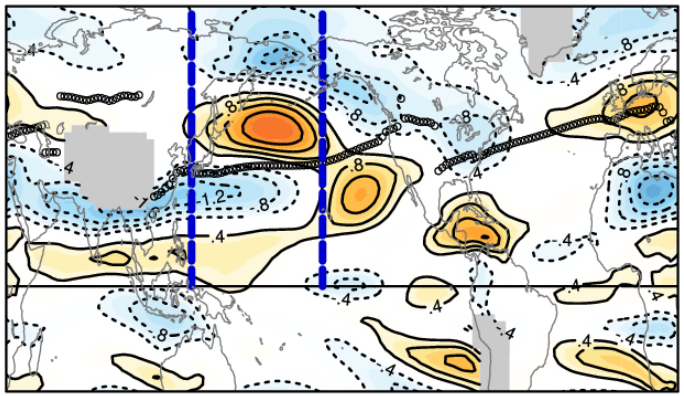




West Pacific Jet Shifts





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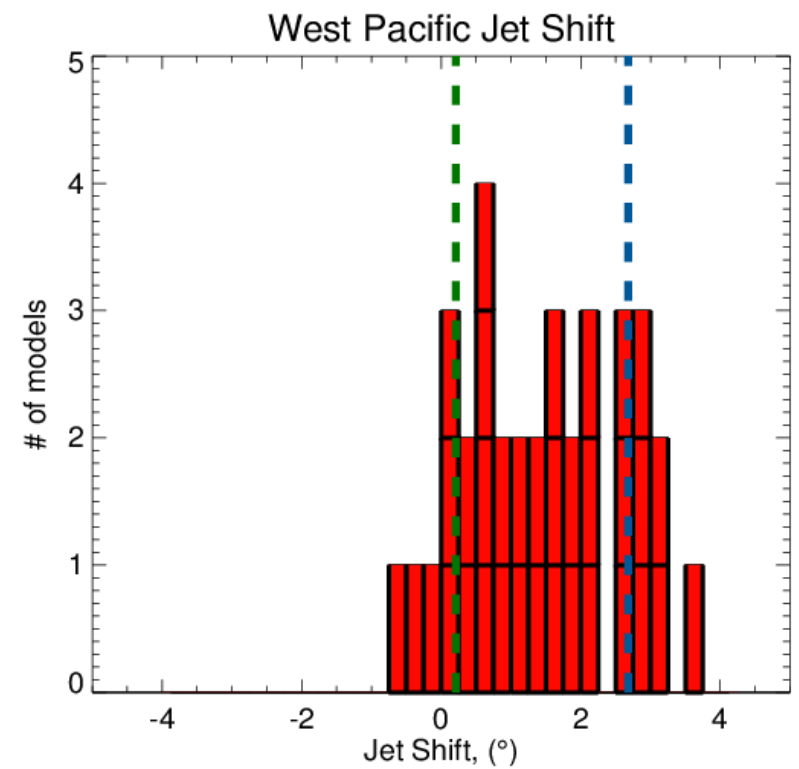

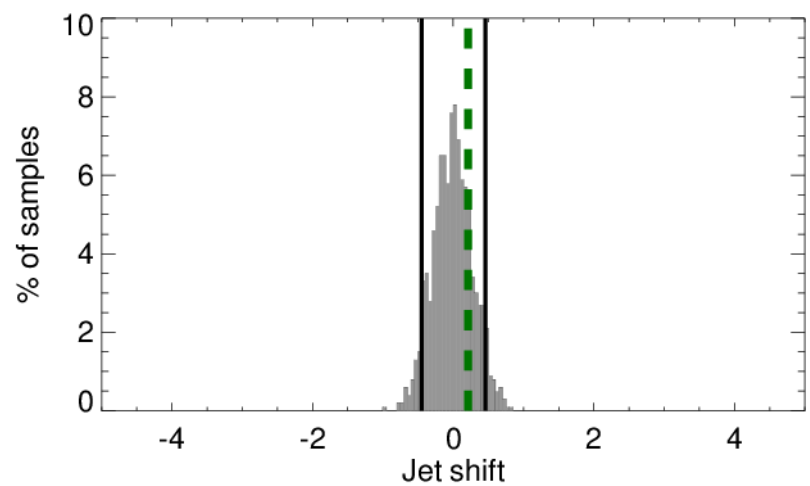

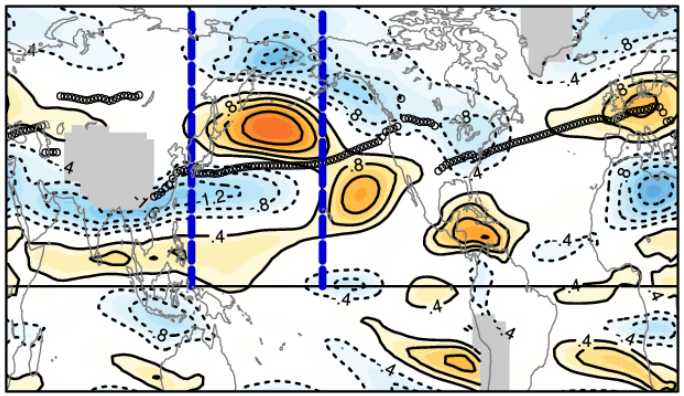

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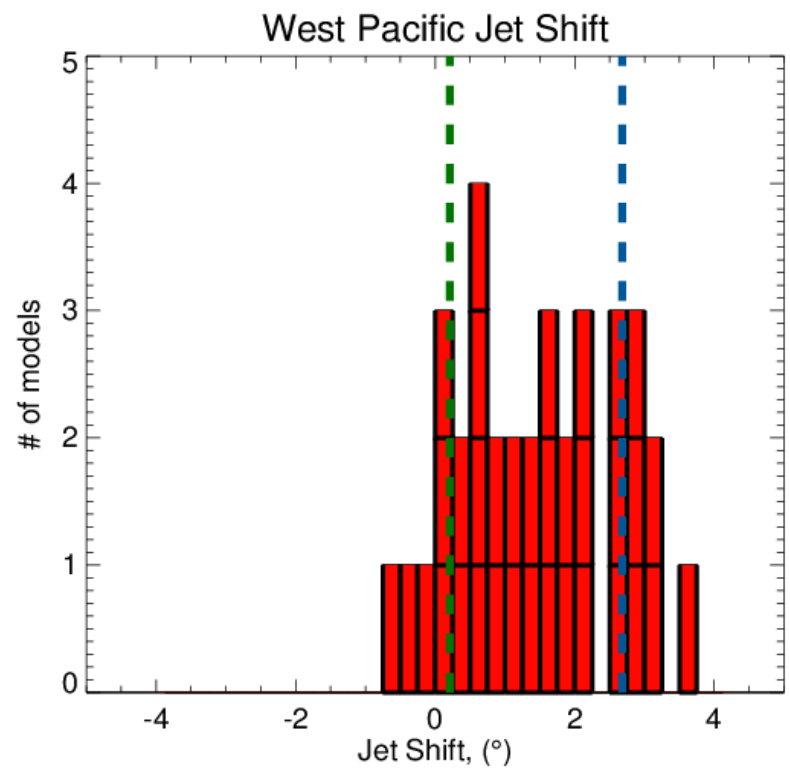
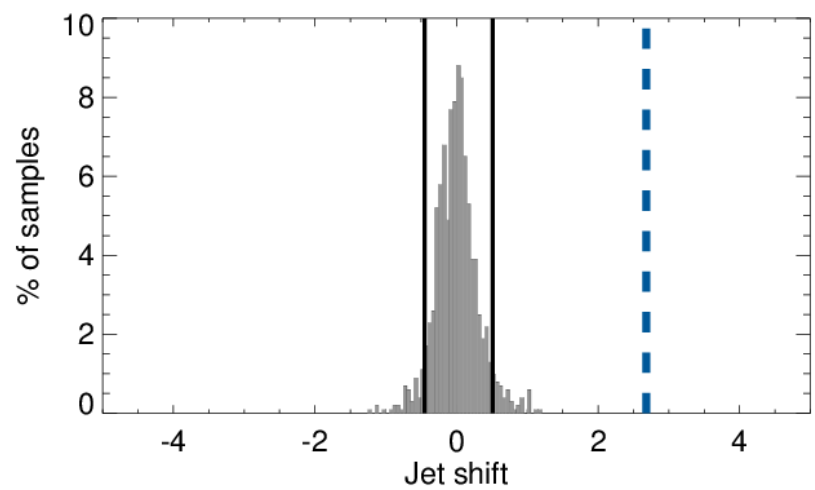
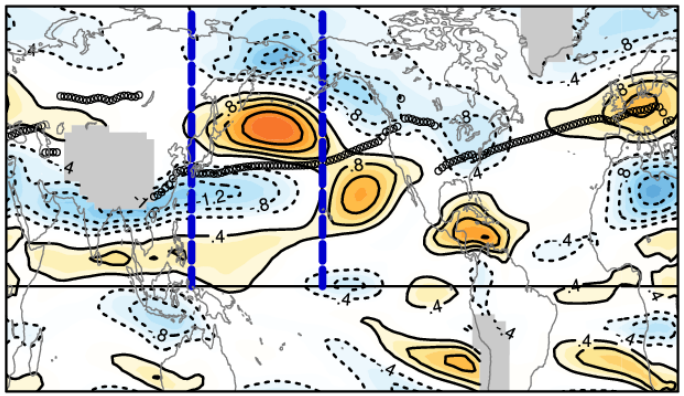
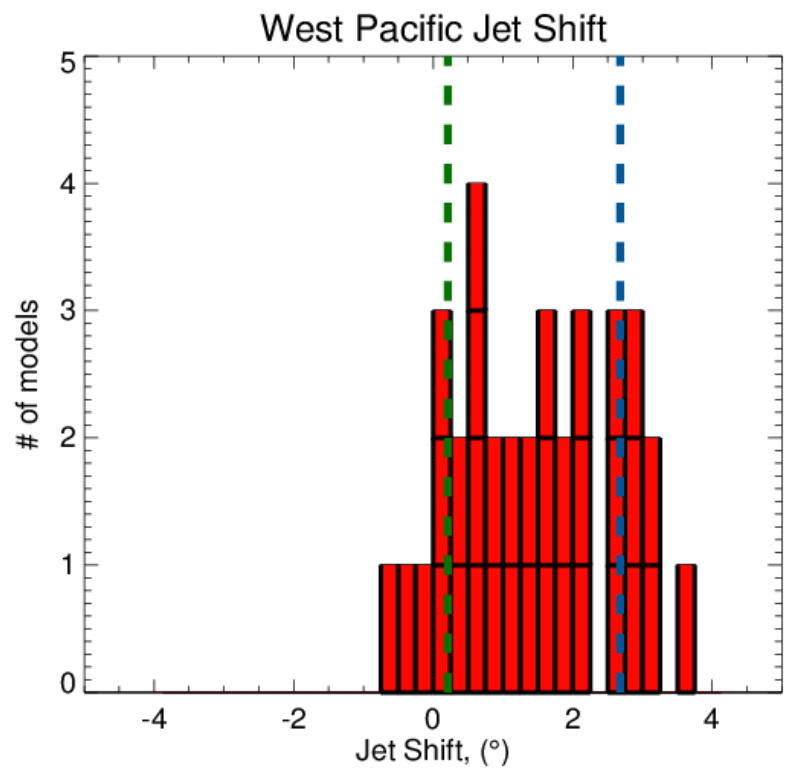


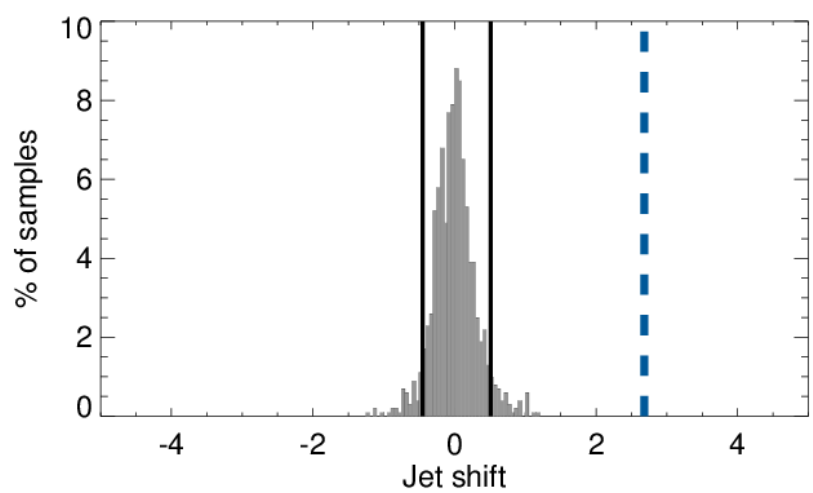






West Pacific Jet Shifts

No significant jet shift in CCSM4
Significant jet shift in MPI-ESM-LR



Methods

- Dealing with calendars
- Assessing significance of differences
- Exploiting model spread
- Making use of available scenarios

- Not all models behave in the same way

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Identify possible emergent constraints on how we think the real world will change

- Not all models behave in the same way
- This is a good thing
- Can exploit the model spread to understand the relationship between different aspects of the circulation

and

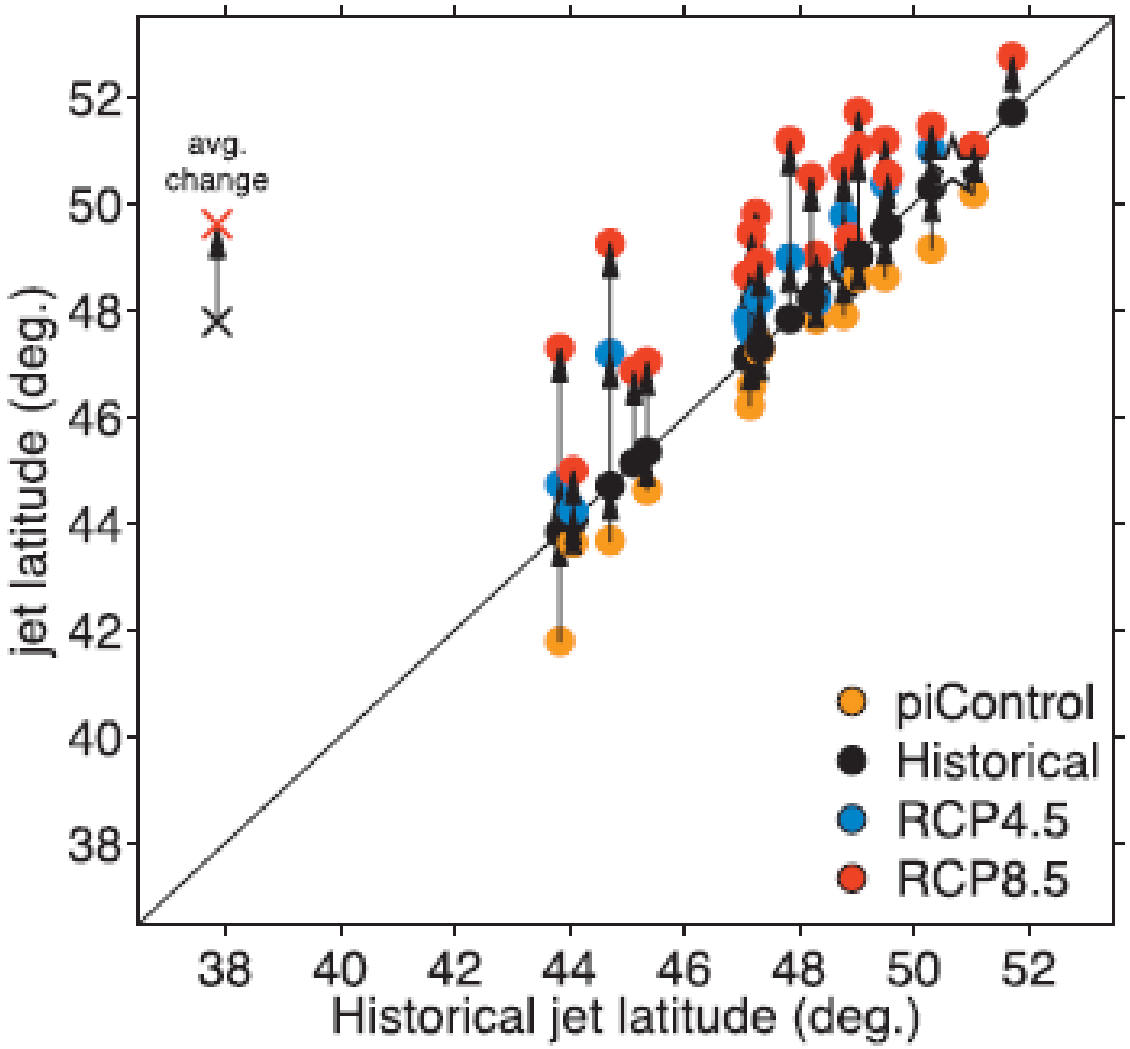
Identify possible emergent constraints on how we think the real world will change

but

This should always be accompanied by a mechanistic understanding of what's going on

An example: southern hemisphere jet shifts

Southern Hemisphere jet shift (annual mean)



Poleward jet shift

Barnes and Polvani (2013)

An example: southern hemisphere jet shifts

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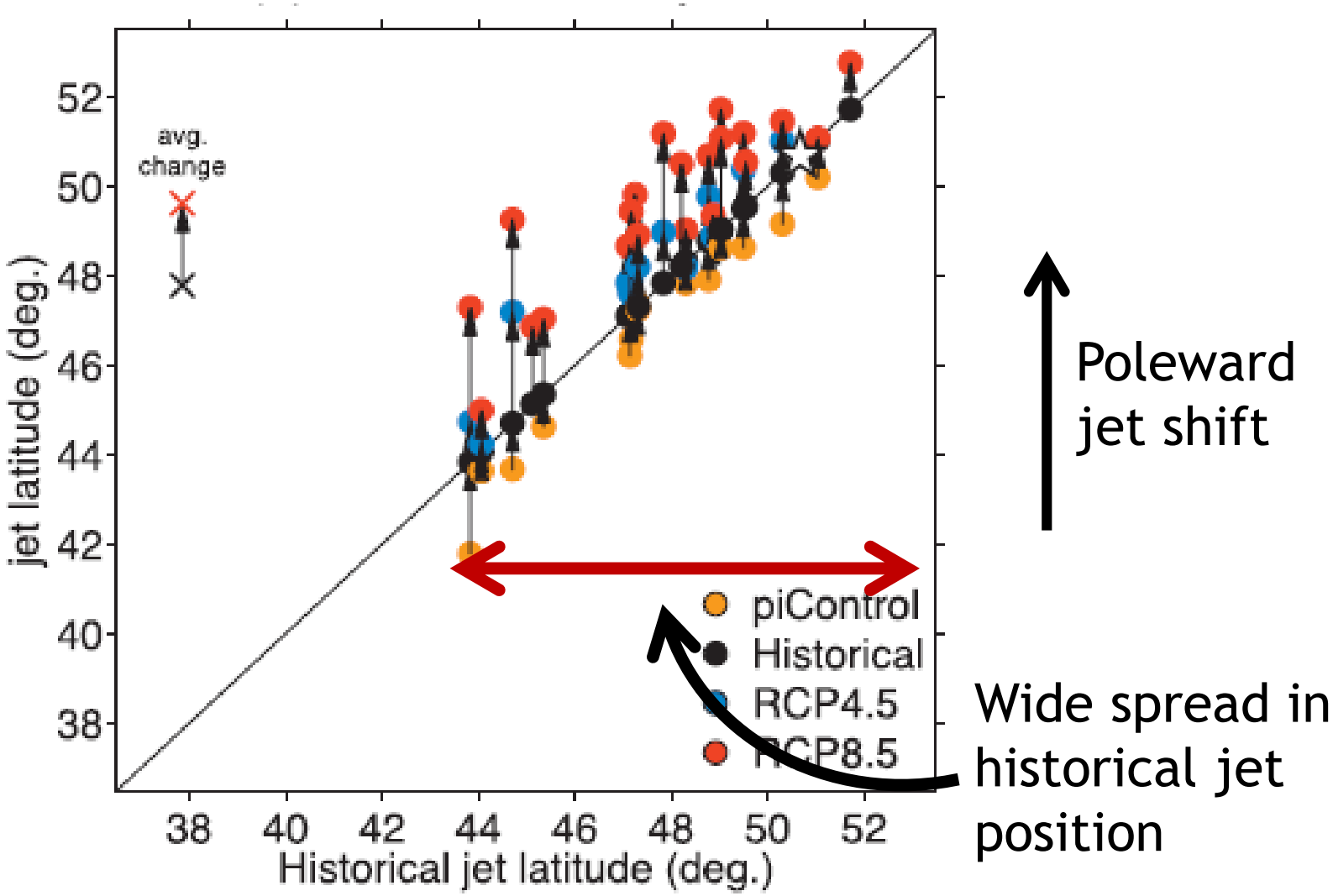
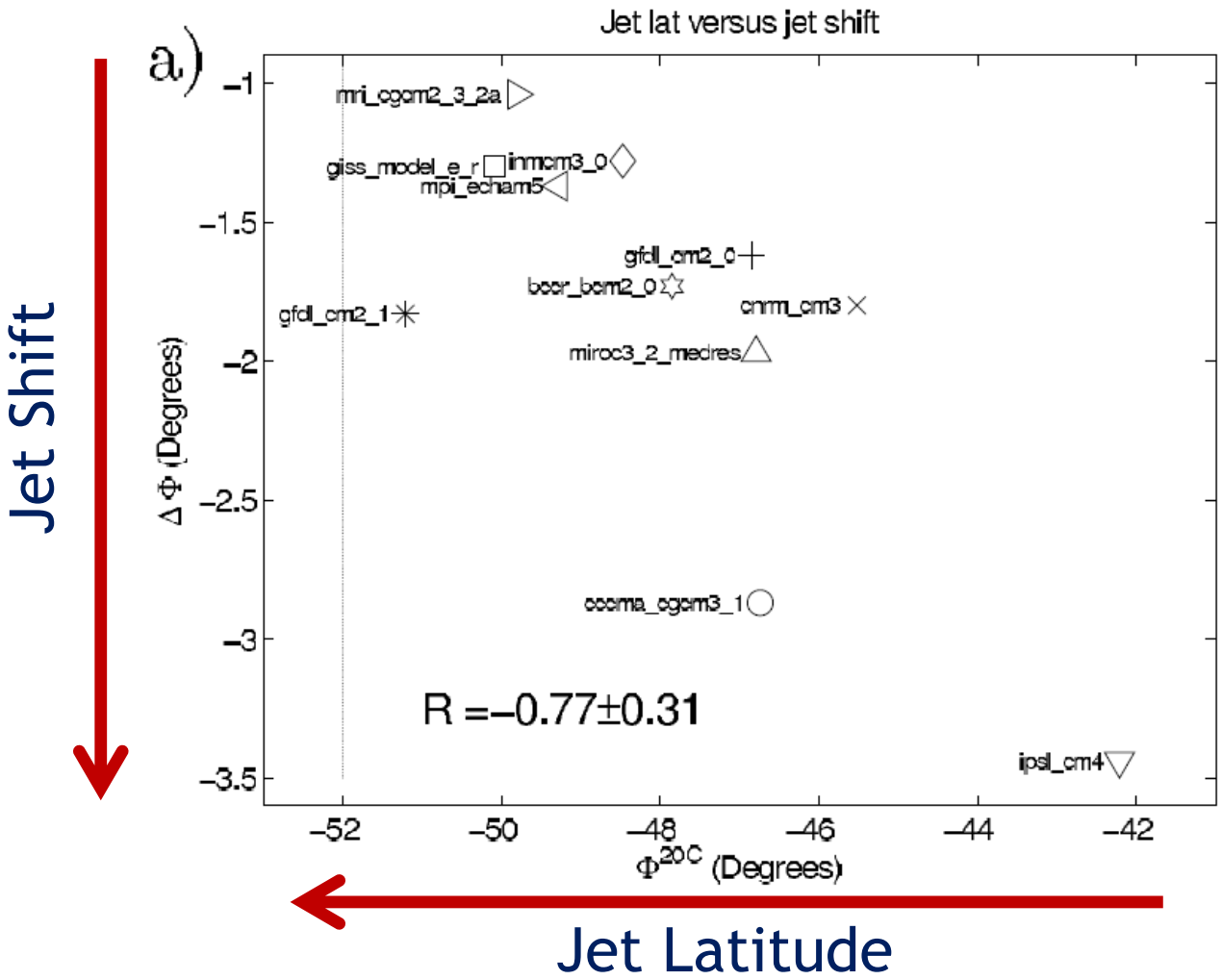


Barnes and Polvani (2013)

Lower latitude jets shift further poleward under anthropogenic forcing



Kidston and Gerber (2010)

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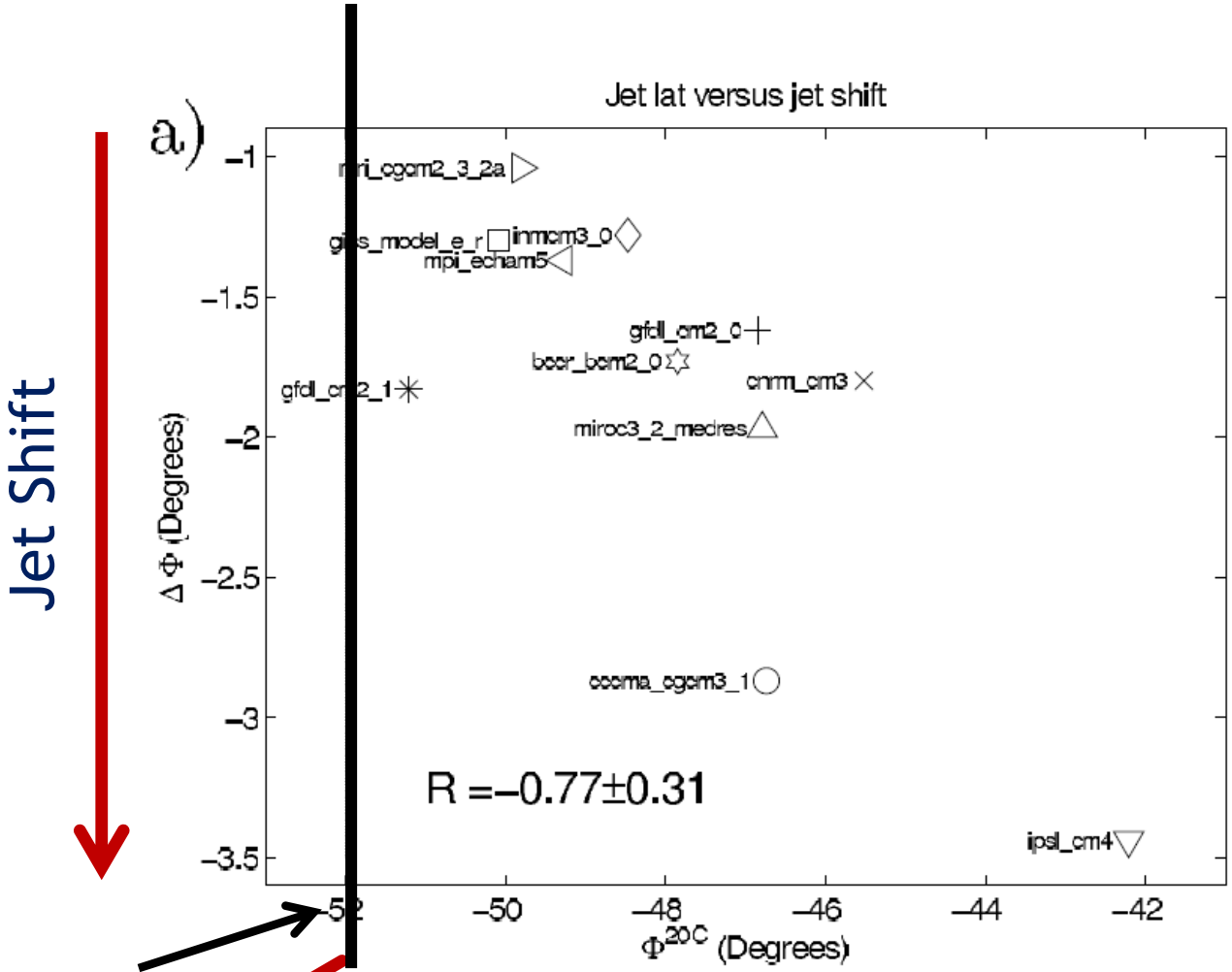


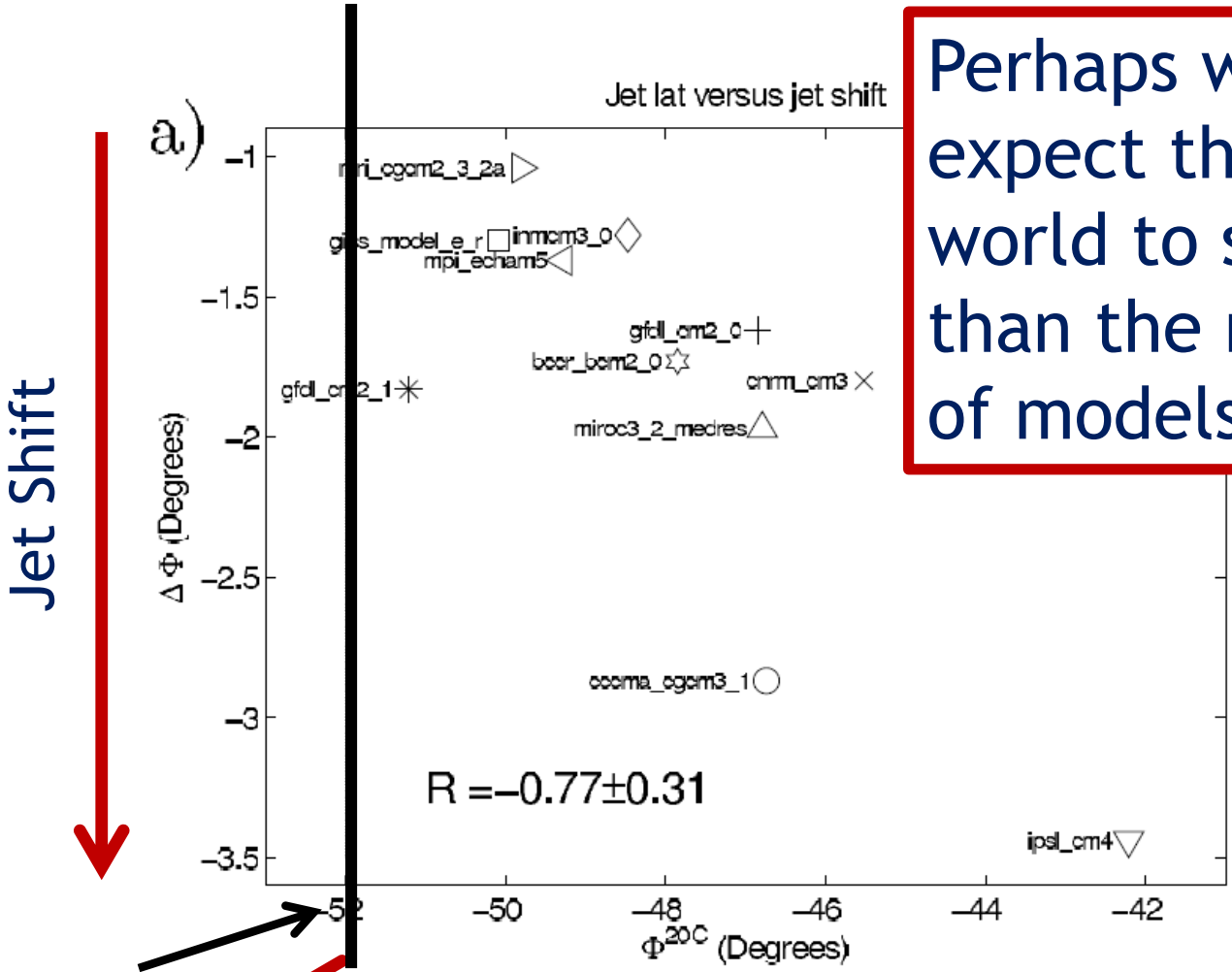
Jet Shift

Reanalysis jet position

Jet Latitude

Kidston and Gerber (2010)

Lower latitude jets shift further poleward under anthropogenic forcing



Jet Shift

Jet Latitude

Reanalysis jet position

Perhaps we should expect the real world to shift less than the majority of models?

Kidston and Gerber (2010)

Methods

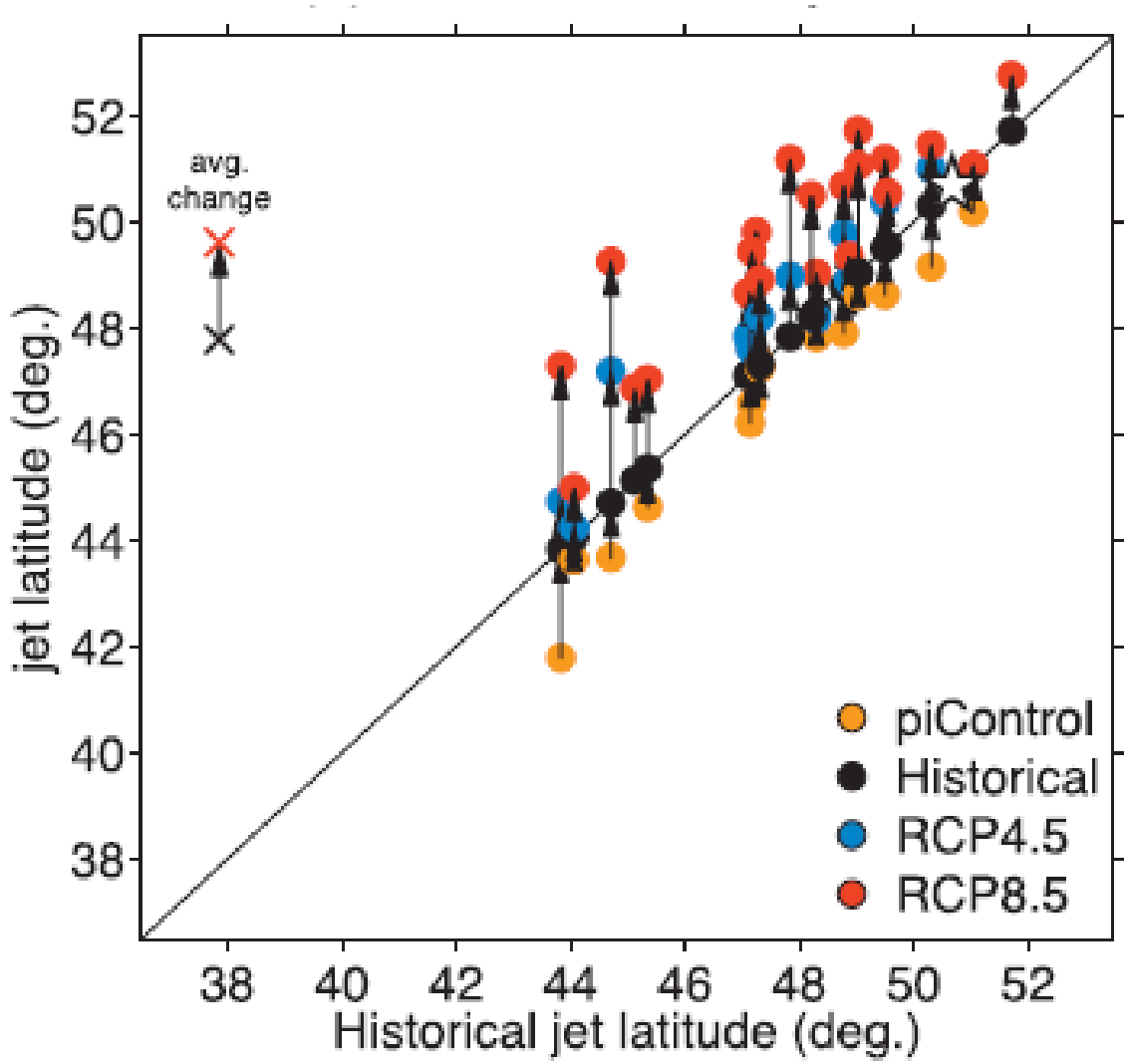
- Dealing with calendars
- Assessing significance of differences
- Exploiting model spread
- Making use of available scenarios

Many scenario's are available in CMIP5

piControl
historical
RCP4.5
RCP8.5
abrupt4xCO2
amip
amip4K
amip4xCO2
amipFuture

and more to come in CMIP6.

Back to the Southern Hemisphere Jet…

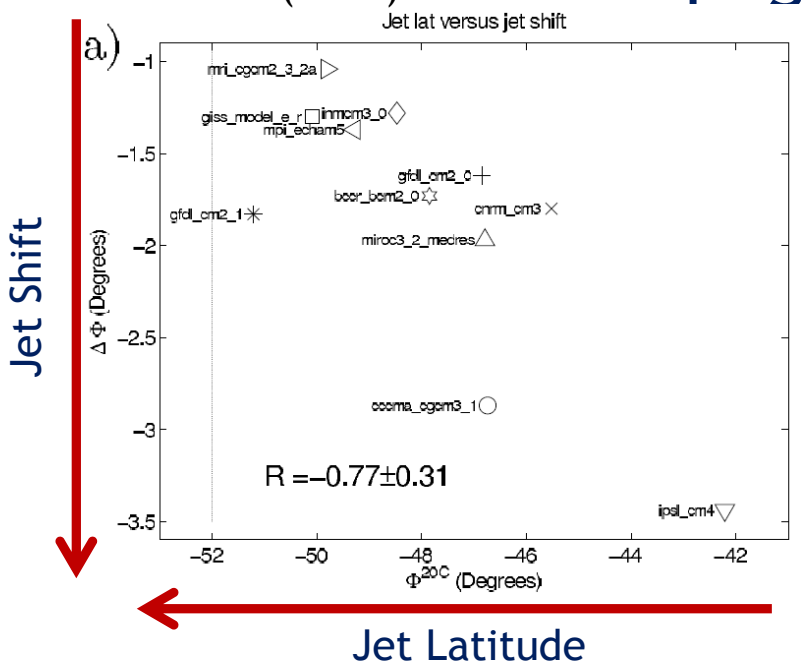


Example use of multiple scenarios

Barnes and Polvani (2013)

Lower latitude jets shift further poleward under anthropogenic forcing

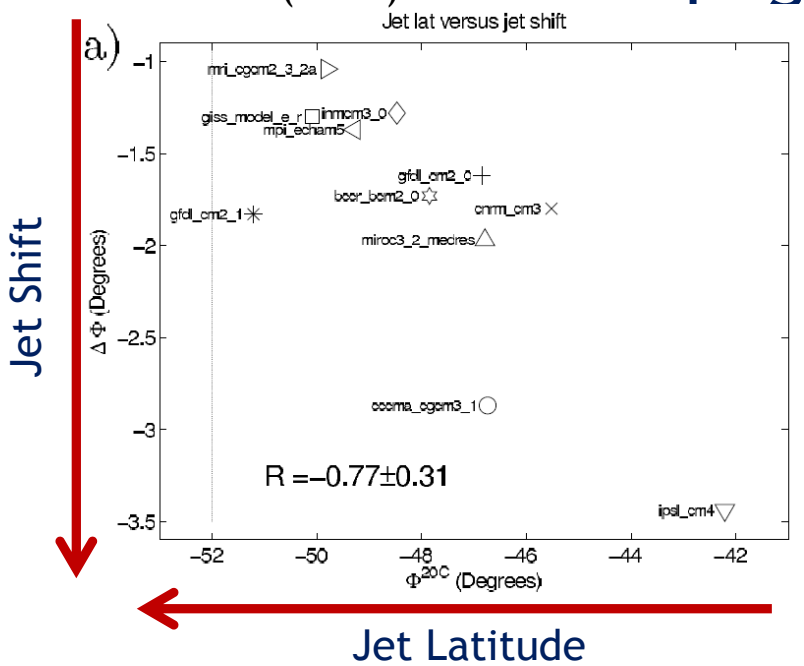
Kidston and Gerber (2010)



Annual Mean

Lower latitude jets shift further poleward under anthropogenic forcing

Kidston and Gerber (2010)



Annual Mean

Seasonality

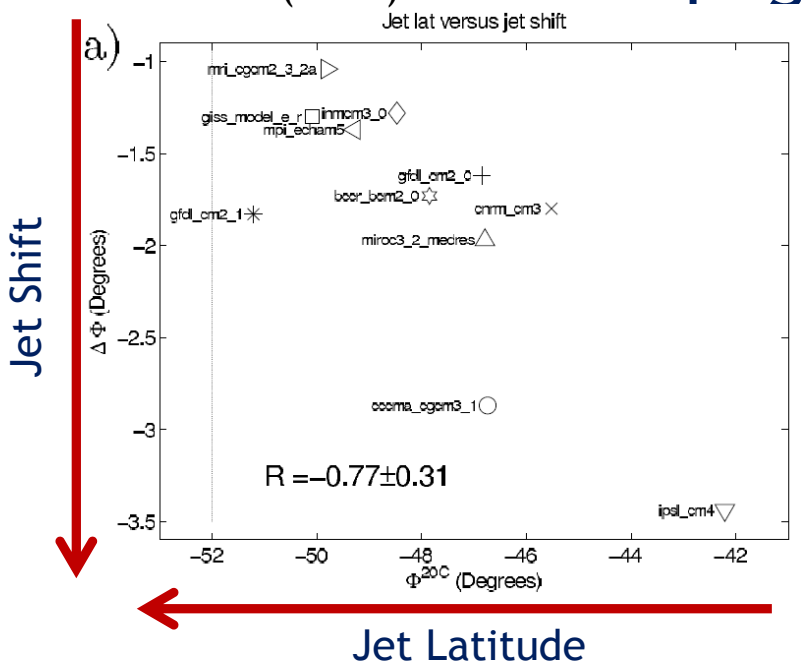
DJF: -0.08

JJA: -0.81

Hypothesized to be due to the influence of ozone depletion in DJF

Lower latitude jets shift further poleward under anthropogenic forcing

Kidston and Gerber (2010)



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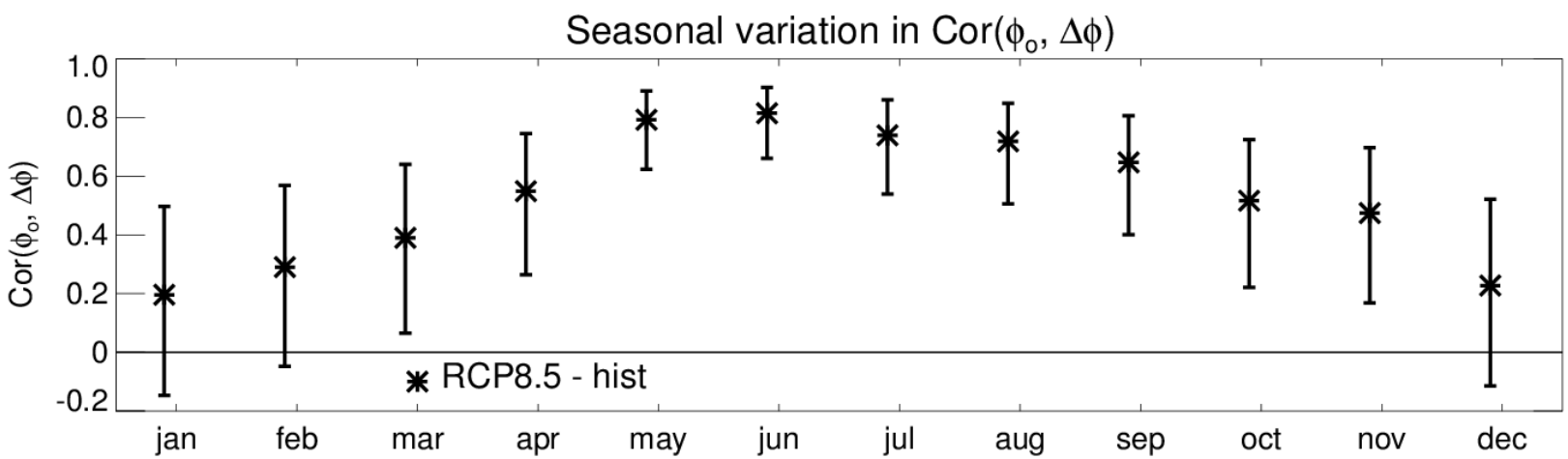

Simpson and Polvani (2016)

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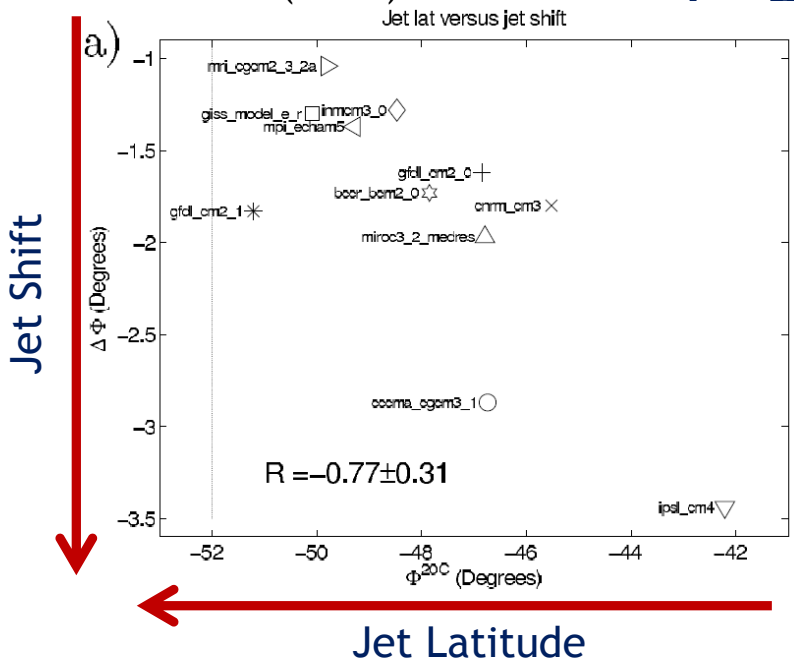

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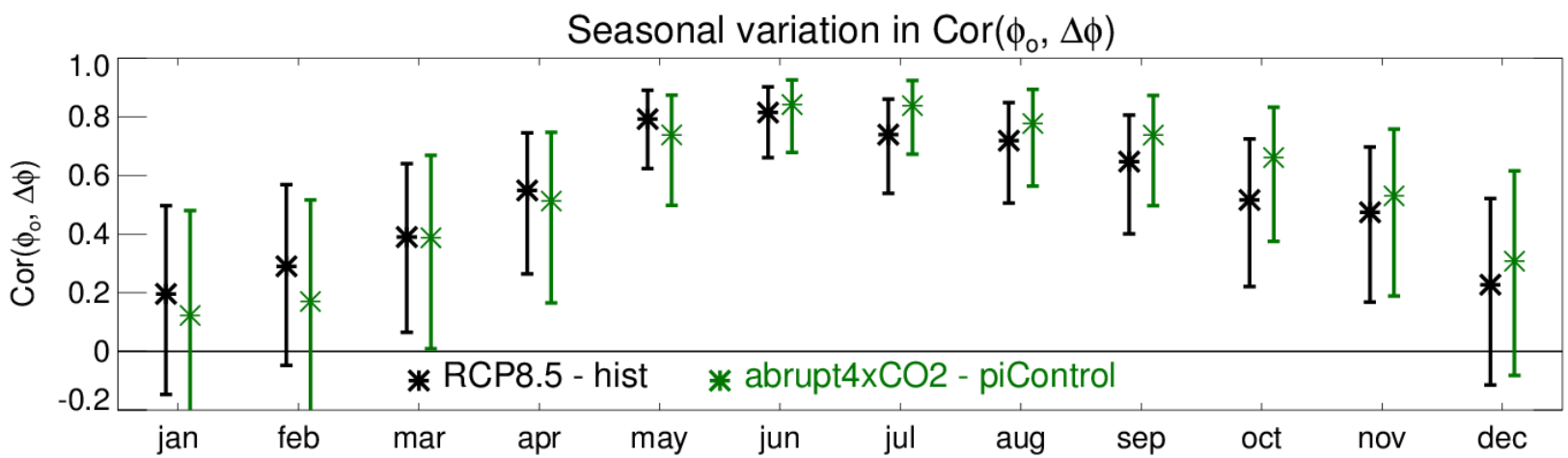
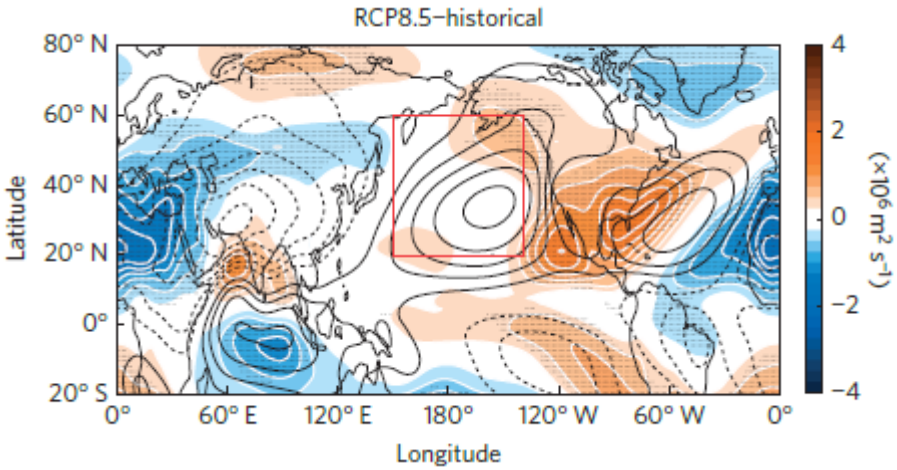


Simpson and Polvani (2016)

Another example…distinguishing between influence of direct radiative forcing and SST warming



925hPa eddy stream function

RCP8.5 - historical

Summer (JJA)

Shaw and Voigt (2015)

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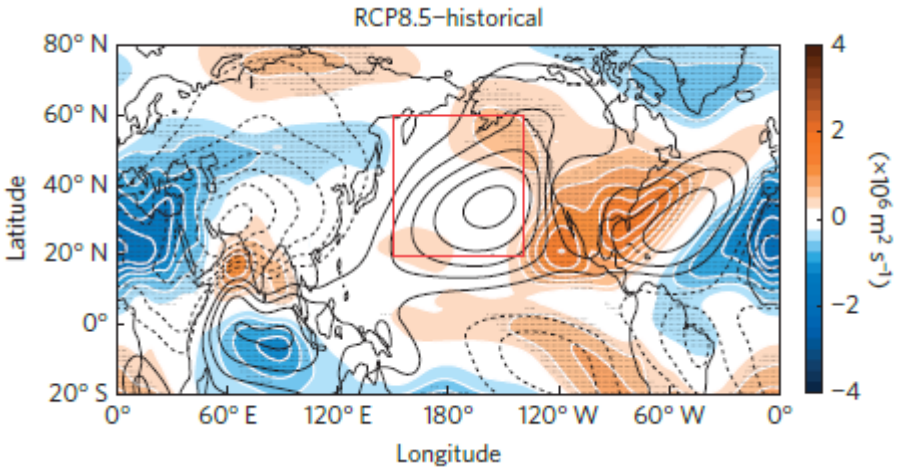

925hPa eddy stream function
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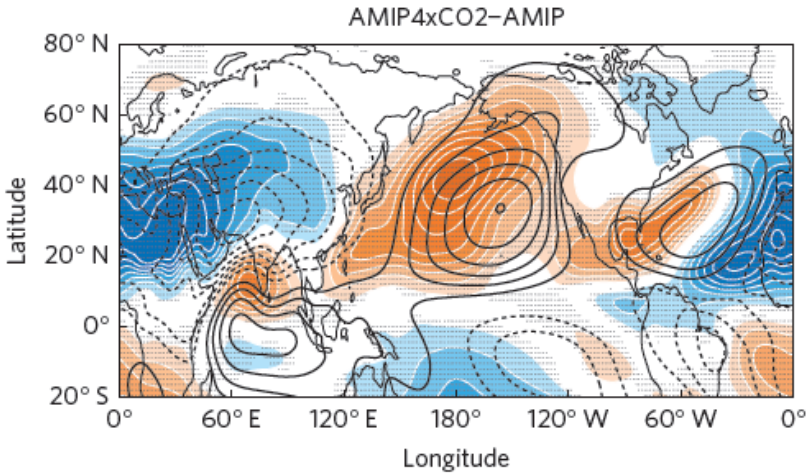
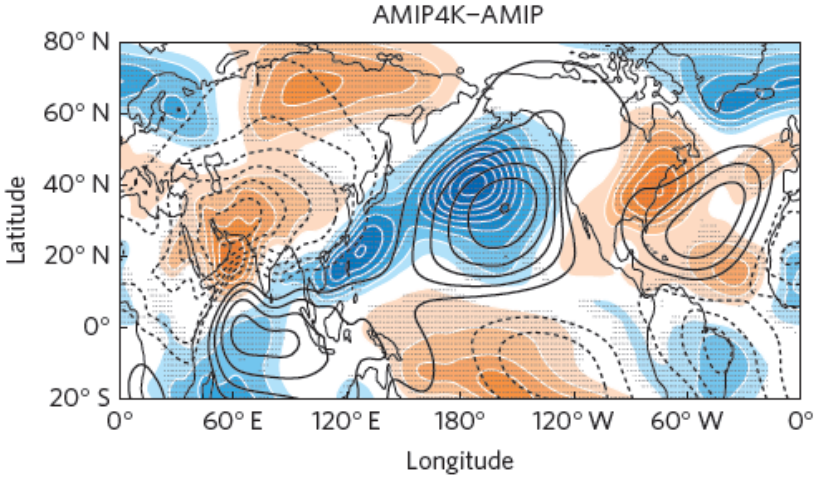
AMIP4xCO2 - AMIP



AMIP4K - AMIP



Shaw and Voigt (2015)

Outline

Part 1: Methods for analyzing circulation change in the CMIPs

Part 2: An example – the meridional wind response to climate change and impacts on North American hydroclimate.

(with Richard Seager (LDEO), Mingfang Ting (LDEO), Tiffany Shaw (U. Chicago))

Examine the meridional wind anomalies that occur under climate change

Past = (1979-2005) of historical

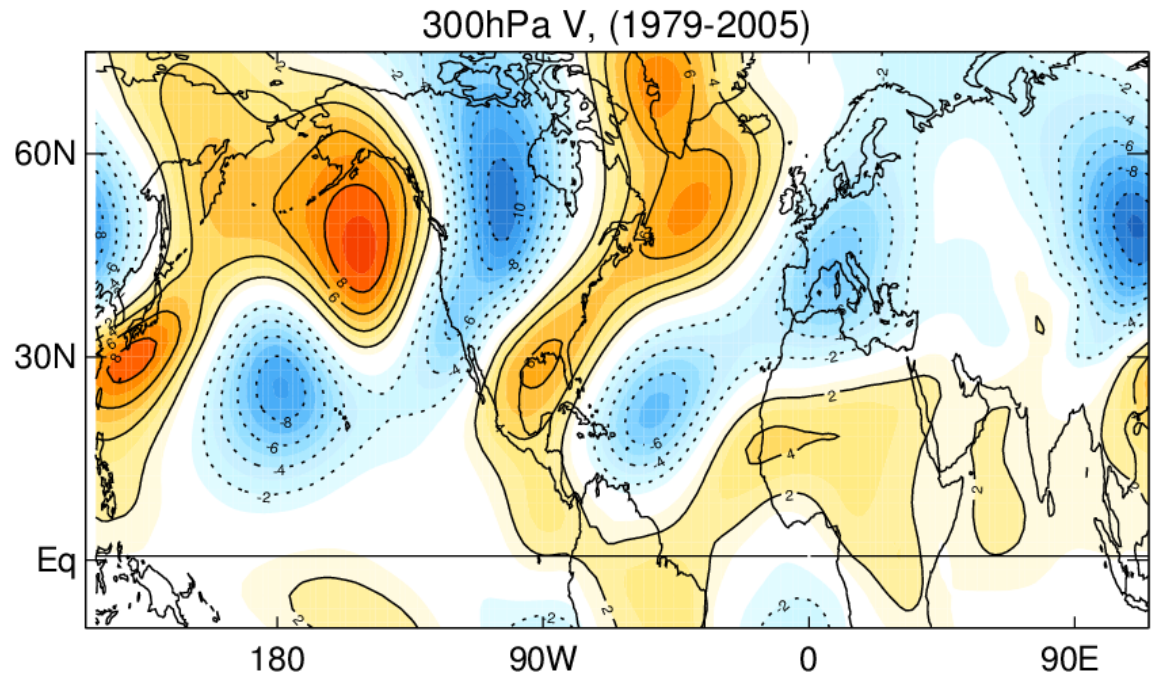
Future = (2070-2099) of RCP8.5

35 models

All available ensemble members

DJF

Past,
contour=2m/s

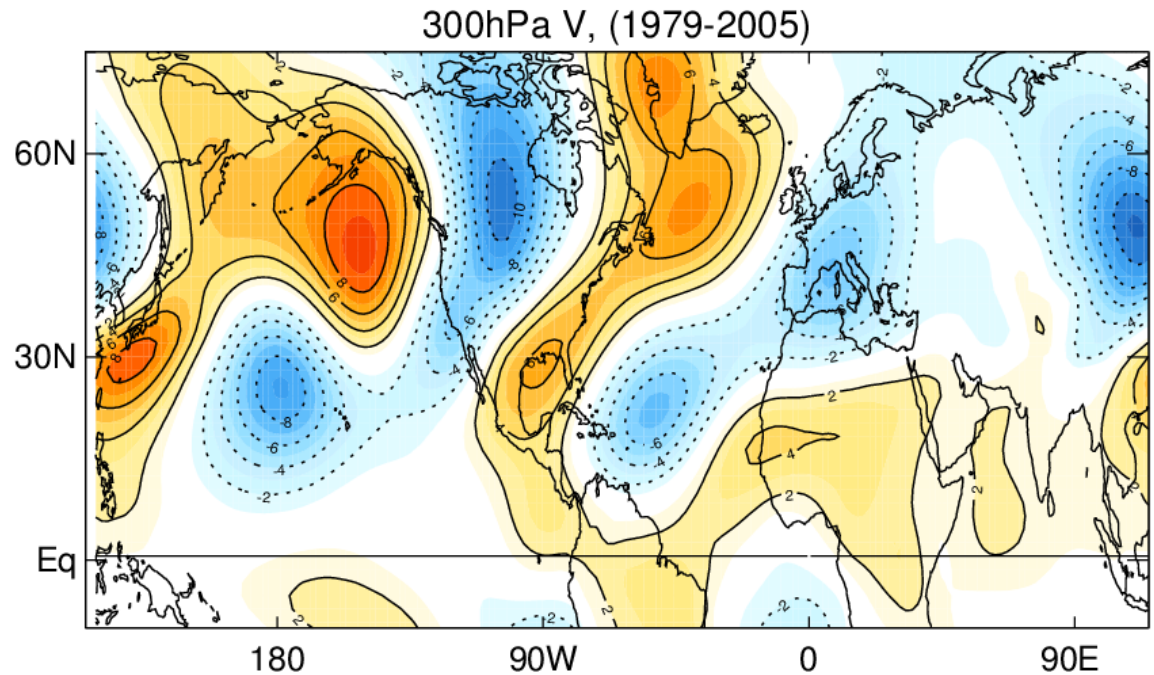


300hPa V
Multi-model mean

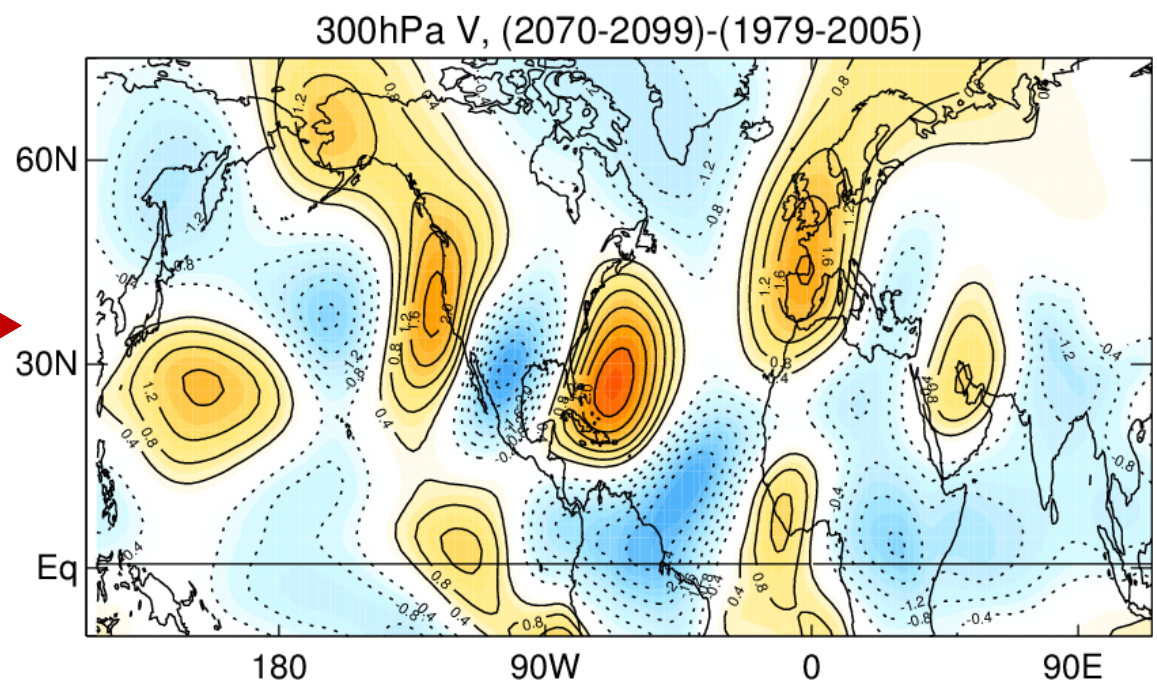
Simpson et al (2016)

Past,
contour=2m/s

300hPa V
Multi-model mean



Future-Past
contour=0.4m/s



Simpson et al (2016)

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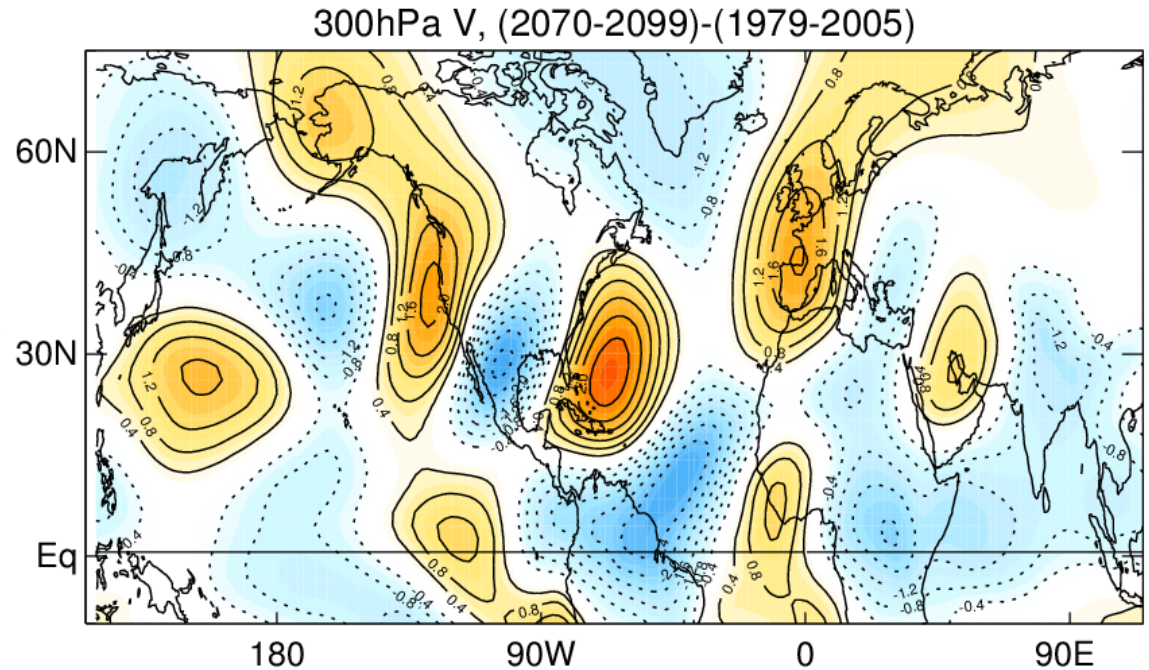
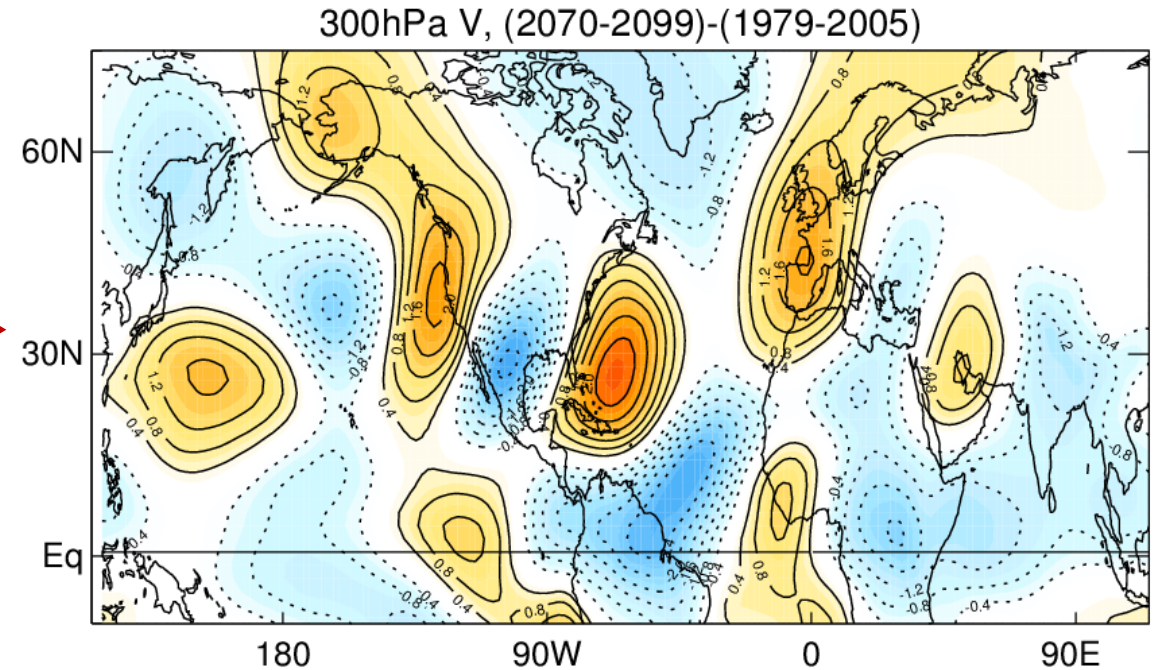


V, Multi-model mean

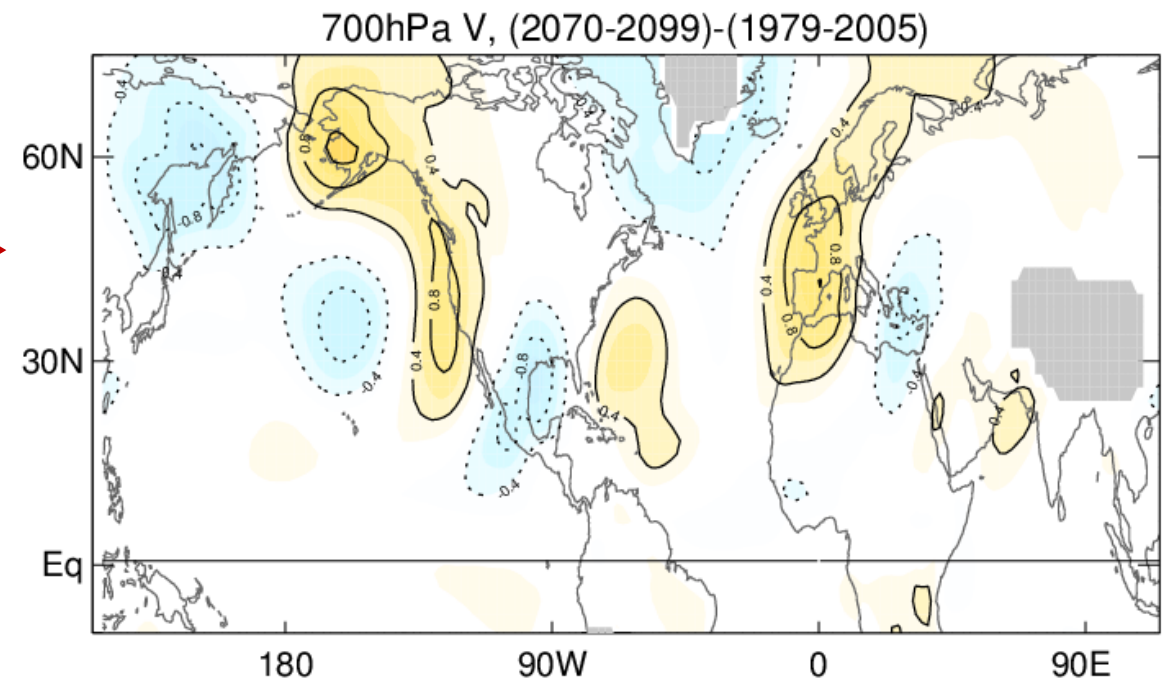
Simpson et al (2016)

300hPa
contour=0.4m/s

V, Multi-model mean



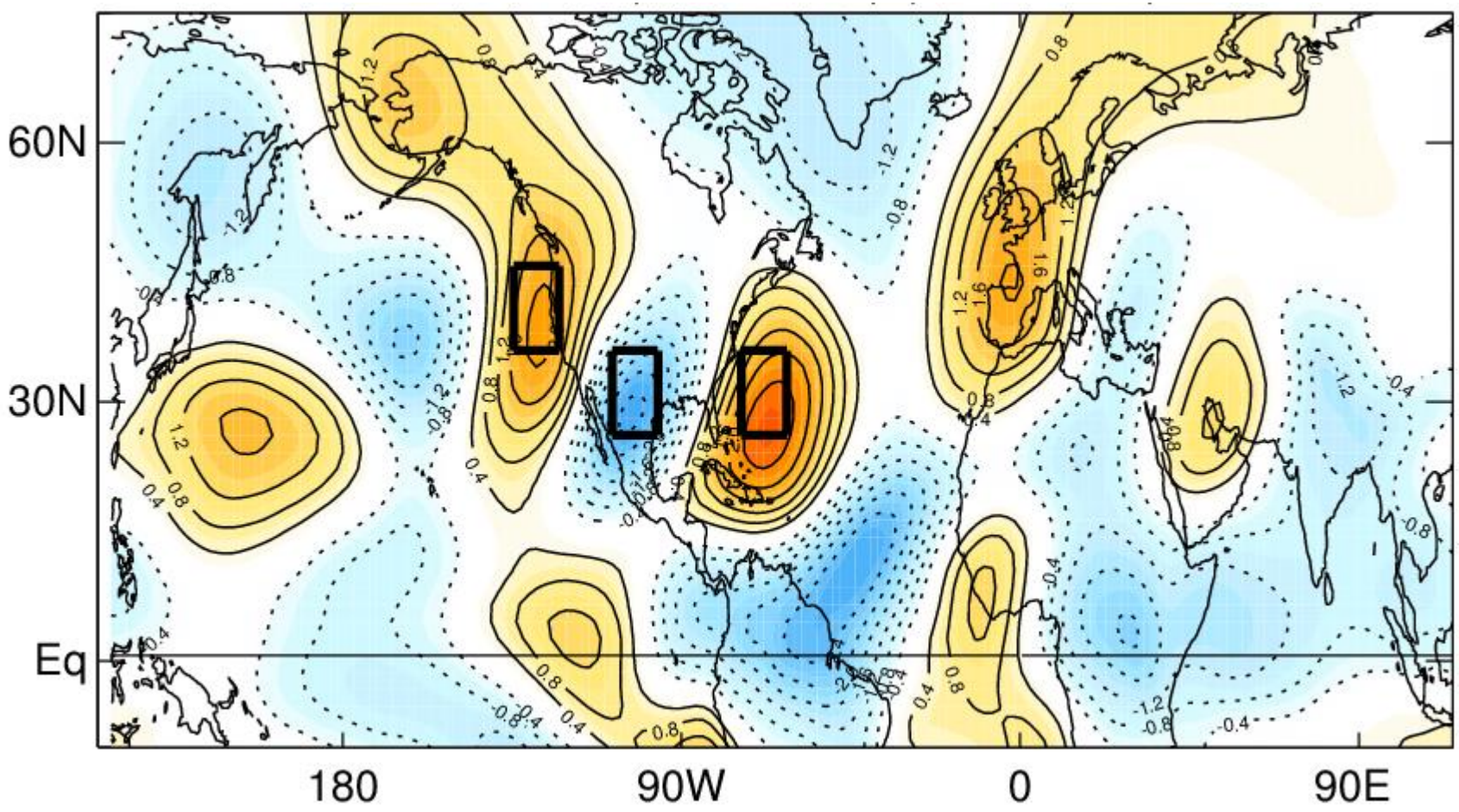
700hPa
contour=0.4m/s



Simpson et al (2016)

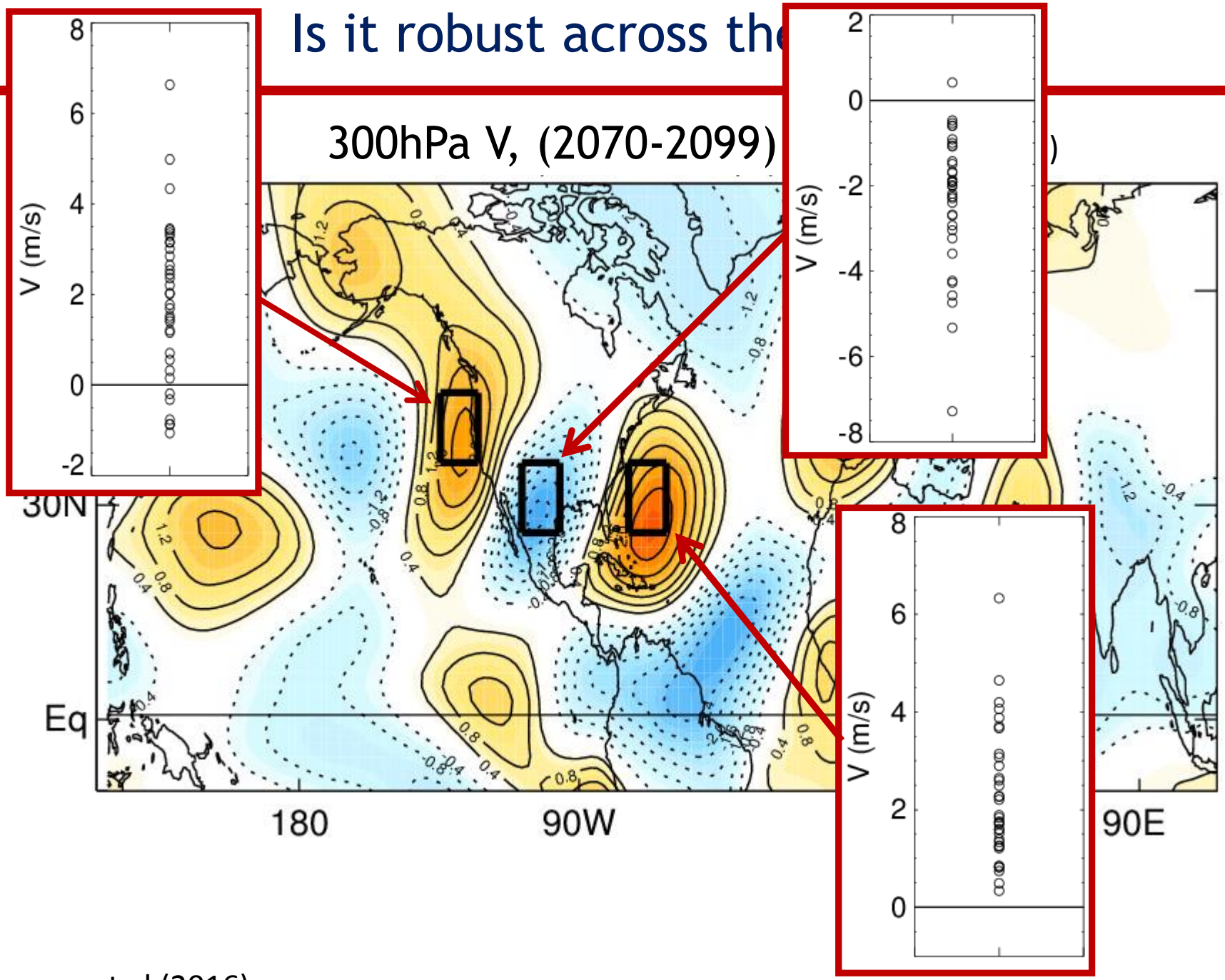
Is it robust across the models?

300hPa V, (2070-2099) – (1979-2005)



Simpson et al (2016)

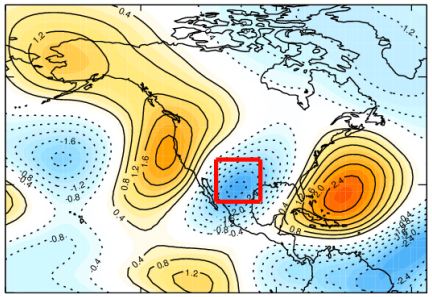
Is it robust across the

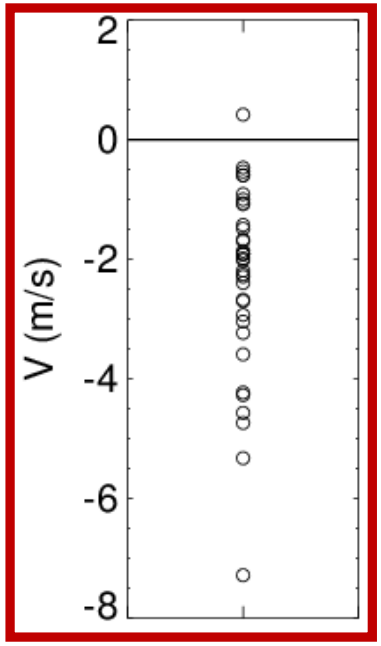


Simpson et al (2016)

How significant is this change for each model? Can we be sure it represents a forced response, not just sampling of the natural variability?

The South West v anomaly compared to natural variability





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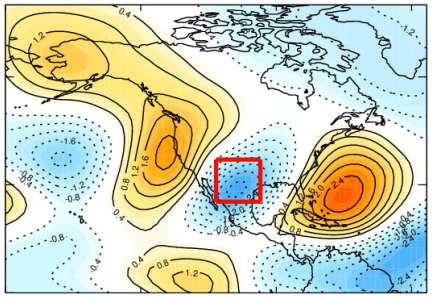
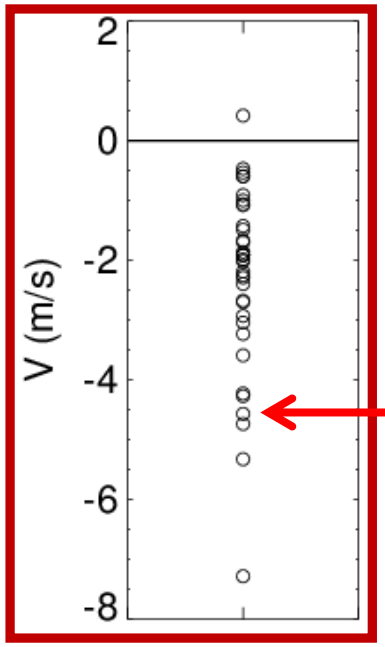
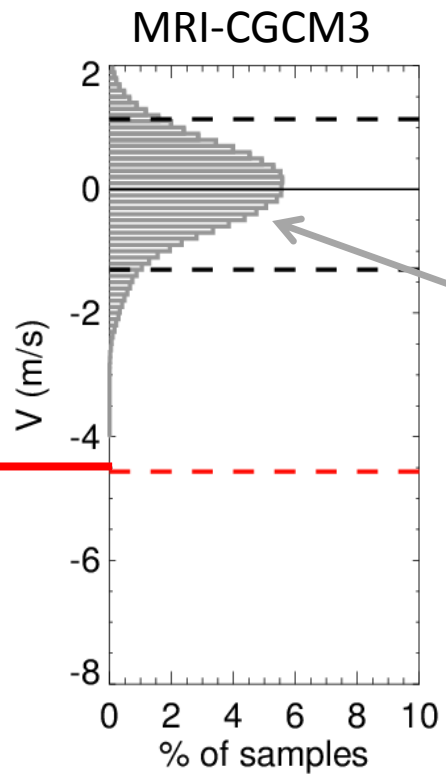


Random sampling from the pre-industrial control simulation



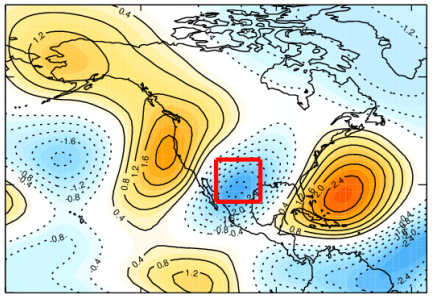


1 rcp8.5 member

3 historical members

Distribution of differences between one 30 year chunk and the mean of three 27 year chunks, randomly sampled from the piControl

The South West v anomaly compared to natural variability



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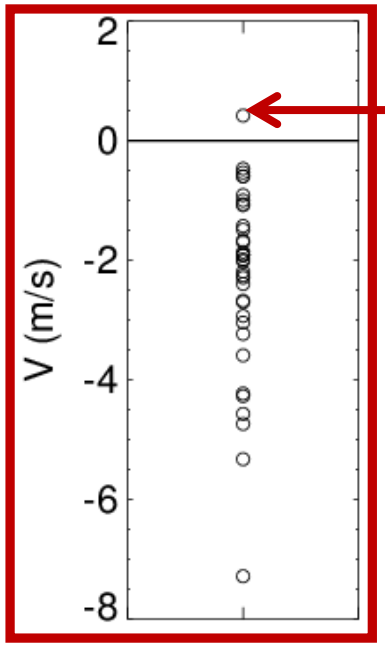
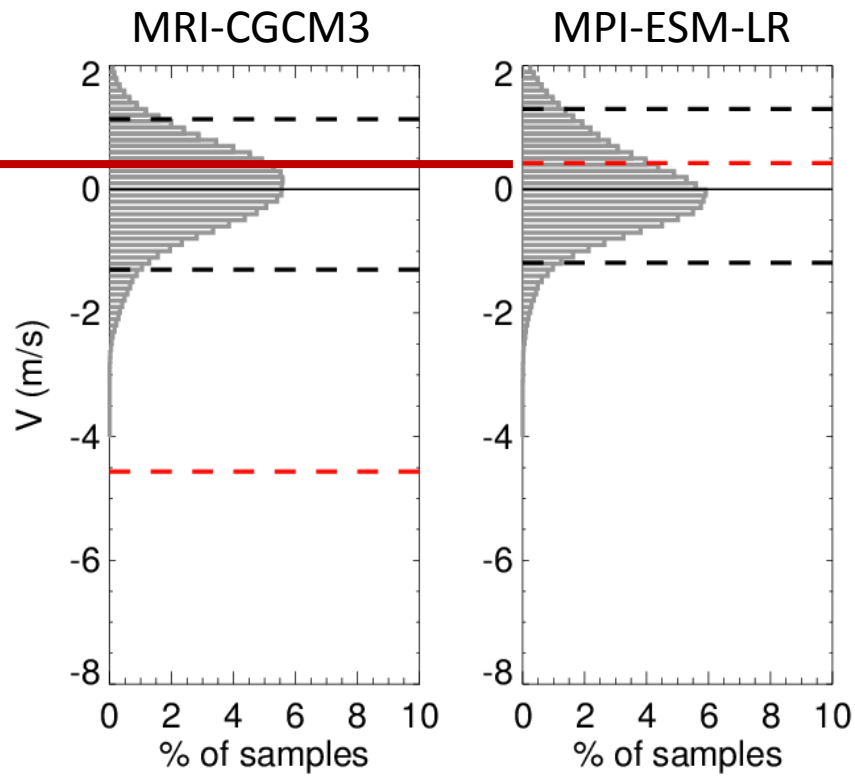
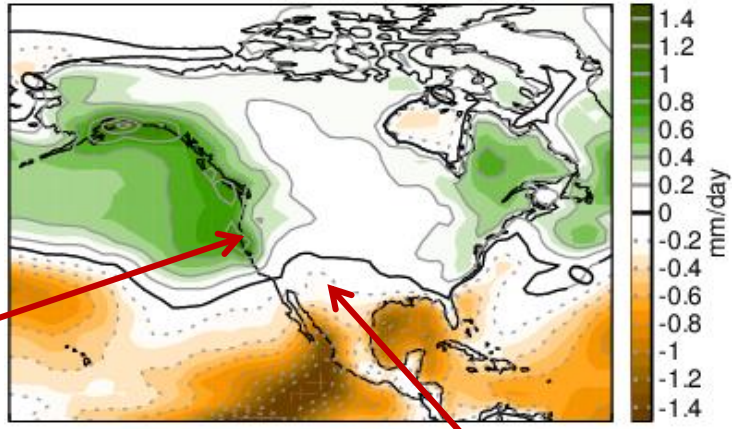




Exploiting the model spread to demonstrate the close link between the meridional wind change and regional hydroclimate change over North America

The relationship between v and P-E

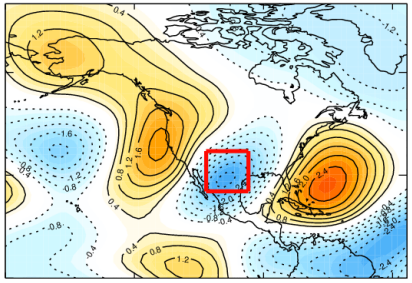
Multi-model mean

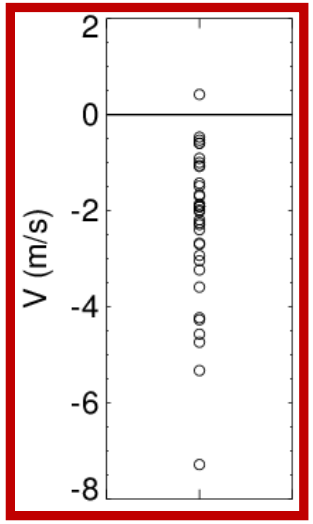


Wetter

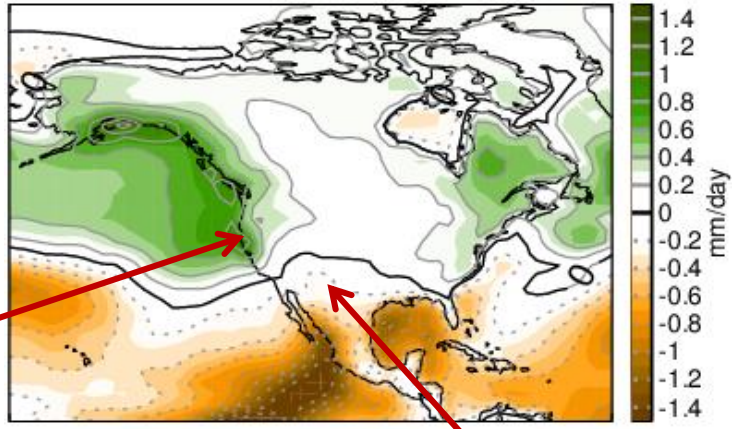
Drier

The relationship between v and P-E





Multi-model mean →



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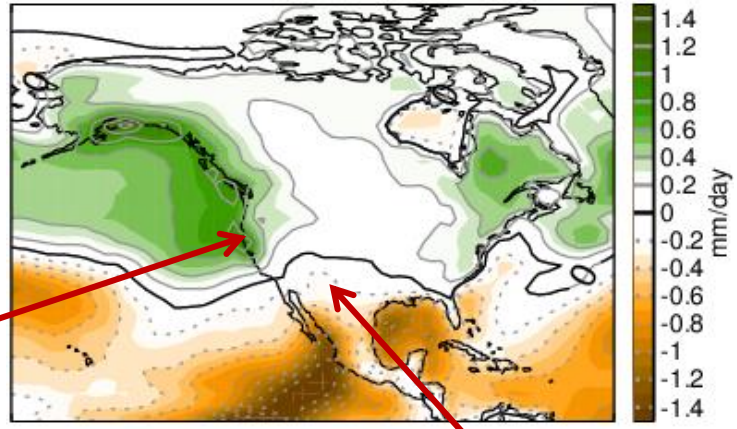
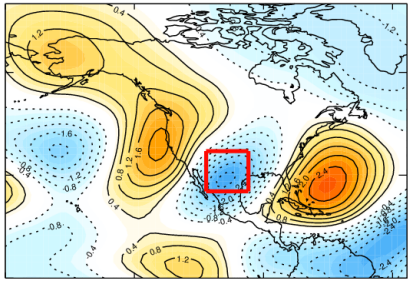
The relationship between v and P-E

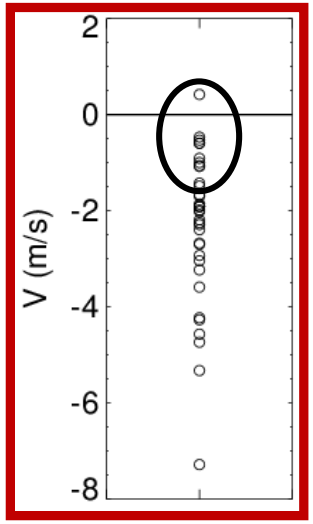
Multi-model mean →



Wetter

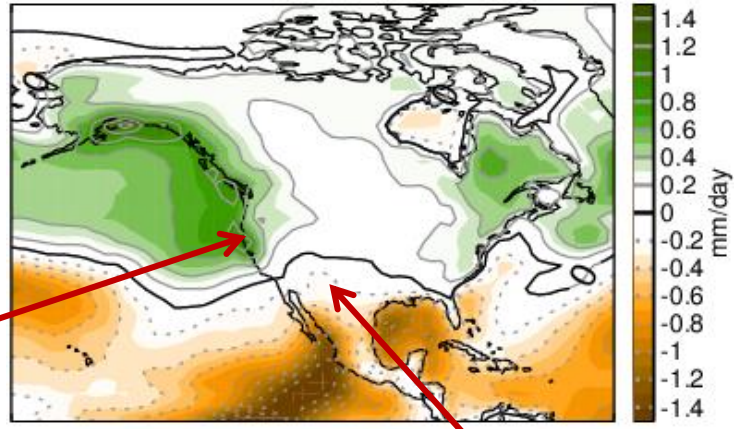
Drier





The relationship between v and P-E

Multi-model mean →



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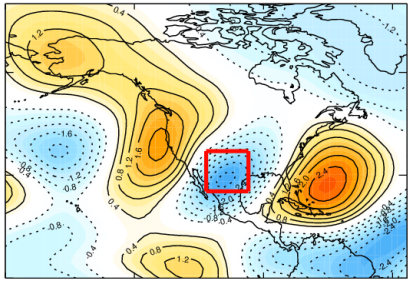
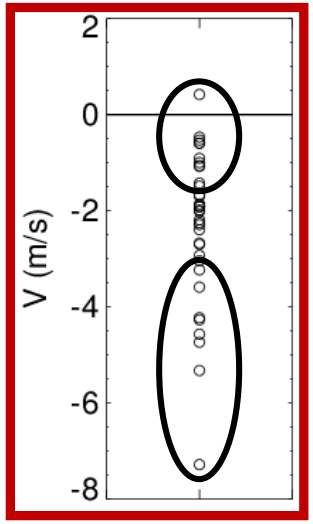
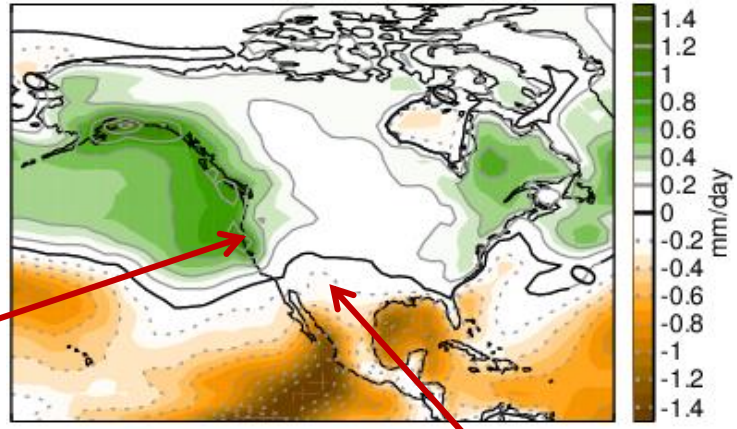




The relationship between v and P-E

Multi-model mean →



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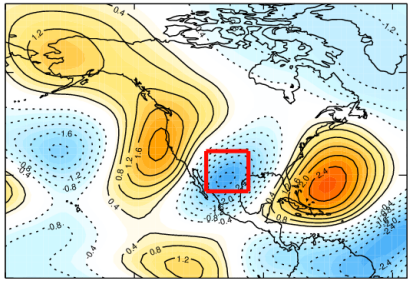
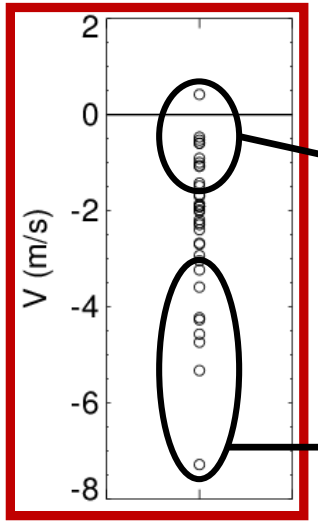
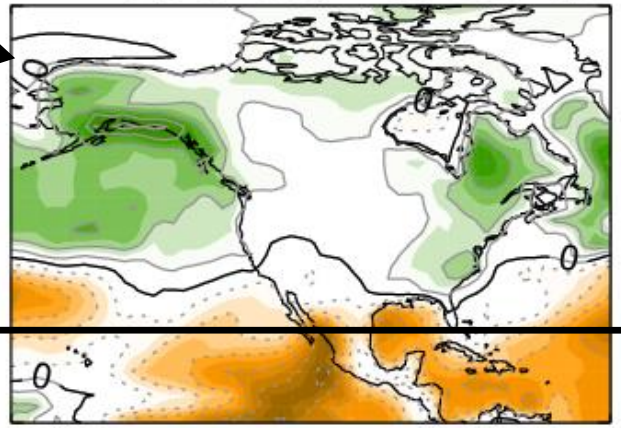
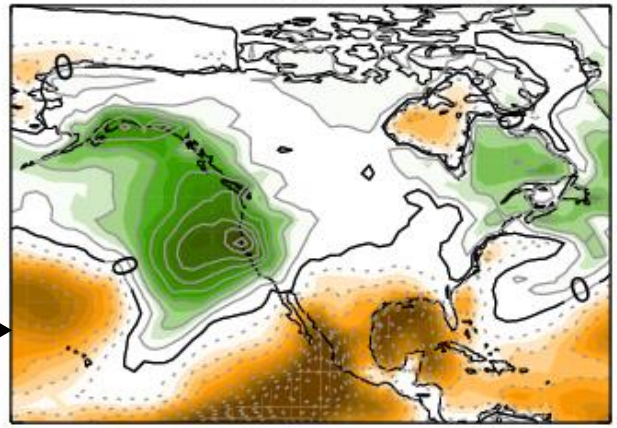




P-E Future-Past, Weakest 25%

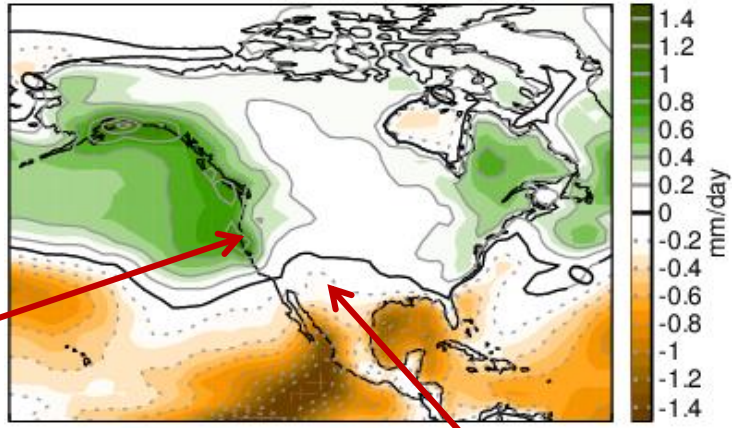


P-E Future-Past, Strongest 25%



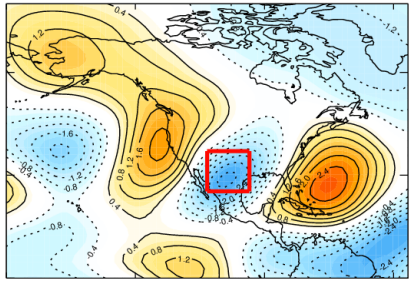
The relationship between v and P-E

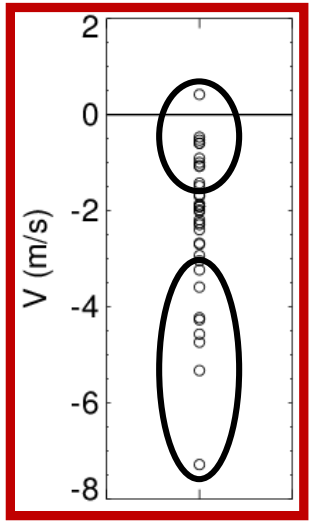
Multi-model mean →

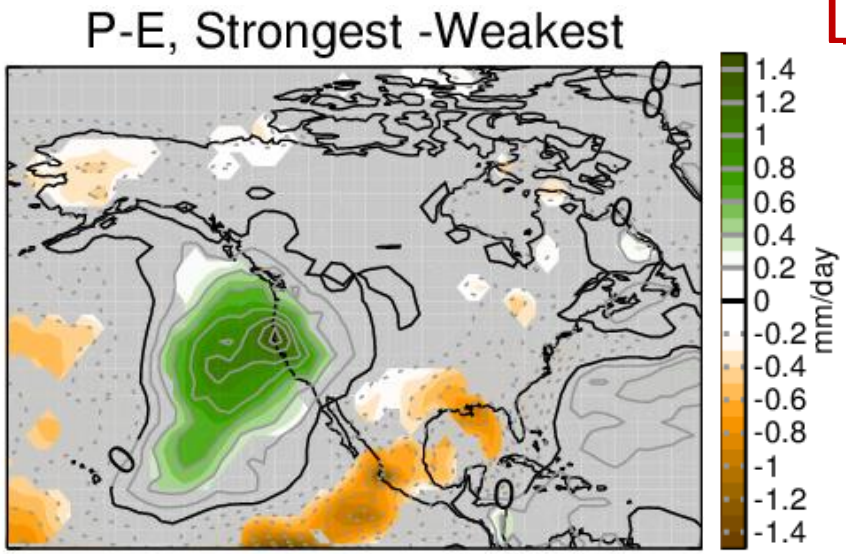


Wetter

Drier



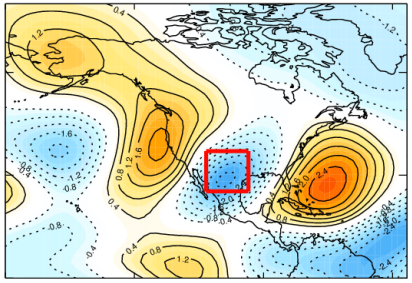




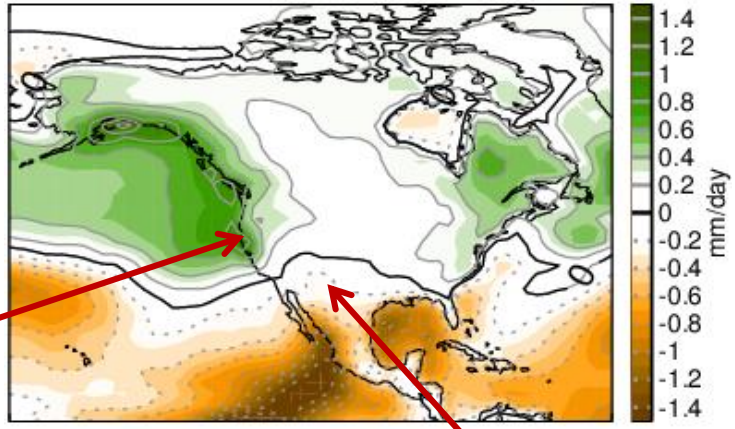
Grey = not statistically significant

Cor(v*,P-E) over California of ~ 0.77

The relationship between v and P-E



Multi-model mean →



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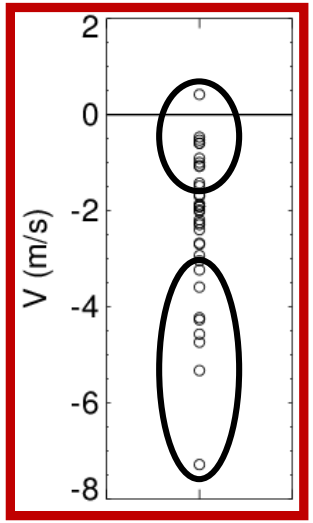
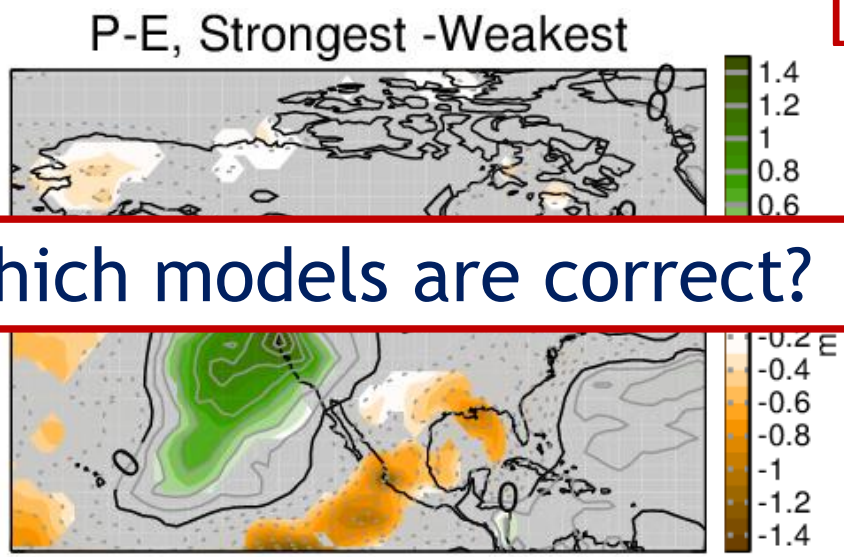
Drier





Which models are correct?

Grey = not statistically significant

Cor(v*,P-E) over California of ~ 0.77

Understanding the mechanism responsible for the multi-model mean response.

Going beyond the CMIP archive.

- Stationary wave modelling to pull apart the mechanisms responsible for the meridional wind change.
- Found an important role for the increased zonal wind in the sub-tropical upper troposphere in changing the stationary wave field.

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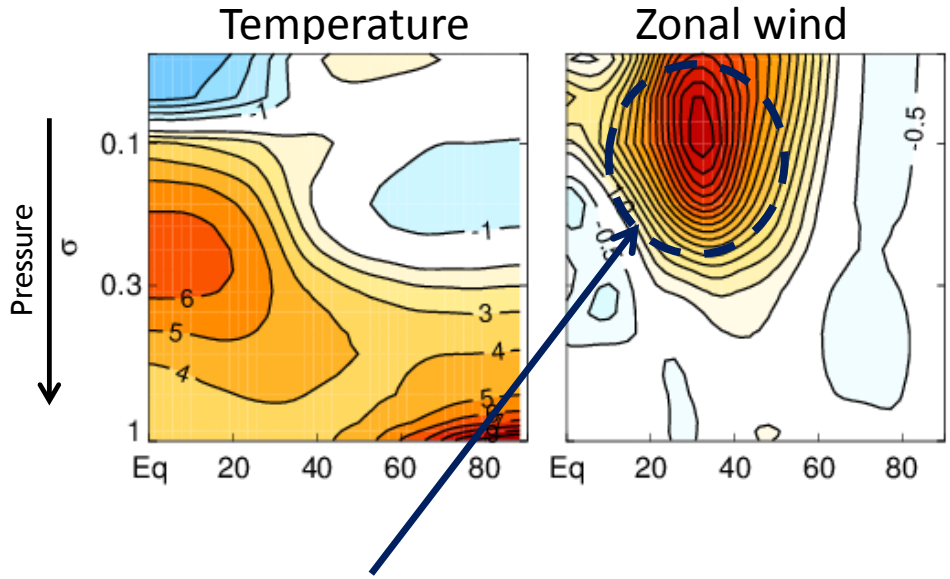

Future – Past difference in zonal mean temperature and zonal wind

Acceleration of the zonal wind in the sub-tropical upper troposphere is key

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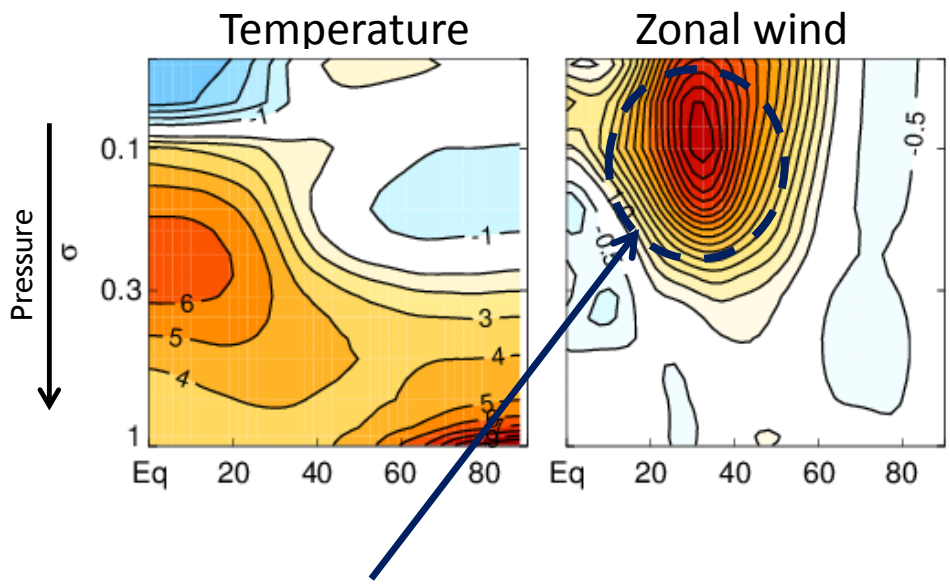
- Found an important role for the increased zonal wind in the sub-tropical upper troposphere in changing the stationary wave field.



Future – Past difference in zonal mean temperature and zonal wind

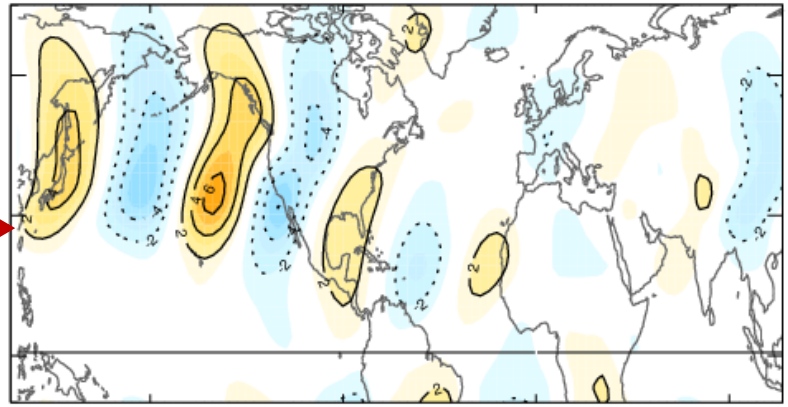
Acceleration of the zonal wind in the sub-tropical upper troposphere is key

Acts to lengthen the preferred scale of intermediate wavelength stationary waves
Zonal wavenumbers 4 and above

See Simpson, Seager, Ting and Shaw (2016), Nat. Clim. Change, 6, 65-70 for more details

Filtered 300hPa meridional wind (zonal wavenumbers four and above)

Past Climatology (contour=2m/s)



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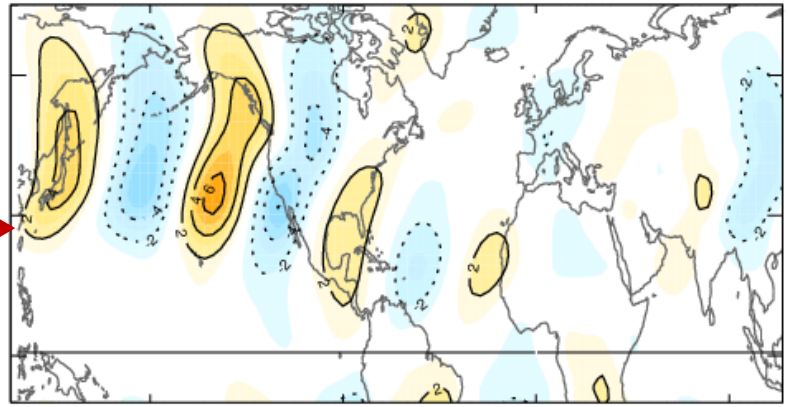
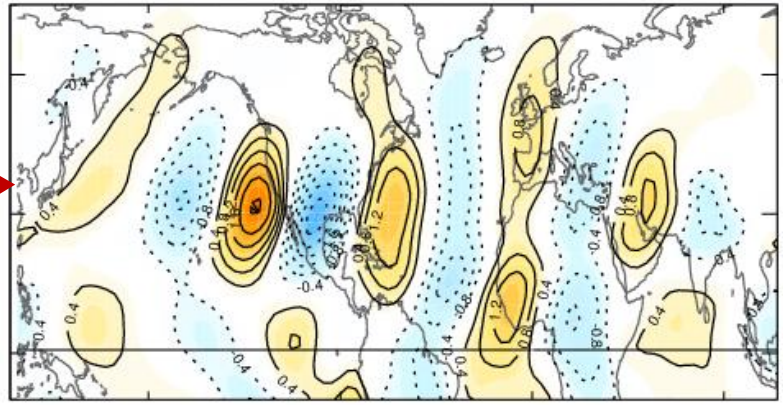


CMIP5 multi-model mean

Future-Past Difference contour=0.4m/s



Filtered 300hPa meridional wind (zonal wavenumbers four and above)

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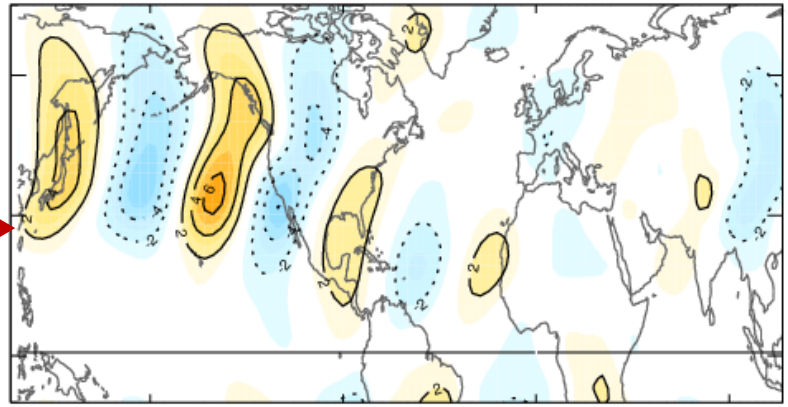

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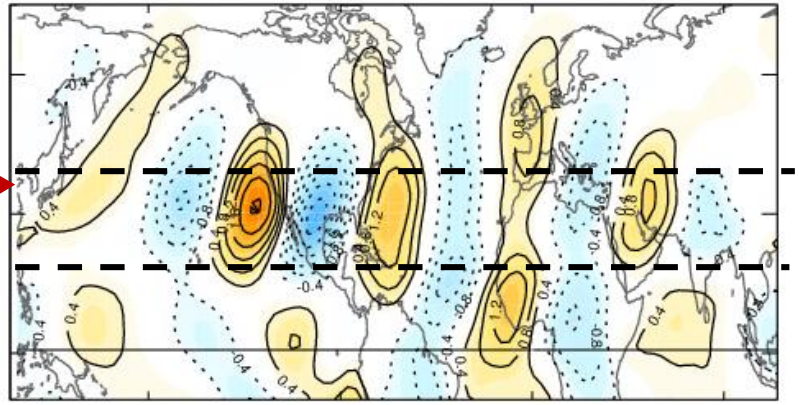

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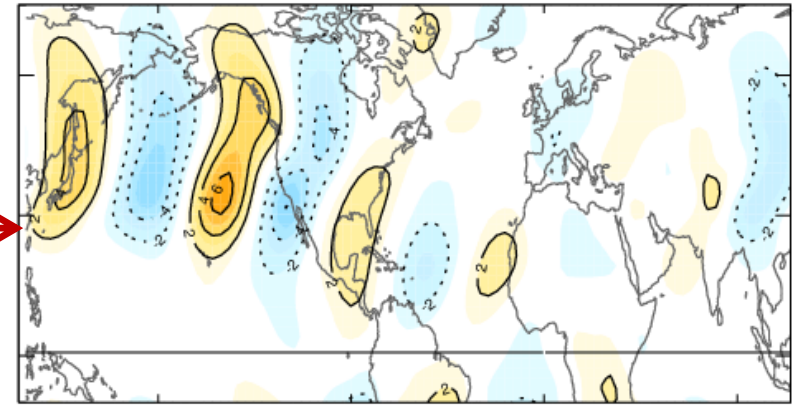

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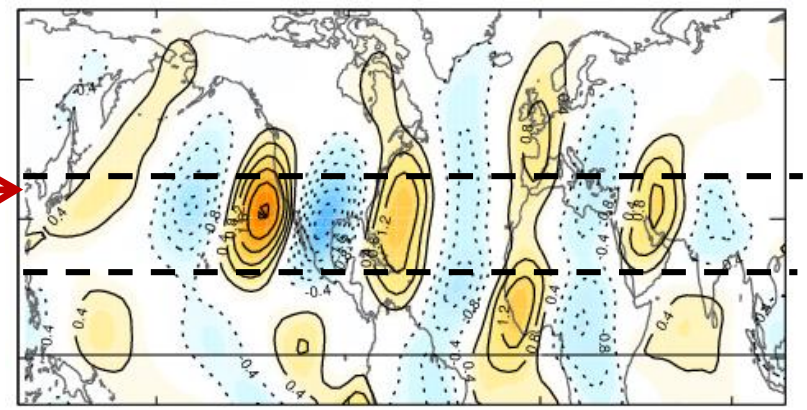
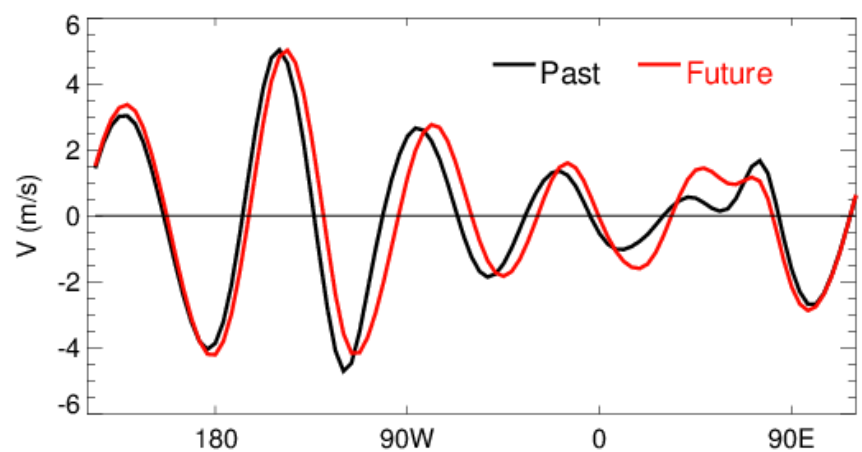
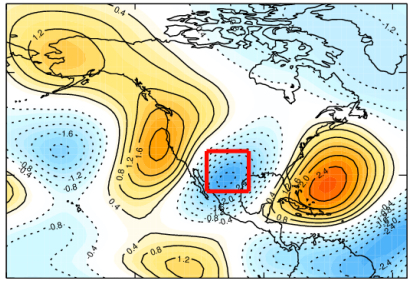
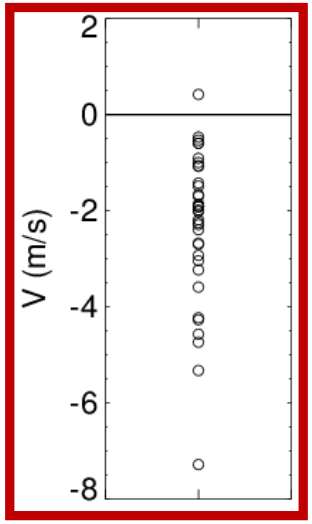


A lengthening of the preferred scale of intermediate wavelength stationary waves, consistent with a reduced stationary wavenumber in the presence of the accelerated zonal wind

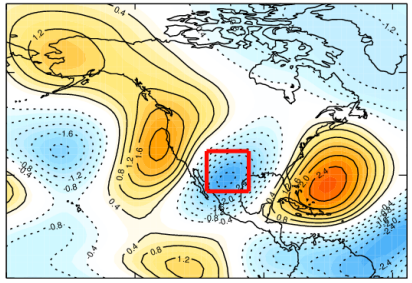


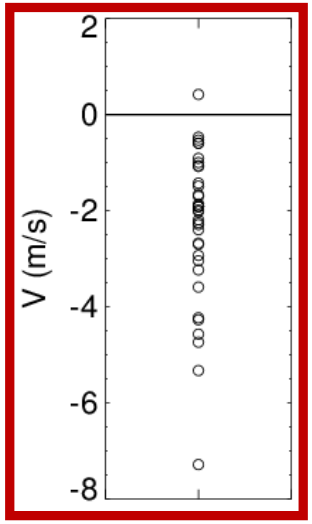




Given this hypothesized mechanism, can we go back to the CMIP5 data and understand the model spread?

Why the spread in the magnitude of the response?





Two Factors:

(1) The amplitude of the intermediate scale stationary waves in a model's climatology

Larger Amplitude → Larger response

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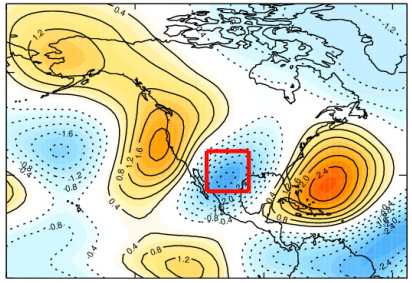
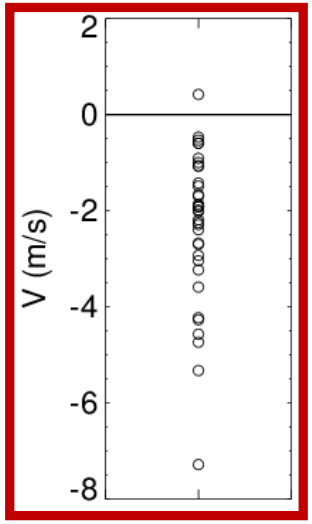




Two Factors:

(1) The amplitude of the intermediate scale stationary waves in a model's climatology

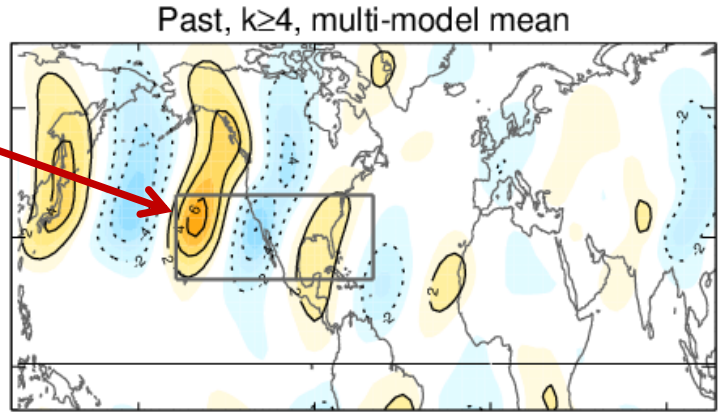
Larger Amplitude → Larger response

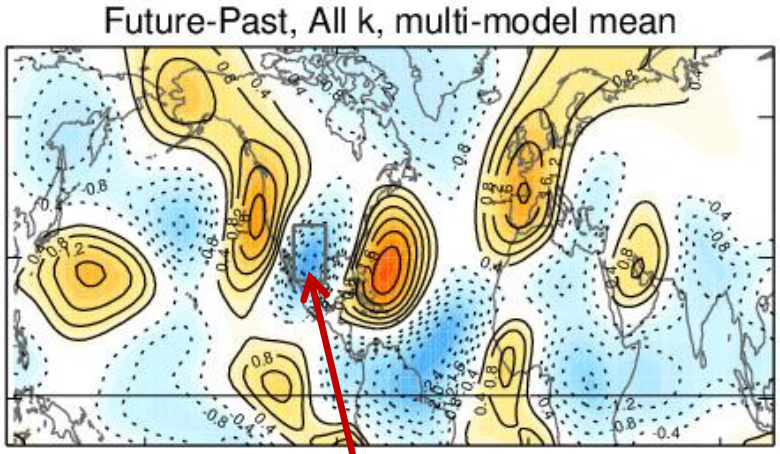
(2) The increase of the zonal wind in the sub-tropical upper troposphere

Larger increase → Larger response

Regression of the meridional wind response against those two quantities

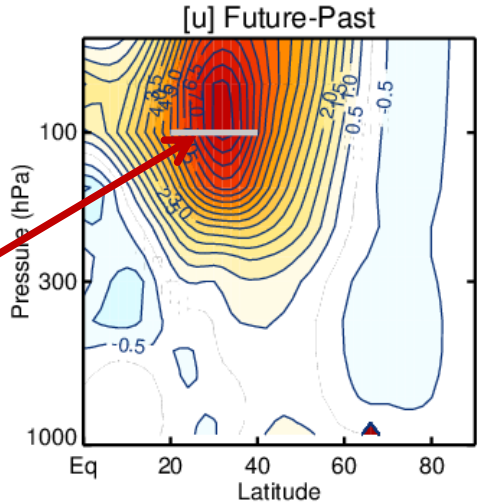
Climatological k≥4 amplitude this region





VS

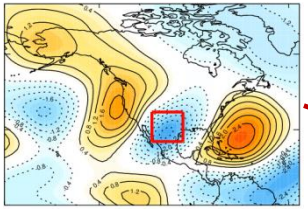
South West North American v* response

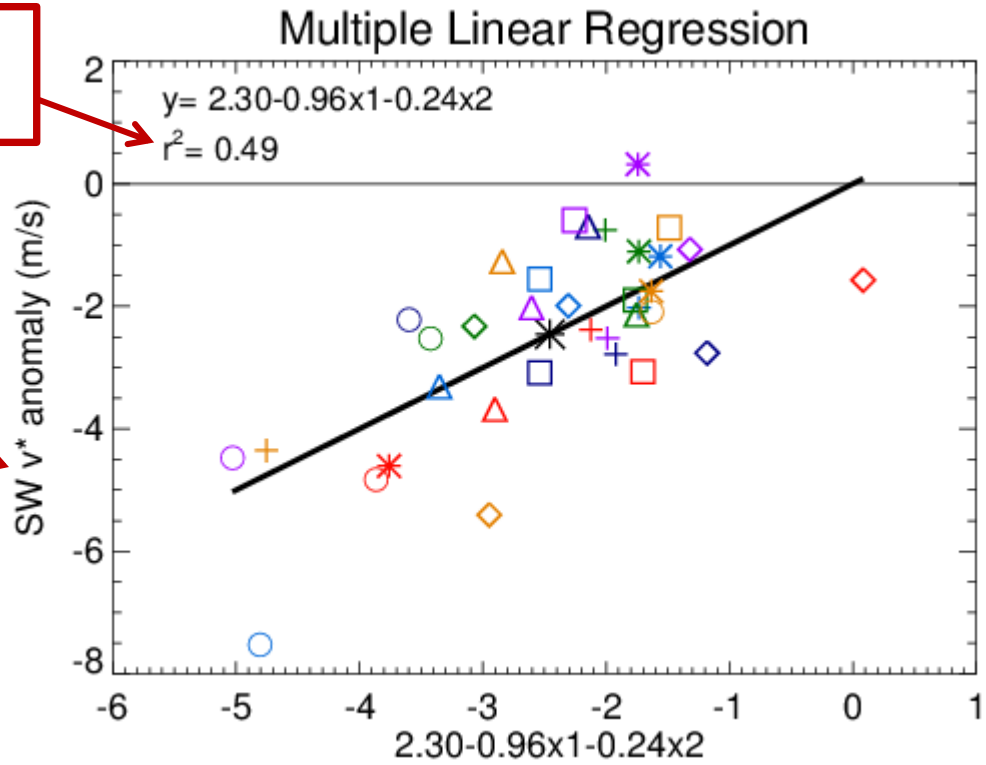


Westerly acceleration in the sub-tropical upper troposphere

Multiple linear regression of North American v* response onto climatological wave amplitudes and [u] response

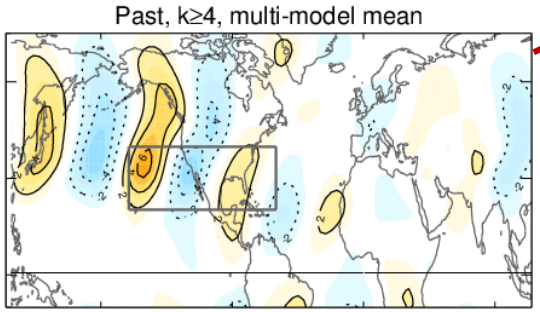
~49% of model variance explained

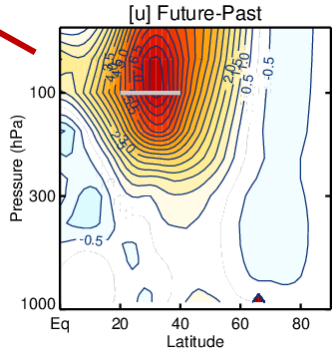




Increasing amplitude of response

~37%





~12%

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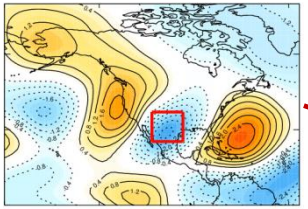

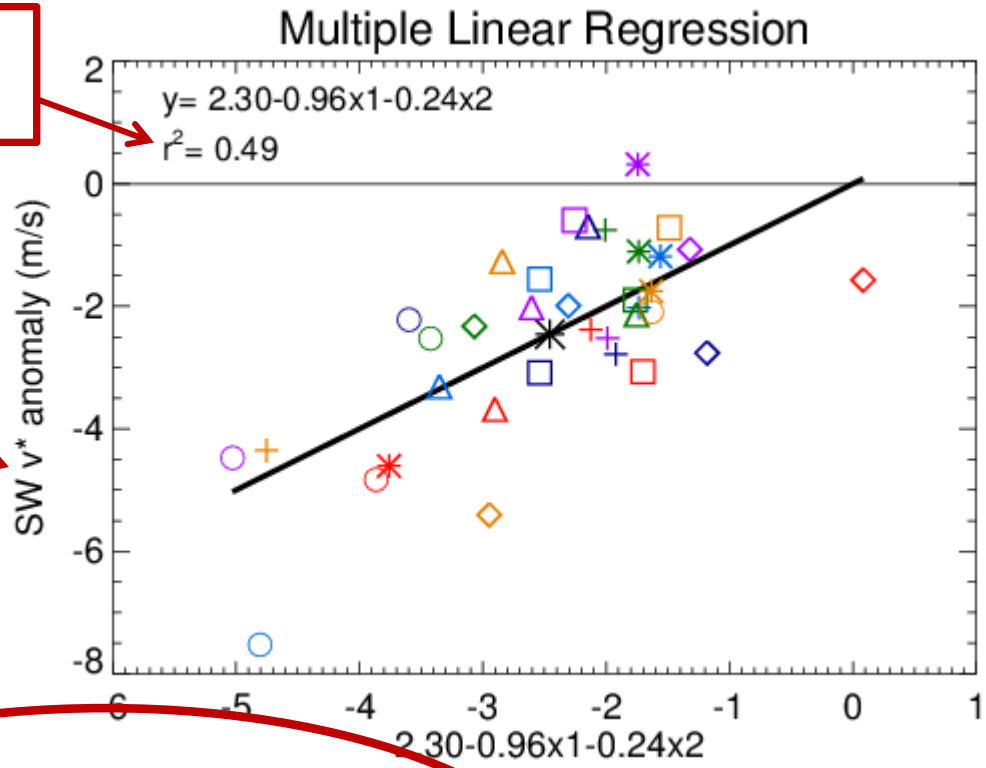

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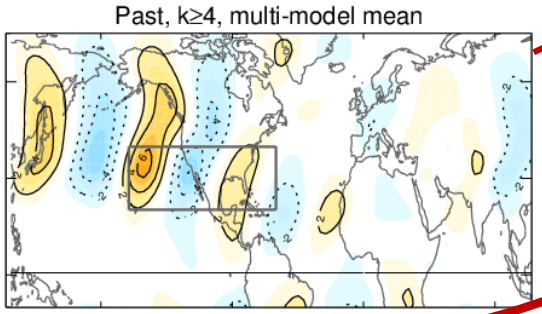
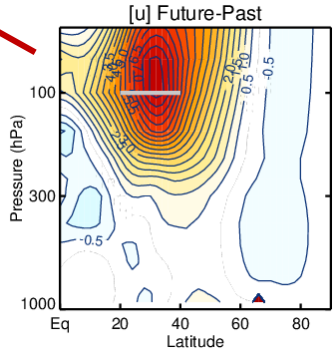
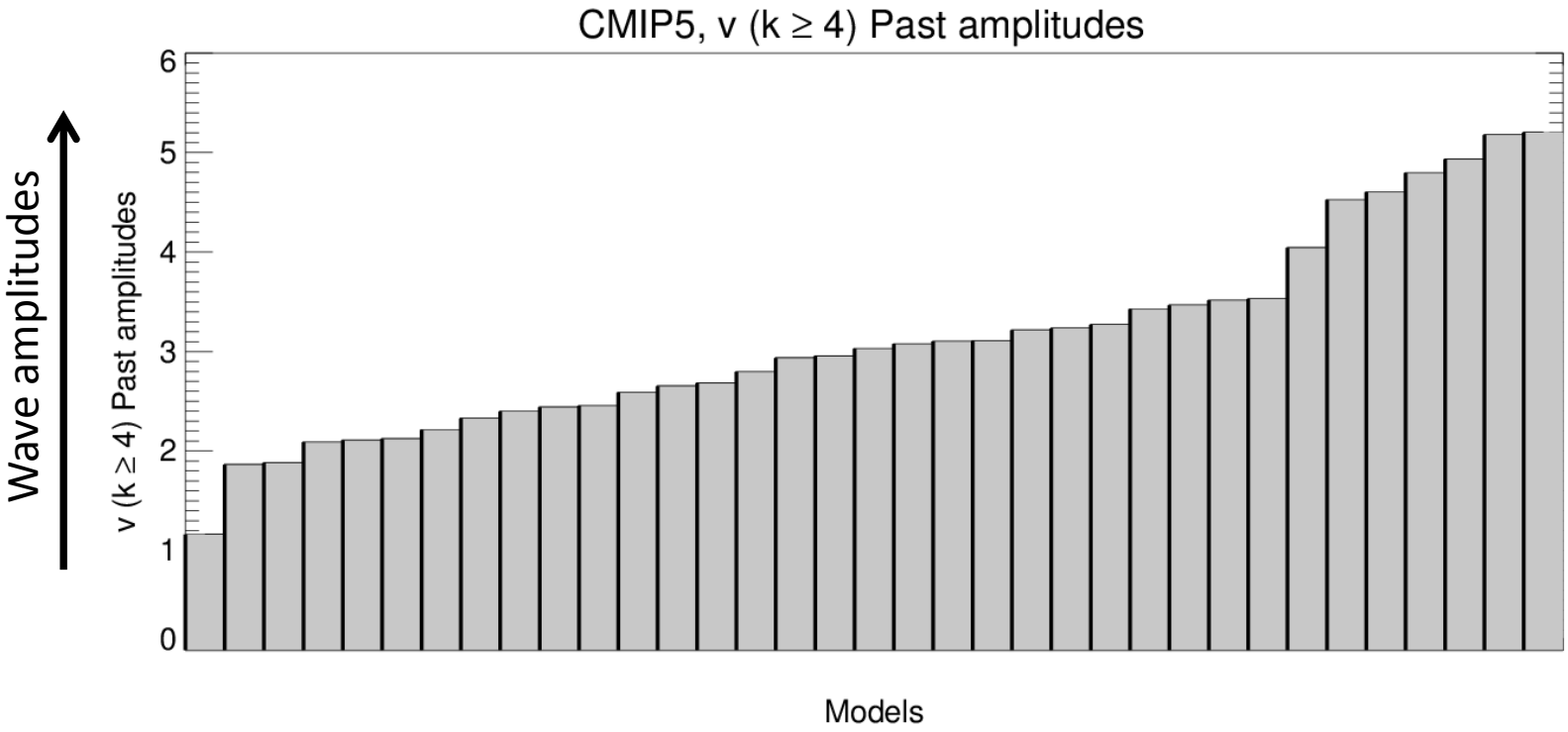




~12%

Using the relationship between climatological wave amplitudes and the forced response to place a constraint on how we think the real world will change.

Most models have climatological v* amplitudes that are too large in this region



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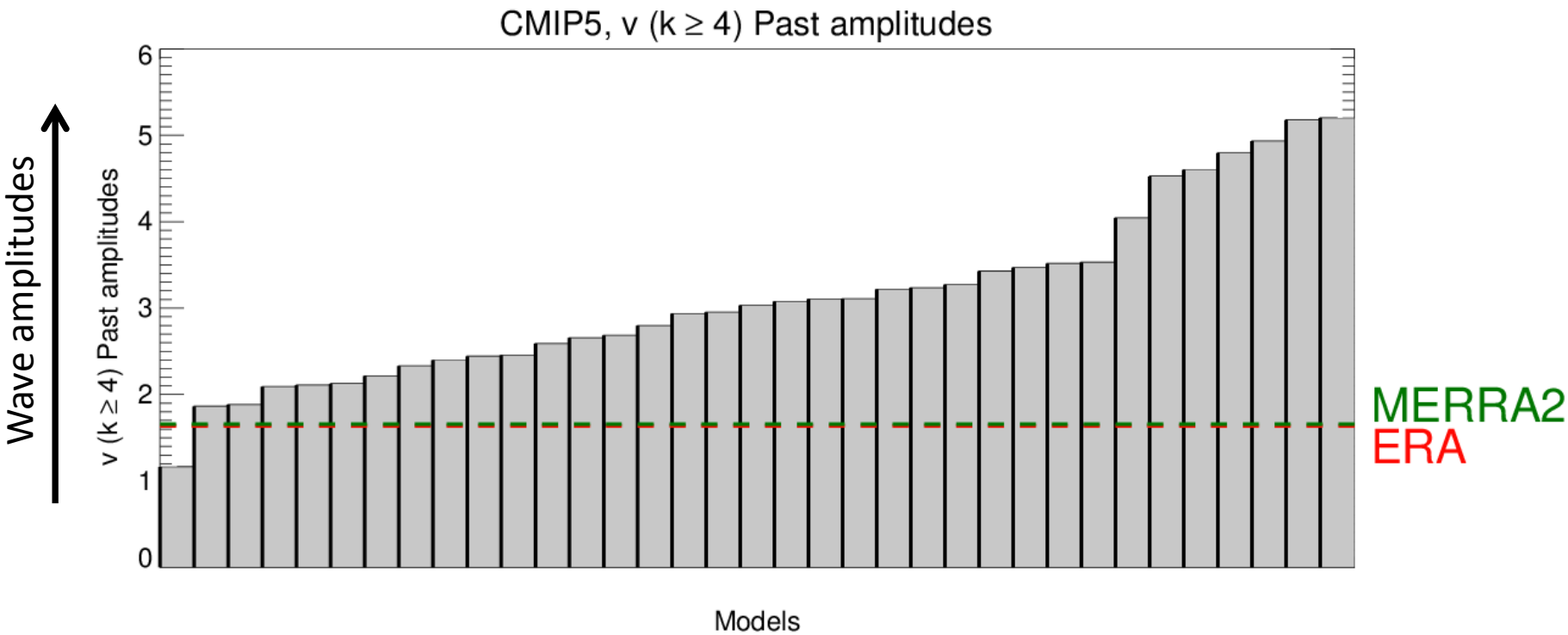

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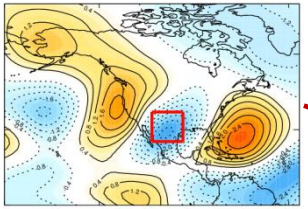

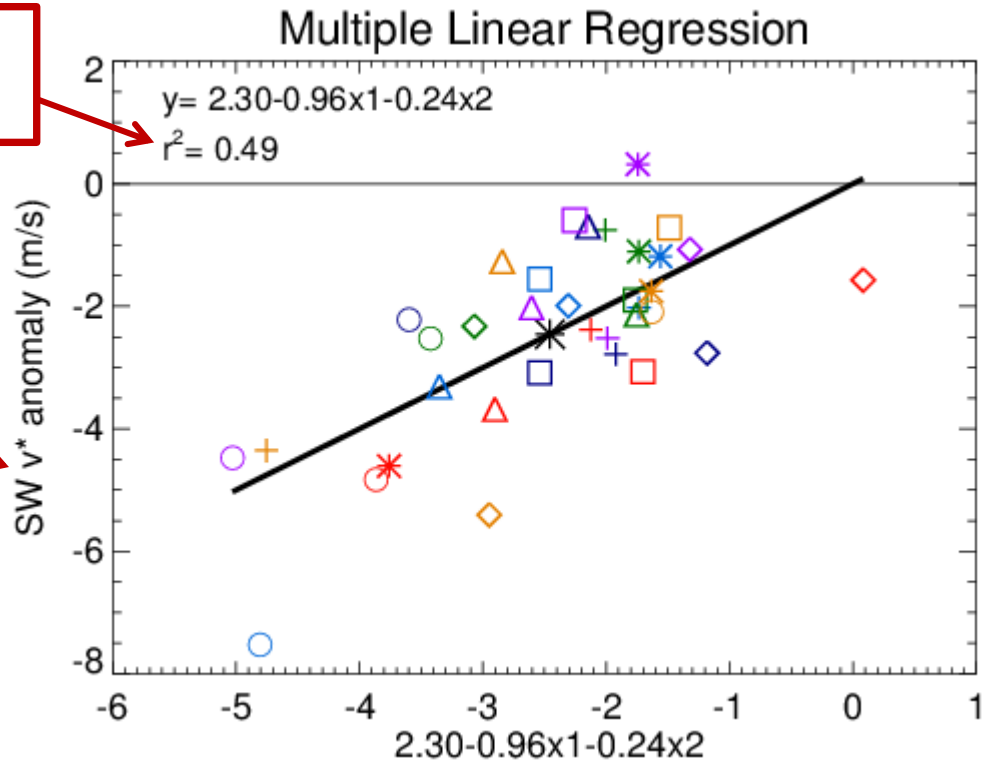

Increasing amplitude of response

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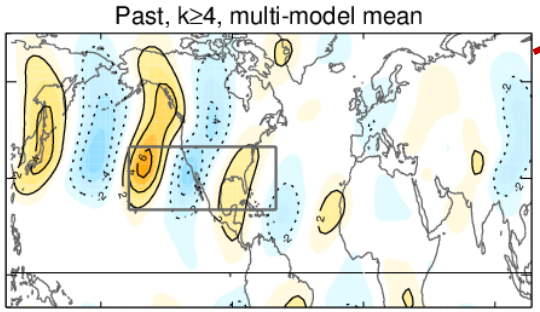

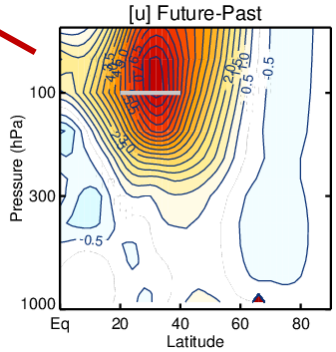

~12%

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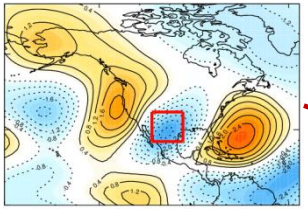
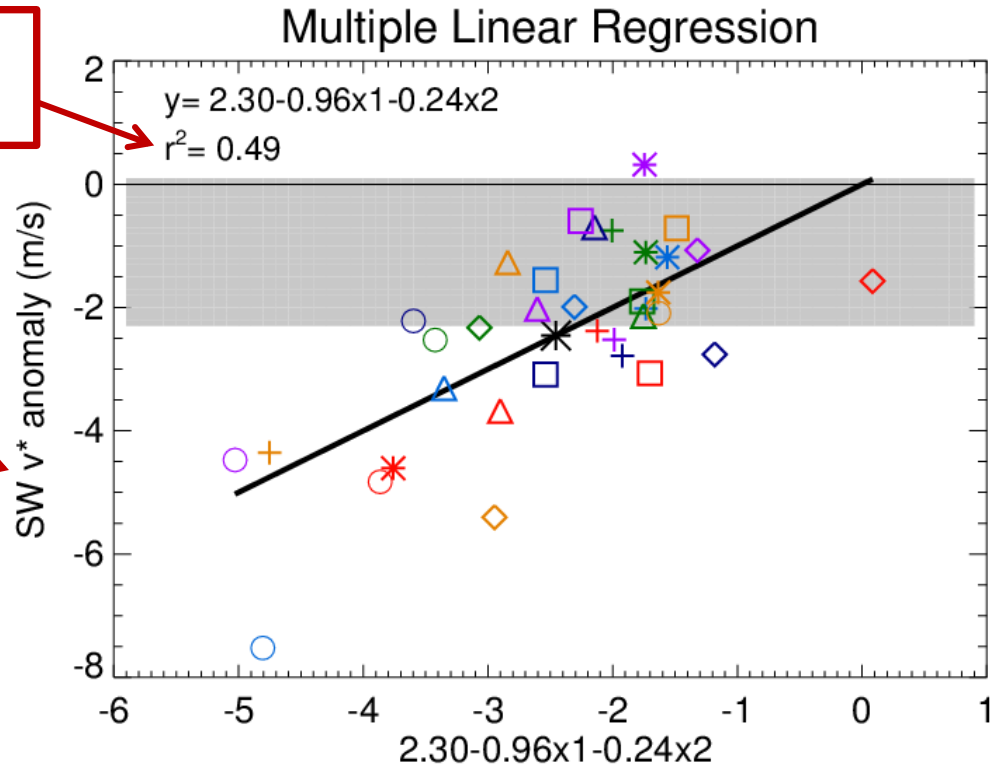
~49% of model variance explained

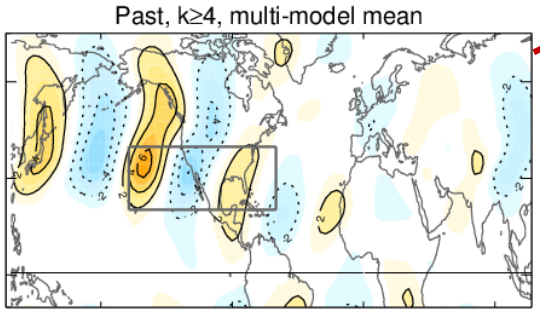


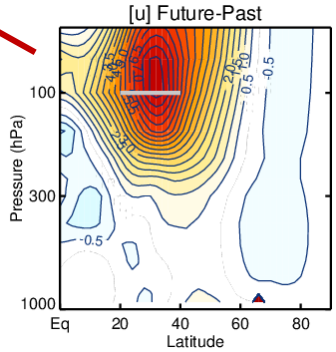


Predicted real world range

Increasing amplitude of response

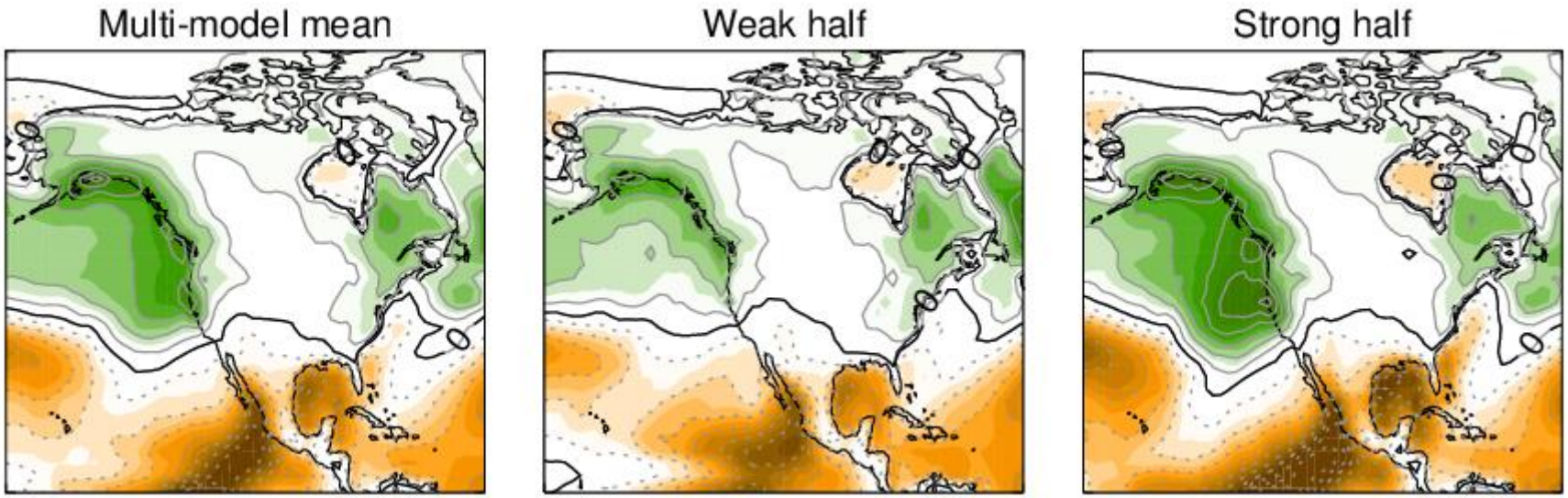
~37%





~12%

The real world is unlikely to become as wet in the U.S. west coast or as dry over Mexico and the interior southwest as the multi-model mean predicts



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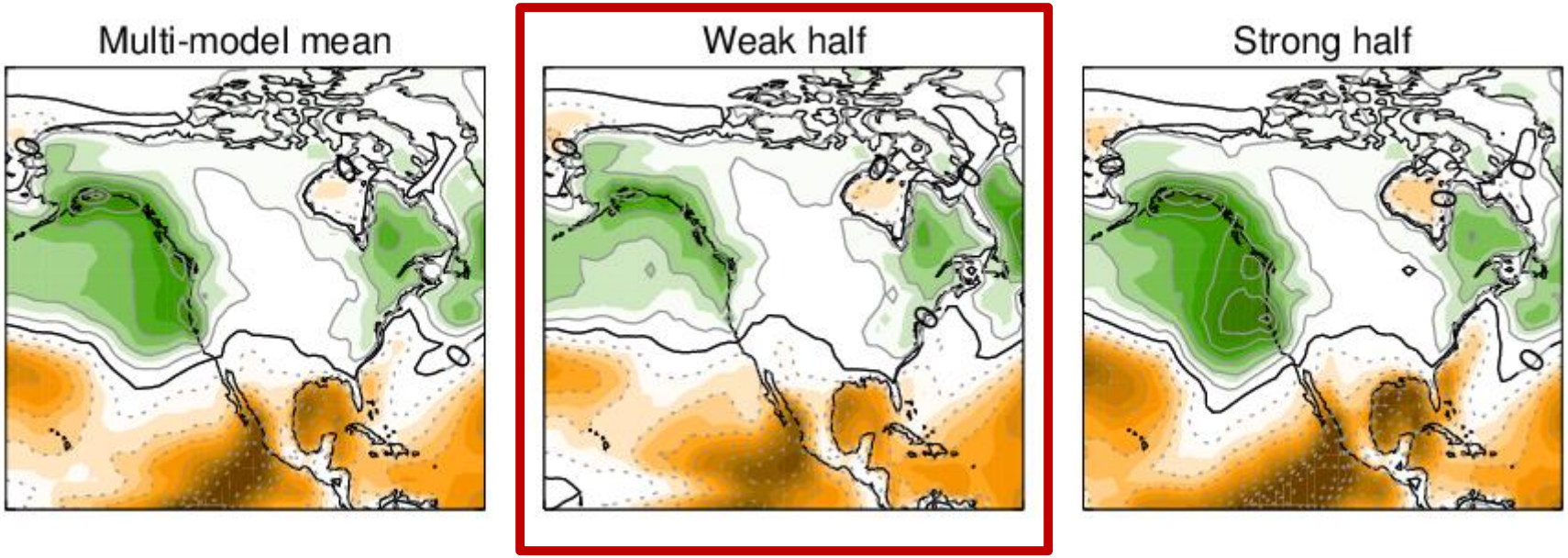

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(7) Link between a models climatology and its forced response allows a constraint to be placed on the future of the real world.

Thanks!

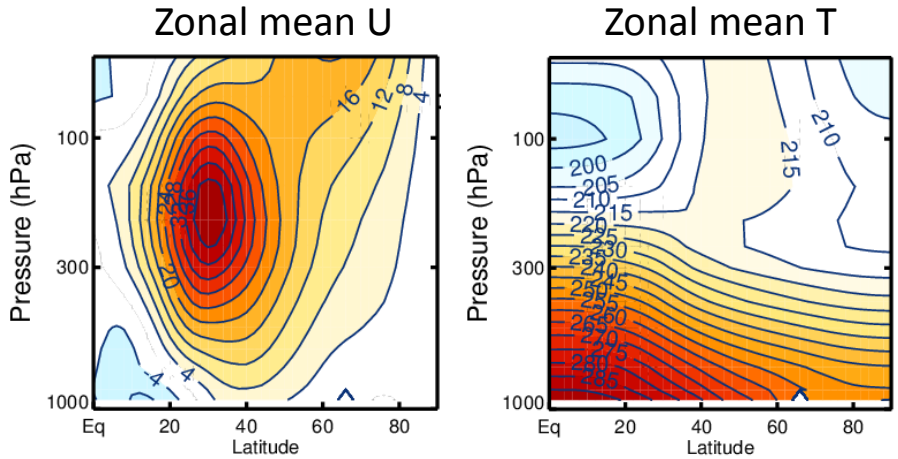
islas@ucar.edu

Example NCL script for grabbing out a specified variable/level/time period:

/glade/u/home/islas/cmiptutorial/output_time_level_var.ncl

Extra Slides

zonal mean basic state

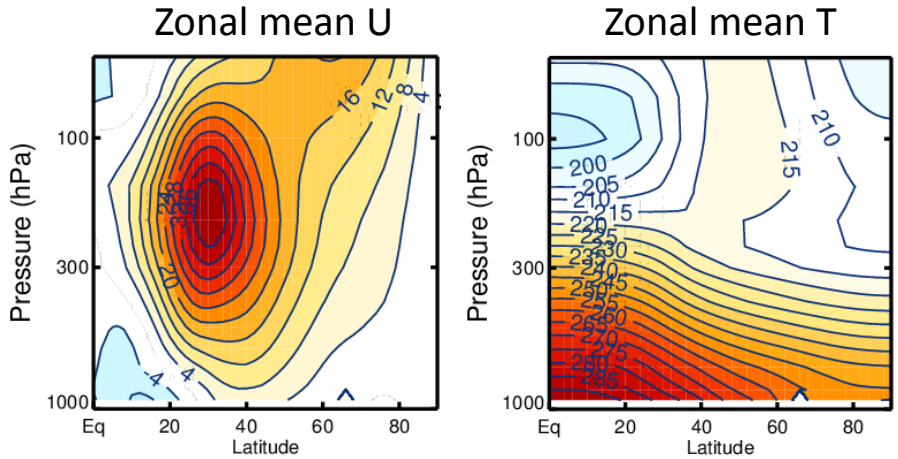


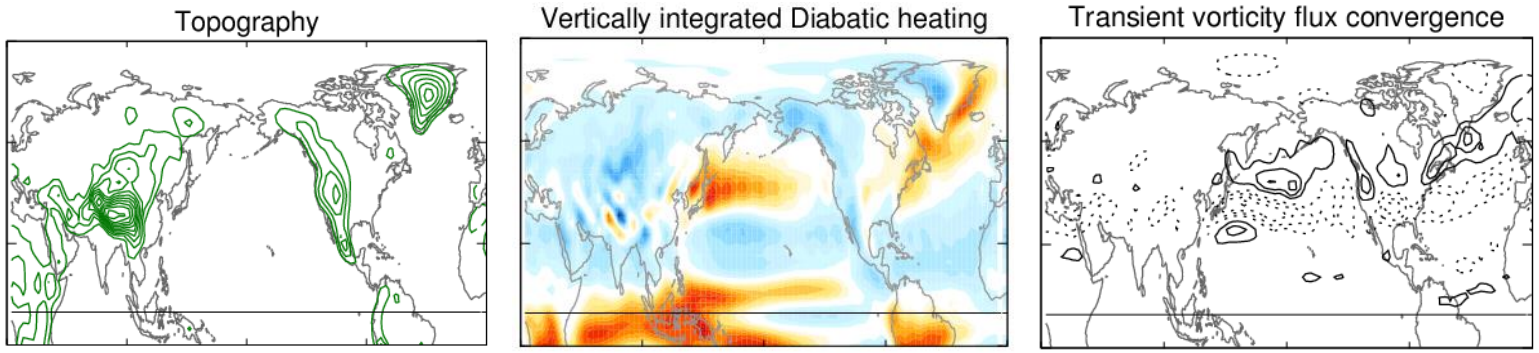
e.g., Held et al (2002)

zonal mean basic state

+

zonally asymmetric forcings





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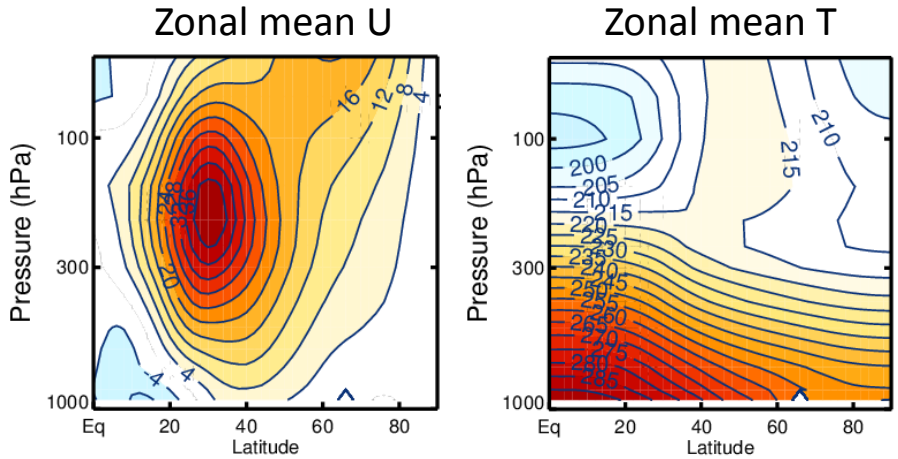
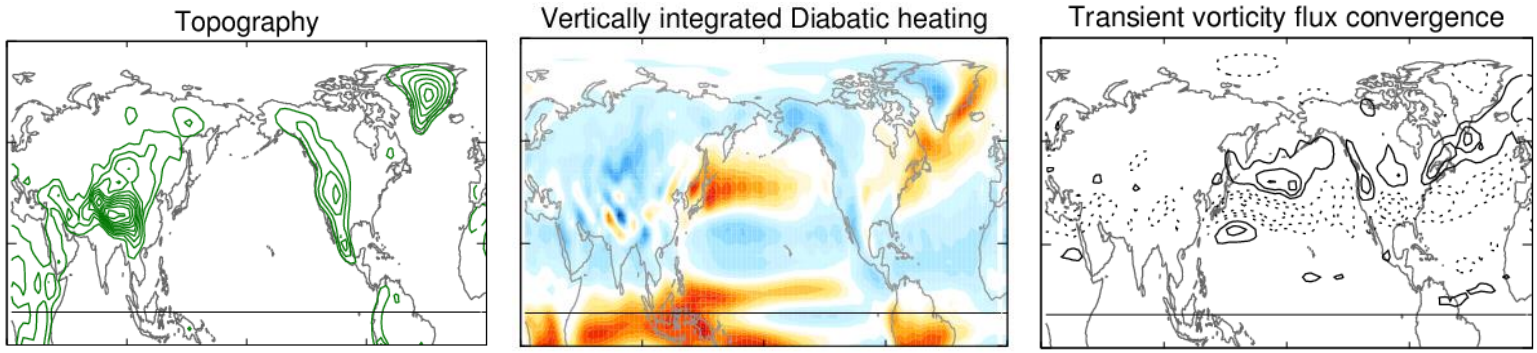
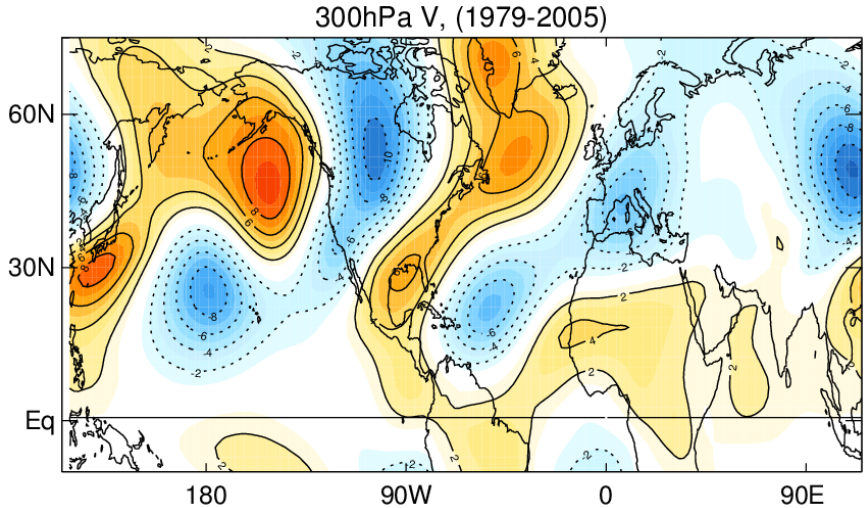
Stationary waves







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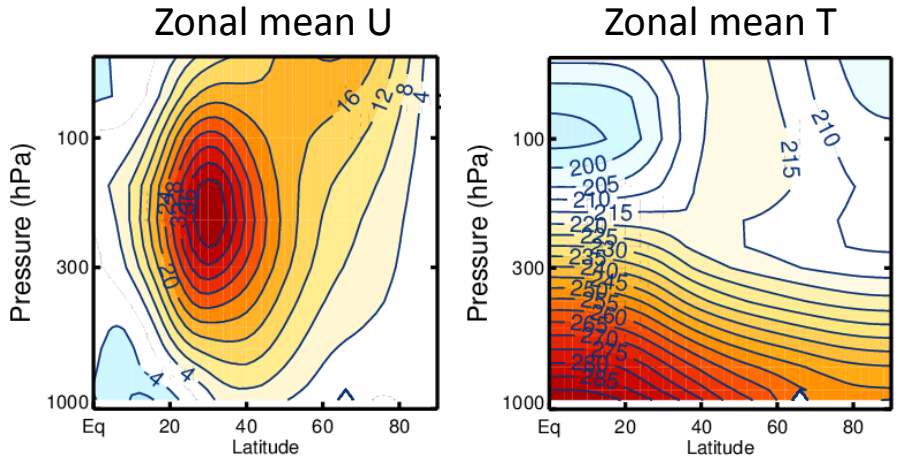

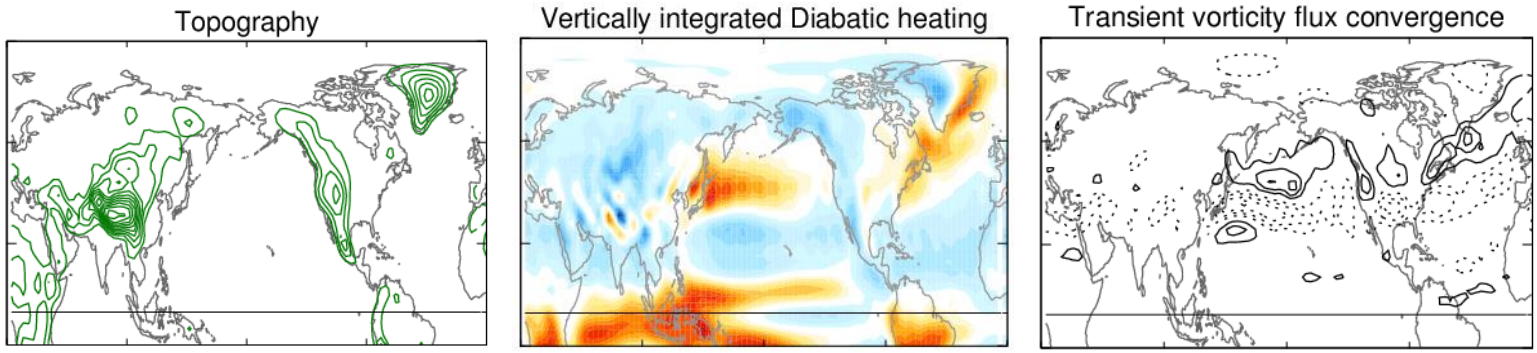

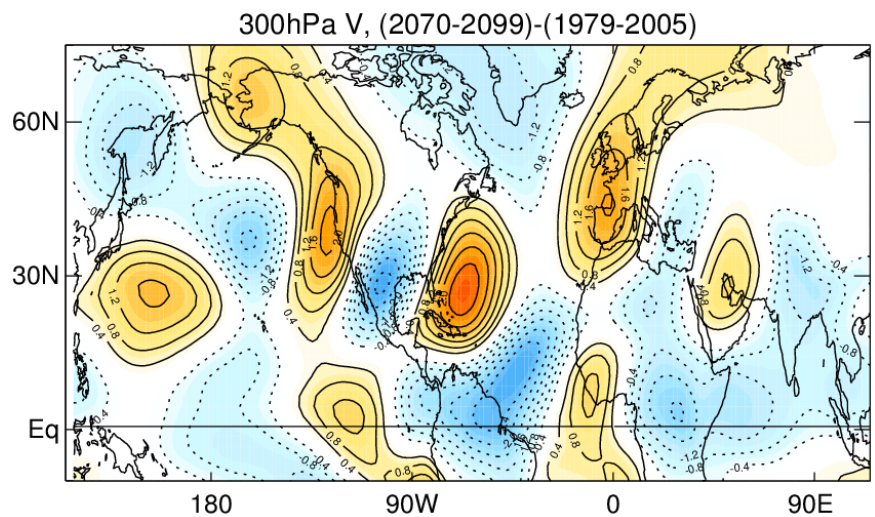

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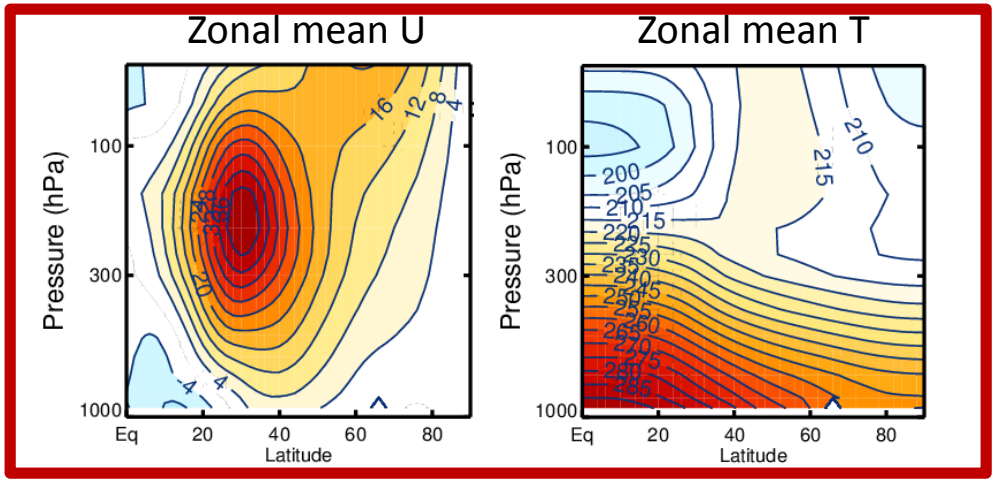

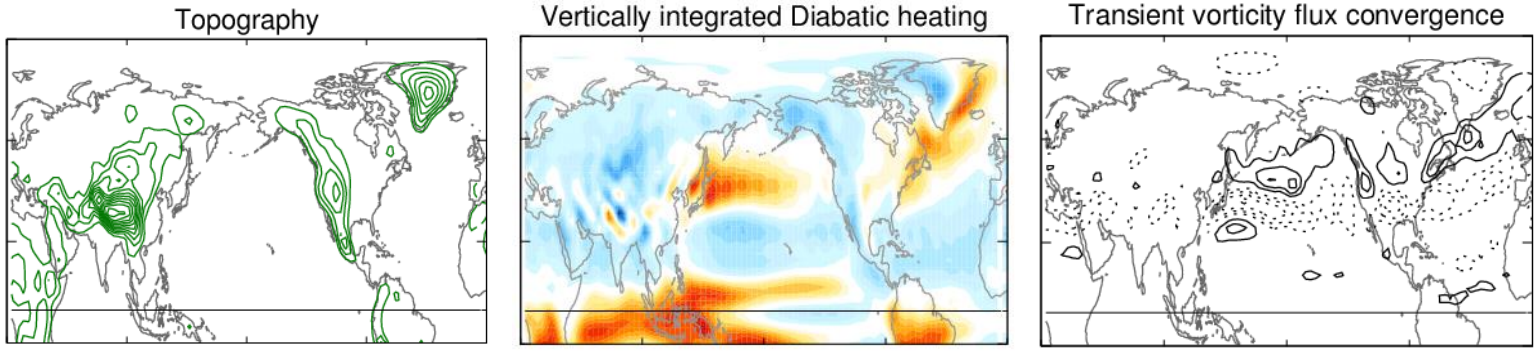

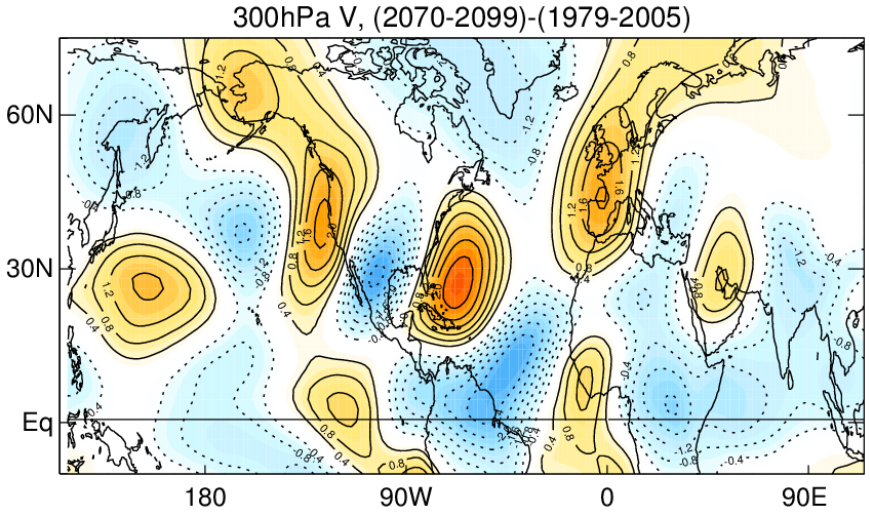

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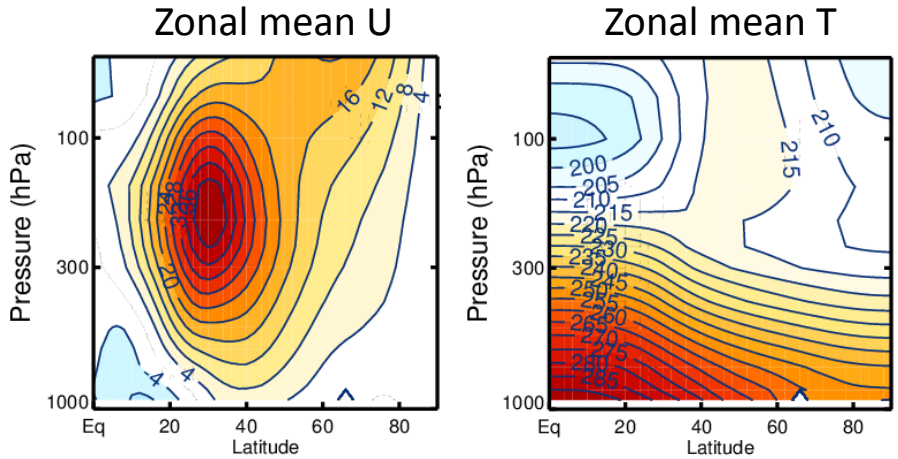

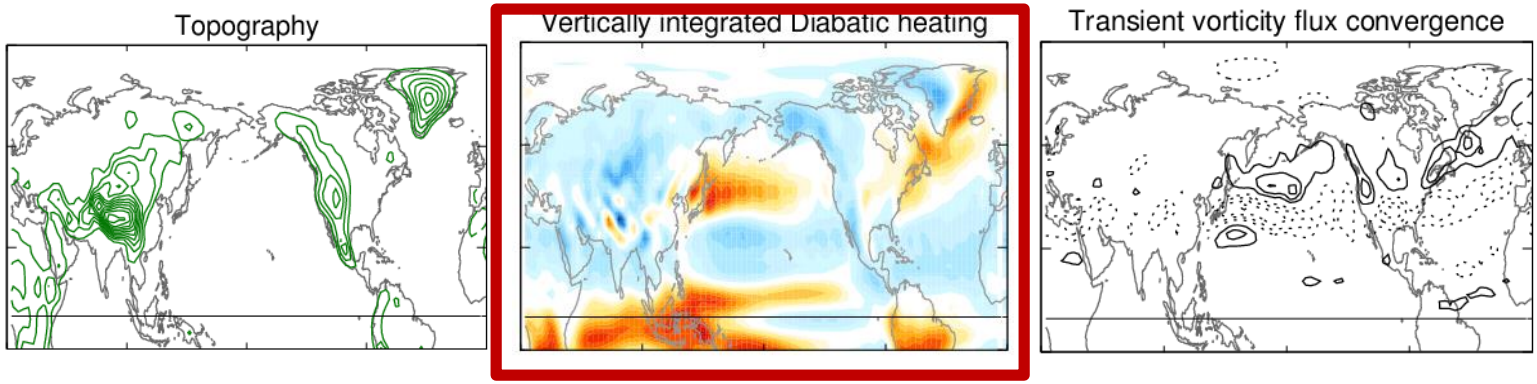

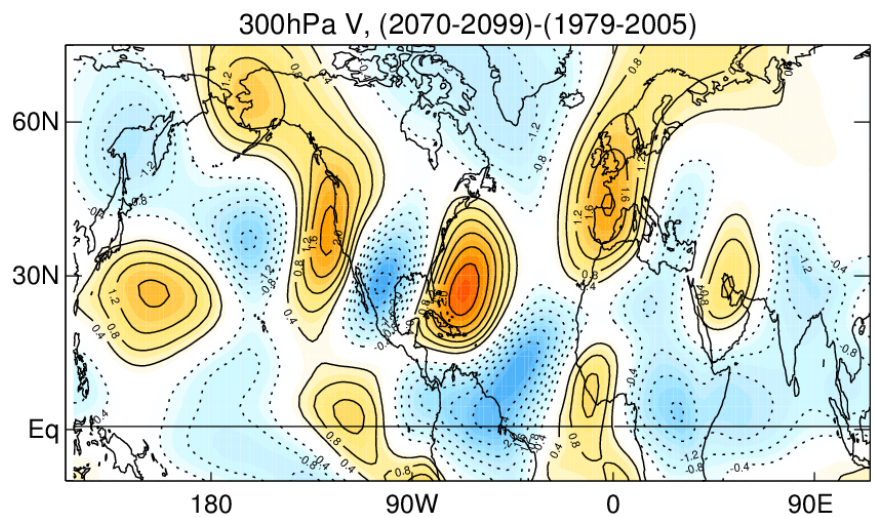

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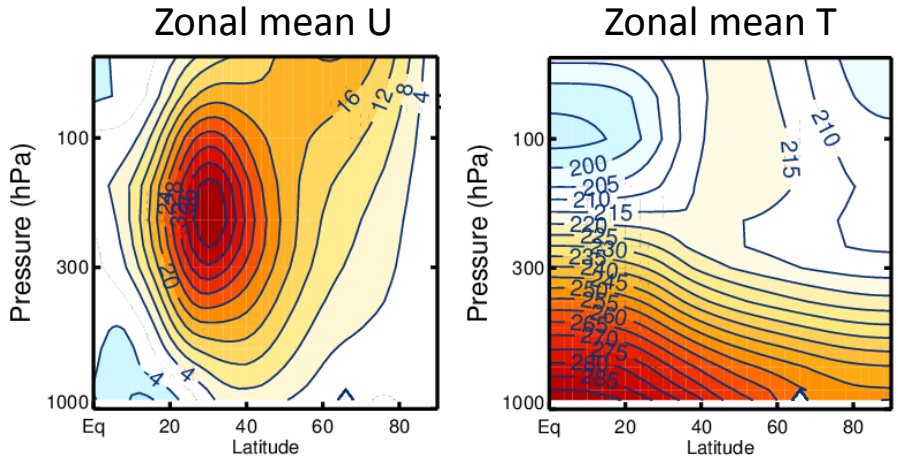

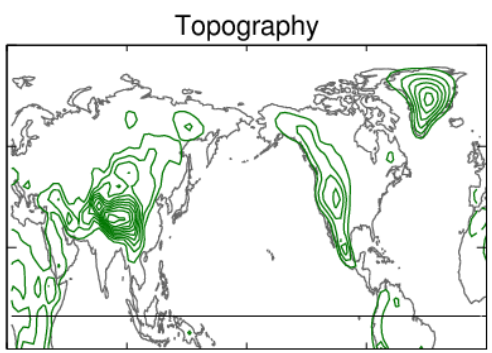

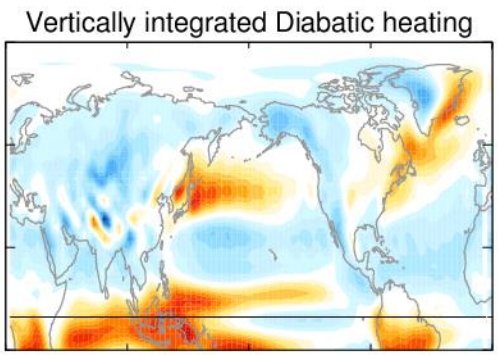

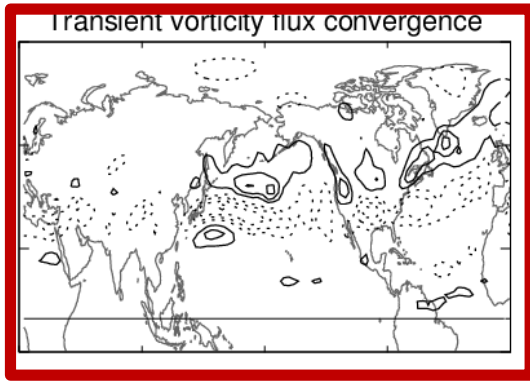

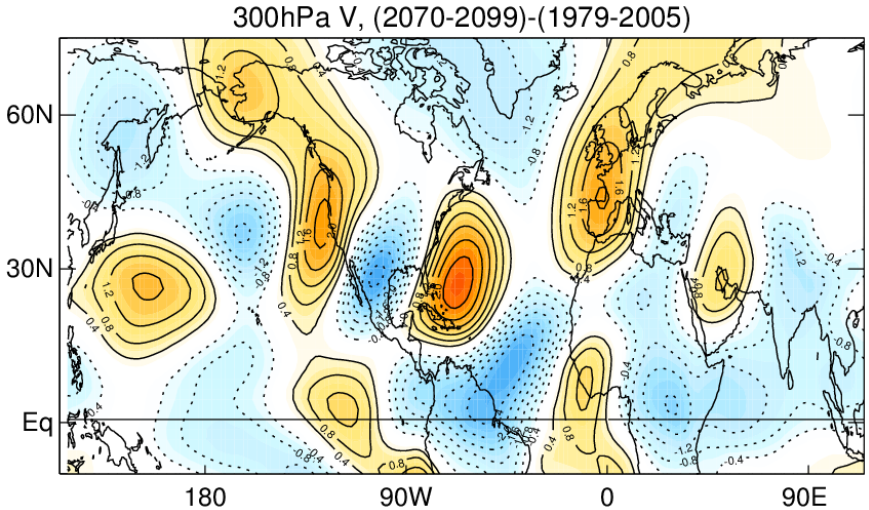

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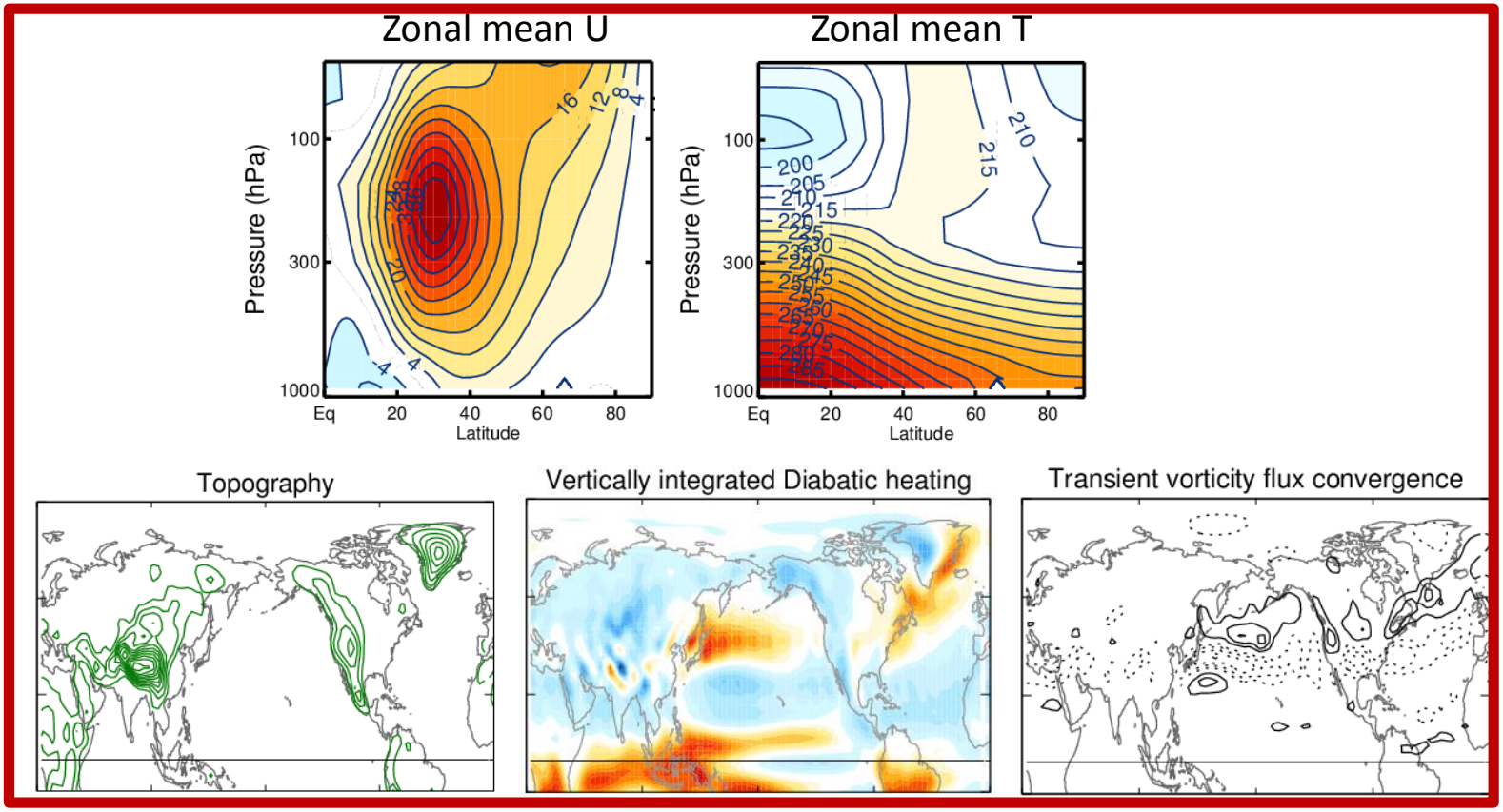

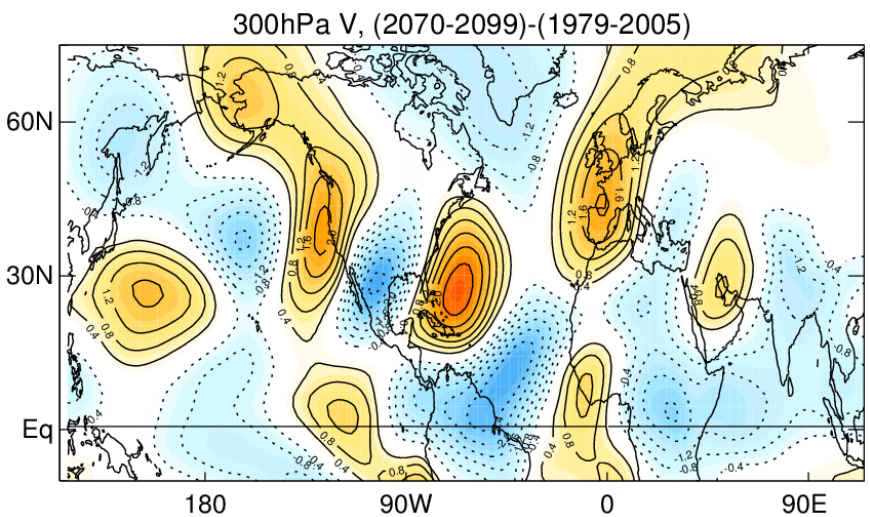

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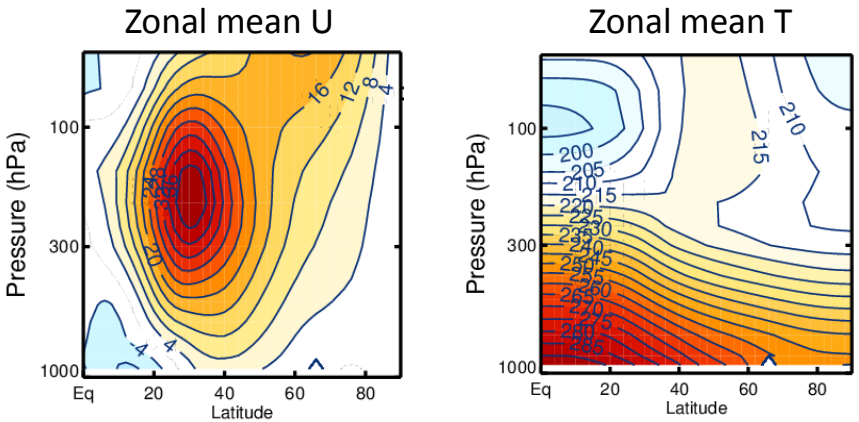
Stationary Wave Modelling

Idealized model set up. Solving the non-linear primitive equations for the steady state stationary wave response to asymmetric forcings within a prescribed zonal mean basic state, under idealized dampings.

Model described in Ting and Yu (1998), Held et al (2002)

Stationary Wave Modelling

zonal mean basic state



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Stationary Wave Modelling

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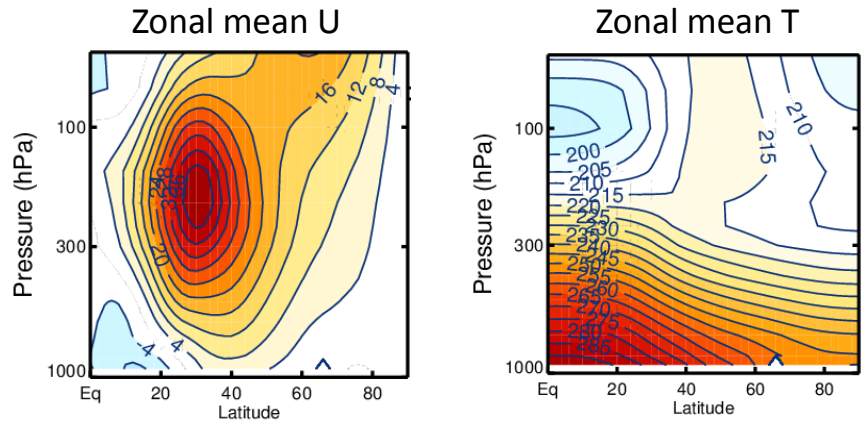
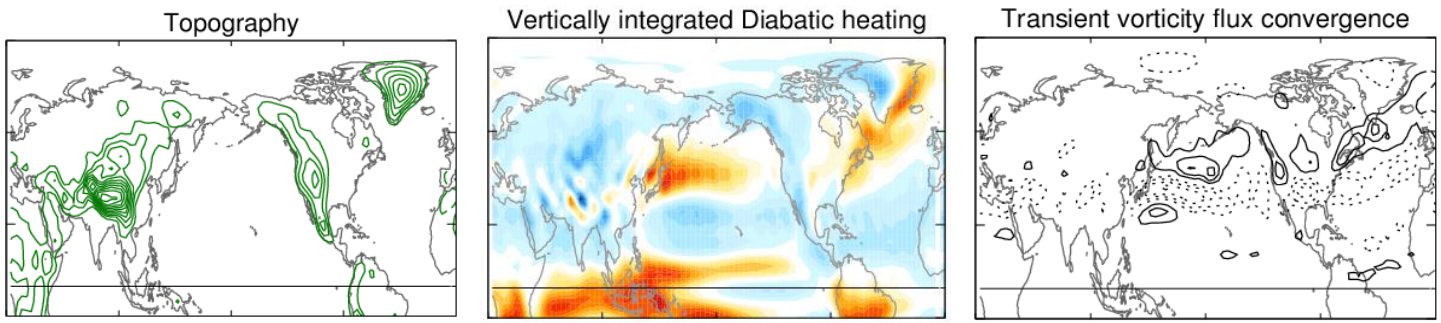
Zonally asymmetric forcings





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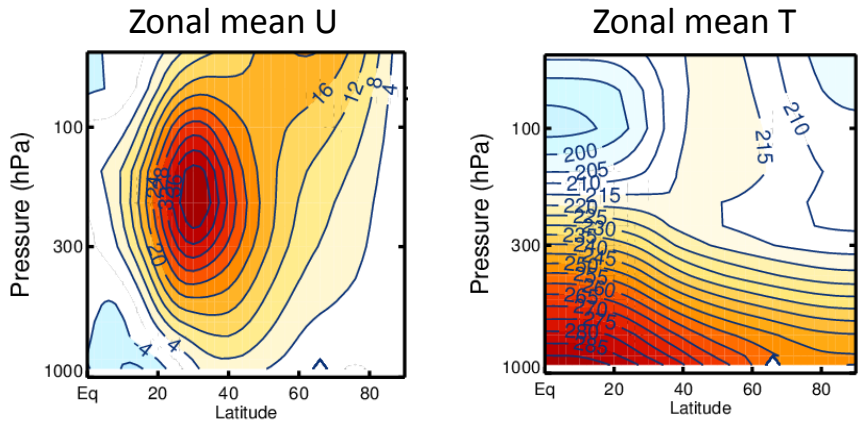

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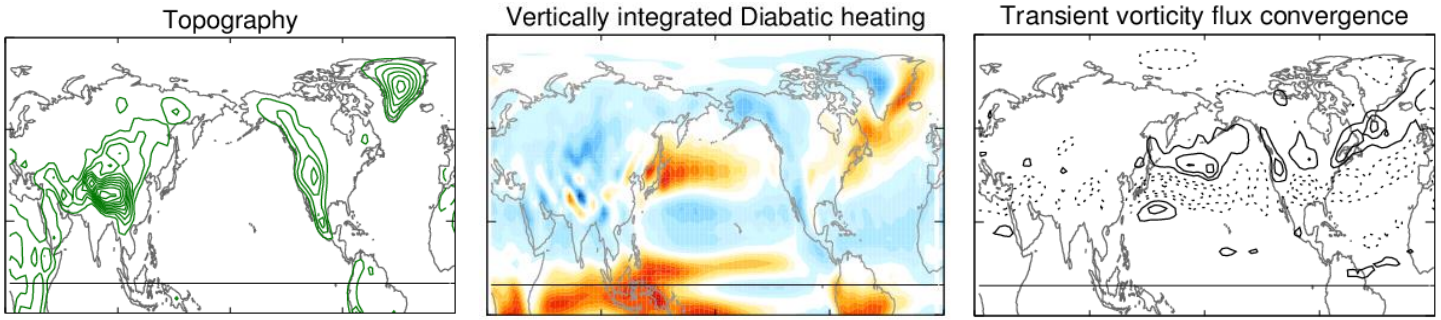

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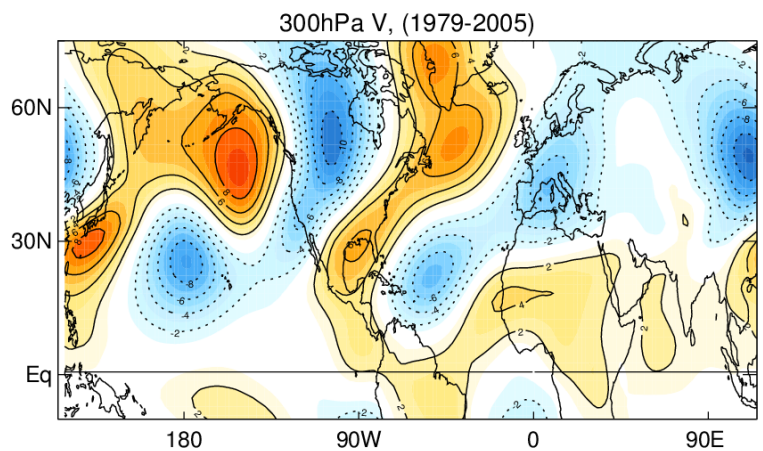
Stationary waves



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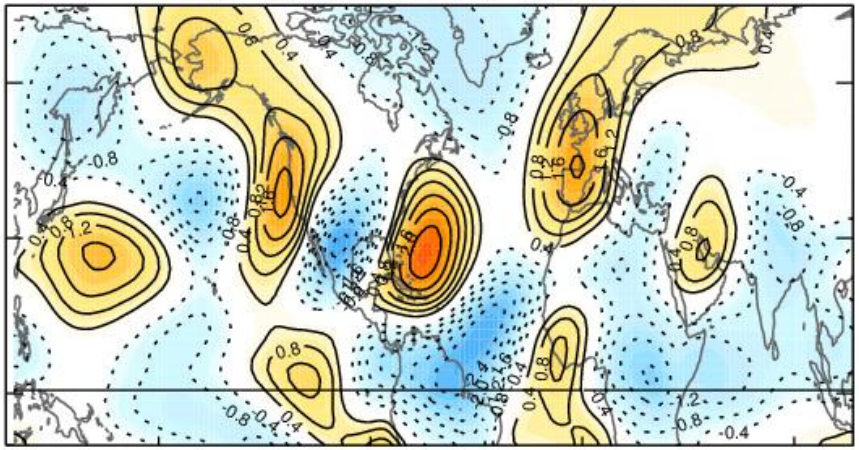
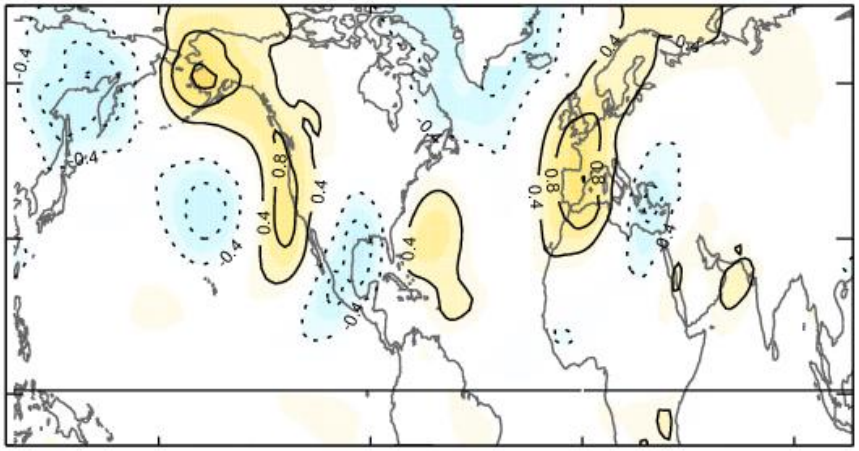
Can we reproduce the wave response?

CMIP5 multi-model mean

CMIP5, 300hPa V, Future-Past



CMIP5, 700hPa V, Future-Past



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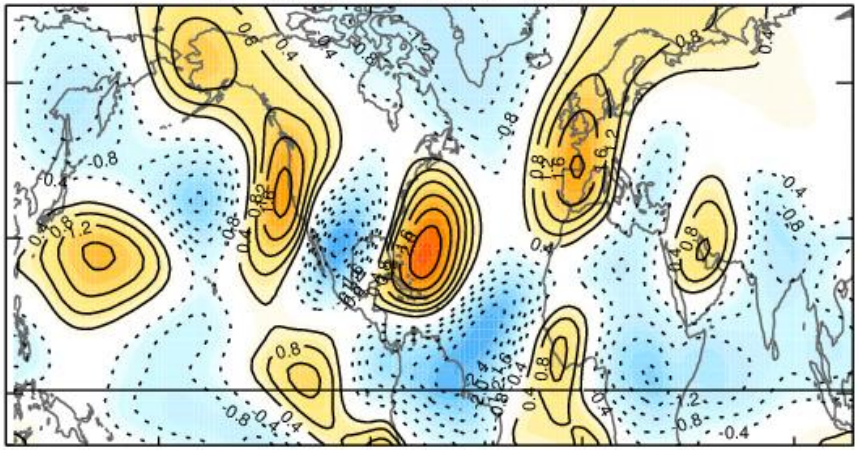
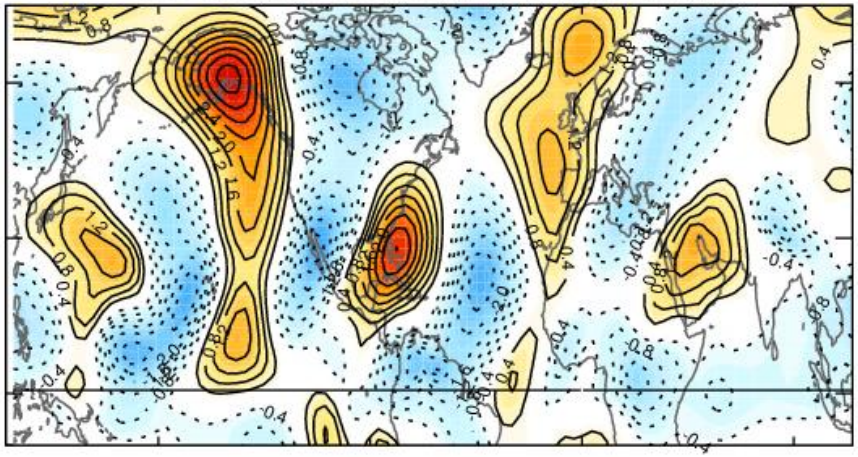
Stationary wave model

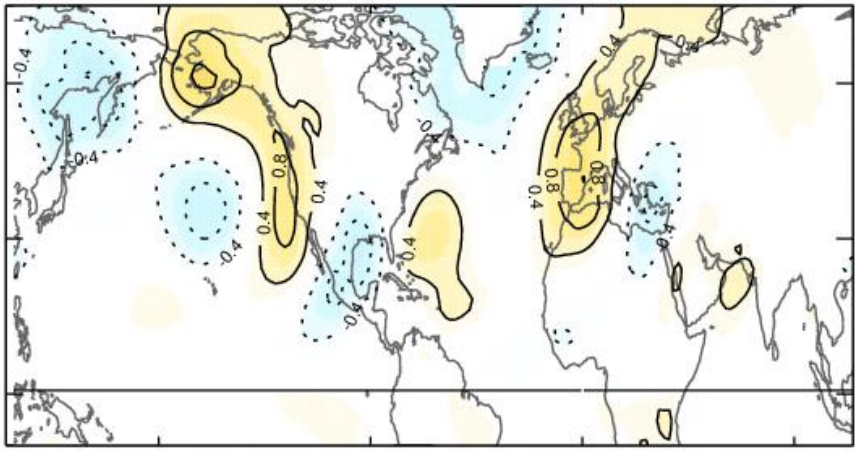
CMIP5, 300hPa V, Future-Past



SW model, 300hPa V, Future-Past



CMIP5, 700hPa V, Future-Past



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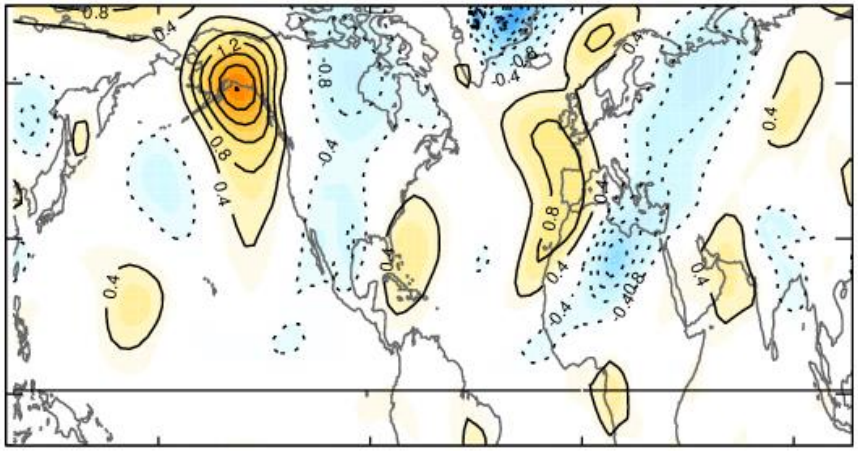
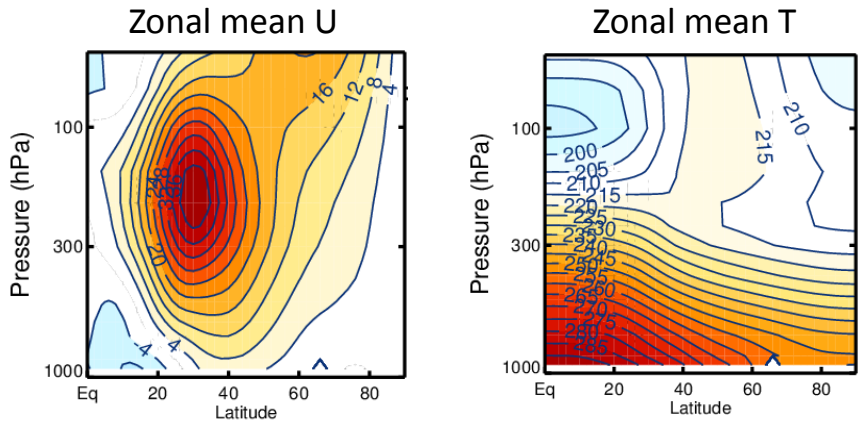


Stationary Wave Modelling

zonal mean basic state



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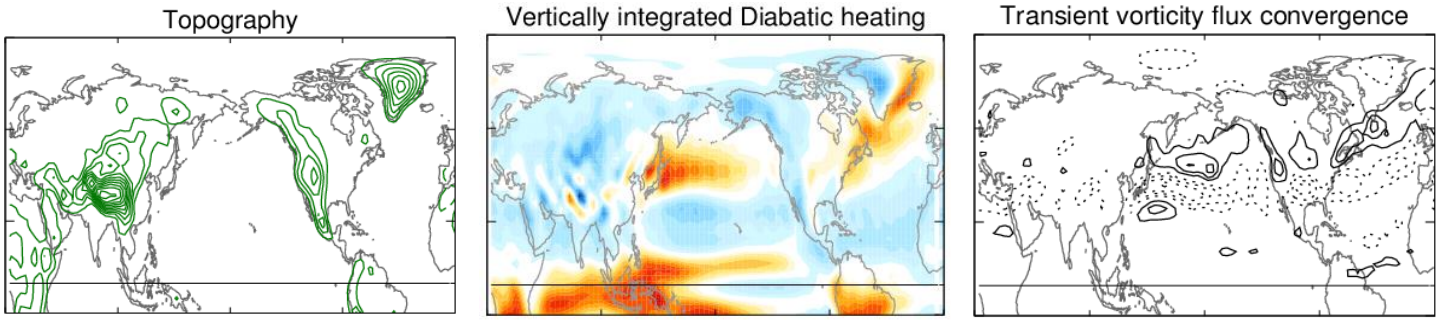
Zonally asymmetric forcings



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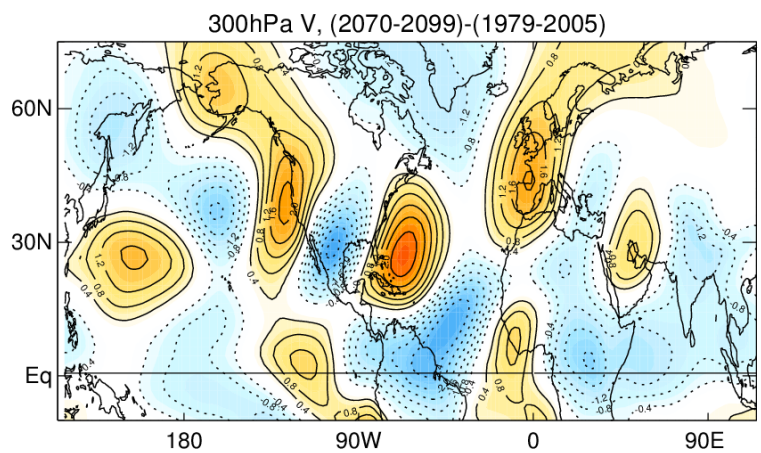
Stationary waves



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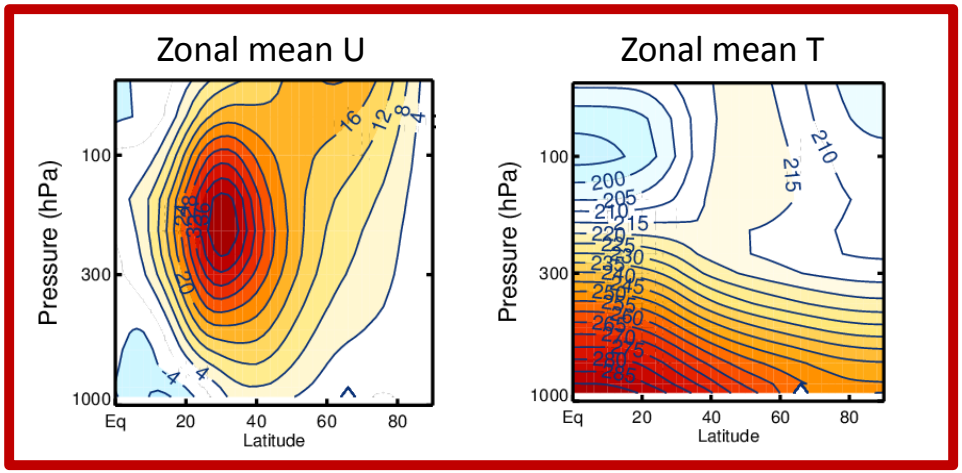
Stationary Wave Modelling

zonal mean basic state



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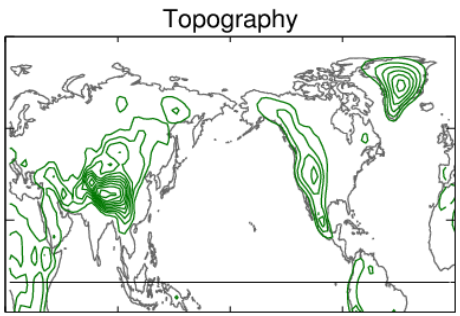
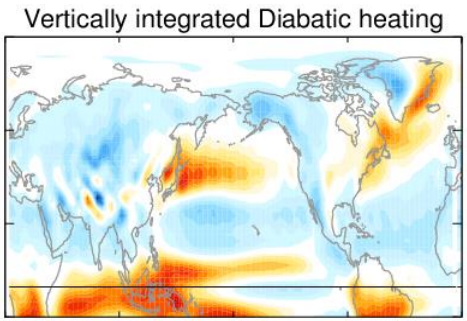
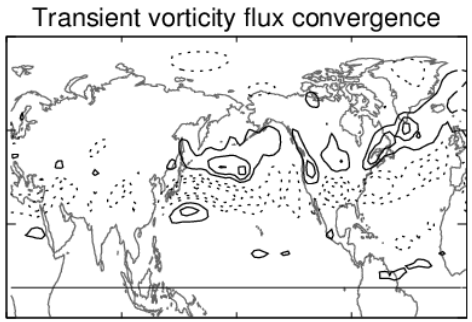
Zonally asymmetric forcings







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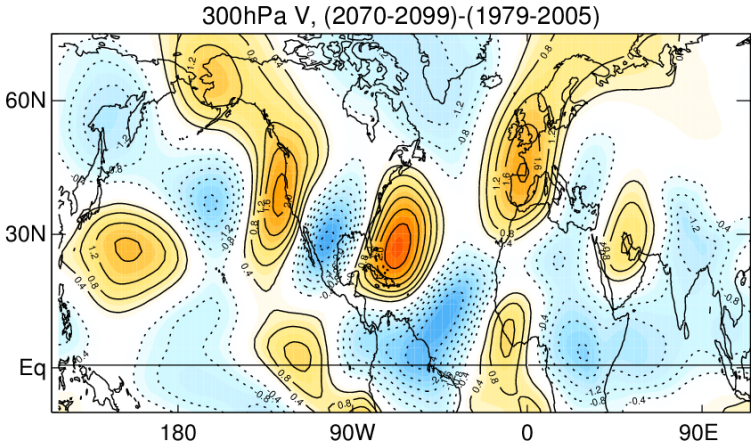

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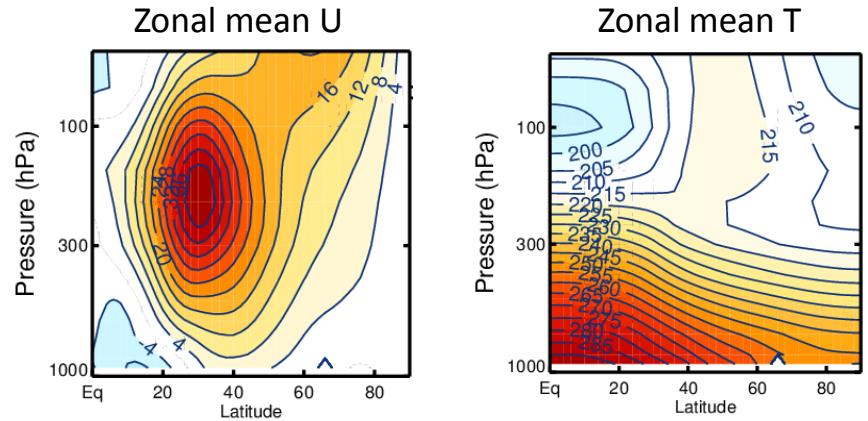
Stationary Wave Modelling

zonal mean basic state



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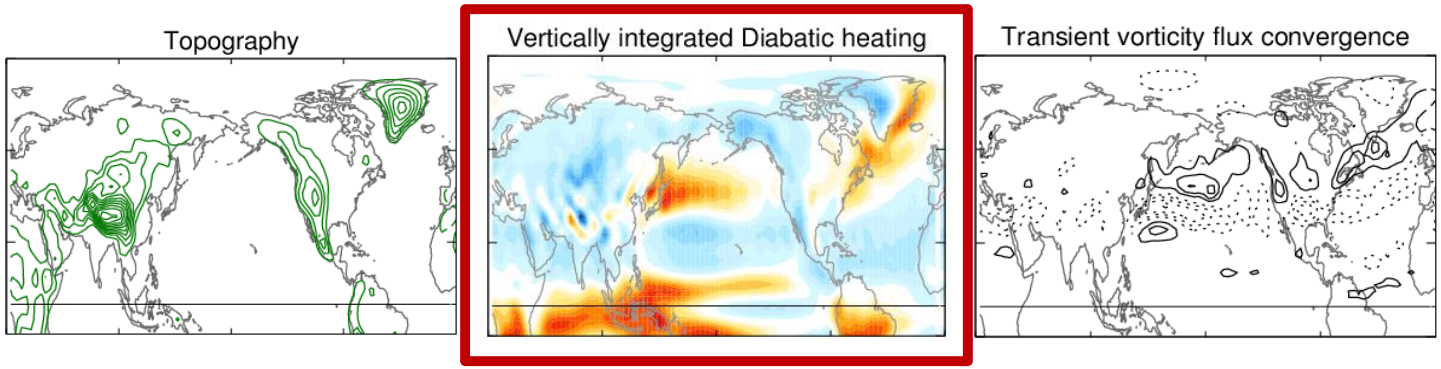

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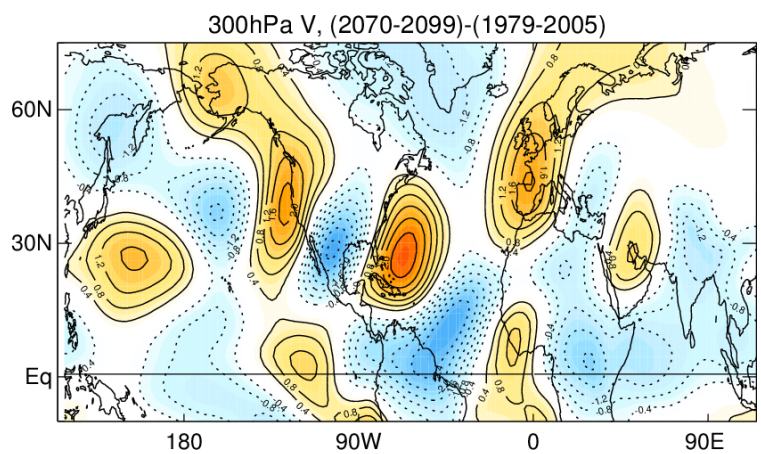
Stationary waves



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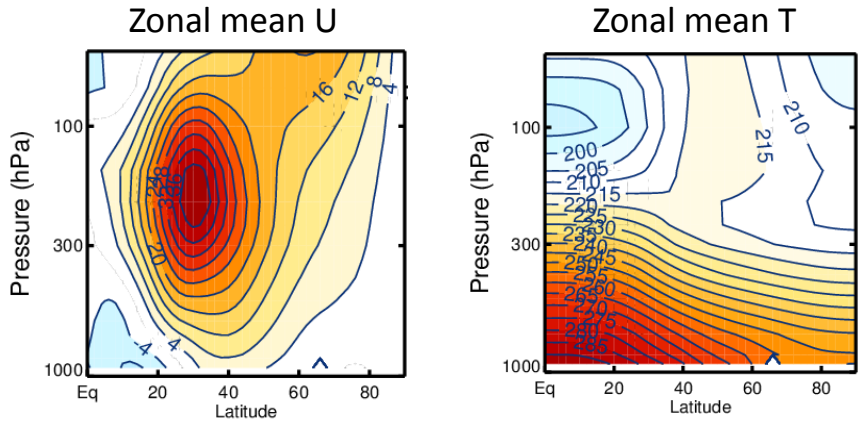
Stationary Wave Modelling

zonal mean basic state



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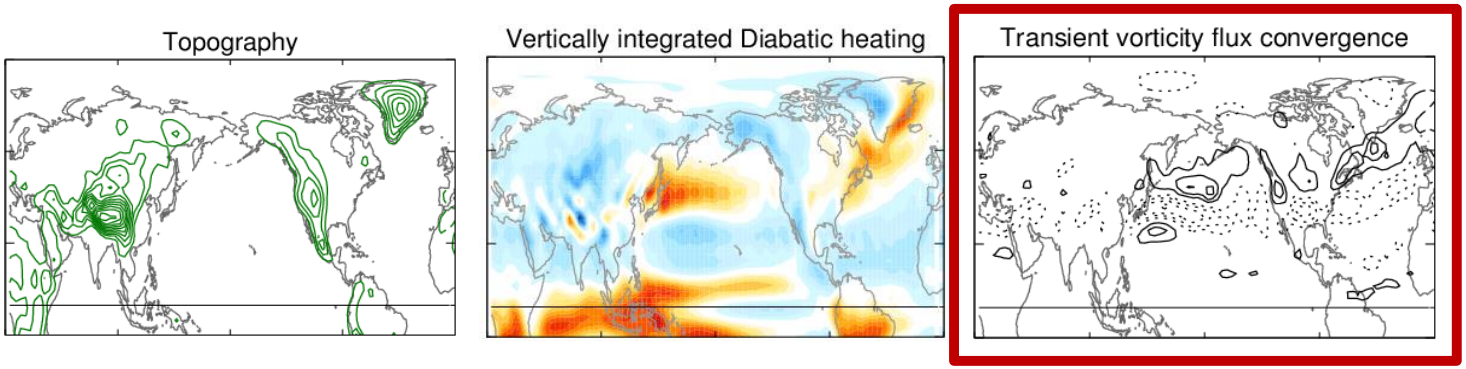
Zonally asymmetric forcings



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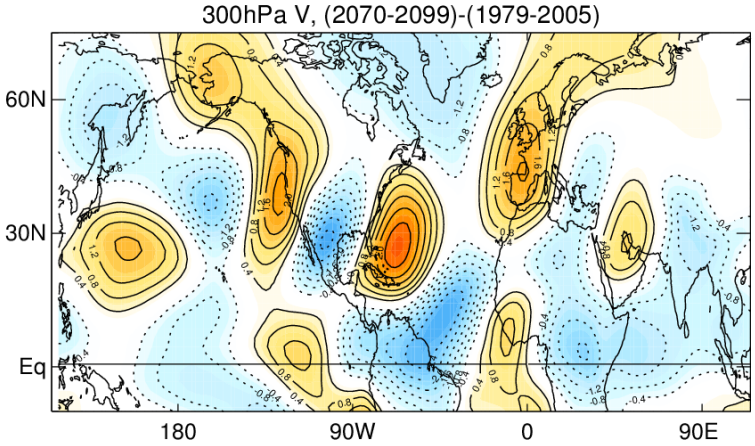
Stationary waves



Model described in Ting and Yu (1998), Held et al (2002)

Stationary Wave Modelling

zonal mean basic state

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Zonally asymmetric forcings

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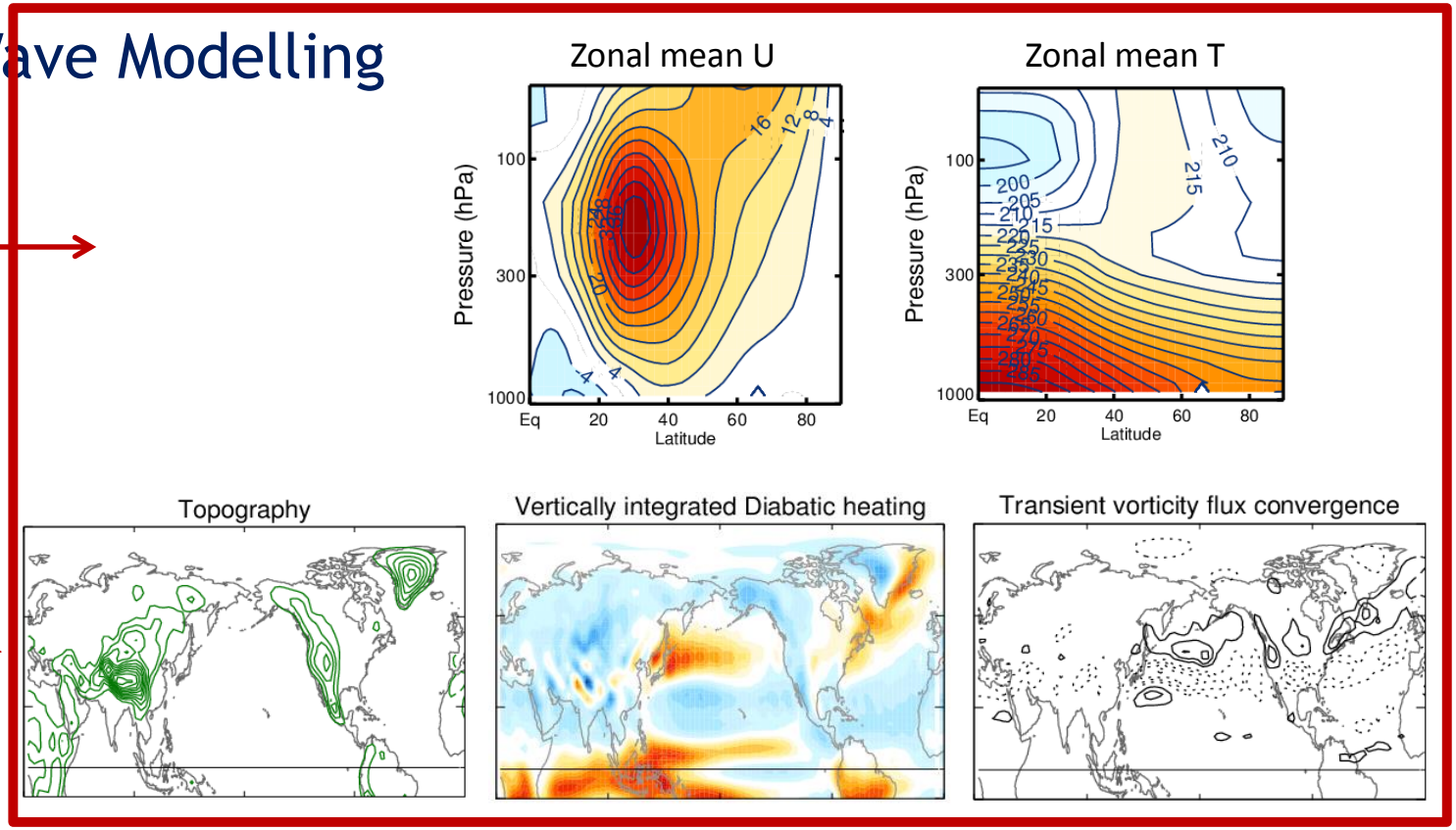
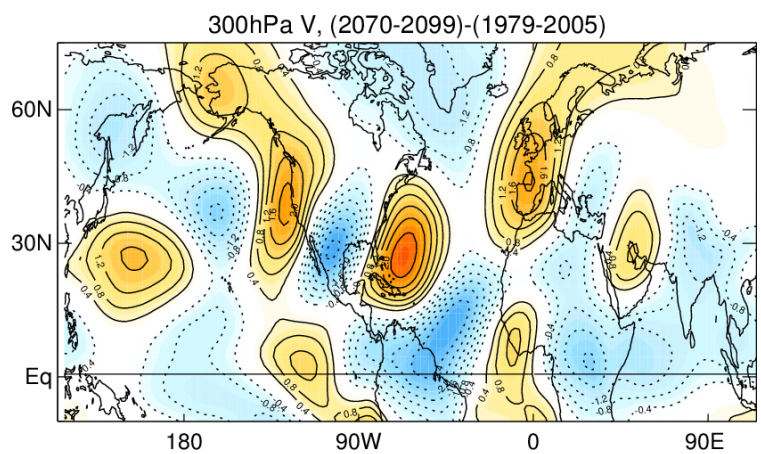
Stationary waves

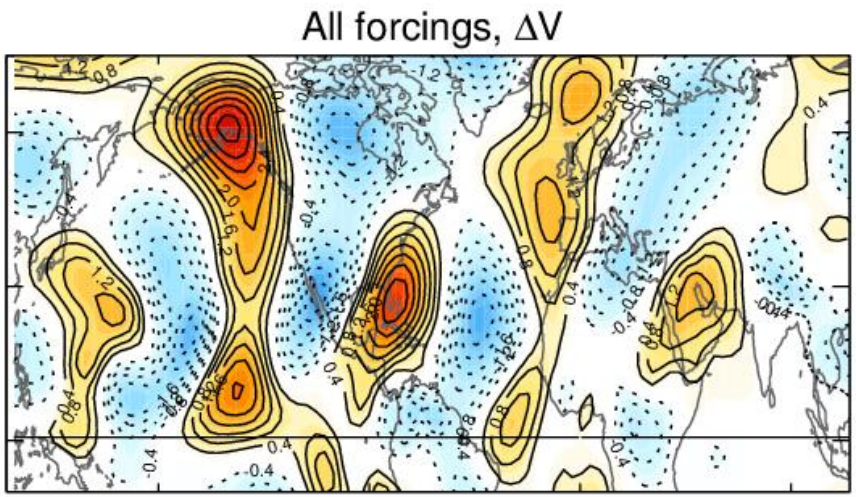




Model described in Ting and Yu (1998), Held et al (2002)

The change in the zonal mean basic state is primarily responsible

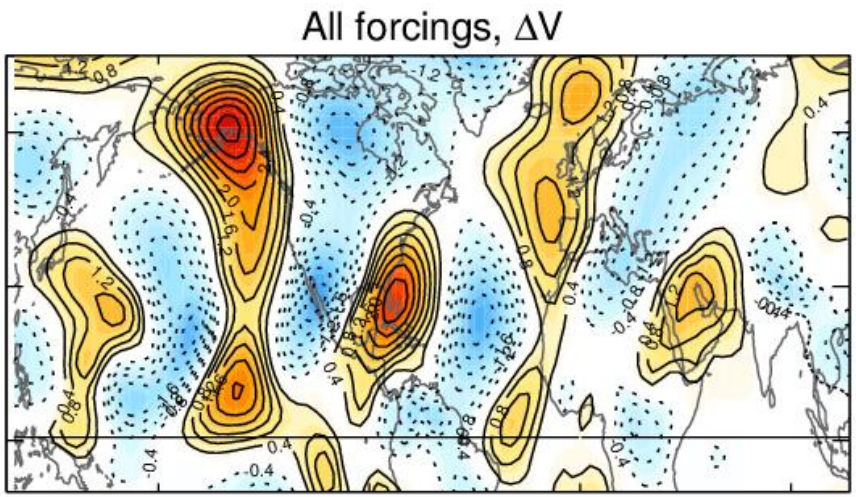
Changing everything

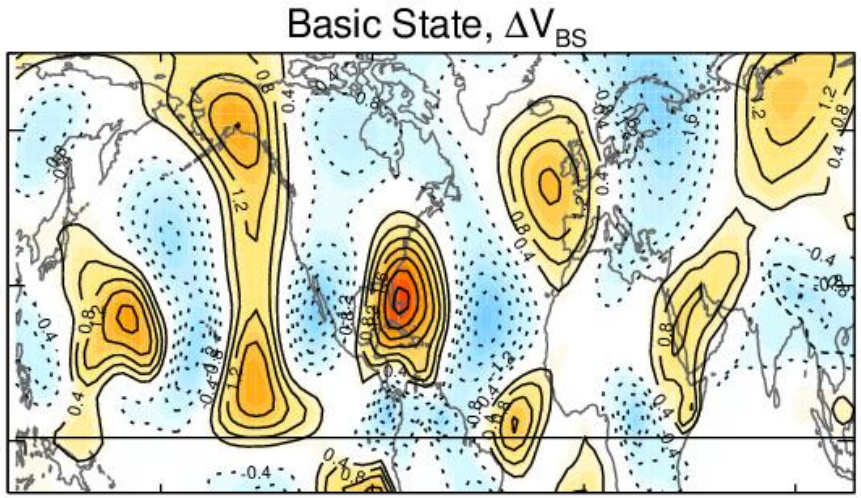


300hPa meridional wind response

The change in the zonal mean basic state is primarily responsible

Changing everything



300hPa meridional wind response

Only changing the zonal mean basic state