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# Global Warming and Midlatitude Circulation

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Yochanan Kushnir, Mingfang Ting, Ben Cook

# Zonal mean mid-latitude circulation change

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It is well established that under global warming the mid-latitude westerlies are expected to shift poleward

e.g.

Yin 2005; Fyfe and Saenko 2006; Miller et al 2006; Previdi and Liepert 2007; Kidston and Gerber 2010; Swart and Fyfe 2012; Wilcox et al 2012; Woolings and Blackburn 2012; Barnes and Polvani 2013; Bracegirdle et al 2013; Gillett and Fyfe 2013

Is this true locally?

Is there a consensus on other stationary wave changes in the future which may not resemble a poleward shift?

# CMIP5 assessment of the zonal and seasonal variations in the mid-latitude circulation response to global warming

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Past = 1979-2005, Historical

Future = 2070-2100, RCP8.5

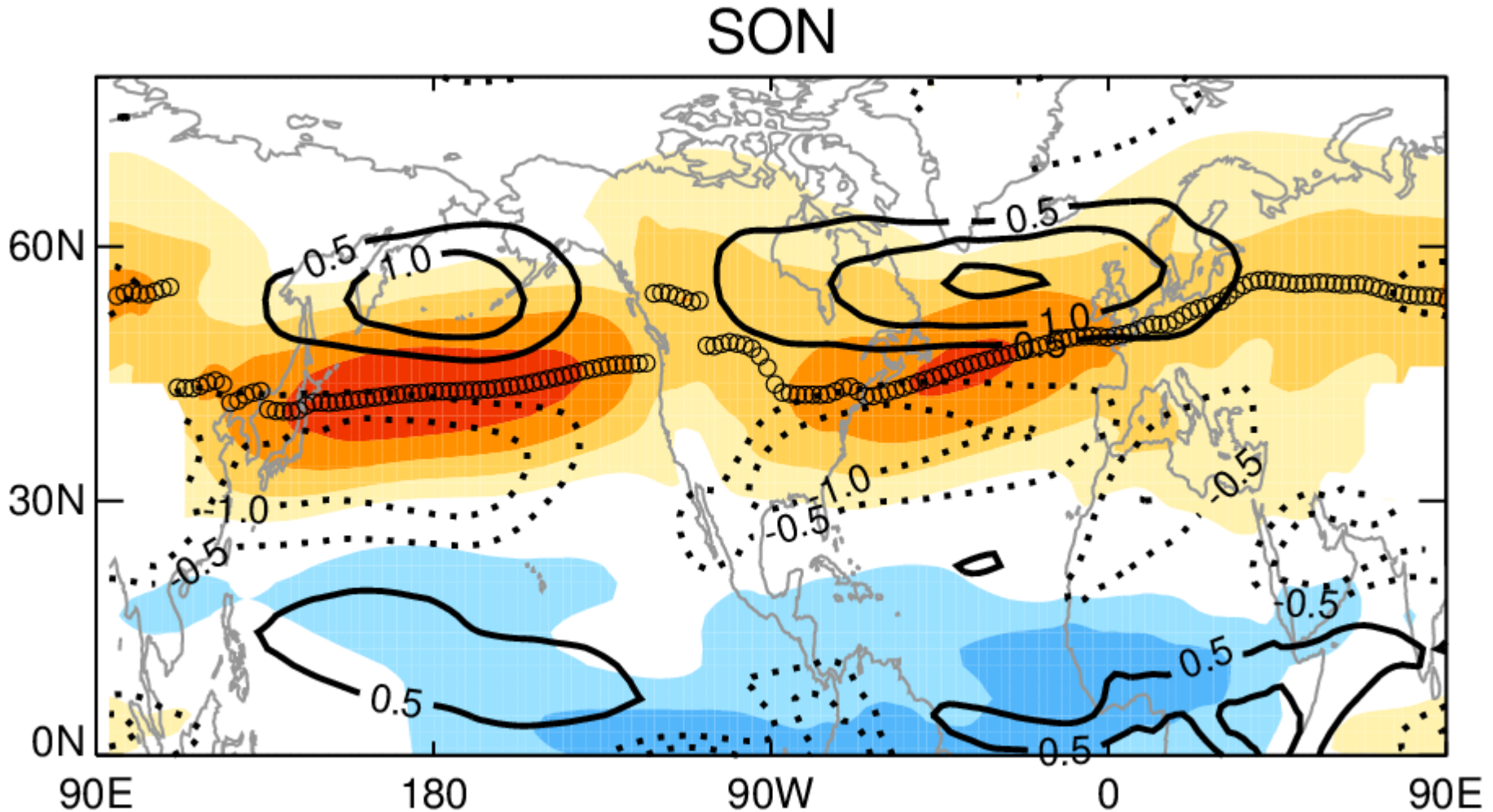
35 models

All available ensemble members

Focus on the Northern Hemisphere



# 700hPa zonal wind, SON

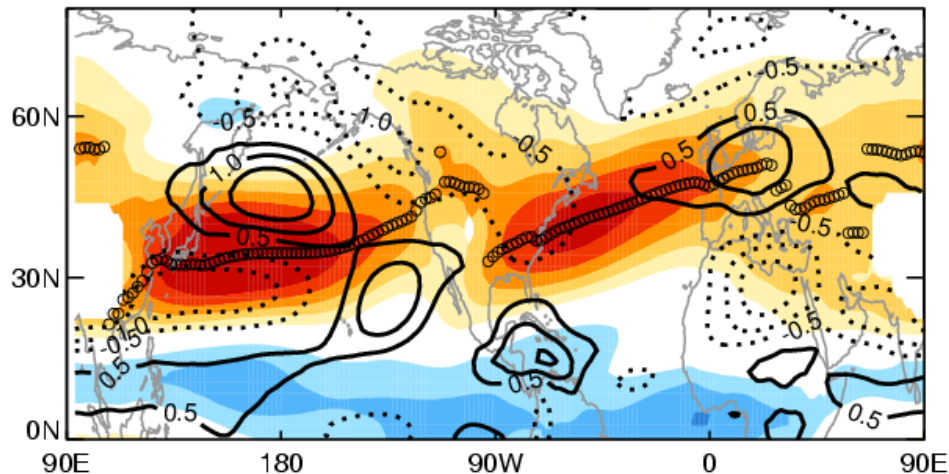


Shading = Past climatology, Contours=Future-Past difference

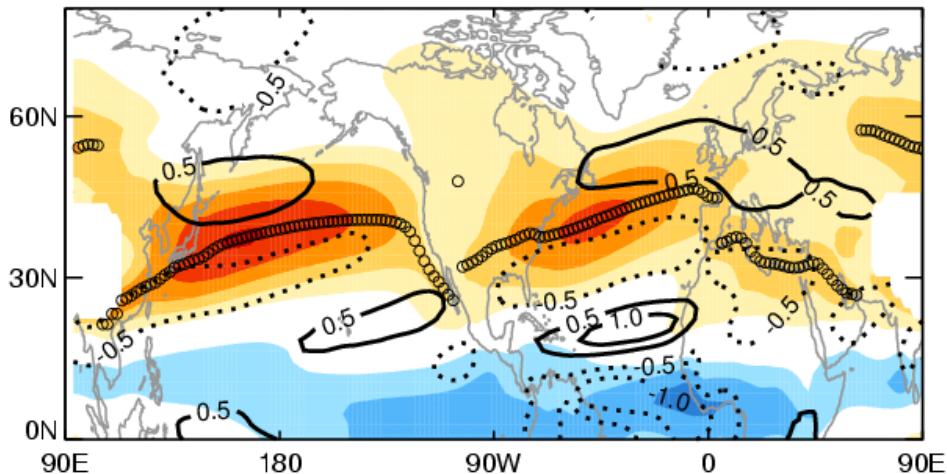
○ = Climatological jet latitude

# 700hPa zonal wind, all seasons

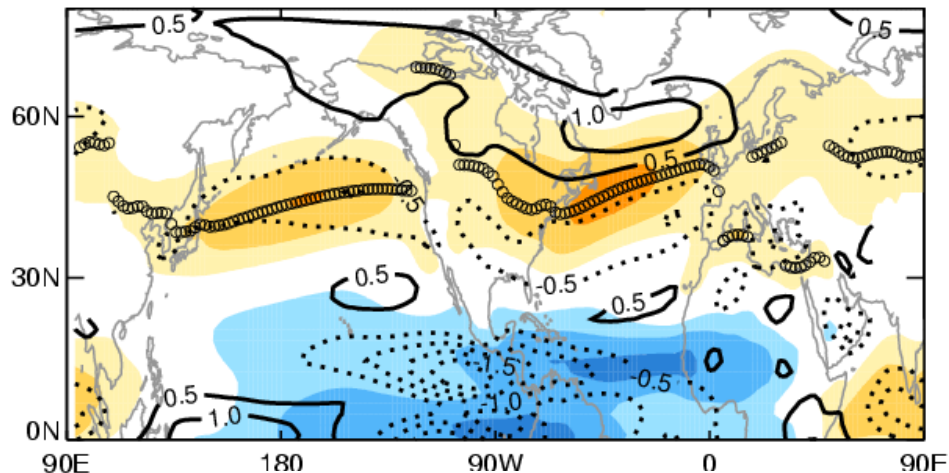
DJF



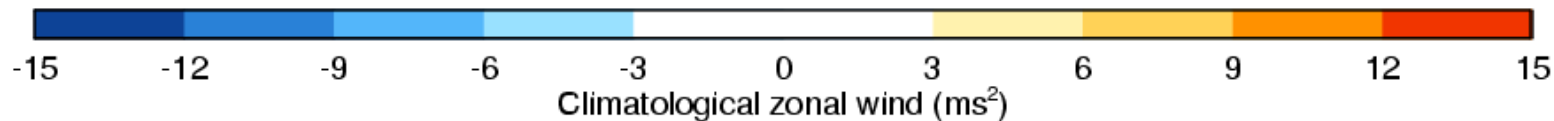
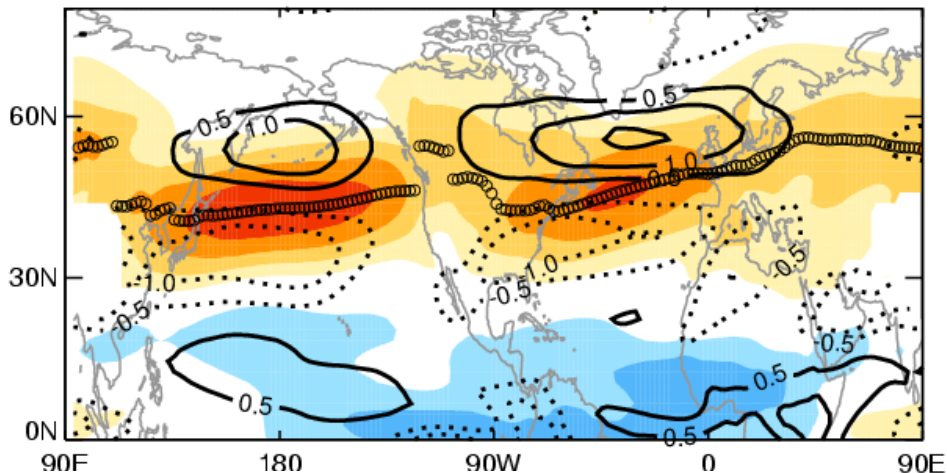
MAM



JJA

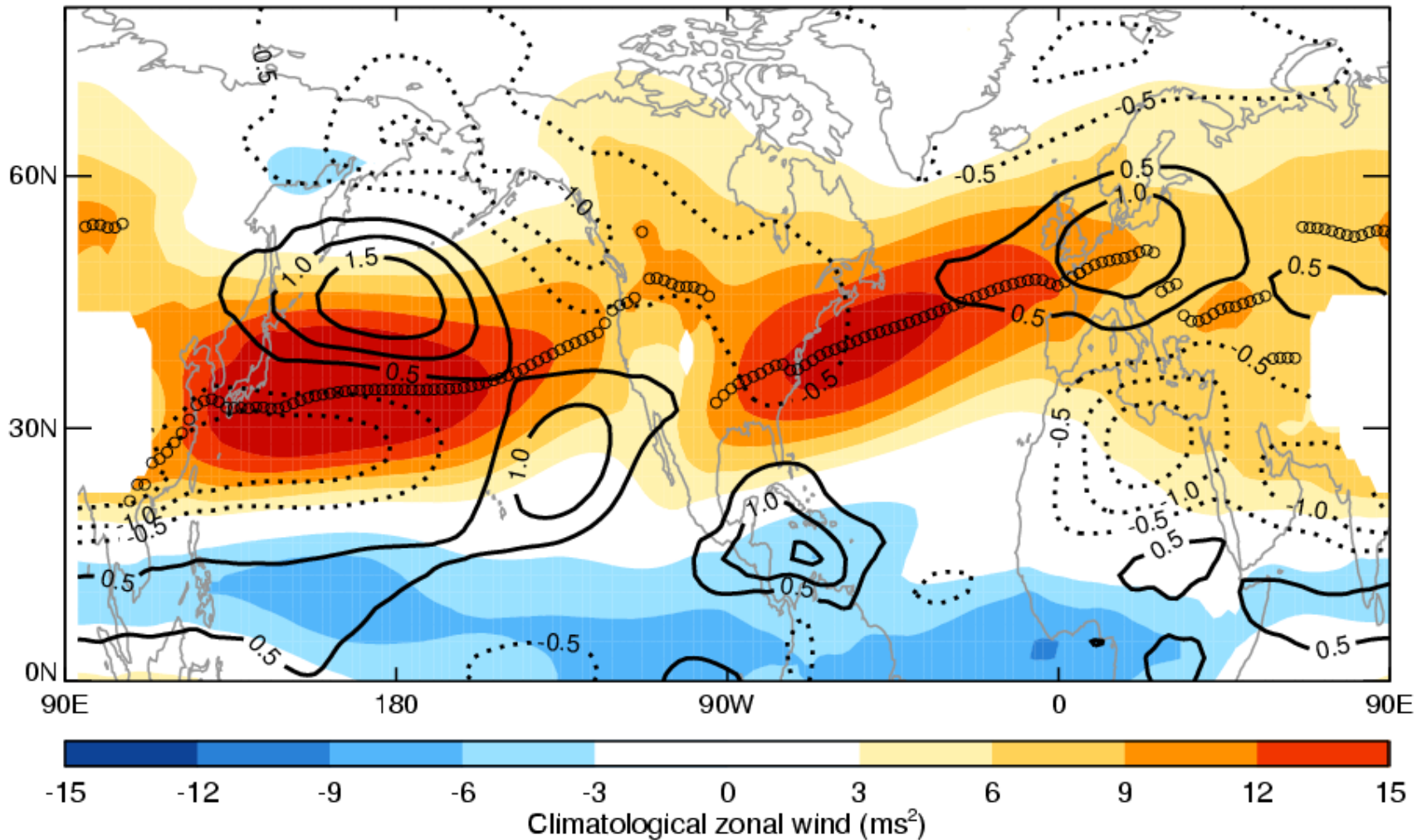


SON



Simpson et al (2014), JAS see also Lorenz and DeWeaver (2007) for CMIP3

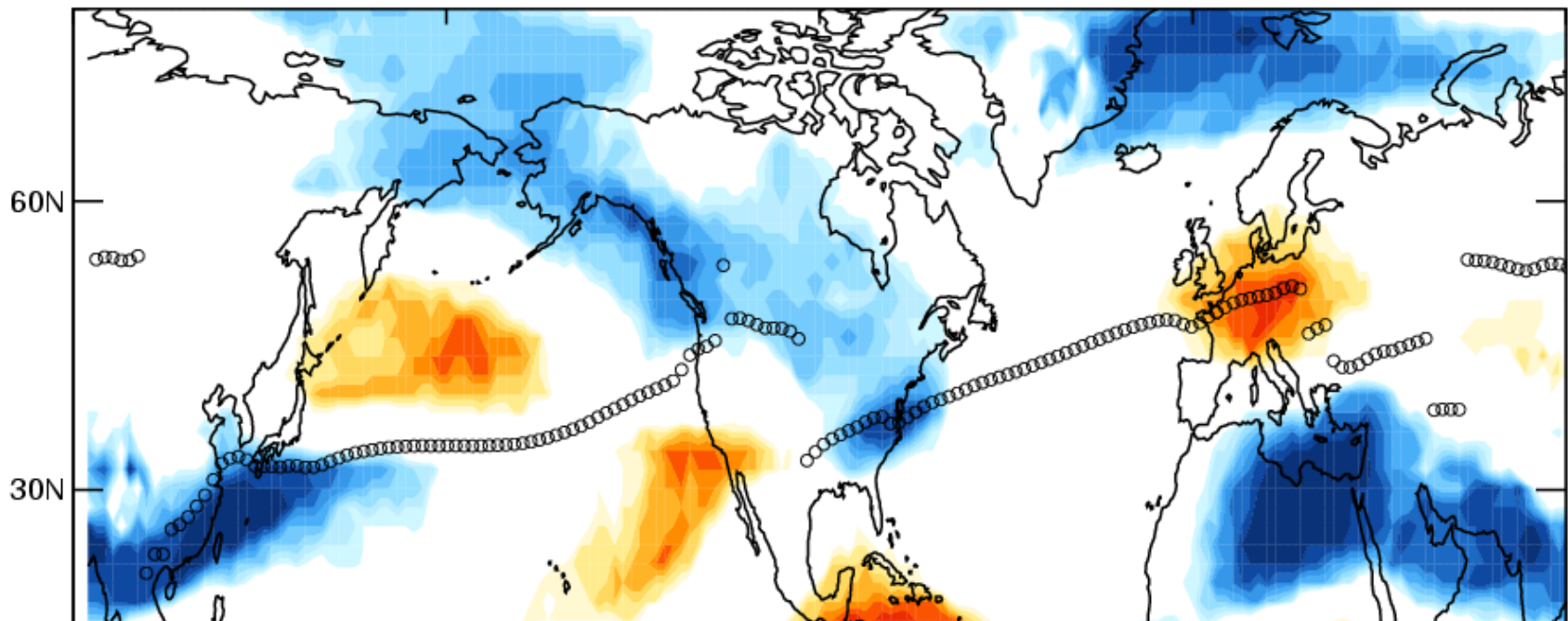
# 700hPa zonal wind, DJF



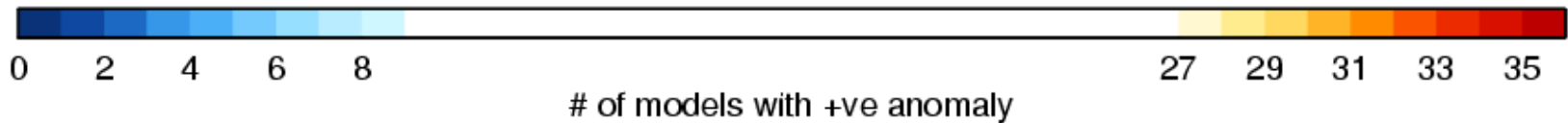
Shading = Past climatology, Contours=Future-Past difference

○ = climatological jet maximum

# Model consensus on sign of anomaly



Stationary wave changes are important during NH winter



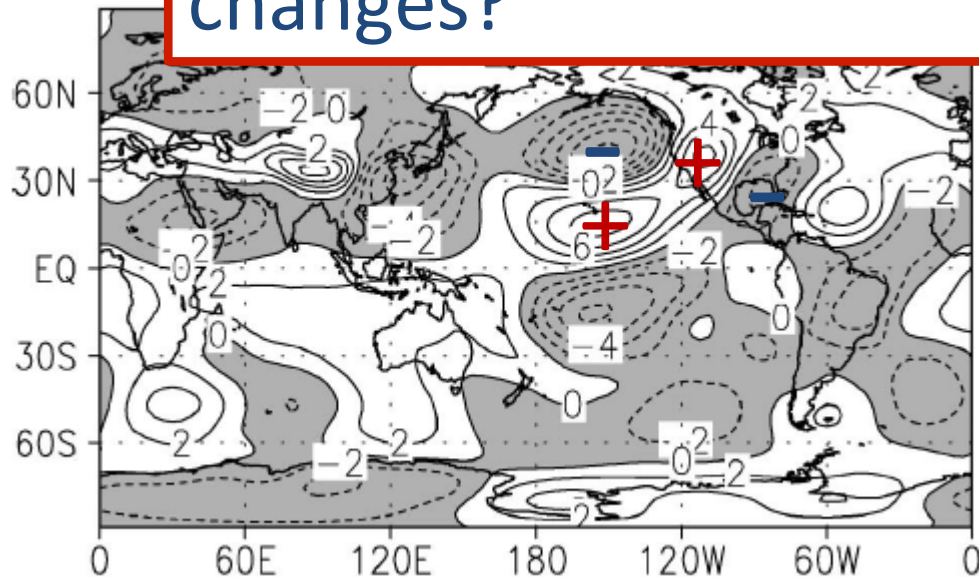


# Past studies on the stationary wave response to climate change



Stephenson and Held (1993)  
GFDL model, R15L9  
DJF, 500hPa eddy geopotential

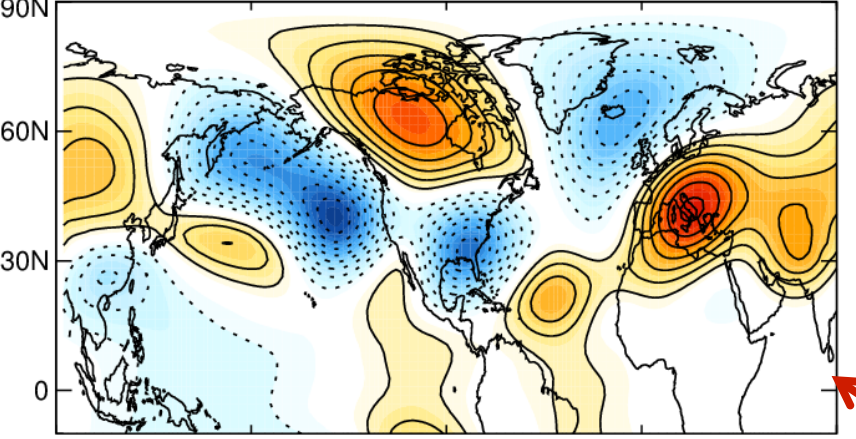
Are we now getting toward a model consensus on NH winter stationary wave changes?



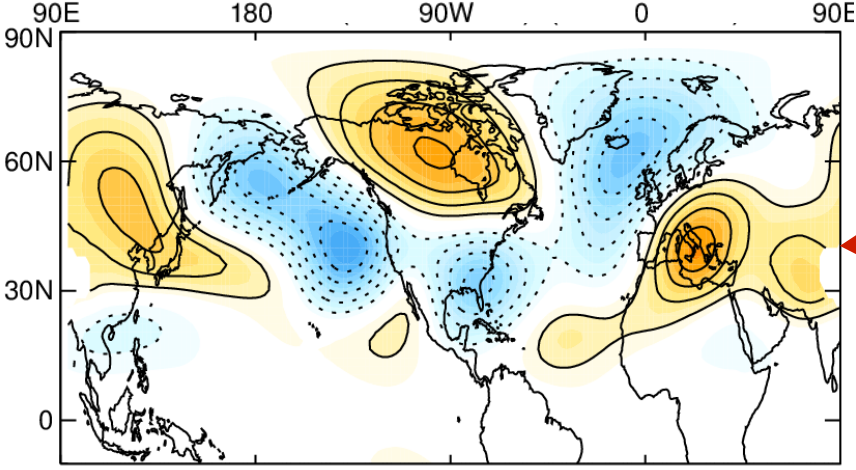
GFDL model, R30L14  
250hPa eddy geopotential height  
response to IPCC "IS92a scenario"

# Stationary Wave Changes in CMIP5

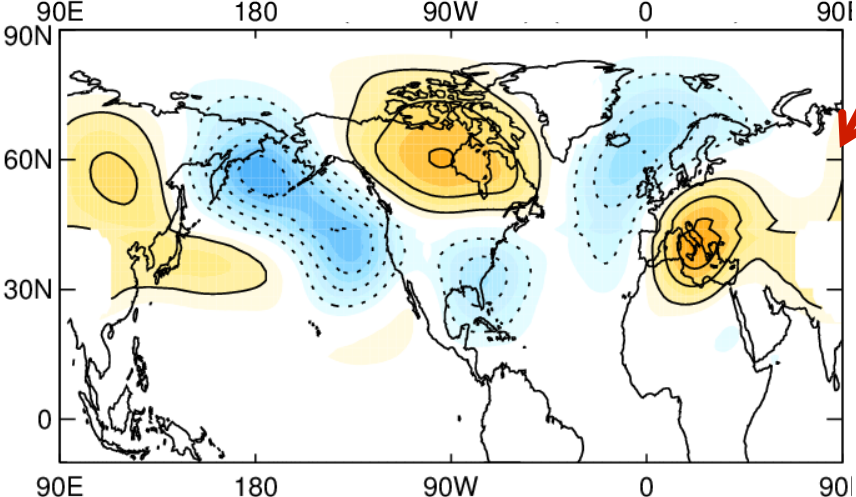
## Eddy geopotential height (2070-2099)-(1979-2005)



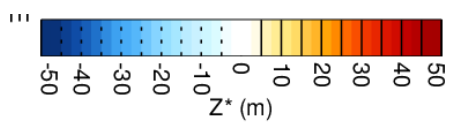
250hPa



500hPa



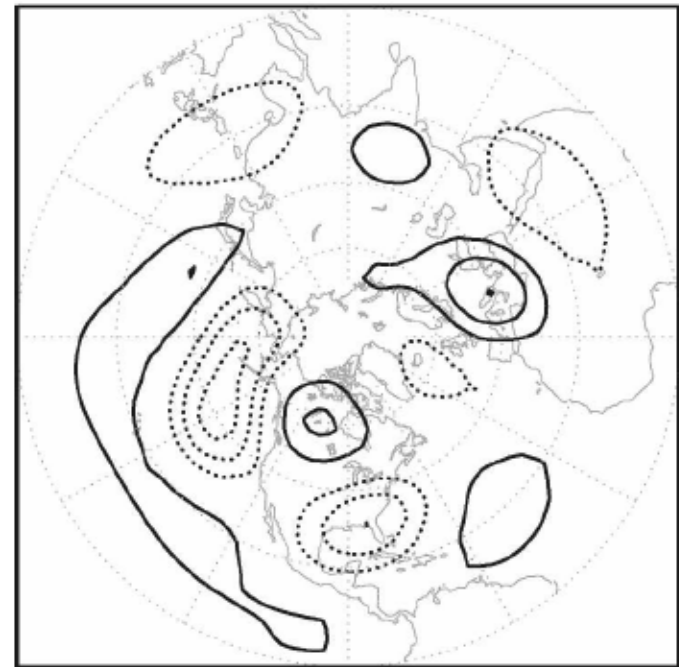
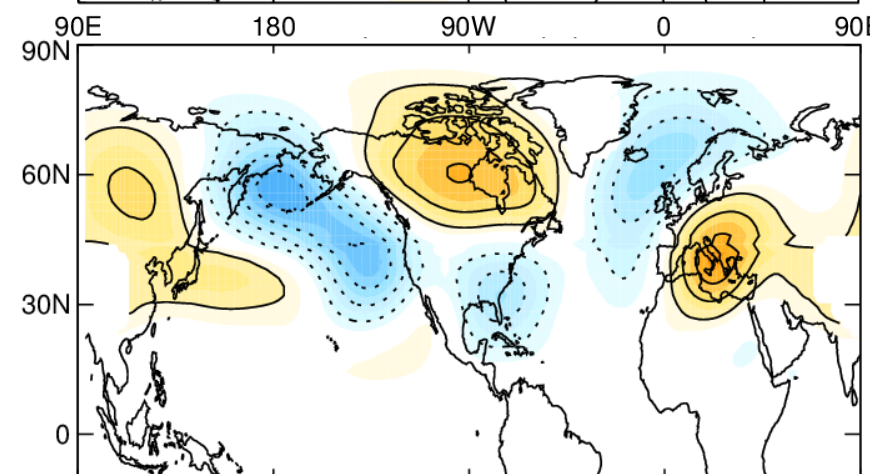
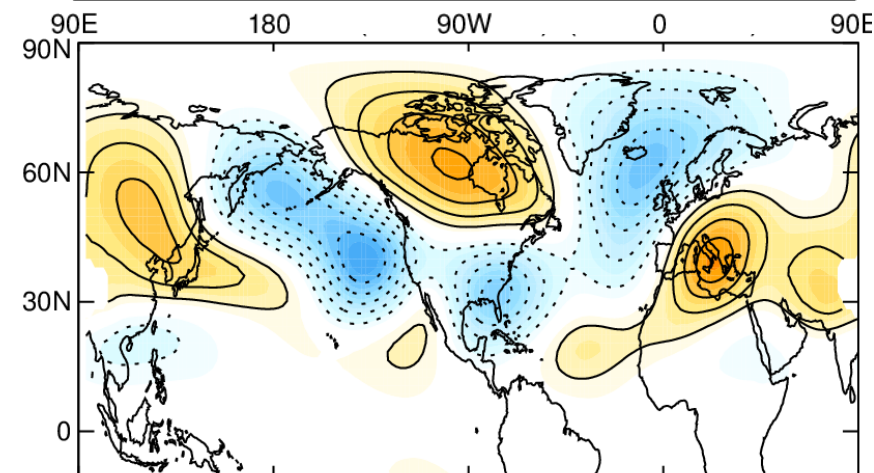
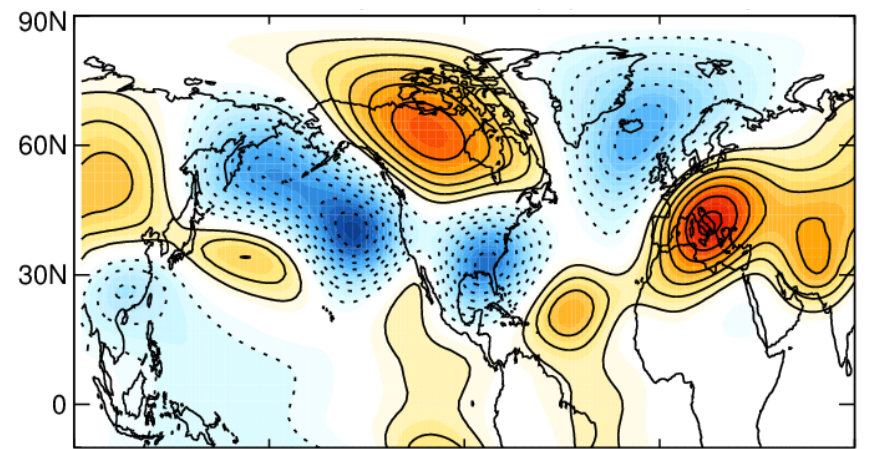
700hPa



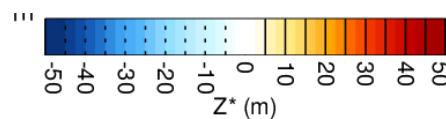
# Stationary Wave Changes in CMIP5

## Eddy geopotential height (2070-2099)-(1979-2005)

7 out of 14 CMIP3 models with similar stationary wave responses



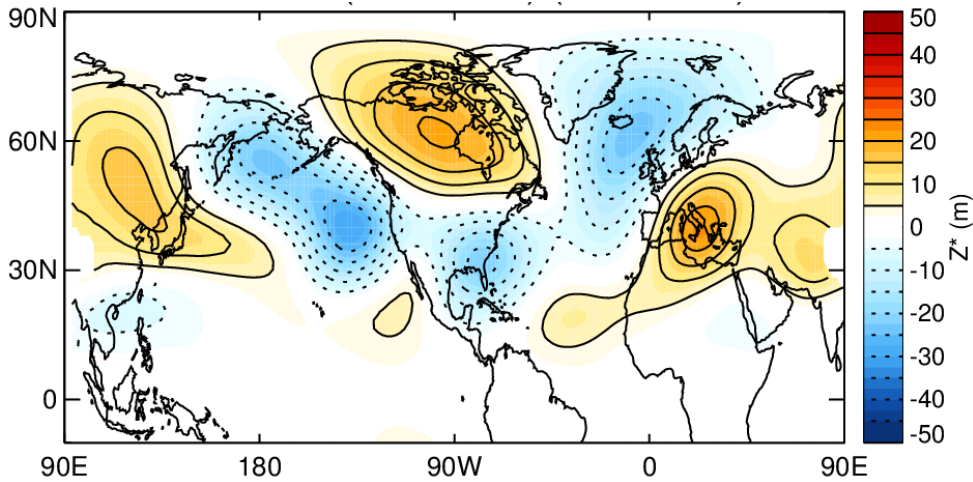
Brandefelt and Körnich (2008)



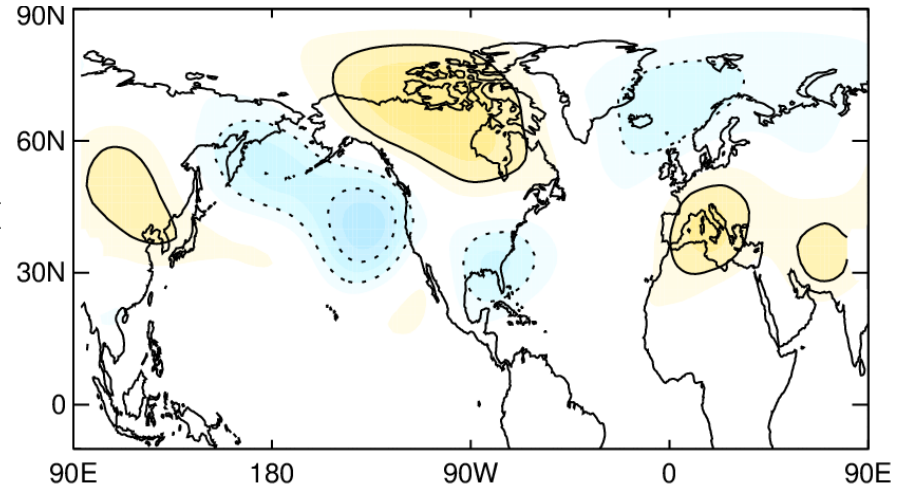


# 500hPa Z\*

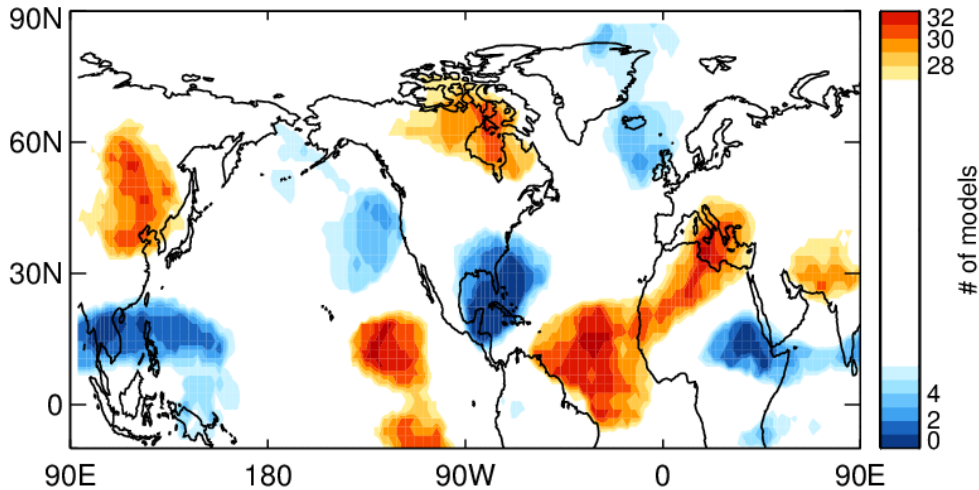
(2070-2100)-(1979-2005)



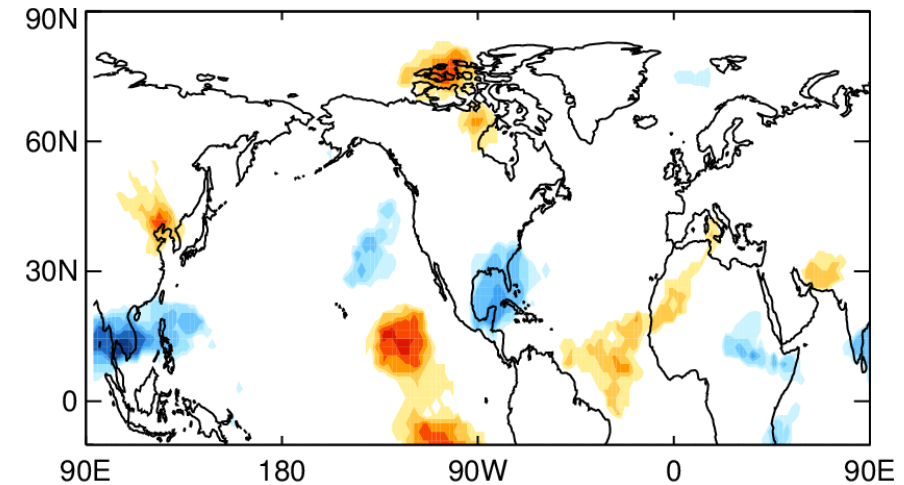
(2021-2040)-(1979-2005)



Model Consensus



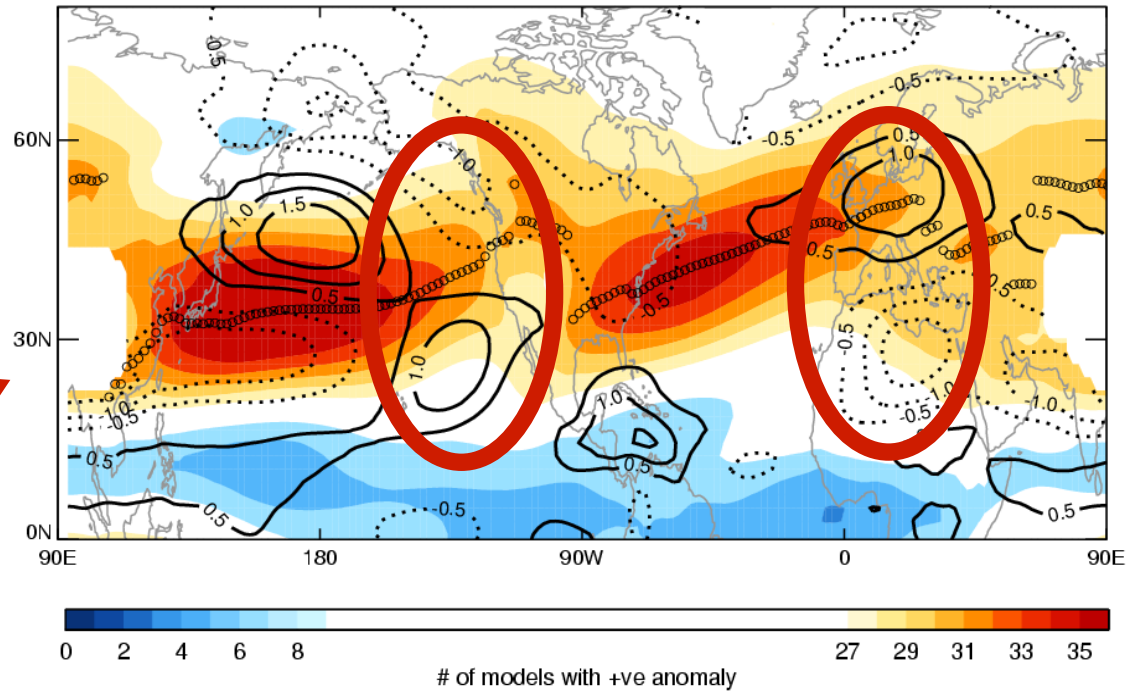
Model Consensus



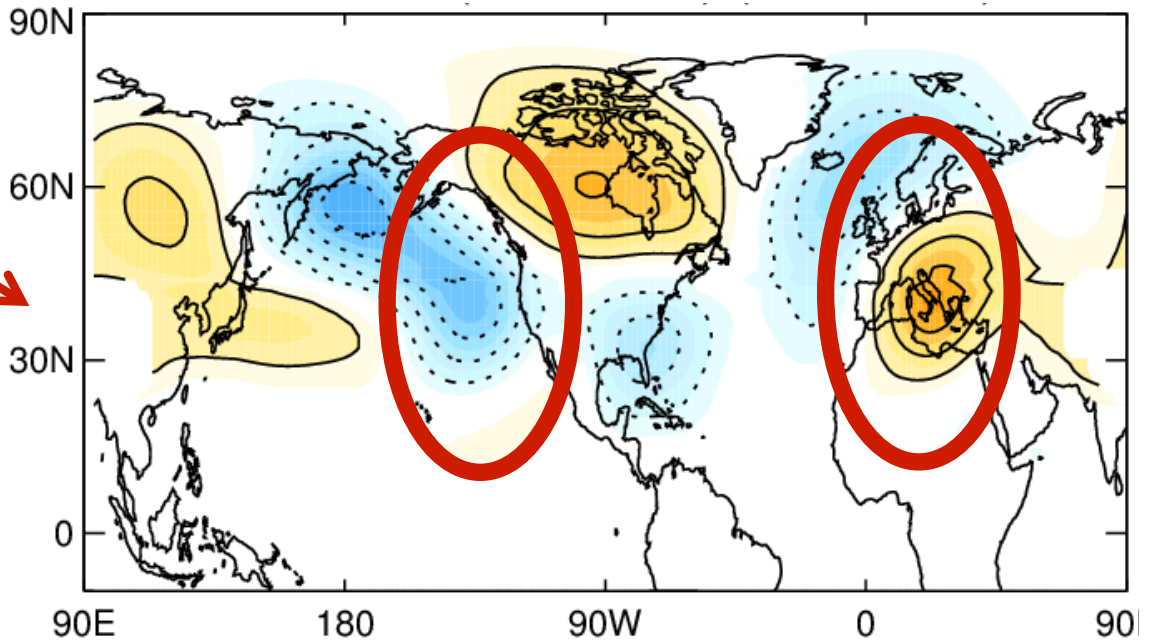


Now we have a model consensus on at least some features during NH winter.....

Zonal wind anomalies (700hPa)

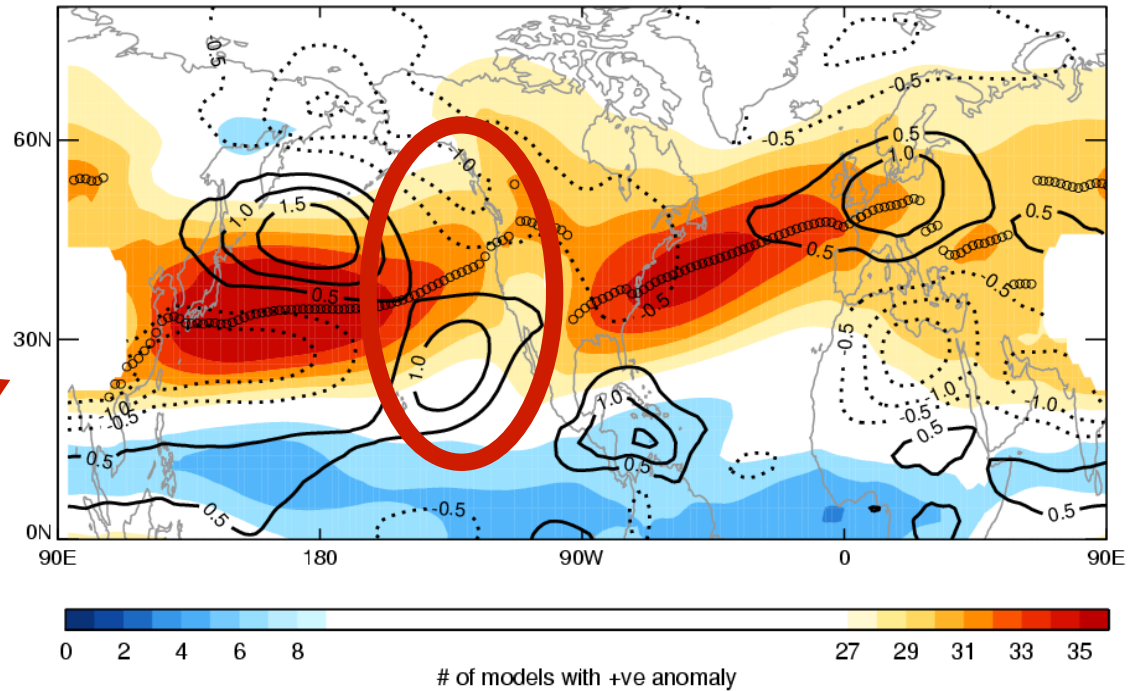


Eddy geopotential height anomalies (700hPa)

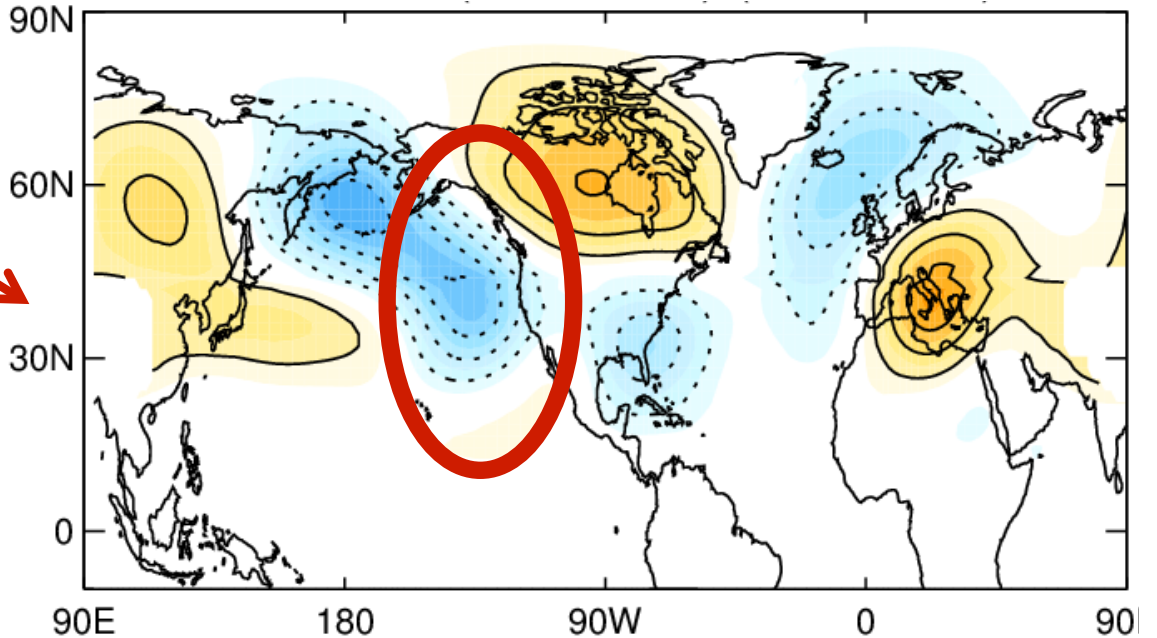


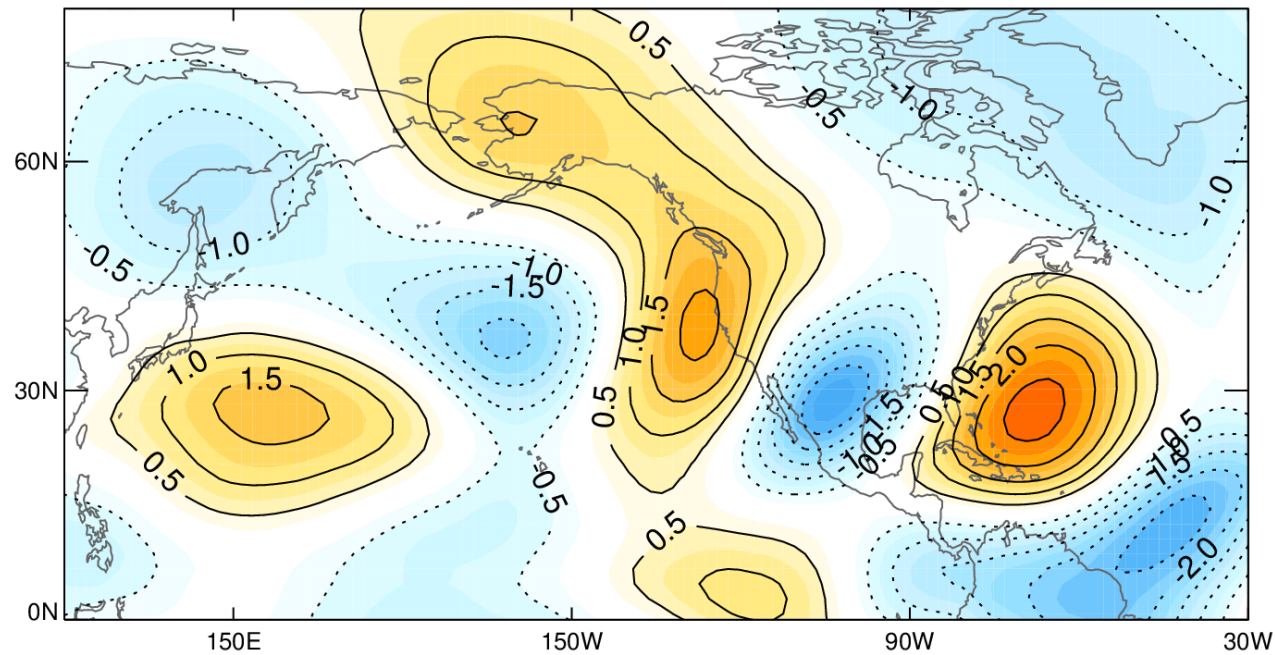
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Zonal wind anomalies (700hPa)

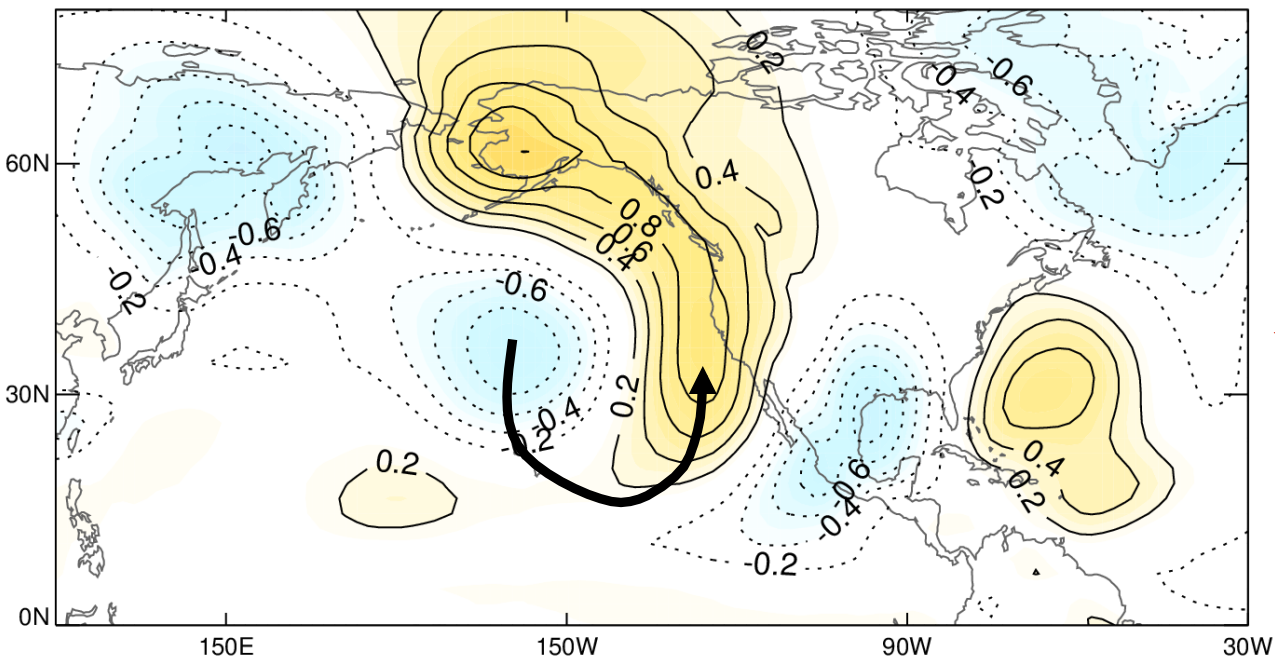


Eddy geopotential height anomalies (700hPa)





← 300hPa meridional wind anomaly

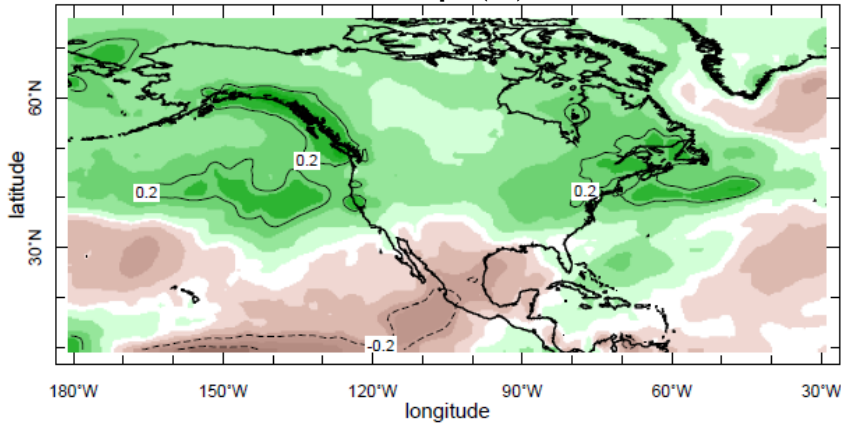


← 700hPa meridional wind anomaly

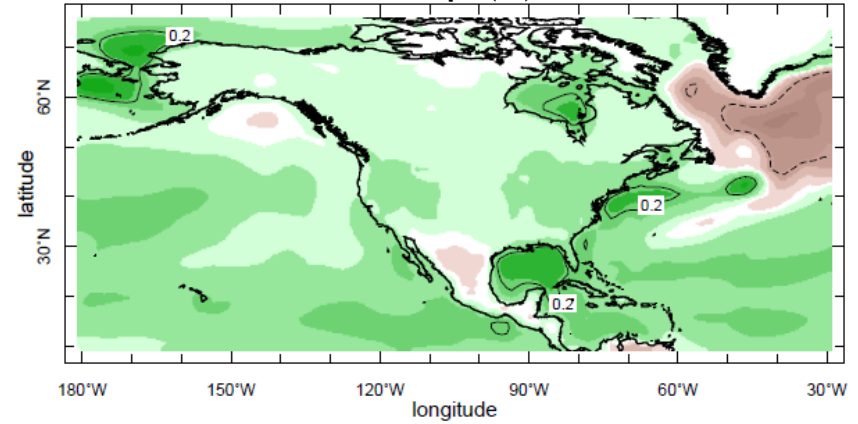
# Implications of the East Pacific circulation response

Seager et al (2014) - Moisture budget analysis of CMIP5 response  
(2021-2040)-(1979-2005), NDJFMA, RCP8.5, 22 models

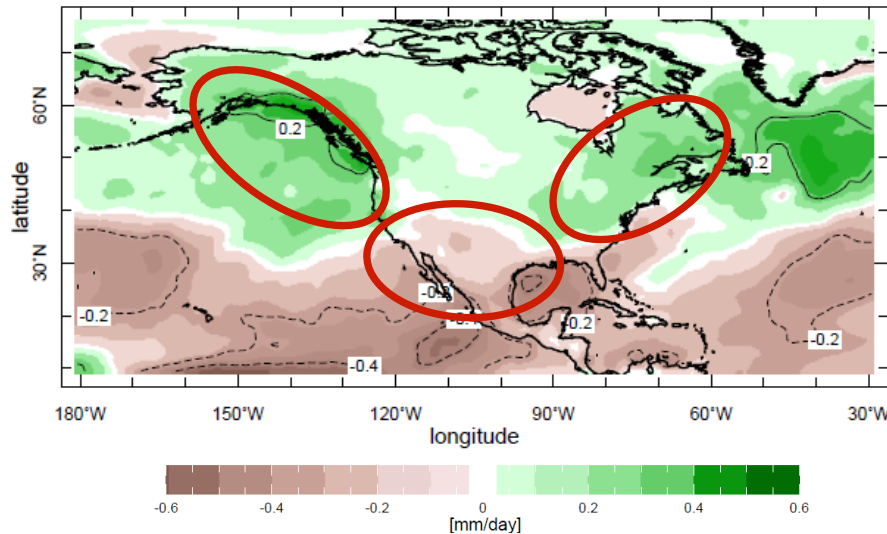
Precip (P)



Evap (E)



P-E

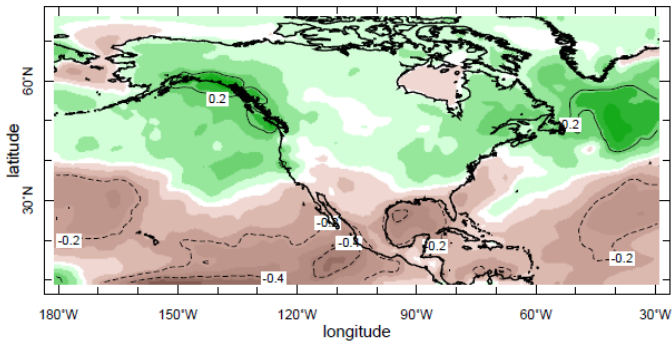


$$-\frac{1}{g\rho_w} \nabla \cdot \sum_{k=1}^K \mathbf{u}_k q_k dp_k$$

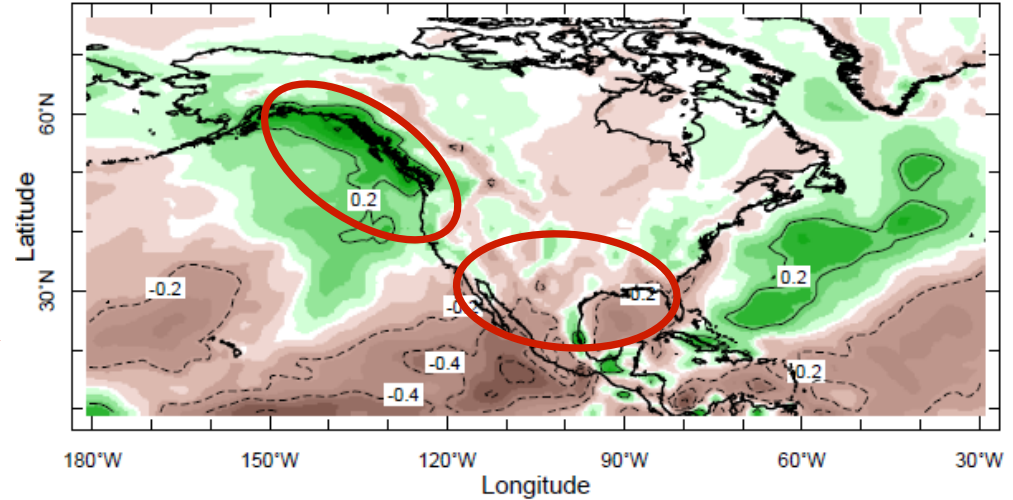


# Implications of the East Pacific circulation response

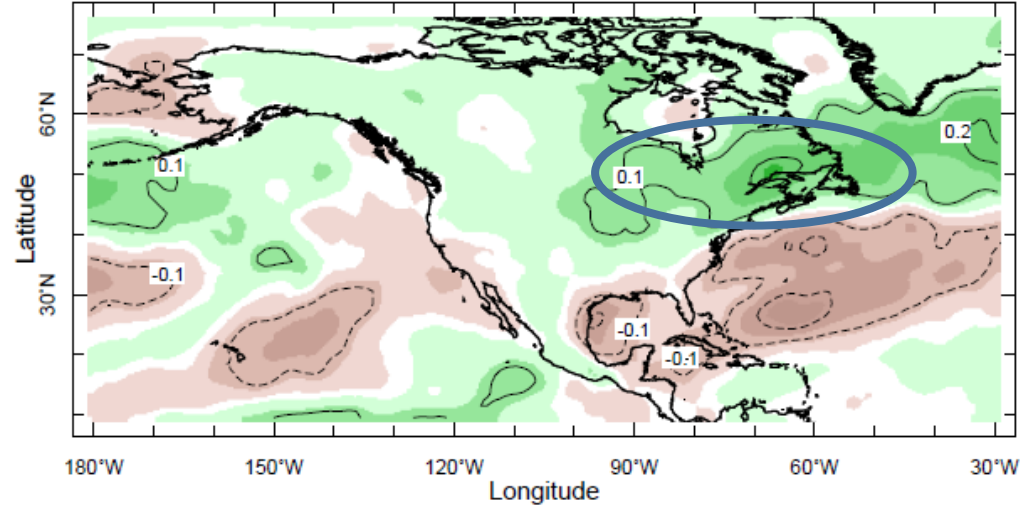
P-E



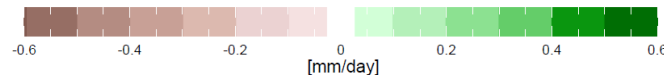
Mean flow moisture flux convergence



Moisture flux convergence by sub-monthly transients

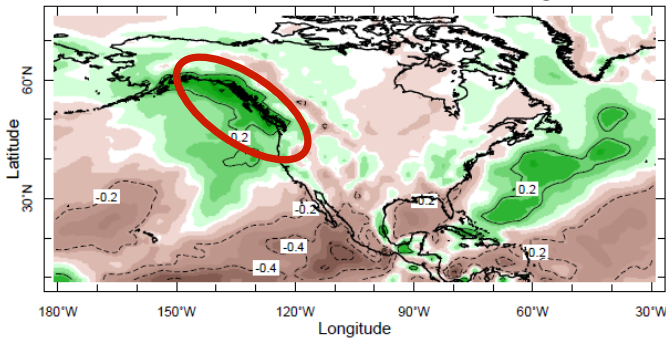


$$-\frac{1}{g\rho_w} \nabla \cdot \sum_{k=1}^K (\overline{\mathbf{u}_k \bar{q}_k} + \overline{\mathbf{u}'_k q'_k}) \overline{dp}_k$$

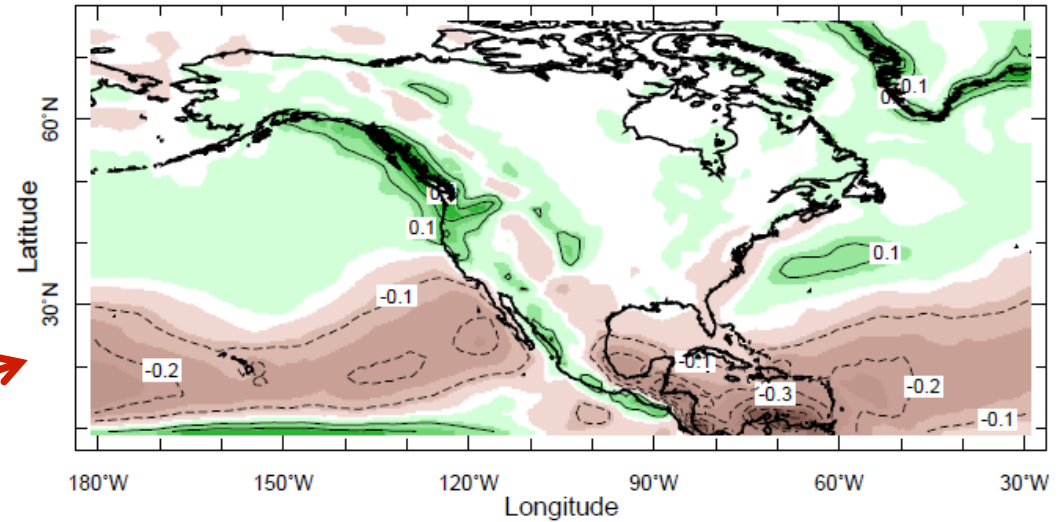


# Implications of the East Pacific circulation response

Mean flow moisture flux convergence



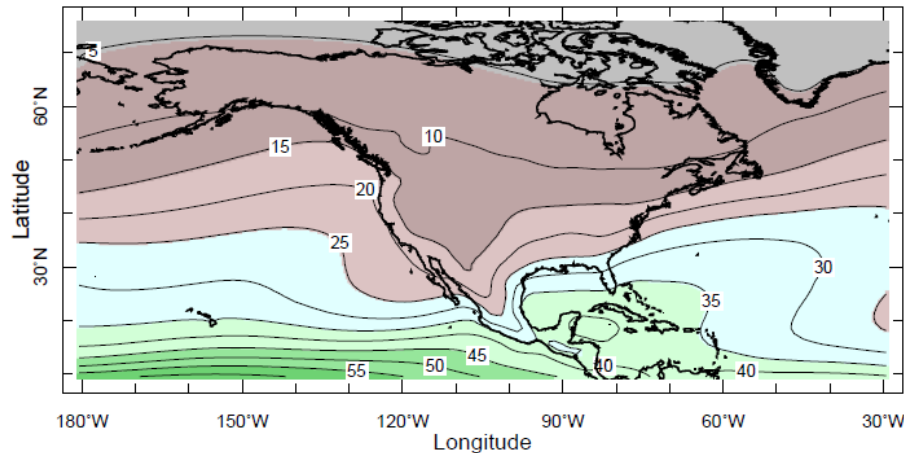
Contribution from unchanged divergent flow acting on changed specific humidity



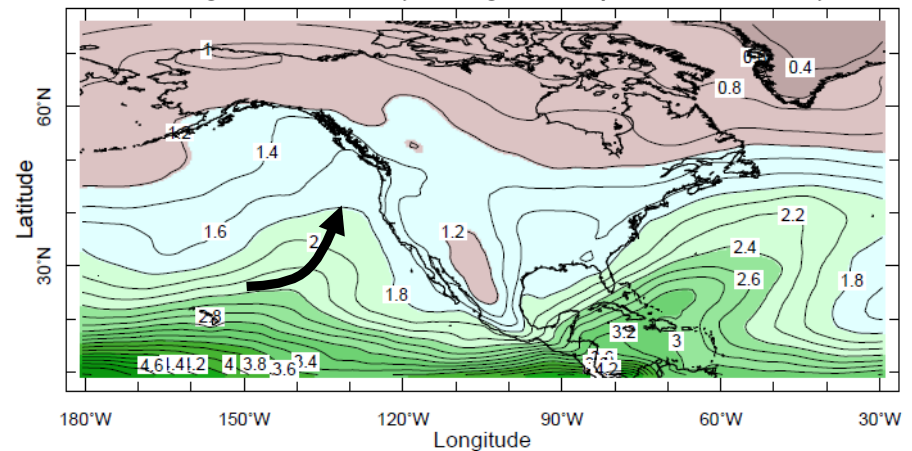
$$-\frac{1}{g\rho_w} \sum_{k=1}^K \nabla \cdot \bar{\mathbf{u}}_{k,20} \Delta \left( \overline{q_k} \overline{dp_k} \right)$$

→

Past climatological vertically integrated specific humidity

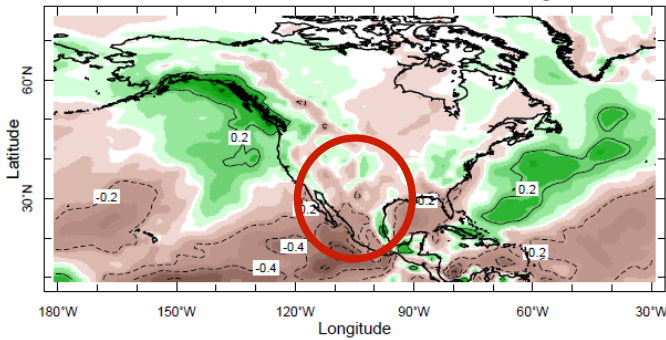


Change in vertically integrated specific humidity

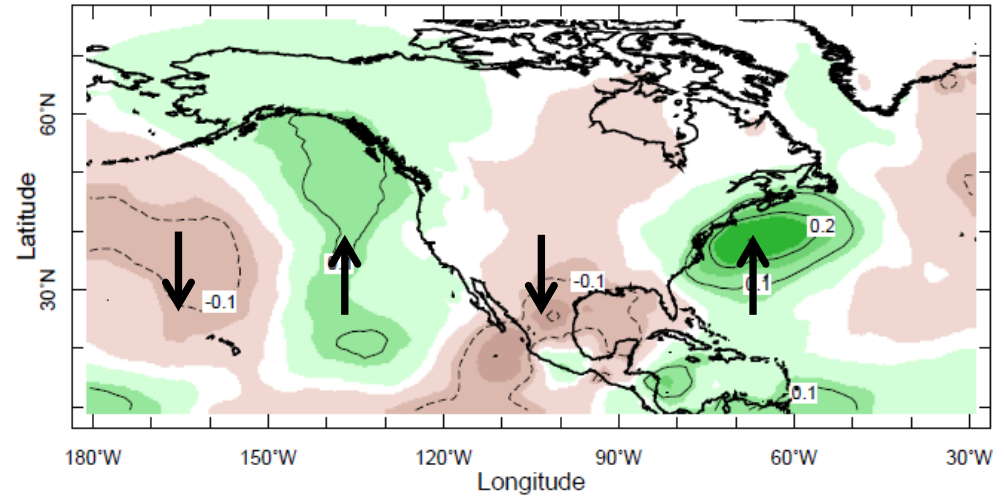


# Implications of the East Pacific circulation response

Mean flow moisture flux convergence



Contribution from advection across climatological moisture gradients by the anomalous mean flow

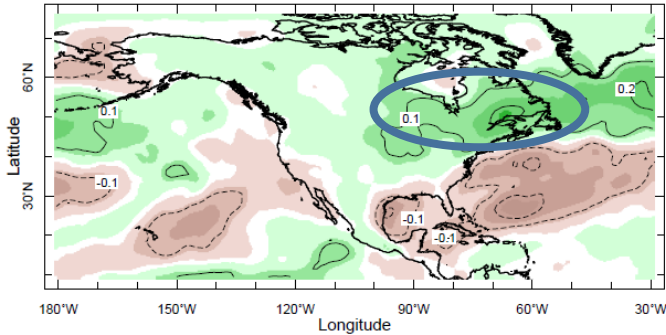


$$-\frac{1}{g\rho_w} \sum_{k=1}^K \nabla \bar{q}_{k,20} \cdot \Delta \left( \bar{\mathbf{u}}_k \bar{d}\rho_k \right)$$

→

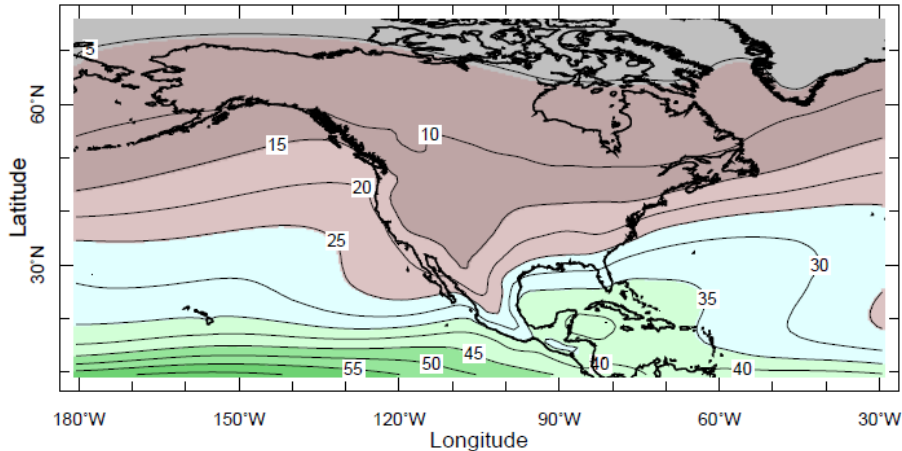
# Implications of the East Pacific circulation response

Moisture flux convergence by sub-monthly transients

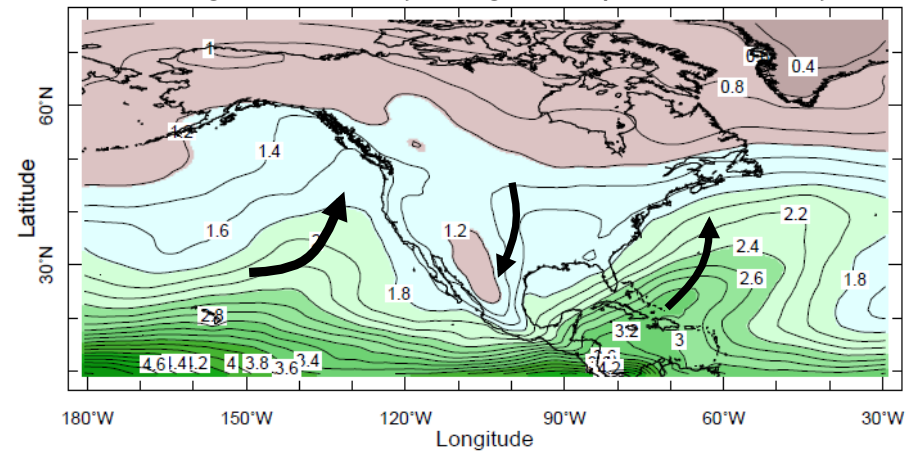


Transient eddy activity is actually weakening at low levels here

Past climatological vertically integrated specific humidity



Change in vertically integrated specific humidity





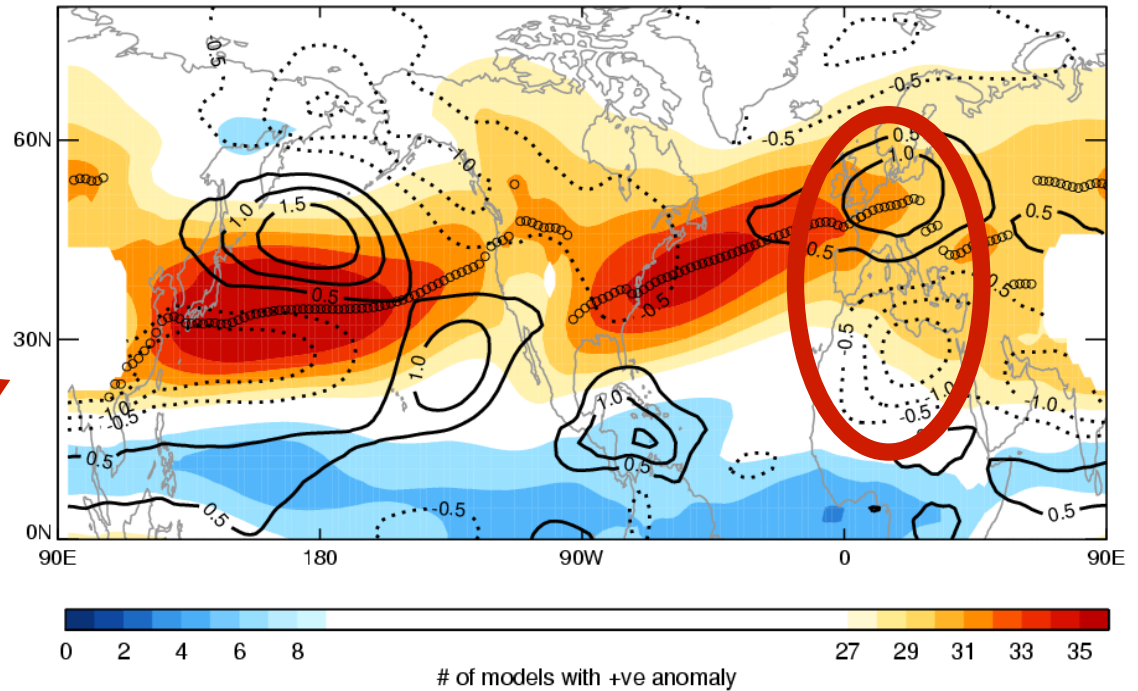
# Summary for the East Pacific/North America

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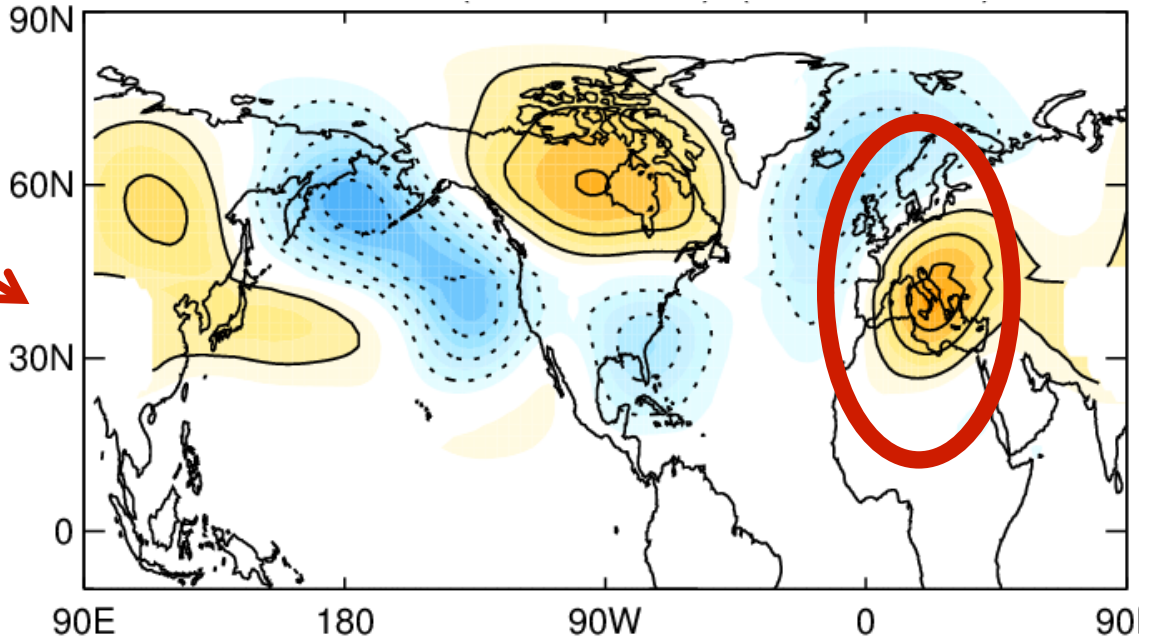
- Consensus on a wave train anomaly across the Pacific and North America
- This results in the equatorward shifted jet in the East Pacific
- And perhaps more importantly alternating signed meridional wind anomalies across North America that contribute toward
  - wetting in the North West
  - drying in the South
  - wetting in the North East
- We need to gain a complete understanding of this circulation anomaly, understand what it depends on and therefore determine whether we expect the real world to behave in the same way

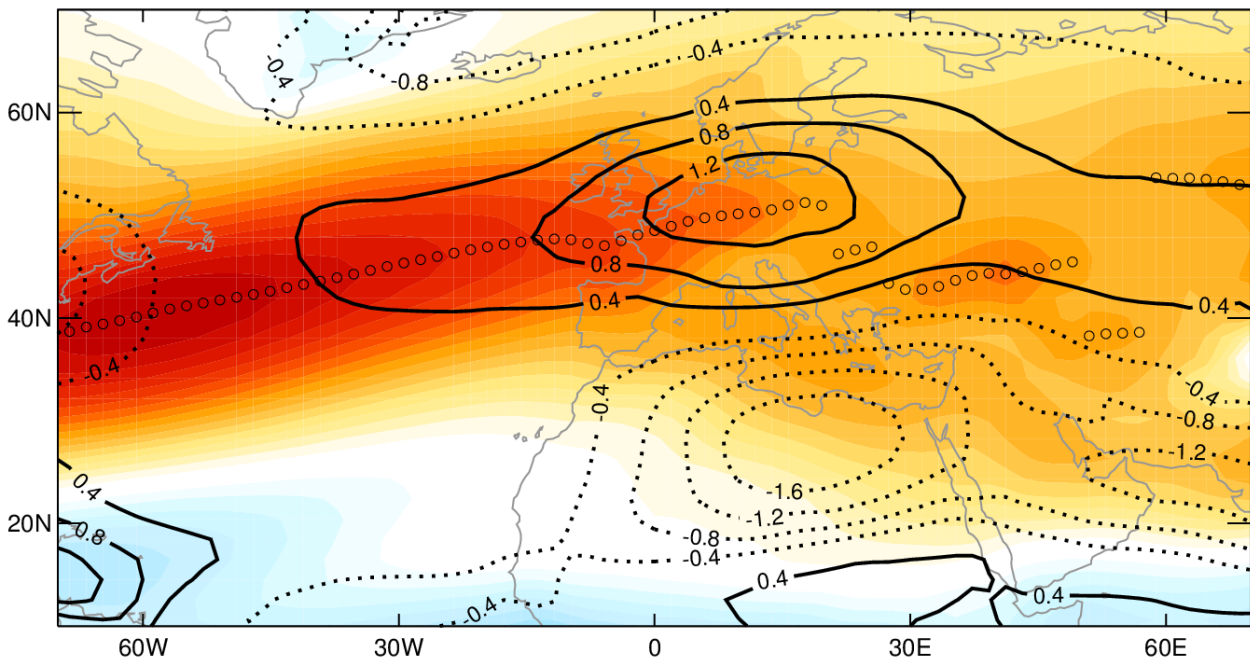
Now we have a model consensus on at least some features during NH winter.....

Zonal wind anomalies (700hPa)

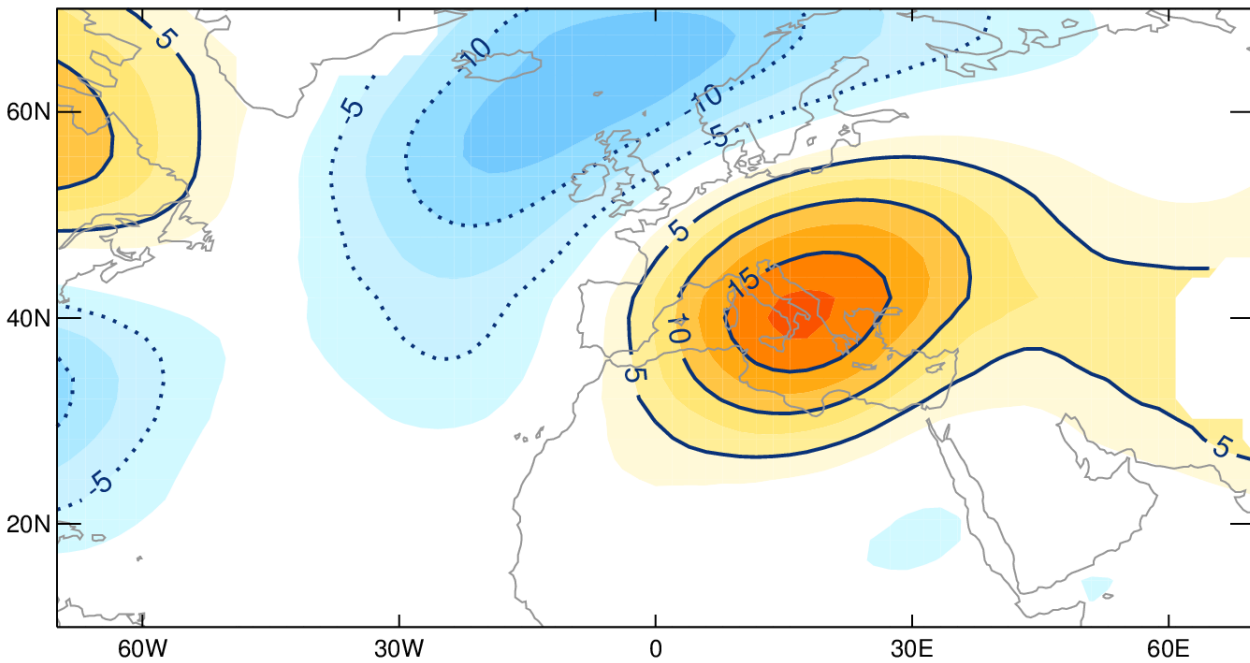


Eddy geopotential height anomalies (700hPa)





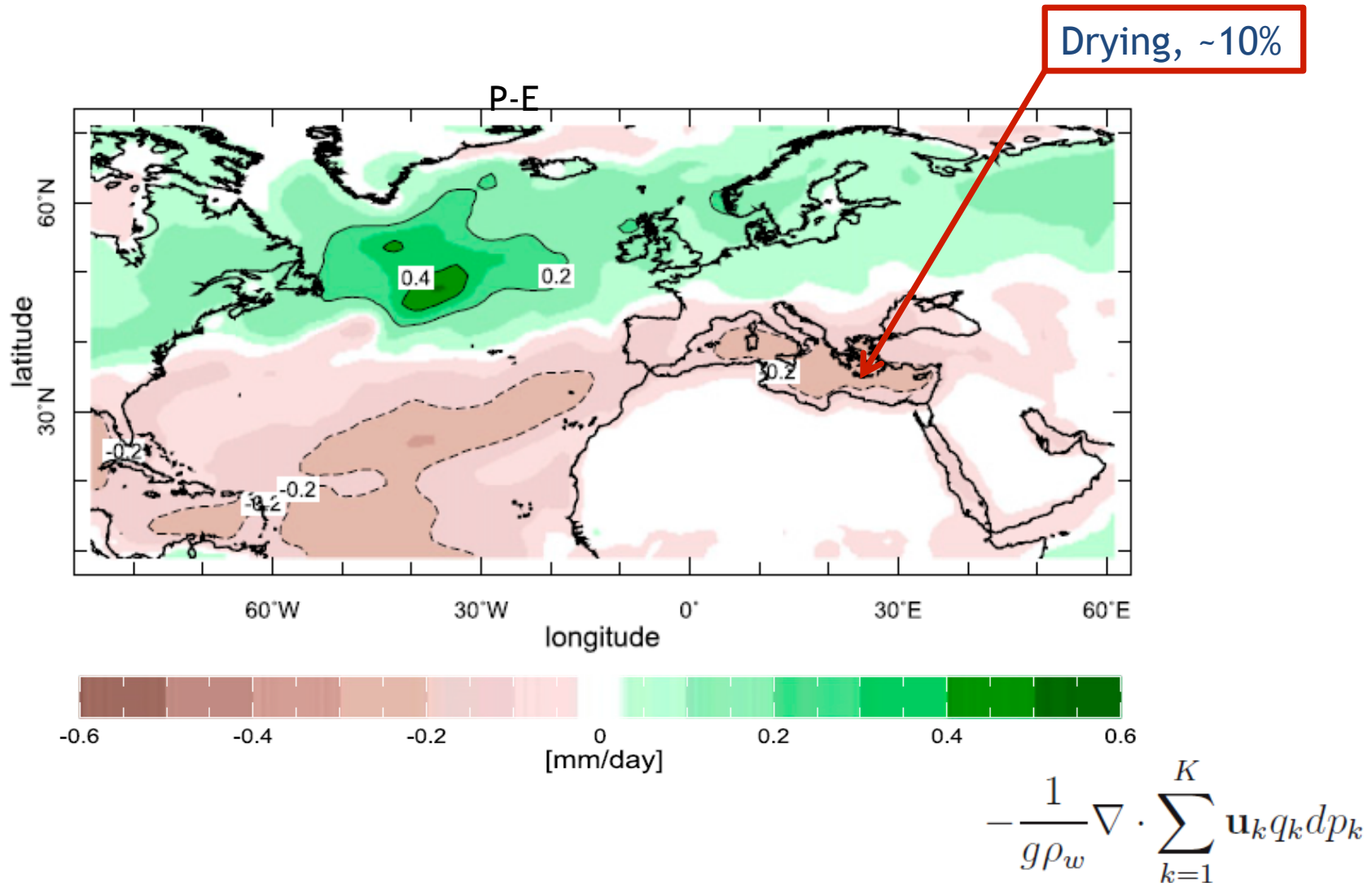
700hPa zonal wind



700hPa eddy geopotential height

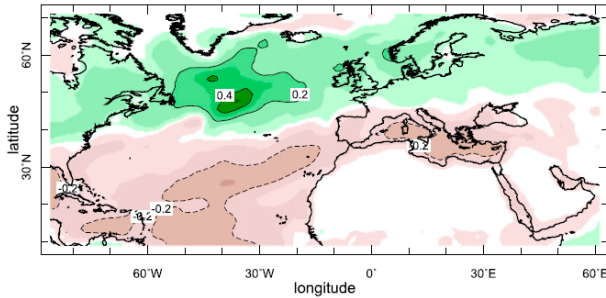
# Contributes to future drying of the Mediterranean

Seager et al (2014b) - Moisture budget analysis of CMIP5 response  
(2021-2040)-(1979-2005), NDJFMA, RCP8.5, 16 models

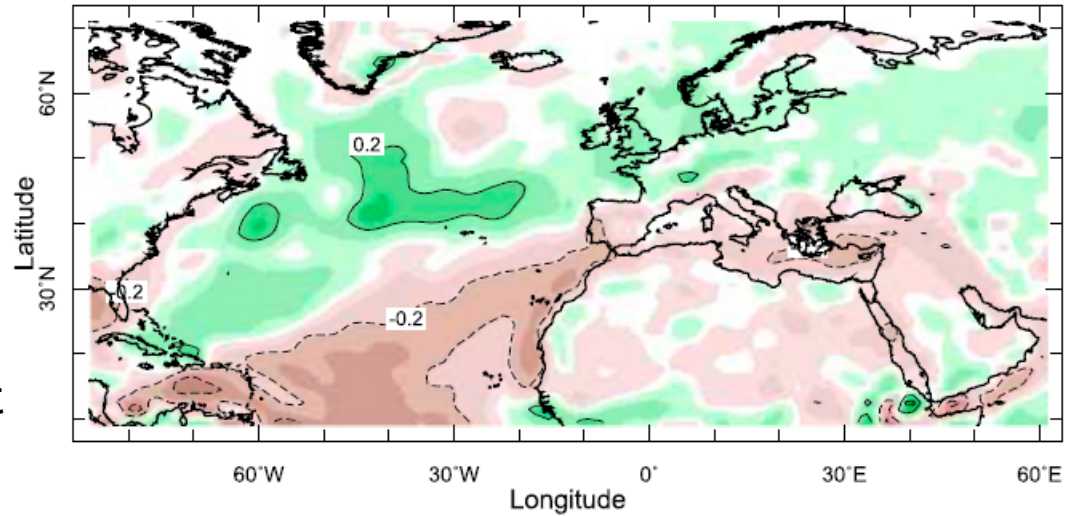


# Contributes to future drying of the Mediterranean

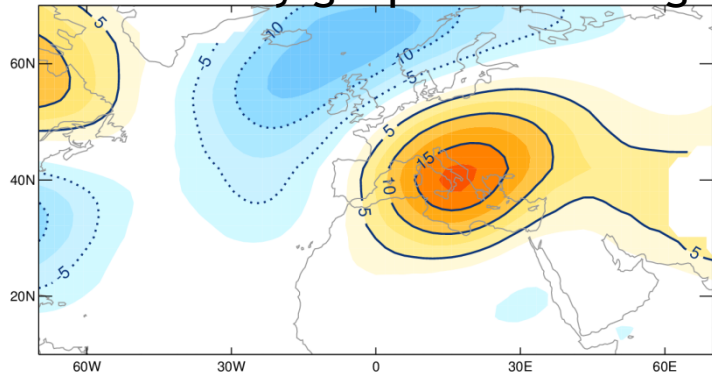
P-E



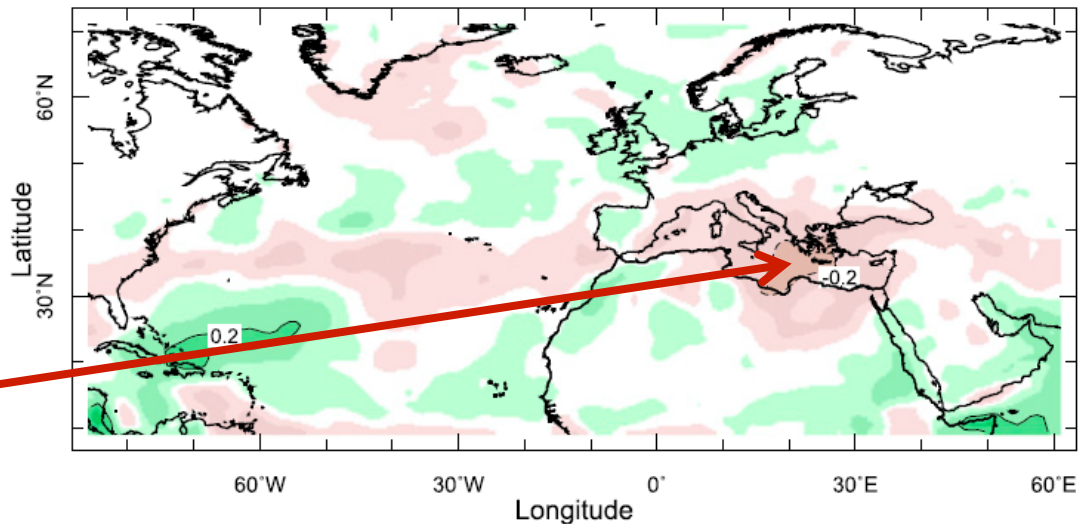
Contribution from mean flow moisture flux convergence



700hPa eddy geopotential height



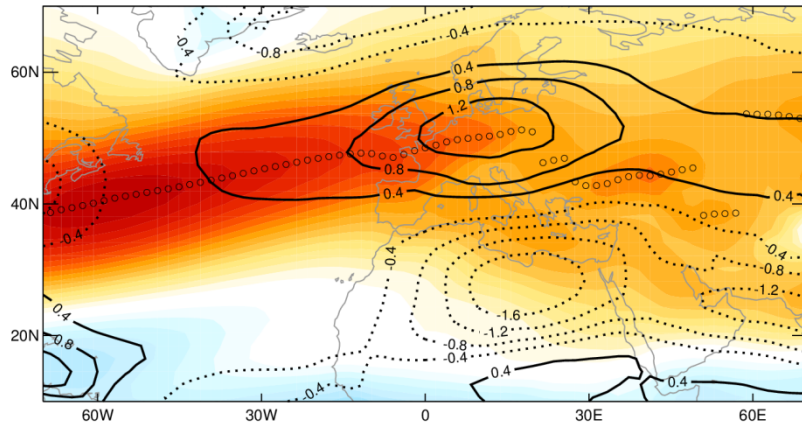
Contribution from change in divergent flow



Enhanced subsidence  
and low level  
divergence



# Associated with changes in storminess

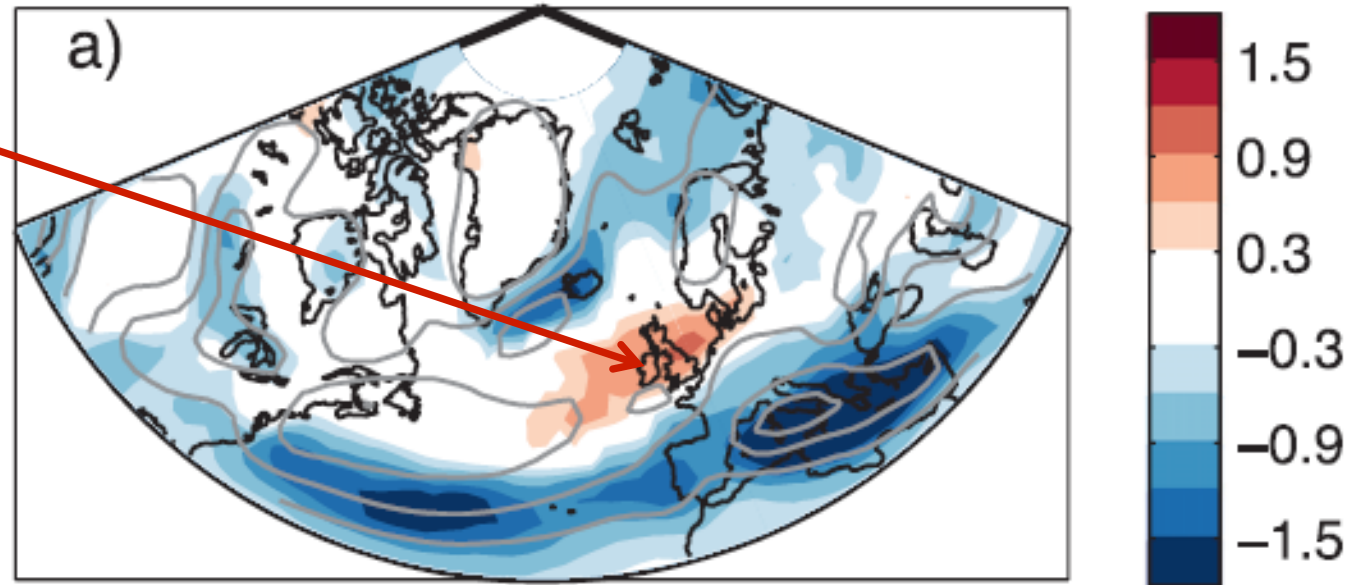


Zappa et al (2013) J. Clim., 26, 5846-5862

track density DJF

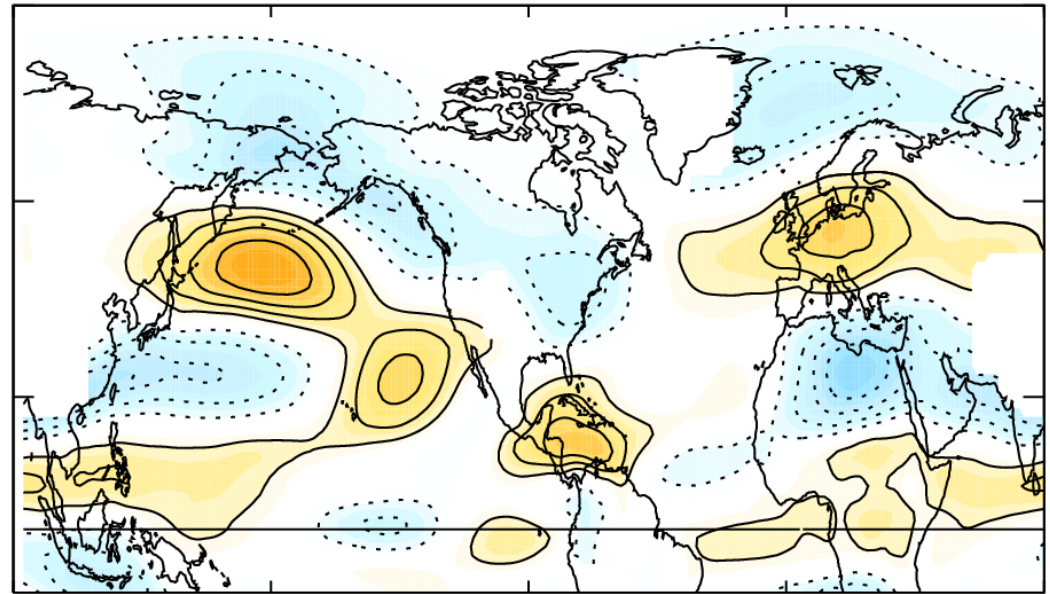
~ 1 more cyclone per month

RCP8.5 (2070-2099) –  
Historical (1979-2005)



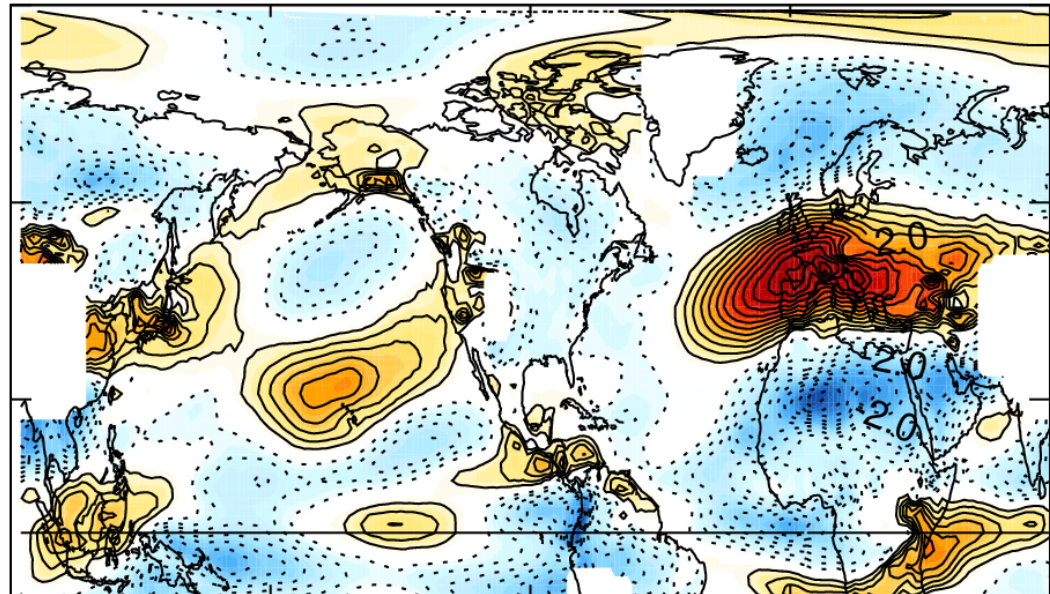
Can we trust these predictions?

700hPa zonal wind Future-Past difference



CMIP5 model mean bias

700hPa zonal wind bias, CMIP5-ERA-Interim



# Conclusions

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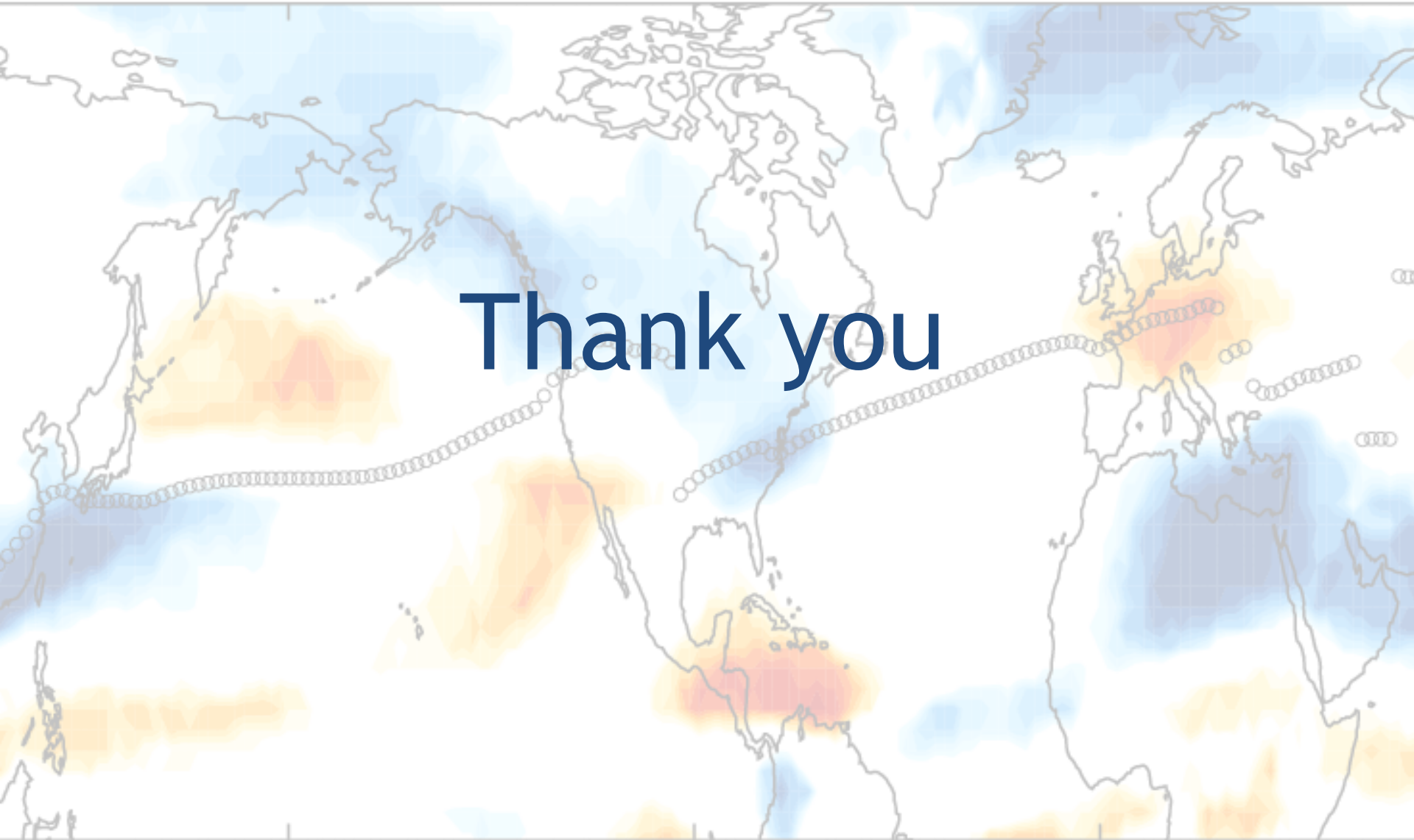
- There is substantial zonal and seasonal variation in the mid-latitude circulation response to climate change
- In NH winter, in particular, stationary wave changes dominate the circulation response locally with important implications for the hydroclimate of North America and Europe and the Mediterranean
- It is important that we understand these changes and how model biases may impact on them so that we can improve our confidence in future predictions for the real world.





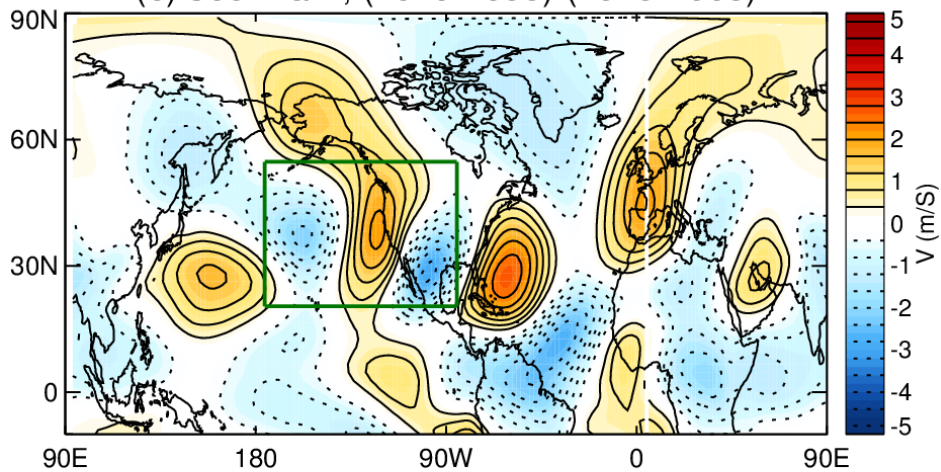
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THE EARTH INSTITUTE AT COLUMBIA UNIVERSITY

Thank you

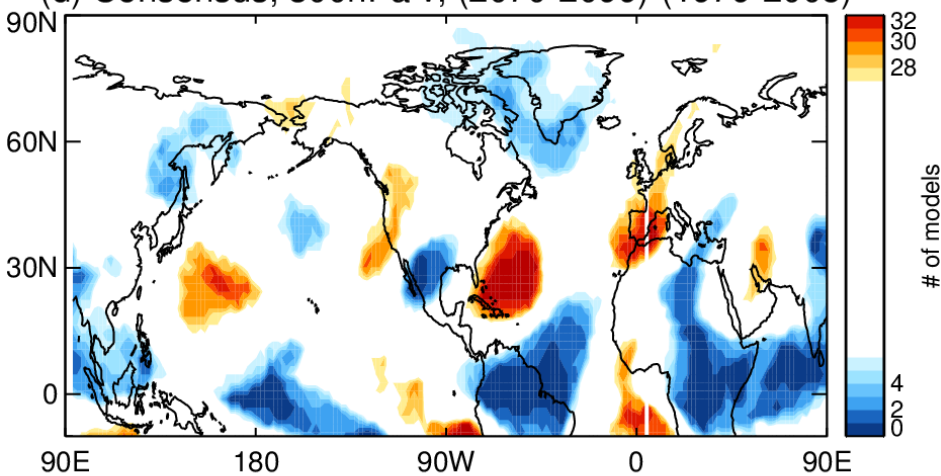




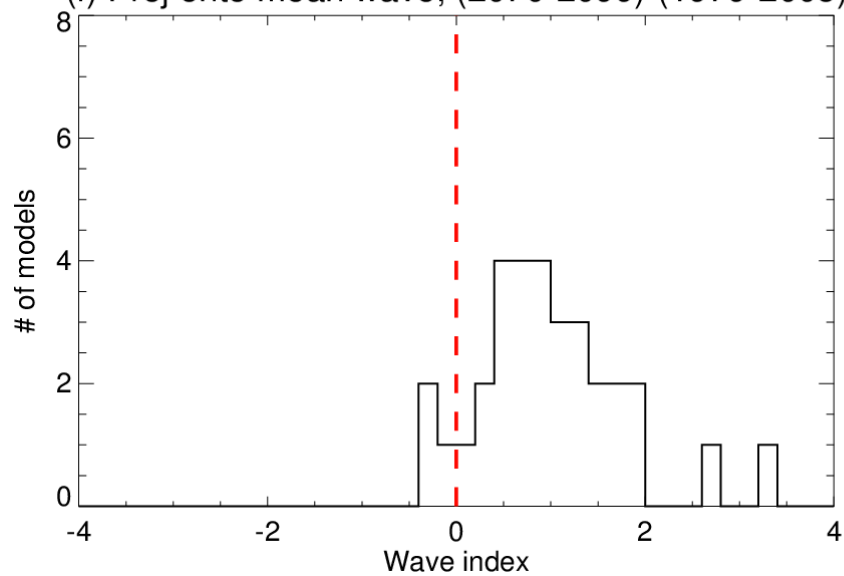
(b) 300hPa V, (2070-2099)-(1979-2005)



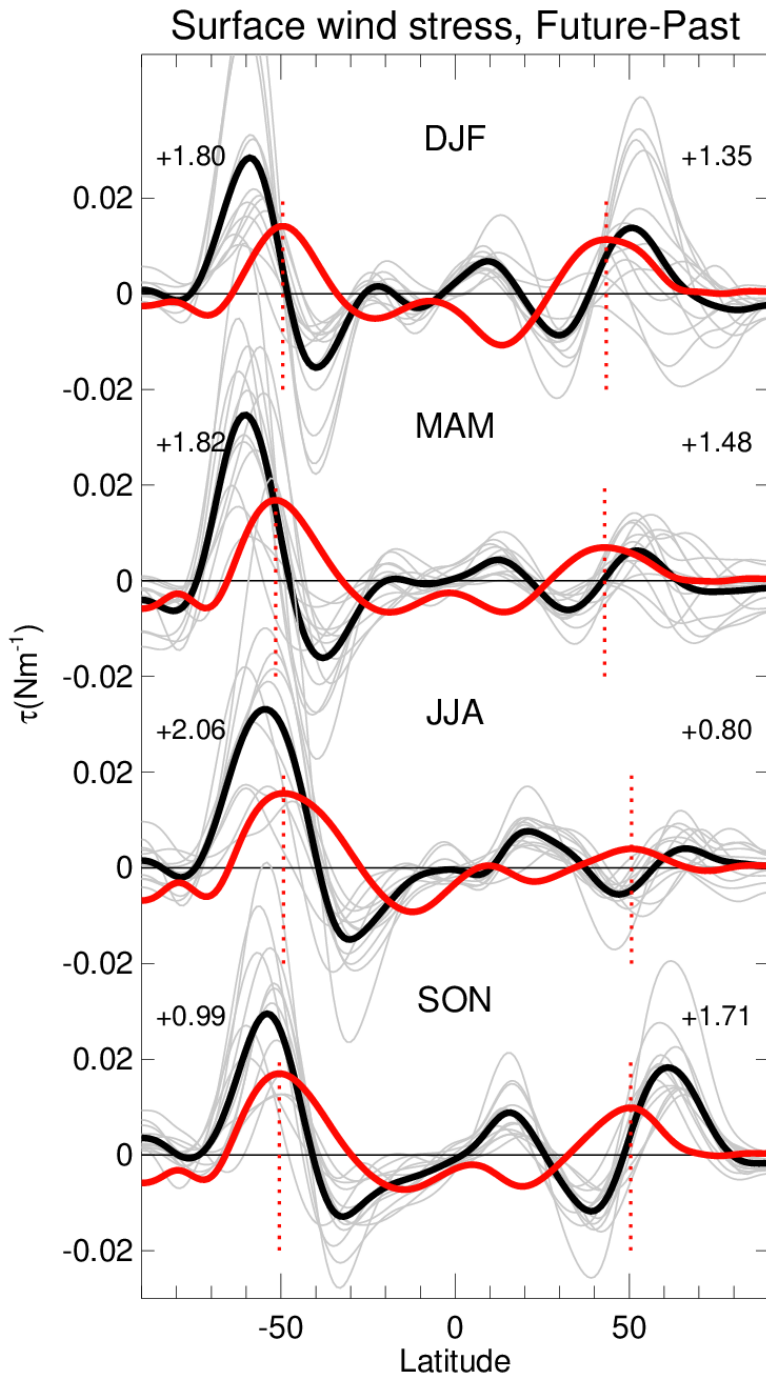
(d) Consensus, 300hPa v, (2070-2099)-(1979-2005)



(f) Proj onto mean wave, (2070-2099)-(1979-2005)



# The momentum budget in CMIP5



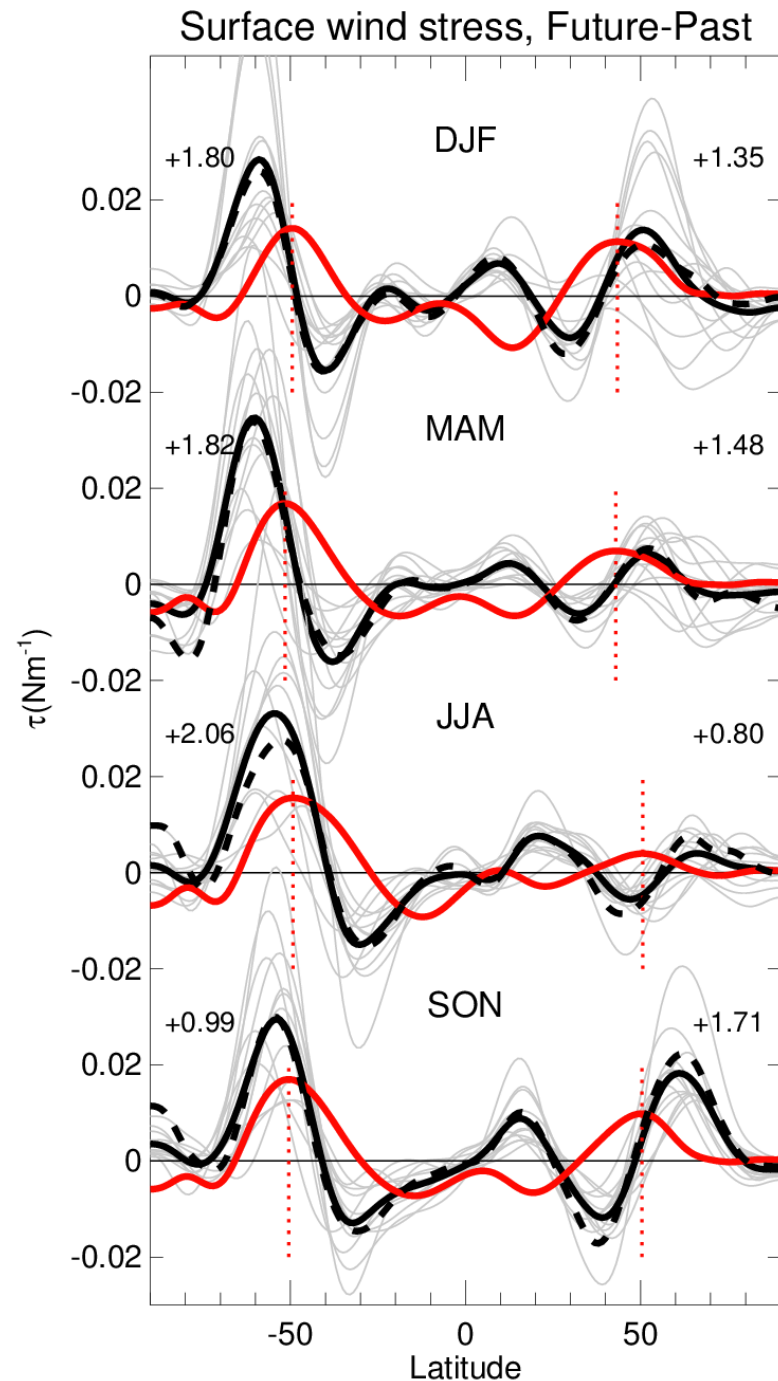
Surface wind stress 

 Climatology/10.

 Future-Past

13 model subset

# The momentum budget in CMIP5



Surface wind stress —

Sum of vertically integrated momentum budget terms

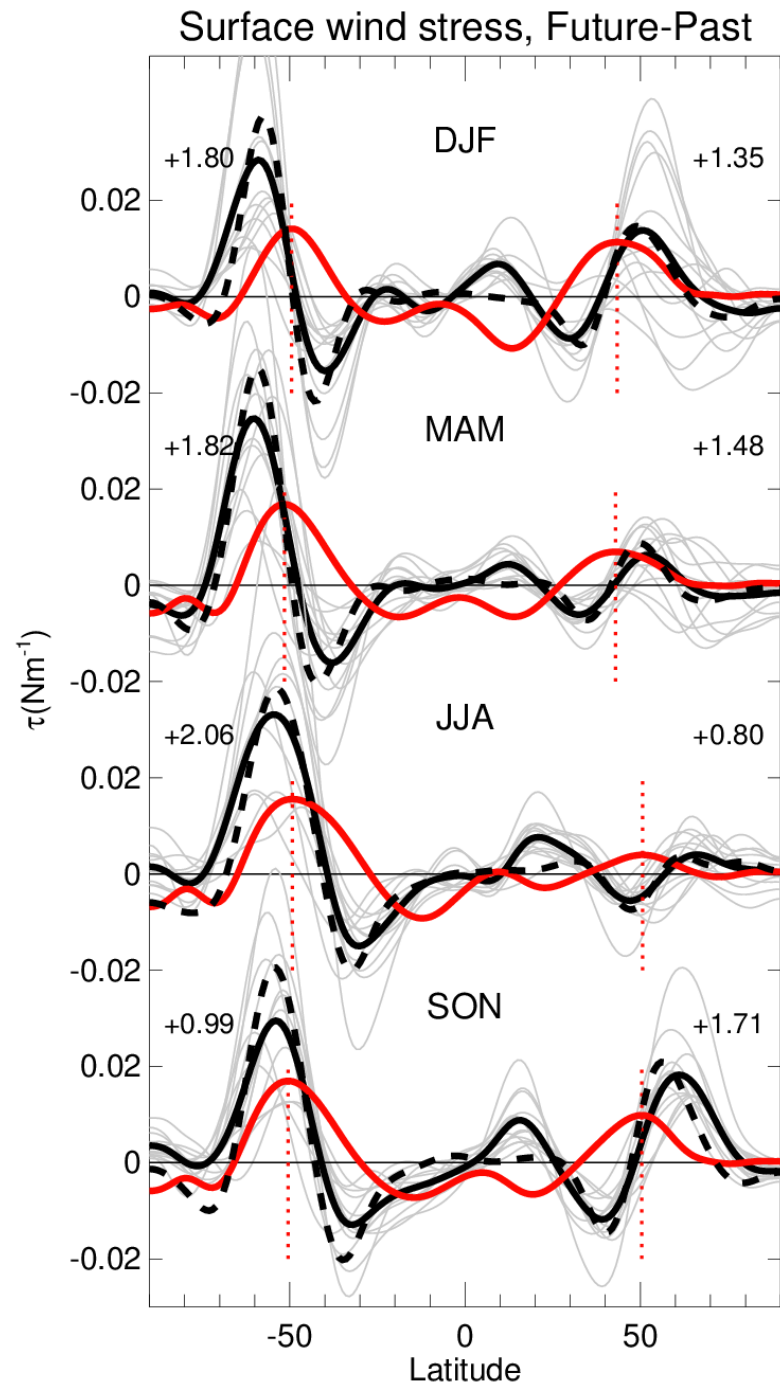
— — — |

— Climatology/10.

— Future-Past

13 model subset

# The momentum budget in CMIP5



Surface wind stress —

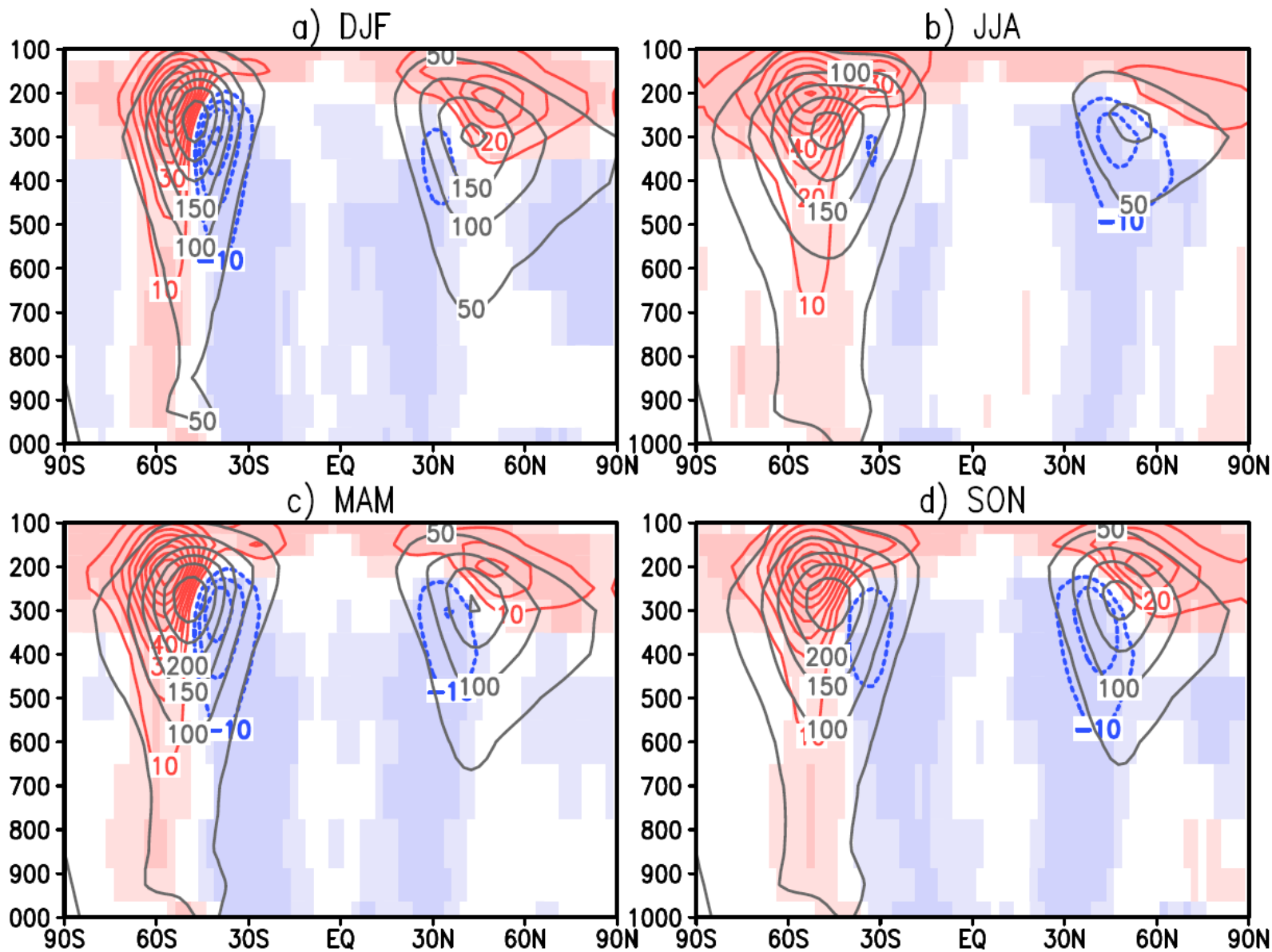
Vertically integrated 10 day high pass filtered meridional eddy momentum flux convergence

— — — —

— Climatology/10.

— Future-Past

13 model subset

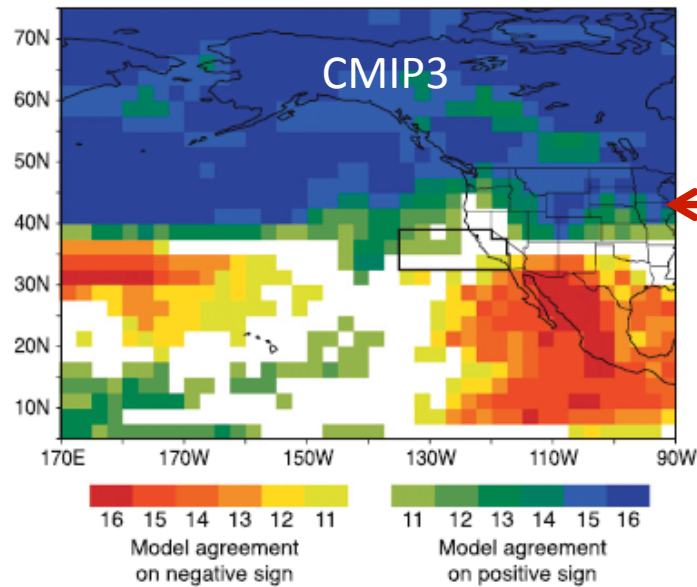
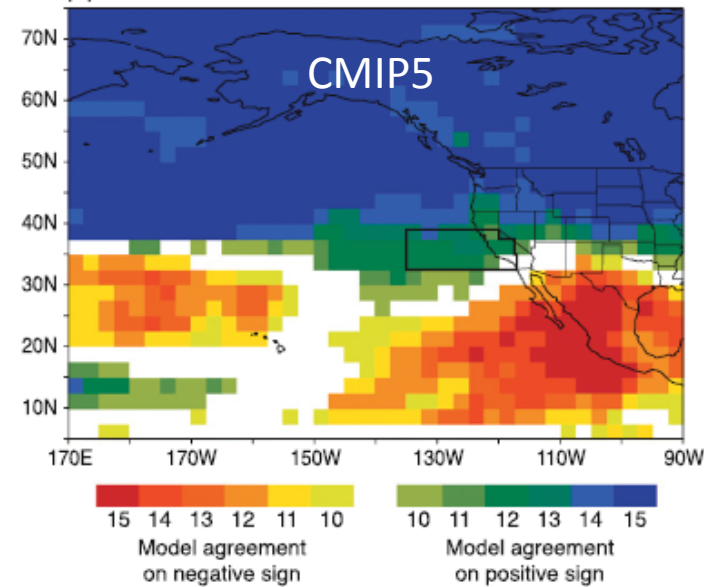


Chang et al (2012) –  $v'^2$  response

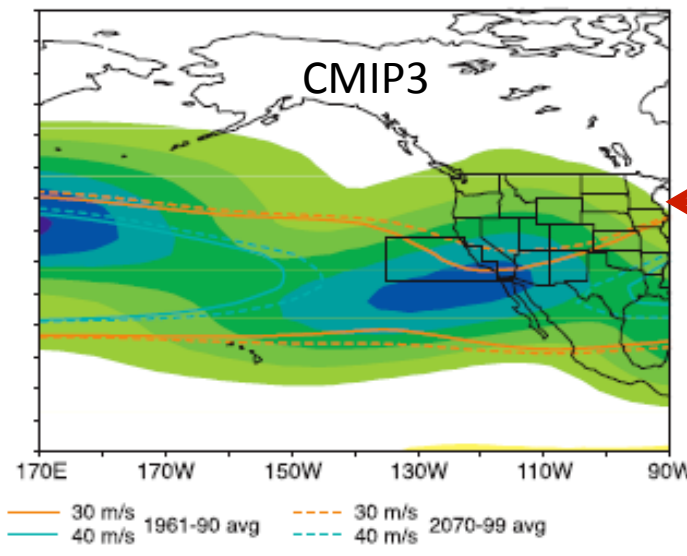
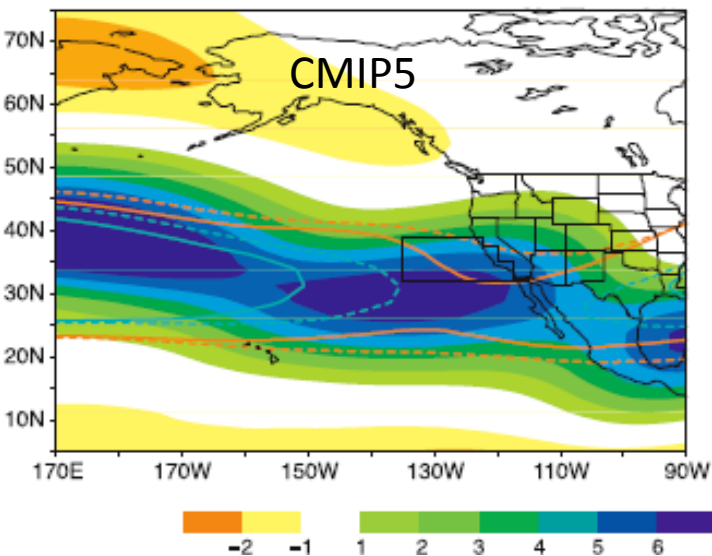


# Implications of the East Pacific circulation response

Neelin et al (2013) - CMIP5/CMIP3 comparison of DJF California Precip



Model consensus on precip changes

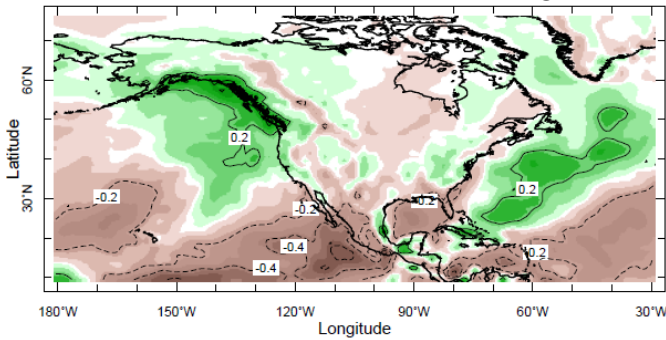


Change in 200hPa zonal wind

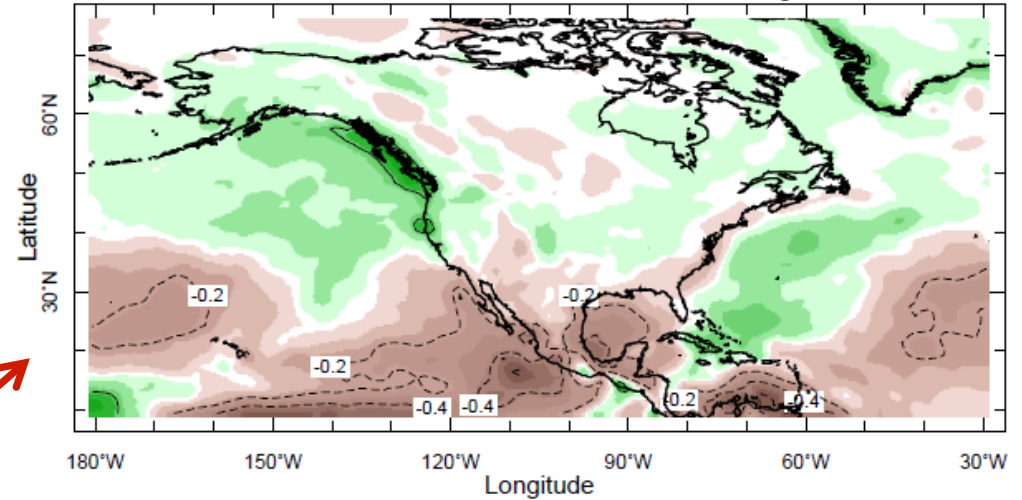


# Implications of the East Pacific circulation response

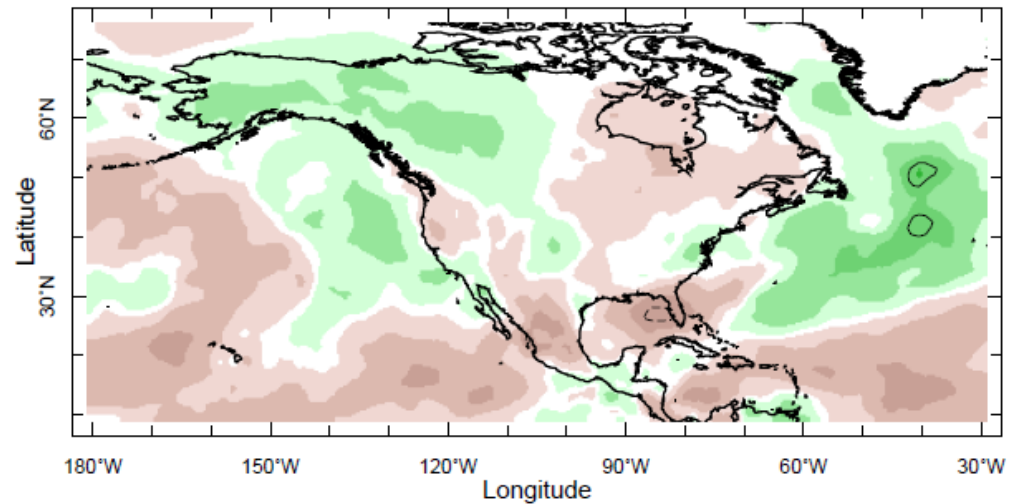
Mean flow moisture flux convergence



Contribution from mass convergence



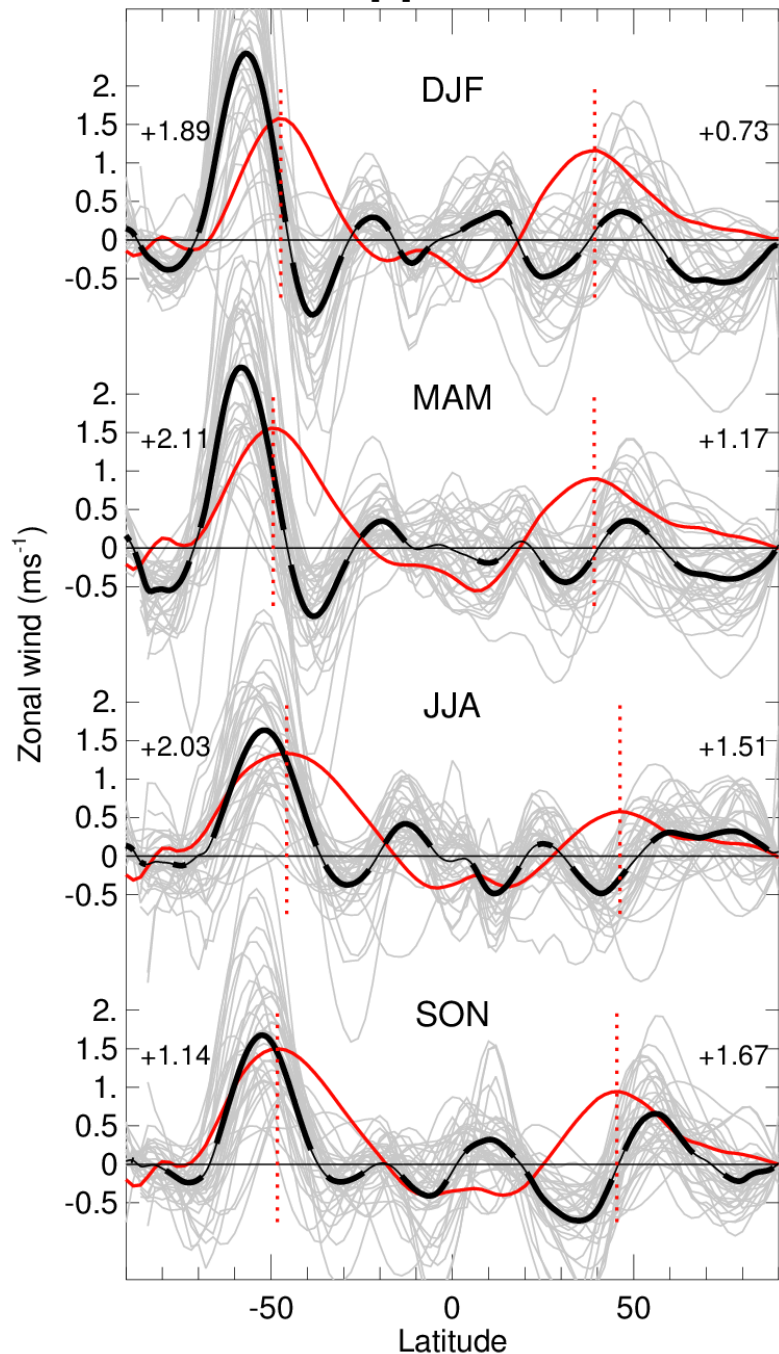
Contribution from advection across moisture gradients



$$-\frac{1}{g\rho_w} \sum_{k=1}^K (\bar{\mathbf{u}}_k \cdot \nabla \bar{q}_k + \bar{q}_k \nabla \cdot \bar{\mathbf{u}}_k) \bar{d}p_k$$



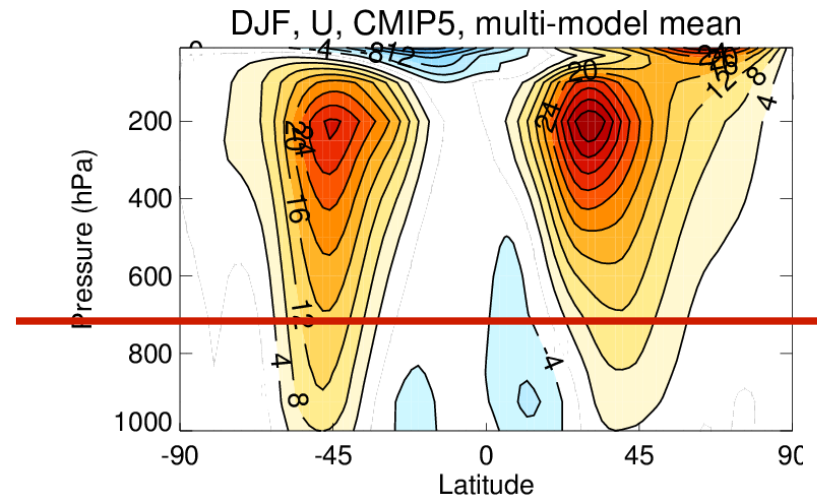
700hPa [ $\bar{u}$ ], Future-Past



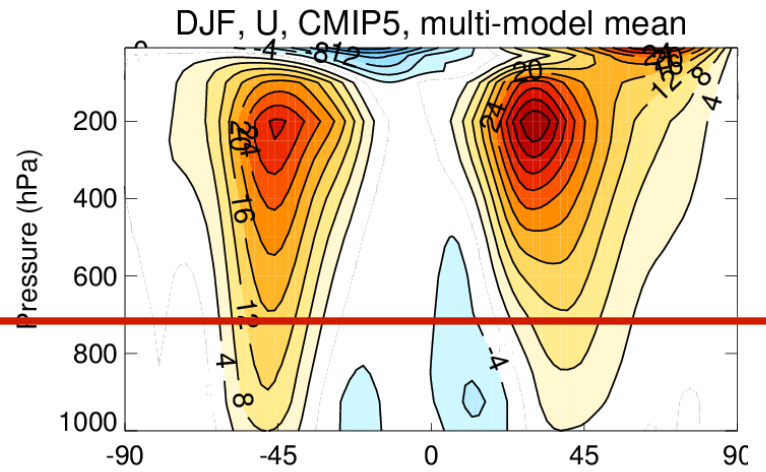
A poleward shift of the zonal mean in each hemisphere and season

Maintained by high frequency (<10 day) transient meridional eddy momentum flux convergence

In the zonal mean, the CMIP5 models predict a poleward shift of the mid-latitude westerlies in each season in both hemispheres

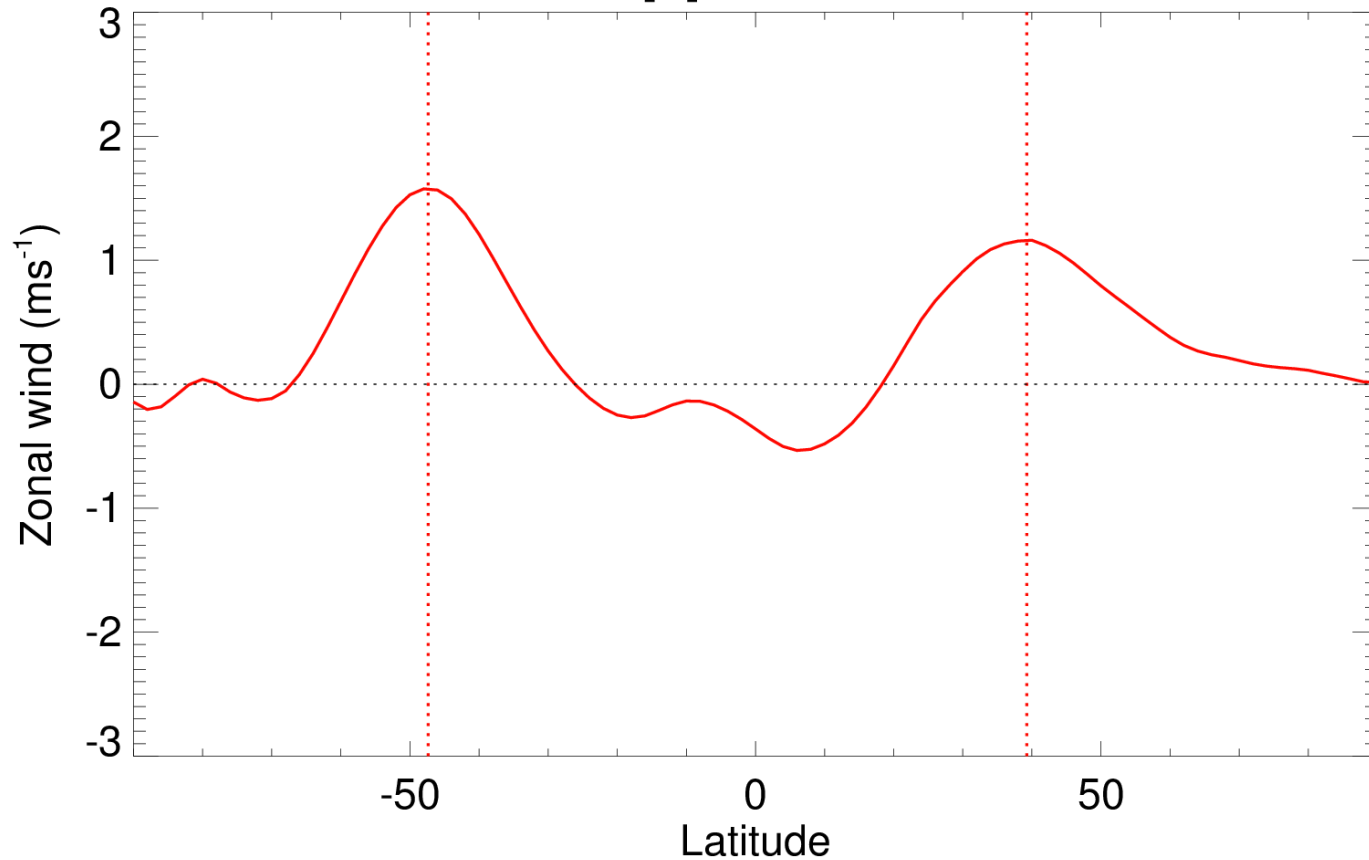


# Climatological wind / 10

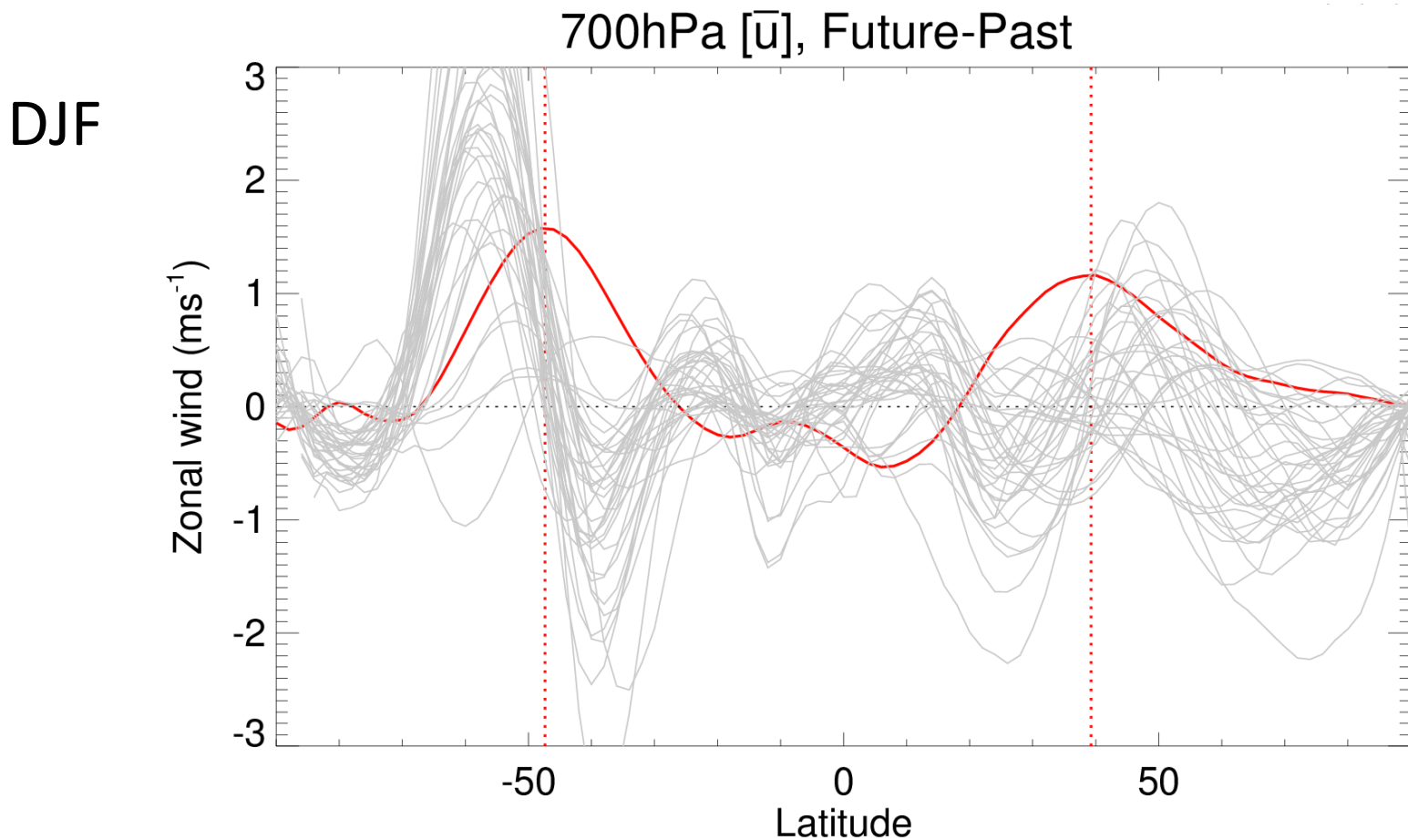
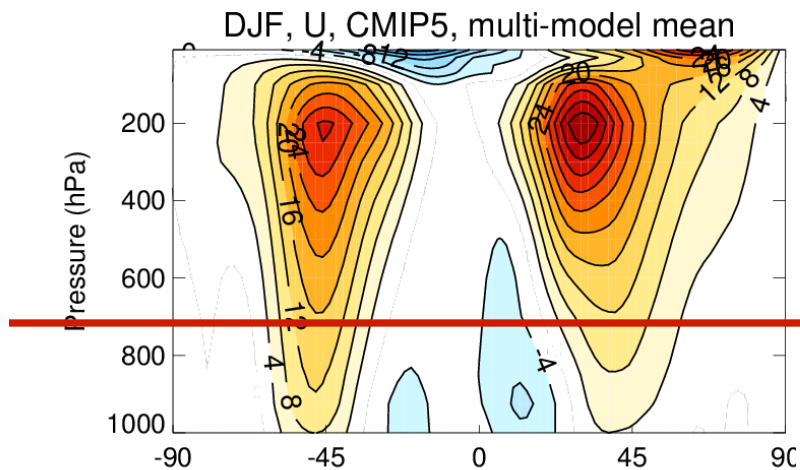


## 700hPa [ $\bar{u}$ ], Future-Past

DJF

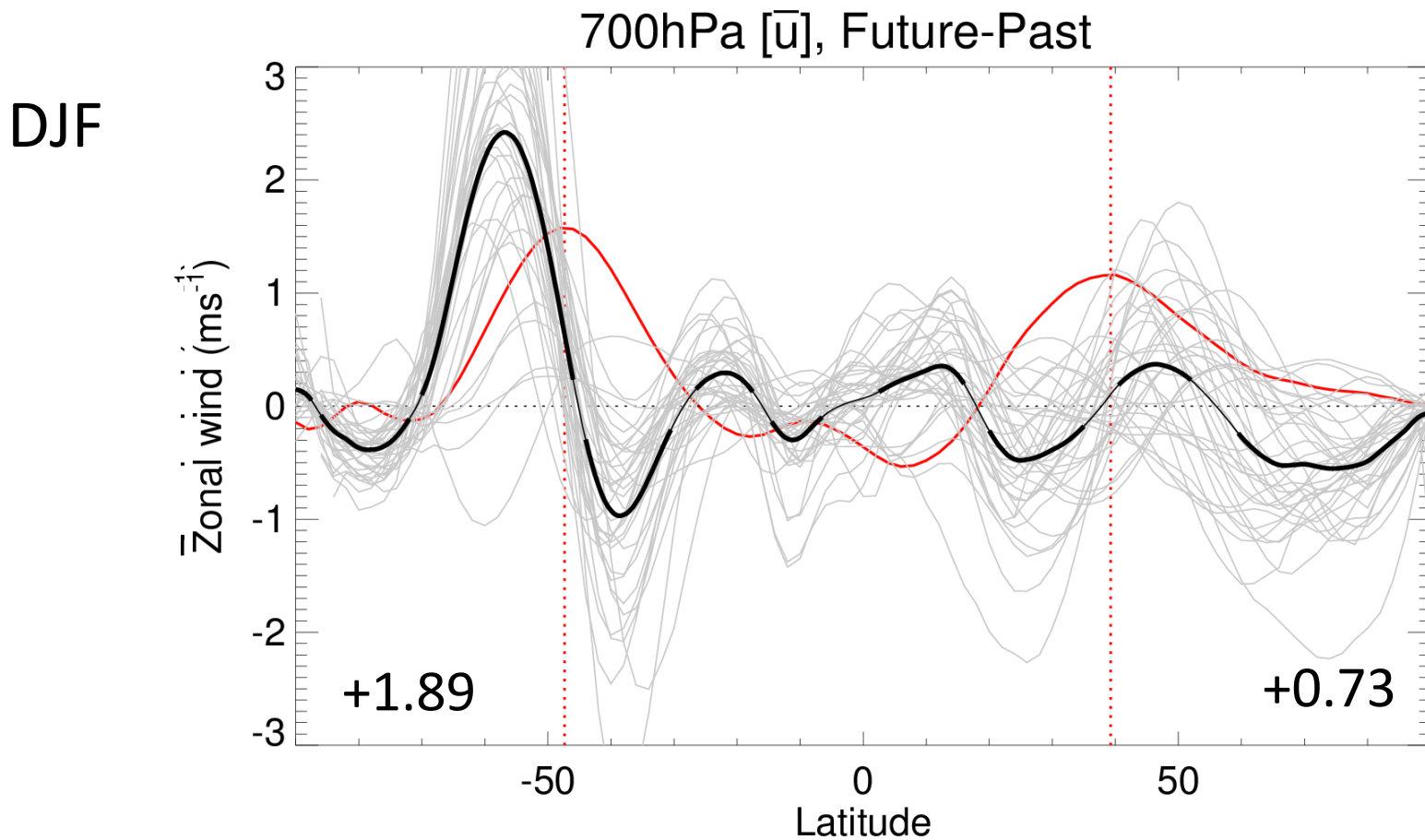
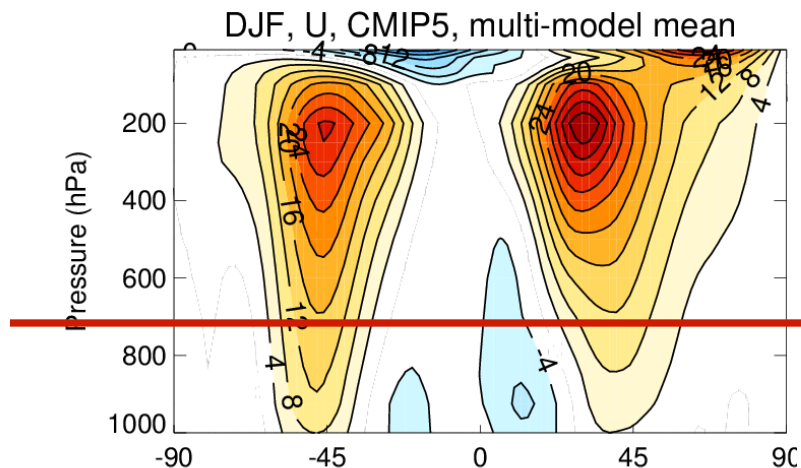


- Climatological wind / 10
- Individual model, RCP8.5, (2070-2100)-(1979-2005)

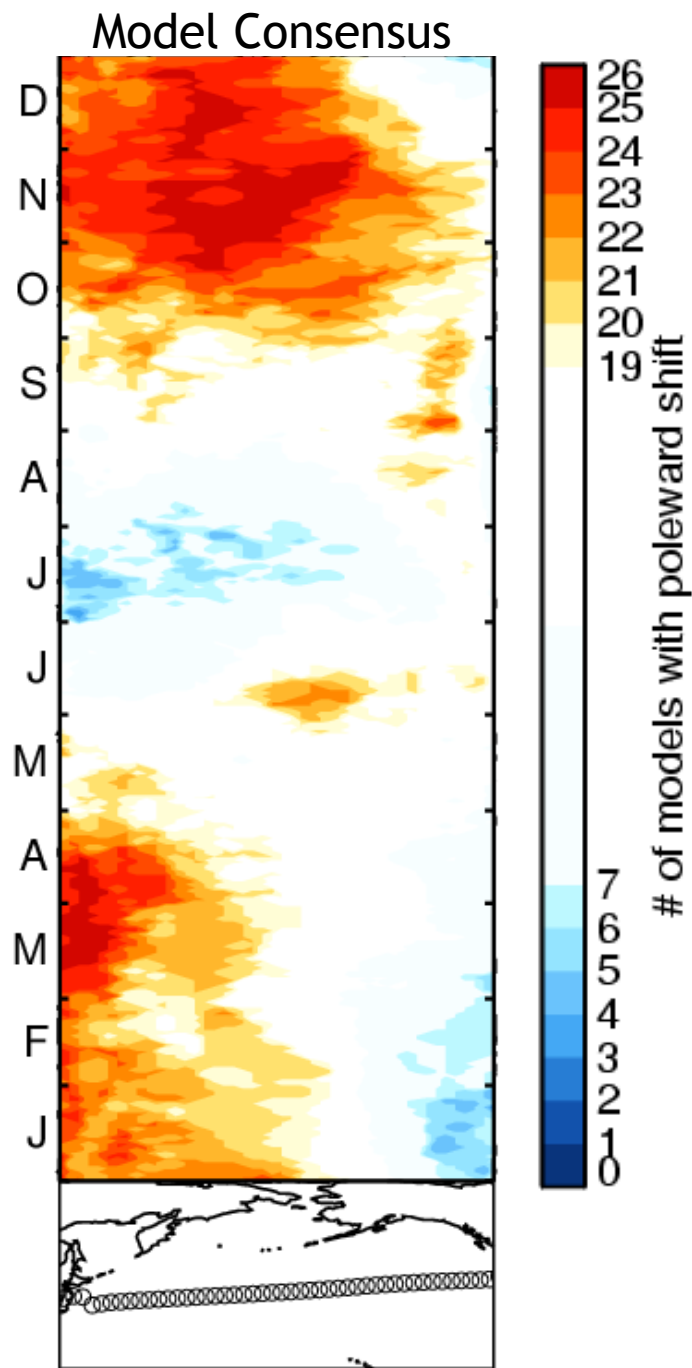
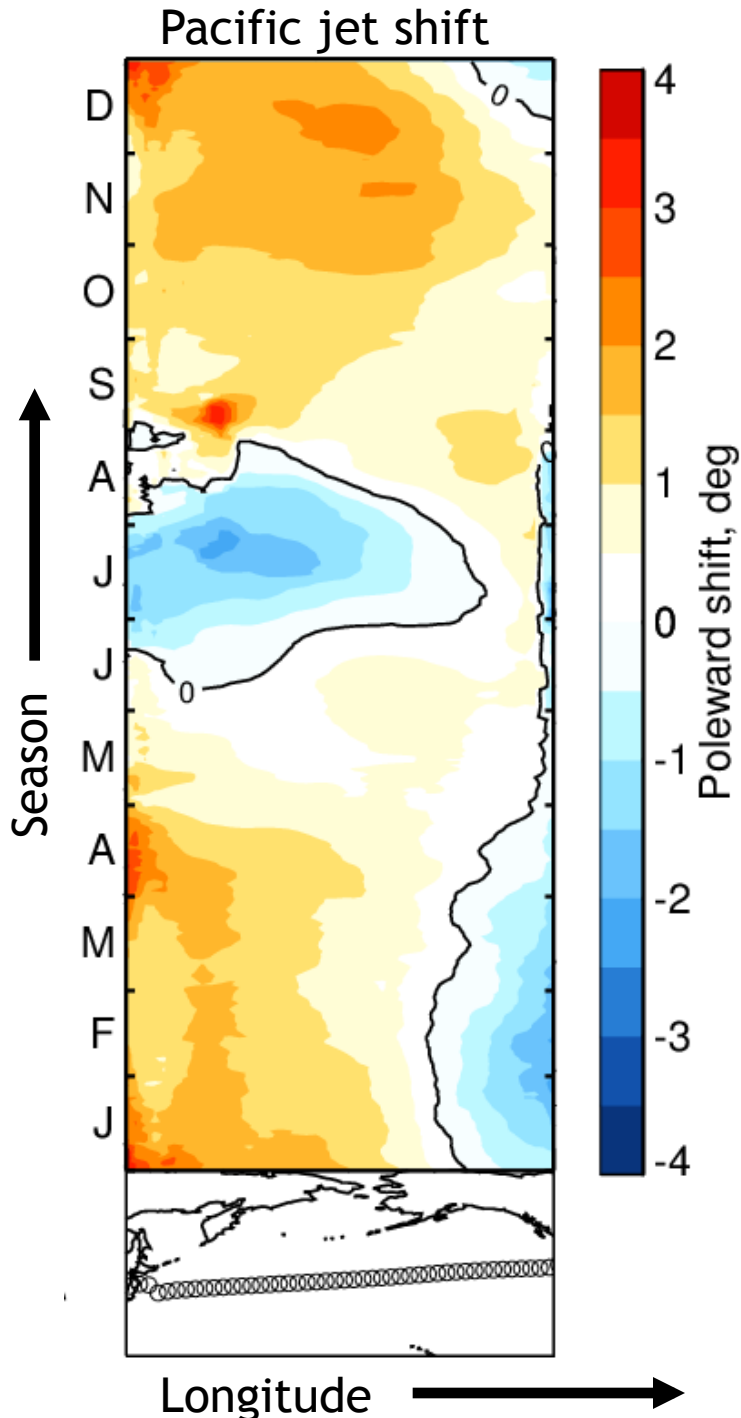




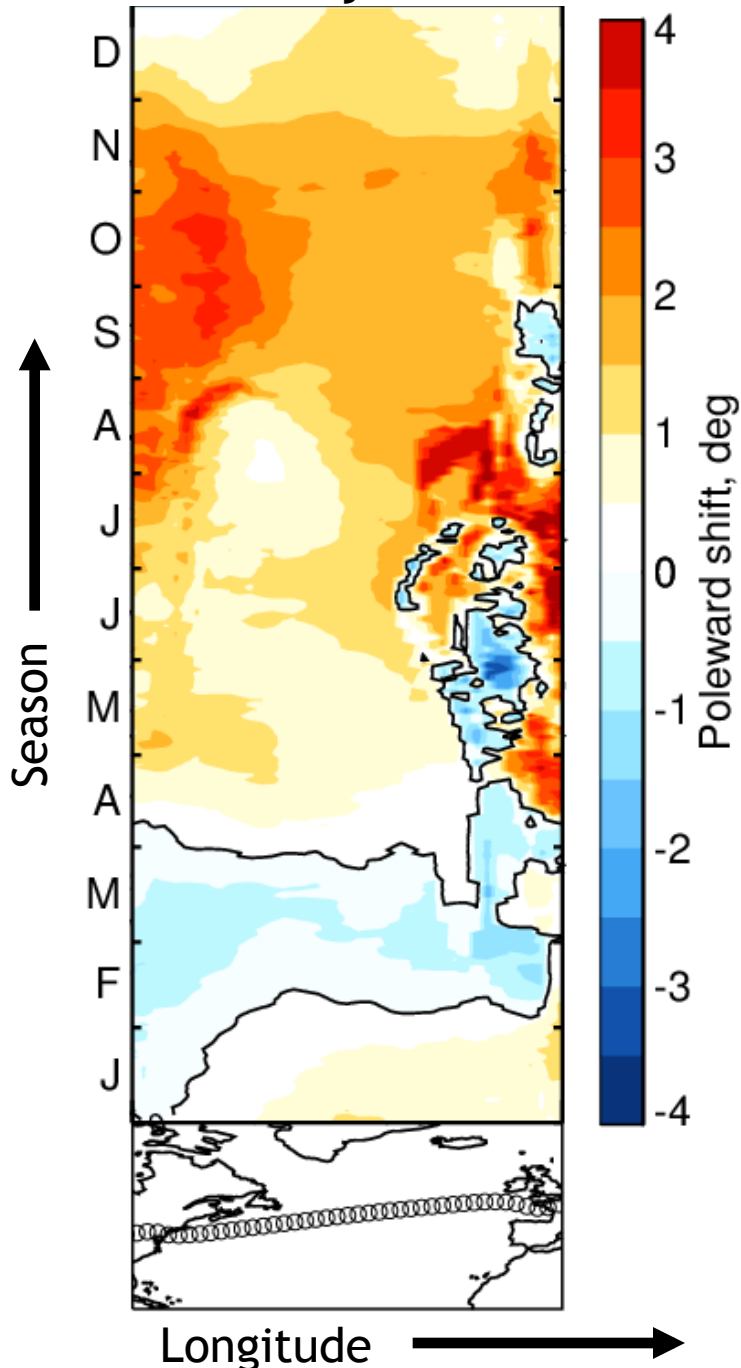
- Climatological wind / 10
- Individual model, RCP8.5, (2070-2100)-(1979-2005)
- Multi-model mean



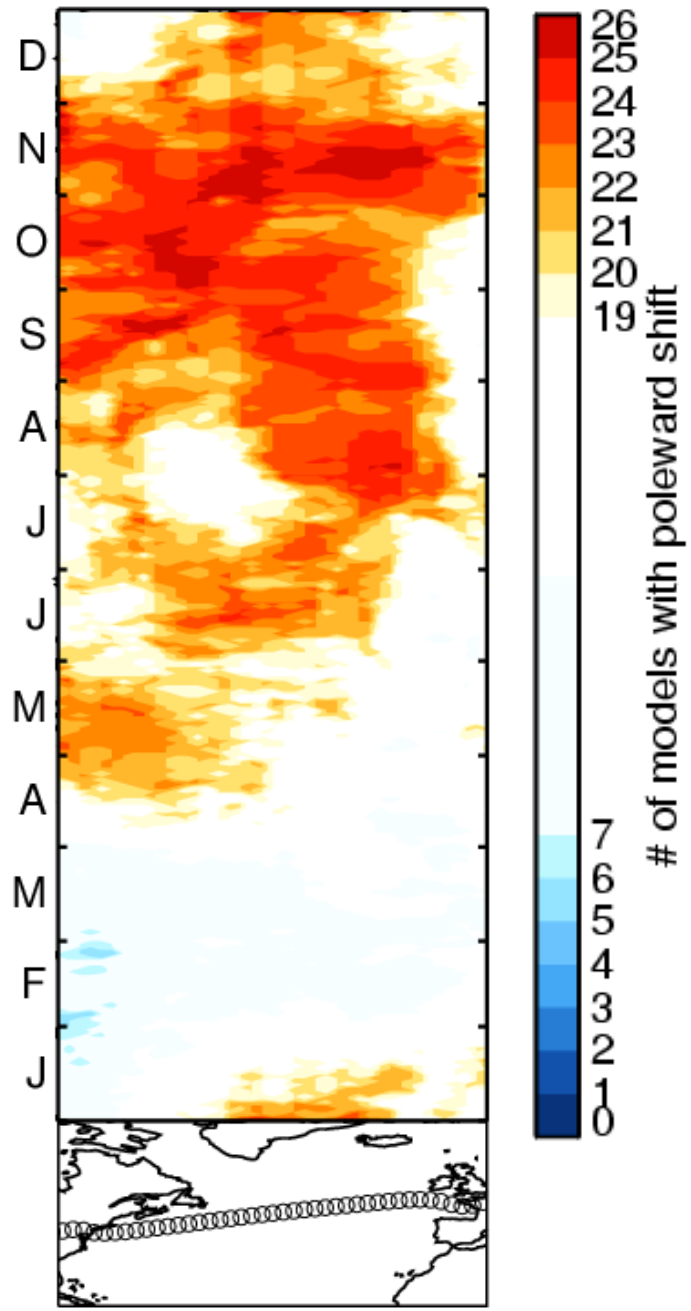
# Pacific



Atlantic jet shift



Model Consensus

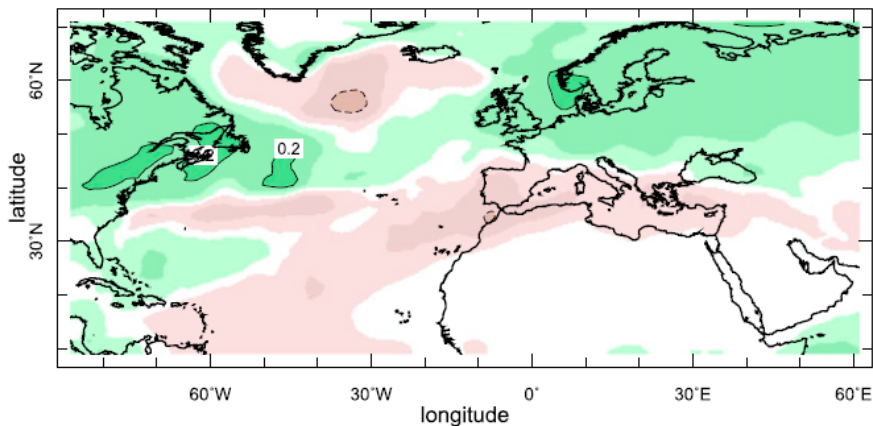


Atlantic

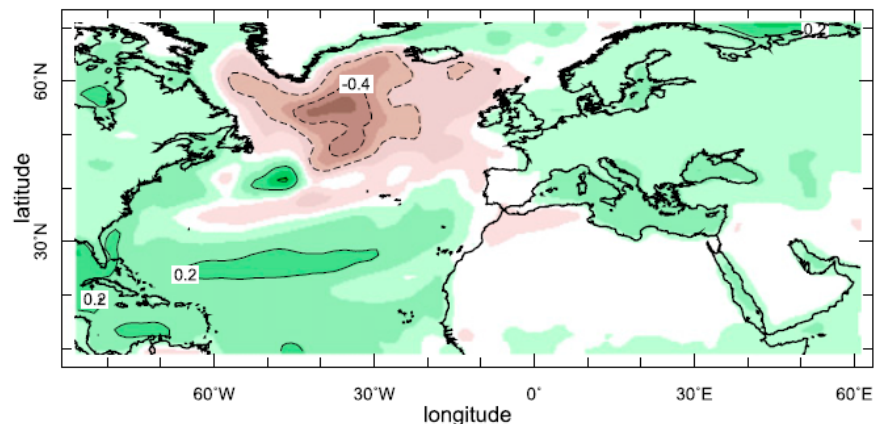
# Contributes to future drying of the Mediterranean

Seager et al (2014b) - Moisture budget analysis of CMIP5 response (2021-2040)-(1979-2005), NDJFMA, RCP8.5, 16 models

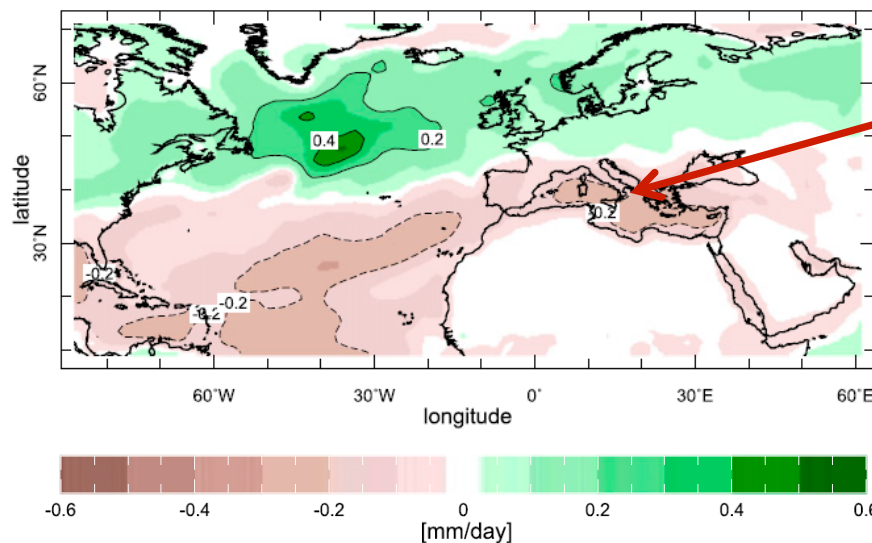
Precip (P)



Evap (E)



P-E

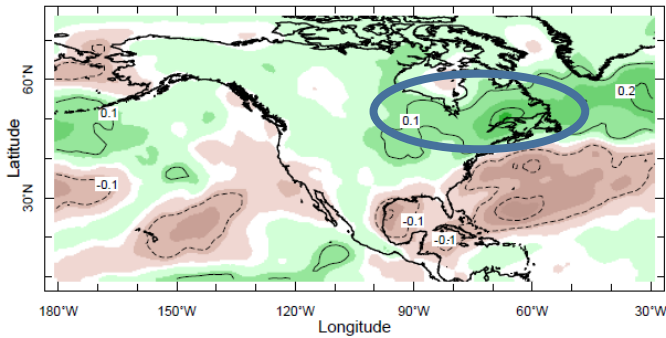


Drying, ~10%

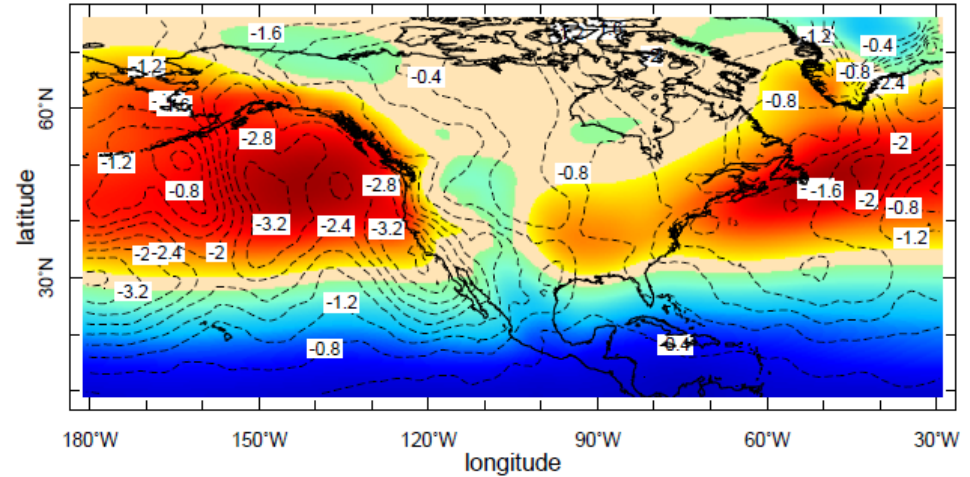
$$-\frac{1}{g\rho_w} \nabla \cdot \sum_{k=1}^K \mathbf{u}_k q_k dp_k$$

# Implications of the East Pacific circulation response

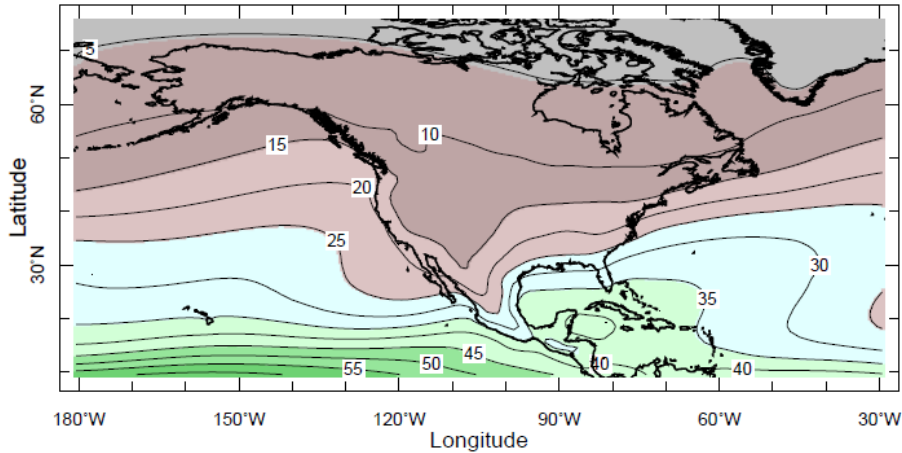
Moisture flux convergence by sub-monthly transients



Sub-monthly meridional velocity variance (colours=climatology, contours=change)



Past climatological vertically integrated specific humidity



Change in vertically integrated specific humidity

