The North Atlantic decadal variability: its climate impacts and its origins

Yohan Ruprich-Robert

ICAS seminar, virtually in Leeds, April 27 2021

INADEC
H2020-MSCA-800154

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EXCELENCIA SEVERO OCHOA

PRIMAVERA

BSC Barcelona Supercomputing Center
Centro Nacional de Supercomputación

MARIE CURIE ACTIONS

INADEC
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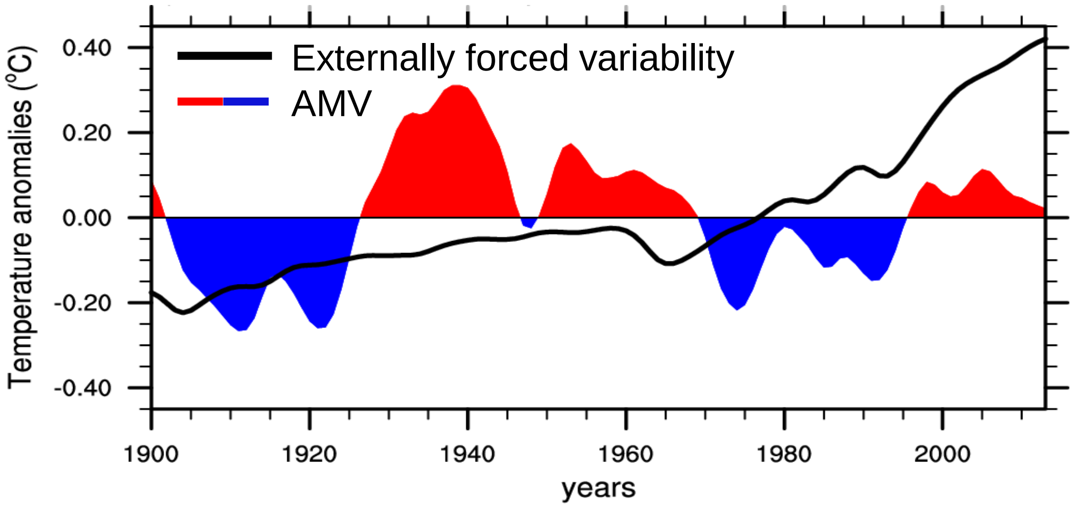
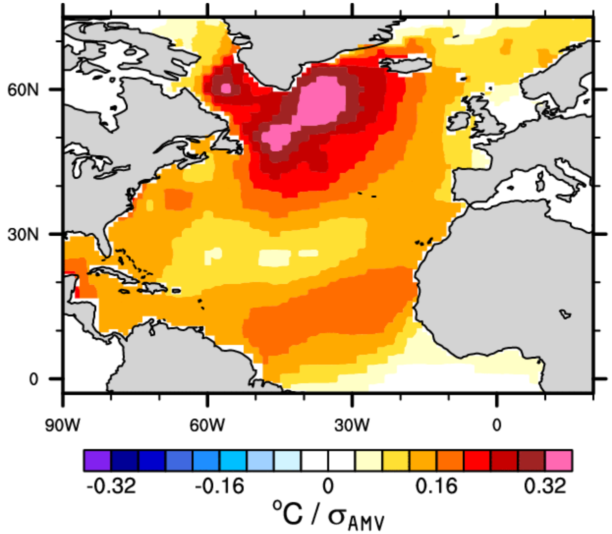
Atlantic Multidecadal Variability (AMV)

North Atlantic SST time series (Ting et al. 2009)



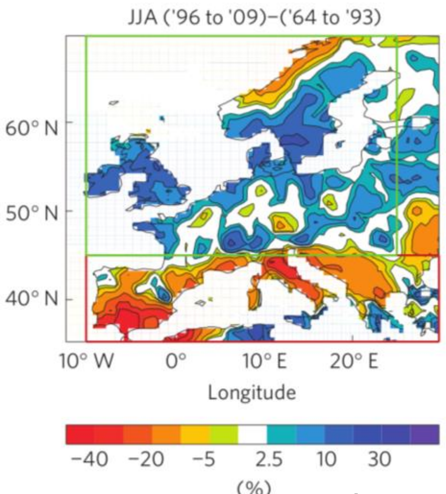
AMV pattern



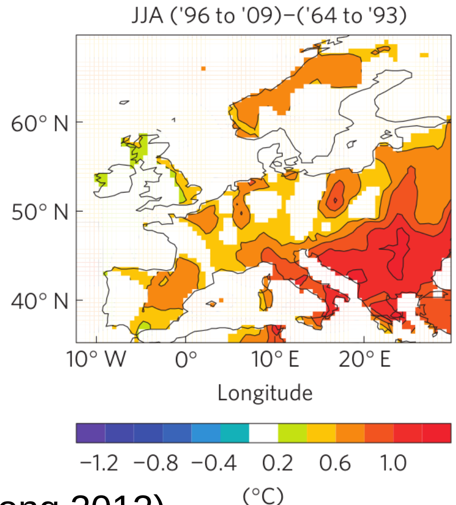
AMV climate impacts

➢ **Impacts on Europe and Mediterranean region during summer (JJA)**

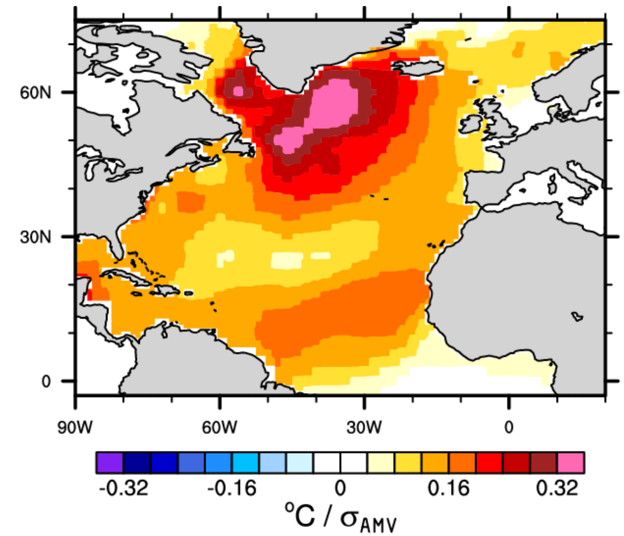
Precipitation



Temperature



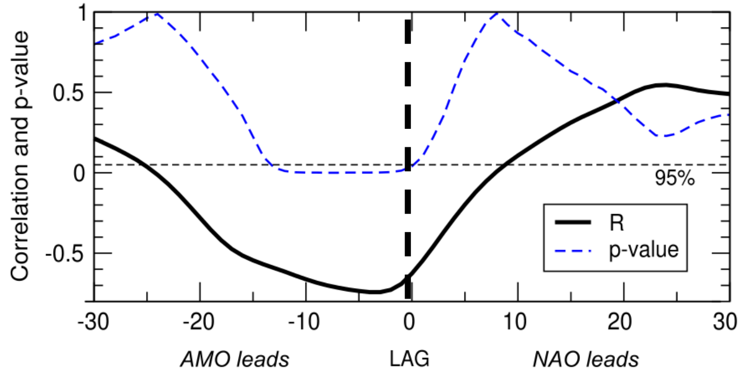
AMV pattern

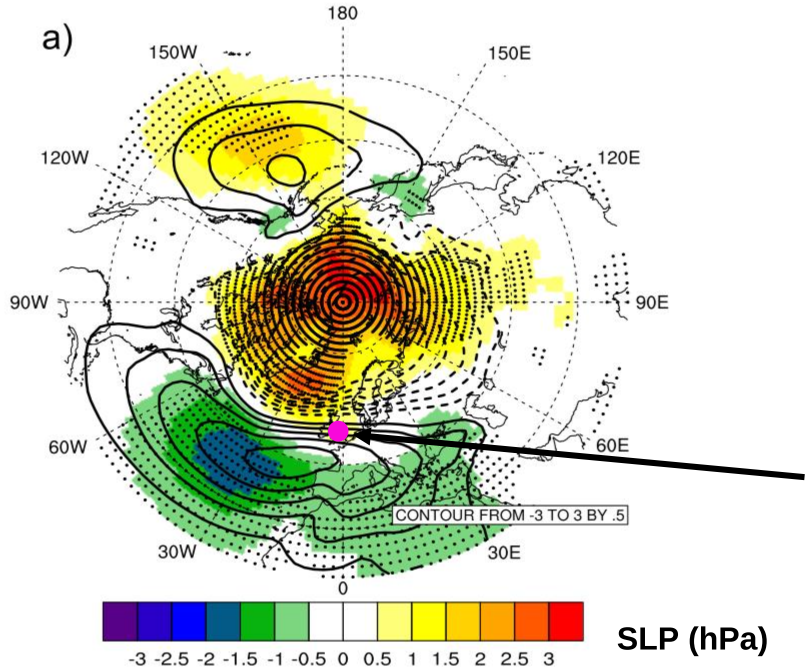


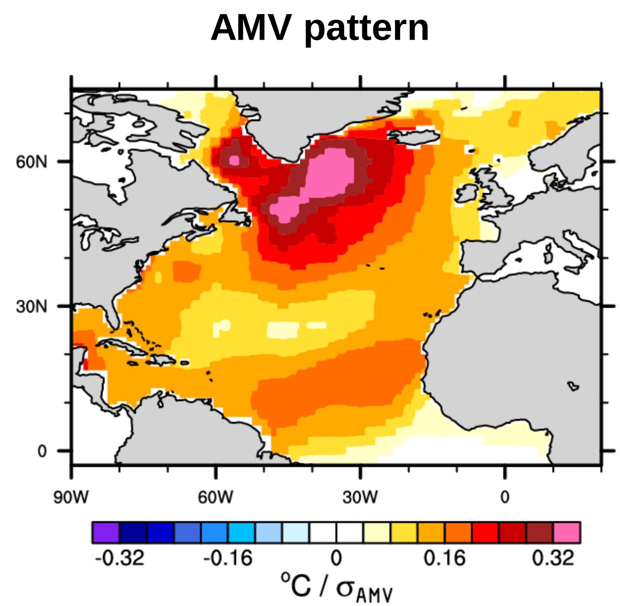
(Sutton and Dong 2012)

AMV climate impacts

- Impacts on North Atlantic atmospheric circulation in winter (DJFM)







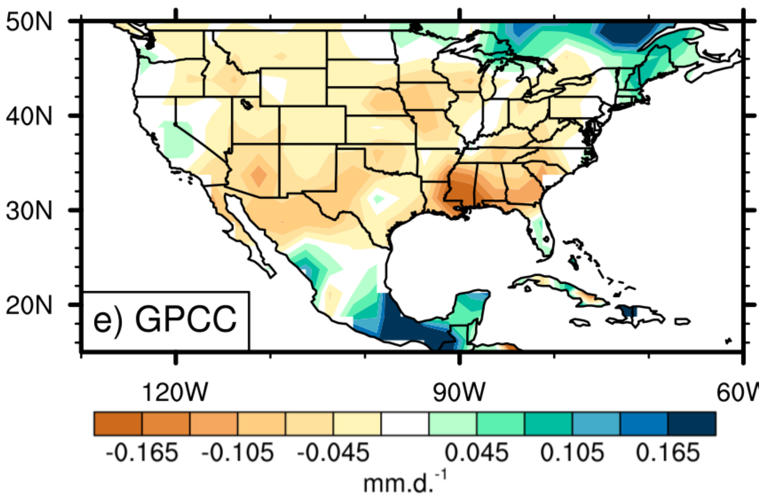
(Peings and Magnusdottir 2014)

Gastineau and Frankignoul 2012; Omrani et al. 2014; Davini et al. 2015; Kwon et al. 2020; Ruggieri et al. 2020

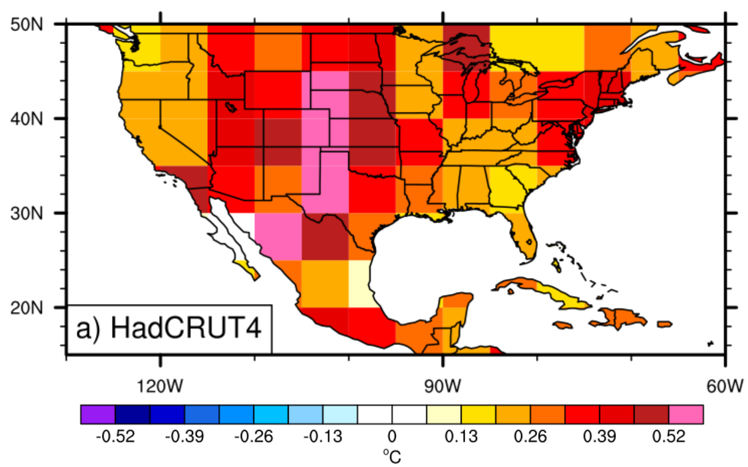
AMV climate impacts

➢ **Impacts on North America**

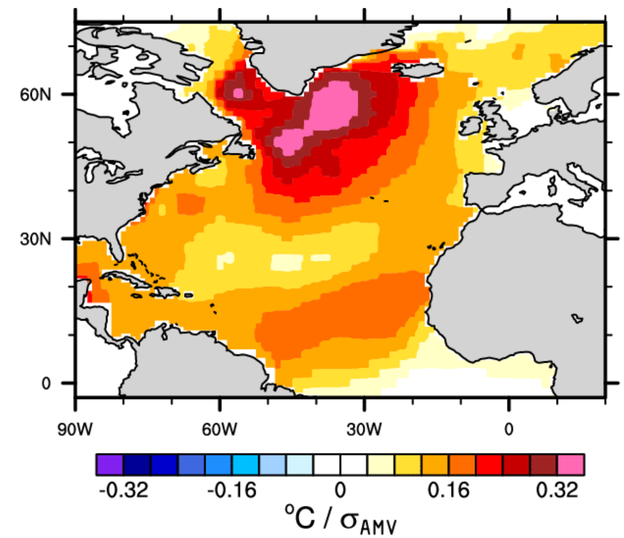
Annual precipitation



Summer temperature



AMV pattern

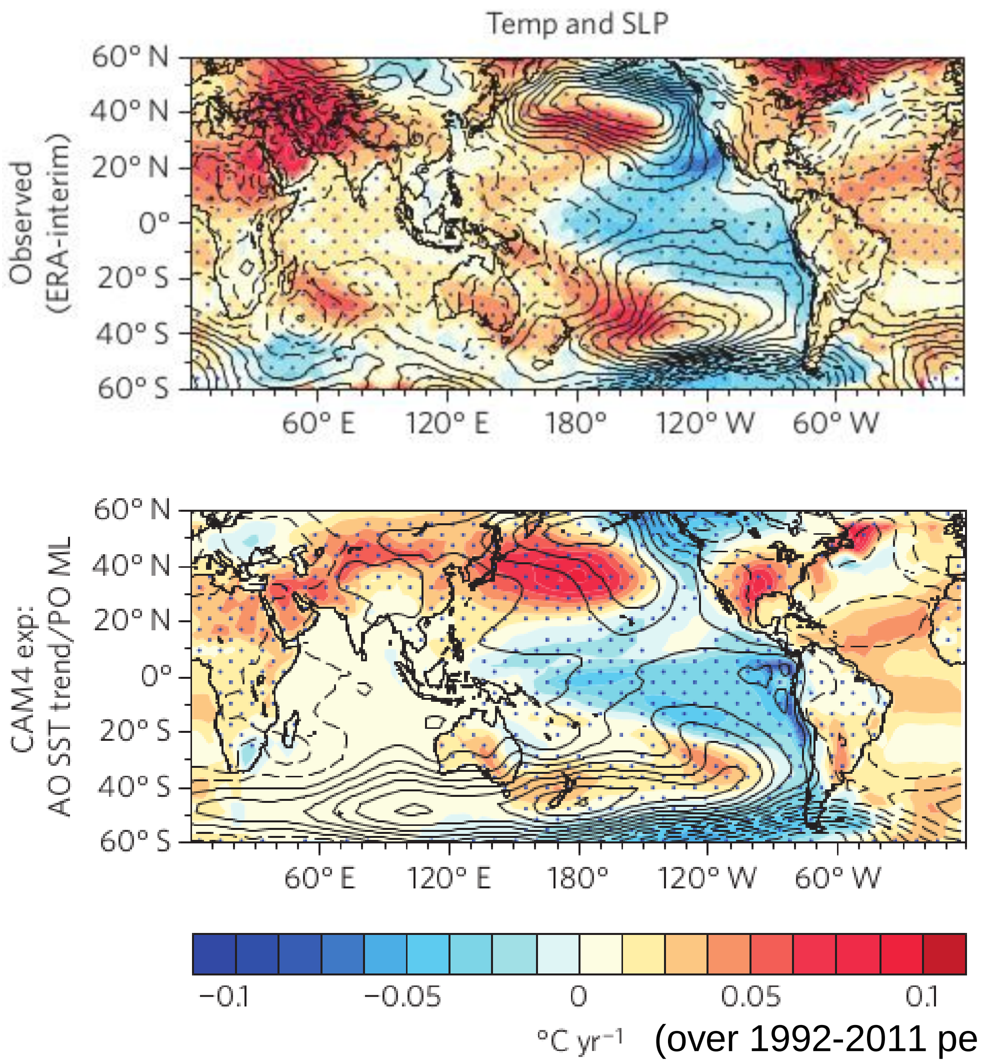


(Ruprich-Robert et al. 2018)

Enfield 2001; McCabe et al. 2004 ; Sutton and Hodson 2005; Hodson et al. 2010; Kushnir et al. 2010

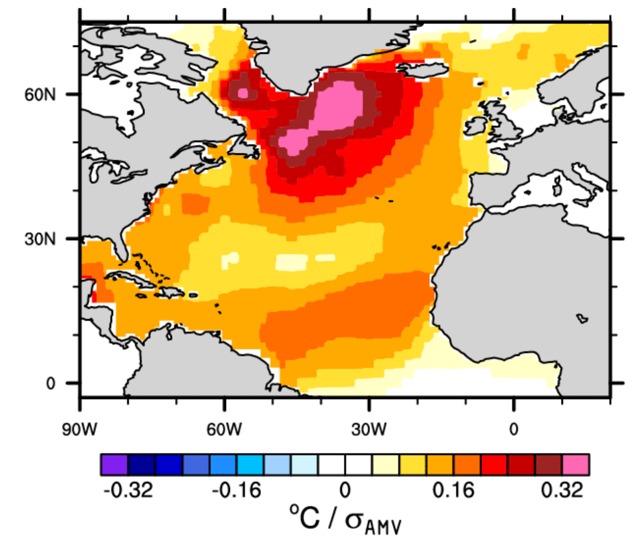
AMV climate impacts

➢ **Impacts on Pacific**



(over 1992-2011 period)

AMV pattern



(McGregor et al. 2014)

d'Orgeville and Peletier 2007; Zhang and Delworth 2007; Li et al. 2016; Zanchettin et al. 2016; Ruprich-Robert et al. 2017

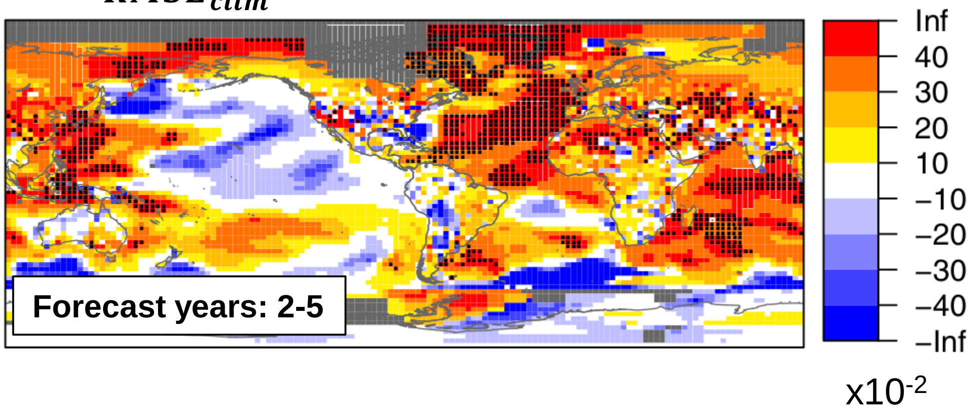
Motivations

- **Observed AMV linked to climate variability over many area of the globe**
  - Droughts over N. and S. America
  - European summer temperature
  - Sahel drought
  - Arctic sea-ice
  - Tropical cyclone activity
  - Hiatus
  - …

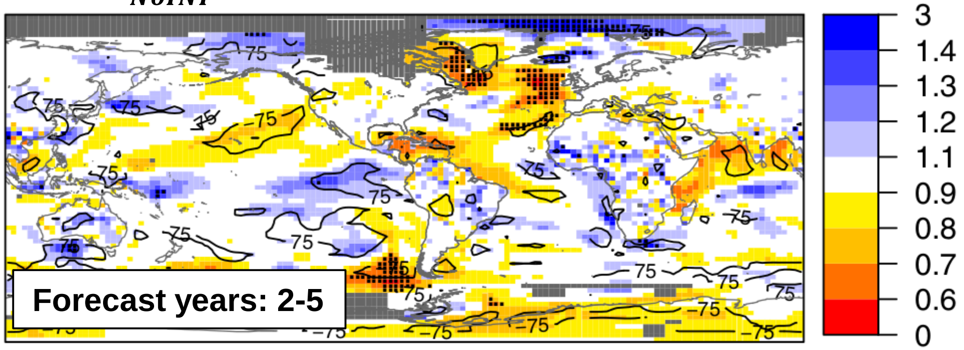
Predictability of the AMV and its impacts

Annual SST / T2m prediction skill score

$$1 - \frac{RMSE_{INI}}{RMSE_{clim}}$$



$$\frac{RMSE_{INI}}{RMSE_{NoINI}}$$



The North Atlantic is the most predictable region at decadal timescale but no skill for its teleconnections

(Doblas-Reyes et al. 2013)

Predictability of the AMV and its impacts

Annual SST / T2m prediction skill score

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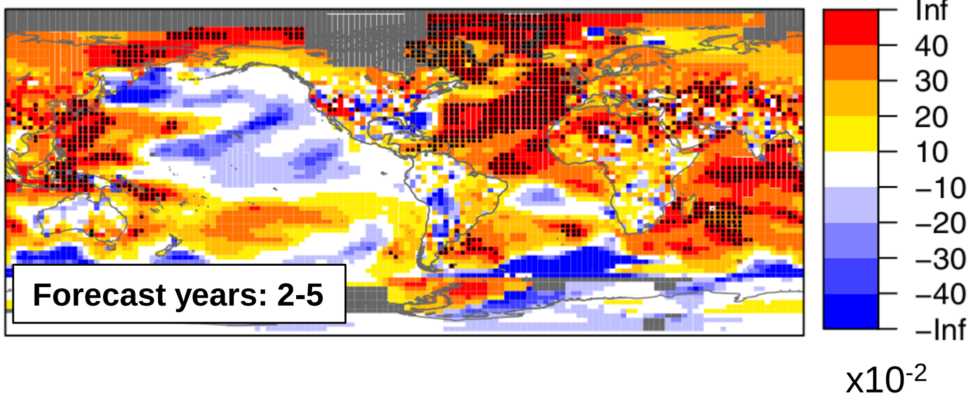

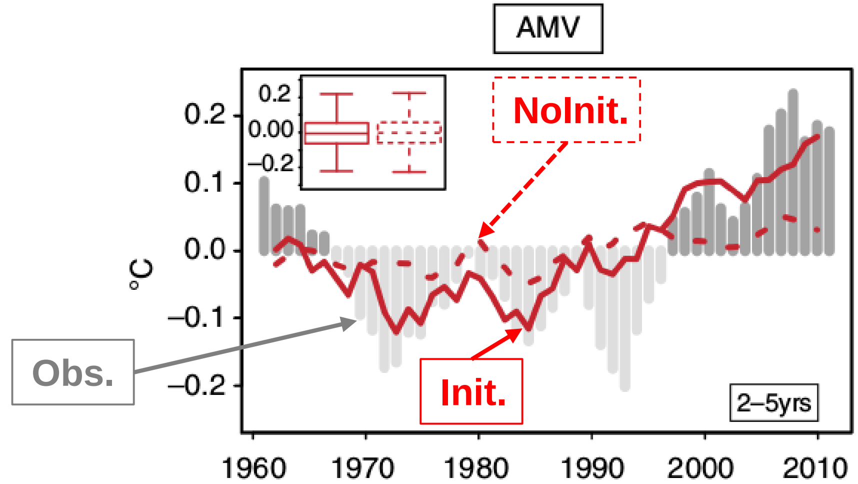

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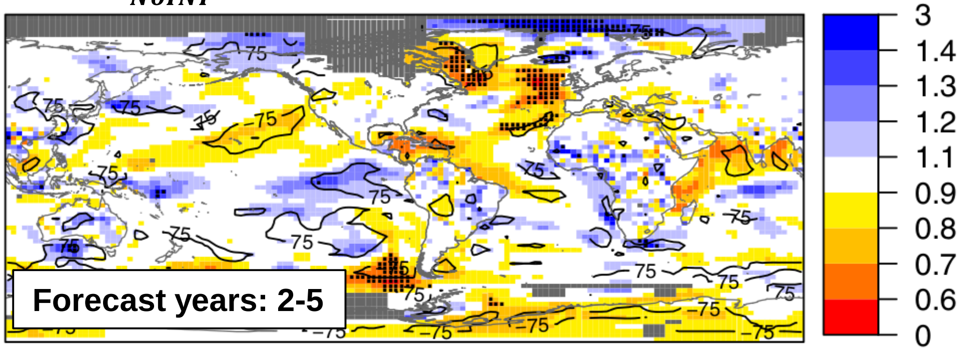

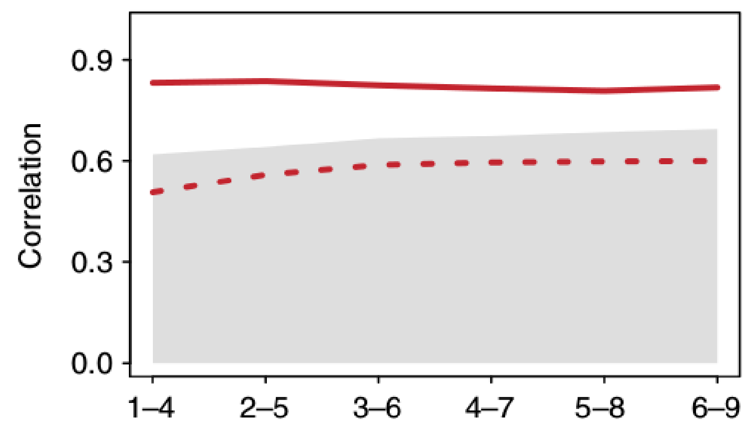

The North Atlantic is the most predictable region at decadal timescale but no skill for its teleconnections

Motivations

- **Observed AMV linked to climate variability over many area of the globe**
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  - Tropical cyclone activity
  - Hiatus
  - …

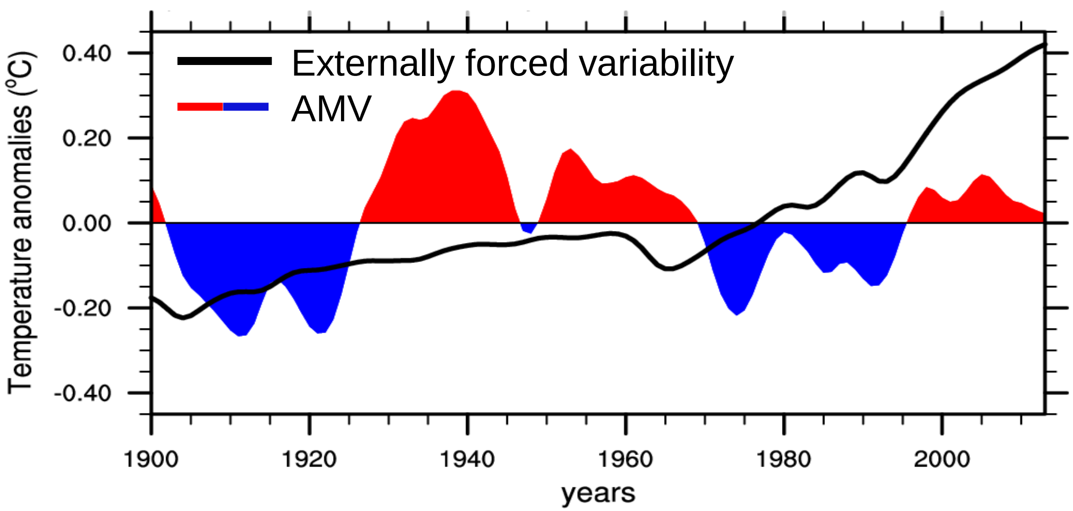
- **The North Atlantic is the most predictable region at decadal timescale**

- **Lack of prediction skill over land ➔ paradoxical given suspected AMV impacts**
  - Hypothesis 1: AMV is not the primary driver of those observed variations
  - Hypothesis 2: models do not correctly simulate these teleconnections
  - Hypothesis 3: signal to noise problem

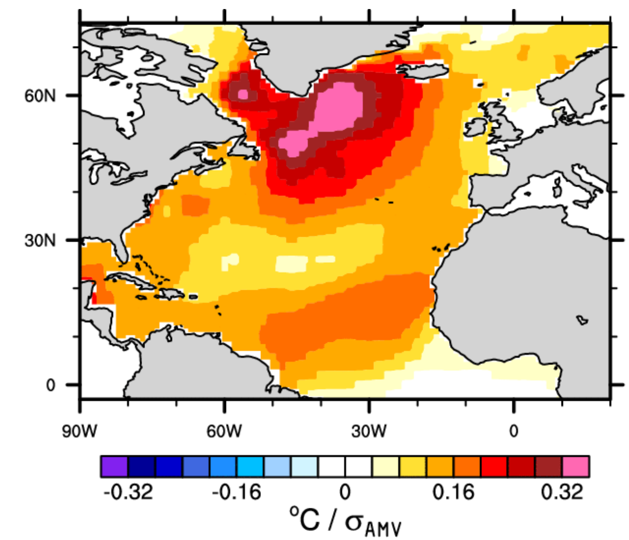
Link between observed AMV and tropical Pacific

Atlantic Multidecadal Variability (AMV)

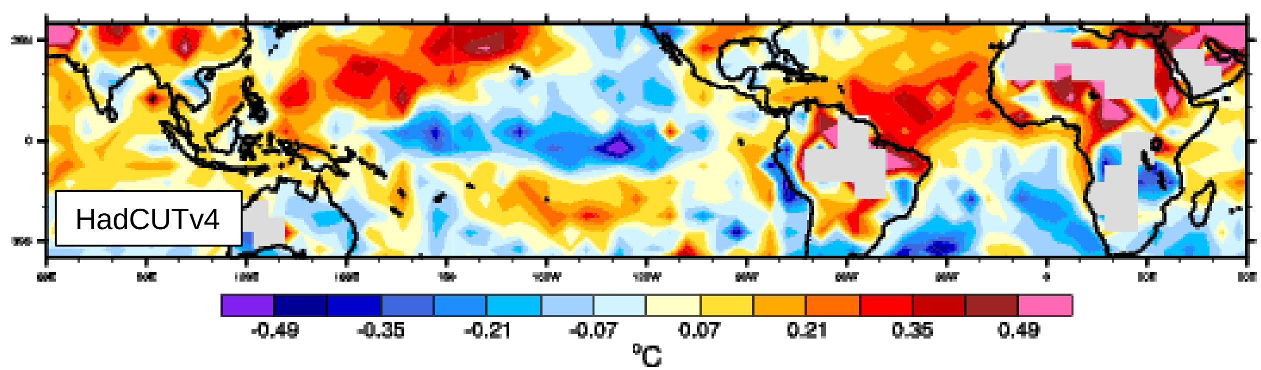
North Atlantic SST time series (Ting et al. 2009)



Observed AMV pattern



2m temperature – Observed AMV composites: DJFM



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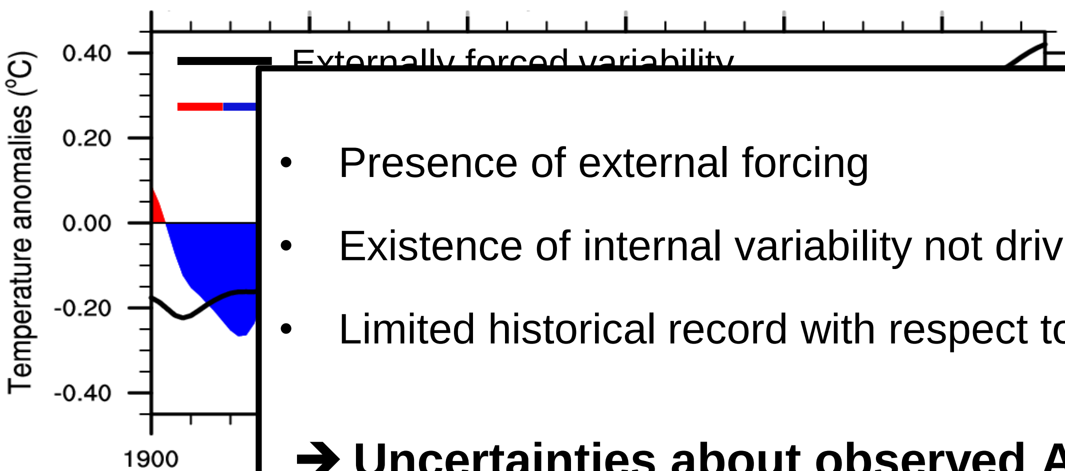

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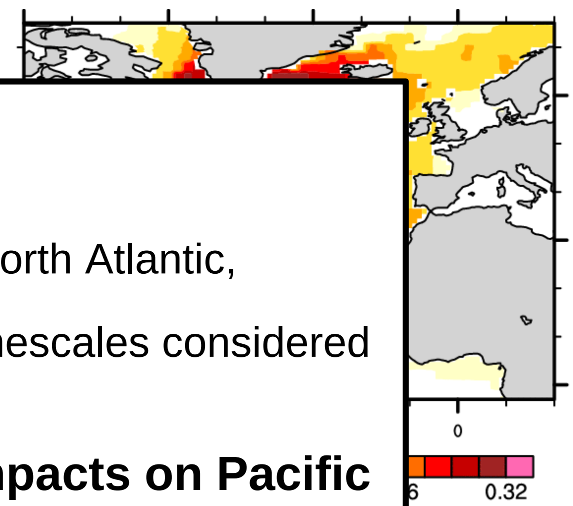
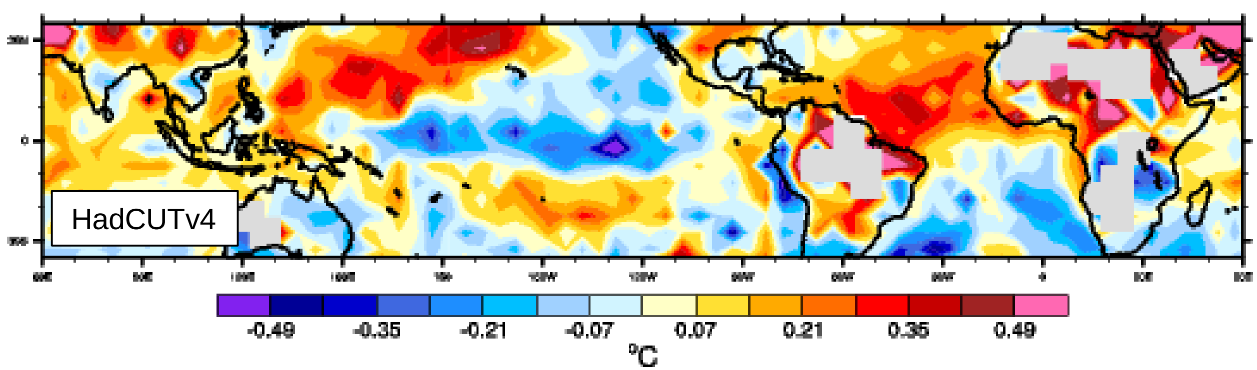


- Presence of external forcing
- Existence of internal variability not driven by North Atlantic,
- Limited historical record with respect to the timescales considered

➔ **Uncertainties about observed AMV impacts on Pacific**

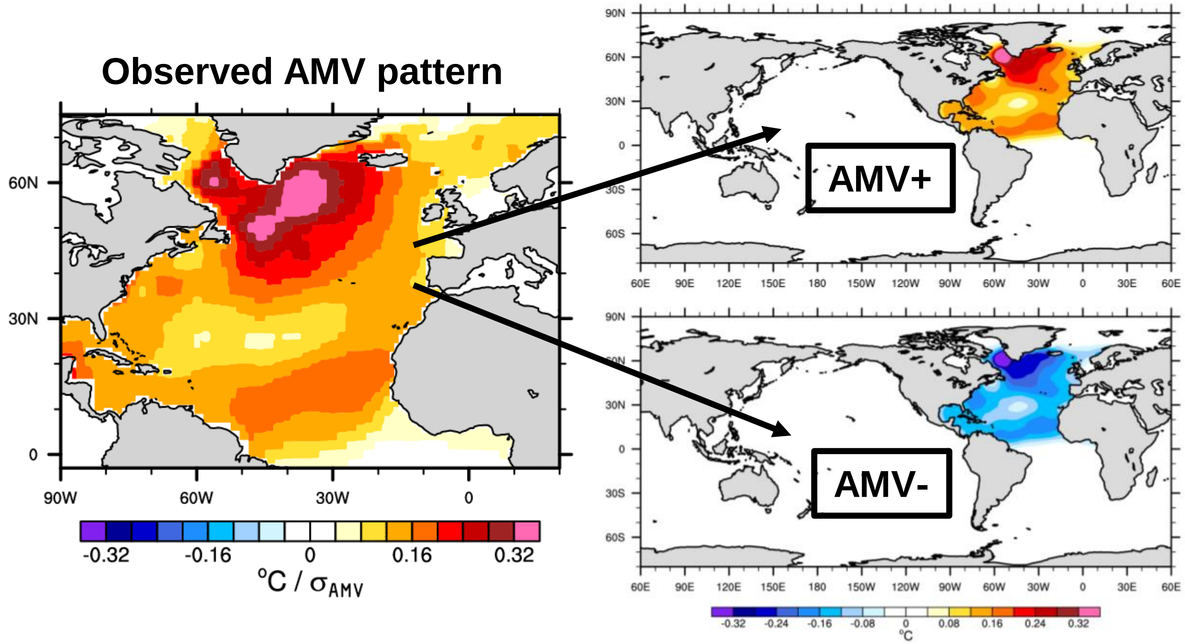
2m temperature – Observed AMV composites: DJFM



Targeted numerical experiments: the idealized AMV simulations

Coupled Global Climate Model

Observed AMV pattern



Protocol:

Observed AMV pattern anomalies imposed over CGCM N. Atlantic

Free ocean-ice-land-atmosphere interactions outside of N. Atlantic

10yr long large ensemble experiments

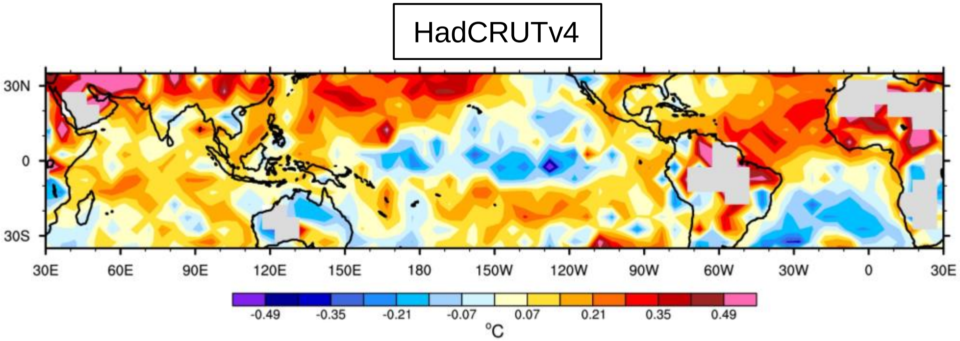
- ➢ **Total of 21 sets of simulations (from 13 CGCMs)**

- ➢ 1xAMV forcing (9)
- ➢ 2xAMV forcing (7) + (2) SLAB ocean
- ➢ 3xAMV forcing (3)

Protocol adopted by Decadal Climate Prediction Panel of CMIP6 (Boer et al. GMD 2016)

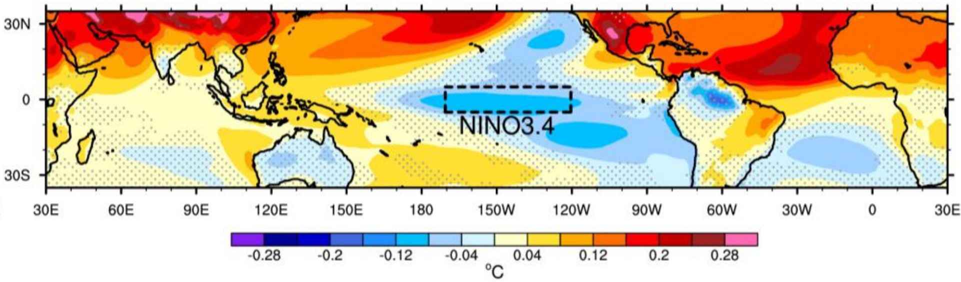
Multi-Model Mean confirms observed AMV – Pacific link…

T2m – Observed AMV composites: DJFM



T2m – MMM AMV+ - AMV-: DJFM

(10yr averaged ensemble mean)

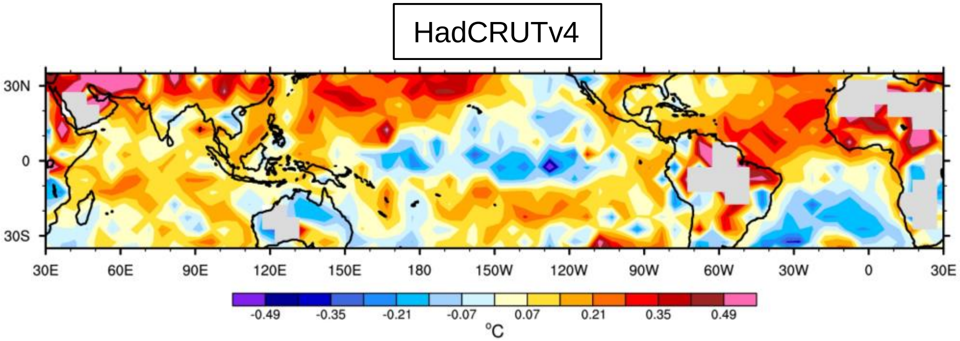


MMM = Multi Model Mean

T2m = 2-meter air temperature

… but large inter-model spread

T2m – Observed AMV composites: DJFM



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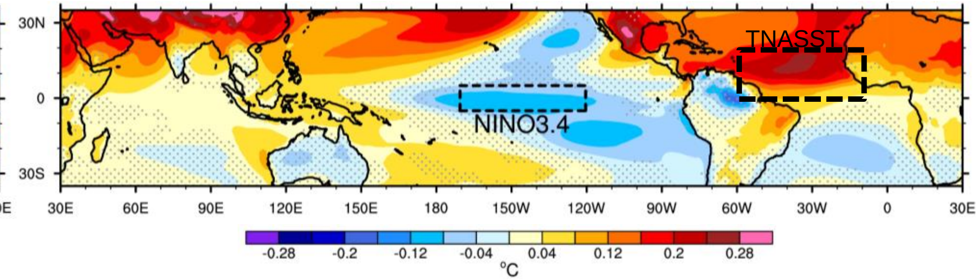

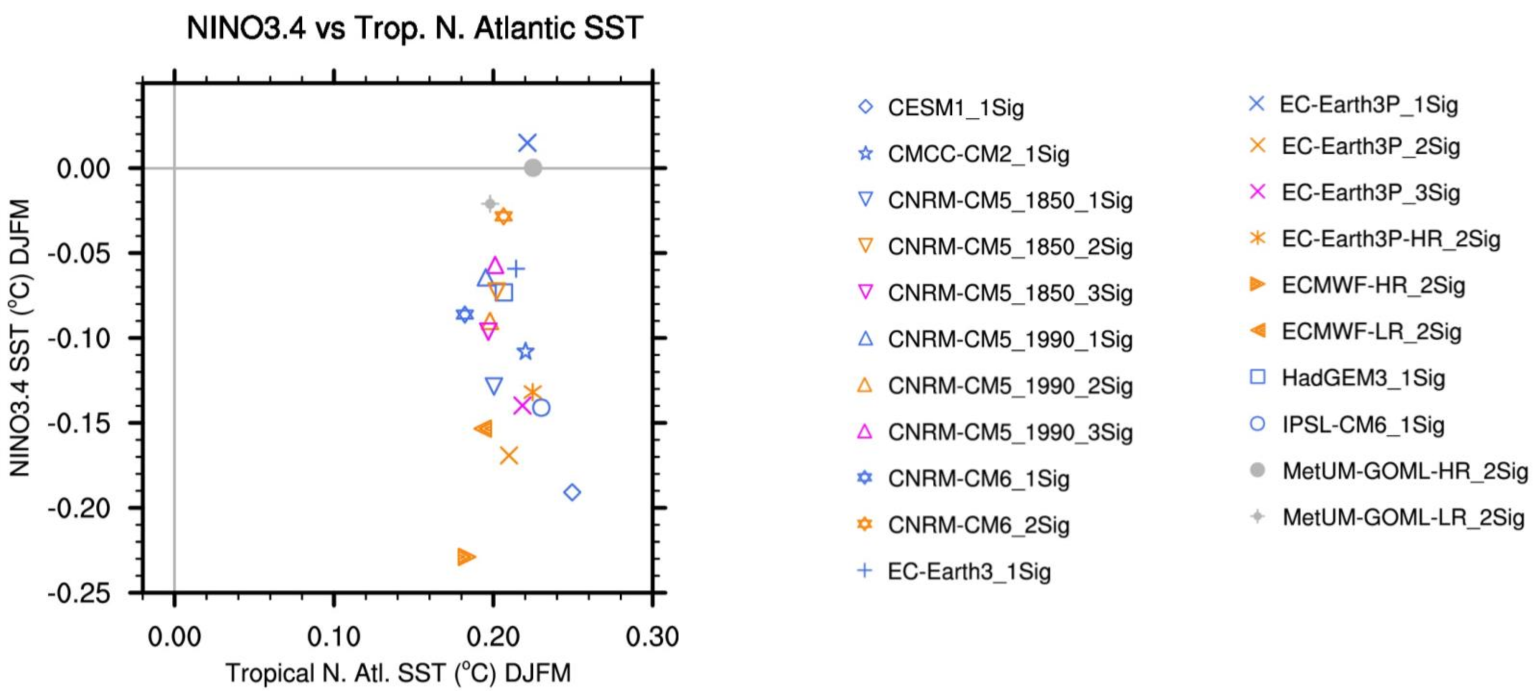

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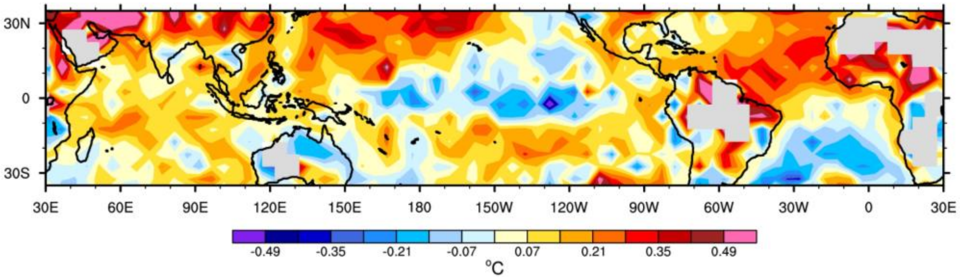
Origins of the inter-model spread?

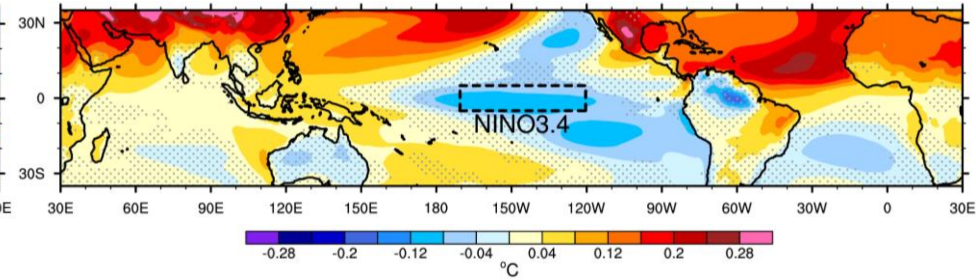
T2m – Observed AMV composites: DJFM

HadCRUTv4



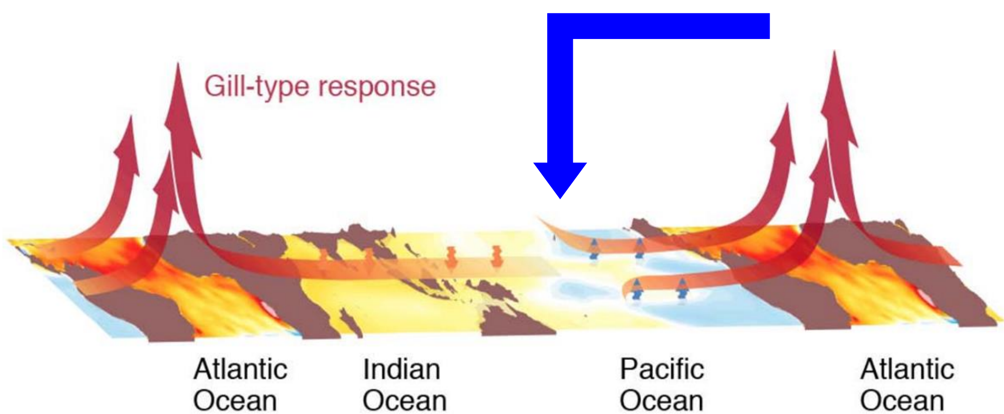
T2m – MMM AMV+ - AMV-: DJFM

(10yr averaged ensemble mean)

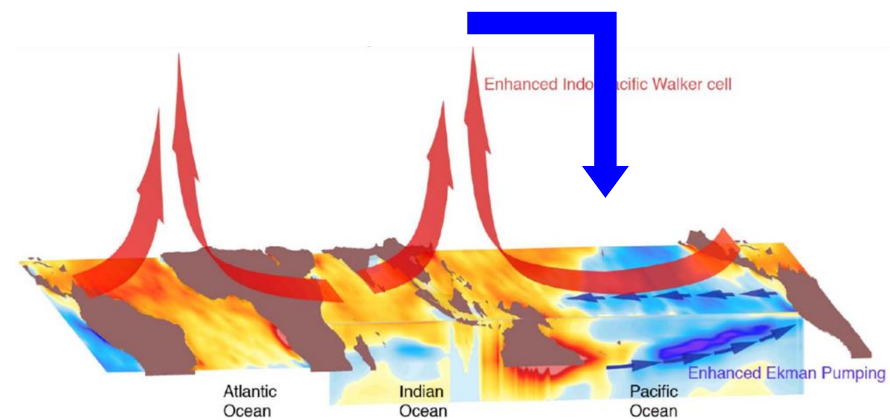


- **Li et al. (2016) decomposed AMV – Pacific impacts:**

Phase-1: Atlantic forcing



Phase-2: Indo-Pacific feedback



MMM = Multi Model Mean

T2m = 2-meter air temperature

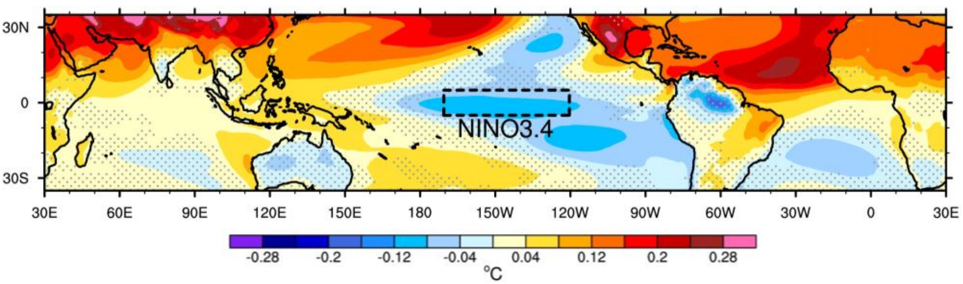
1) Is the winter Pacific response linked to summer Pacific conditions?

Inter-model correlation of -0.87 between DJFM NINO3.4 and JJAS Trop. Pac. descent ✓

MMM AMV+ - AMV-

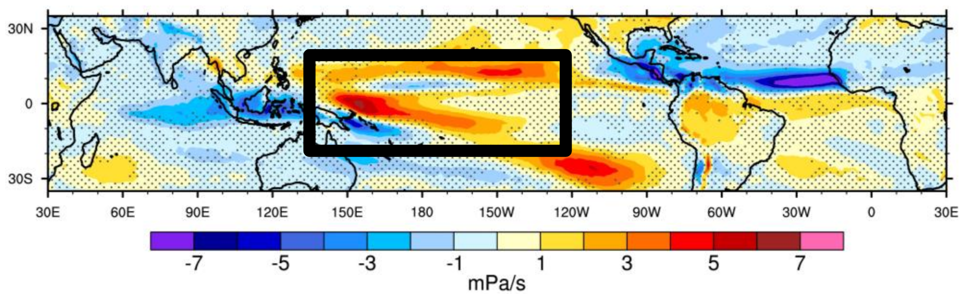
(10yr averaged ensemble mean)

DJFM – T2m

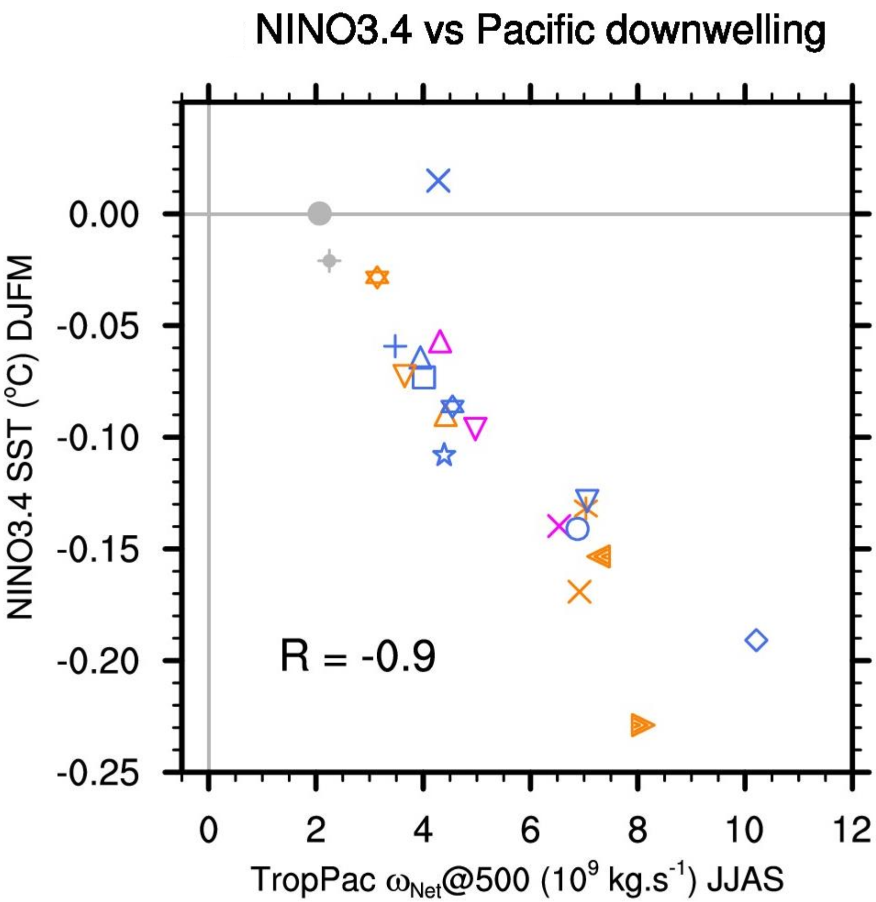


VS

JJAS – wap@500hPa



(wap: vertical air transport on pressure coordinates)



MMM = Multi Model Mean

(vertical transport = positive downward)

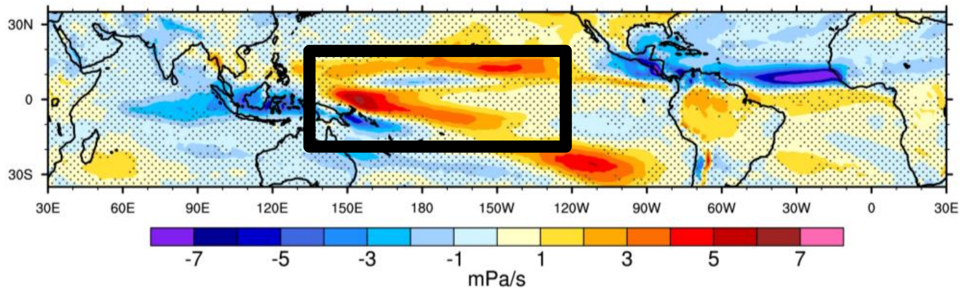
2) Is the Pacific subsidence linked to ascent over tropical regions?

Trop. Pac. descent almost completely compensated by ascent within tropics ✓

MMM AMV+ - AMV-

(10yr averaged ensemble mean)

JJAS – wap@500hPa



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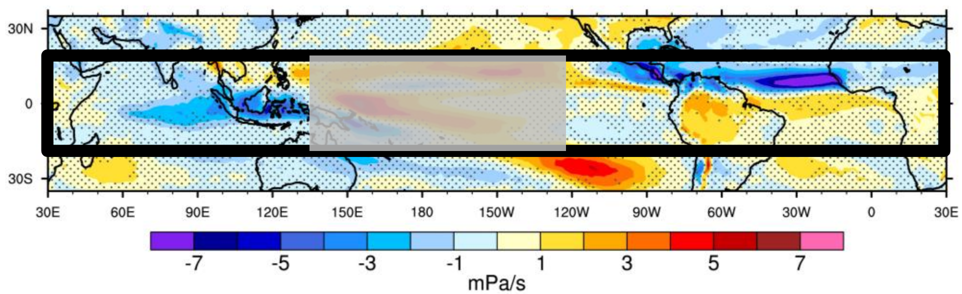
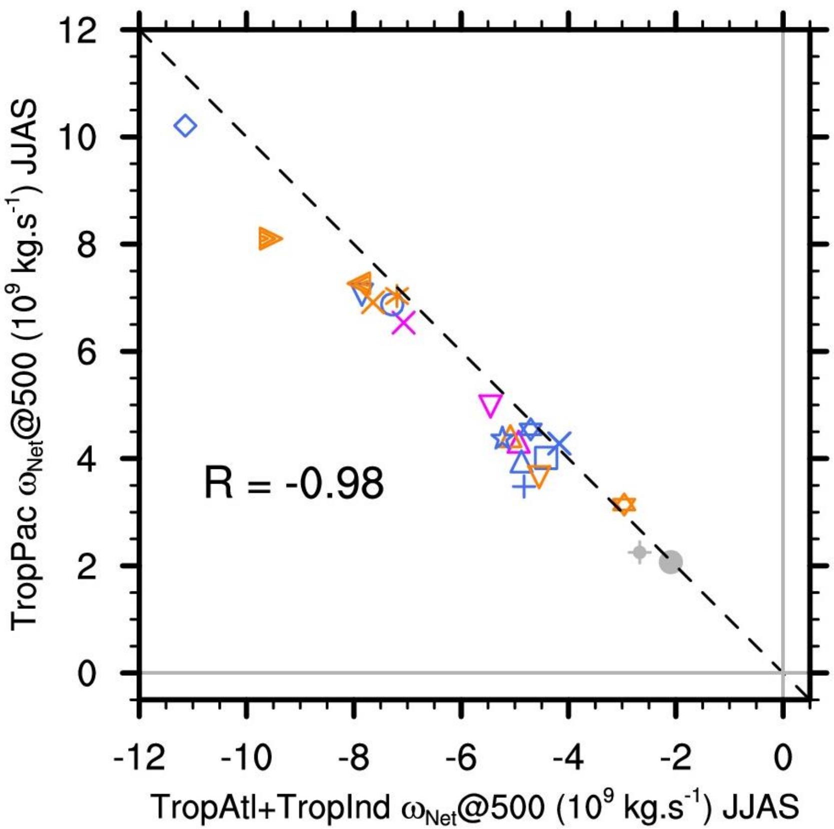


(wap: vertical air transport on pressure coordinates)

Pacific vs Atlantic-Indian ω@500



MMM = Multi Model Mean

(positive vertical transport = downward motion)

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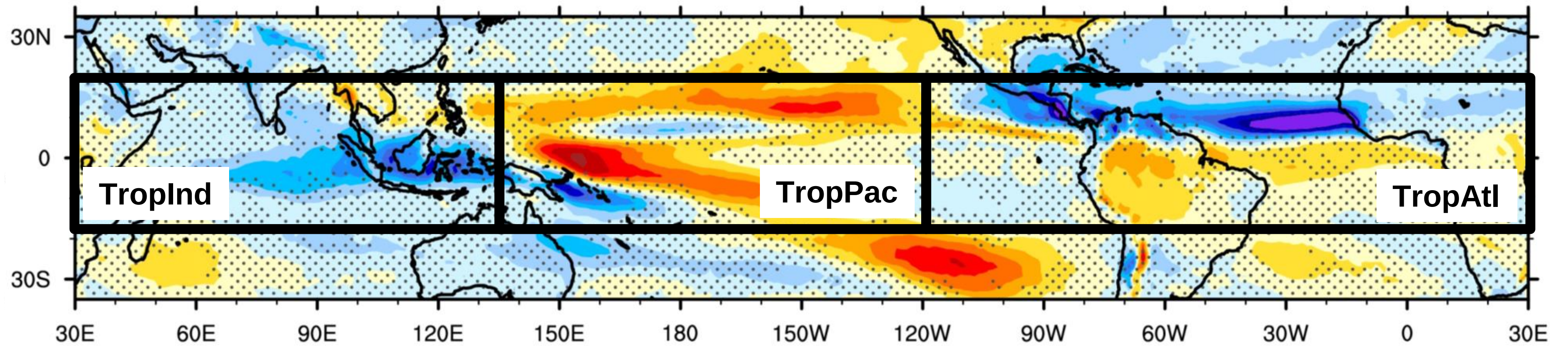
$$Var(wap^{500}_{Pac}) \sim Var(wap^{500}_{Ind}) + Var(wap^{500}_{Atl}) + COV$$



(wap: vertical air transport on pressure coordinates)

(positive vertical transport = downward motion)

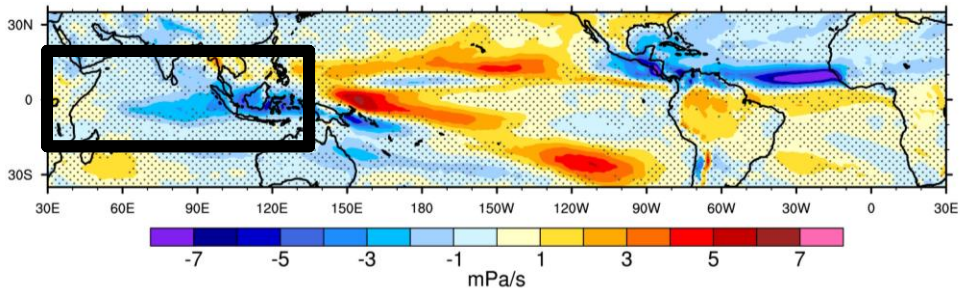
3) Which region dominates the ascent anomalies?

$$Var(wap^{500}_{Pac}) \sim \boxed{Var(wap^{500}_{Ind})} + Var(wap^{500}_{Atl}) + COV$$

69% **19%**

MMM AMV+ - AMV-
(10yr averaged ensemble mean)

JJAS – wap@500hPa



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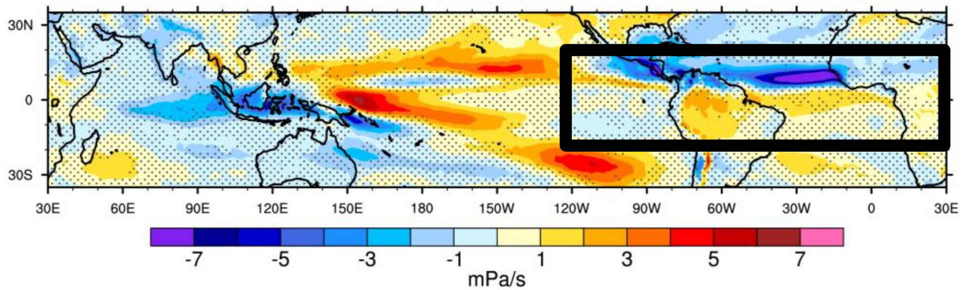
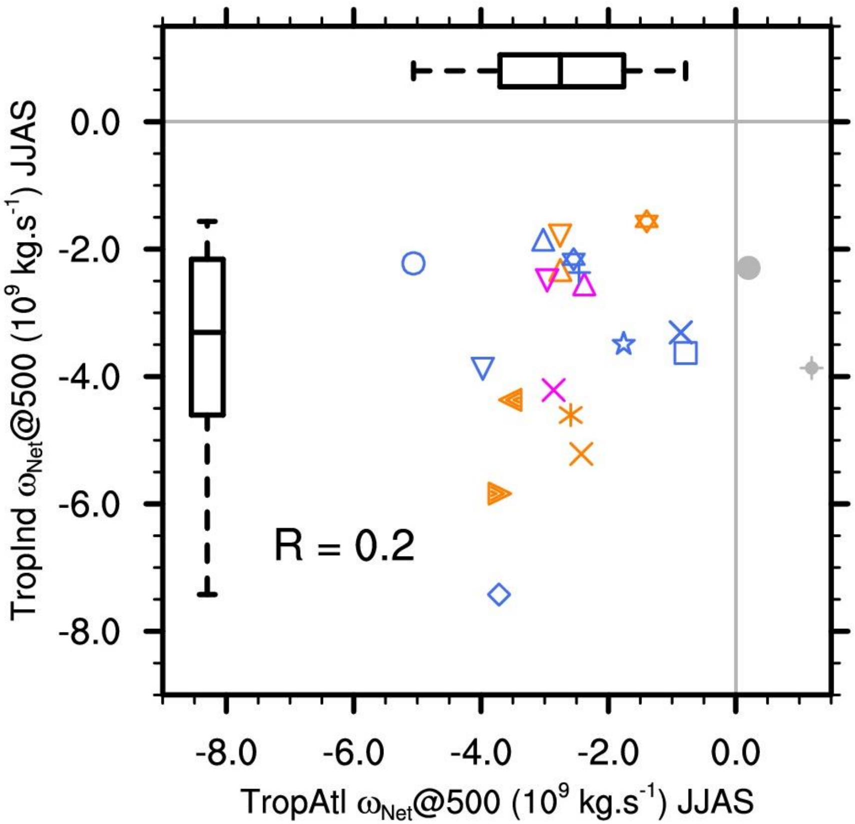


(wap: vertical air transport on pressure coordinates)

Indian & Atlantic ω@500



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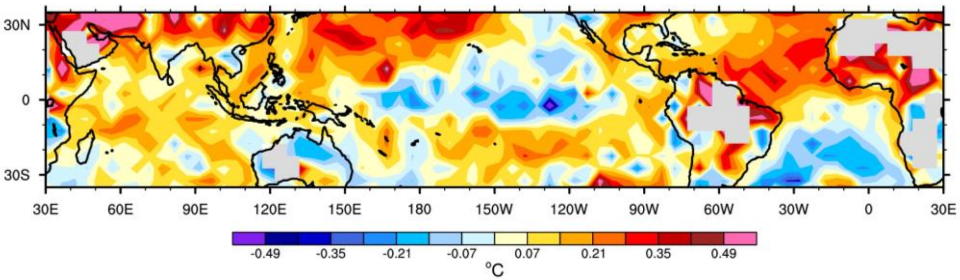
Origins of the inter-model spread?

T2m – Observed AMV composites: DJFM

HadCRUTv4



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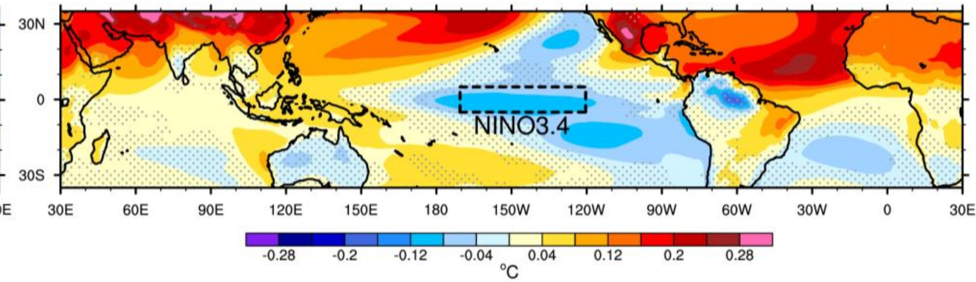

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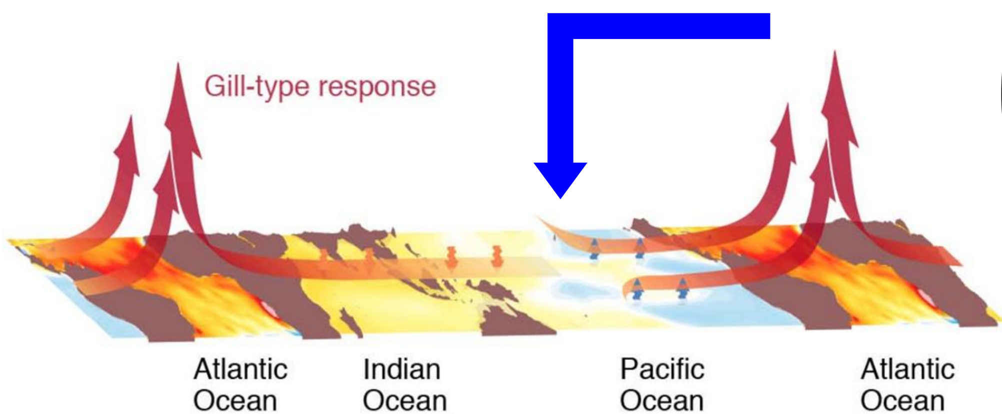
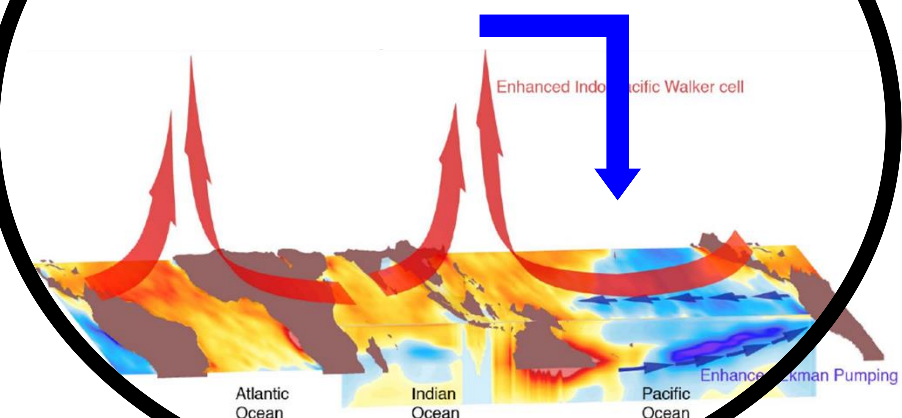


Phase-2: Indo-Pacific feedback



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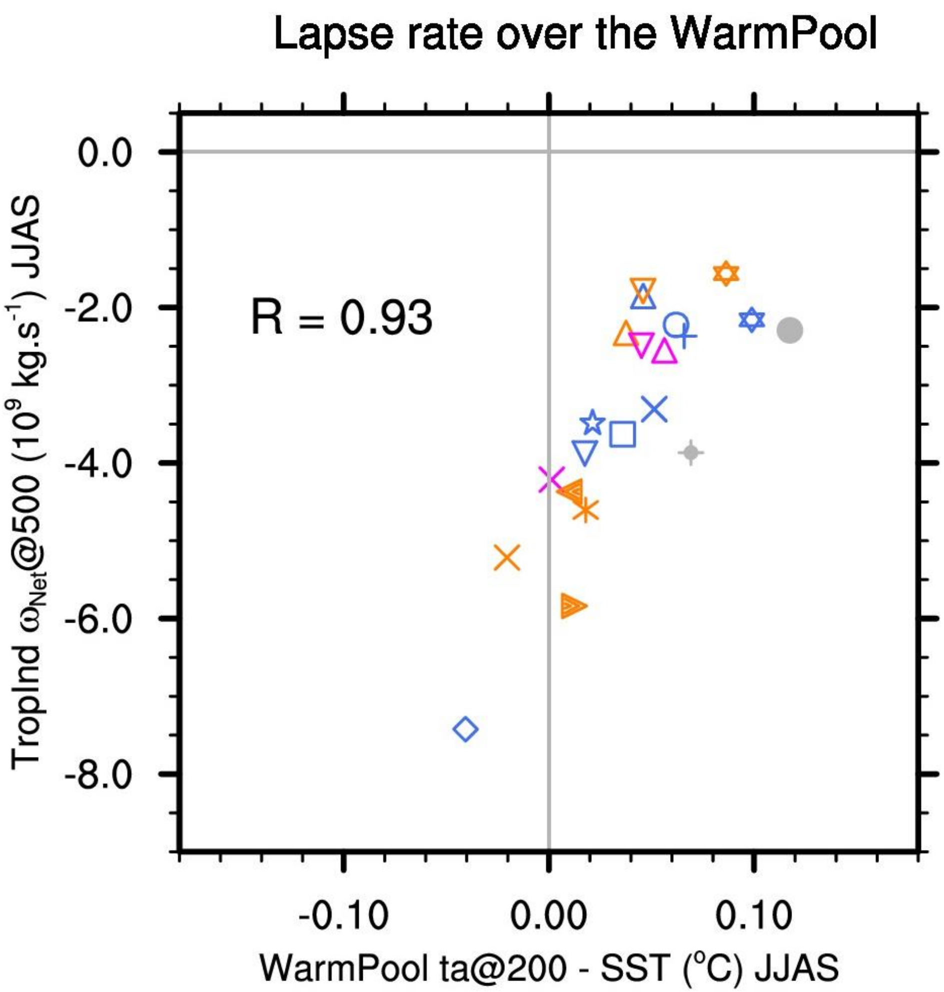
T2m = 2-meter air temperature

Origins of spread in TropInd ascent?

Trop. Ind. ascent linked to lapse rate over WarmPool



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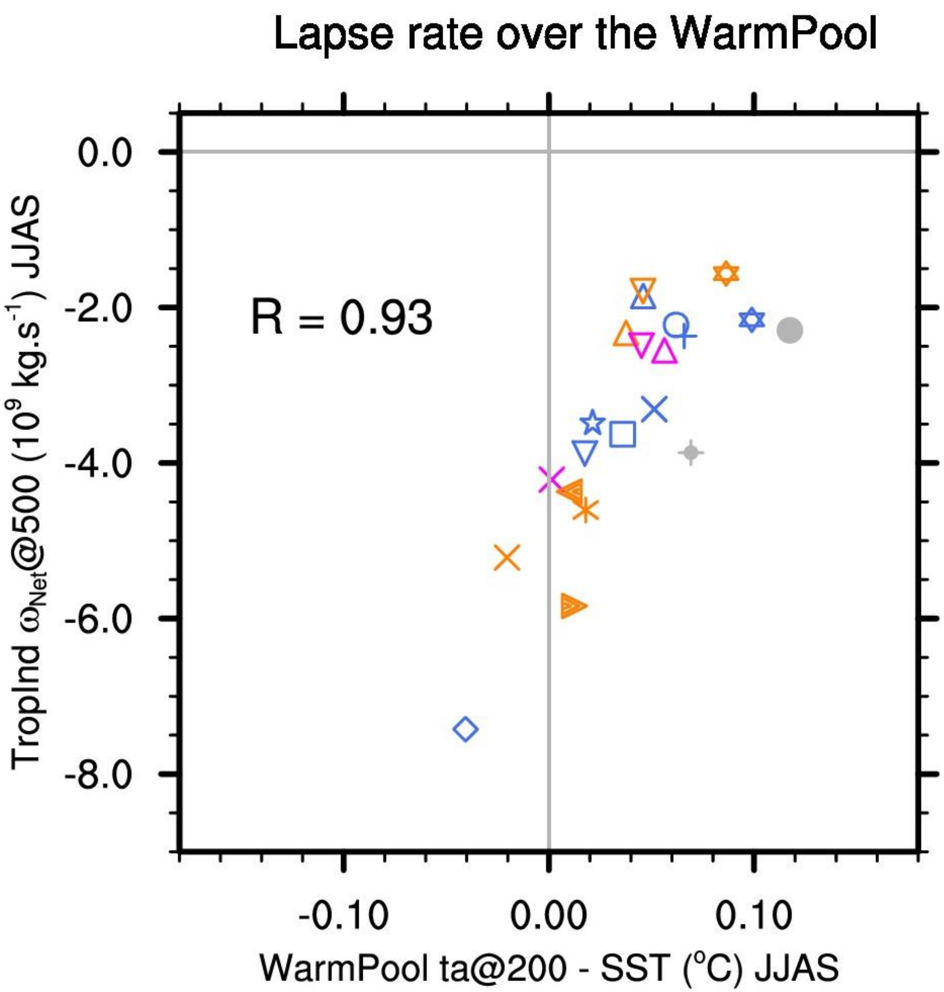

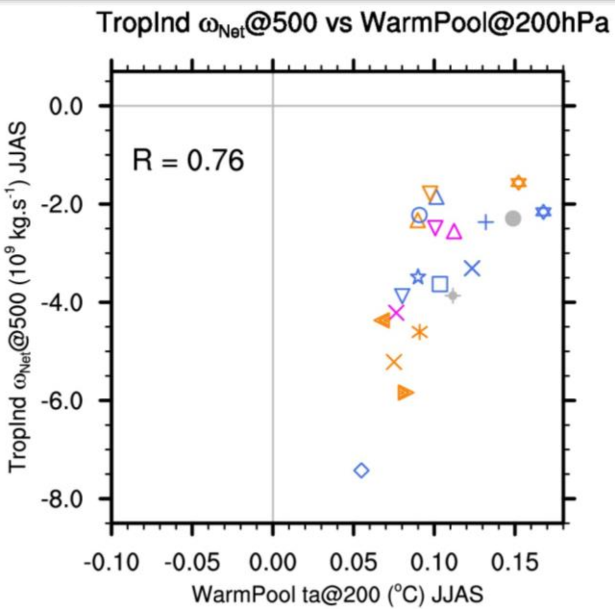

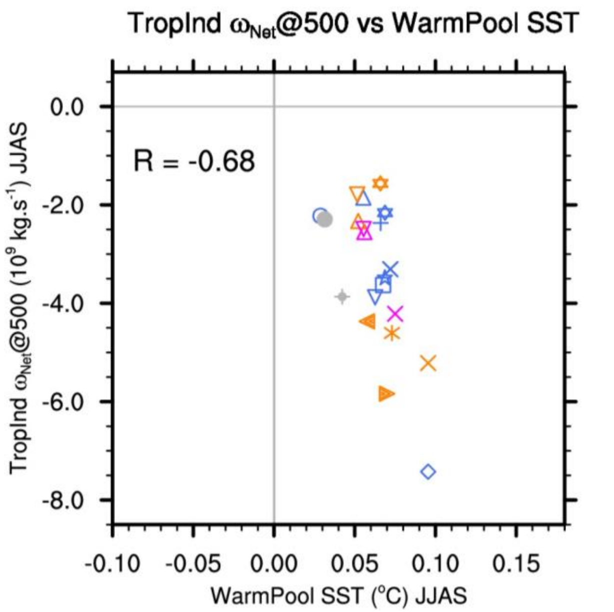

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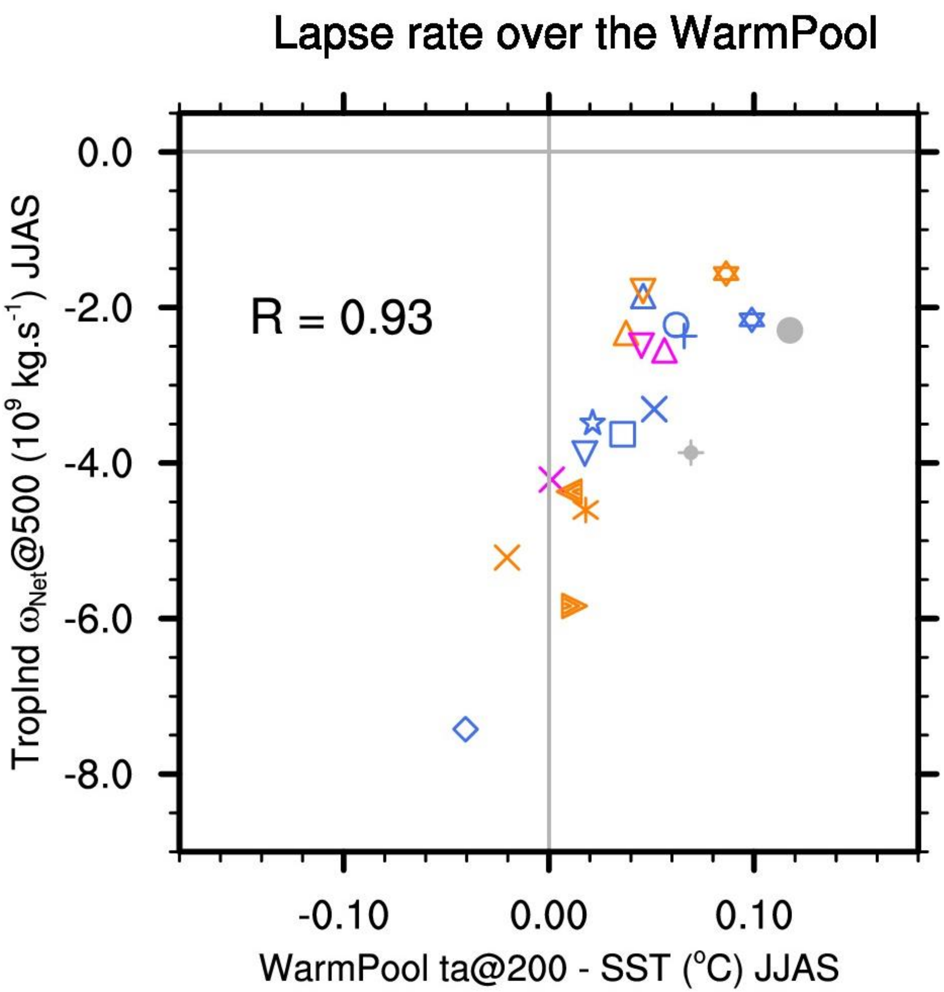
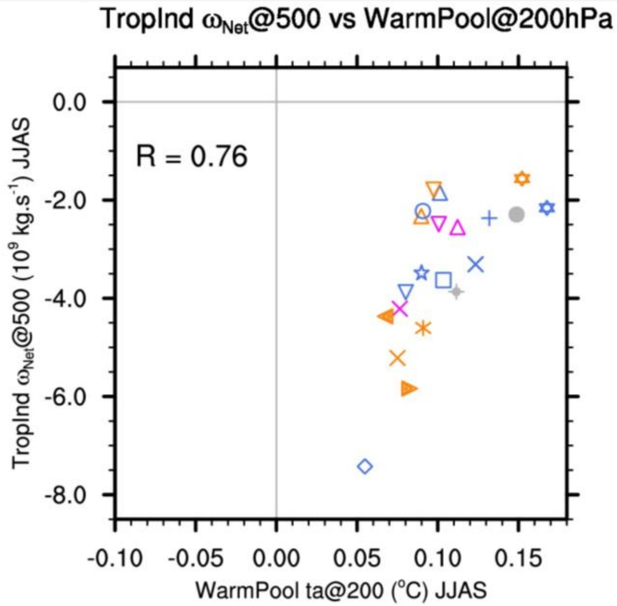
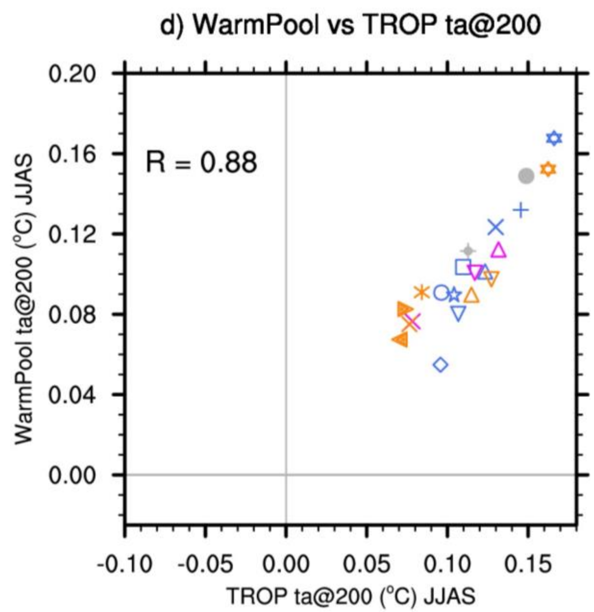




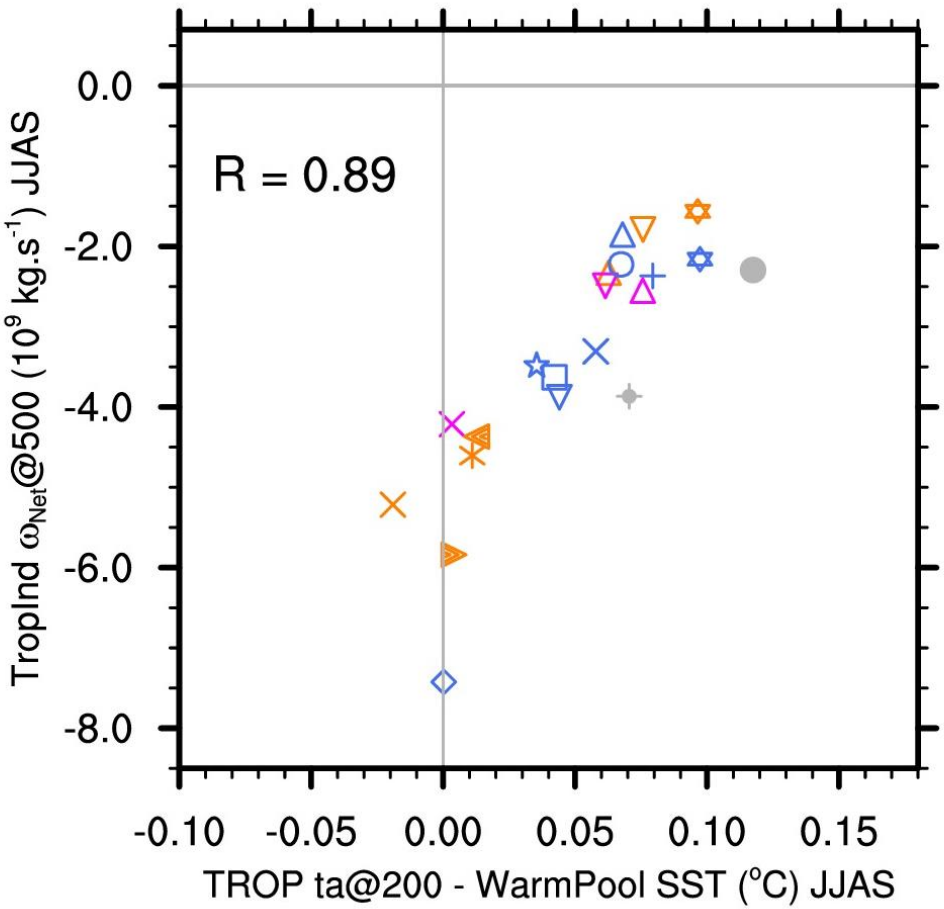


(positive vertical transport = downward motion)

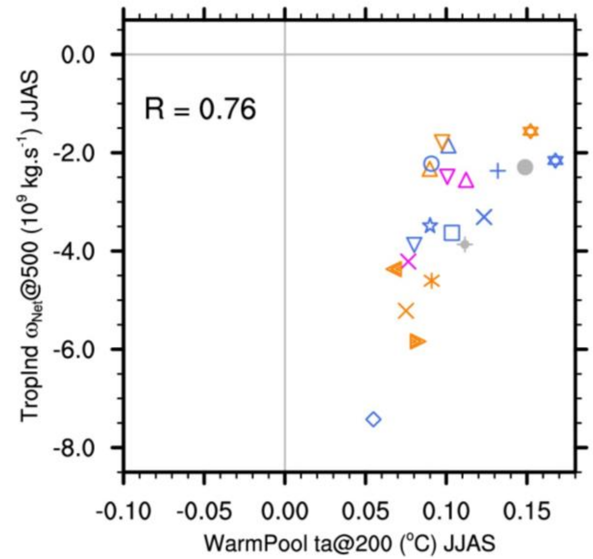
Origins of spread in TropInd ascent?

Trop. Ind. ascent linked to lapse rate over WarmPool

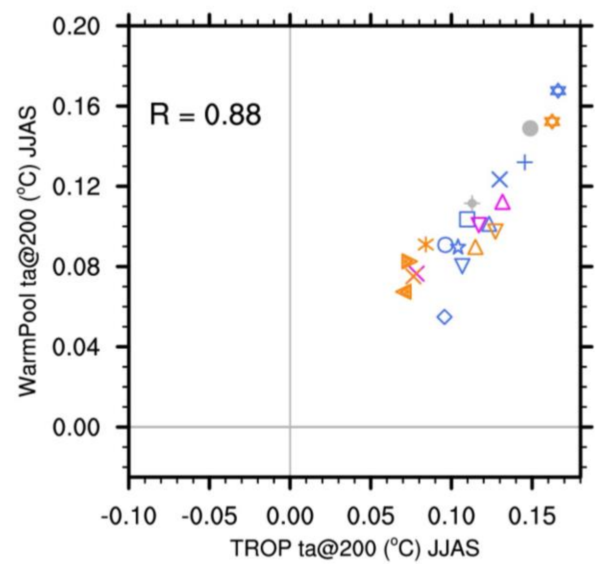
e) TropInd ω_{Net} vs TROP ta@200 - WP SST



TropInd ω_{Net}@500 vs WarmPool@200hPa



d) WarmPool vs TROP ta@200



(positive vertical transport = downward motion)

Origins of spread in tropical upper troposphere temperature?

- **Mean tropical troposphere temperature profile** often considered in a moist-adiabatic equilibrium with **mean tropical SST**.

- But regions with no convection (e.g. cold SST regions) are not directly connected to upper troposphere.

- Sobel et al. (2003) proposed to use **precipitation weighted mean SST $\boldsymbol{PSST}$**:

$$\mathrm{P}SST = \frac{\langle Pr \times SST \rangle}{\langle Pr \rangle}$$

where $\langle Pr \rangle$ is the sum over the tropics (20ºS-20ºN) of the precipitation.

- Here, we generalized this formula to also take into account changes over land by using the surface **equivalent potential temperature $\boldsymbol{\theta_E}$**:

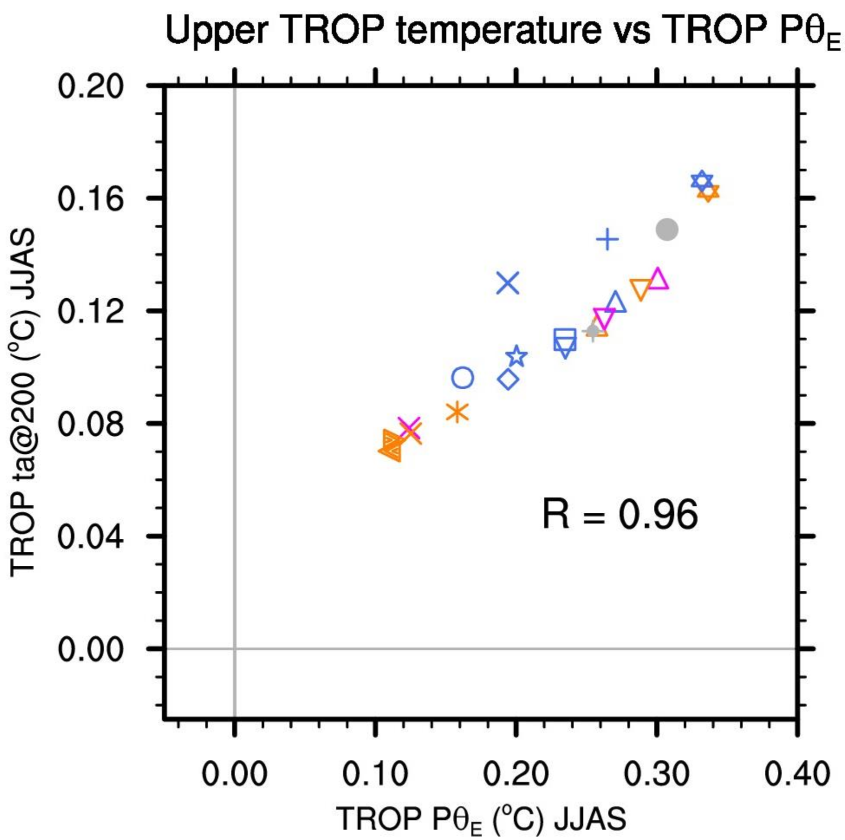
$$\mathbf{P}\boldsymbol{\theta_E} = \frac{\langle \boldsymbol{Pr} \times \boldsymbol{\theta_E} \rangle}{\langle \boldsymbol{Pr} \rangle}$$

Origins of spread in tropical upper troposphere temperature?

$$\mathbf{P}\boldsymbol{\theta}_E = \frac{\langle \boldsymbol{Pr} \times \boldsymbol{\theta}_E \rangle}{\langle \boldsymbol{Pr} \rangle}$$

$$(\mathbf{P}\boldsymbol{\theta}_E)' = \boldsymbol{f}_{Pr'}(\boldsymbol{Pr}', \boldsymbol{\theta}_{E,C}) + \boldsymbol{f}_{\theta'_E}(\boldsymbol{Pr}_C, \boldsymbol{\theta}'_E)$$

$$= \boldsymbol{P}'\boldsymbol{\theta}_{E,C} \qquad\qquad = \boldsymbol{P}_C\boldsymbol{\theta}'_E$$

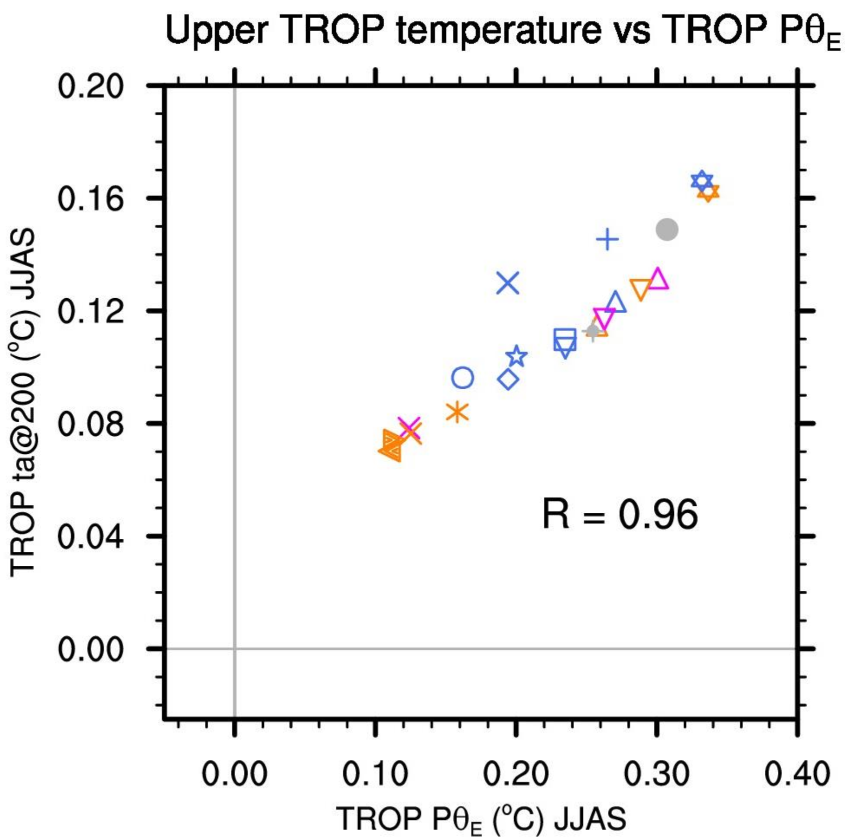


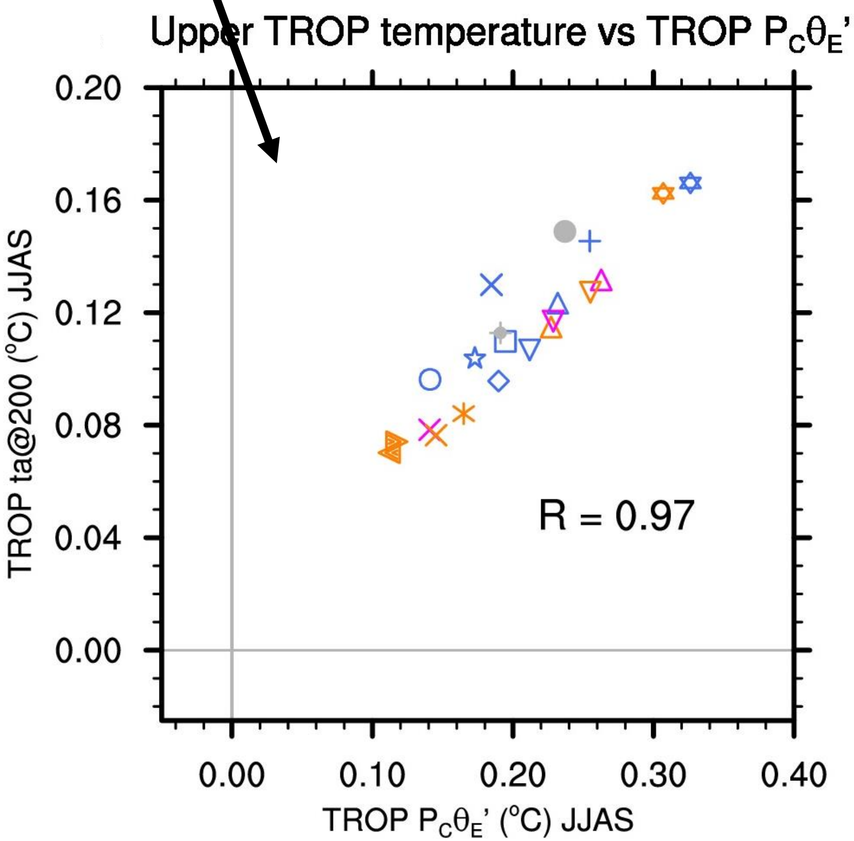
Origins of spread in tropical upper troposphere temperature?

$$\mathbf{P}\boldsymbol{\theta}_E = \frac{\langle Pr \times \theta_E \rangle}{\langle Pr \rangle}$$

$$(\mathbf{P}\boldsymbol{\theta}_E)' = f_{Pr'}(Pr', \theta_{E,C}) + f_{\theta_E'}(Pr_C, \theta_E')$$

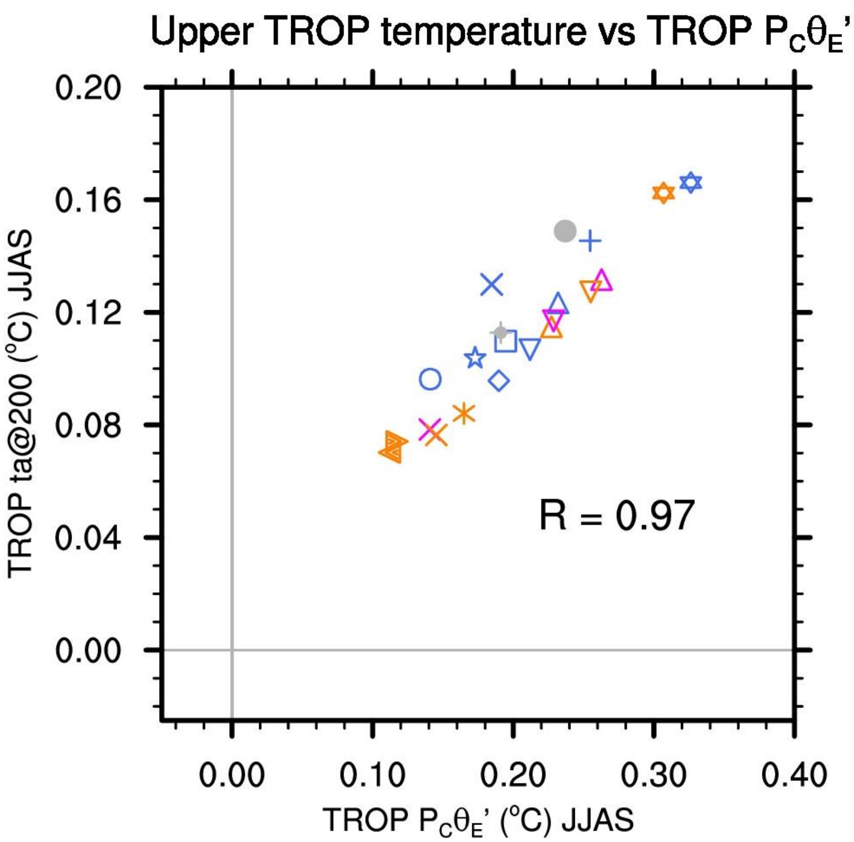
$$= P'\theta_{E,C} \qquad = P_C\theta_E'$$

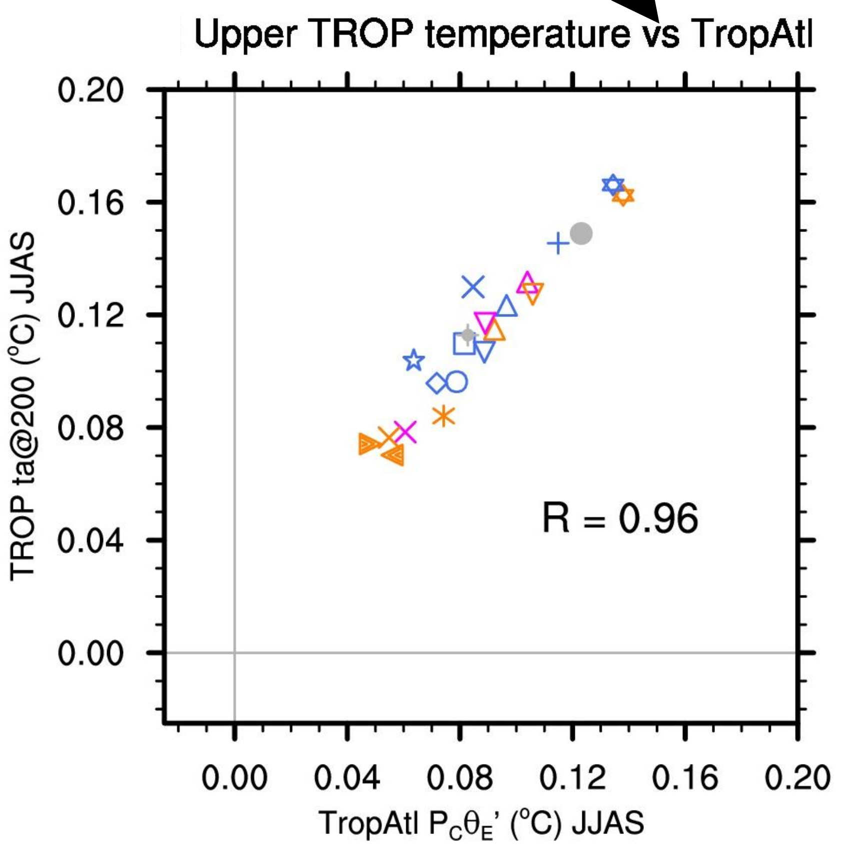




Origins of spread in tropical upper troposphere temperature?

$$P_C\theta'_E = \frac{\langle Pr_C \times \theta'_E \rangle}{\langle Pr_C \rangle} = \frac{\langle Pr_C \times \theta'_E \rangle_{Ind}}{\langle Pr_C \rangle} + \frac{\langle Pr_C \times \theta'_E \rangle_{Pac}}{\langle Pr_C \rangle} + \frac{\langle Pr_C \times \theta'_E \rangle_{Atl}}{\langle Pr_C \rangle}$$

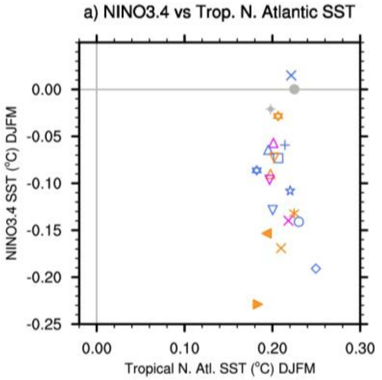




To summarize

- Idealized AMV experiments confirm the observed link between AMV and tropical Pacific:
  - ➢ 20/21 simulations show tropical Pacific cooling in response to AMV warming.

- Large inter-model spread in Trop. Pac. cooling response to a given AMV warming
  - ➢ factor 5 among models



- Spread coming from Trop Pac. descent response in summer:
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  - ➢ 69% Trop. Ind. ascent.

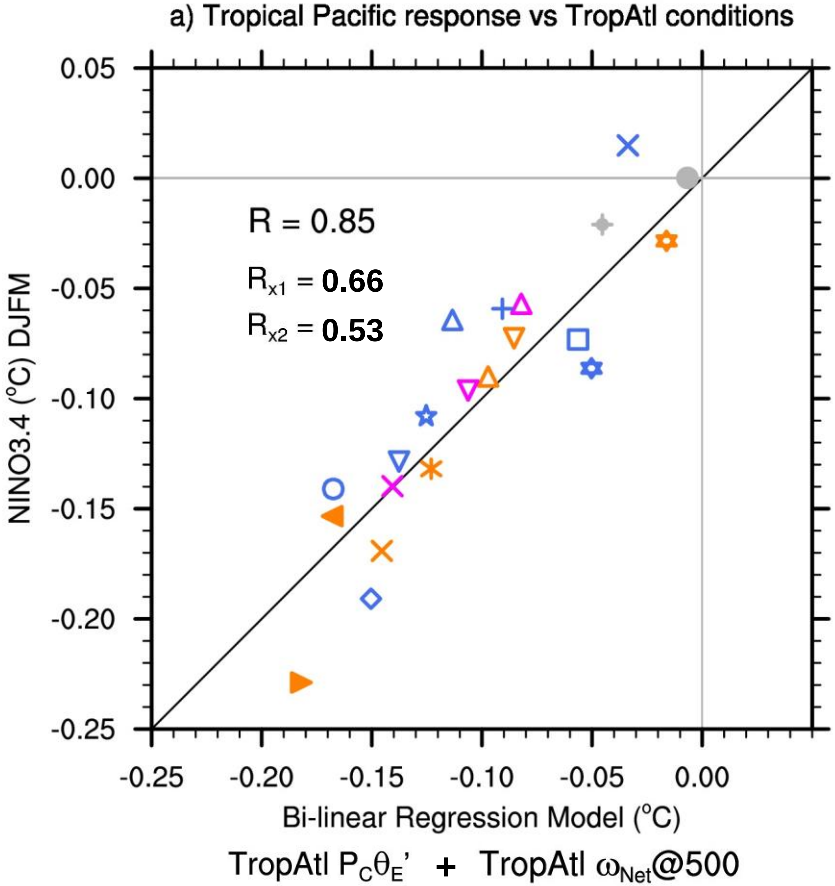
- Trop. Ind. ascent spread linked to upper troposphere response
  - ➢ dictated by Trop. Atl. injection of moist static energy: $\frac{\langle Pr_c \times \theta'_E \rangle_{Atl}}{\langle Pr_c \rangle}$

2 variables control the spread in the Trop. Pac. response:

➢ **Trop. Atl. ascent (wap@500)**

➢ **Trop. Atl. injection of moist static energy ($P_C\theta'_E$)**

To summarize



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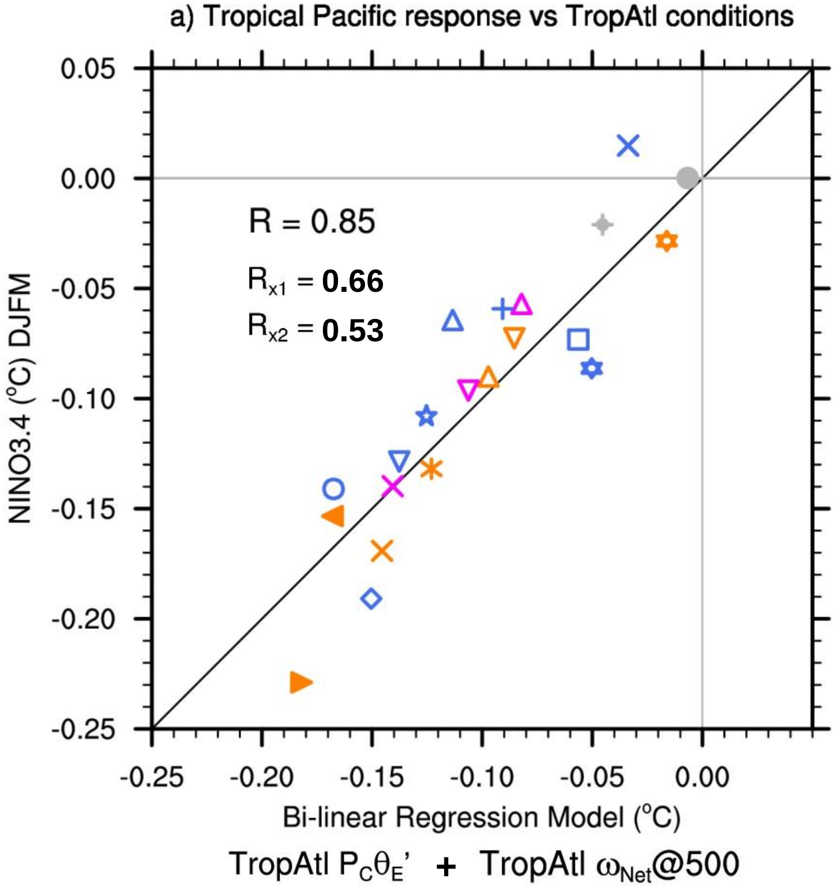

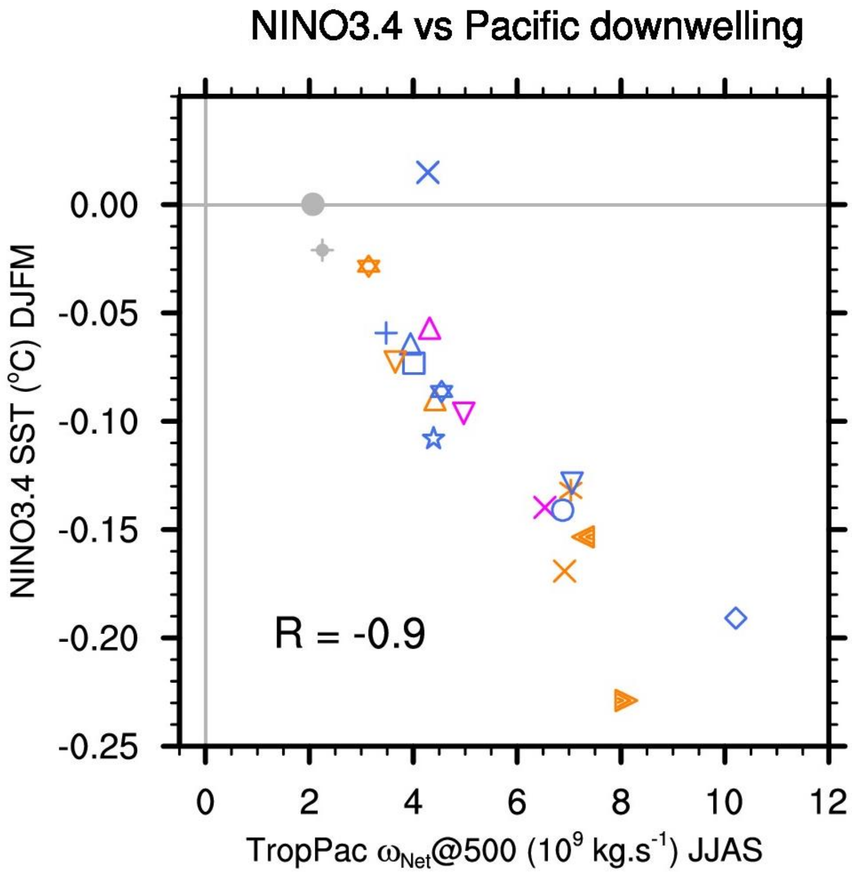

2 variables control the spread in the Trop. Pac. response:

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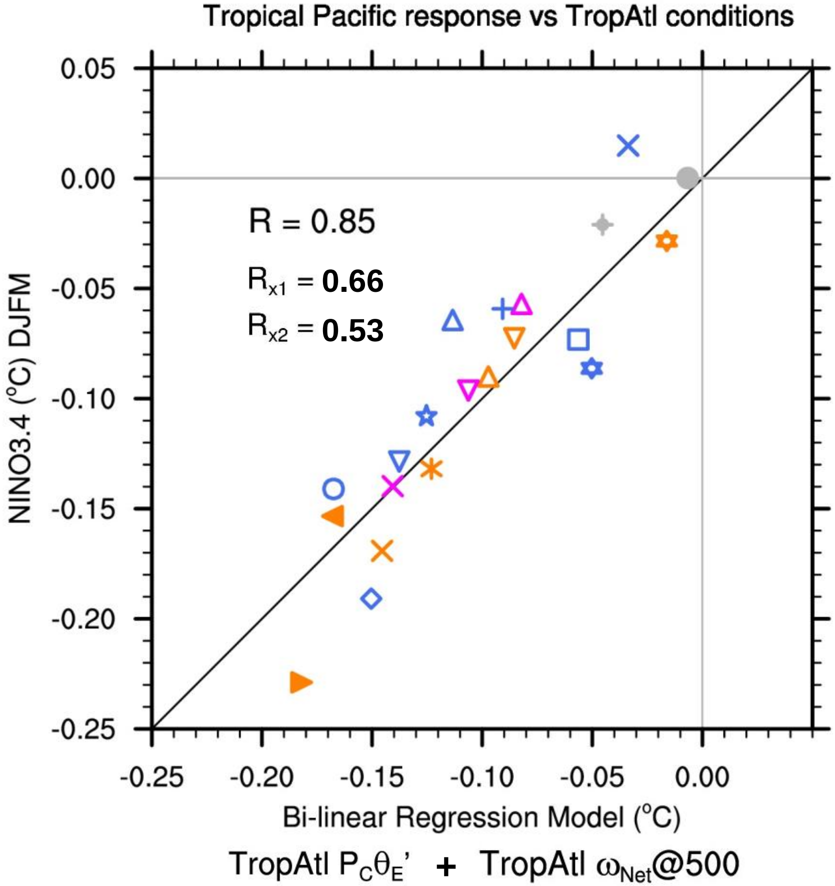
Origins of the different model responses over TropAtl



Origins of summer differences in:

Trop. Atl. wap@500

Trop. Atl. $\boldsymbol{P_C\theta'_E}$

In balanced with Atlantic – Pacific SST difference

(McGregor et al. 2014)

Origins of the different model responses over TropAtl

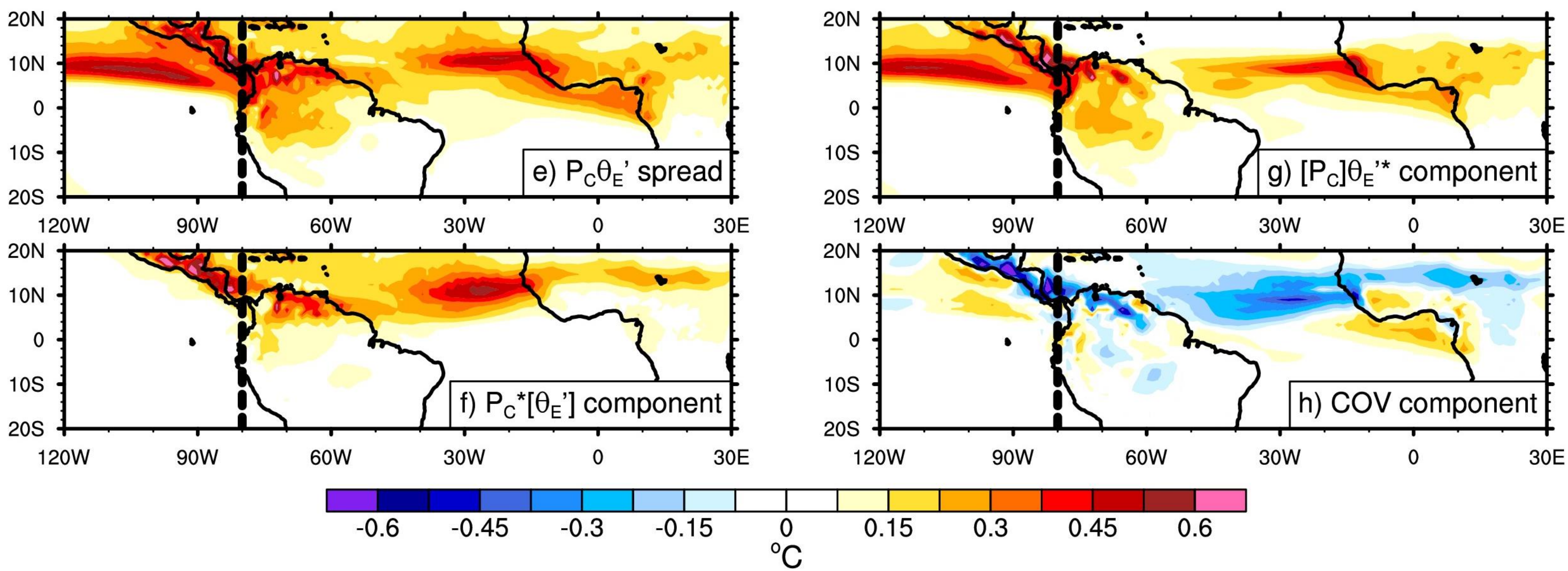
$$P_C\theta'_E = \frac{\langle Pr_C \times \theta'_E\rangle}{\langle Pr_C\rangle} = [P_C\theta'_E] + (P_C\theta'_E)^*$$

$[x]$: multi-model mean (MMM)
x^*: deviation from MMM

$$(P_C\theta'_E)^* = f_{Pr_C{}^*}(Pr_C, [\theta'_E]) + f_{\theta'_E{}^*}([Pr_C], \theta'_E)$$

Differences in climatological precipitation

Differences in θ'_E response



Origins of the different model responses over TropAtl

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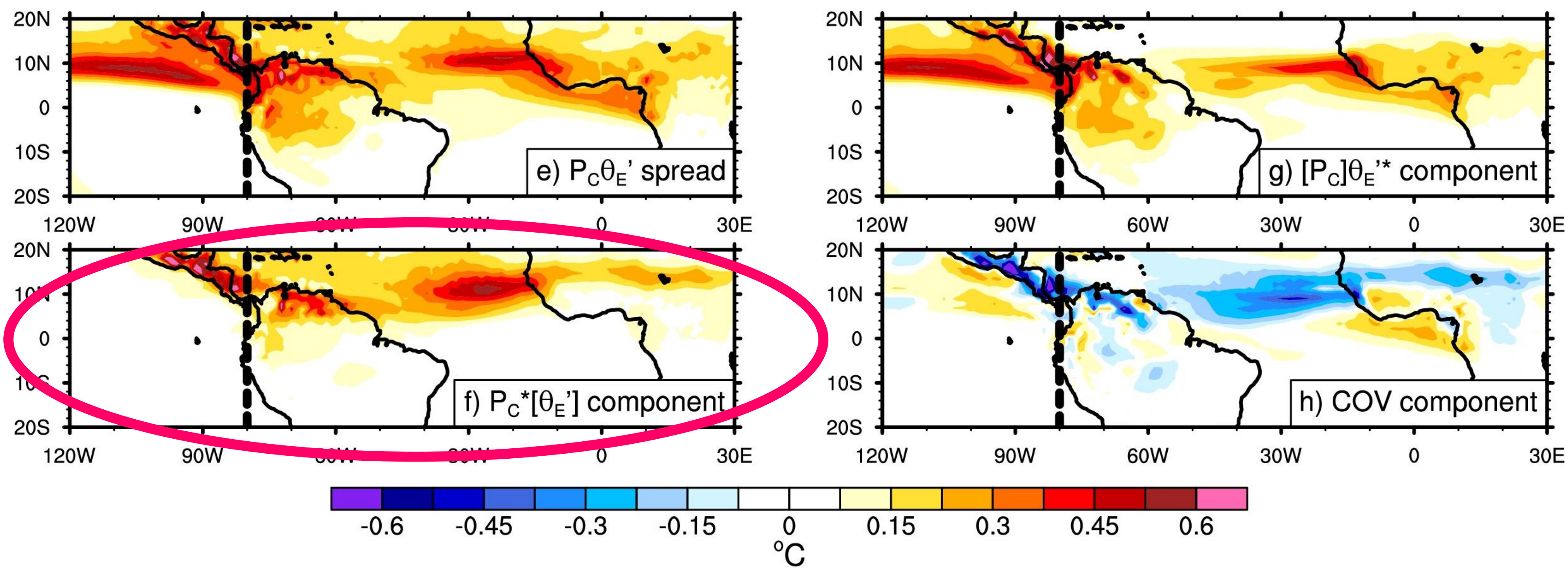
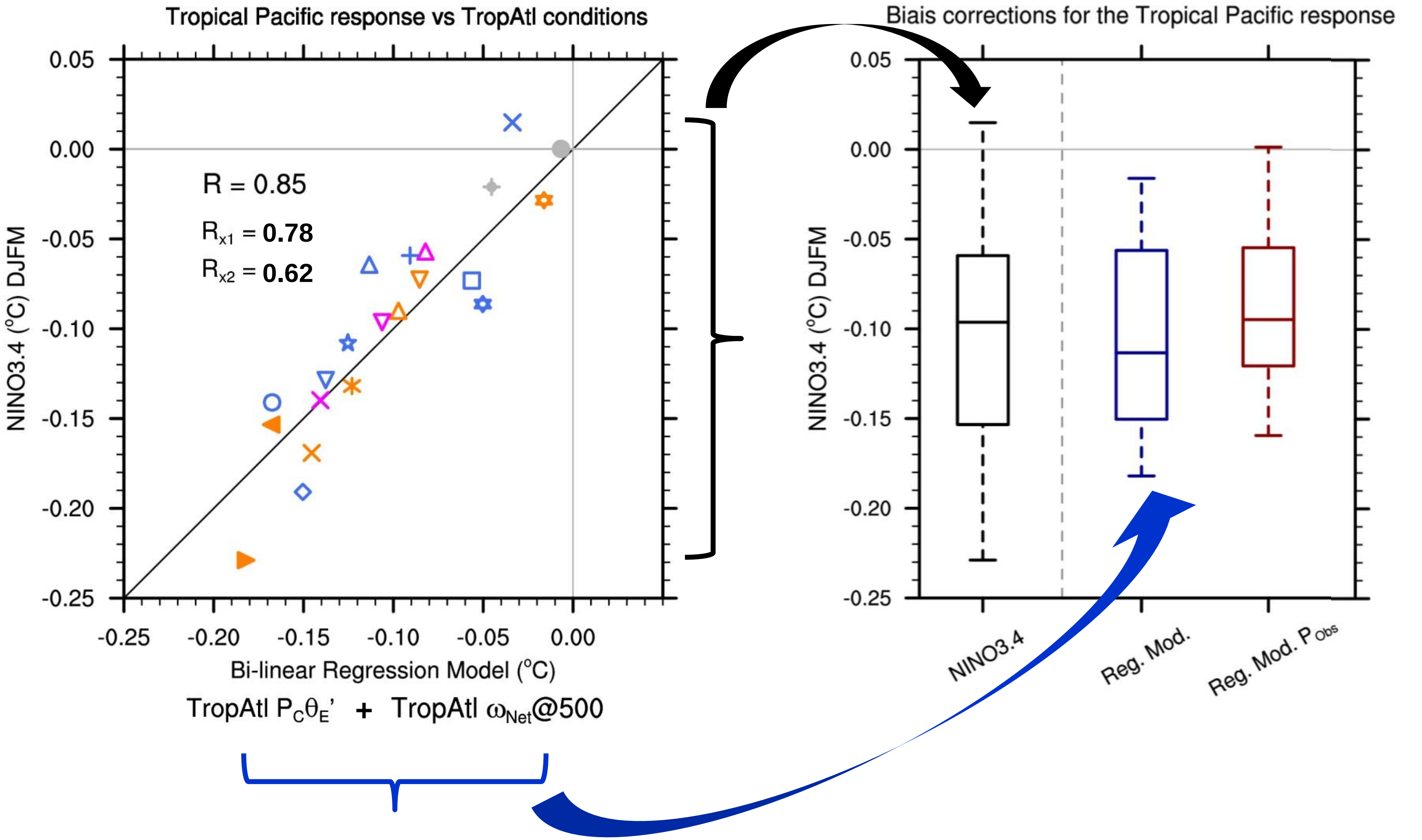


Origins of the different model responses over TropAtl



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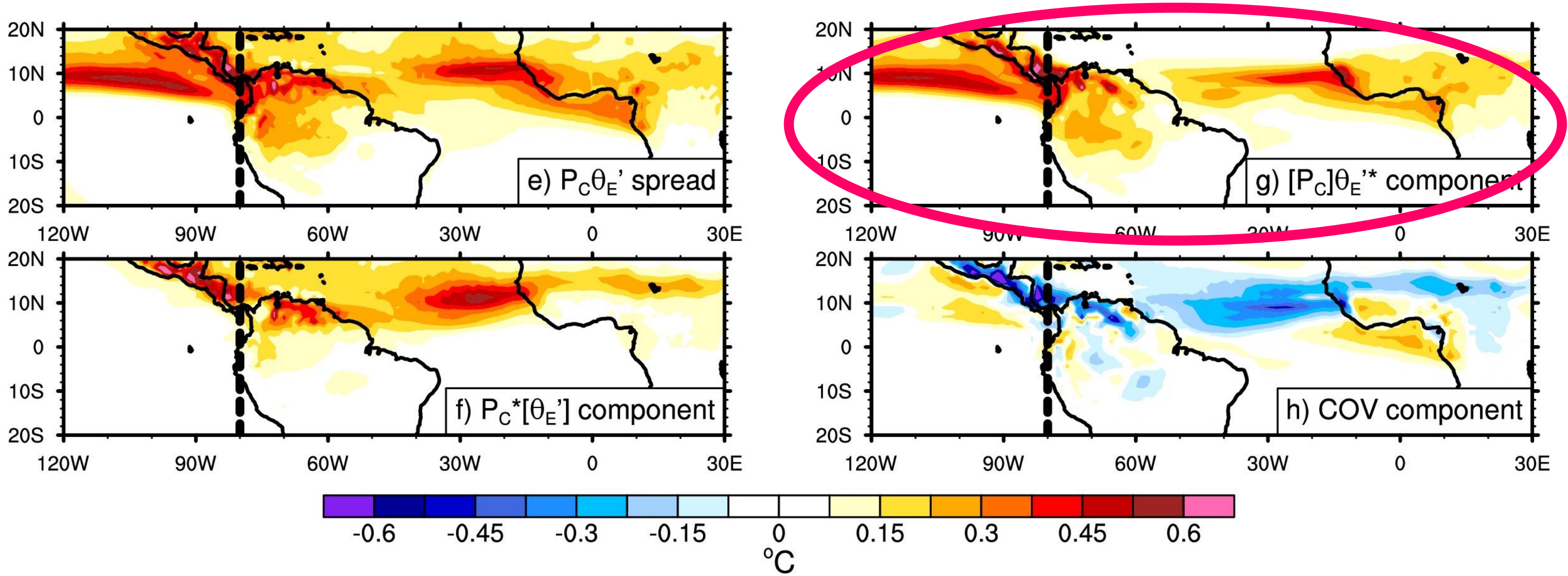

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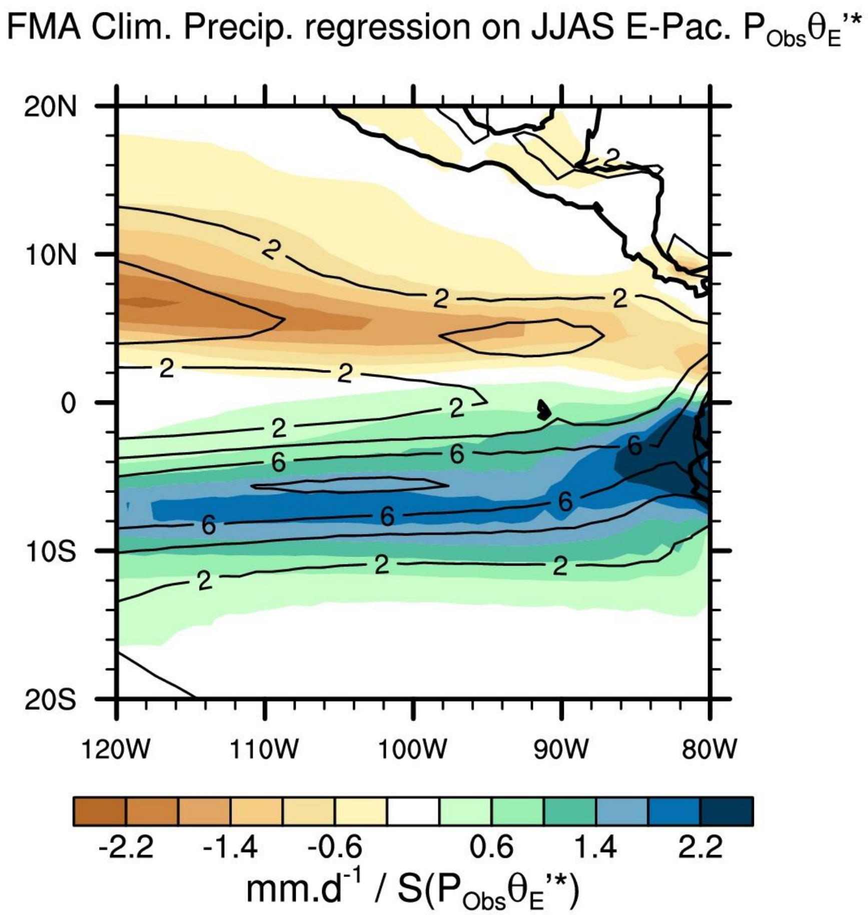
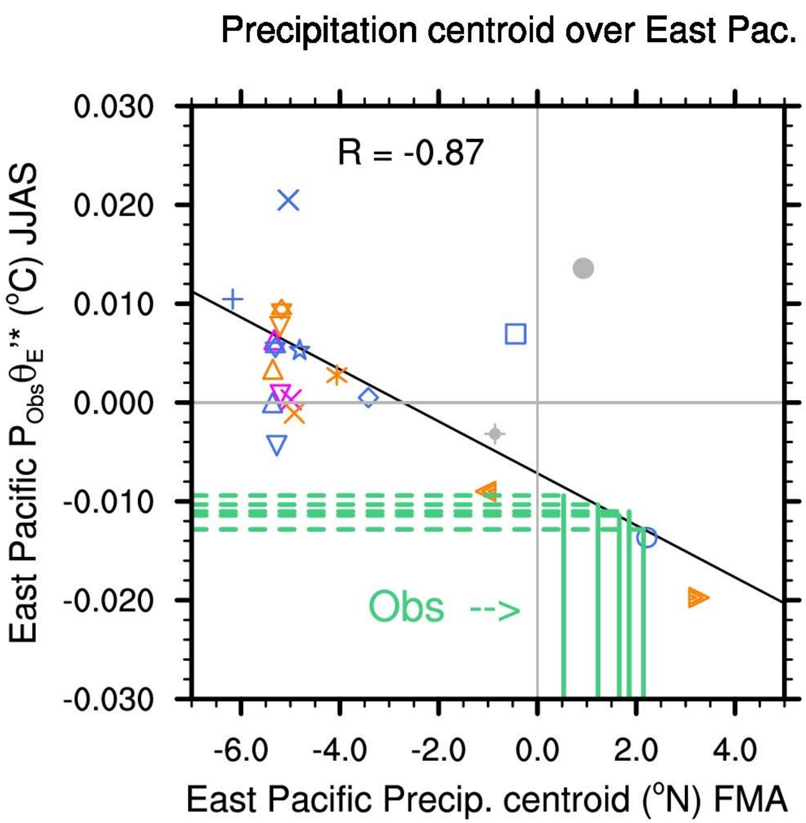
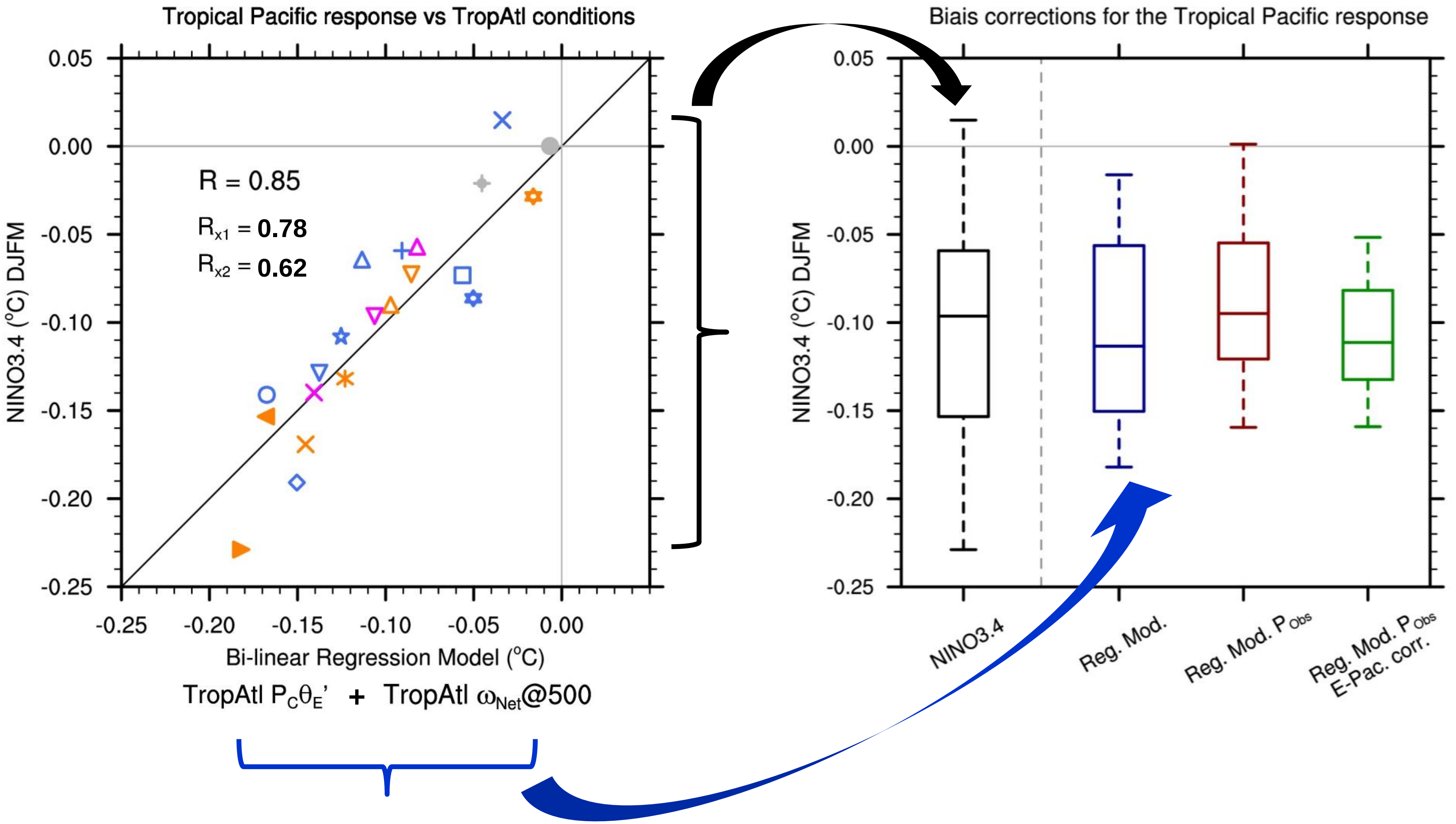




Origins of the different model responses over TropAtl



Analytically correcting for mean model precipitation biases:

~0.2ºC tropical Atlantic warming ➔ -0.11ºC ± 0.03ºC winter NIÑO3.4 SST cooling

Summary

- Idealized AMV experiments confirm the observed link between AMV and tropical Pacific:
  - 20/21 simulations show tropical Pacific cooling in response to AMV warming.

- Large inter-model spread in Trop. Pac. cooling response to a given AMV warming
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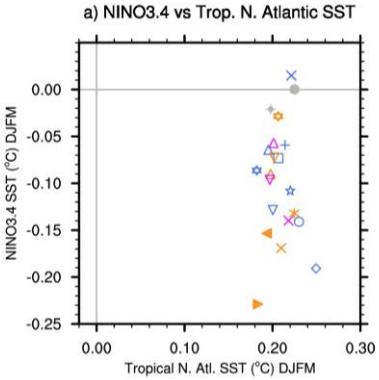

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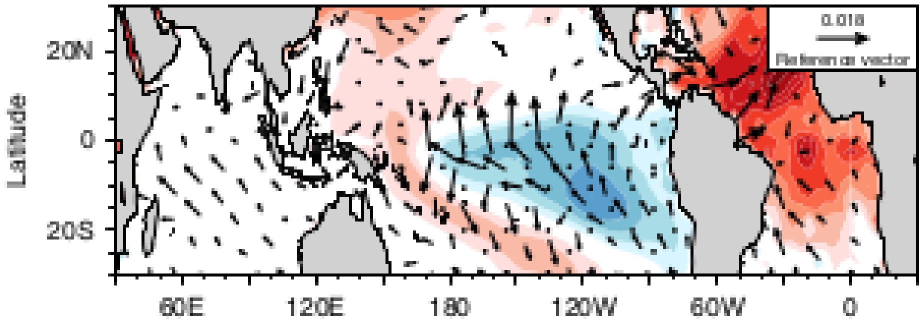
- Spread in Trop. Atl. $\frac{\langle Pr_c \times \theta'_E \rangle_{Atl}}{\langle Pr_c \rangle}$ linked to model differences in mean precipitation

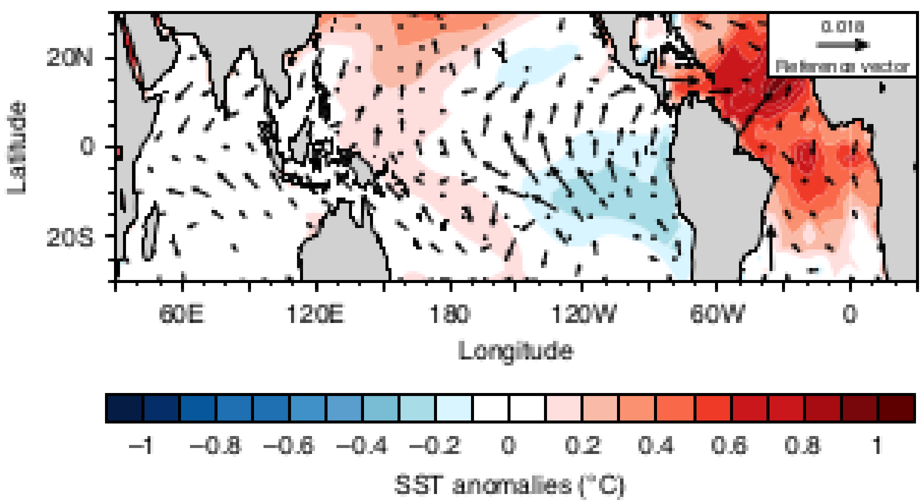
Analytically correcting for mean model biases, we estimate that in response to a ~0.26ºC AMV warming, the winter NIÑO34 SST cools by -0.11ºC $\pm$ 0.03ºC

Underestimation of the AMV impact on the Pacific due to mean biases

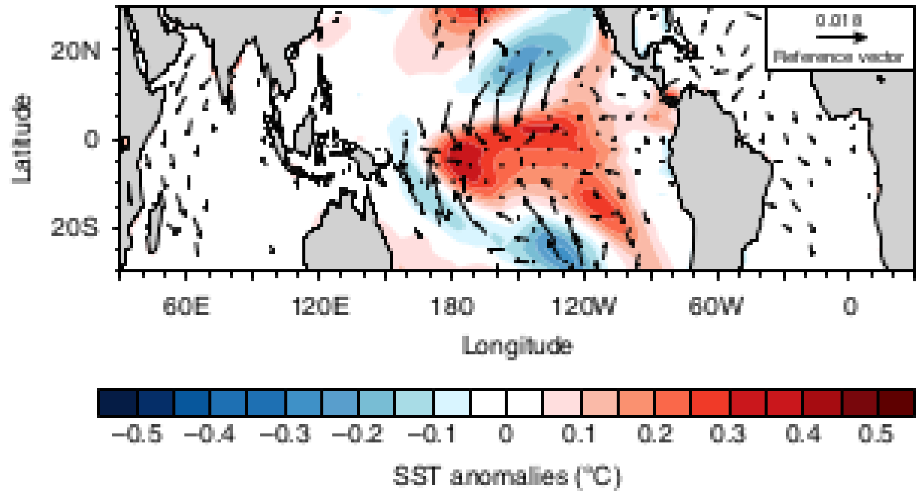
Observed SST mean state



CMIP5 SST mean state



Response differences between CMIP5 exp – OBS exp



(Li et al. 2020)

See also Kajtar et al. 2018; McGregor et al. 2018

AMV impacts on Tropical Cyclones

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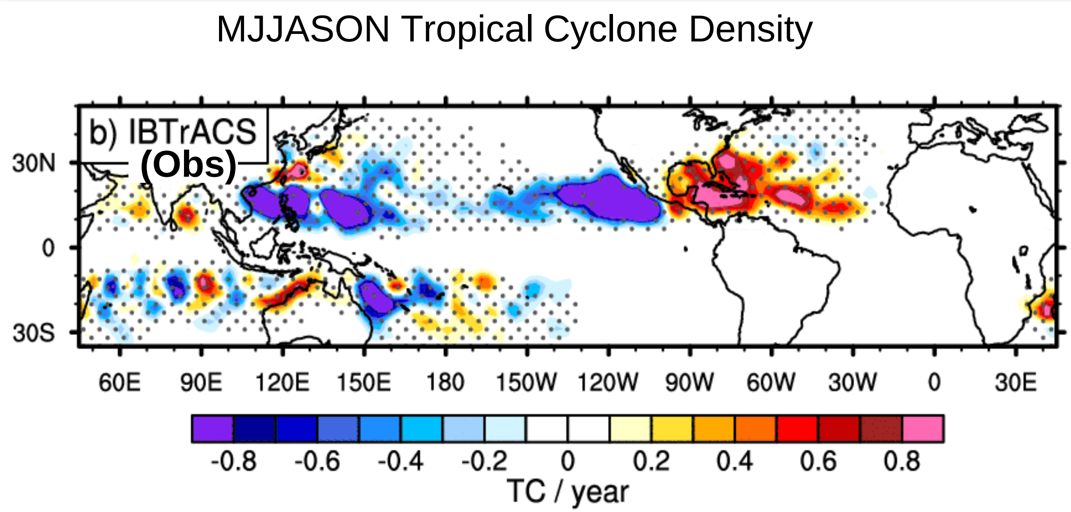
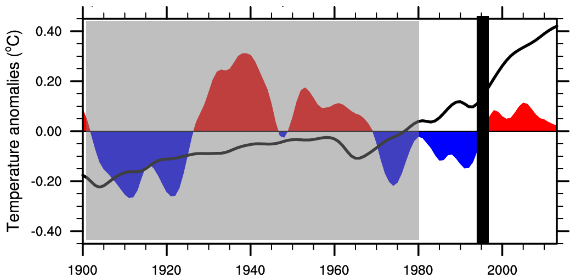
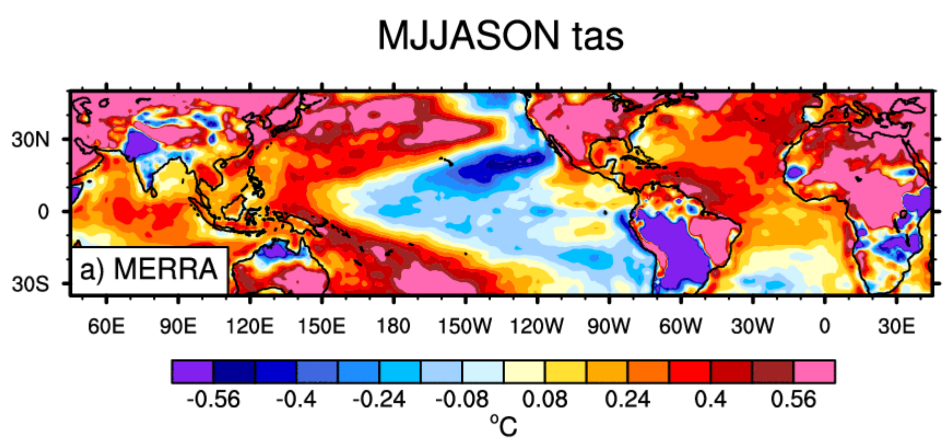
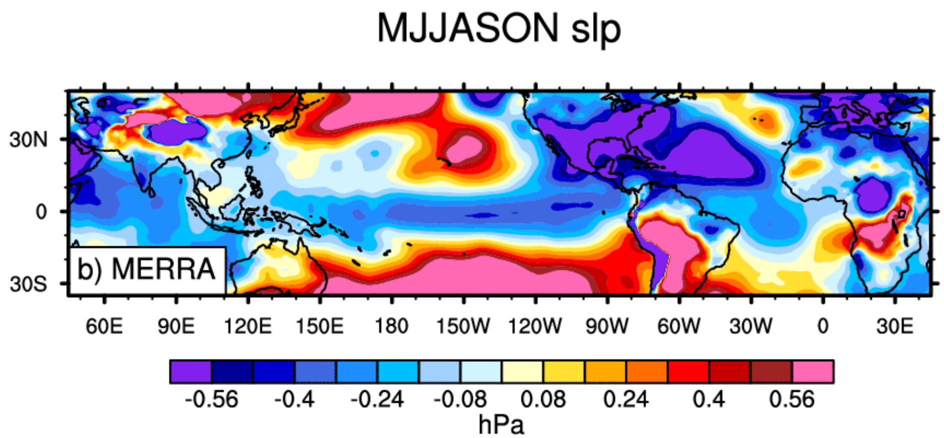




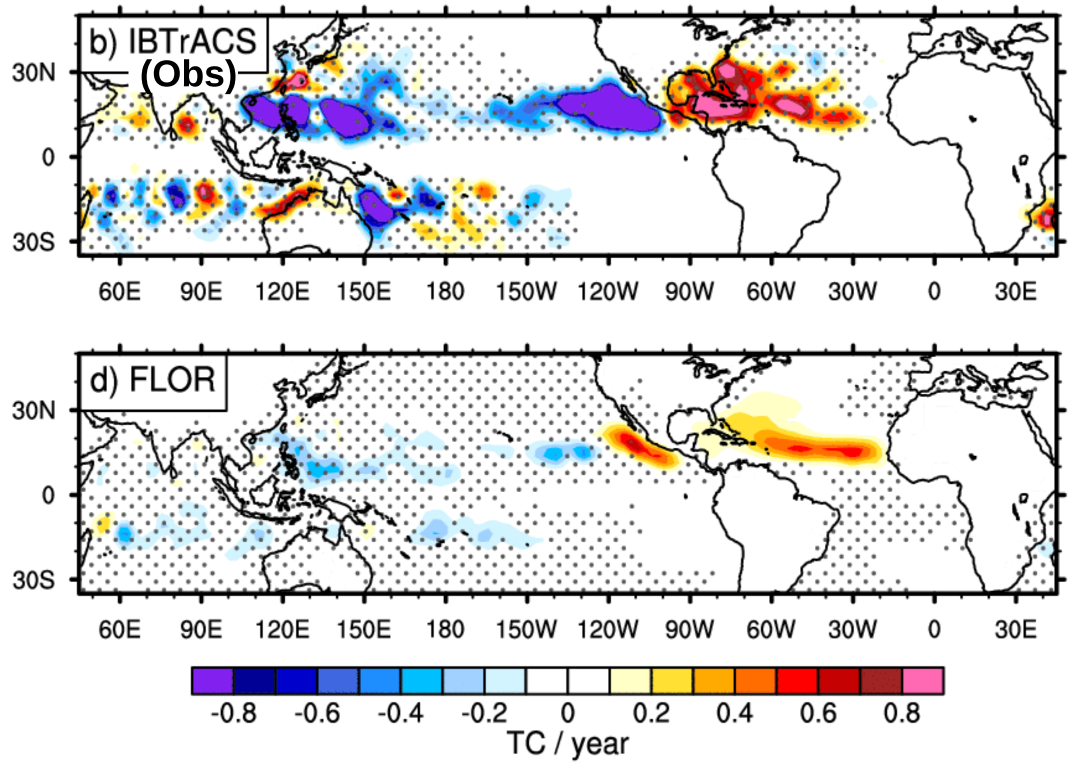
Obs = 1996-2011 vs 1980-1995

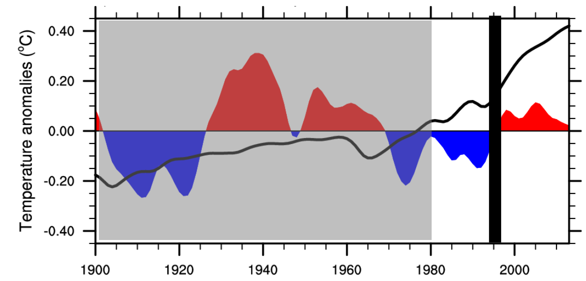




AMV impacts on Tropical Cyclones

MJJASON Tropical Cyclone Density





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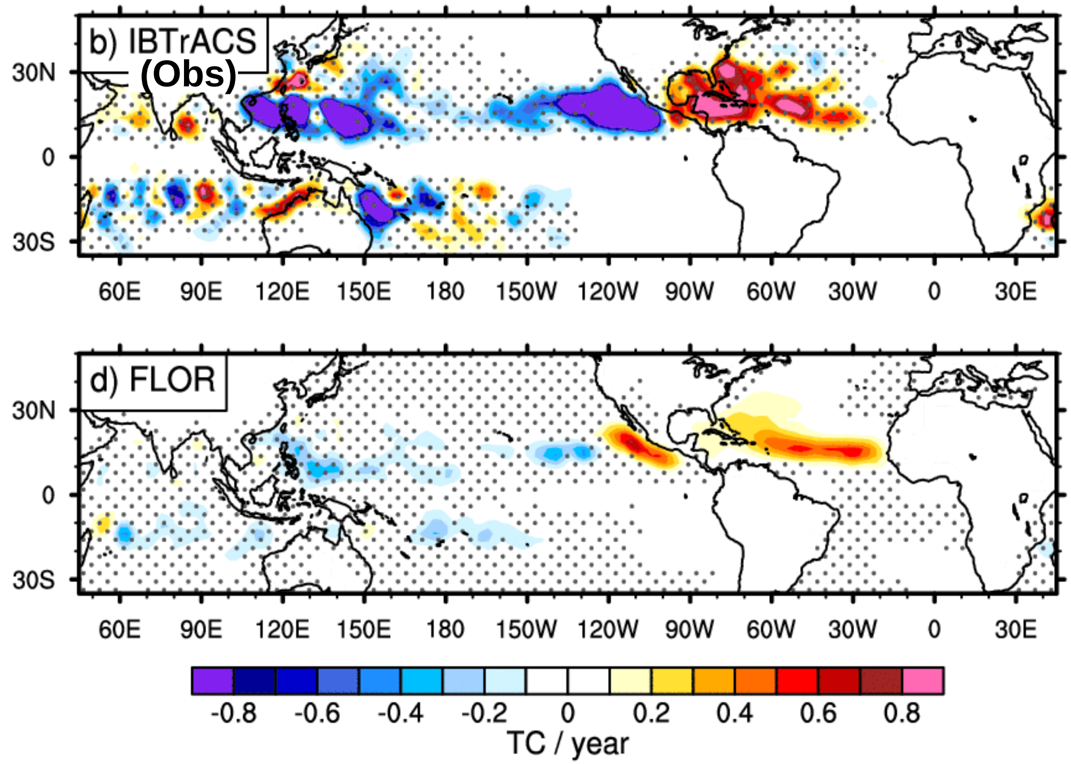

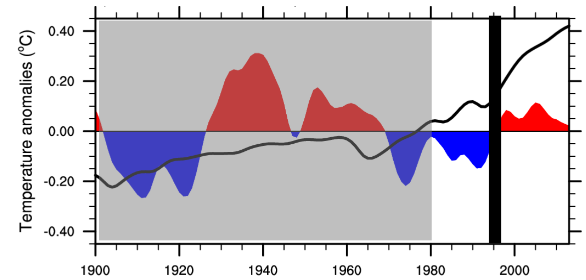

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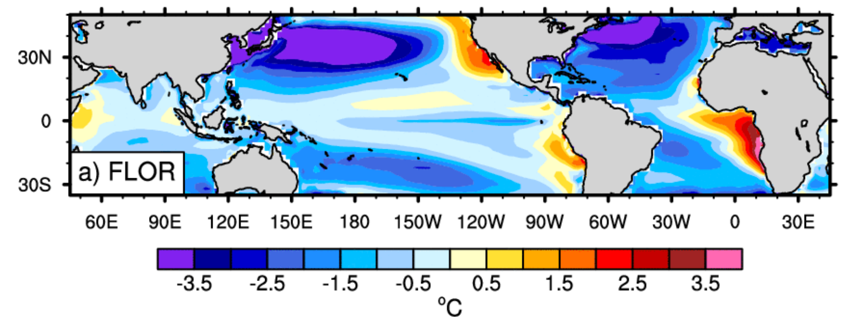
MJJASON sst biases



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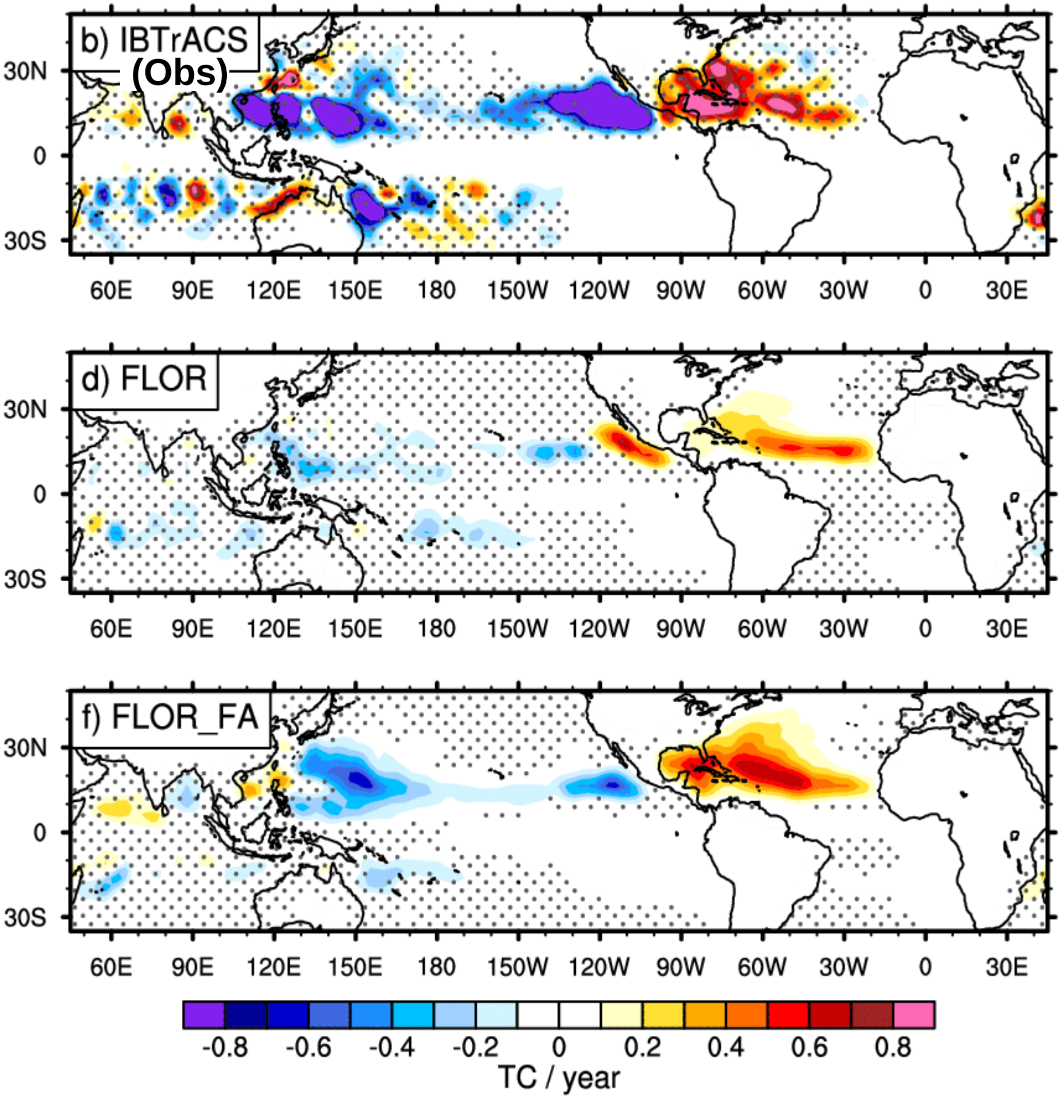

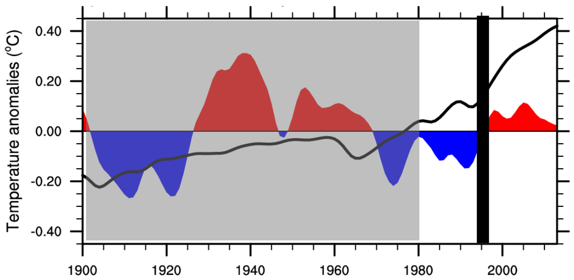

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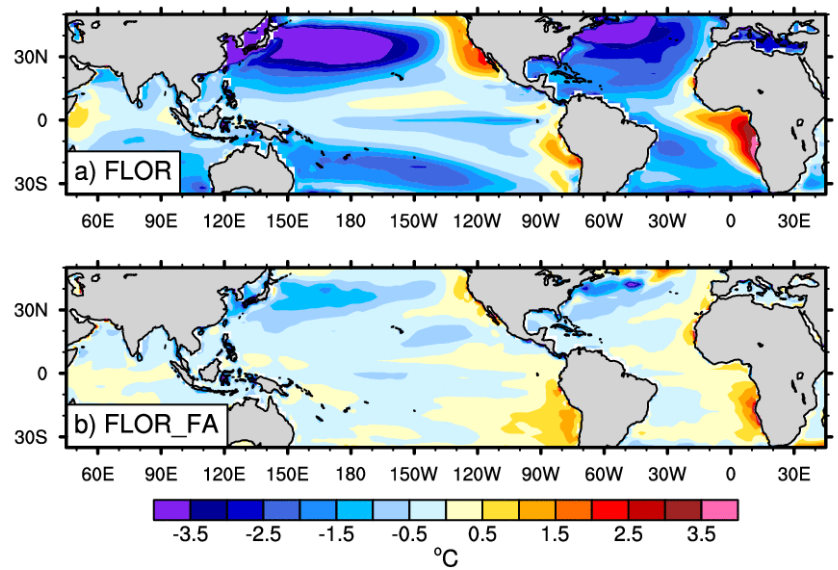

(Results never published)

To conclude

According to CMIP6/DCPP-C AMV idealized simulations:

- An AMV warming drives a tropical Pacific cooling
  - ➢ Large inter-model spread in the amplitude of this cooling
  - ➢ Explained by different Indo-Pacific feedback amplitude
  - ➢ Driven by amount of moist static energy injection from Atlantic surface
  - ➢ 65% of this spread explained by different model climatological precipitation

- Warm AMV drives more TC over Atlantic and less over Pacific
  - ➢ Driven by SST and wind shear anomalies

- AMV modulates ENSO activity and impacts (not shown)
  - ➢ Less extreme ENSO events during warm AMV conditions
    - ➔ for more info: ask Paloma Trascasa Castro

Mean model biases impact the simulated climate responses to AMV

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Thank you!

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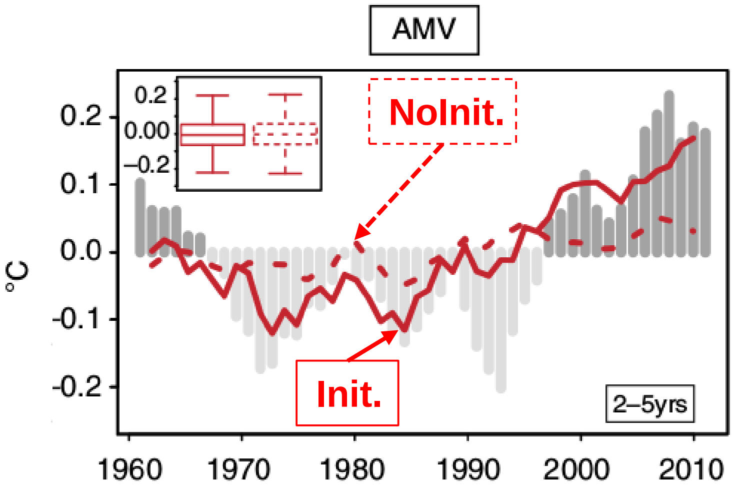
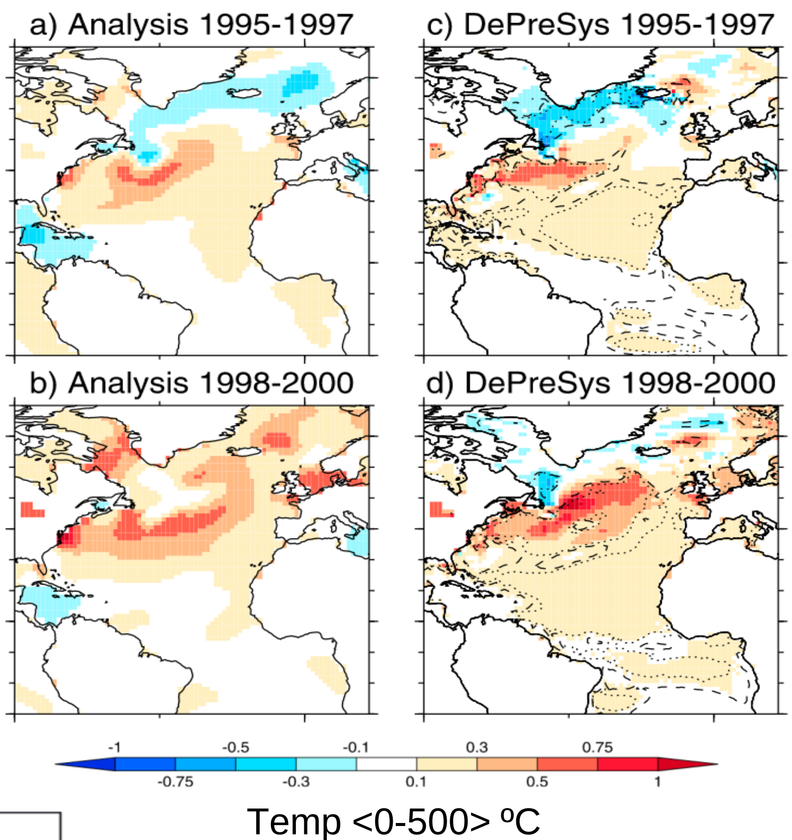
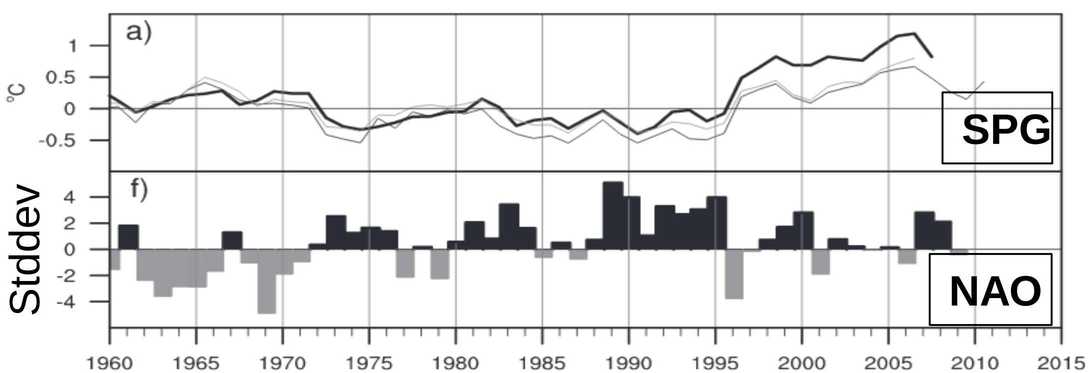
Mean model biases impact the simulated climate responses to AMV

The origins of the AMV

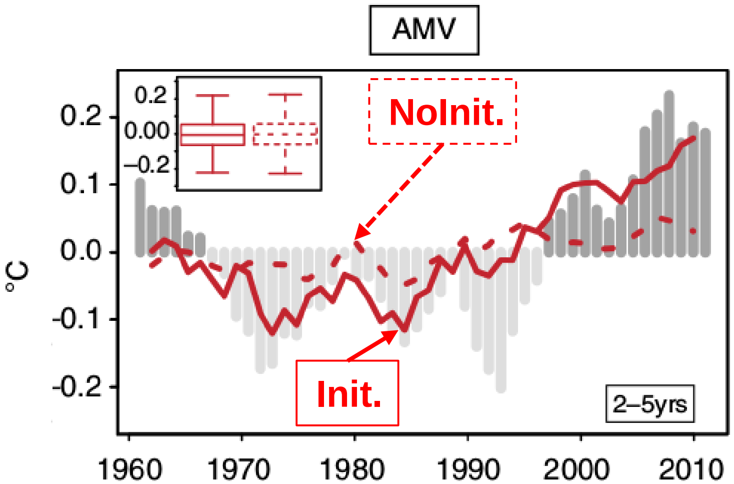


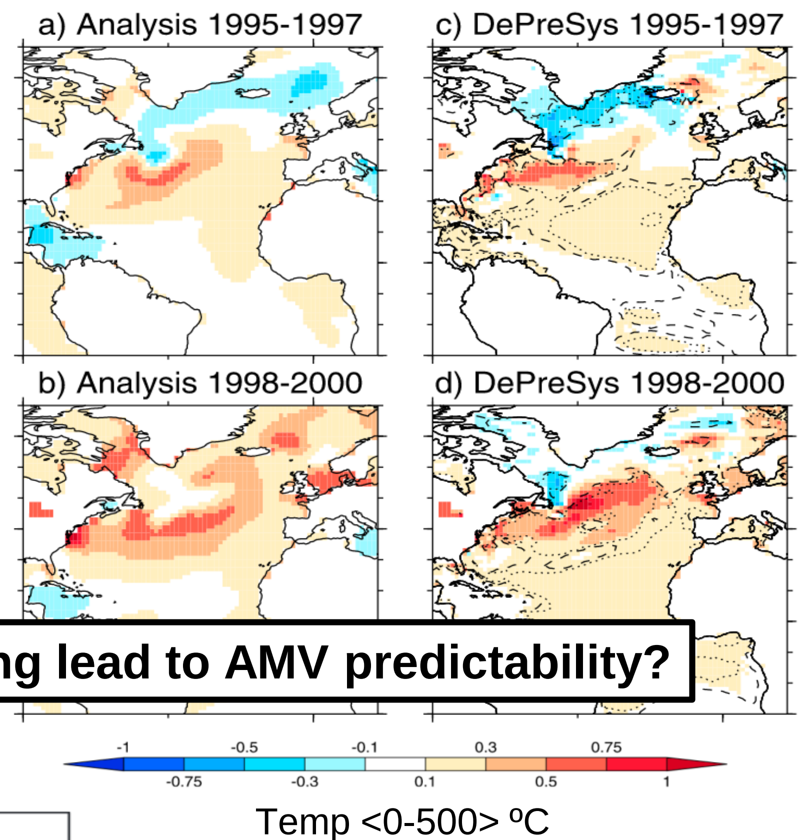




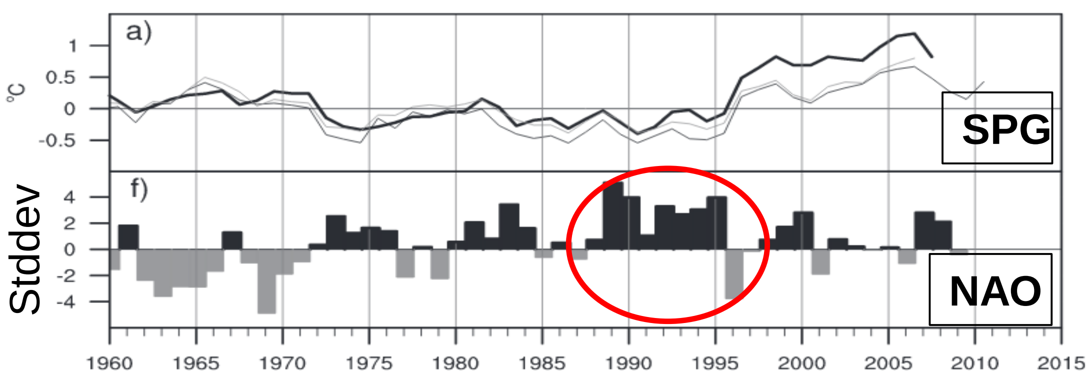
(Doblas-Reyes et al. 2013) (Yeager et al. 2012) (Robson et al. 2012)

The origins of the AMV





What kinds of atmospheric forcing lead to AMV predictability?



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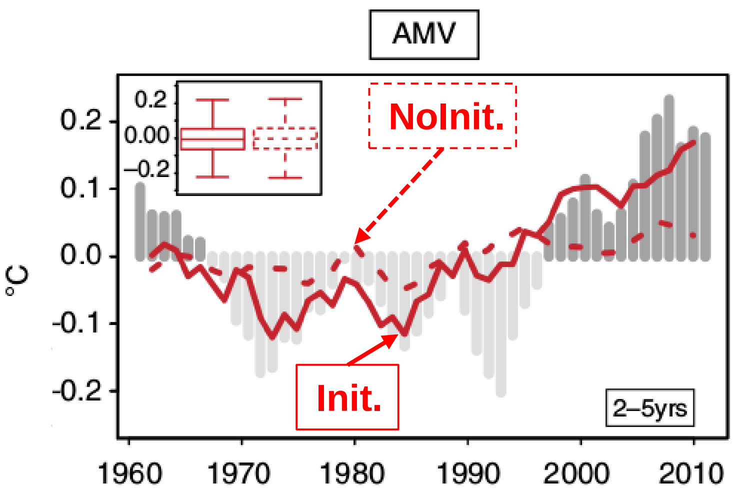

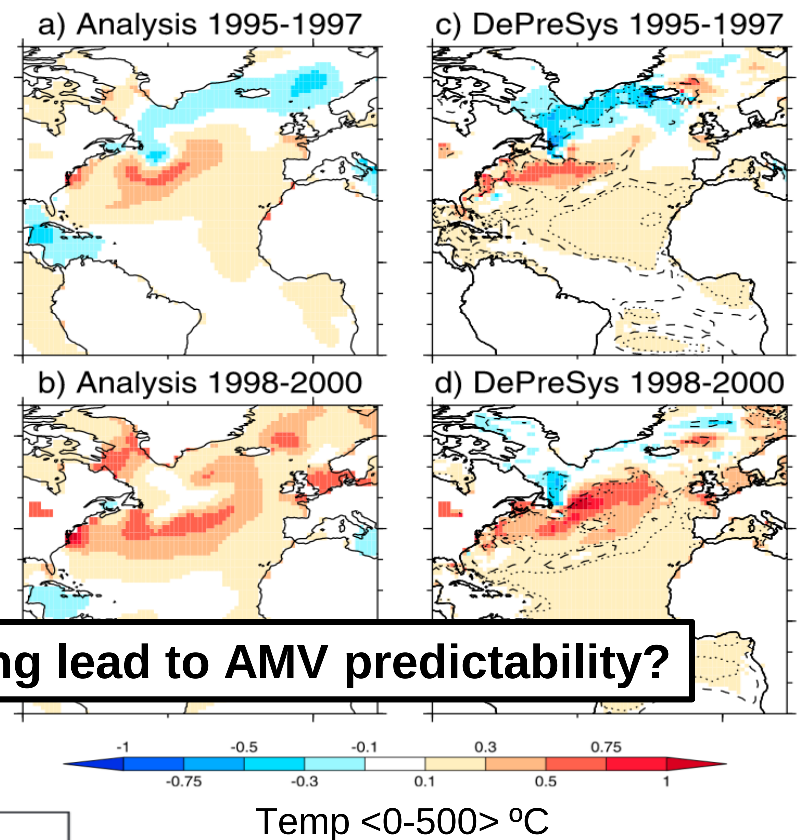

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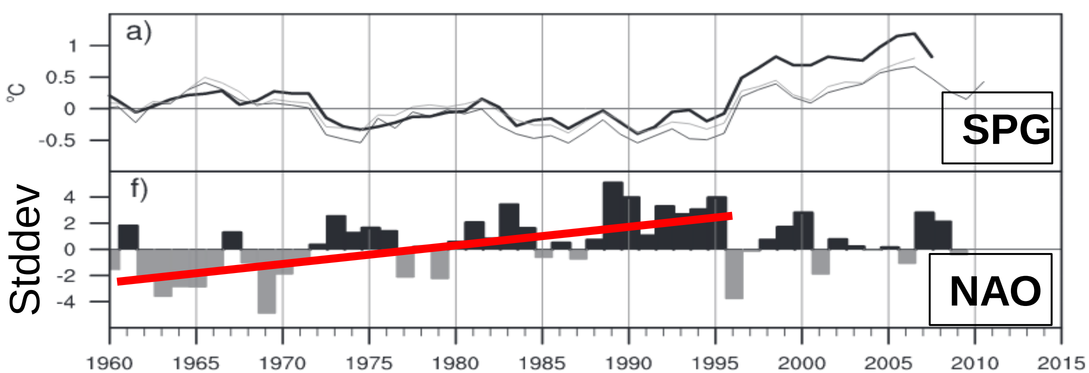
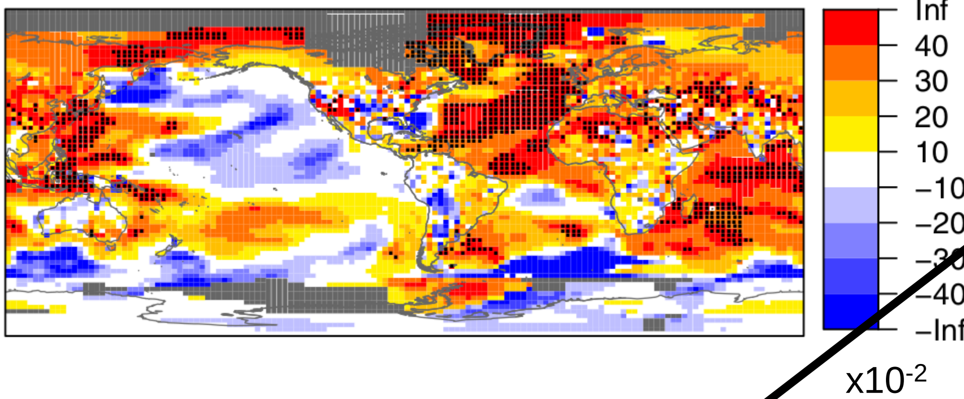
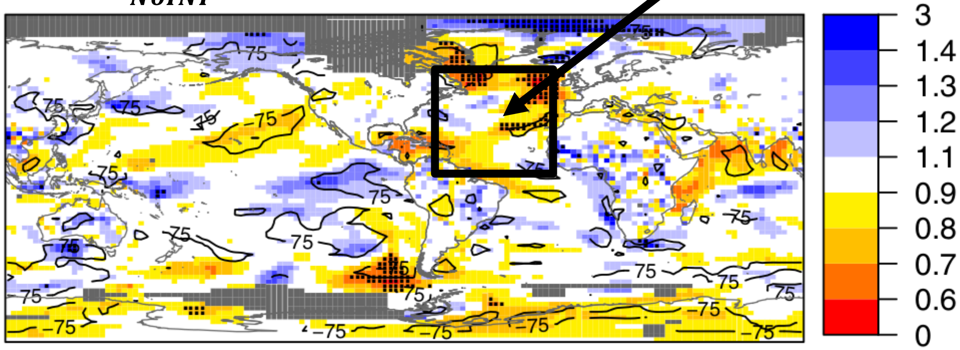


The origins of the AMV

$$1 - \frac{RMSE_{INI}}{RMSE_{clim}}$$



$$\frac{RMSE_{INI}}{RMSE_{NoINI}}$$



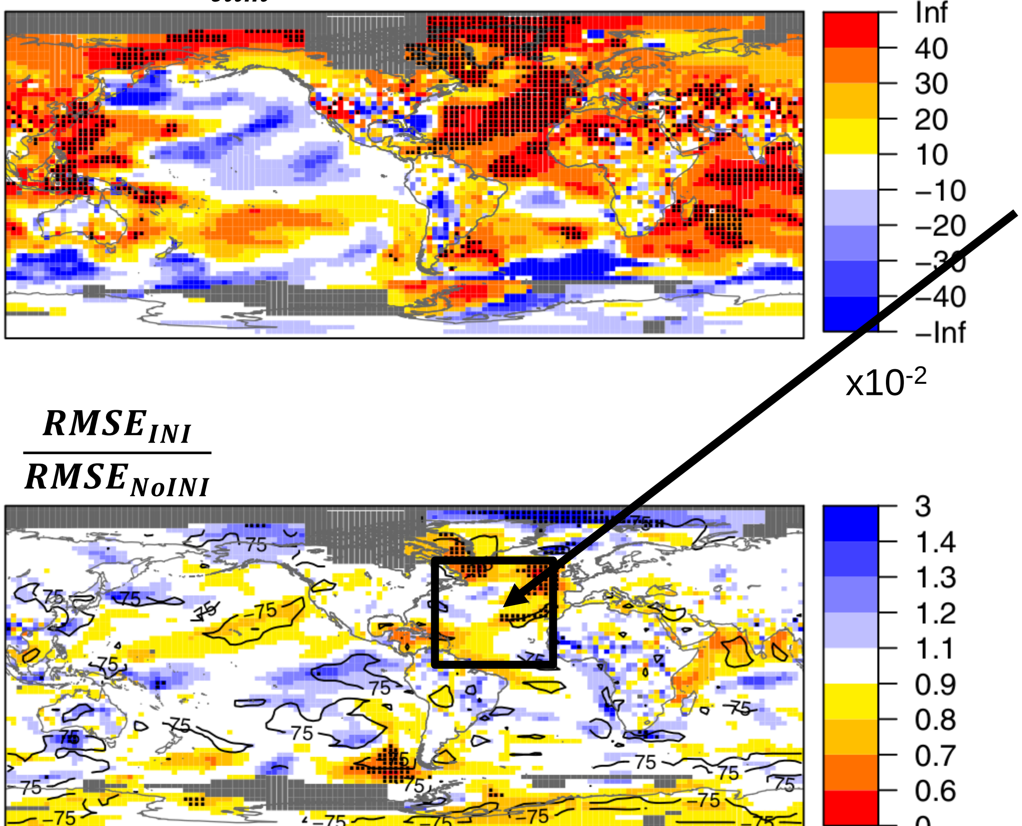
Not only internal variability but also partial correction of model response to external forcings

(Doblas-Reyes et al. 2013)

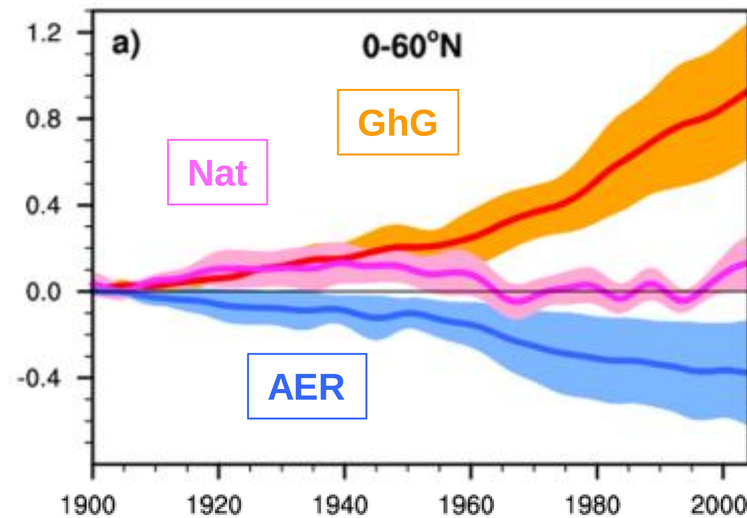
The origins of the AMV

$$1 - \frac{RMSE_{INI}}{RMSE_{clim}}$$

$$\frac{RMSE_{INI}}{RMSE_{NoINI}}$$



N. Atlantic SST externally forced (CMIP5)



Large uncertainties exist on the North Atlantic SST response to external forcing

- **Sensitivity to GhG**
- **Representation of anthropogenic aerosols**
- **Representation of African dust**

(Doblas-Reyes et al. 2013) (Terray 2012)

Summary

According to CMIP6/DCPP-C type protocol simulations:

- **An AMV warming drives a tropical Pacific cooling**
  - ➢ **But factor 10 among models**
  - ➢ **Explained by Indo-Pacific feedback / South Atlantic cooling**
  - ➢ **Potentially linked to mean state conditions**
- **Warm AMV drives more TC over Atlantic and less over Pacific**
  - ➢ **Mechanism = SST and wind shear anomalies**
- **Warm AMV drives more heat waves over North America and Mediterranean region**

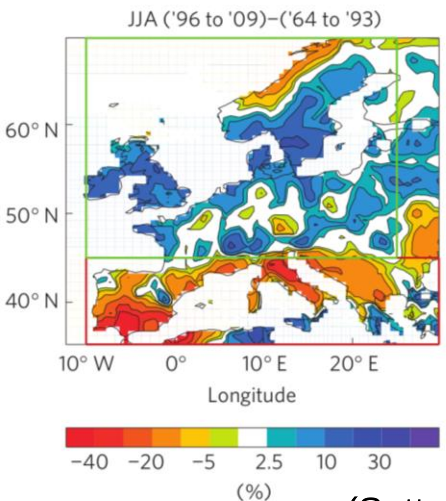
Can we use those information to predict the future?

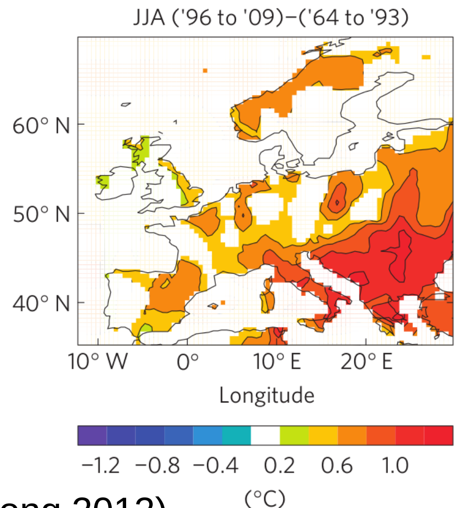
➢ **It depends of what drive the AMV and whether models can simulate it…**

Thank you!

AMV climate impacts

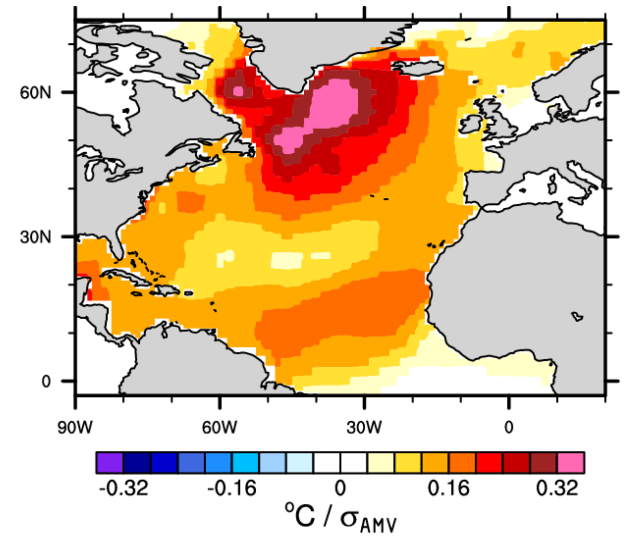
➢ **Impacts on Europe and Mediterranean region during summer (JJA)**

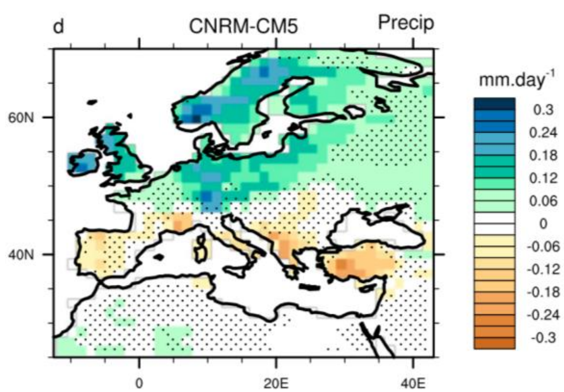


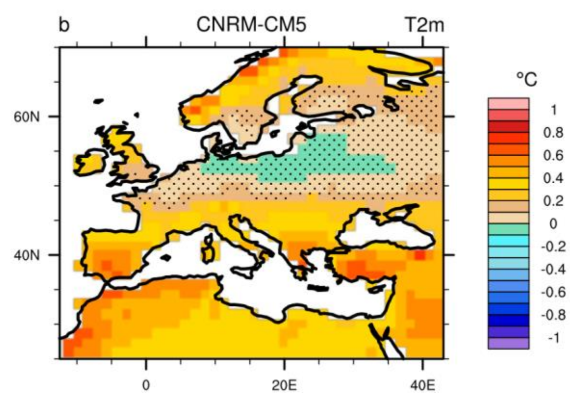


(Sutton and Dong 2012)

AMV pattern







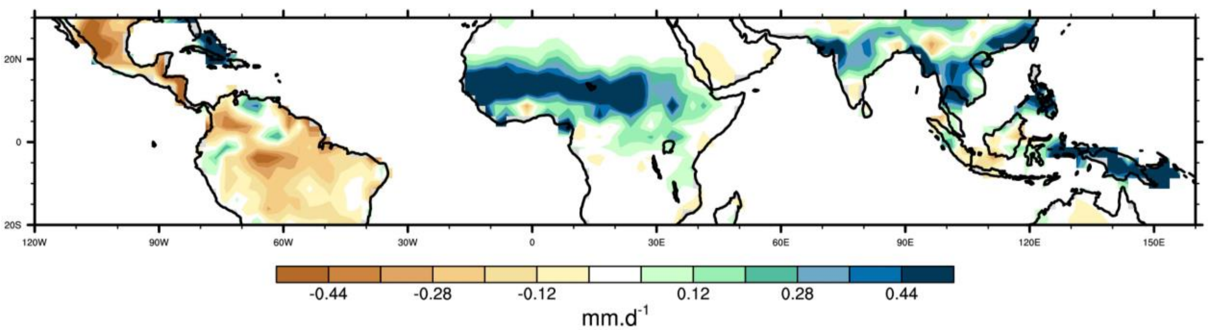
(Qasmi et al. 2021)

Sutton and Hodson 2005; Kushnir and Stein 2010; Boé and Habbets 2014

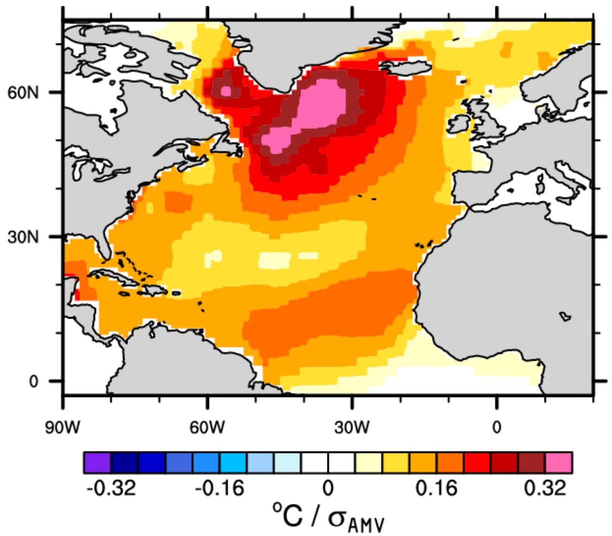
AMV climate impacts

- **Impacts on tropical precipitation**

NOAA_PrecL - JJAS



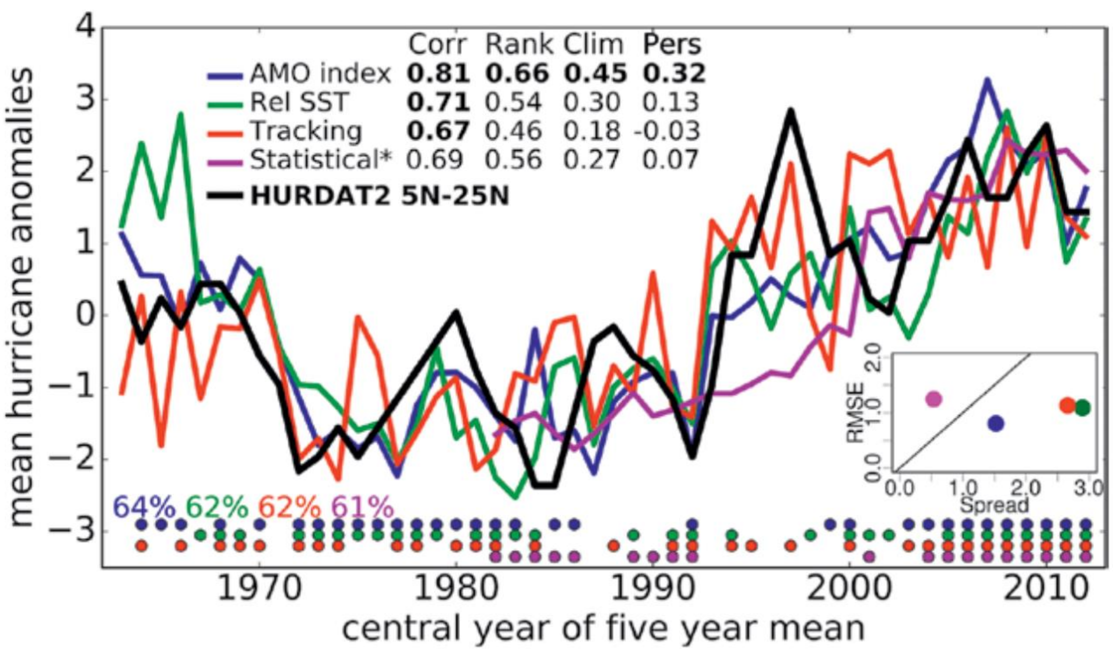
AMV pattern



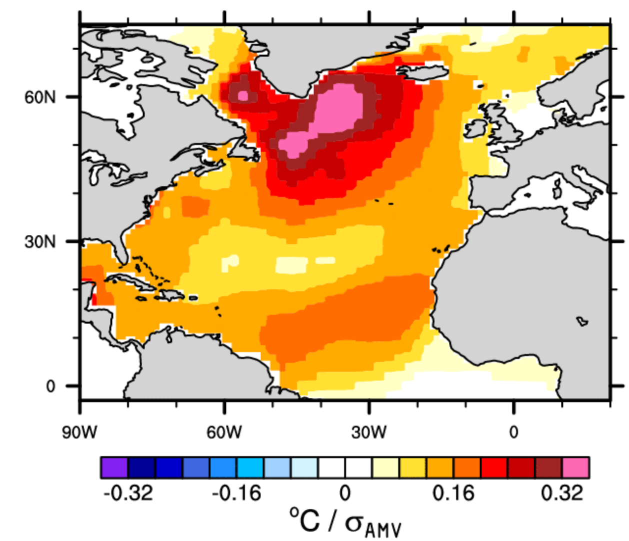
Folland et al. 2001; Zhang and Delworth 2006; Mohino et al. 2011; Wang et al. 2012; Martin and Thorncroft 2014; Krishnamurthy and Krishnamurthy 2015; Monerie et al. 2019

AMV climate impacts

- **Impacts on tropical cyclone activity**



AMV pattern



(Caron et al. 2018)

AMV impacts predictability

Annual SST / T2m prediction skill score

$$1 - \frac{RMSE_{INI}}{RMSE_{clim}}$$

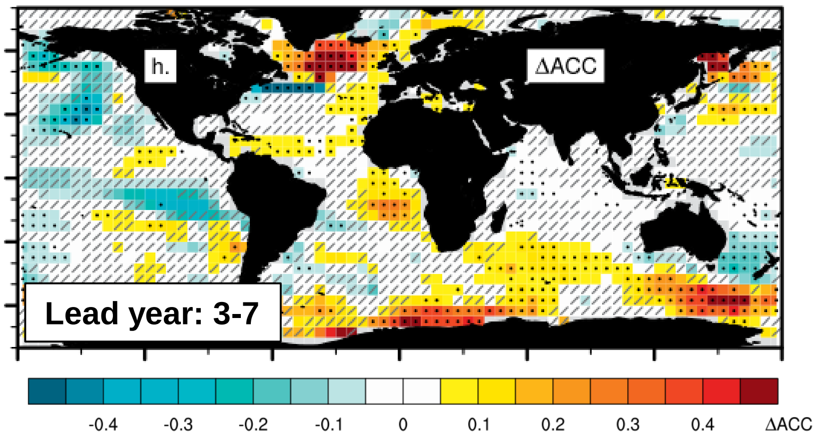
Lead year: 2-5

x10^{-2}

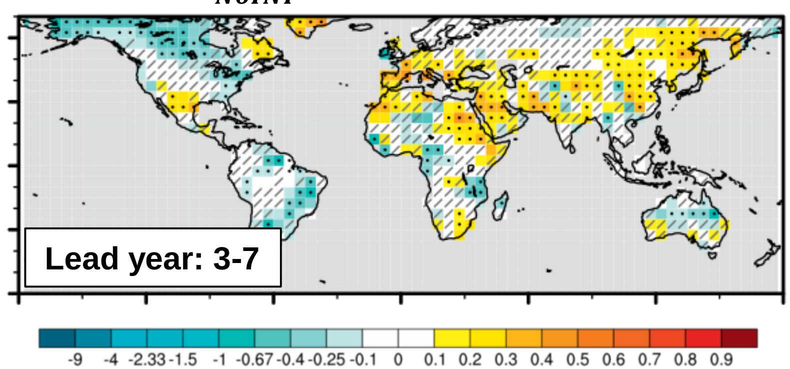
$$\frac{RMSE_{INI}}{RMSE_{NoINI}}$$

Lead year: 2-5

$\Delta ACC = ACC_{INI} - ACC_{NoINI}$



$$1 - \frac{RMSE_{INI}}{RMSE_{NoINI}}$$



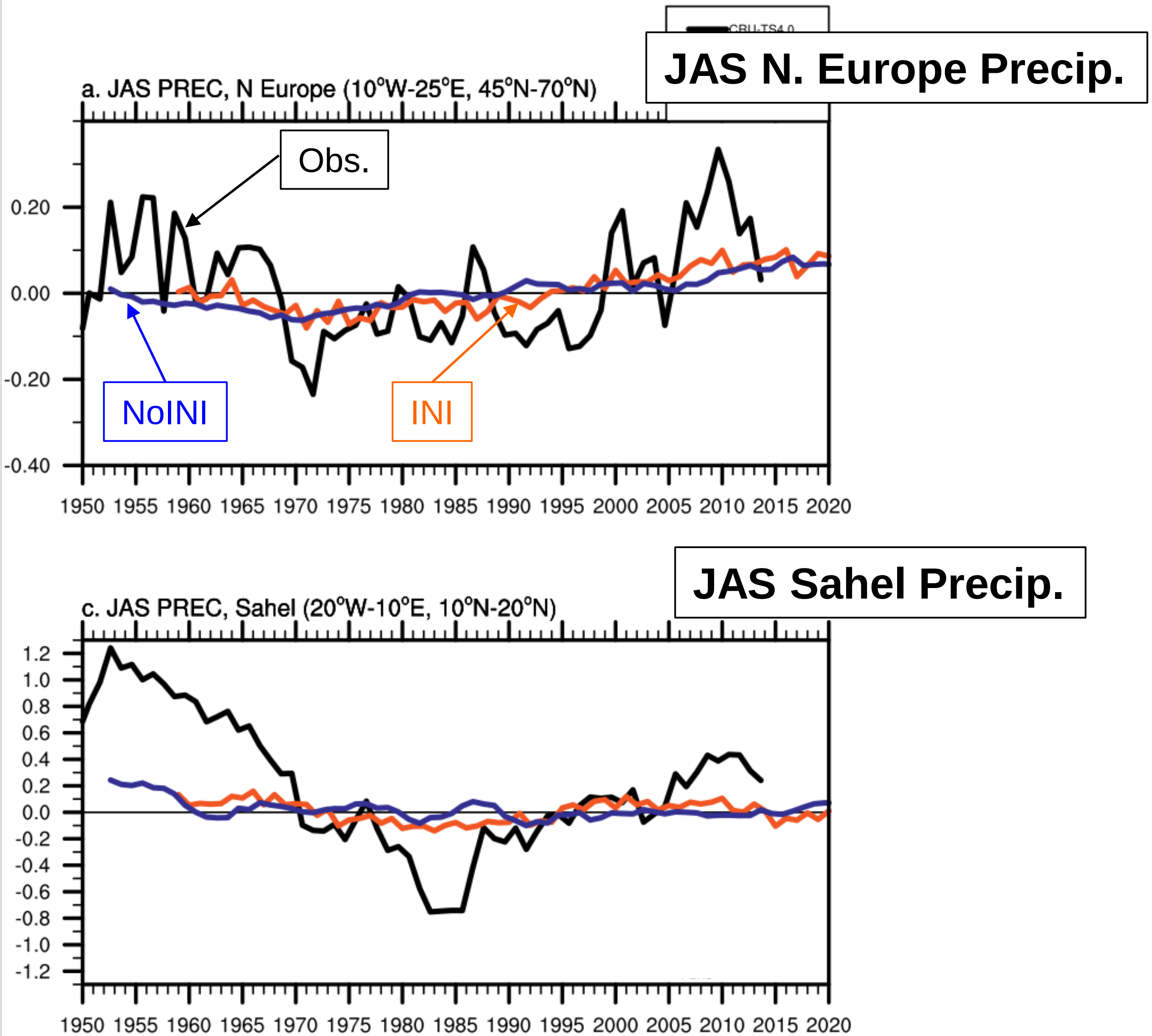
The North Atlantic is the most predictable region at decadal timescale but no skill for its teleconnections

➔ Signal to noise problem?

(Doblas-Reyes et al. 2013)

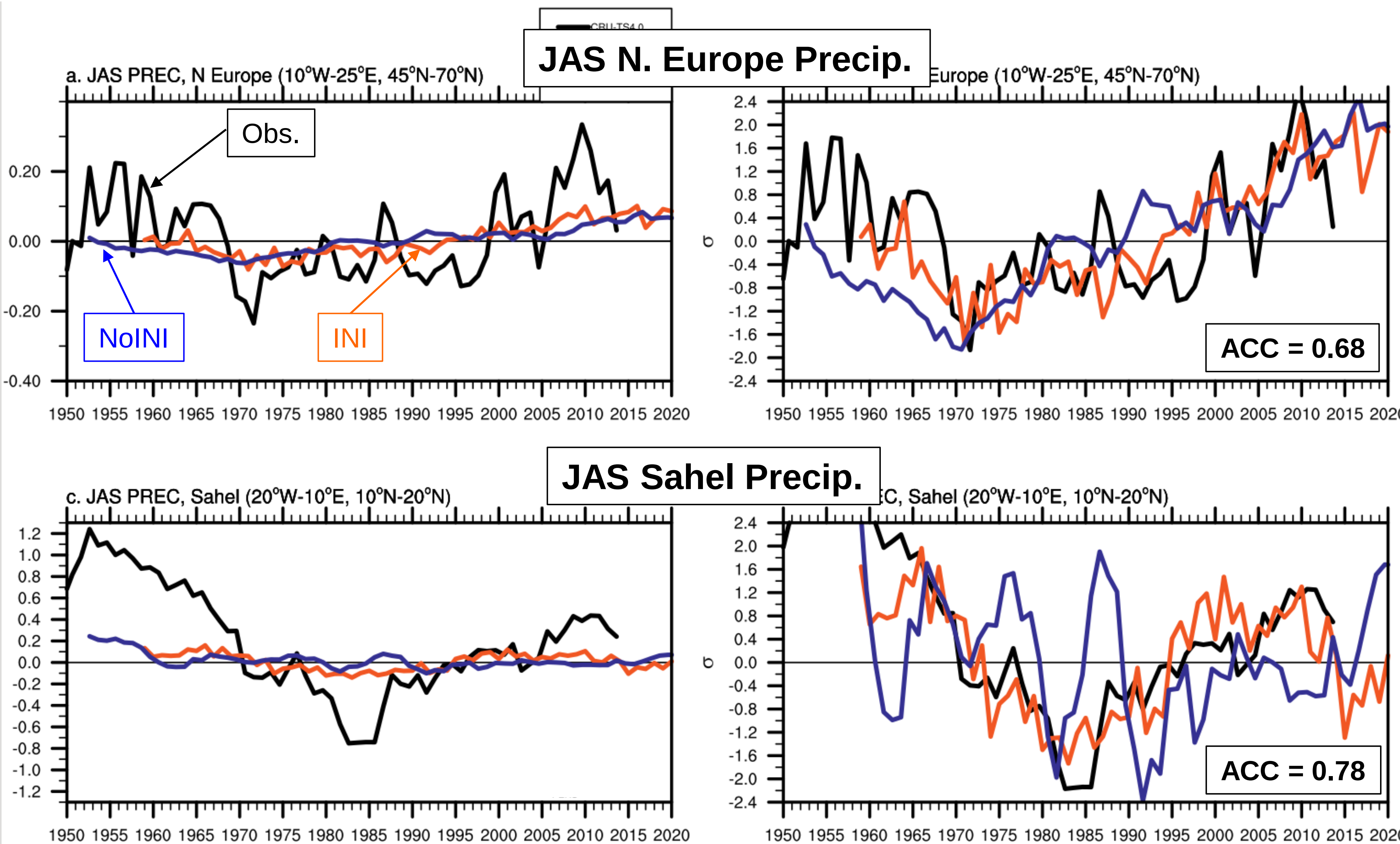
(Yeager et al. 2018)

Predictability of the AMV and its impacts



(Yeager et al. 2018)

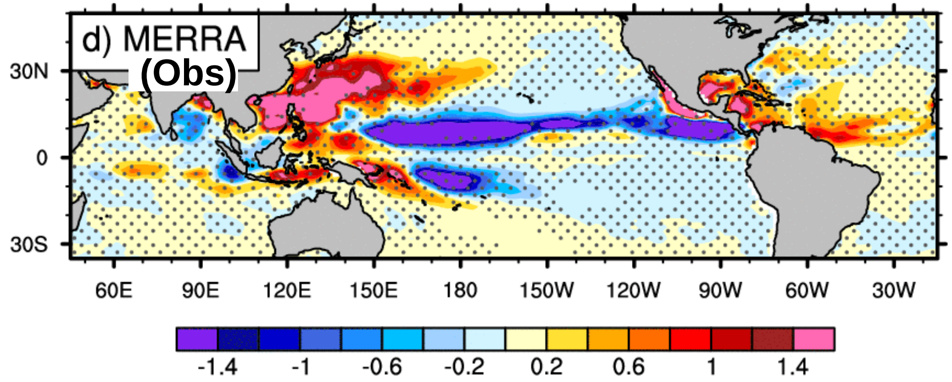
Predictability of the AMV and its impacts



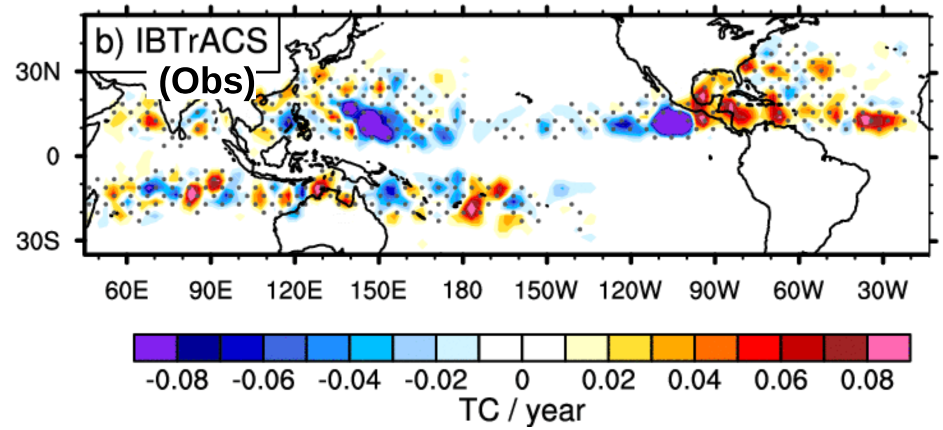
(Yeager et al. 2018)

AMV impacts on Tropical Cyclones

MJJASON GPI AMV+ - AMV-



MJJASON Tropical Cyclone Genesis



Obs = 1996-2011 vs 1980-1995

GPI = Genesis Potential Index (e.g., Camargo et al. 2007)

➔ empirical formula linking large scale conditions and TC formation

$$\boldsymbol{GPI} = \left|10^5 \eta\right|^{3/2} \left(\frac{\mathcal{H}}{50}\right)^3 \left(\frac{V_{\mathrm{pot}}}{70}\right)^3 (1 + 0.1 V_{shear})^{-2}$$

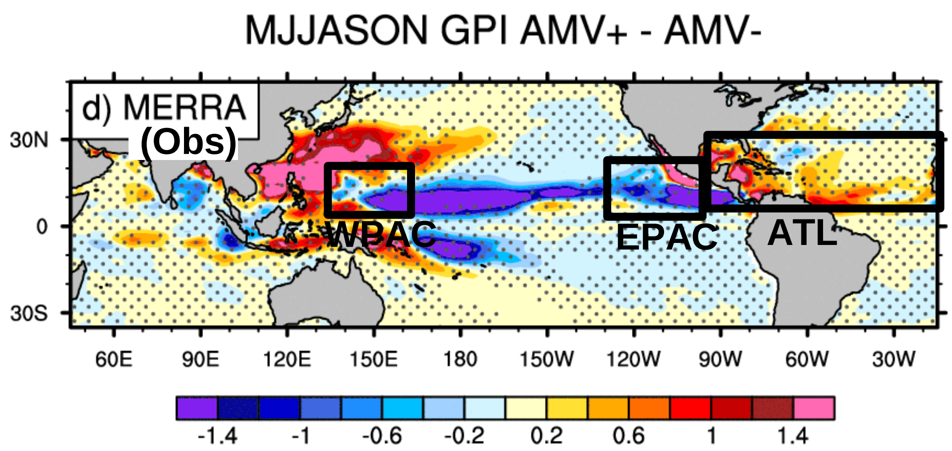
Vorticity (850hPa)

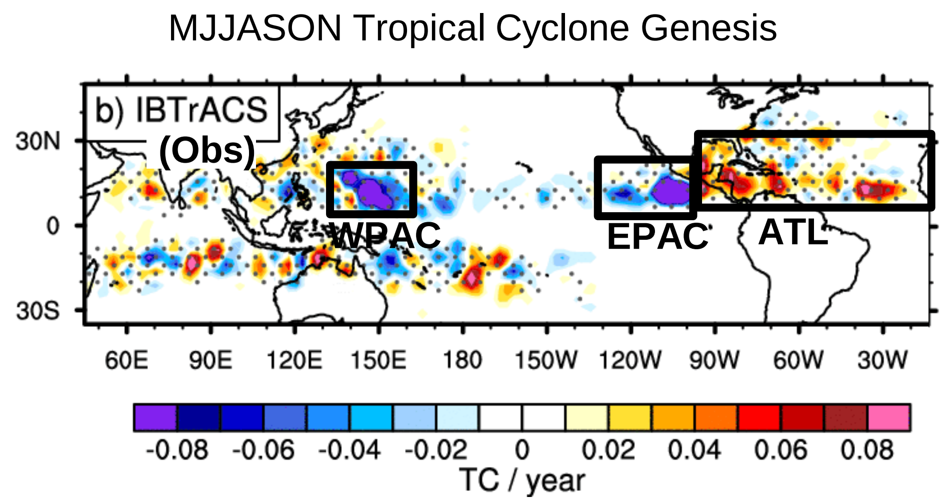
Relative Humidity (700hPa)

Wind Max
f(SST, Atmo. Stability)

Vertical Wind Shear

AMV impacts on Tropical Cyclones





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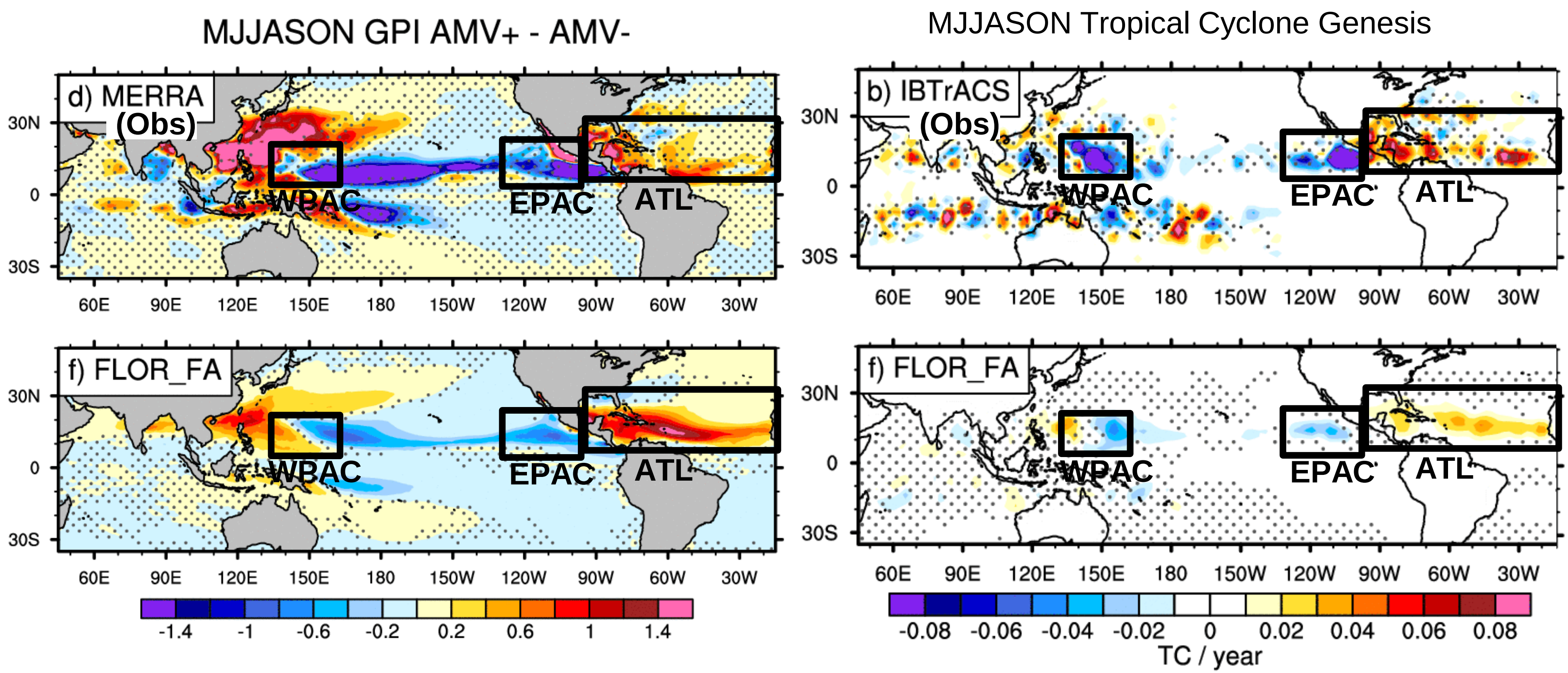
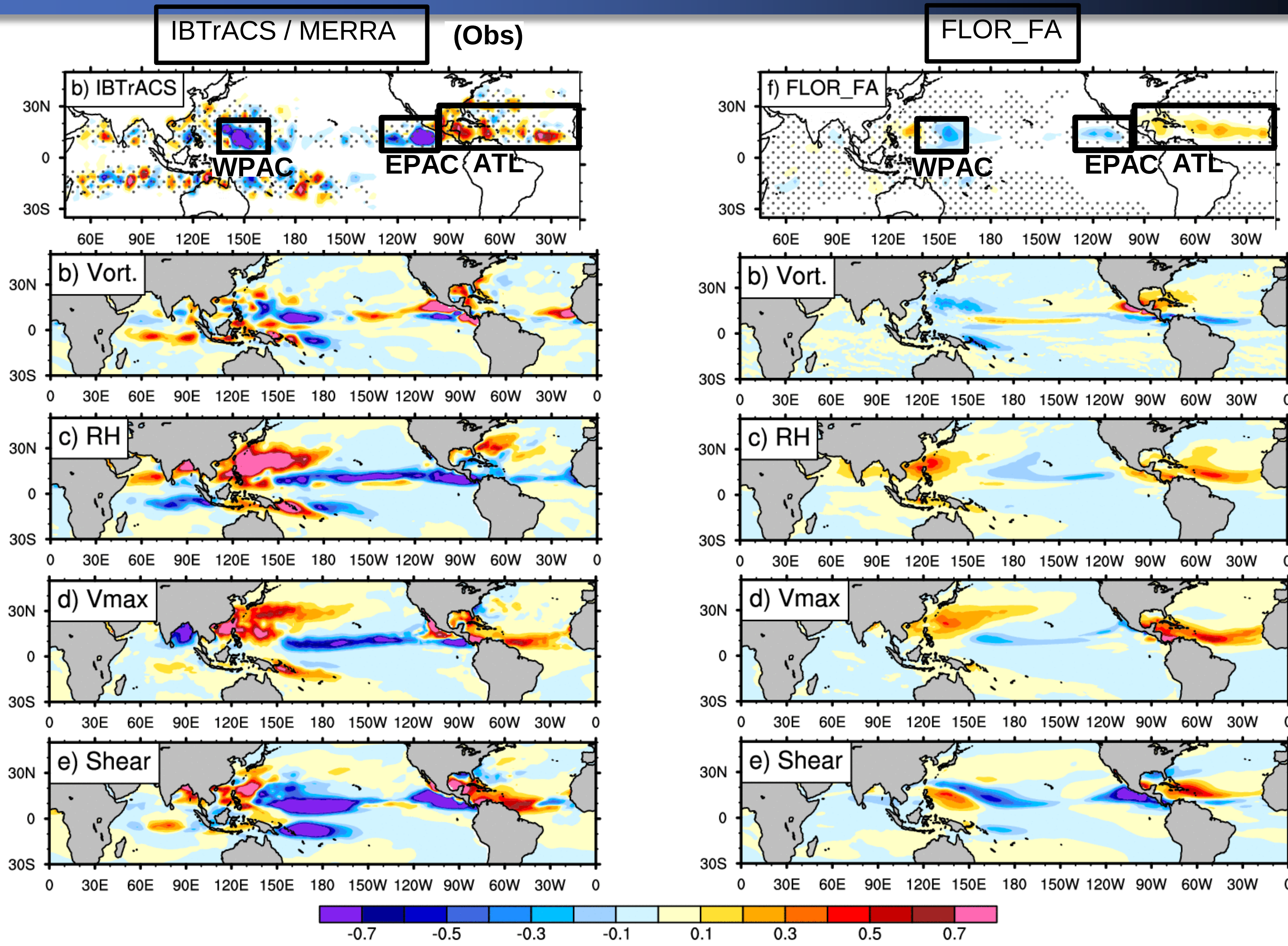
AMV impacts on Tropical Cyclones

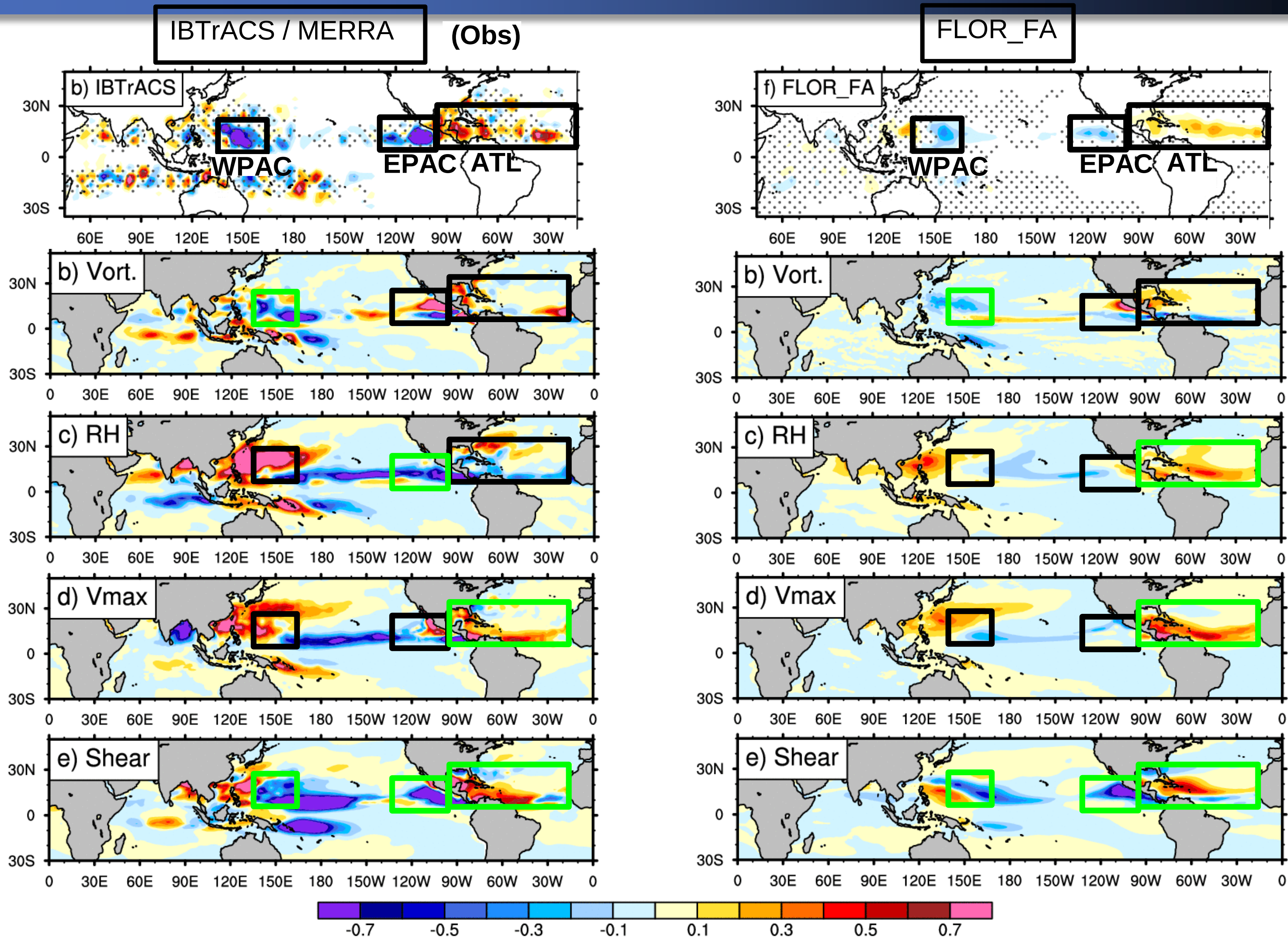


GPI = Genesis Potential Index

AMV impacts on Tropical Cyclones



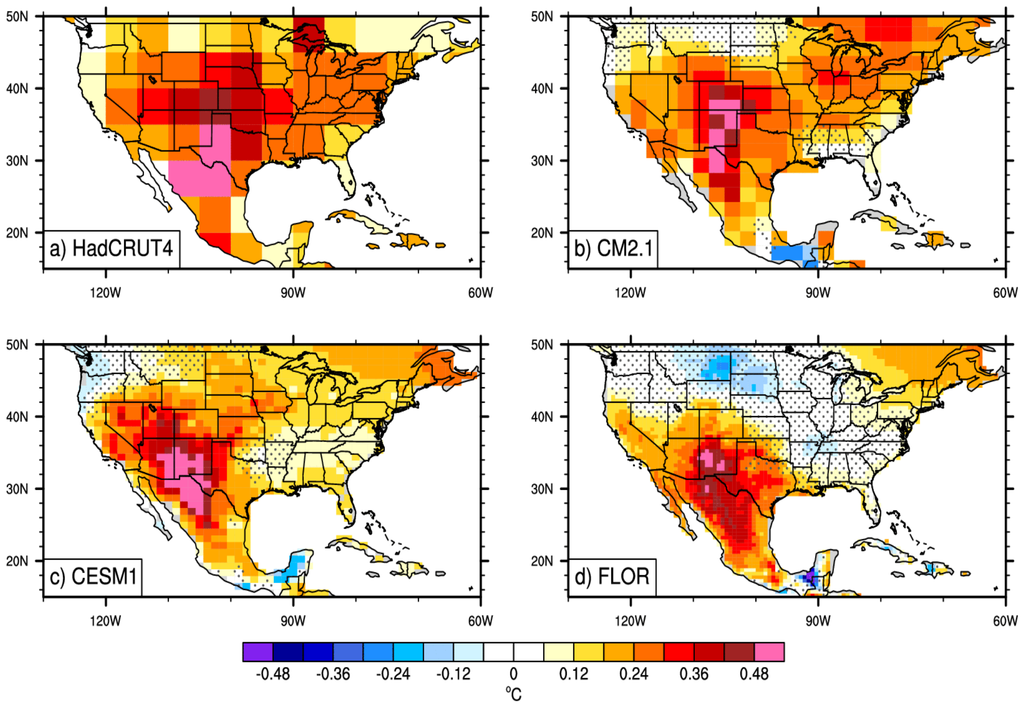
AMV impacts on Tropical Cyclones

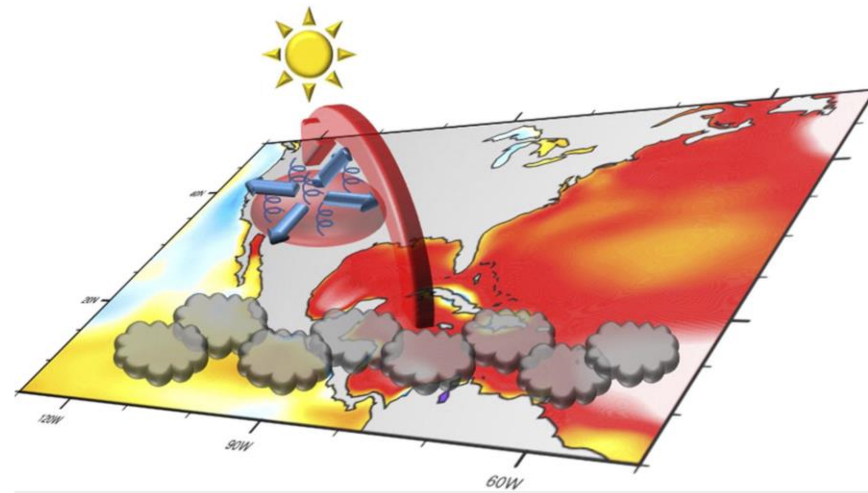


AMV impacts on North American and Euro-Mediterranean summer climate

AMV impacts on North America

June-July-August 2-meter air temperature AMV+ - AMV-





June-July-August Heat Wave days AMV+ - AMV-