Using a hierarchy of models to understand wave-mean flow interactions

Christopher G. Fletcher
Dept. of Geography & Environmental Management,
Interdisciplinary Centre on Climate Change (IC^3),
University of Waterloo, Ontario, Canada.

<u>In collaboration with:</u>

Paul J. Kushner
Dept. of Physics, University of Toronto.

Karen L. Smith
Lamont-Doherty Earth Observatory.

Christophe Cassou
CNRM-CERFACS, Toulouse, France.

Ivan Minokhin, William Xu
Graduate students at University of Waterloo.

WATERLOO
ENVIRONMENT

Introduction

- The wintertime Northern Annular Mode (Thompson and Wallace 2000) (NAM) is a coupled stratosphere-troposphere mode of variability influenced by wave-driving from the troposphere
- We would like to forecast the sign/amplitude of the seasonal mean NAM to increase seasonal predictability at the surface, but different surface forcings are associated with opposite-signed NAM responses:

Surface processes affecting the NAM

- The wintertime Northern Annular Mode (Thompson and Wallace 2000) (NAM) is a coupled stratosphere-troposphere mode of variability influenced by wave-driving from the troposphere

(N)AO / NAM— (weak vortex)	Reference	(N)AO / NAM+ (strong vortex)	Reference
El Nino	(Garfinkel and Hartmann 2008)	La Nina	(Iza et al. 2016)
Indian Ocean cooling (?)		Indian Ocean warming	Hurrell et al. (2004)
		West Pacific warming	Nishii et al. (2010)
Eurasian surface cooling	(Cohen & Entekhabi 1999)		
Arctic sea ice loss	(Kim et al. 2014)		

Research question

Q: What explains the sign/amplitude of the winter mean NAM response to surface forcing?

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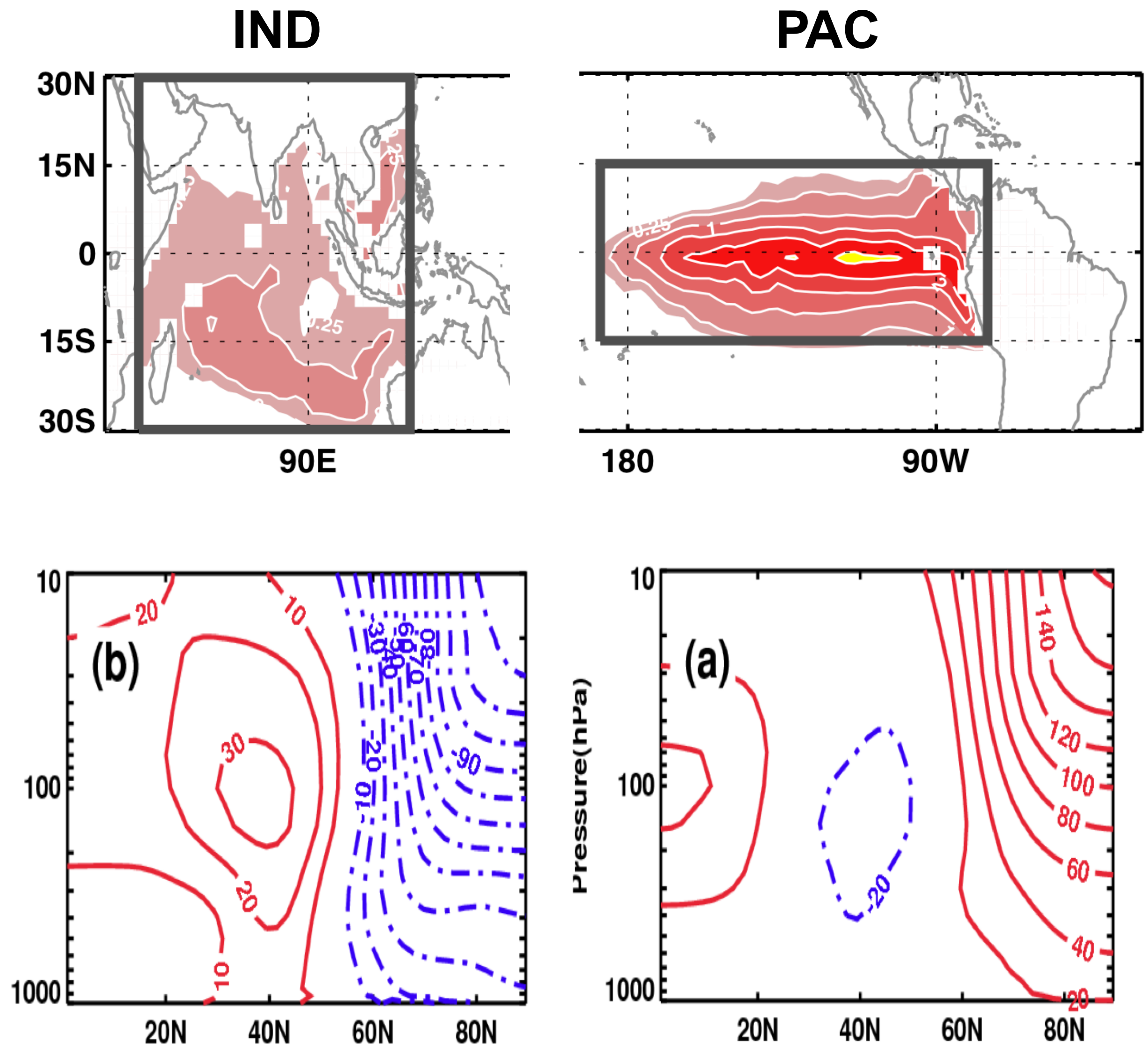
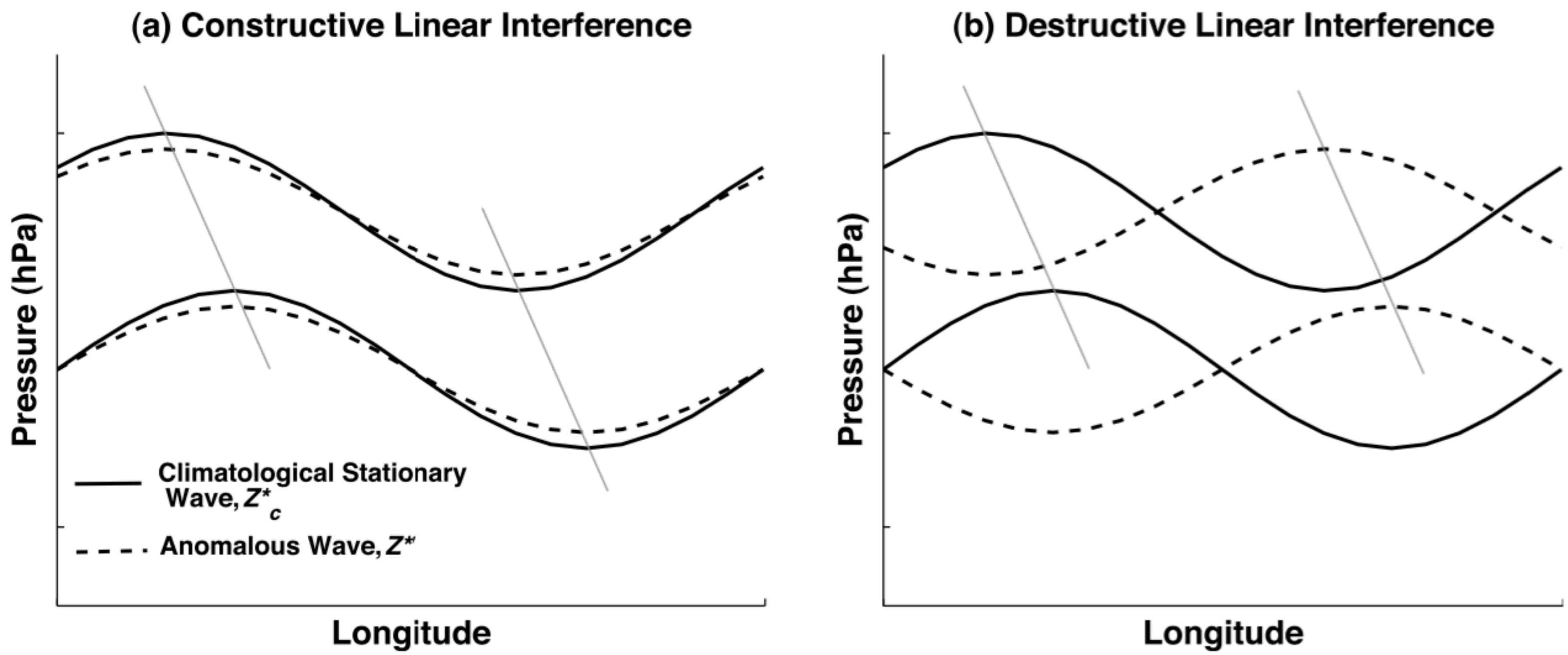
The NAM response to tropical warming

- In the GFDL-AM2.1 AGCM, we find opposite-signed JF mean strat-trop NAM response to imposed SST warming in the Indian vs Pacific ocean basins.



 Fletcher and Kushner **[2011]**

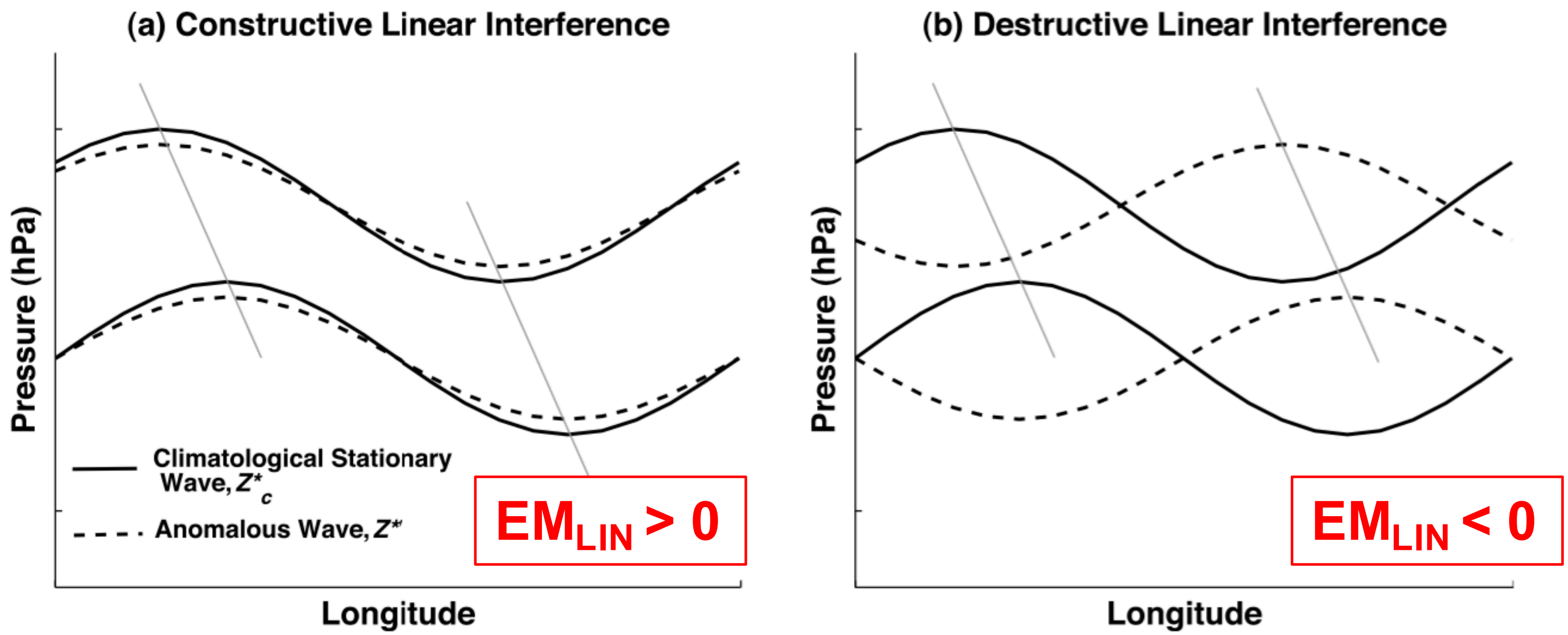
Theory: linear interference



- Zonal mean circulation anomalies in the polar stratosphere are driven by EP-flux divergence of planetary waves, which is proportional to v*T*
- $\overline{v^*T^*} > 0$ = NAM– and $\overline{v^*T^*} < 0$ = NAM+
- So what determines the sign of v*T*?

***Smith and Kushner* [2012]**

Theory: v*T* decomposition



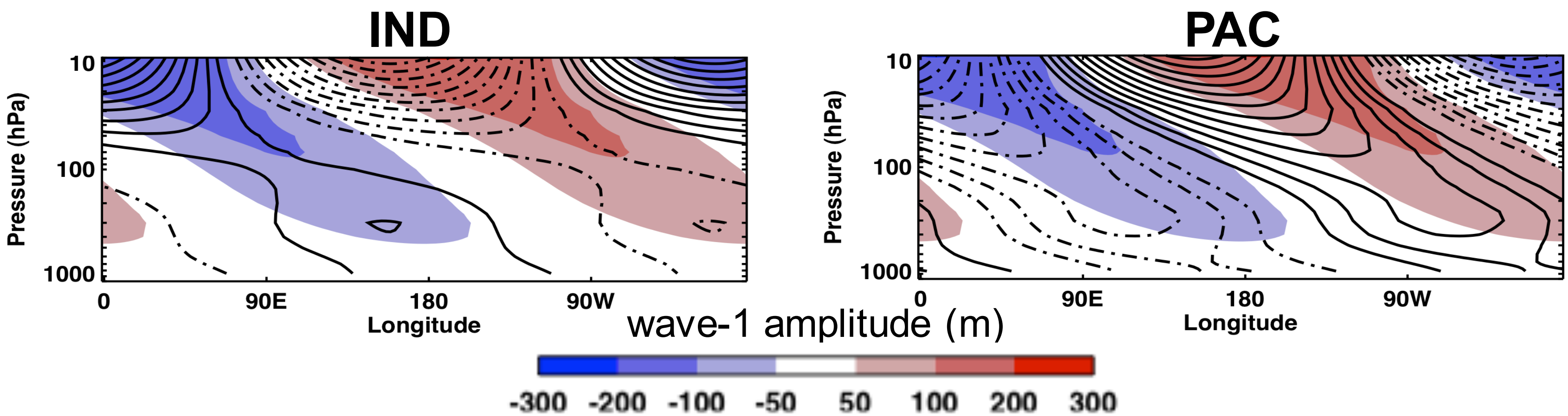
$$\text{TOTAL} = \text{EM}_{\text{LIN}} + \text{EM}_{\text{NL}} + \text{FL}$$

$$\Delta\{\langle v^* T^* \rangle\} = \{v_c^* \Delta\langle T^* \rangle\} + \{\Delta\langle v^* \rangle T_c^*\} + \{\Delta\langle v^* \rangle \Delta\langle T^* \rangle\} + \Delta\{\langle v^{*\prime} T^{*\prime} \rangle\}$$

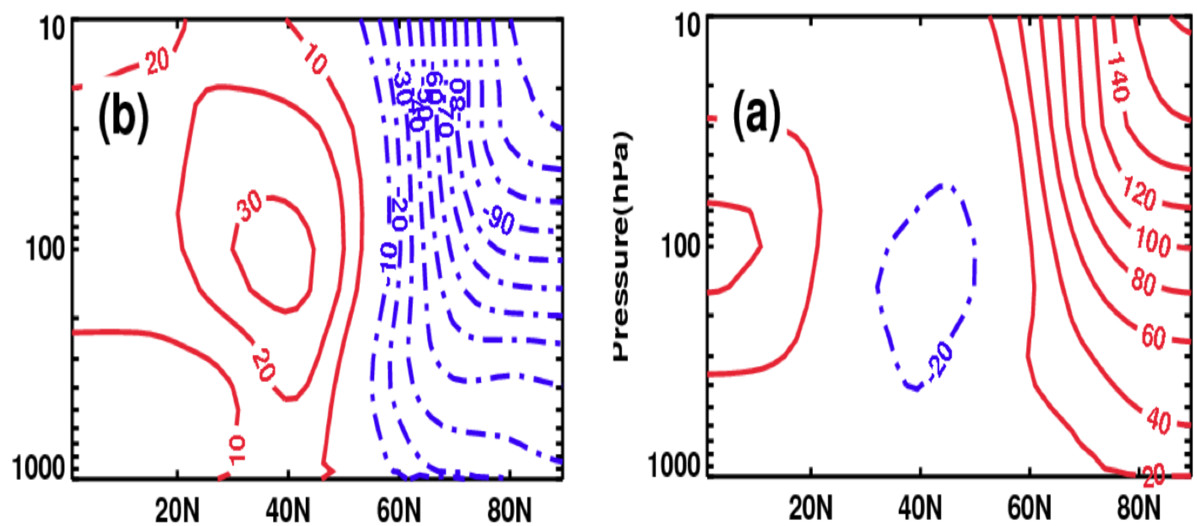
Ensemble mean	$<A>$	Ensemble eddy	A'
Zonal mean	$\{A\}$	Zonal eddy	A^*
Ctrl Climatological mean	A_c	Response (Pert – Ctrl)	ΔA

Fletcher and Kushner [2011]

Linear interference and the NAM

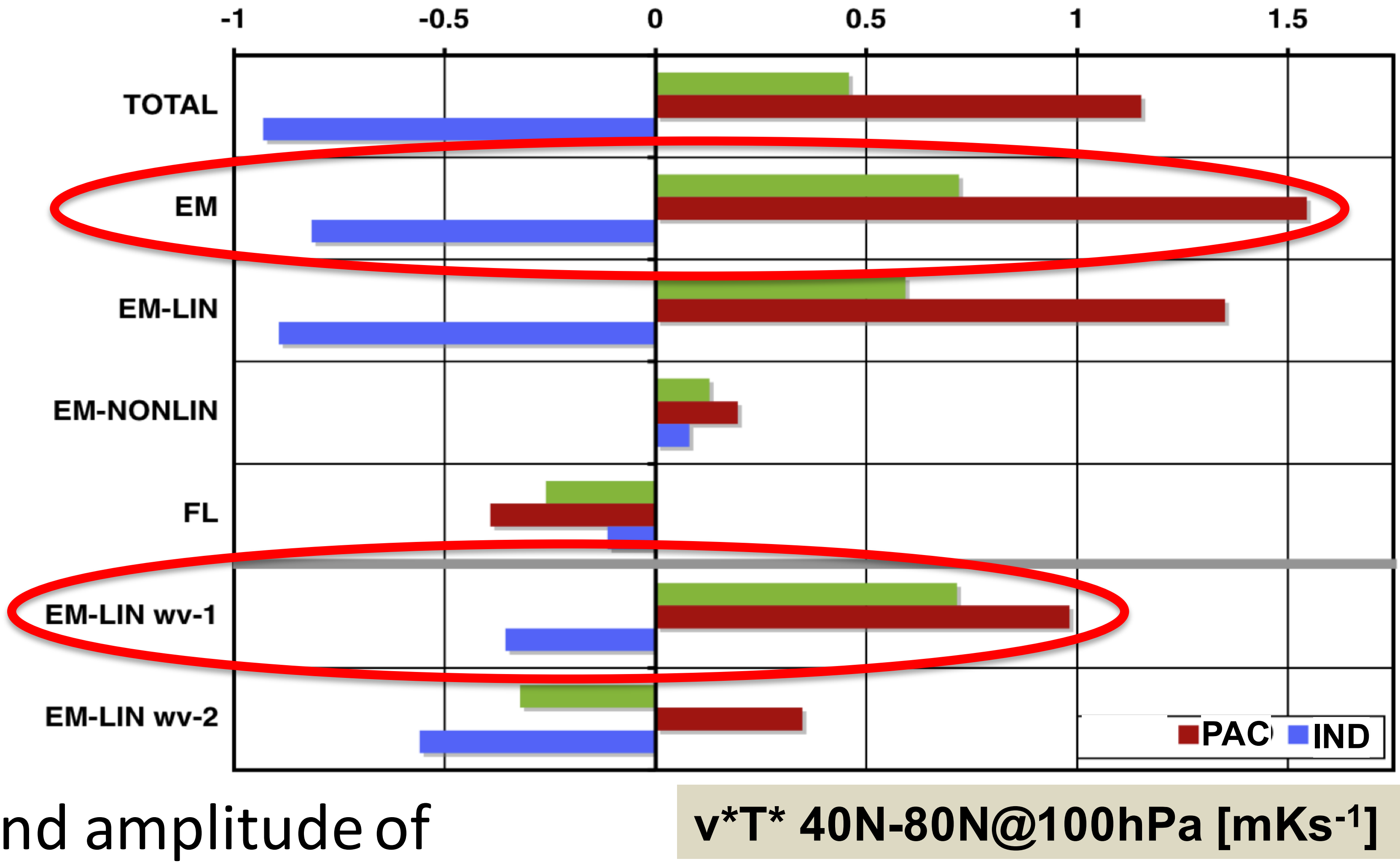


- Opposite phasing of zonal wave-1 response with the climatology



C.G. Fletcher: Modeling Hierarchies Workshop, Princeton, NJ. Nov 2-4, 2016. ***Fletcher and Kushner* [2011]**

Linear interference and the NAM



The sign and amplitude of the NAM response are largely explained by EM_{LIN} from zonal wave-1.

Fletcher and Kushner [2011]

Linear interference and the NAM

Karen Smith showed the same thing in 2010 using the GFDL HS model with a stratosphere and imposed Eurasian surface cooling.

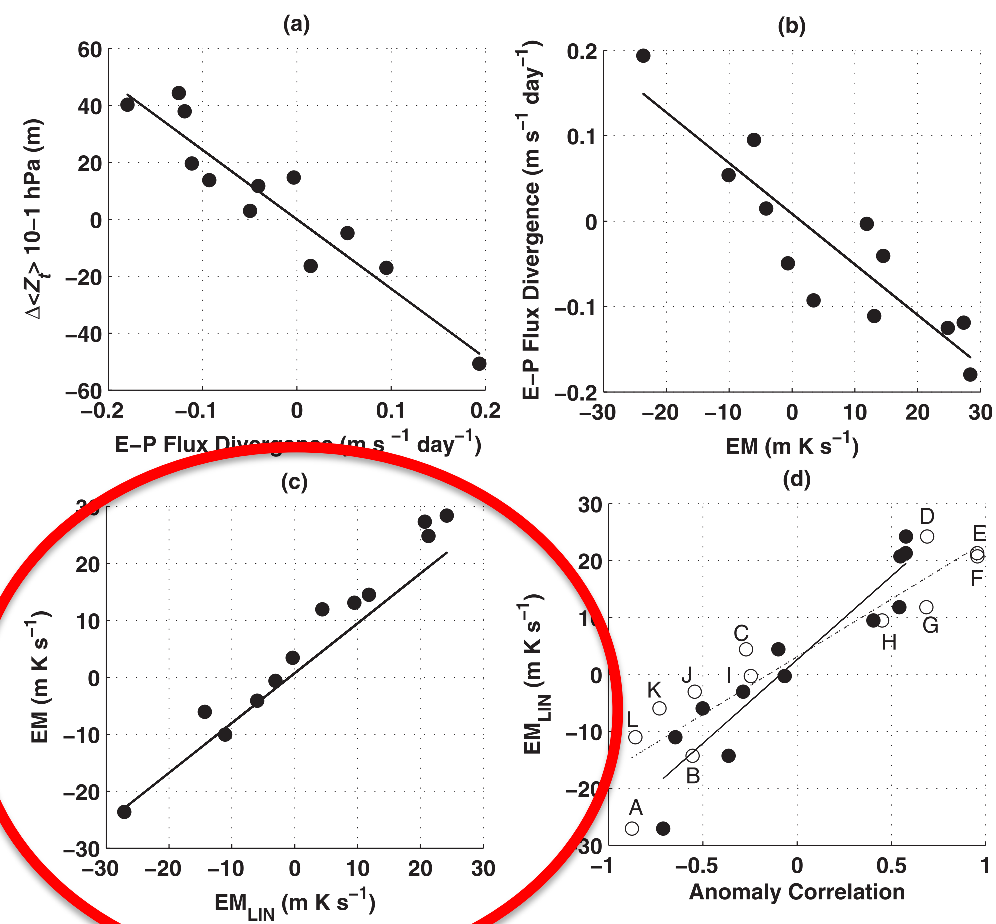
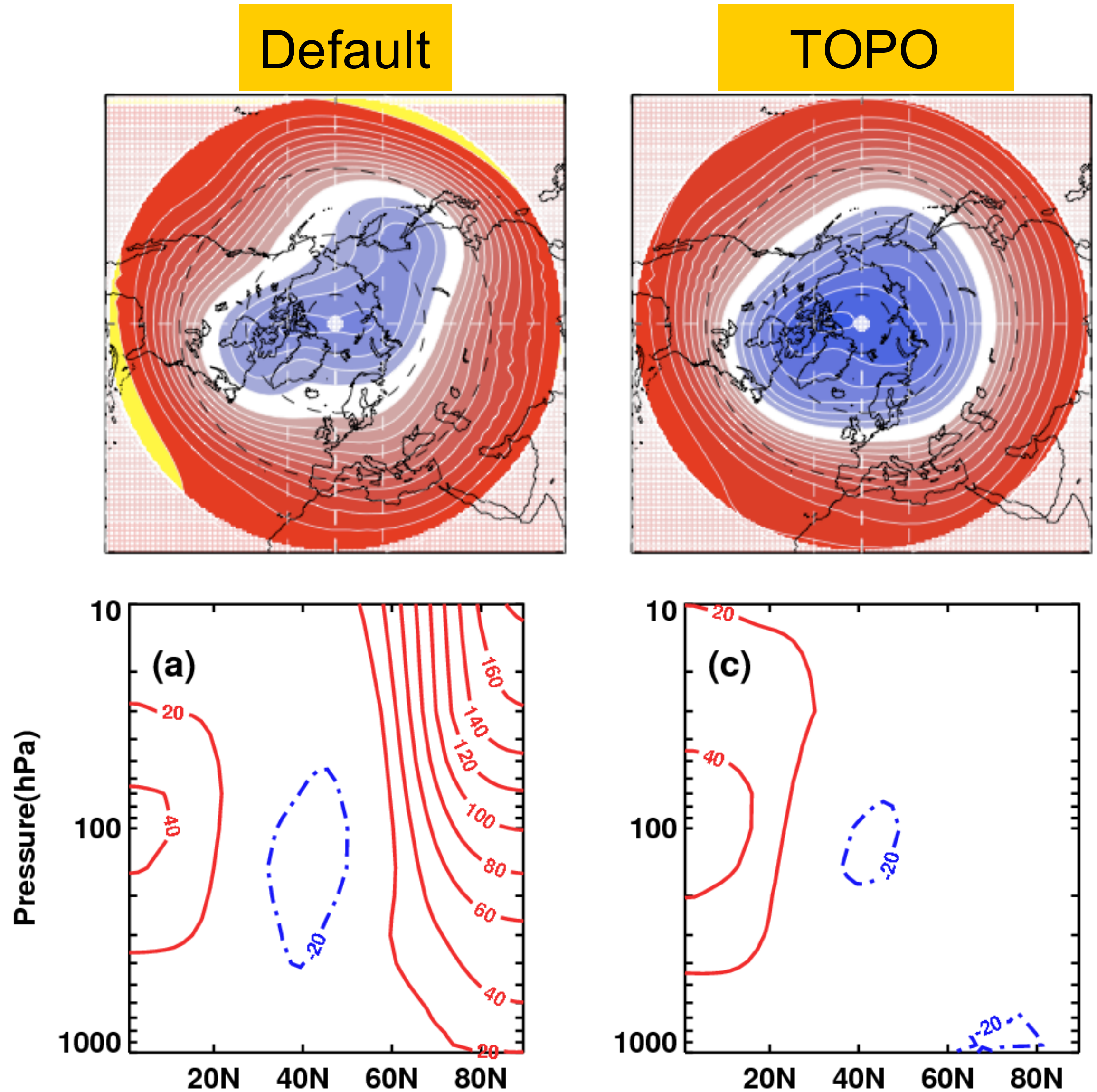


FIG. 6. Dependence of the SGCM response on forcing location (simulations A–L in Table 1). (a) The TOTAL E–P flux divergence response averaged over 40°–80°N, 10–1 hPa, and days 1–22 vs the 10–1-hPa $\Delta\langle Z_t\rangle$ averaged over the polar cap and over days 10–40. (b) $\Delta\{\langle v^*\rangle\langle T^*\rangle\}$ (EM) at 10 hPa, averaged over 40°–80°N, and cumulative to day 22 vs the E–P flux divergence response. (c) EM_{LIN} vs EM. (d) The all-wave (solid circles) and wave-1 (open circles) spatial correlation between $\Delta\langle Z^*\rangle$ and $\langle Z_c^*\rangle$ vs EM_{LIN}.

***Smith et al.* [2010]**

Idealized boundary forcing

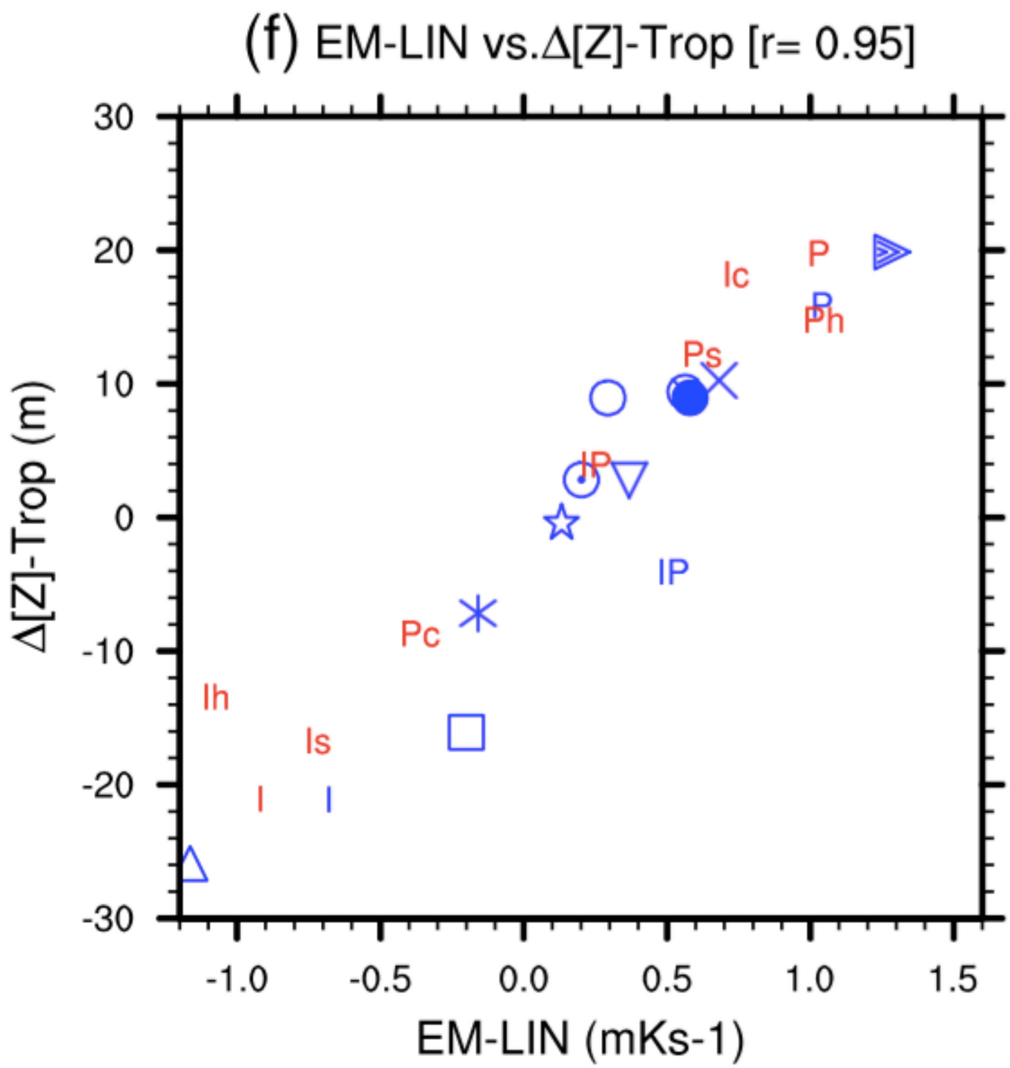
- TOPO: a full AGCM with idealized Pacific SST warming and perturbed (flattened) topography over Eurasia
- The NAM- response vanishes due to reducing wave-1 amplitude ("tuning out" linear interference so that v^*_c and T^*_c--> 0).



 ***Fletcher and Kushner* [2011]**

Sensitivity to AGCM configuration

- By adding another AGCM (CAM4) we showed that the linear interference framework is robust across physics schemes and various horizontal and vertical resolutions.



Fletcher and Kushner **[2013]**

Coupled ocean-atmosphere results

- In Fletcher and Cassou (2015) we used a 1000-yr free-running control simulation from a CMIP5-class ESM (CNRM-CM5) to examine the effects of ocean-atmosphere interaction and intraseasonal variability.
- We also performed ocean nudging to isolate independent sources of variability emerging from the Pacific and TIO basins

Coupled ocean-atmosphere results

- PAC (NAM-) comes from the canonical response to ENSO
- IND (NAM+) from internal variability over the TIO.
- Lin. interference suggests internal atmospheric variability over TIO (e.g. MJO) modulates ENSO teleconnections

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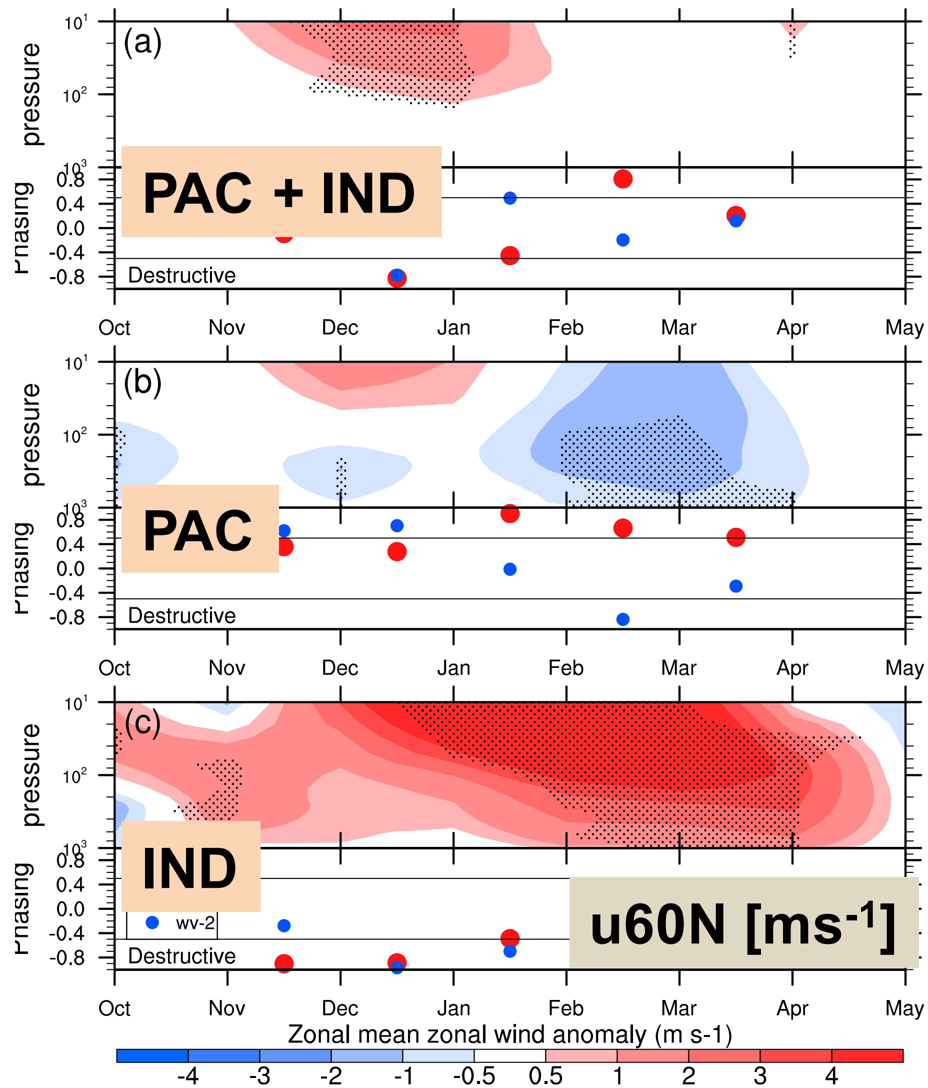
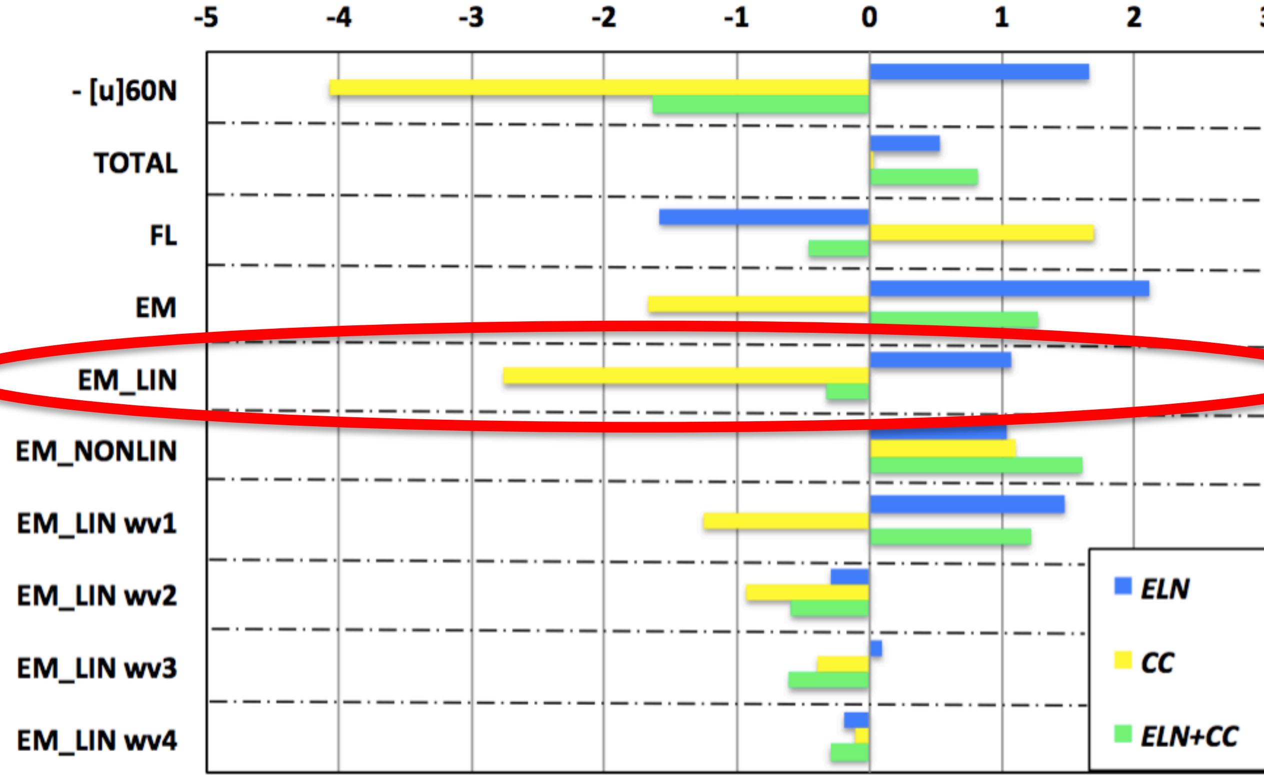


FIG. 4. Upper half of each panel shows the time–height cross section of the monthly zonal mean zonal wind anomalies at 60°N (color shading; m s^{-1}), with stippling indicating areas where the wind anomalies are significantly different from zero ($p < 0.05$) for (a) P_aI_a, (b) P_aI_n, and (c) P_nI_a. Lower half of each panel shows the pressure-weighted correlation r_{zp} (see section 2d) for wave 1 (red) and wave 2 (blue). A threshold of $r_{zp} = 0.5$ ($r_{zp} = -0.5$) is used to denote months as having constructive (destructive) linear interference.

***Fletcher and Cassou* [2015]**

Linear Interference & Climate change



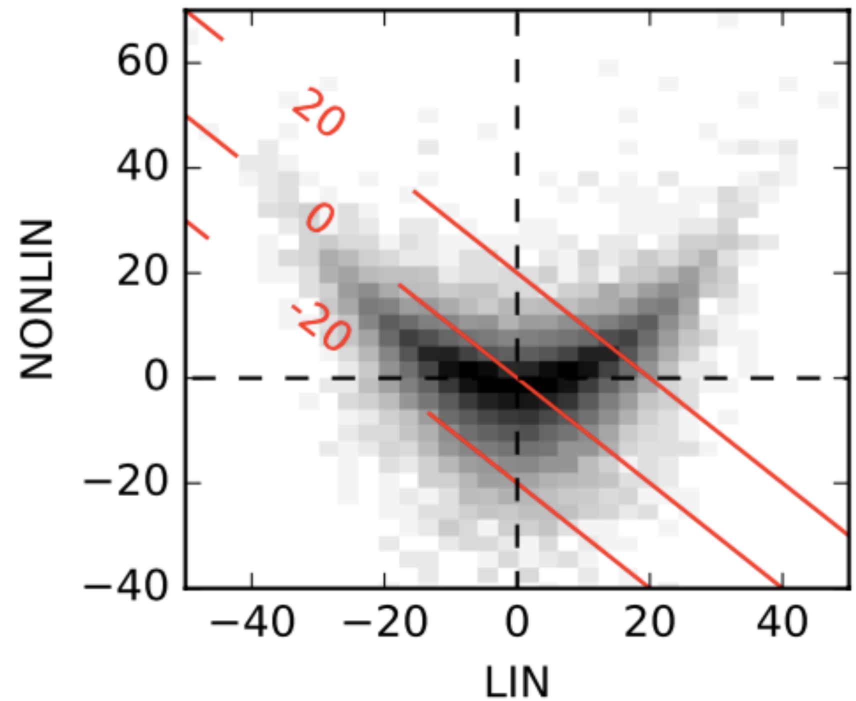
- We compared interannual variability (ELN) and climate change (CC).
- In GFDL-AM2.1 linear interference in CC is complicated by radiative-dynamical forcing/responses.
- But linear interference is still important in CC: $EM_{LIN} < 0$ with contributions from waves 1-4. But overall the picture is much less clear, and with greater intermodel variability.

***Fletcher and Minokhin* [2015]**

Recent/ongoing work

- Watt-Meyer and Kushner (in prep): observed skewness of v*T* distribution results from nonlinear interaction between EM_{LIN} and EM_{NL}.

- Applications to:
  – tropical-extratropical teleconnections in seasonal-to-decadal predictability (Molteni et al. 2015)
  – transient eddy variability and its connections to tropical convection and Arctic warming (Goss et al. 2015).



*Toy statistical model results for linear interference. Shading shows the number of DJF days (log scale). Red lines indicate constant TOTAL v*T*. Figure courtesy of Oliver Watt-Meyer (UofT).*

Conclusions and reflection

- Linear interference of planetary waves explains the sign/amplitude of the NAM response to multiple surface perturbations
- Robust to model configuration, details of perturbation, (time scale)
- We, like many others here, employ a "hierarchy of opportunity" from the models in our toolkit. Are there opportunities to design/create more appropriate tools?

References

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The end.

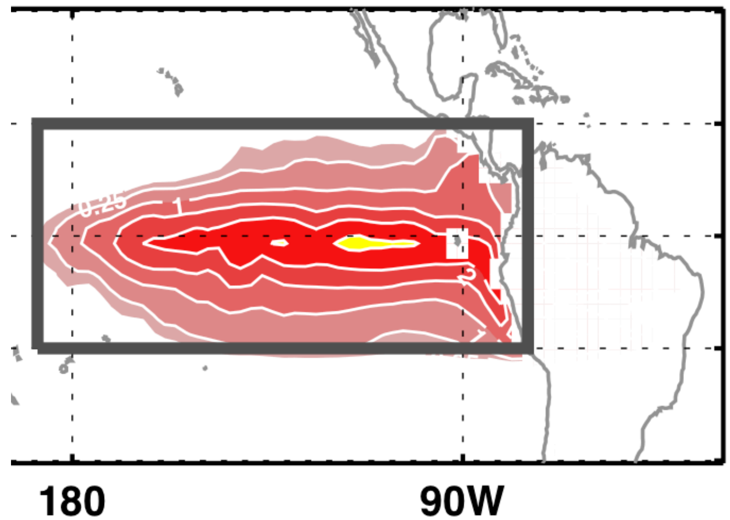
AGCM experimental design

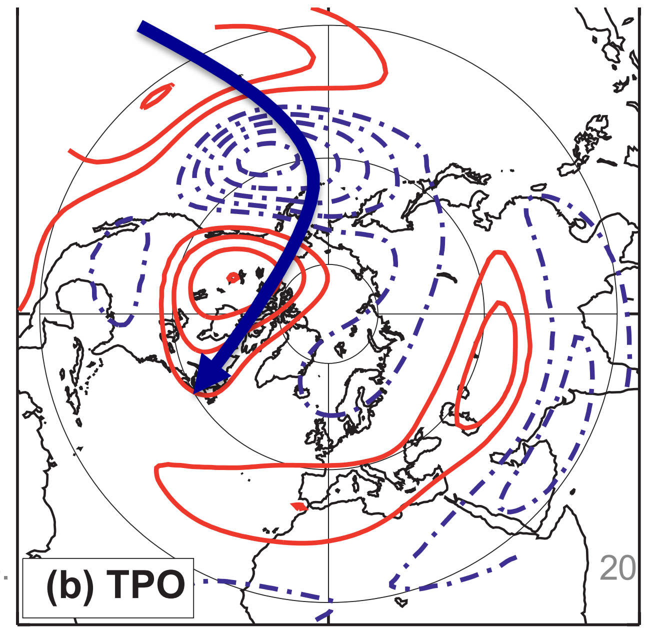
Experimental Design:
CTRL: 100 years of GFDL-AM2 forced by repeating seasonal cycle of SST/ice; fixed 1990 atmospheric composition.
PERT: same as CTRL but with a fixed SST anomaly added to climatology.

$$\Delta X = X_{PERT} - X_{CTRL}$$

All plots show JF mean ensemble mean responses from N=100 realizations of each experiment.

Pacific Warming

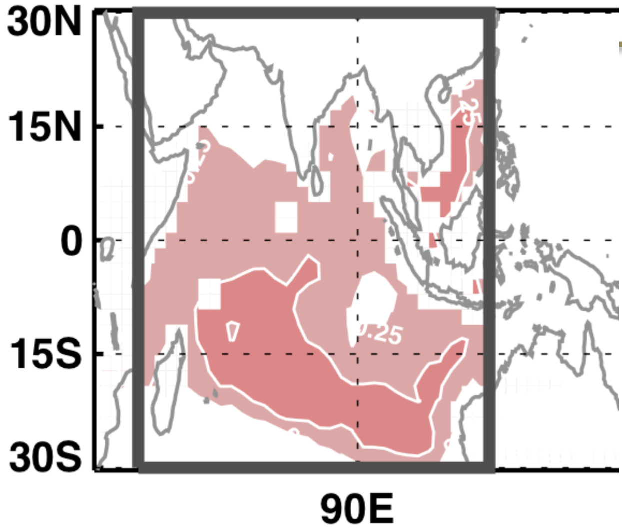


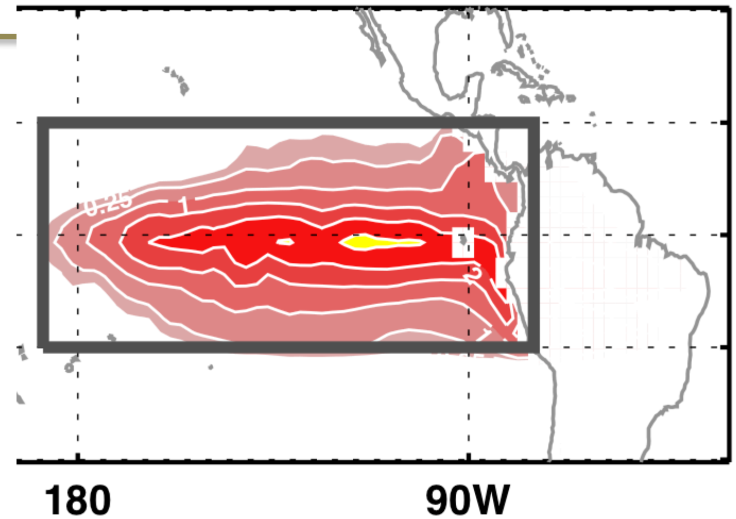


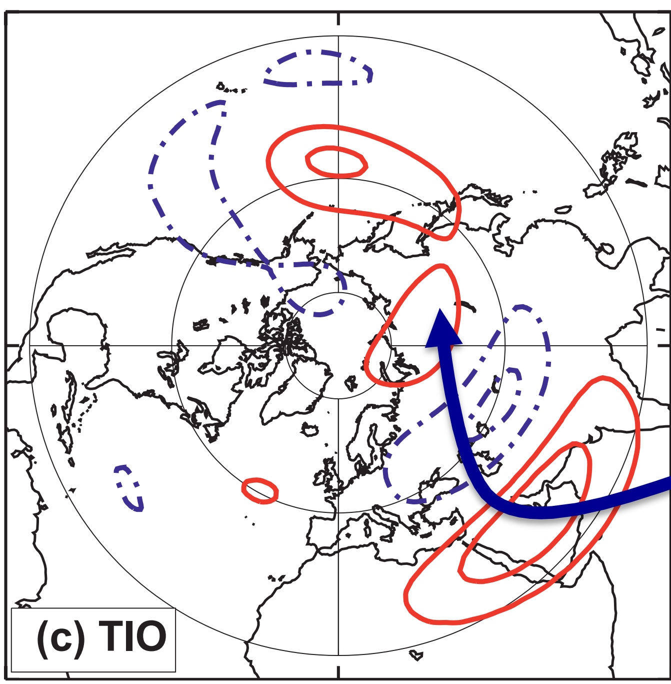
Fletcher and Kushner [2011]

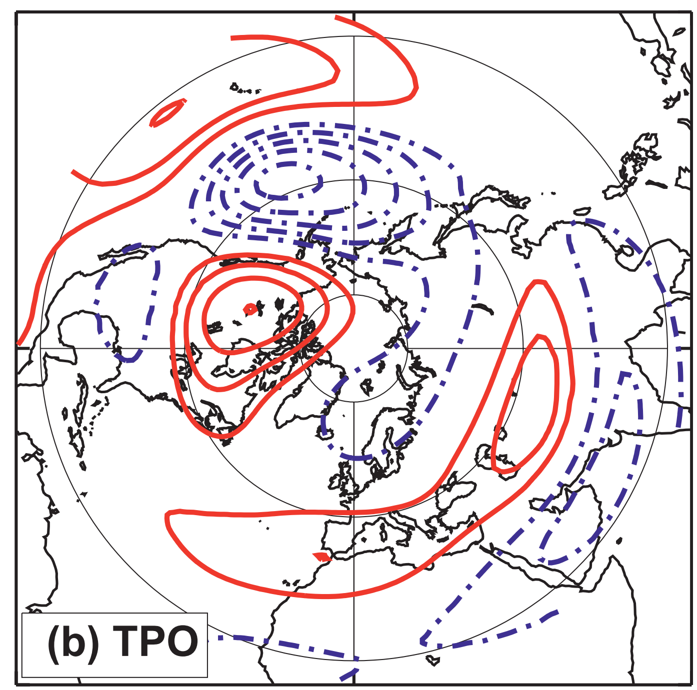
Indian Ocean Warming

Pacific Warming



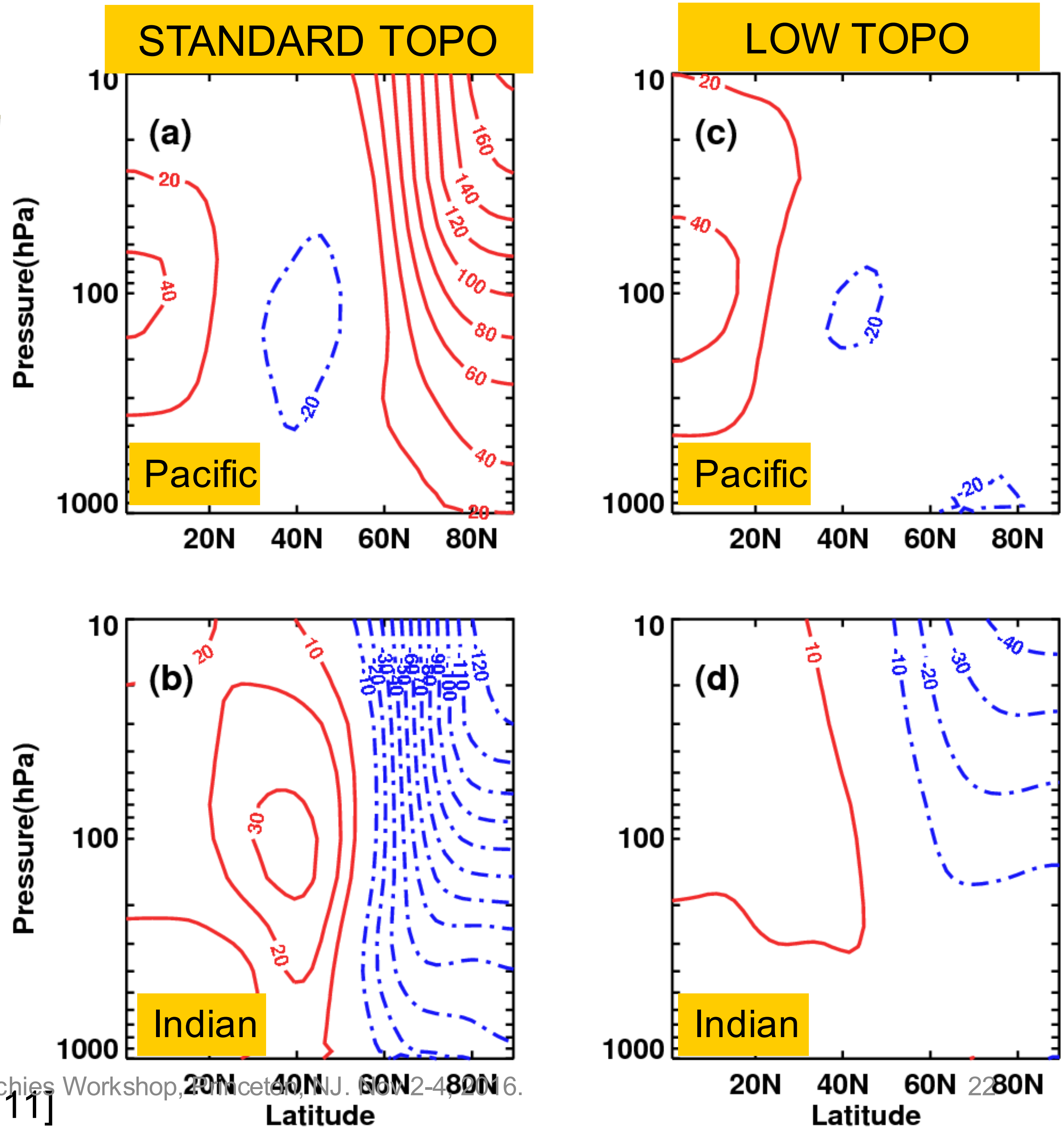






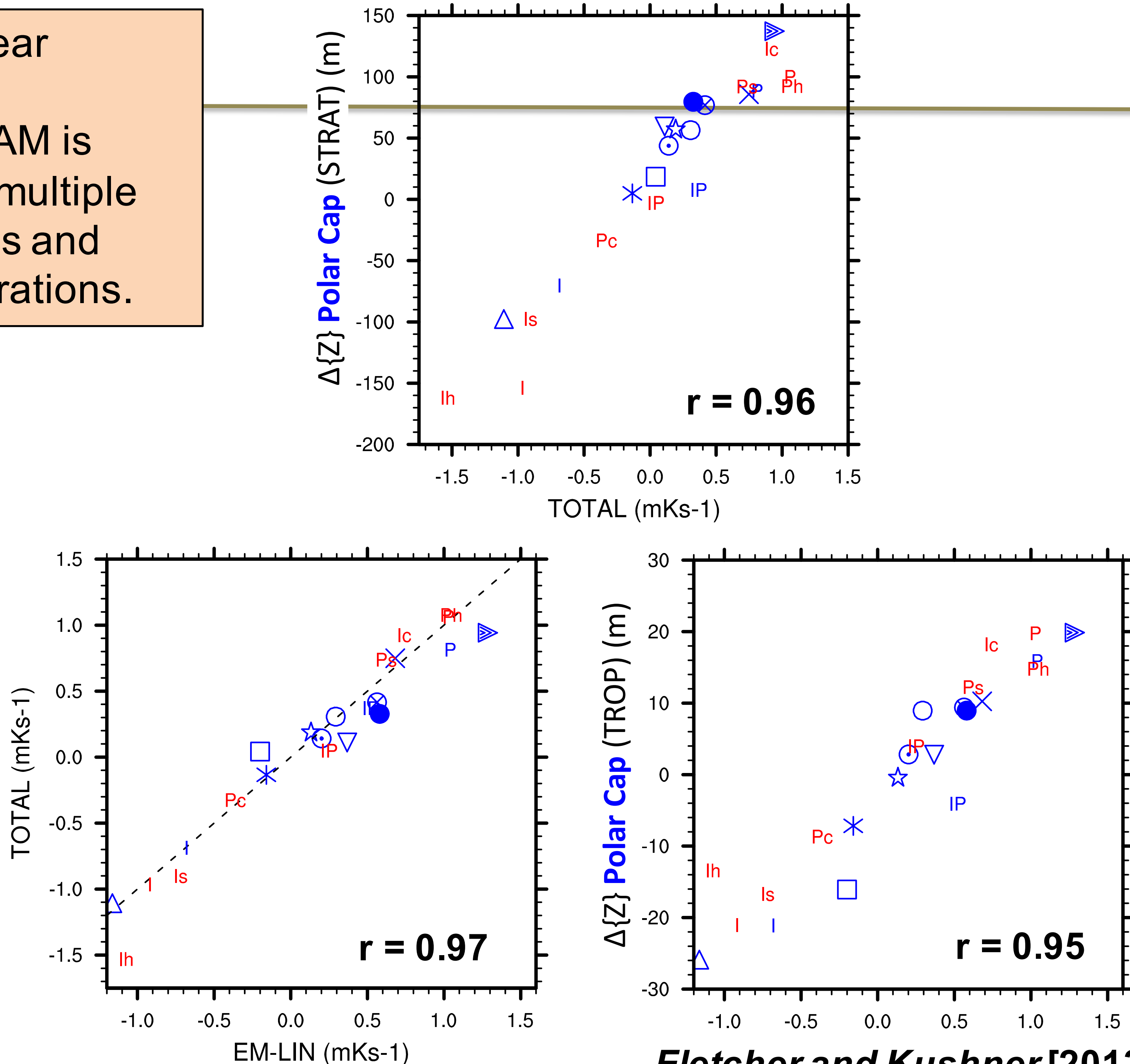
Fletcher and Kushner [2011]

Reducing the amplitude of Z^*_{climo} dramatically reduces dNAM because $EM_{LIN} \sim 0$.



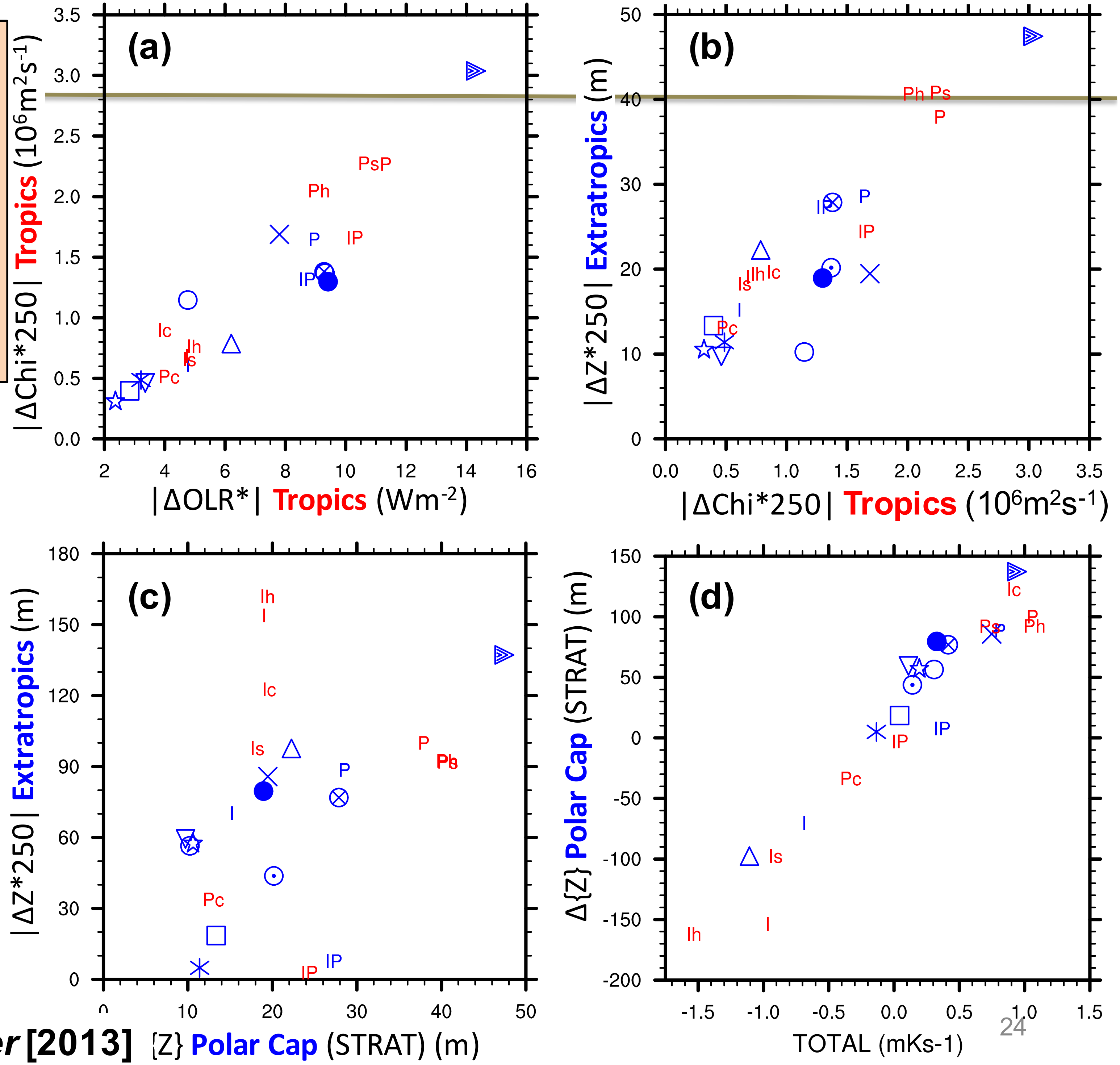
Fletcher and Kushner [2011]

The role of linear interference in explaining ΔNAM is robust across multiple forcing patterns and model configurations.



Fletcher and Kushner [2013]

Robust scaling from Tropics to extratropics across multiple forcing patterns and model configurations.



***Fletcher and Kushner* [2013]**