# Intermodel differences in upwelling in the tropical tropopause layer among CMIP5 models

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**Abstract**

The climatology of upwelling in the tropical tropopause layer (TTL) in current climate simulations and in future climate projections is examined using models participated in the Coupled Model Intercomparison Project Phase 5 (CMIP5). Large intermodel differences in upwelling in the TTL appear in the current climate simulations. Model composite analysis and upwelling diagnosis based on the zonal momentum budget indicate that the intermodel differences in upwelling are controlled by meridional eddy momentum fluxes associated with tropical planetary waves and midlatitude synoptic waves. Future climate simulations indicate that upwelling changes in the TTL are significantly correlated with the upwelling in current climate simulations. Models with strong (weak) TTL upwelling in the current climate simulations tend to project strong (weak) upwelling enhancement in the future climate. The intermodel differences in the upwelling change arise from the same dynamical factors as the current climate cases. The contribution of sea surface temperature (SST) to the intermodel upwelling differences is examined by SST-prescribed simulations in CMIP5. The contribution of intermodel SST differences to the upwelling is smaller than that of intrinsic atmospheric intermodel differences. The significant correlation of the tropical upwelling between the current climate simulations and the future changes appears to be independent of the target latitude range.

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## Introduction

- Upwelling in the tropical tropopause layer (TTL; 100 hPa in this study) in current climate (1979-2003 in historical simulations) and future climate (2075-2099 in RCP8.5 simulations) is examined using models participated in Coupled Model Intercomparison Project phase 5 (CMIP5).
- To assess contributions of intermodel SST difference, AMIP (observed SST in current climate) and AMIP4K (prescribed SST 4K warmer than AMIP SST) simulations in CMIP5 are compared with historical and RCP8.5 simulations.
- Upwelling diagnosis is performed based on Haynes' (1991) "downward control principle."
- Composite analysis is also performed based on upwelling magnitude grouping.

## Key findings

- Models with strong TTL upwelling in the current climate tend to project strong TTL upwelling enhancement in future climate.
- Intermodel differences in the upwelling are controlled mainly by atmospheric model uncertainty rather than SST uncertainty.
- Tropical planetary waves and midlatitude synoptic waves are main drivers for intermodel differences in the upwelling.

Yoshida, K., R. Mizuta, and O. Arakawa: Intermodel differences in upwelling in the tropical tropopause layer among CMIP5 models, JGR, accepted.

## Latitudinal range sensitivity of the results

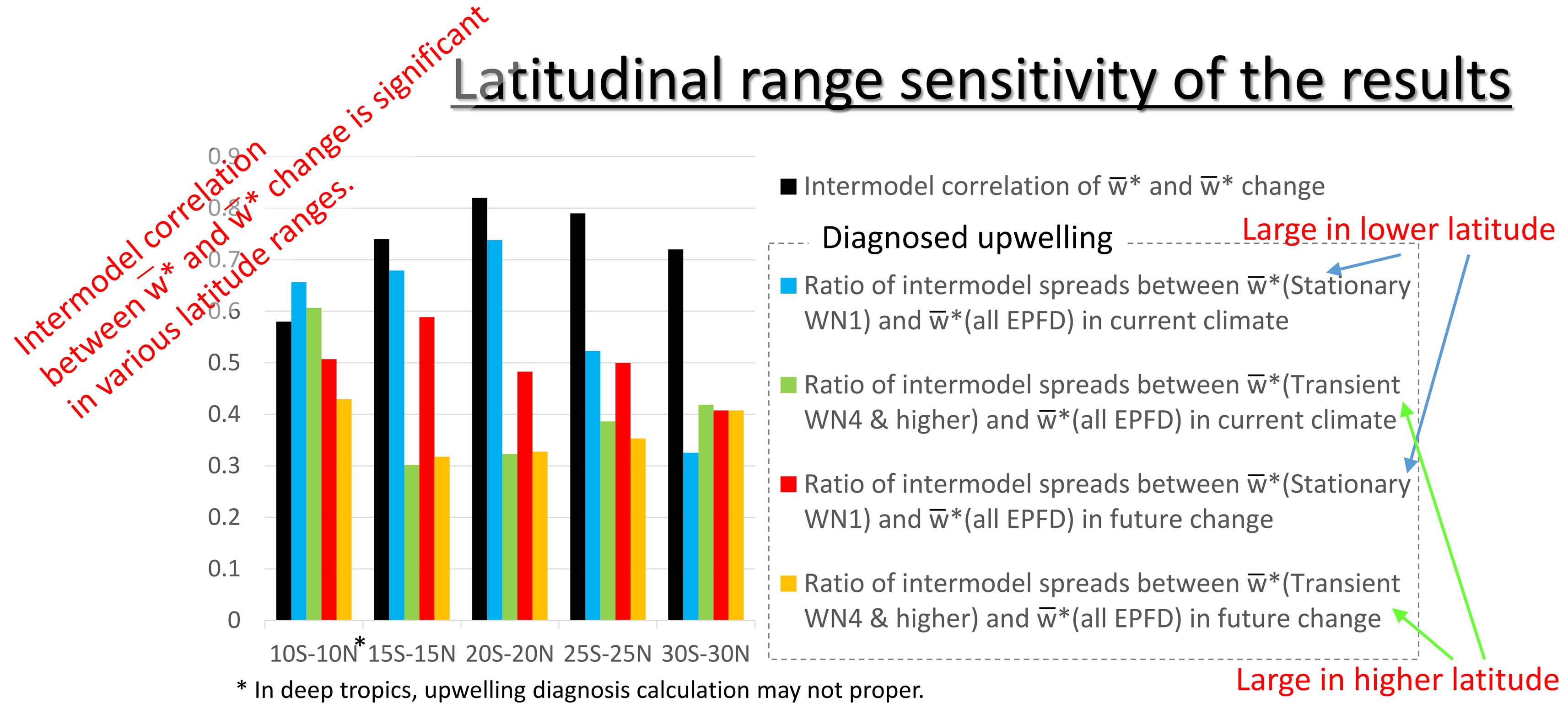



**Figure 7.** Statistics of the annual mean climatology of tropical mean upwelling at 100 hPa with various latitude ranges in historical simulations and future changes

## Climatologies in current climate

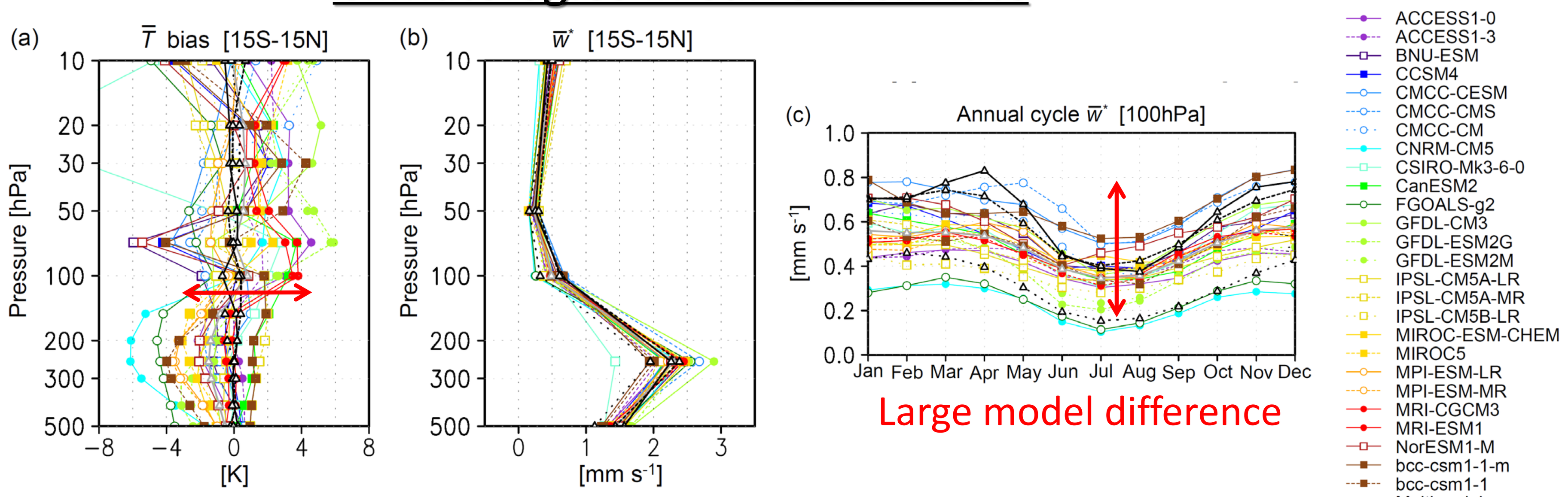



**Figure 1.** Annual mean climatology (1979–2003) of tropical mean (15°S–15°N) profiles of (a) temperature bias and (b) residual mean vertical velocity; and (c) climatological annual cycle of the residual mean vertical velocity at 100 hPa.

## Intermodel relationship of upwelling in various simulations

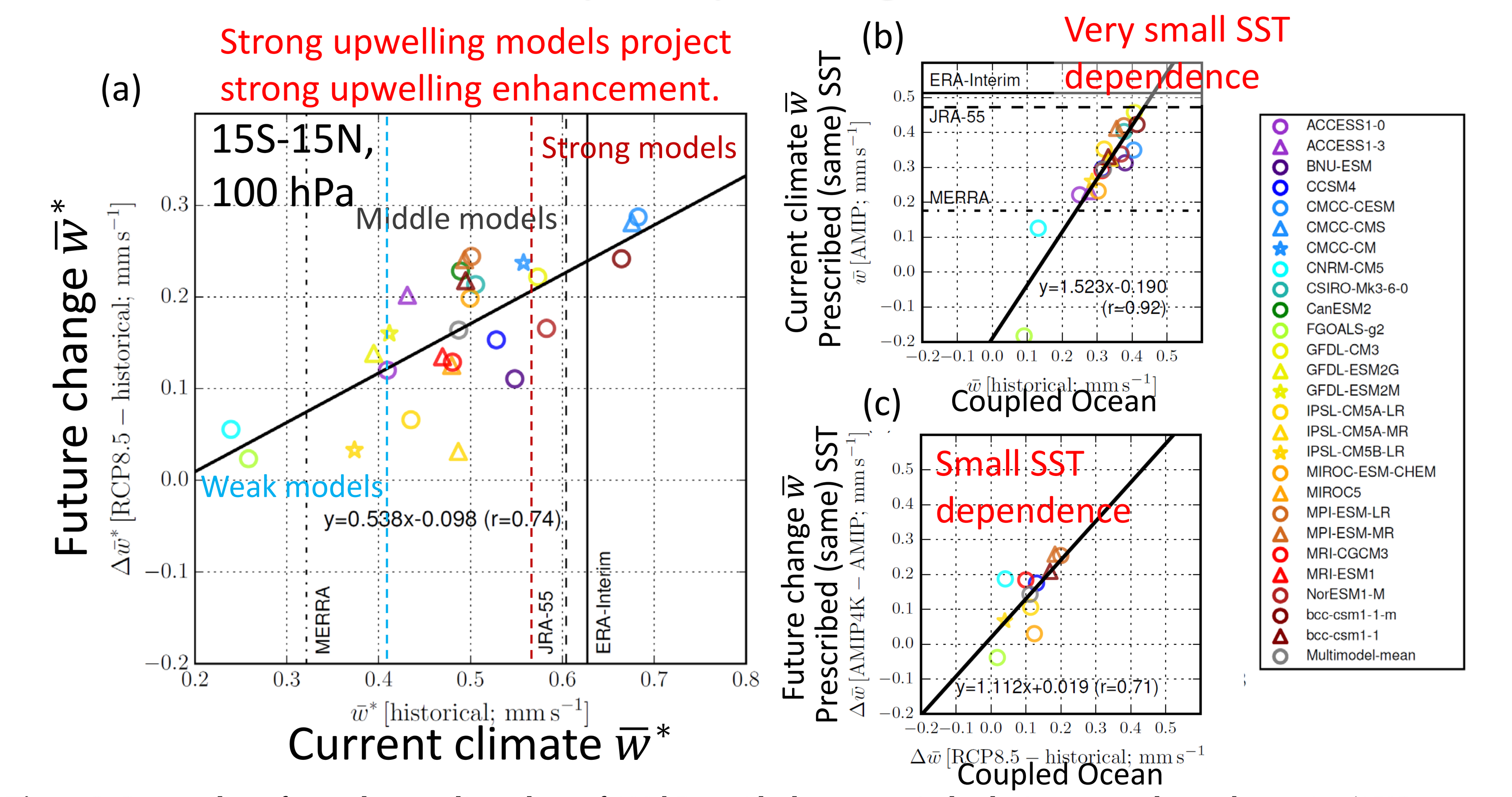



**Figure 2.** Scatter plots of annual mean climatology of 100 hPa residual mean vertical velocity averaged over the tropics (15°S–15°N) in (a) the historical simulations and the future changes (RCP8.5) and 100 hPa zonal mean vertical velocity in (b) historical and AMIP and in (c) difference in RCP8.5 and historical and difference in AMIP4K and AMIP .

## Upwelling diagnosis

Latitudinal mean upwelling is diagnosed by vertical integration of meridional mass outflow along constant zonal mean angular momentum lines. In steady state, meridional mass out flow is balanced with zonal forcing, and contributions of each forcing to the upwelling can be diagnosed separately.

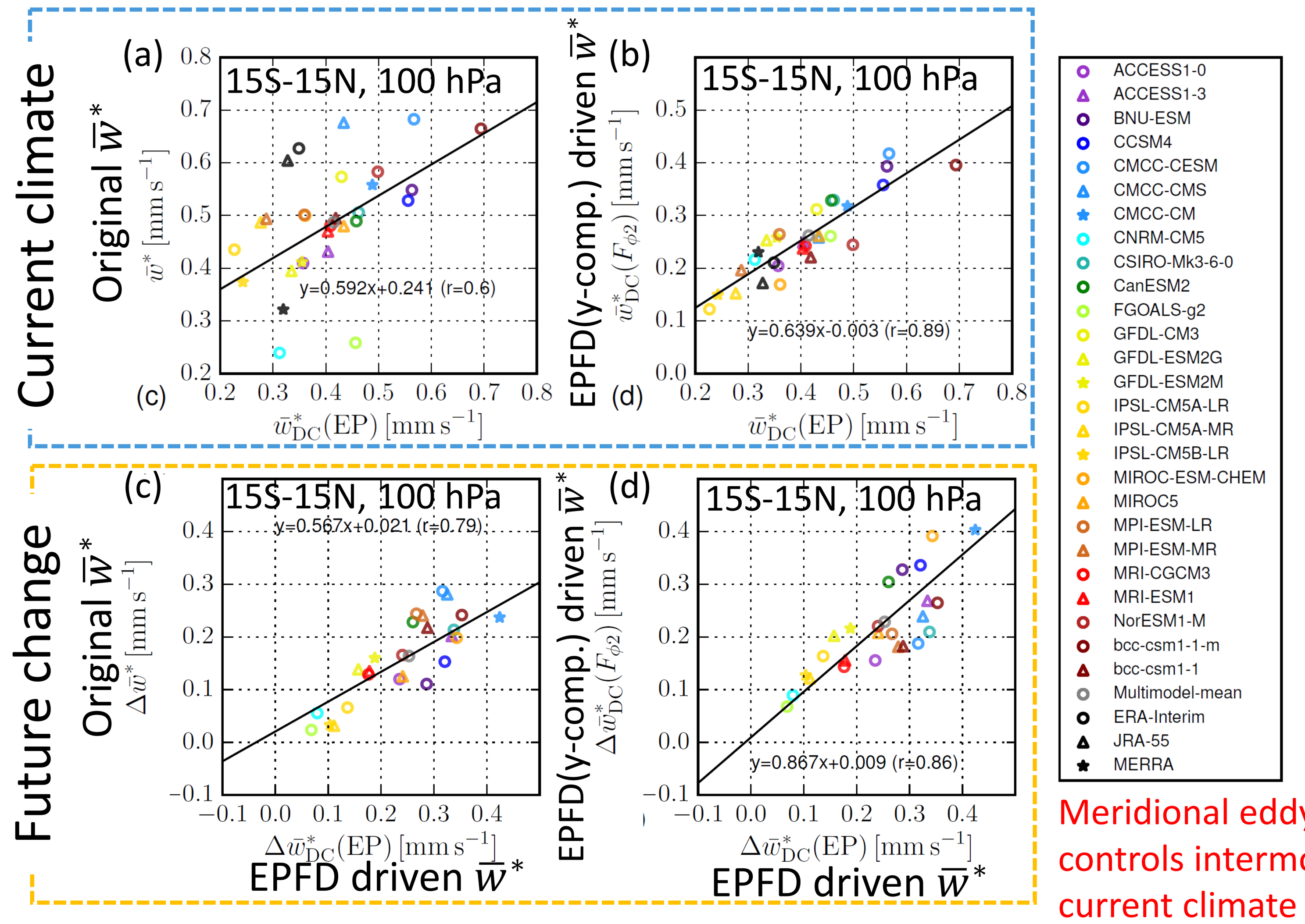
$$\langle \bar{w}^*_{DC} \rangle (z) = \left( \rho_0 \int_{\varphi_1}^{\varphi_2} a \cos\varphi' \, d\varphi' \right)^{-1} \left\{ \cos\varphi \int_z^{\infty} \rho_0 \frac{\bar{u}_t - (\rho_0 a \cos\varphi)^{-1} \nabla \cdot \mathbf{F} - \bar{X}}{\hat{f}} dz' \right\}_{\varphi_1}^{\varphi_2}$$

EP flux: $\mathbf{F} \equiv (0, F_{\varphi 1} + F_{\varphi 2}, F_{z1} + F_{z2})$

$$F_{\varphi 1} \equiv \rho_0 a \cos\varphi \, \bar{u}_z \frac{\overline{v'\theta'}}{\bar{\theta}_z}, \quad F_{z1} \equiv \rho_0 a \cos\varphi \, \hat{f} \frac{\overline{v'\theta'}}{\bar{\theta}_z},$$

$$F_{\varphi 2} \equiv -\rho_0 a \cos\varphi \, \overline{u'v'}, \quad F_{z2} \equiv -\rho_0 a \cos\varphi \, \overline{u'w'}$$

## Upwelling diagnosis based on "downward control principle"




Meridional eddy momentum flux controls intermodel w̄* difference in current climate and future change.

**Figure 3.** Scatter plots of annual mean climatologies (1979–2003) averaged over the tropics (15°S–15°N) between diagnosed upwelling and residual mean vertical velocity.

## Climatological eddy horizontal wind & geopotential height

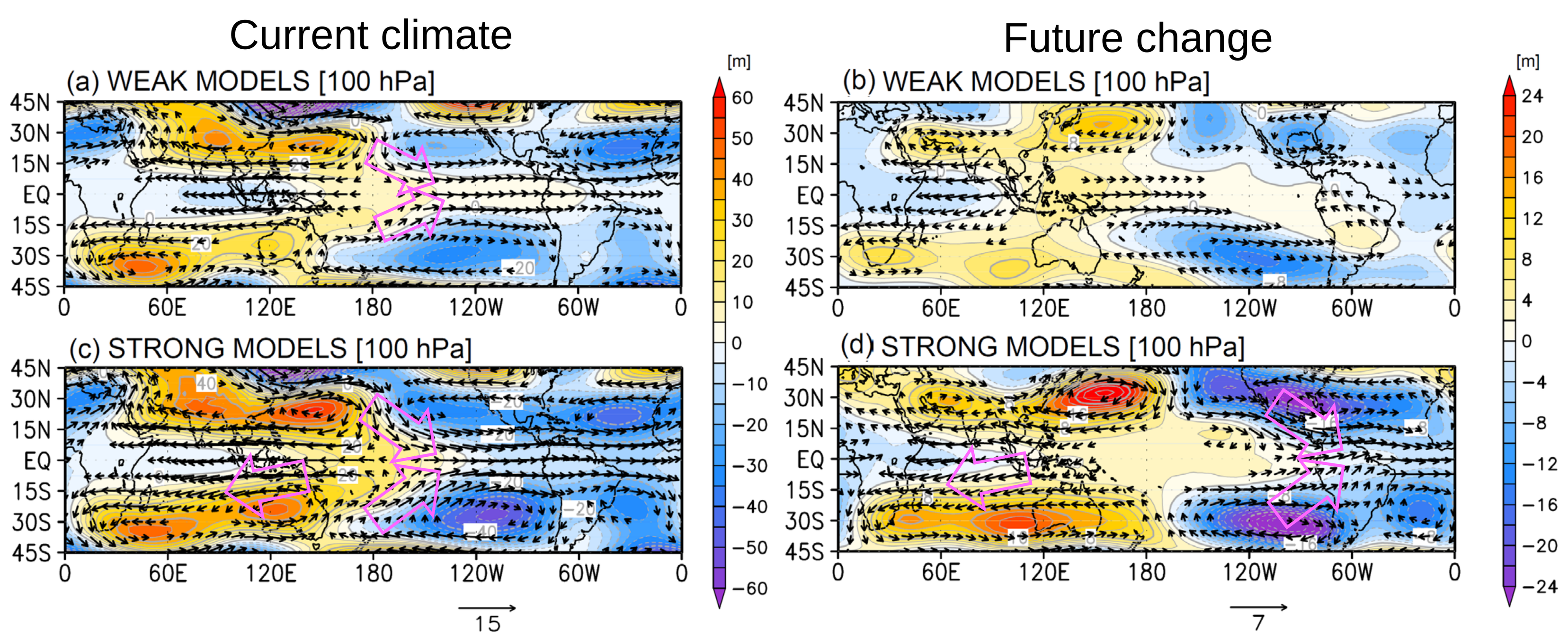



**Figure 6.** Annual mean climatology (1979–2003) of departure from zonal mean in (vectors) horizontal wind (m s⁻¹) and (colors) geopotential height at 100 hPa for (a) weak models and (c) strong models and (b, d) their future changes.

## EP flux, EP flux divergence, & zonal wind

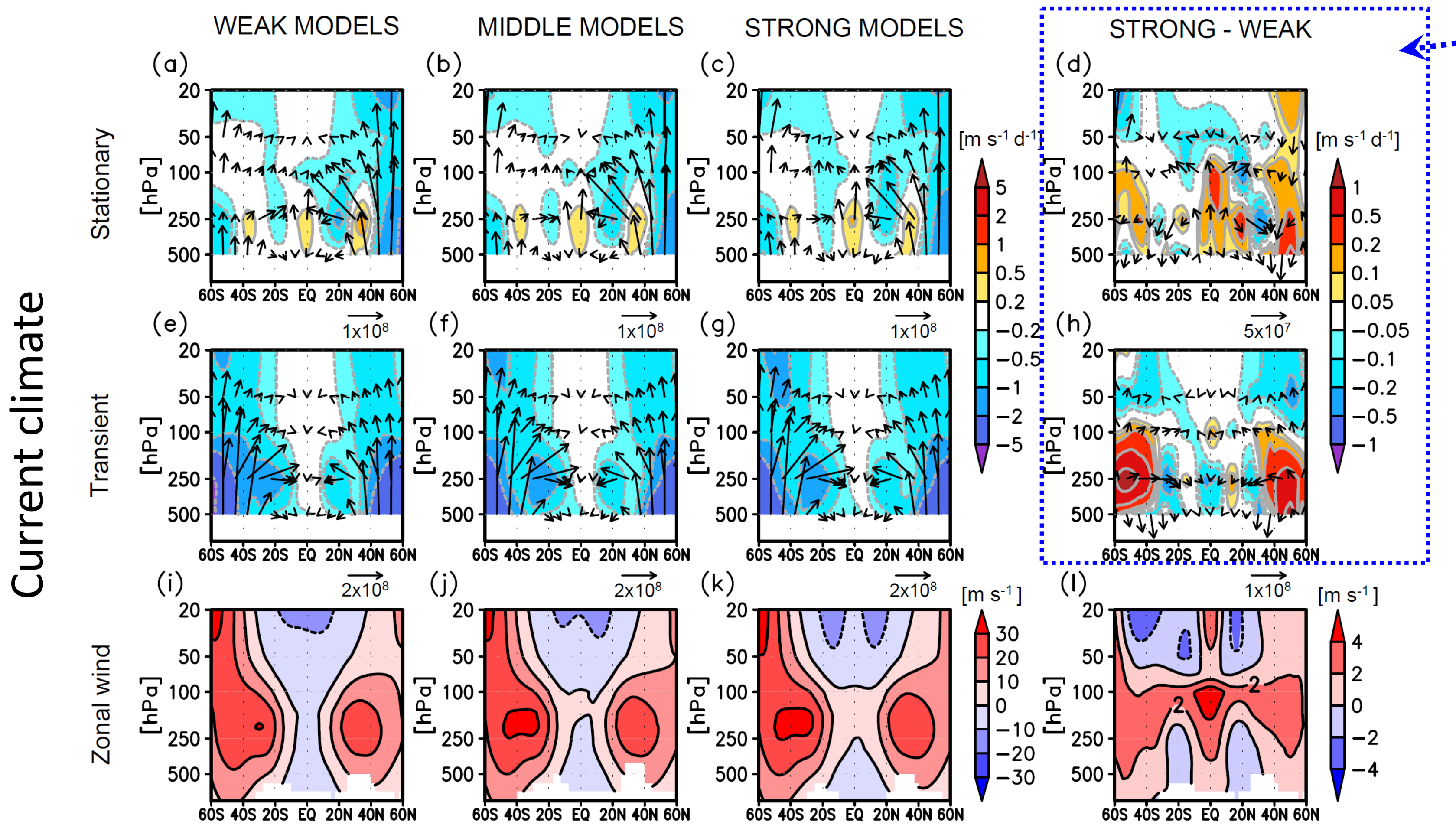



**Figure 4.** Annual mean climatology (1979–2003) of (a-h) Eliassen–Palm (EP) flux (vector) and EP flux divergence (color) and (i-l) zonal mean zonal wind in (a, e, i) weak models, (b, f, j) middle models, (c, g, k) strong models, and (d, h, l) difference between strong and weak models. EP flux and EP flux divergence are divided into (top) stationary waves and (middle) transient waves.

Tropical stationary waves and midlatitude synoptic waves are different among groups. Westerly in the tropical upper troposphere may relate tropical wave activity.

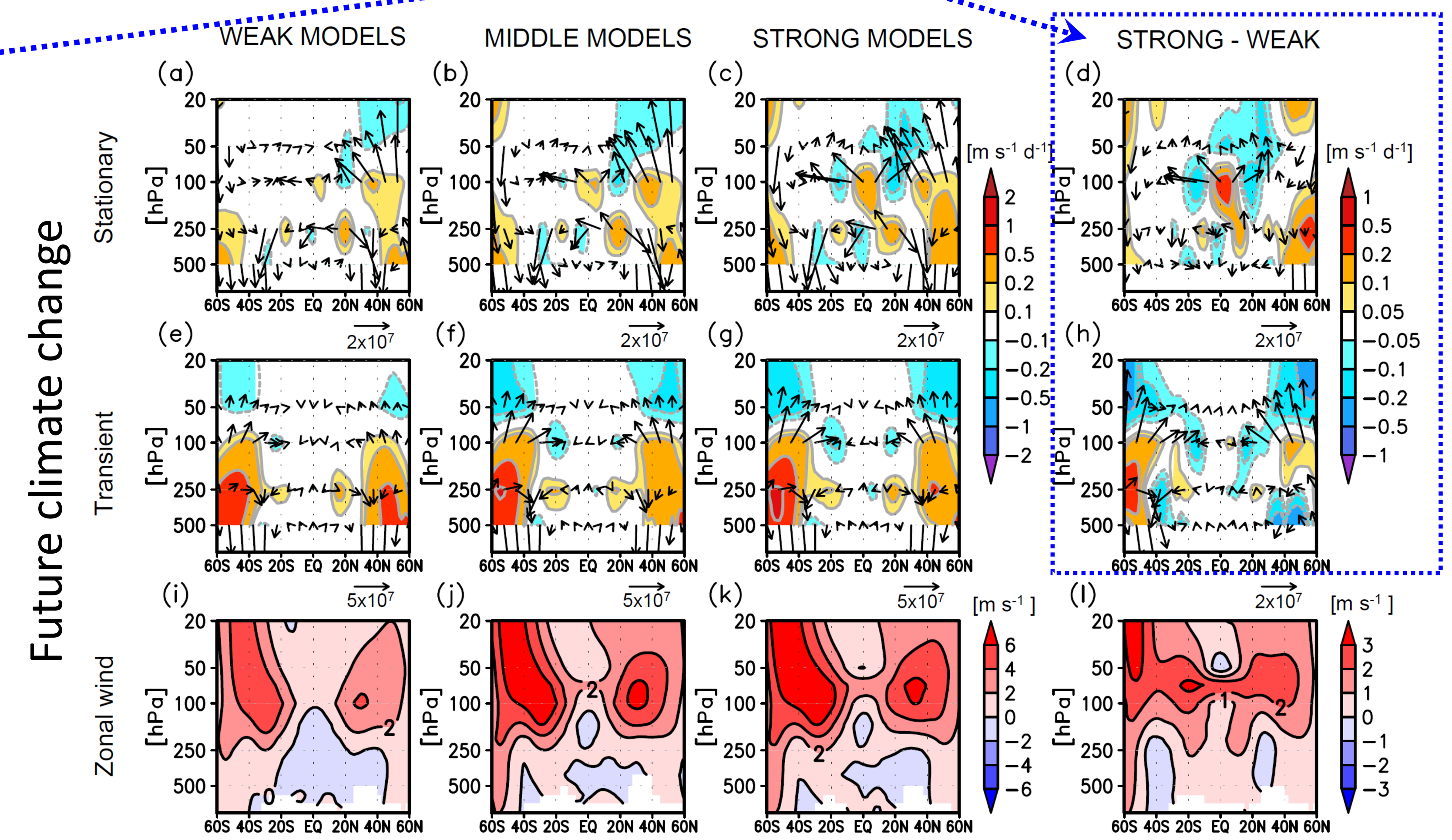



**Figure 5.** Same as Figure 4, but for future climate change calculated as differences between the RCP8.5 and historical simulations.

Similarity of the upwelling and related wave forcing between the current climate and future change may be explained by upward shift of tropospheric circulation (e.g. Oberländer-Hayn et al., GRL, 2016), which retains individual model features in the current climate.

## Acknowledgements

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