GeophysicalResearchLetters

Supporting Informationfor

Multi-decadal weakening of Indian summer monsoon circulation induces an increasing northern Indian Ocean sea level

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Section S1.

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Introduction

Description about the Ocean General Circulation model and idealized experiments are described in section S1. Additional figures supporting the results from the manuscript are provided as Figure S1, Figure S2, Figure S3 and Figure S4.

Section S1. Ocean Model and idealized wind perturbation experiments

The Ocean General Circulation Model (OGCM) used for the study is from a global configuration of the Modular Ocean Model version 4p1 [MOM4p1, *Griffies et al*., 2009]. The zonal resolution is 1° and the meridional resolution is 0.33° between 10°S and 10°N and gradually becoming 1° poleward of 30°S and 30°N. The OGCM has 40 vertical levels. The OGCM is spun-up by initializing the model with annual climatologies of temperature and salinity from *Levitus et al*, [1998] and forced with climatological forcing derived from CORE [Coordinated Ocean-ice Reference Experiments, *Griffies et al*., 2009; *Large and Yeager*, 2009]. The model is integrated for 120 years to reach a steady state in the upper ocean circulation.

Following model spin-up, two idealized experiments are performed with OGCM using idealized Gill-type wind forcing [*Gill*, 1980]. *Gill*, [1980] elucidated the basic dynamics of large-scale tropical circulation responses to idealized heating. He showed that the large-scale summer monsoon flow broadly resembles an n=2 planetary (Rossby) wave forced by an antisymmetric forcing with respect to the equator [i.e., heating (cooling) to the north (south) of equator]. We determine the idealized wind perturbations by computing a Gill-type wind response to a specified atmospheric diabatic heating anomaly [*Gill*, 1980], with a detailed description given in *Krishnan and Swapna*, [2009]. The chosen wind perturbations broadly mimic the structure of large-scale circulation patterns during a strong summer monsoon circulation (exp1) and a weak summer monsoon circulation (exp2). The idealized wind forcing for a strong monsoon is superimposed on the climatological winds from the Coordinated Ocean-ice Reference Experiments [*Griffies et al*., 2009; *Large and Yeager*, 2009] to obtain the total wind forcing for exp1. Likewise, a weak monsoon forcing is superimposed on climatology to obtain the wind forcing for exp2. All other forcing remains based on climatology in order to isolate the role of wind changes on the Indian Ocean dynamical response. The thermosteric sea level from model experiments are computed using equation (1) discussed in section 2.3.

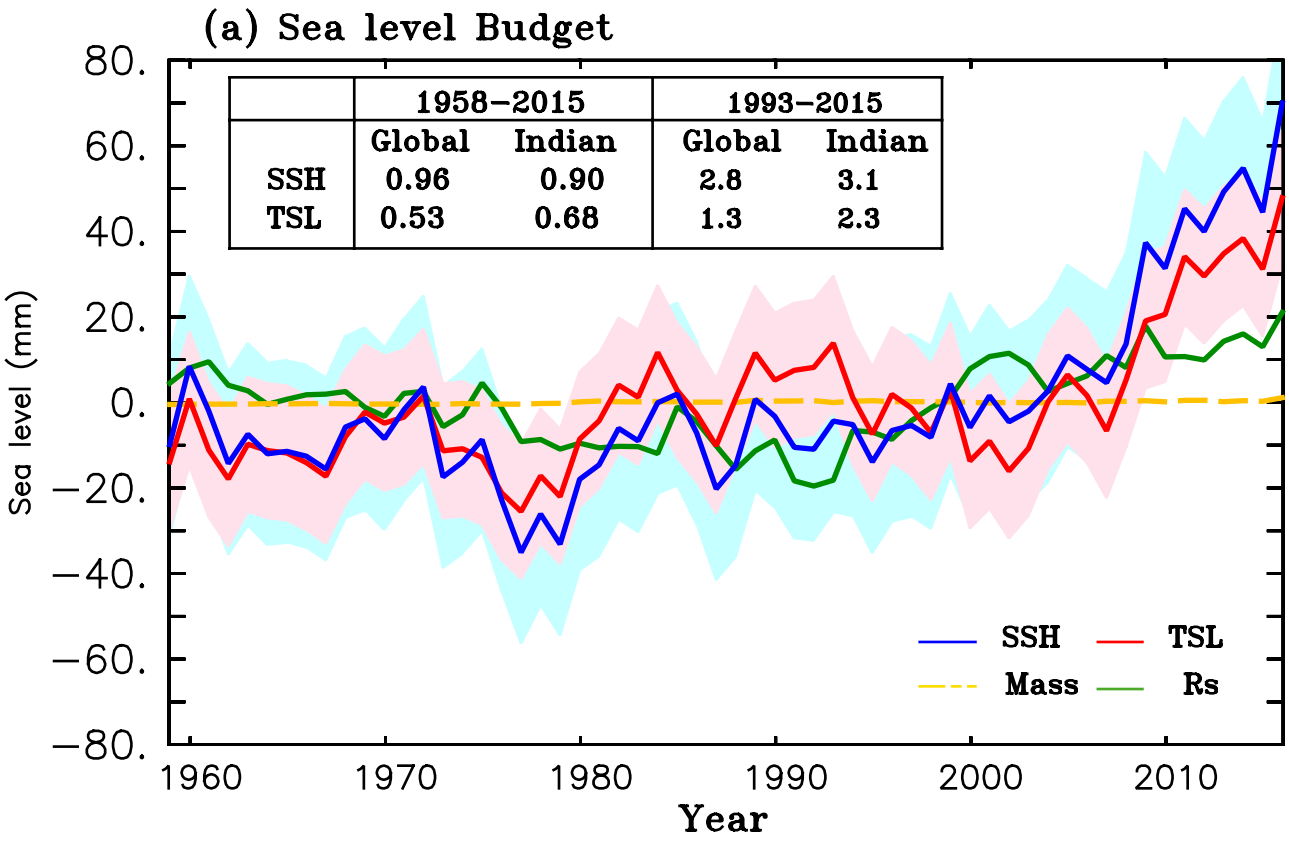

Figure S1. Annual estimates of sea level budget (mm yr^{-1}) in the upper 2000 m in the north Indian Ocean (50° E-110° E and 5^oS-25^oN) based on ORAS4 data. The error bars are one standard error.

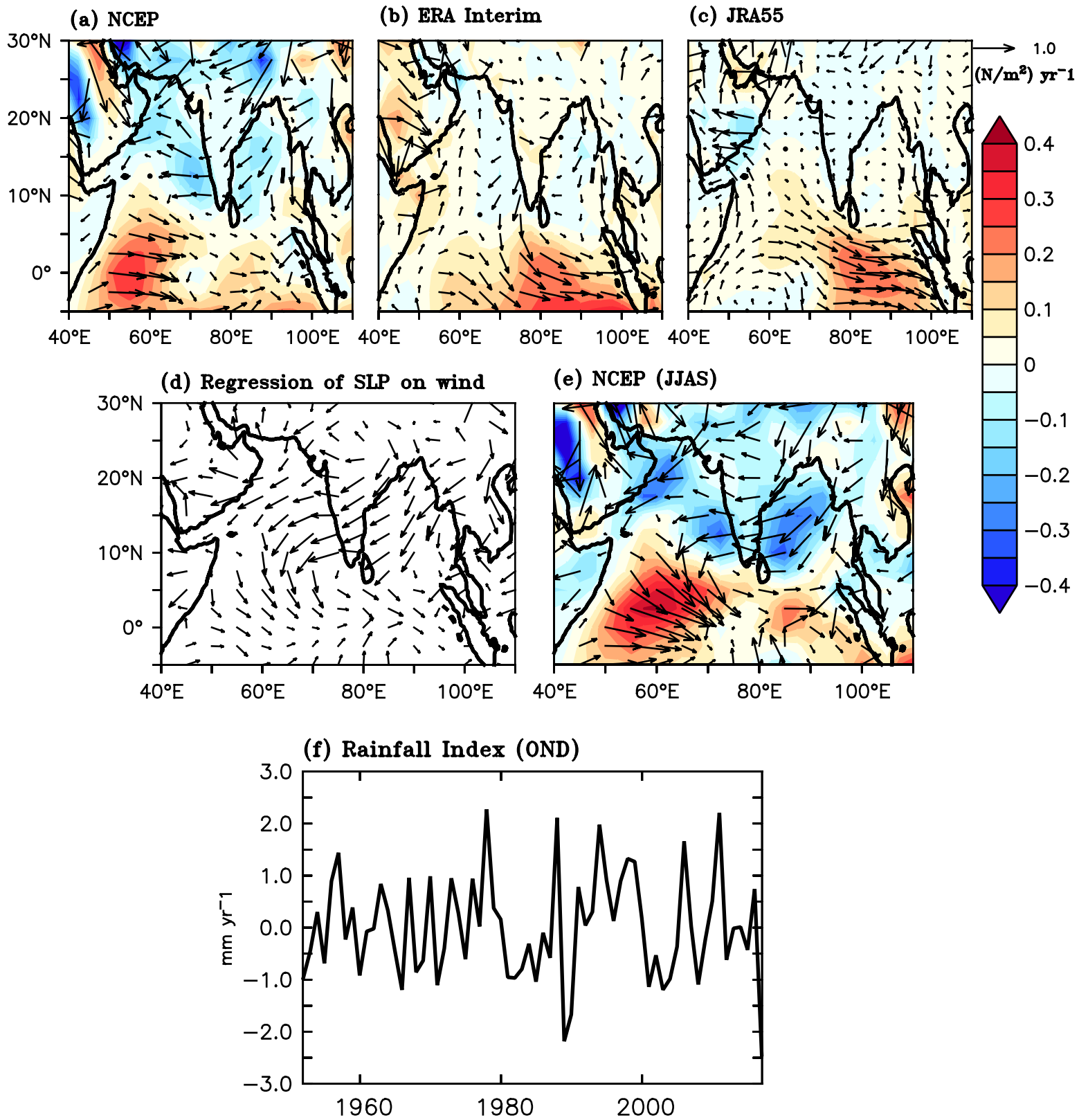

Figure S2 (a) Spatial pattern of annual mean long-term trend in wind stress anomalies (vector, (N m -2) yr^{-1}) for the period 1960-2012 in the northern Indian Ocean from (a) NCEP (b) ERA and (c) JRA55. The trend in zonal wind stress anomalies is shaded in figure. (d) Anomaly pattern generated by regressing summer monsoon wind anomalies (m sec^{-1}) on summer sea level pressure anomalies (hpa) over monsoon trough region (70°E-90°E; 16°N-28°N), (e) Spatial pattern of long-term trend in summer monsoon wind stress anomalies (N m $^{-2}$) yr^{-1}. (f) Time series of north-east monsoon (Oct-Dec) rainfall anomalies (mm yr^{-1}).

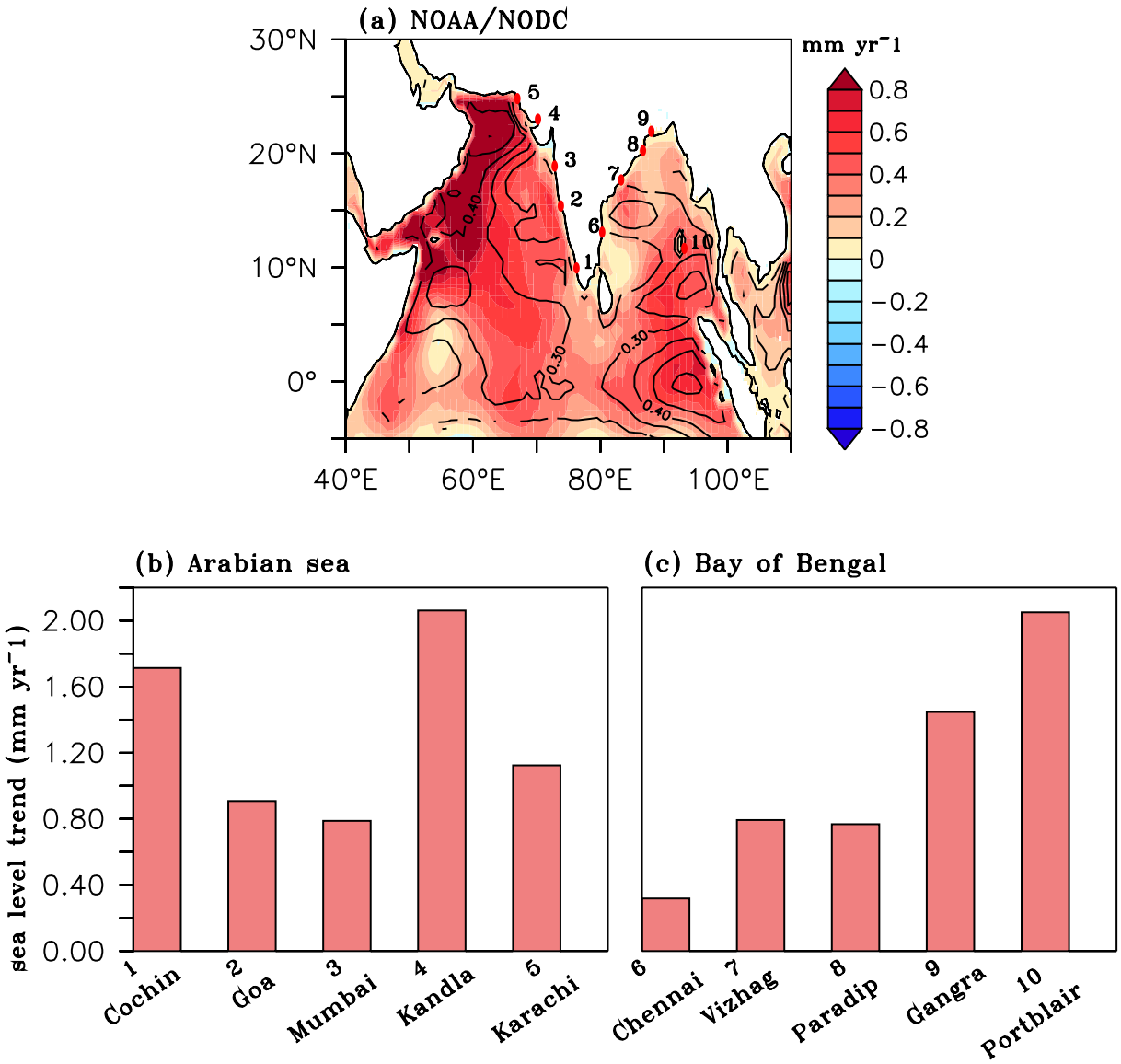

Figure S3. Spatial pattern of long-term trend of thermosteric sea level anomalies (mm year^{-1}) in the northern Indian Ocean from NOAA/NODC for 1955-2015. The significant trend above 90% confidence level is contoured. Observed long-term trend at selected tide gauge stations from PSMSL published by NOAA in the (b) Arabian Sea and (c) Bay of Bengal.

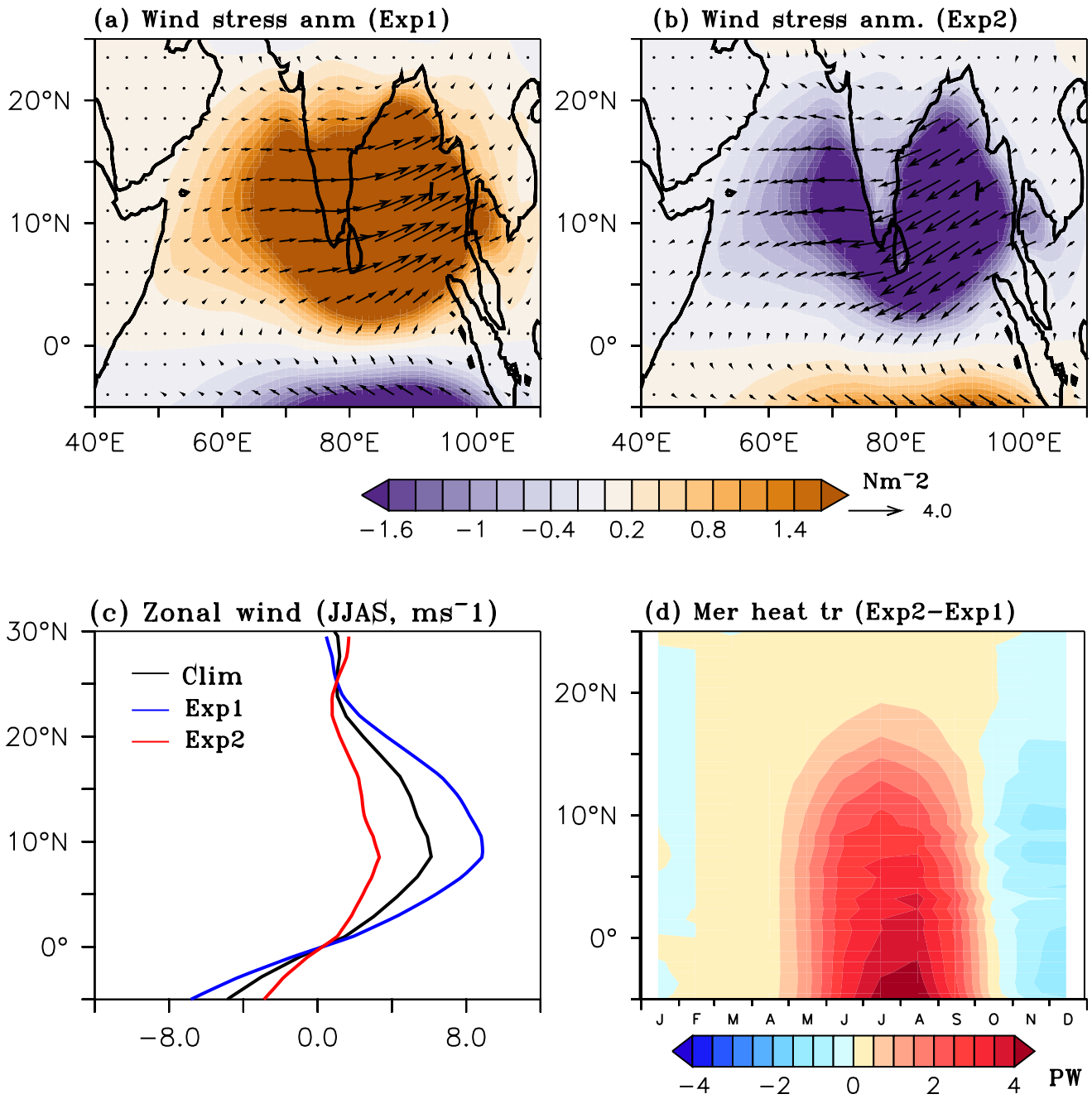

Figure S4. Wind stress anomalies (N m $^{-2}$, vector) and zonal wind stress anomalies (N m^{-2}, shaded) from the idealized experiment for (a) Exp2 and (b) Exp1. (c) Zonal mean of zonal wind stress (N m^{-2}) in the northern Indian Ocean for the summer monsoon season (June-September) for climatology (black), exp1 (blue) and exp2 (red) (d) Difference in model response between exp2 and exp1 is shown for Meridional heat transport (PW).