

Supplementary Information For
Midlatitude Mesoscale Thermal Air-sea Interaction Enhanced by Greenhouse Warming

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Table. S1 Eddy statistics and coupling coefficient of mesoscale sea surface temperature and turbulent heat flux in observations (2003-2007) and high-resolution Community Earth System Model (CESM-HR) (1956-2005) in four western boundary current regions, i.e., the Kuroshio Extension (KE), the Gulf Stream (GS), the Agulhas Return Current (ARC) and the Brazil-Malvinas Confluence (BMC). The coupling coefficients are computed for each season, winter (DJF), spring (MAM), summer (JJA), and autumn (SON). The observed SSH is derived from Copernicus Marine Environment Monitoring Service (CMEMS), and the observed heat fluxes are derived from Japanese Ocean Flux Data Sets with Use of Remote Sensing Observations version3 (J-OFURO3). Source data are provided as a Source Data file.

Eddy Statistics									
		KE		GS		ARC		BMC	
		Anti	Cyc	Anti	Cyc	Anti	Cyc	Anti	Cyc
Amplitude (cm)	CMEMS	14.49	15.9	11.5	14.93	17.07	18.66	15.31	13.28
	CESM-HR	15.95	14.2	11.38	12.78	15.98	18.7	16.17	15.79
Radius (km)	CMEMS	93	90	80.34	76.82	97.47	93.83	80.12	86.71
	CESM-HR	102.9	103.5	85.38	86.81	89.47	86.39	78.94	76.21
Number (per winter)	CMEMS	6170	4536	1809	2878	6167	7185	7217	7021
	CESM-HR	5627	4639	1556	2865	5491	6508	6653	6621
Coupling Coefficient(W/m ²)									
		KE		GS		ARC		BMC	
		Anti	Cyc	Anti	Cyc	Anti	Cyc	Anti	Cyc
DJF	J-OFURO3	44.61	46.37	40.76	43.93	37.98	38.64	34.66	34.42
	CESM-HR	46.52	45.56	42.94	46.48	34.91	37.58	34.23	35.99
MAM	J-OFURO3	33.84	36.45	32.97	29.97	39.13	39.71	35.99	37.57
	CESM-HR	34.48	32.75	32.89	31.21	36.92	37.39	38.21	37.42
JJA	J-OFURO3	31.16	30.71	28.67	29.94	40.76	42.53	35.49	34.64
	CESM-HR	31.06	30.88	31.08	30.14	42.36	41.81	37.43	37.75
SON	J-OFURO3	44.73	44.25	37.84	38.98	38.38	37.88	32.44	32.71
	CESM-HR	46.10	45.80	39.55	38.77	36.44	38.44	31.90	33.22

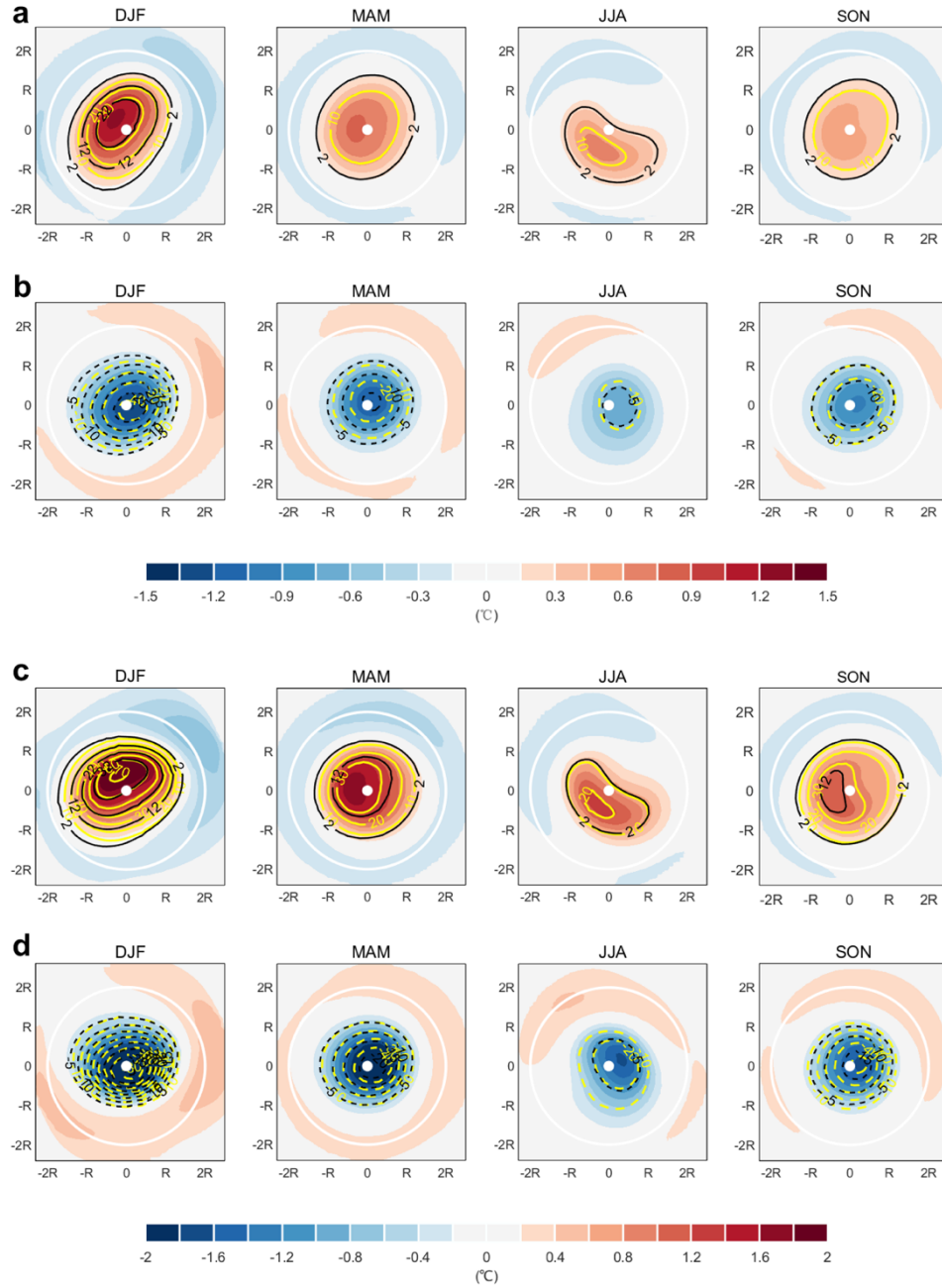


Fig. S1 Seasonal eddy composites in observation and high-resolution Community Earth System Model (CESM-HR). (a) Composites of sea surface temperature (SST, color shading), latent (LHF, yellow contours, W/m^2) and sensible heat flux (SHF, black contours, W/m^2) anomalies associated with anticyclonic warm eddies across winter (DJF), spring (MAM), summer (JJA), and autumn (SON), averaged within four western boundary current (WBC) regions based on observations (Copernicus Marine Environment Monitoring Service and Japanese Ocean Flux Data Sets with Use of Remote Sensing Observations version3, CMEMS and J-OFURO3) during 2003-2007. The white circle represents one eddy radius and the white dot marks the eddy center. (b) as for a, but for cyclonic cold eddies. (c, d) as for a, b, but for CESM-HR during historical periods (1956-2005). Source data are provided as a Source Data file.

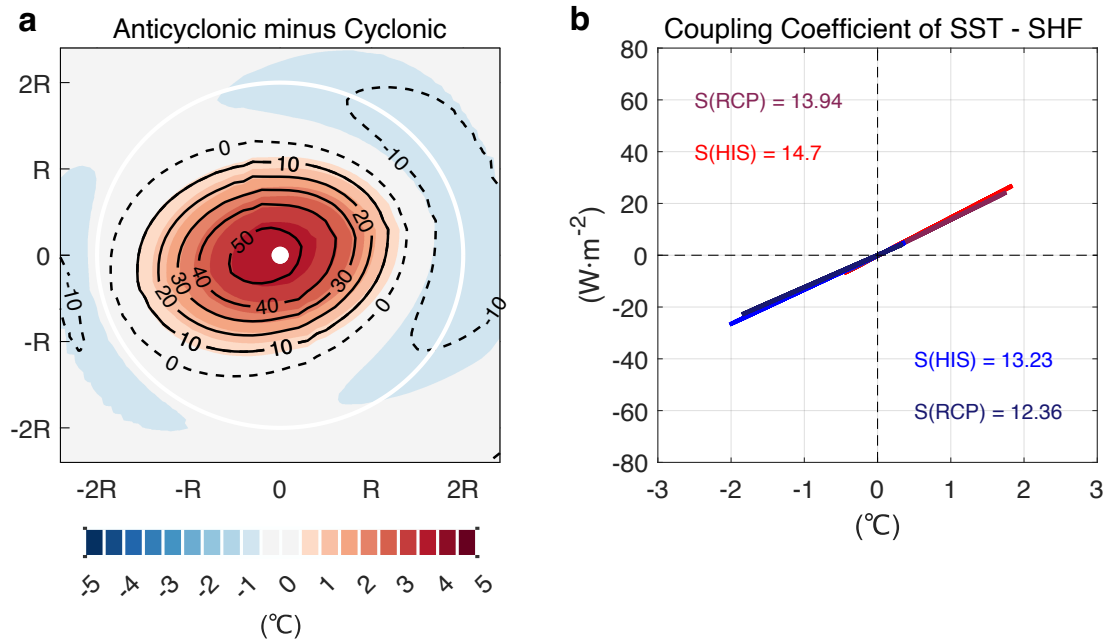


Fig. S2 Mesoscale sea surface temperature-latent heat flux (SST-LHF) coupling in high-resolution Community Earth System Model (CESM-HR). (a) Composites of SST (color shading) and sensible heat flux (SHF, contours) anomalies associated with mesoscale oceanic eddies during historical periods (1956-2005) in CESM-HR. Shown are winter season mean anomalies in anticyclonic warm minus cyclonic cold eddy composites within four western boundary current (WBC) regions. The white circle represents one eddy radius and the white dot marks the eddy center. (b) Mesoscale SST-SHF coupling strength during historical (HIS, 1956-2005) and future (RCP, 2063-2100) periods in CESM-HR for warm (red) and cold (blue) eddies averaged across four WBC regions. The coupling strength is computed using the linear regression coefficient between SST and SHF anomalies within twice the radius of eddy composites. Source data are provided as a Source Data file.

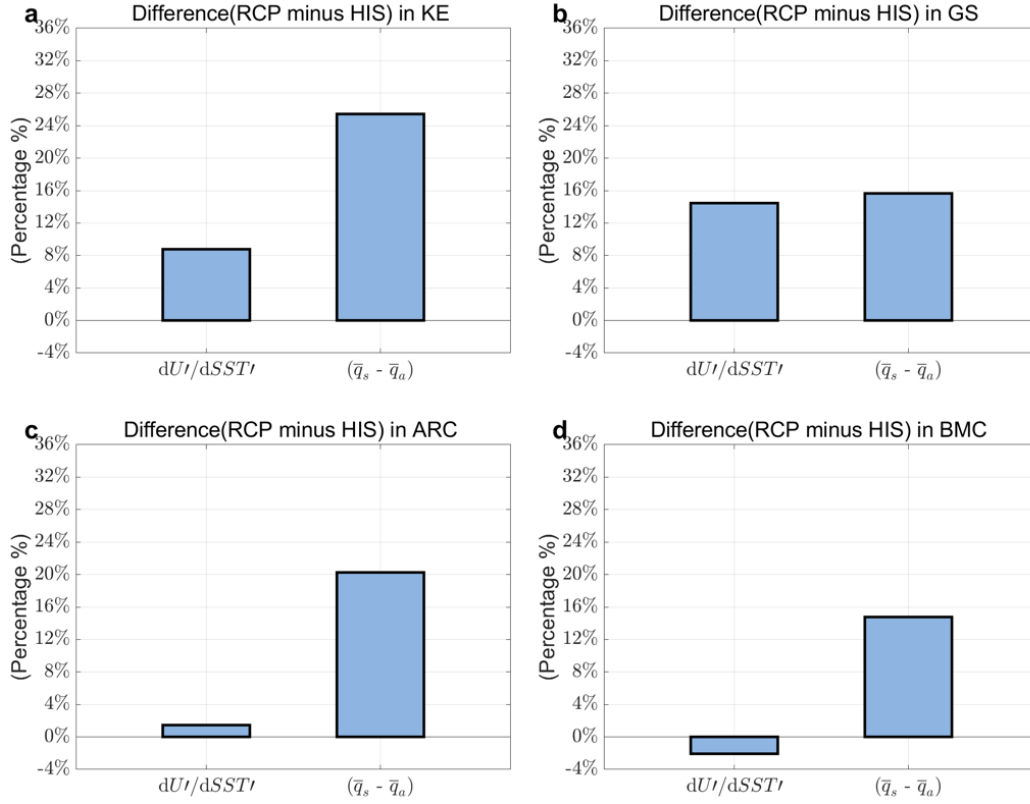


Fig. S3 Decomposition of mesoscale dynamic adjustment response under greenhouse warming. (a) Fractional changes in mesoscale wind coupling $\frac{dU'_{10}}{dSST'}$ and large-scale air-sea humidity differences $(\bar{q}_s - \bar{q}_a)$ between future (RCP) and historical (HIS) periods in high-resolution Community Earth System Model (CESM-HR) in the Kuroshio Extension (KE) region. (b-d) as in a, but for the Gulf Stream (GS), the Agulhas Return Current (ARC) and the Brazil-Malvinas Confluence (BMC) region, respectively. Source data are provided as a Source Data file.

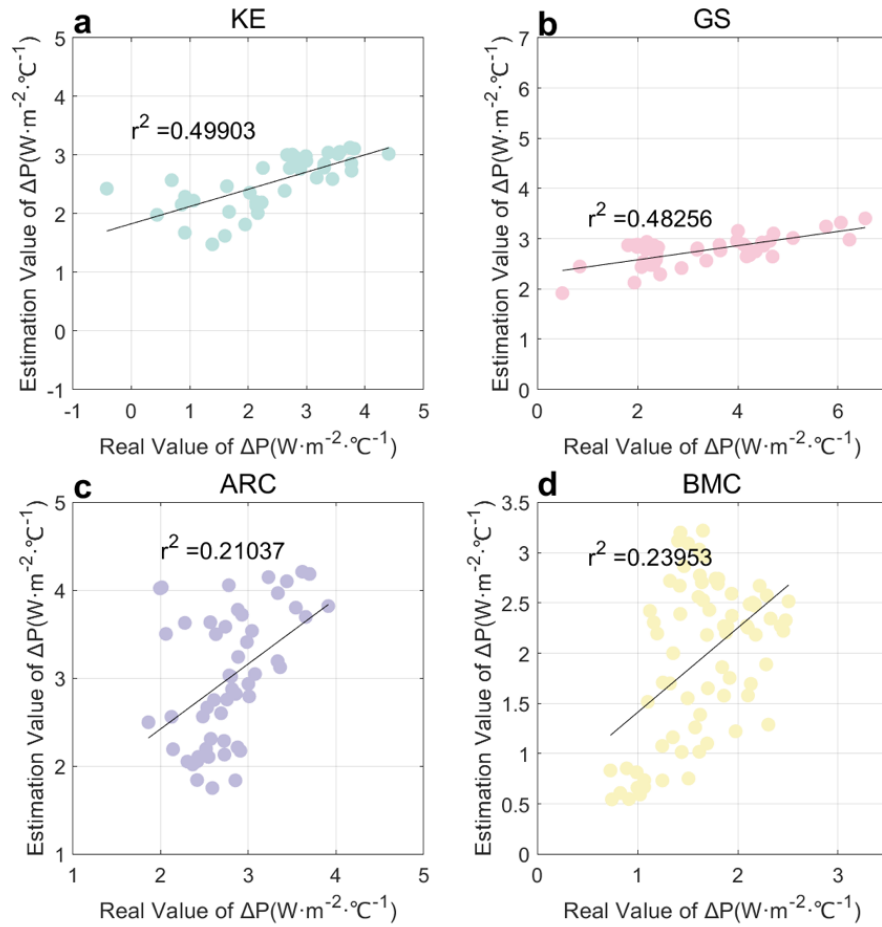


Fig. S4 Correlation of projected and estimated mesoscale sea surface temperature-latent heat flux (SST-LHF) coupling changes in response to greenhouse warming. (a) Scatter plot and linear regression (black lines) correlating actual projection with estimates of mesoscale SST-LHF coupling changes (ΔP) between future (2031-2050) and historical (1950-1969) periods in high-resolution Community Earth System Model (CESM-HR) for the Kuroshio Extension (KE) region. r^2 represents the explained variance by the regression. Each data point denotes an average within a $4^\circ \times 4^\circ$ grid box. (b-d) as for a, but for the Gulf Stream (GS), the Agulhas Return Current (ARC) and the Brazil-Malvinas Confluence (BMC) region, respectively. Source data are provided as a Source Data file.

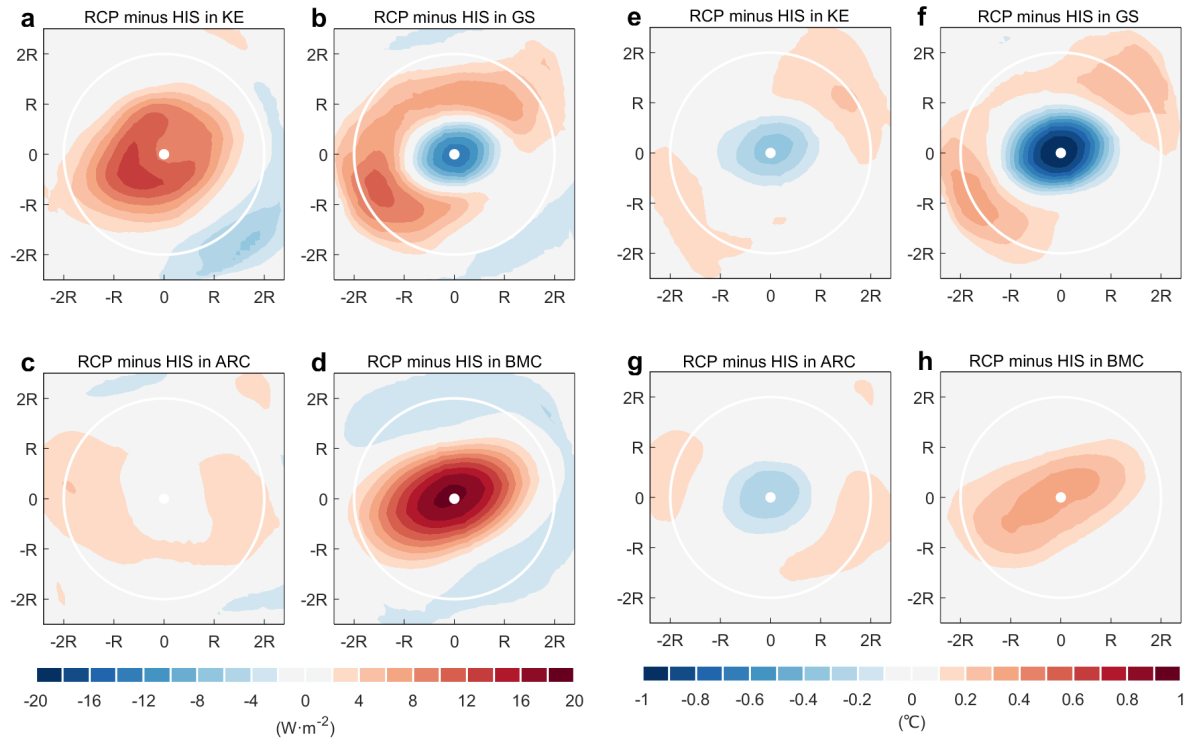


Fig. S5 Composite difference of latent heat flux (LHF) anomalies (color shading) associated with mesoscale oceanic eddies between future (RCP, 2063-2100) and historical periods (HIS, 1956-2005) in the (a) Kuroshio Extension (KE), (b) the Gulf Stream (GS), (c) the Agulhas Return Current (ARC) and (d) the Brazil-Malvinas Confluence (BMC) region. Shown are winter season mean anomalies in anticyclonic warm minus cyclonic cold eddy composites within four western boundary current (WBC) regions. The white circle represents one eddy radius and the white dot marks the eddy center. (e-h) as in (a-d), but for eddy-induced sea surface temperature (SST) anomalies. Source data are provided as a Source Data file.