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Lifecycle-dependent roles of mesoscale heat transport in marine heatwaves and cold-spells in the East Sea (Japan Sea)

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ABSTRACT

Marine heatwaves (MHWs) and marine cold-spells (MCSs) in the East Sea occur within a dynamically active marginal sea, yet their lifecycle-scale ocean heat transports remain poorly quantified. We diagnose the 1993–2022 upper-ocean heat budget using daily GLORYS12 reanalysis and ERA5 surface fluxes. Linear trends are removed only for event detection, and grid exceedances are linked into independent space-time (longitude–latitude–time) objects: 4,377 MHW and 4,968 MCS objects for 0–50 m temperature. Surface and 0–50 m events overlapped only partly (Dice coefficients 0.603 and 0.650), showing that sea-surface temperature is an incomplete proxy for layer-integrated extremes. Mesoscale heat-flux convergence contributed 56.6% of basin-mean MHW growth but only 27.9% of MCS growth, for which mean-flow convergence was dominant, and its sign reversed among five non-overlapping dynamical regions. In contrast, mesoscale convergence supplied the equivalent of 107.2% of MHW decay and 144.4% of MCS recovery, while residual processes opposed the net change. Thus, growth pathways were process- and region-dependent, whereas post-peak evolution exhibited a coherent mesoscale tendency to relax both warm and cold anomalies. Fixed-depth and deformation-scale sensitivity experiments support this phase asymmetry, positioning mesoscale transport as a consistent terminator, rather than a universal initiator, of East Sea temperature extremes.

Keywords: marine heatwaves, marine cold-spells, mesoscale heat transport, heat-flux convergence, East Sea, spatiotemporal objects

Introduction

Marine heatwaves are discrete, prolonged periods of anomalously high ocean temperature, conventionally detected above a seasonally varying 90th percentile threshold for at least five days [1]. Their cold counterparts, marine cold-spells, are defined analogously below the 10th percentile [2]. Both phenomena reorganize habitat, primary production and species distributions, alter trophic interactions, and can cause severe losses to fisheries and aquaculture [2–5]. Fixed-baseline MHW exposure has increased with global warming of the ocean [3], while the predictability of individual events depends on whether they are organized by persistent large-scale climate anomalies or by rapidly evolving boundary currents and mesoscale turbulence [4, 6]. Since most marine organisms occupy the ocean interior, surface-only detection can also miss subsurface thermal extremes whose vertical extent, ecological exposure and memory differ from the satellite signature [7, 8]. A recent synthesis of marine heatwaves observations and mechanisms provides broader context for these challenges [9].

An upper-ocean heat budget provides a mechanistic bridge between event statistics and physical causation. Temperature extremes may arise from anomalous air-sea heat exchange, mean-current advection, mesoscale heat transport, entrainment, vertical motion and mixing [4]. Bian et al. [10] used an eddy-rich global coupled simulation and reported that mesoscale heat-flux convergence supplied 81% of global MHW growth and 74% of decay, with even larger fractions in western boundary-current systems. That result established mesoscale transport as a potentially first-order MHW driver, but its transferability to marginal seas remains uncertain. Their analysis used a fixed 3° spatial filter, model-diagnosed budgets for 1920–1934, grid-local events rather than independent space-time objects, and did not examine MCSs. A compact marginal sea such as the East Sea has smaller and spatially varying deformation radii, coastally constrained currents, strong fronts and substantial seasonal changes in mixed-layer depth. These characteristics can change both the physical meaning of a fixed filter and the relative importance of mesoscale and mean transport.

A complementary global analysis using an ocean state estimate found that atmospheric forcing dominates many regions, while advection and diffusion remain crucial in western boundary currents and other energetic regimes [11]. Mesoscale modulation of boundary-current heat transport has likewise been documented regionally [12]. These contrasting results motivate a conservative regional test rather than assuming universal mesoscale dominance.

Previous East Sea studies have established a detailed but still fragmented picture. Surface MHW days and cumulative intensity increased rapidly during 1982–2020, whereas the surface heat-flux trend indicated enhanced ocean heat loss, implicating oceanic heat supply [13]. Summer events are broadly associated with reduced cloud and wind and enhanced shortwave heating, whereas winter events near the subpolar front (SPF) are linked to the northward displacement of the East Korea Warm Current (EKWC) and frontal system [14]. Individual East Korea Bay (EKB) events also involve lateral heat transport [15], and boreal-summer event patterns are modulated by synoptic and intra-seasonal atmospheric circulation [16, 17]. Subsurface studies show that surface-detected events can remain shallow, occupy the mixed layer or coexist with warming to 200 m [18]; direct depth-resolved detection reveals strong thermocline events associated with Tsushima Warm Current (TWC) transport, the EKWC and eddies [19, 20]. Winter variability and resurgent summer events further emphasize the roles of the Arctic Oscillation, stratification and post-typhoon mixed-layer recovery [21, 22]. Most recently, winter MCSs along the western boundary were linked to cold and fresh intrusions, horizontal advection, and entrainment [23]. Nevertheless, no prior study has applied one conservative lifecycle budget to independent, basin-wide MHW and MCS objects while separating mean and mesoscale horizontal heat-flux convergence.

In this study, we test whether the global mesoscale-dominance hypothesis [10] applies to both warm and cold extremes in the East Sea. We introduce four adaptations: (i) trends are removed before threshold detection to isolate transient extremes from the linear warming background; (ii) connected exceedances are merged into independent space-time objects rather than counted as thousands of grid events; (iii) the mean-mesoscale separation follows a locally estimated deformation scale (R_d ; deformation radius); and (iv) five exclusive dynamical regions avoid spatial duplication. We quantify how sea-surface and 0–50 m object catalogues overlap, compare growth and decay budgets for MHWs and MCSs, decompose the mesoscale term into its three Reynolds components, and test robustness to a 30 m layer and a broader “ $9 \times R_d$ ” filter.

Methods

Ocean and atmospheric data

Daily three-dimensional potential temperature and horizontal velocity for 1993–2022 were obtained from the Copernicus Marine Environment Monitoring Service GLORYS12 global ocean reanalysis [24]. Native vertical levels intersecting each diagnostic layer were retained, including partial lower cells. GLORYS12 assimilates altimetric sea level, sea-surface temperature, sea-ice concentration and in-situ temperature and salinity observations into the NEMO ocean–sea–ice system. ERA5 surface net shortwave and longwave radiation and latent and sensible heat fluxes were converted from hourly accumulations to daily means, placed on a downward-positive convention, and bilinearly interpolated to the GLORYS12 grid [25]. Temperature, velocity and flux fields were matched on a common daily 365-day climatological calendar. The constants used in the executable analysis were $\rho_0 = 1026 \text{ kg m}^{-3}$ and $c_p = 4000 \text{ J kg}^{-1} \text{ K}^{-1}$.

The analysis was restricted to East Sea water identified by the project coastline mask, excluding the adjacent northwestern Pacific. Five candidate dynamical regions represent the East Korea Warm Current (EKWC), East Korea Bay, Ulleung Basin (UB), the subpolar front (SPF), and the Japan-side current system. Where candidate boxes overlapped, each grid cell was assigned to the region whose box centre had the smallest normalized zonal–meridional distance. This produced mutually exclusive masks (0% final overlap); remaining East Sea cells were retained as ‘Other East Sea’ for basin-wide accounting. Each object was assigned to the region containing its peak-intensity cell. Coordinates and the allocation rule are given in Supplementary Methods.

Fixed-layer temperature and detrended event detection

The primary state variable is the thickness-weighted mean potential temperature over the upper $H = 50 \text{ m}$, $T_{m,H}$. Layer weights account for partial cells at H . SST is used only to construct an alternative event catalogue for catalogue-overlap analysis; the closed process attribution reported below uses the same fixed-layer state variable for endpoints and process terms. This prevents a non-conservative comparison between an SST endpoint change and a 50 m heat budget. The physical implications of fixed-depth and mixed-layer control volumes are discussed in refs. [26, 27].

$$T_{m,H}(x, y, t) = \frac{1}{H} \int_{-H}^0 T(x, y, z, t) dz \quad (1)$$

At each wet grid cell, a least-squares linear trend was estimated from the complete daily series and subtracted while retaining the original temporal mean. Detrending was used only to select events; lifecycle temperature changes and all process anomalies were calculated from the physical, non-detrended reanalysis fields. This distinction removes the deterministic linear-warming contribution from percentile exceedance without artificially removing heat from the subsequent budget. The ecological burden under the observed warming trend is therefore not estimated here.

$$T_d(x, y, t) = T(x, y, t) - \hat{\beta}(x, y)[t - \bar{t}] \quad (2)$$

where the temporal mean is retained. The detrended series T_d is used only for event selection; all endpoint changes and process terms use the original reanalysis fields.

The warming background shown in Fig. 1 was estimated separately from annual-mean SST at each grid cell. The ordinary least-squares slope over 1993–2022 (30 annual means; cells with fewer than 20 valid years were excluded) was tested against zero with a two-sided Student’s t test on the regression slope ($df = n - 2$), and multiplicity across East Sea grid cells was controlled with the Benjamini–Hochberg false-discovery-rate procedure at $q = 0.05$ [28]. Stippling in Fig. 1 denotes cells that remain significant after this control; the use of annual means removes most of the serial correlation of the daily record from the trend test.

For each calendar day, a climatological mean and the 90th and 10th percentiles were estimated with an 11-day moving sample window and smoothed with a 31-day moving mean [1]. A MHW (MCS) grid event was a period

above the 90th percentile (below the 10th percentile) lasting at least five days; interruptions of at most two days were joined. Leap days were mapped to a consistent 365-day climatological calendar.

Catalogue correspondence was evaluated from event cell-days. If A and B denote the $T_{m,50}$ and SST event cell-day sets, respectively, the Jaccard and Dice indices are given as

$$J = \frac{|A \cap B|}{|A \cup B|}, \quad D = 2|A \cap B|/(|A| + |B|) \quad (3)$$

An object was ‘matched-any’ when it shared at least one cell-day with an object in the other catalogue; maximum object-pair Jaccard scores and grid-wise fixed-only/shared/SST-only fractions were also calculated.

Independent spatiotemporal event objects

Grid exceedances were linked into independent three-dimensional (longitude-latitude-time) objects using eight-neighbor horizontal connectivity and temporal intervals that overlapped or were separated by no more than one day. Connected components were merged transitively by a union-find algorithm, following the general rationale of recent object-based MHW framework [29–31]. Thus, a basin-wide event occupying many cells contributes one object, not one observation per cell. Each object stores its duration, number of unique grid cells, cell-days, peak intensity, peak location and peak year. No minimum-area filter beyond grid connectivity was imposed, and this choice is evaluated as a limitation because many objects were spatially small.

For mechanistic integration, the standard threshold start and end were extended to the nearest pre-event and post-event extrema in the layer-temperature anomaly within a maximum 20-day search window [10]. The peak was the warmest anomaly for a MHW and the coldest anomaly for a MCS. Growth extends from the pre-event extremum to the peak; decay (or recovery for MCSs) extends from the peak to the post-event extremum. Search windows were clipped to avoid unrestricted drift into the seasonal cycle or adjacent events.

Heat-budget decomposition

The fixed-layer temperature tendency is written as the sum of mean-current heat-flux convergence (HFC_M), mesoscale heat-flux convergence (HFC_E), net surface heat input retained in the layer (NHF), and a diagnosed residual (RES):

$$\frac{\partial T_{m,H}}{\partial t} = HFC_M + HFC_E + NHF + RES \quad (4)$$

Unlike an earlier layer-mean implementation, horizontal heat-flux convergence was calculated at every native vertical level using a spherical finite-volume divergence and was then depth-averaged over 0–H. This retains vertical shear-temperature covariance and preserves coastally truncated control-volume faces. The Reynolds separation was performed independently at each level. Large-scale fields, denoted by an overbar, were obtained with a spatially varying low-pass filter; primes are deviations from that low-pass field. The baseline filter half-width was $6 \times Rd$, bounded between 45 and 120 km, where Rd is a stratification-based local deformation-scale estimate [32]. Separate zonal and meridional metric distances were used.

$$HFC_M = -\langle \nabla_h \cdot (\bar{u}\bar{T}) \rangle_H, \quad (5)$$

$$HFC_E = -\langle \nabla_h \cdot (u'T') \rangle + \nabla_h \cdot (\bar{u}T') + \nabla_h \cdot (u'\bar{T}) \rangle_H$$

The three HFC_E components are termed the covariance term, mean-current transport of temperature perturbations, and perturbation-velocity transport across the mean temperature field, respectively. Thus, HFC_E is broader than the pure covariance $-\nabla \cdot (u'T')$; retaining and reporting all three components avoids attributing cross terms to isolated eddy cores. Positive convergence warms the layer and negative convergence cools it.

$$NHF = [Q_{net} - Q_{SW}(-H)]/(\rho_0 c_p H) \quad (6)$$

where $\rho_0 = 1026 \text{ kg/m}^3$, $c_p = 4000 \text{ J/kgK}$ and downward heat flux is positive. The NHF was also retained

as shortwave, longwave, latent and sensible components. The *RES* was computed exactly as the layer-temperature change minus the three resolved integrated contributions. It contains vertical advection, heat flux through the lower boundary, unresolved entrainment and mixing, reanalysis assimilation increments, cross-product and discretization errors not captured by the retained terms, and mismatches between ERA5 and GLORYS. Contributions from unresolved submesoscale motions may be present in *RES* together with the listed terms, but cannot be isolated by this diagnostic and are not interpreted separately. The retained shortwave component used the Paulson–Simpson Jerlov-I transmission [33]:

$$Q_{SW}(-H) = Q_{SW}(0)[0.58 e^{-H/0.35} + 0.42 e^{-H/23}] \quad (7)$$

Lifecycle integration, regional aggregation and statistics

For process X , the lifecycle contribution was integrated from the start t_s to peak t_p and from t_p to the end t_e after removal of the day-of-year climatology: $C_{grow,X} = \int_{t_s}^{t_p} X_{anom} dt$ and $C_{decay,X} = \int_{t_p}^{t_e} X_{anom} dt$. The observed changes are $\Delta T_{anom,grow} = T_{anom}(t_p) - T_{anom}(t_s)$ and $\Delta T_{anom,decay} = T_{anom}(t_e) - T_{anom}(t_p)$. We report the raw contribution in $K/phase$ and the signed net-change ratio $100C_X/\Delta T_{anom}$. Ratios above 100% indicate that a process exceeds the net change and is opposed by other terms; a negative ratio indicates opposition to the phase change. Absolute-budget shares were retained only as supplementary diagnostics and were not compared directly with Bian et al. [10].

Daily anomalies were summed from $t_s + 1$ to t_p for growth and from $t_p + 1$ to t_e for decay/recovery, matching the endpoint differences. A term-object estimate was retained only when at least 90% of phase days were valid. Repeated grid-event estimands belonging to the same object and cell were first averaged; the resulting unique cells were then weighted by spherical cell area, so each connected object formed one statistical sample. Further equations and implementation details are provided in Supplementary Methods.

Uncertainty was quantified with a pairs cluster bootstrap in which the calendar year containing each object's peak anomaly ('peak year') defined the cluster; peak year is a cluster label, not a subset of unusually active years. For each of 2,000 replicas, the 30 peak-year clusters (1993–2022) were sampled with replacement, all objects assigned to a selected year were retained together, and object-weighted basin or regional estimates were recomputed from annual sums and counts [34]. Percentile 95% confidence intervals were the 2.5th and 97.5th percentiles and are the primary inferential criterion. The reported p_{boot} is a descriptive two-sided sign-tail probability from the ordinary cluster bootstrap, not a null-centered test; a wild-cluster test is a useful sensitivity as a sensitivity check where formal few-cluster inference is required [35]. Gridded tests required at least ten independent objects and used a one-sample t test followed by Benjamini-Hochberg false-discovery-rate control at $q = 0.05$ [28].

Sensitivity experiments

Two sensitivity experiments were performed. First, the complete calculation was repeated for $H = 30 m$ using the same $6 \times Rd$ filter, including level-wise convergence, penetrative correction, object detection and independent-object bootstrap. This tests whether the $50 m$ result depends on including the seasonal thermocline. Second, $H = 50 m$ was retained while the filter half-width was increased from $6 \times Rd$ to $9 \times Rd$. A $3 \times Rd$ experiment was not selected because the imposed $45 km$ lower bound would clip most of the East Sea to the same minimum scale, producing little effective separation from the baseline. A variable mixed-layer-depth budget was not substituted for H : changing the lower boundary introduces explicit entrainment/detrainment, moving-boundary and basal heat-flux terms and therefore cannot be obtained by replacing $50 m$ with MLD in the fixed-layer denominator.

Code availability

The complete MATLAB (R2024b) workflow used for detrending, fixed-layer integration, spherical finite-volume heat-flux convergence, space–time object tracking, cluster-bootstrap uncertainty quantification, plotting

and sensitivity experiments is available from the corresponding author upon editor or reviewer request during review, and will be archived in a public repository with a versioned DOI upon acceptance.

Results

Warming background and event inventories. GLORYS12 SST increased by $0.332\text{ }^{\circ}\text{C/decade}$ during 1993–2022, and 72.6% of the sea area had a locally significant linear trend (Fig. 1). Grid-cell trends ranged from approximately 0.111 to $0.581\text{ }^{\circ}\text{C/decade}$ between the 5th and 95th percentiles. The detrended catalogue therefore targets transient departures around the changing local mean rather than allowing the regional warming trend to inflate late-period exceedances. In Supplementary Table S1, the detrended catalogue for two extremes, MHWs and MCSs, is given for surface (SST) and fixed-layer ($T_{m,50}$).

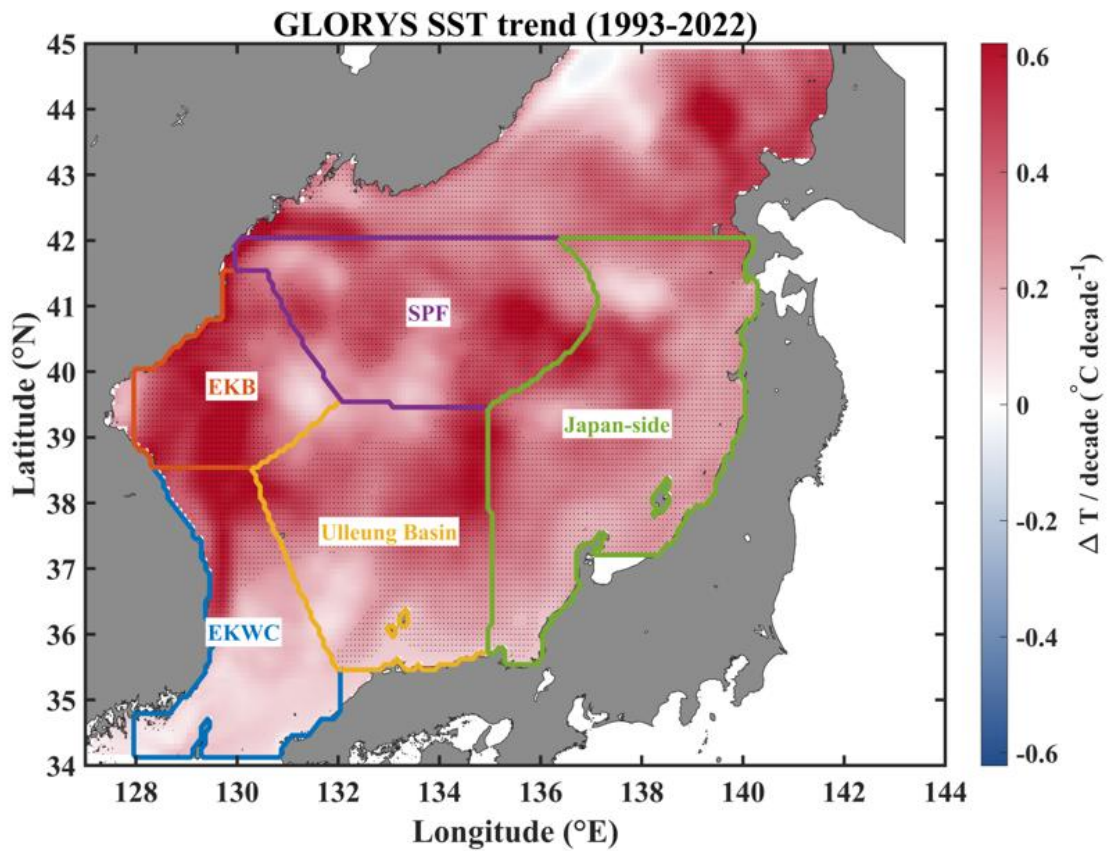


Figure 1. GLORYS12 SST trend and mutually exclusive dynamical regions. Colors show the 1993–2022 linear SST trend ($^{\circ}\text{C/decade}$); stippling denotes trends significant after false-discovery-rate control (see Methods). Thick outlines delimit the East Korea Warm Current (EKWC), East Korea Bay (EKB), Ulleung Basin (UB), subpolar front (SPF), and Japan side regions used for object assignment.

SST and $T_{m,50}$ events overlap only partly. The $T_{m,50}$ catalogue contained 4,377 MHW and 4,968 MCS objects, whereas SST yielded 4,965 MHW and 5,929 MCS objects. Surface and fixed-layer extremes shared only 43.14% of MHW and 48.13% of MCS union cell-days (Fig. 2). Cell-day Jaccard coefficients were 0.431 for MHWs and 0.481 for MCS; the corresponding Dice coefficients were 0.603 and 0.650. About 50.6% of $T_{m,50}$ MHW objects and 58.1% of $T_{m,50}$ MCS objects shared at least one cell-day with an SST object, but only 30.4% and 32.2%, respectively, reached a maximum object-pair Jaccard overlap of 0.1. The maps show fixed-layer-only

occurrences along dynamically active frontal and current regions as well as broad surface-only exposure.

This incomplete overlap justifies treating SST as an event-selection sensitivity rather than as a physically interchangeable state variable. The principal process attribution below uses $T_{m,50}$ because its endpoint temperature and all integrated terms refer to the same conserved layer.

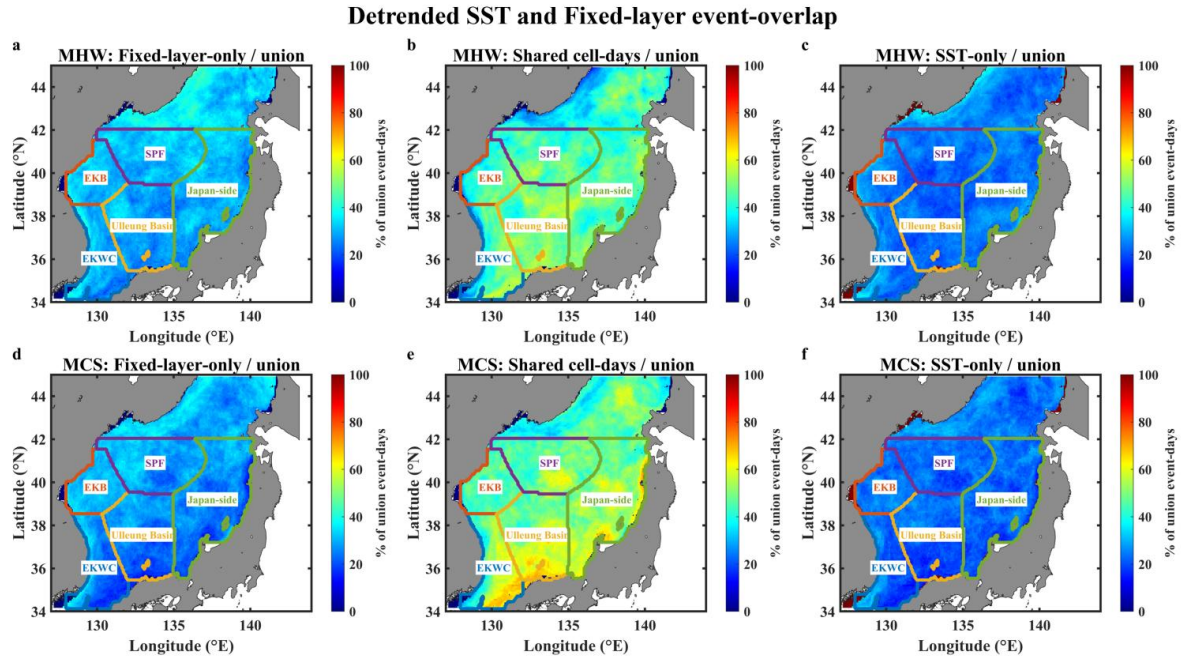


Figure 2. Spatial overlap of detrended SST and 0–50 m temperature ($T_{m,50}$) extreme-event catalogues. Panels show (a–c) MHWs and (d–f) MCSs; columns report the fractions of union cell-days unique to $T_{m,50}$, shared by both definitions, and unique to SST, respectively. Summary metrics are calculated from independent space-time objects and cell-day masks.

Basin-mean lifecycle heat budgets. MHW growth warmed the layer by 1.409 K on average (Table 1; Fig. 3). HFC_E supplied 0.797 K (56.6%) and HFC_M 0.725 K (51.5%), whereas NHF contributed only 0.063 K (4.5%). RES was -0.176 K (-12.5%), offsetting part of the resolved horizontal convergence. Thus, the detrended independent-object analysis indicates co-control by mesoscale and mean horizontal transport, rather than an exclusively mesoscale or atmospheric growth pathway. The corresponding gridded HFC_E pattern is shown in Supplementary Fig. S2.

Table 1. Whole-domain 0–50 m lifecycle budgets based on independent objects and peak-year cluster bootstrap. Percentages are signed ratios to the net phase change, not absolute-budget shares.

Extreme	Phase	Term	ΔT_{anom} (K)	Contribution (K)	% of ΔT_{anom}	95% CI (%)	p_{boot}
MHW	Growth	HFC_E	+1.409	+0.797	+56.6	[2.1, 118.1]	0.039
		HFC_M	+1.409	+0.725	+51.5	[1.4, 101.5]	0.044
		NHF	+1.409	+0.063	+4.5	[3.3, 5.7]	<0.001
		RES	+1.409	-0.176	-12.5	[-80.0, 54.9]	0.77
	Decay	HFC_E	-1.315	-1.410	+107.2	[60.6, 151.3]	<0.001

MCS		HFC_M	-1.315	-0.635	+48.3	[14.8, 87.5]	0.003
		NHF	-1.315	-0.085	+6.5	[5.2, 7.7]	<0.001
		RES	-1.315	+0.815	-62.0	[-106.2, -14.7]	0.01
		HFC_E	-1.494	-0.417	+27.9	[-14.0, 71.0]	0.198
	Growth	HFC_M	-1.494	-1.213	+81.2	[24.9, 129.5]	0.005
		NHF	-1.494	-0.071	+4.8	[3.4, 6.1]	<0.001
		RES	-1.494	+0.207	-13.9	[-57.0, 32.7]	0.528
		HFC_E	+1.501	+2.167	+144.4	[96.1, 187.8]	<0.001
	Decay	HFC_M	+1.501	+0.352	+23.5	[-28.3, 76.4]	0.372
		NHF	+1.501	+0.092	+6.1	[5.1, 7.1]	<0.001
		RES	+1.501	-1.110	-73.9	[-116.5, -28.4]	<0.001
		HFC_E	-1.494	-0.417	+27.9	[-14.0, 71.0]	0.198
	Growth	HFC_M	-1.494	-1.213	+81.2	[24.9, 129.5]	0.005
		NHF	-1.494	-0.071	+4.8	[3.4, 6.1]	<0.001
		RES	-1.494	+0.207	-13.9	[-57.0, 32.7]	0.528
		HFC_E	-1.494	-0.417	+27.9	[-14.0, 71.0]	0.198

MHW decay was more consistently mesoscale controlled. HFC_E cooled the layer by 1.410 K, equivalent to 107.2% of the net -1.315 K change; HFC_M added -0.635 K (48.3%) and NHF -0.085 K (6.5%). Positive RES (+0.815 K) opposed the cooling. The >100% HFC_E ratio indicates compensating unresolved or vertical processes rather than a budget error: object-wise closure was at machine precision by construction, while the separated HFC_E components closed to within approximately 10^{-5} K on average. Its spatial distribution is shown in Supplementary Fig. S3.

Cold-event growth followed a different pathway. MCSs cooled by 1.494 K; HFC_M contributed -1.213 K (81.2%), HFC_E -0.417 K (27.9%) and NHF -0.071 K (4.8%), with a small opposing RES . The HFC_E confidence interval crossed zero, whereas HFC_M was robust. During MCS recovery, however, HFC_E warmed the layer by 2.167 K (144.4% of the +1.501 K recovery), far exceeding HFC_M (+0.352 K) and NHF (+0.092 K), while RES removed 1.110 K. The consistent feature across warm and cold extremes is therefore the importance of mesoscale transport during termination, not universal dominance during onset. Gridded MCS growth and recovery contributions are shown in Supplementary Figs. S4 and S5.

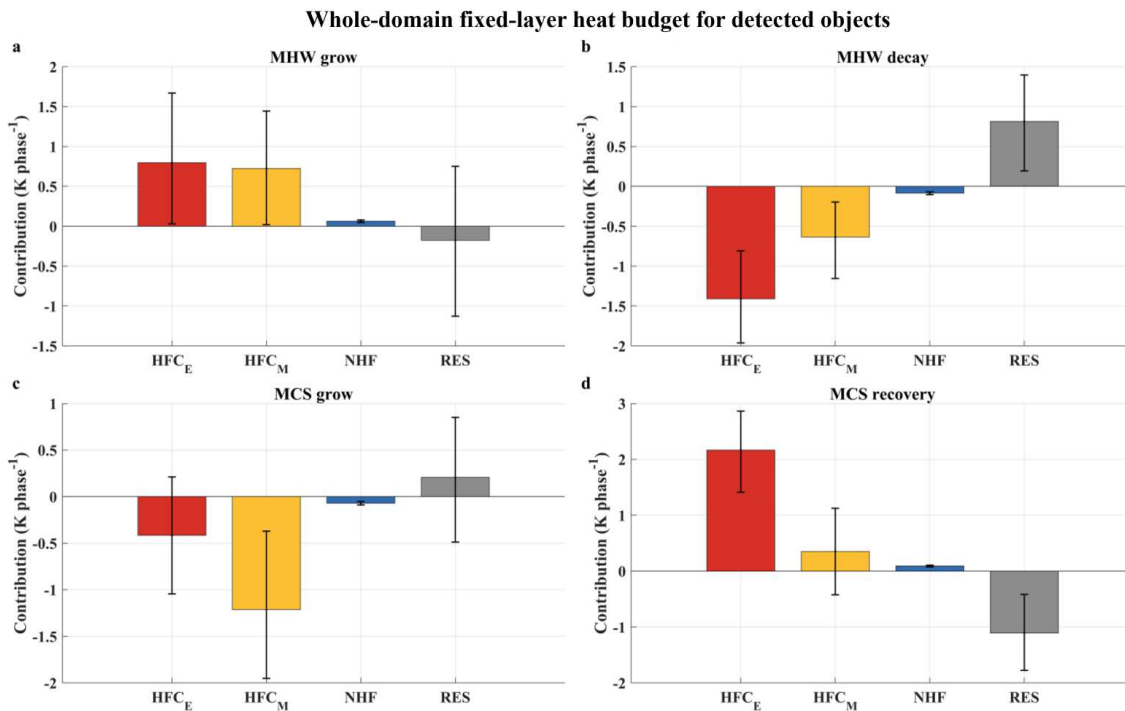


Figure 3. Whole-domain lifecycle contributions for detrended $T_{m,50}$ objects: (a) MHW growth, (b) MHW decay, (c) MCS growth, and (d) MCS recovery. Bars show object-mean HFC_E , HFC_M , NHF , and RES contributions (K per event phase); whiskers show 95% peak-year cluster-bootstrap confidence intervals. Positive values warm and negative values cool the layer.

Regional asymmetry across five dynamical regimes. The basin mean conceals pronounced sign reversals (Figs. 4 and 5). During MHW growth, HFC_E was positive in the subpolar front (+0.336 K; 23.3% of ΔT_{anom}) and Japan-side region (+2.993 K; 234.8%), weakly positive along the EKWC (+0.224K; 17.6%), but negative in East Korea Bay (-0.443 K) and the Ulleung Basin (-0.802 K). Only the subpolar-front and Japan-side ratios were distinguishable from zero at the 5% level, and the Japan-side interval was very wide. These patterns show that mesoscale anomalies can either converge warm water or oppose MHW growth depending on the background current, frontal gradient and object position.

During MHW decay, HFC_E was negative in all five regions, from -0.899 K along the EKWC to -3.319 K in the Ulleung Basin (significantly so in EKB, UB and SPF); it exceeded 100% of the regional net cooling in East Korea Bay, the Ulleung Basin, subpolar front and Japan-side region (point estimate). Regional MCS growth was again non-mirror-symmetric: HFC_E strongly opposed cooling along the EKWC (+2.222 K; -156.9% of ΔT_{anom}), was nearly neutral in the Ulleung Basin, and enhanced cooling in East Korea Bay, the subpolar front and Japan-side region. In contrast, MCS recovery exhibited positive HFC_E in every region, with ratios from 67.3% in East Korea Bay to 274.9% in the Ulleung Basin. The robust spatial coherence during termination contrasts with the heterogeneous onset pathways. Complete regional values are listed in Supplementary Table S2; signed absolute-magnitude-normalized shares are shown in Supplementary Figs. S6 and S7.

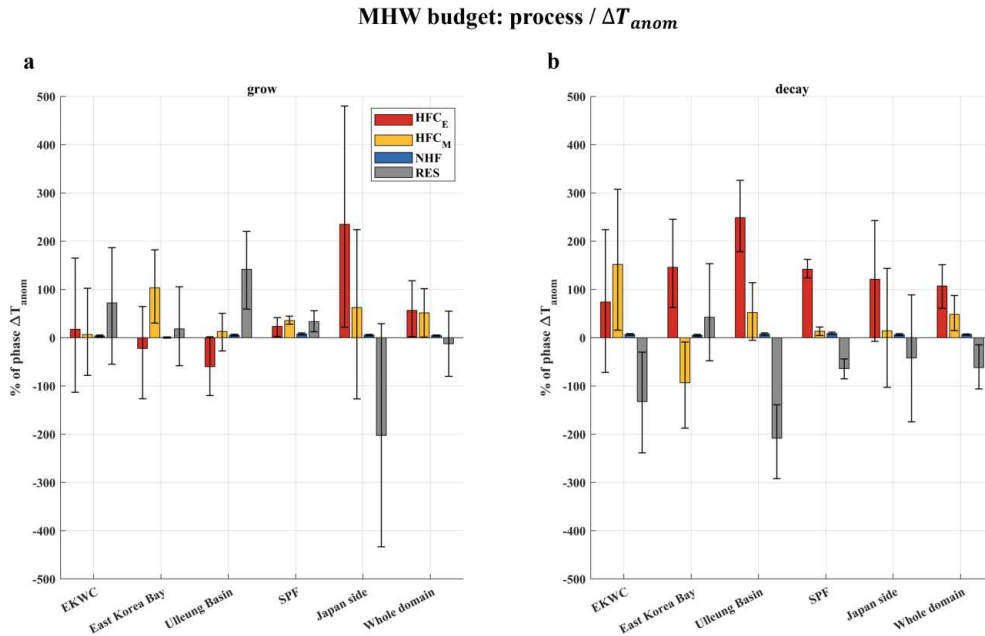


Figure 4. Regional lifecycle heat-budget contributions for $T_{m,50}$ -detected MHW objects: (a) growth and (b) decay. Bars report signed net-change ratios, $100 C_X/\Delta T_{anom}$, for HFC_E , HFC_M , NHF , and RES ; whiskers are 95% peak-year cluster-bootstrap confidence intervals. Objects are assigned by their peak cell to five mutually exclusive regions. Values above 100% indicate compensation by other terms, whereas negative values oppose the net phase change.

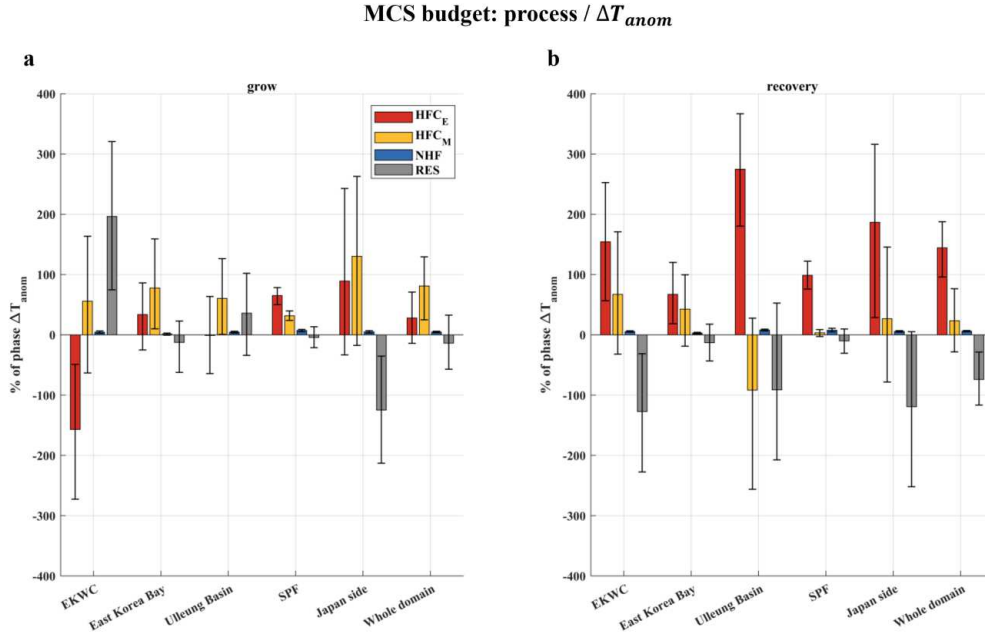


Figure 5. As in Fig. 4, but for MCS (a) growth and (b) recovery. Positive percentages during recovery indicate warming toward climatological conditions. The sign reversal along the EKWC during growth demonstrates that MHW and MCS formations are not simple mirror images.

Different Reynolds components organize each lifecycle phase. The total HFC_E term arose from different component balances (Fig. 6). MHW growth combined the pure covariance term (+0.344 K) and mean-current transport of temperature perturbations (+0.460 K), whereas perturbation-velocity transport across the mean temperature field was near zero (-0.007 K). During MHW decay all components cooled, with the largest contribution from perturbation velocity across the mean gradient (-0.741 K), followed by mean-current transport of T' (-0.432 K) and covariance (-0.237 K).

MCS growth contained strong cancellation: covariance and mean-current transport of T' cooled by -0.394 and -0.822 K, respectively, while $u'\bar{T}$ transport warmed by +0.799 K. During recovery the balance reversed; $u'\bar{T}$ transport supplied +1.870 K and mean-current transport of T' +0.464 K, partly offset by covariance (-0.167 K). Thus, the robust termination signal is primarily a perturbation-flow interaction with the strong mean East Sea temperature gradients, not simply the divergence of $u'T'$ within isolated eddy cores.

Three components of HFC_E

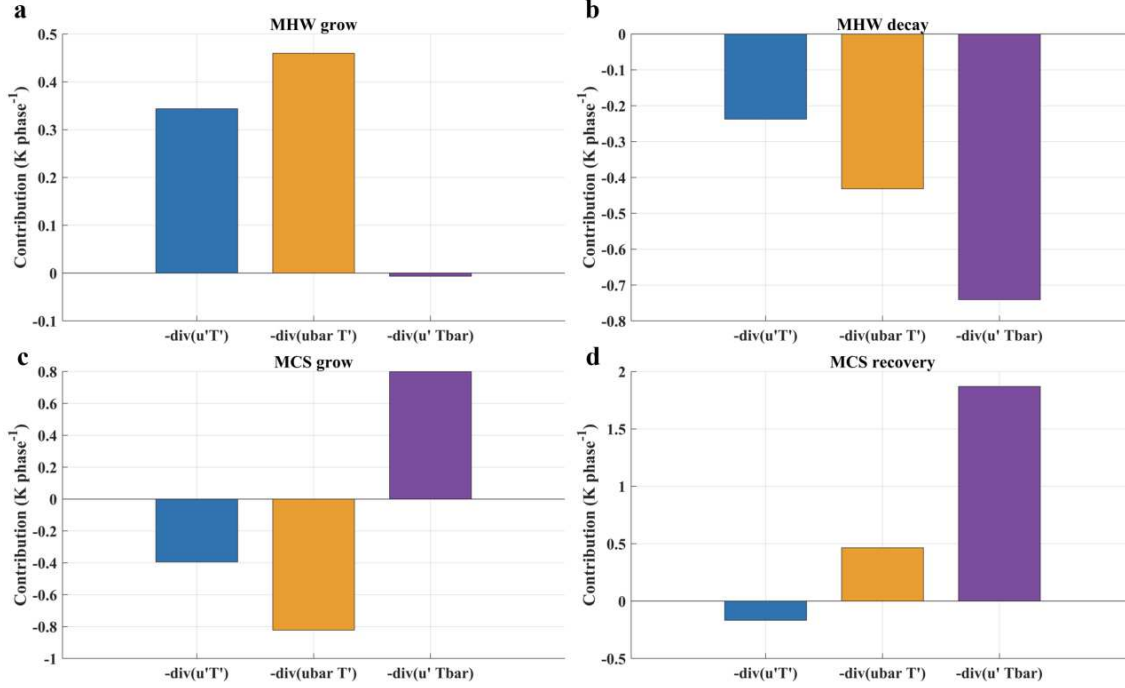


Figure 6. Reynolds decomposition of whole-domain HFC_E for (a) MHW growth, (b) MHW decay, (c) MCS growth, and (d) MCS recovery. Contributions are shown for pure mesoscale covariance $-\nabla \cdot (u'T')$, mean-current transport of temperature perturbation $-\nabla \cdot (\bar{u}T')$, and perturbation-velocity transport across the mean temperature field $-\nabla \cdot (u'\bar{T})$. The component sum reproduces total HFC_E to numerical precision apart from finite-filter commutation and discretization error.

Surface-flux feedback and sensitivity. Although NHF was smaller than horizontal convergence, its sign systematically favored lifecycle relaxation. Latent and sensible heat fluxes dominated: MHW growth received +0.030 and +0.026 K from latent and sensible components, whereas decay received -0.045 and -0.029 K. MCS growth received -0.034 and -0.028 K, and recovery +0.047 and +0.030 K. Shortwave and longwave contributions were smaller. This symmetry is consistent with turbulent air-sea feedback on an existing temperature anomaly, but does not exclude atmospheric control of currents, stratification or mesoscale organization. Component-resolved surface-flux contributions are shown in Supplementary Fig. S1.

The core termination result persisted in both sensitivity experiments (Fig. 7). MHW-decay HFC_E was -1.410 K (107.2%) in the H50-6×Rd baseline, -2.480 K (191.0%) for H30-6×Rd and -1.664 K (126.5%) for H50-9×Rd. MCS-recovery values were +2.167 K (144.4%), +2.008 K (130.7%) and +2.323 K (154.8%), respectively. Magnitudes changed with depth and the scale assigned to the low-pass filter, as expected, but HFC_E remained the leading resolved relaxation term. Growth budgets were more sensitive, reinforcing the conclusion that the mesoscale contribution during growth is region- and definition-dependent.

Fixed-depth and deformation-scale sensitivity

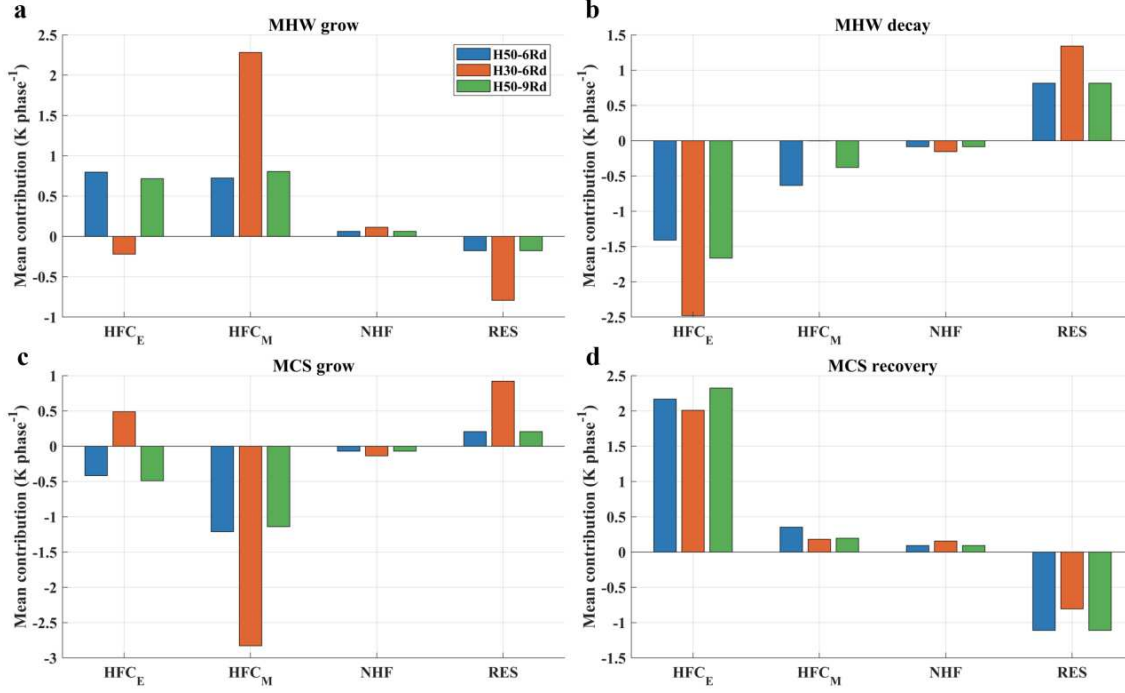


Figure 7. Fixed-depth and deformation-scale sensitivity for (a) MHW growth, (b) MHW decay, (c) MCS growth, and (d) MCS recovery. Whole-domain object-mean lifecycle contributions are compared among the H=50 m with a 6×Rd filter (baseline), H=30 m with 6×Rd, and H=50 m with 9×Rd. Every experiment repeats layer integration, event detection, object construction and process integration rather than rescaling the 50 m result.

Discussion

A termination mechanism rather than a universal initiation mechanism

Our principal result refines the global conclusion that mesoscale heat-flux convergence is a crucial MHW driver [10]. In the East Sea, HFC_E is important during MHW growth, but it shares the basin-mean warming with HFC_M and reverses sign among regions. MCS growth is more clearly controlled by HFC_M . In contrast, HFC_E consistently cools MHWs and warms MCSs after their peaks, usually exceeding the net phase change because RES and occasionally mean transport oppose it. Mesoscale motions therefore appear to erode established temperature anomalies efficiently by reorganizing strong background gradients, even when they did not initiate the anomaly. This phase asymmetry would be obscured by annual MHW-day statistics or contemporaneous eddy-event co-location.

The difference from Bian et al. [10] is not necessarily contradictory. Their global average combines many dynamically distinct regions, uses a fixed 3° filter and grid-local events, and diagnoses a fully model-consistent heat equation. The East Sea is a compact, topographically constrained basin in which the EKWC, North Korea Cold Current, subpolar front and warm/cold eddy field have dimensions comparable to the filter scale. Independent-object weighting also prevents a single broad event from contributing thousands of nominal samples. Our HFC_E retains the same Reynolds cross-terms but the deformation-scale filter moves the mean-eddy boundary toward locally relevant mesoscale dimensions. The 9×Rd experiment demonstrates that numeric contributions depend on this scale choice, while the lifecycle contrast is more stable. The contrast with the state-estimate result of Sala et al. [11] further indicates that global attribution depends on region, closure framework, and event definition.

Relation to previous East Sea studies

The positive MHW-growth contributions from both HFC_E and HFC_M provide a direct process counterpart to earlier inferences that increasing East Sea MHW exposure cannot be explained by surface heating alone [13] and that lateral transport is important in East Korea Bay [15]. The subpolar-front signal is consistent with winter frontal displacement and EKWC northward penetration [14], but our component analysis adds a distinction: the event-scale effect can arise from mean currents carrying mesoscale temperature anomalies or perturbation velocities crossing the mean gradient, not only from a bulk shift of the entire front. Conversely, the negative MHW-growth HFC_E in parts of the western basin shows that a region may host vigorous eddies while mesoscale convergence actively limits warming. Comparable western-boundary-current evidence links eddy-current interactions to anomalous poleward heat transport [12].

The modest surface/ $T_{m,50}$ overlap supports prior evidence for multiple vertical MHW structures [18] and direct subsurface events [19, 20]. It also explains why a surface-detected heatwave can coexist with weak or opposing $T_{m,50}$ heat convergence: the surface layer may respond rapidly to shortwave or turbulent forcing while the deeper layer is controlled by current and thermocline processes. The strong HFC_M contribution to MCS growth complements the recent western-boundary winter MCS result [23], in which cold, fresh water intrusion and horizontal advection were central. Our basin-wide analysis extends that case-study mechanism but does not resolve its salinity-controlled entrainment pathway, which remains in *RES*.

Interpretive cautions

Several cautions are essential. First, a signed contribution above 100% is physically possible and denotes compensation; it must not be described as a fractional partition of a positive-only budget. Second, HFC_E includes three terms and should not be equated with pure $u'T'$ covariance or with heat retained inside tracked anticyclonic and cyclonic eddy contours. Third, statistical significance is based on only 30 peak-year clusters; some regional confidence intervals are wide, especially where a few large objects dominate. Fourth, detrending changes the scientific question. The results describe transient dynamical extremes around a linearly changing background, not the total fixed-baseline ecological exposure experienced during warming. Parallel fixed-baseline statistics are appropriate for impacts but not for the present mechanism isolation [36]. Fifth, the direct connectivity algorithm can join distinct features through narrow space-time bridges, while the absence of a minimum-area criterion leaves many small objects (median four to five cells). Recent object frameworks demonstrate that splitting, merging, minimum-volume and overlap rules can affect event counts [29–31]. Sixth, ERA5 fluxes and GLORYS12 temperature/velocity are not generated by one perfectly closed model budget. *RES* includes vertical and numerical physics, assimilation increments, remaining finite-volume and filter-commutation errors, and product mismatch. Unresolved submesoscale motions may contribute to *RES*, but they cannot be separated from vertical, numerical, assimilation and cross-product effects and are not assigned an independent causal role here. Finally, GLORYS12 is eddy-rich but does not resolve the full submesoscale range in the East Sea; strong coastal gradients, narrow jets and cross-frontal secondary circulations remain incompletely represented. Wide regional intervals are expected because the effective inferential sample is 30 peak-year clusters, interannual object counts are uneven, and the signed contribution ratio is a ratio of two varying estimands.

Fixed depth versus mixed-layer depth

The 30 m sensitivity is a new budget because all depth-dependent quantities—temperature endpoint, velocity–temperature products, spherical convergence, transmitted shortwave and heat capacity—are recomputed over 0–30 m. It is not a simple multiplication of the 50 m terms by 50/30. The same principle explains why a grid- and time-varying MLD cannot be inserted as H in the fixed-layer equations. A moving control volume requires explicit entrainment/detrainment associated with $\partial h/\partial t$ and $u \cdot \nabla h$, the temperature jump across the base, basal turbulent and radiative fluxes, and consistent treatment of detrainment. MLD also depends on the chosen density or temperature criterion and can outcrop or deepen beyond available daily vertical resolution [8, 22]. A mixed-layer heat budget is an important next step, but should be presented as a separate formulation rather than a sensitivity switch. This distinction follows established mixed-layer heat-budget formulations [26, 27]

Future sensitivity and validation

Further work should (i) compare $3\times R_d$, $6\times R_d$ and $9\times R_d$ without a clipping floor that collapses distinct scales; (ii) use Gaussian and spectral filters and quantify commutation residuals; (iii) impose minimum object area/volume and explicitly handle splitting and merging; (iv) stratify by season, because atmospheric forcing, MLD and frontal pathways differ strongly between summer and winter [14, 17, 21–23]; (v) repeat budgets at 20, 30, 50, 100 and 200 m to connect shallow and thermocline extremes [7, 18–20]; and (vi) validate event and current structures with OSTIA/OISST, Argo, ESROB, satellite altimetry and regional high-resolution models. Explicit vertical advection, entrainment and model-diagnosed mixing would convert RES from a broad closure term into testable processes. Finally, matching MHW/MCS objects to independently tracked anticyclonic and cyclonic eddies would distinguish generic mesoscale heat convergence from eddy polarity, translation and life stage.

Conclusions

A detrended, independent-object heat-budget analysis reveals that mesoscale transport plays phase- and region-dependent roles in East Sea marine temperature extremes. SST and $T_{m,50}$ events overlap only partially, so surface catalogues cannot substitute for a layer-conservative mechanism analysis. HFC_E and HFC_M jointly support basin-mean MHW growth, while HFC_M dominates MCS growth. Once an extreme reaches its peak, HFC_E becomes the most coherent resolved relaxation mechanism: it cools MHWs and warms MCSs across nearly all dynamical regions, often more strongly than the net temperature change because vertical and unresolved processes compensate it.

The Reynolds components show why a broad label such as ‘eddy heat transport’ is insufficient. MHW growth mainly combines pure covariance and mean-current transport of temperature perturbations, whereas termination is dominated by perturbation velocities acting on the mean temperature field. The 30 m and $9\times R_d$ experiments preserve the central lifecycle contrast while changing contribution magnitudes.

The key distinction is therefore not simply between warm and cold extremes, but between lifecycle phases. Their growth is governed by different combinations of mean and mesoscale transport and varies regionally, whereas post-peak mesoscale heat transport consistently acts to reduce established thermal anomalies. This lifecycle asymmetry provides a principal refinement to previous views of mesoscale forcing as a general driver of marine temperature extremes.

Data availability

The 1993–2022 daily GLORYS12V1 reanalysis data used in this study are publicly available from the Copernicus Marine Data Store under the Global Ocean Physics Reanalysis product (product ID: GLOBAL_MULTIYEAR_PHY_001_030) at https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/services (persistent DOI: <https://doi.org/10.48670/moi-00021>; accessed on 7 April 2025).

ERA5 hourly data on single levels used in this study are publicly available from the Copernicus Climate Data Store at <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview> (DOI: <https://doi.org/10.24381/cds.adbb2d47>; accessed on 10 April 2025).

Derived independent-object catalogues and summary tables will be deposited in a public repository upon acceptance; during review they are available from the corresponding author on reasonable request.

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Author contributions statement

Conceptualization, G.L. and J.-J.P.; methodology, G.L.; formal analysis, G.L.; investigation, G.L.; data curation, G.L.; writing—original draft preparation, G.L.; writing—review and editing, G.L. and J.-J.P.; visualization, G.L.; supervision, J.-J.P.; funding acquisition, J.-J.P. and G.L. All authors have read and agreed to the published version of the manuscript.

Competing interests

The author(s) declare no competing interests.

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