constrained by a trade-off between mean temperatures near physiological optima (~24 °C) and the risk of frequent excursions into suboptimal or lethal warmth in highly variable environments, emphasizing the importance of temporal variability as a concurrent limiting factor (Lluch-Cota et al., 2023). A mechanistic "metabolic index" calibrated for red abalone shows that warming and deoxygenation shift the temperature of maximal oxygen supply to cooler values, shrinking viable habitat-especially for larger individuals-and offering a framework to link physiology with projected range contractions under climate change (Duncan et al., 2023).

3 Temperature Variability in Marine Aquaculture Environments

3.1 Seasonal and diurnal temperature variation patterns in natural marine waters

In shallow coastal habitats typical of many aquaculture sites, temperature is dominated by a strong seasonal cycle, with warm summers and cold winters, overlaid by rapid short-term variability. Hourly records from a 5 m coastal site in the eastern Adriatic show that seasonal changes are prevalent, but diurnal changes are quasi-persistent year-round, and rapid shifts during stratified seasons can reach 2 °C per hour, with marine heatwaves and cold spells strongest in spring and summer (Vilibić et al., 2022). Similar patterns emerge in the northern Yellow Sea, where bottom temperatures at aquaculture sites exceed 20 °C in late summer and fall below 5 °C in winter, with some locations experiencing fortnightly oscillations of several degrees linked to tidal currents and thermal fronts. Such high-frequency variability has direct implications for benthic invertebrates and farmed stocks. The Adriatic study notes that rapid changes of up to 2 °C per hour may affect benthic communities and species physiology, particularly under global warming where environmental conditions are already near tolerance thresholds. In the Yellow Sea, modelled bottom-temperature variability has been linked to damage in bottom-cultured scallops, and a spatial index of variability has been proposed to guide site selection and design of temperature-stress experiments, a concept directly transferable to abalone aquaculture planning (Asplin et al., 2021).

3.2 Occurrence patterns of extreme high- and low-temperature events

Beyond regular cycles, extreme warm events—marine heatwaves—are increasingly recognized as a major threat to marine ecosystems, fisheries and aquaculture. A hierarchical framework defines marine heatwaves as prolonged, discrete, anomalously warm water events with temperatures above the 90th percentile for at least five days, emphasizing metrics such as duration, intensity and spatial extent to enable consistent comparison of events and their biological impacts (Hobday et al., 2016). Global analyses show that the most extreme marine heatwaves preferentially occur in summer, when mixed layers are shallow and winds weak, and that their duration has increased multi-decadally, with about 60% of the ocean experiencing its longest-duration event since 2010. Historical reconstructions over 1925-2016 reveal that globally, marine heatwave frequency and duration increased by 34% and 17%, respectively, leading to a 54% rise in annual marine heatwave days, largely attributable to rising mean ocean temperatures (Oliver et al., 2018). For aquaculture, regional case studies in the western Mediterranean show marine heatwaves have become about three times more frequent with 50% longer durations compared with the 1980s, including a 2022 event where anomalies up to 4.2 °C persisted the entire summer—conditions that exceeded fish thermal welfare thresholds and raise concerns for farmed stocks (Atalah et al., 2024).

3.3 Long-term trends in seawater temperature under climate change

Long-term observational and modelling studies show that coastal and open-ocean temperatures are rising, reshaping the background conditions on which shorter-term variability is superimposed. A global coastal analysis using CMIP6 models projects significant coastal sea surface warming, with most basins experiencing about a 1 °C increase by mid-century and some regions exceeding 2 °C anomalies relative to 1995-2014, indicating that nearshore systems where aquaculture is concentrated will face faster and more variable warming than previously observed (Varela et al., 2023). High-resolution analyses of coastal sea surface temperatures over three decades similarly report that 71% of the world's coastlines are significantly warming, with heterogeneous rates, a marked decrease in extremely cold events on 46% of coasts, and more frequent extremely hot days on 38%, as well as earlier onset of the warm season in many temperate regions. At the global scale, ocean heat content has increased markedly, with reanalysis indicating a 62-year warming signal and a statistically significant acceleration in recent decades, meaning that a growing fraction of the ocean now reaches its maximum yearly heat content in the most recent years (Storto and Yang, 2024).