



Animal indicators of climate stress in Mediterranean marine protected areas: evidence limits and monitoring design

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<https://doi.org/10.67784/1005>

Abstract. Animal observations can reveal ecological change in marine protected areas, but their conservation importance and their ability to diagnose climatic causes are different properties. This critical narrative synthesis examines how those two properties differ across four observation classes: benthic condition, coastal fish composition, seabird reproduction and unusual animal occurrences. Selected primary studies and methodological papers were compared according to response mechanism, observation scale, environmental exposure and alternative explanations. The first author's doctoral thesis on Al Hoceima National Park, Morocco, provided the local application context without contributing new population estimates or climate-attribution results. The synthesis identifies three recurring interpretation problems: mismatched spatial and temporal scales, changing observation effort, and transfer of relationships between species or regions without local testing. It develops an indicator–evidence matrix, a minimum record specification and a conceptual decision diagram that separates conservation urgency from confidence in a climatic explanation. Benthic condition surveys paired with temperature at organism depth offer a tractable event-monitoring approach; fish thermal composition requires repeated, comparable community sampling; reproductive measures integrate wider food-web and disturbance effects; and isolated occurrences primarily support verification and targeted follow-up. A worked detection example demonstrates why repeated non-detection remains conditional on observation probability. For Al Hoceima, the proposed first step is to recover and pair existing benthic photographs and temperature records before expanding monitoring. The contribution is a testable design for interpretation, not a validated early-warning system or evidence of local climate-driven decline.

Keywords: animal indicators, climate attribution, coastal monitoring, detection probability, marine heatwaves, Mediterranean Sea.

Introduction. An animal can be an important conservation target without being a specific indicator of climate stress (Piatt et al., 2020; Garrabou et al., 2022). A species may disappear from observations because it moved, became less detectable or experienced a local pressure (MacKenzie et al., 2002). Conversely, a relatively inconspicuous benthic population may reveal a thermal disturbance when biological condition and environmental exposure are measured at compatible spatial and temporal scales (Garrabou et al., 2022). Choosing indicators solely because they are visible, charismatic or already monitored therefore risks conflating ecological significance with diagnostic capability (MacKenzie et al., 2002; Piatt et al., 2020).

Mediterranean evidence provides both reasons to monitor and reasons to constrain interpretation. Garrabou et al. (2022) linked recurrent animal mass-mortality events during 2015–2019 with marine heat exposure across regions and depths. Givan et al. (2018) found that thermal affinity helped explain changes in eastern Mediterranean fish abundance. These studies support temperature-sensitive biological pathways, but they do not establish that every local loss, arrival or compositional difference has the same cause. Basin-wide warming documented by Pastor et al. (2020) supplies environmental context; it cannot replace exposure measurements for a particular population.

The practical problem is especially acute where observations are assembled from habitat mapping, species surveys, opportunistic reports and short projects. Such records may support habitat protection or identify a monitoring opportunity even when they cannot estimate a trend. An assessment that rejects them entirely loses useful information. An assessment that pools them indiscriminately manufactures comparability. The more useful question is what each observation can establish and what additional measurement would change that conclusion.

This study asks: (1) which animal responses offer a biologically plausible signal of thermal stress or reorganization; (2) what evidence distinguishes that signal from sampling effects and competing pressures; and (3) how can monitoring be designed around these distinctions in Al Hoceima National Park (PNAH)? The focus is the biological interpretation of observations. Institutional architecture, participatory scenarios and protected-area management-effectiveness scores are outside the analysis. The term early warning is used only for a proposed monitoring function: predictive lead time, sensitivity and false-alarm rates have not been established.

Material and Method

Evidence-synthesis design and source selection. A critical narrative synthesis was conducted using targeted web retrieval of journal articles, publisher pages and research repositories during manuscript preparation before initial submission. Searches addressed Mediterranean marine heatwaves and animal mortality, fish thermal affinity, ClimateFish monitoring, seabird responses to marine heatwaves, jellyfish bloom attribution and imperfect detection. Searches by exact title or DOI were used to locate the source papers. The purpose was to compare the inferential requirements of contrasting observation types, not to enumerate all relevant publications. No claim of a systematic or exhaustive search or meta-analysis is made.

Sources were retained when they supplied empirical evidence for a response-exposure relationship, a reproducible observation protocol, or a methodological limitation directly relevant to interpretation. Mediterranean field studies were prioritized. The northeast Pacific seabird study was retained as an explicitly external mechanistic comparison rather than evidence for a Mediterranean species response. General commentary was not used to establish biological effects. Publisher or repository records were checked for title, year and DOI; interpretation was restricted to accessible abstracts, methods and results. This mixed access limits the depth of critical appraisal for some sources.

For each response class, extraction addressed the biological quantity, observational unit, thermal-exposure requirement, relevant alternative explanation and strongest defensible inference.

Use of Karim's doctoral thesis manuscript. Karim's doctoral thesis manuscript on marine-observatory development and climate adaptation was examined for habitat and observation context (Karim, 2026). The sections on coralligenous communities describe permanent stations at Alcalá, Topos and Boussekour, photographic quadrats and temperature recorders; the broader diagnostic describes coastal fish, breeding birds and marine-cave conservation targets. These statements are treated as documentary descriptions, not independently verified evidence that the equipment remains operational or that continuous paired time series are available.

Results and Discussion. The evidence synthesis produced the qualitative comparison presented in Table 1. Evidence strength was not converted into a numerical score because the source designs, taxa and response variables are heterogeneous; studies sharing a monitoring approach were not treated as independent replication of a local effect.

The supplied observatory-design and Climagine manuscripts were compared to delimit the present contribution. Their management scores, readiness ratings, governance arrangements, scenarios and proposed composite systems were excluded from the present analysis. Species-specific abundance, breeding and habitat-change estimates from papers

submitted elsewhere are not reanalysed. Historical inventories, including campaigns separated by many years, are not pooled into a climate trend without comparable effort, habitat coverage and taxonomic resolution. Table 2 identifies the restricted use made of Karim's doctoral thesis manuscript and the measurements needed for a future test.

Resulting interpretation framework. The synthesis distinguishes four questions: whether an observation is valid, whether a biological change is demonstrated, whether a thermal explanation is supported, and whether conservation action is urgent. These questions are related but are not interchangeable. Figure 1 represents the last two as separate dimensions. Its categories are qualitative proposals, not estimated probabilities or validated management thresholds. A simple worked probability example is included to expose the assumptions behind interpreting non-detection; its inputs are hypothetical and are not estimates for PNAH.

Biological response and exposure must be matched. The selected evidence supports a response-specific approach rather than a universal animal climate index. Acute condition changes concern individuals or colonies exposed during an event; community composition can integrate recruitment, movement and survival over longer intervals; reproduction is tied to a breeding cycle and a foraging area; occurrence reports reflect both animal presence and observation opportunity. These differences determine what temperature data, baseline and replication are needed.

Hobday et al. (2016) define marine heatwaves using a seasonally varying high-temperature threshold and a minimum duration, allowing events to be described consistently. This climatological definition is not a biological damage threshold. A temperature excursion can meet a heatwave definition without causing a measurable effect in a particular population, while biologically important stress can depend on absolute temperature, acclimatization or interacting pressures. An application should report its reference climatology and temperature depth, and should not silently change the baseline between monitoring periods.

Satellite sea-surface temperature is valuable for regional timing and context. For organisms below the surface, it is an exposure proxy whose relevance needs assessment against water-column structure and local observations. Rubino et al. (2024), working with a long demersal-fish survey, explicitly compared surface and bottom temperature and examined lagged responses. Their results illustrate why the habitat and time scale of the organism matter; their fitted relationship is not a transferable calibration for shallow PNAH surveys.

Benthic condition: a promising event response, with identifiable alternatives. Sessile animals offer spatially explicit observation units because repeated photographs can revisit the same place. Garrabou et al. (2022) provided Mediterranean evidence that paired thermal and mortality observations can support event-level interpretation. The local question should nevertheless be formulated as a test: do newly affected organisms coincide with unusual exposure at their depth, after accounting for physical disturbance and other plausible causes?

A proposed measure is the fraction of assessed colonies showing a predefined condition change. Both numerator and denominator must be retained, together with the condition definition, image-quality rule and observation interval. Where individuals cannot be distinguished, a consistently classified cover measure is preferable to invented colony counts. The two measures describe different biological quantities and should not be combined into one time series.

Rephotographing the same units allows a distinction between old and new damage; surveying only visibly affected places does not estimate park-wide prevalence. Replication should therefore include preselected sites with contrasting exposure or pressure conditions, and records of apparently unaffected units. Images within one site are subsamples, not independent environmental replicates. A difference between depths also cannot automatically be attributed to temperature because depth covaries with light, hydrodynamics and community composition.

Fish composition: thermal affinity needs a stable sampling frame. Givan et al. (2018) found an association between species thermal affinity and abundance change in the eastern Mediterranean, where warming, fishing and biological invasion coexist. ClimateFish provides a complementary monitoring resource based on selected species and standardized visual observations across depth strata (Azzurro et al., 2022). Together, these approaches support repeated, hypothesis-led observation rather than interpretation of every warm-affinity species record as local climatic change.

For a future community analysis, a weighted thermal-composition measure can be defined as the sum of species abundance multiplied by independently sourced thermal affinity, divided by total included abundance. Its meaning depends on the survey and trait data. Counts, biomass and catch weights must not be interchanged. Missing affinities require an explicit coverage report, and a species list must remain stable or changes must be reconciled transparently. No thermal-composition value was calculated for PNAH in this synthesis.

A useful sensitivity analysis would compare results with and without non-indigenous taxa, across habitat strata, and under alternative defensible trait estimates. Species-level trajectories must accompany any aggregate index: the same index change can arise from arrival of warm-affinity taxa, loss of cool-affinity taxa or changing dominance among residents. Fishing, habitat structure, visibility and seasonal recruitment remain candidate explanations. A single-day comparison between natural rock and artificial substrate establishes a spatial contrast; it does not by itself establish a temporal response to warming.

Seabird reproduction: biologically integrated, causally indirect. Breeding outcomes can reflect food-web disruption, but the relevant exposure may occur across a foraging area and before the date of a nest visit. Piatt et al. (2020) documented reproductive failure and mortality associated with the northeast Pacific marine heatwave, using multiple biological and environmental lines of evidence. This is a demonstration of a possible trophic pathway, not a calibration for Mediterranean seabirds or for PNAH.

For local application, the priority is to define the observation unit before interpreting change: occupied territory, breeding pair, nest with eggs and successful nesting attempt are not equivalent denominators. Reproductive measures should retain the observation schedule and the evidence used to classify outcome. Disturbance, weather, prey availability and changes in fishing activity need consideration alongside temperature. A monitoring design that records only final success cannot reliably separate these pathways.

The present synthesis does not reproduce the PNAH osprey breeding series. Its general lesson is that a high-profile conservation target may integrate many pressures and consequently provide limited climatic specificity. That does not diminish its conservation value. It determines the wording of the inference and the supporting measurements required before climate attribution.

Unusual occurrences: verification before trend interpretation. A verified record of a rare, newly observed or intermittently present animal can support an occurrence statement and motivate additional observation. It cannot, by itself, establish colonization, increasing abundance or climate-driven range expansion. Repeated reports may also reflect changes in observer numbers, cameras or reporting platforms. Effort and identification evidence therefore belong in the occurrence record, not in a later reconstruction.

Pitt et al. (2018) showed that claims linking jellyfish blooms to human pressures can exceed the direct evidence and can be generalized from a restricted set of taxa. For PNAH, an isolated gelatinous-organism record should consequently remain event evidence unless standardized observations establish a broader pattern. Evidence for one jellyfish species should not be transferred to another solely because both form conspicuous aggregations.

Non-detection has a different but equally important limitation. MacKenzie et al. (2002) showed why occupancy inference requires accounting for imperfect detection. Under a simplified hypothetical design with constant per-visit detection probability p , conditional independence and unchanged occupancy, the probability of missing a present species on k visits is $(1 - p)^k$. With $p = 0.2$ and $k = 3$, it is 0.512; with $p = 0.5$ and $k =$

3, it is 0.125. These are conditional calculations, not probabilities that the species is absent after a survey. They illustrate why unknown detection effort cannot be repaired by treating missing observations as zero.

For mobile animals using marine caves or passing through coastal waters, the closure and independence assumptions may fail. Camera downtime, field of view, animal availability and repeated records of the same individual also matter. A defensible first output is therefore a documented detection history linked to functioning observation effort. A formal occupancy or habitat-use analysis should only follow when the design supports its assumptions.

Conservation urgency and climatic evidence are separate decisions. A key implication of Table 1 is that confidence in a climate explanation should not be used as the sole threshold for conservation attention. Severe observed harm with an uncertain cause may warrant prompt investigation and feasible reduction of local disturbance. Conversely, a well-supported thermal association with little demonstrated adverse consequence may call for continued monitoring rather than immediate restriction. Figure 1 separates these decisions.

Table 1

Biological response classes, supporting evidence and limits of climatic interpretation
(the matrix is a qualitative synthesis, not a ranking of species sensitivity)

<i>Response / source</i>	<i>Biological measure</i>	<i>Evidence needed</i>	<i>Principal limit</i>
Benthic condition (Garrahou et al., 2022)	Newly affected / assessed colonies; or consistently classified photographic cover	Repeat units; paired temperature at organism depth; condition definition; unaffected comparison units	Physical damage, disease and image changes can mimic a thermal effect. An event survey is not advance warning
Fish composition (Givan et al., 2018; Azzurro et al., 2022; Rubino et al., 2024)	Repeated abundance within fixed strata; thermal composition only with documented trait coverage	Comparable season, habitat, depth and effort; species trajectories; independent thermal affinities	Fishing, movement, recruitment and invasion interact. A spatial contrast cannot establish a warming trend
Seabird reproduction (Piatt et al., 2020)	Outcome per explicitly defined breeding unit; timing and observation history	Consistent denominators; foraging-scale exposure; prey and disturbance context	External mechanistic evidence is not local attribution. Breeding integrates multiple pressures
Gelatinous occurrences (Pitt et al., 2018)	Verified occurrence; standardized encounter rate only when effort is available	Identification evidence; date and location; observation effort; repeated seasonal coverage	An isolated record is not a bloom, expansion or warming response. Taxon transfer is uncertain
Rare-animal non-detection (MacKenzie et al., 2002)	Detection history linked to functioning observation effort	Repeat visits or observation periods; detection model; checks of closure and dependence	Non-detection is not absence. Camera availability and animal availability are different

Figure 1 intentionally avoids a single composite score. Summation could allow excellent identification to compensate numerically for absent exposure data, or serious harm to be downgraded because attribution remains unresolved. Instead, the observation record should state both conclusions explicitly: what ecological concern is supported, and how

strongly temperature contributes to its explanation. The strongest conclusion may remain 'documented change with unresolved cause'.

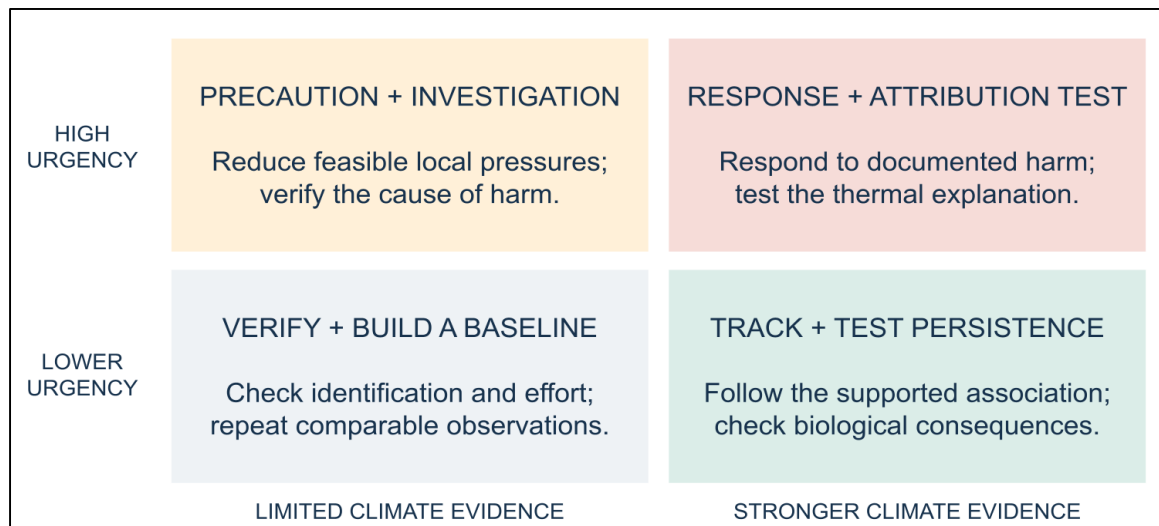


Figure 1. Conceptual separation of conservation urgency and strength of climatic evidence. The quadrants guide interpretation and proportionate follow-up; they are not validated risk classes.

Stronger evidence requires compatible exposure measurements, a demonstrated biological response and assessment of alternatives. Conservation urgency depends on observed harm, reversibility and the consequences of delay.

This distinction also prevents a circular interpretation in which observations are selected because they appear climate-related and are then offered as proof of climate effects. Candidate indicators should be chosen before inspecting the outcome of the next event. The sampling frame should include unchanged or apparently unaffected units. A future test should record unsuccessful alerts as carefully as successful ones, because false alarms and missed events determine whether a system offers useful warning.

Application to Al Hoceima: recover evidence before expanding indicators. Karim's doctoral thesis manuscript identifies an existing opportunity in benthic stations with photographic and temperature components (Karim, 2026). The immediate scientific task is to determine whether their records can be paired: station identifiers, acquisition dates, recorder depths, measurement intervals, gaps and image units must refer to compatible sampling periods. The doctoral thesis description alone cannot establish that this condition is met. Table 2 therefore separates the documented starting point from the additional evidence needed.

If compatible photographs and temperature series are recoverable, a first analysis could describe changes within consistently observed benthic units around documented thermal events. If only an initial photographic survey survives, it should be used to relocate units and establish a repeat baseline, not to estimate an unobserved trajectory. If only regional temperature data are available, exposure uncertainty should remain explicit. Recovering raw files and provenance can be more informative than immediately increasing the number of indicator species.

For fish, the appropriate first design is repeated observation within fixed habitat and depth strata, with consistent seasonal windows and effort. Historical inventories can identify taxa and habitats deserving coverage, but differences in list length cannot be interpreted as change without a common sampling frame. For breeding birds, harmonized denominators and observation histories precede climatic modelling. For unusual occurrences, a verified event register with an effort field precedes any trend claim. These are different starting points, not interchangeable measures of monitoring maturity.

Table 2

PNAH application specification. Local starting points are documentary descriptions in Karim's doctoral thesis manuscript; proposed measurements and analyses have not been implemented or validated by this synthesis

<i>Local starting point</i>	<i>Defensible use now</i>	<i>Minimum additional record</i>	<i>Proposed test / limit</i>
Benthic stations described at Alcalá, Topos and Boussekour; photographs and temperature recorders reported	Identify candidate locations and recover source records; no assertion of present equipment operation	Stable station and image-unit IDs; dates; depth; recorder interval, gaps and calibration history; condition rubric	Pair comparable records around an independently defined event. If pairing fails, establish a repeat baseline
Coastal fish observations and historical inventories	Identify candidate habitats and taxa; retain campaign-specific findings separately	Area or timed effort; habitat/depth stratum; season; visibility; observer; identification and abundance	Repeat comparable units. Do not compare richness across unequal methods as a climate trajectory
Breeding-bird conservation and monitoring described in the doctoral thesis manuscript	Specify biological units and reconcile terminology without reusing submitted breeding results	Visit dates; pair and attempt definitions; outcome evidence; disturbance and prey context	Test repeatability first; later assess competing explanations at the foraging scale
Marine-cave and rare-animal conservation targets	Identify detection-history requirements and sensitive-location controls	Functioning observation periods; field of view; visits; identification confidence; repeat-event rule	Estimate habitat use only if detection and closure assumptions are supportable
Opportunistic unusual-animal reports	Verify and retain an event record; select a follow-up question	Photo or diagnostic evidence; date; location precision; effort; species verification; environmental context	Seek repeat evidence with known effort. Do not infer climatic causation from novelty

A prospective test rather than a claim of validation. The proposed framework is testable at three levels. First, record completeness can be assessed: can each biological observation be linked to its unit, effort, date, habitat and environmental exposure? Second, measurement repeatability can be checked by independent interpretation of a subset of images or records. Third, predictive utility can be examined by developing an alert rule on earlier observations and assessing its performance on later, withheld observations. The third step requires sufficient independent events and cannot be inferred from the first two.

A future benthic analysis should preserve the nesting of organisms or image units within sites. When sample size permits, changes can be modelled against temperature exposure while accounting for repeated measures and measured alternatives. If there are few sites or a single event, descriptive estimates with transparent denominators are preferable to a complex model whose assumptions cannot be assessed. The necessary number of sites and visits should follow a pilot estimate of variability and the size of change that monitoring is intended to detect; no universal sample size is prescribed here.

Assessment should distinguish detection of an event from prediction before it occurs. A post-event condition survey can document impact but has no demonstrated advance warning. A prospective indicator must show that its signal precedes a specified adverse outcome by a useful interval. Evaluation should report that interval, the proportion of relevant events detected and the frequency of alerts without the anticipated outcome. None of these performance quantities is estimated in the present paper.

Competing explanations should be retained throughout model development. For fish, an apparent response may disappear after controlling for habitat or sampling season. For benthos, mechanical disturbance may better explain spatial concentration of affected colonies than temperature. For seabirds, prey information may alter the interpretation of

a breeding anomaly. Such outcomes would revise the indicator's role rather than represent a failed conservation programme. An indicator can remain useful for ecological surveillance even if its thermal specificity proves weak.

Limits and transferability. This synthesis uses a deliberately selected evidence base, with uneven access to full texts, and does not quantify publication bias or the completeness of Mediterranean coverage. Its response classes simplify substantial variation among species, life stages and habitats. Local documentation is secondary to the original monitoring records, and the availability of paired raw data has not been established. These constraints prevent empirical ranking of candidate indicators or claims about which PNAH species has already responded to climate change.

The proposed contribution is the explicit matching of observation type to allowable inference, coupled with separation of urgency from climatic confidence. It complements species studies and monitoring architectures by specifying their biological interpretation requirements. Transfer to another protected area should preserve those requirements while changing taxa, exposure measurements and sampling design to fit local ecology. A shared label such as 'sentinel species' is not sufficient evidence of transferability.

Conclusions. Animal monitoring becomes more informative when each indicator is tied to a biological quantity, an observation model and a plausible exposure pathway. Benthic condition, fish composition, reproduction and unusual occurrences supply different kinds of evidence and should not be collapsed into one climatic score. The proposed matrix and decision diagram make those differences explicit. In Al Hoceima, recovery of paired benthic photographs and temperature records is a defensible first opportunity, followed by standardized repeat sampling where needed. Conservation attention can respond to credible harm while the climatic explanation remains under investigation. Demonstrating an operational early-warning capability will require prospective validation, including lead time, detection performance and false alarms.

Author Contributions. SK conceptualized the study, conducted the literature search and documentary analysis, synthesized the evidence, prepared the tables and figure, and wrote the original manuscript; HB contributed to the methodology, validation and interpretation and critically revised the manuscript; HCD supervised the work, contributed to the conceptual framework and methodology, and critically revised the manuscript. All authors reviewed and approved the manuscript.

Competing Interests. The authors declare no competing interests.

Data Availability. No new field dataset was generated and no unpublished population series was statistically reanalysed. The evidence comparison and application specification are contained in Tables 1 and 2. Published sources are identified by DOI in the reference list. The local documentary context comes from Karim's unpublished doctoral thesis manuscript (Karim, 2026); access to underlying park monitoring records is not asserted.

Ethics Statement. This article is a literature and documentary synthesis. It involved no new animal handling, experimental intervention or recruitment of human participants.

Funding. No dedicated external funding was received for the preparation of this manuscript.

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Received: 29 August 2026. Accepted: 23 September 2026. Published online: 11 October 2026.

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How to cite this article:

Karim, S., Bouazzati, H., & Dekkaki, H. C. (2027). Animal indicators of climate stress in Mediterranean marine protected areas: evidence limits and monitoring design. *Animal Biology & Animal Husbandry*, 19(1), 30-38. <https://doi.org/10.67784/1005>