https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

Suppression of local upwelling in the Gulf of Panama predicted a season in advance

Ronan McAdam[1], Antonella Sanna[1], Giulia Bonino[1], and Enrico Scoccimarro[1]

[1]CMCC Foundation - Euro-Mediterranean Center on Climate Change, Bologna, Italy

Correspondence: Ronan McAdam (ronan.mcadam@cmcc.it)

Abstract. Wind-driven upwelling of subsurface ocean waters to the surface ensures nutrient-rich waters reach the epipelagic zone, supporting some of the most diverse ecosystems and largest fish stocks in the global ocean. In early 2025, the Gulf of Panama experienced a collapse of the local upwelling system not previously observed in historical records, with notable impacts on regional physical and biogeochemical conditions. Predictability of upwelling collapse in relatively local systems on seasonal timescales has yet to be assessed. Here, the predictability of upwelling in the Gulf of Panama is explored in an operational seasonal forecasting system. First, the extreme weakening of the northerly jets driving upwelling and the corresponding extreme sea surface temperatures of 2025 are shown to have been accurately predicted a season in advance. Crucially, hindcasts from the period 1993 to 2024 demonstrate high probabilistic and deterministic skill, and also capture the strong upwelling of 1998. By validating against a high-resolution global ocean reanalysis, an increase in temperature forecast skill with depth is uncovered, making the case for exploiting subsurface information for improved early-warning and description of upwelling events. Lastly, the occurrence of warm upwelling, specifically in 1998, raises a discussion of the most suitable upwelling indicators for the region. The seasonal forecast system sufficiently resolves wind stress-derived Ekman Pumping and the exceptionally weak vertical ocean velocity in 2025. This study demonstrates the capability of seasonal forecasts to provide early warning of upwelling collapse.

1 Introduction

Upwelling is the oceanic process by which cooler, nutrient-rich water is transported from the subsurface to the surface, most commonly driven by wind. The high nutrient concentration of upwelled waters enhances productivity and supports large populations of marine species, ensuring rich biodiversity and large stocks for the fishing industry. While the largest upwelling regions in the global ocean are the Eastern Boundary Upwelling Systems (EBUS) (Bograd et al., 2023), upwelling also occurs on local scales in bays and gulfs (Largier, 2020). Upwelling collapse can induce abrupt changes in the aquatic food web and drastic reductions in fish stocks upon which local economies may rely (Rykaczewski and Checkley, 2008). Early warning of impacts linked to abnormal seasonal upwelling conditions, such as reduced nutrient availability and elevated sea temperatures, has the potential to assist regional authorities, fisheries, and communities in anticipating shifts in fish stock abundance and location, and in mitigating resulting impacts to activities within the Blue Economy.

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

To promote the uptake of forecasts for ocean services, it is necessary to assess the predictability of upwelling in specific locations and ideally demonstrate the long-term reliability of forecasting systems in capturing anomalous conditions and rare instances of collapse. The predictability of upwelling is strongly linked to the prevailing wind systems, which control both offshore Ekman transport associated with Coastal Ekman Upwelling and wind-stress curl associated with Ekman Pumping. In the EBUS, upwelling is predictable on seasonal timescales, as shown for the California (Siedlecki et al., 2016; Amaya et al., 2024) and Benguela (Sylla et al., 2026) systems. Predictability of local upwelling systems, and in particular the skill of forecasting systems, is less explored.

The Gulf of Panama (GoP), situated in the Eastern Tropical Pacific Ocean, is home to a seasonal upwelling system driven by a narrow northerly wind jet (D'Croz et al., 1991). Upwelling typically occurs between January and March, and enhancement of nutrients and chlorophyll in this season has been observed within the Gulf and further equatorward towards the coasts of Colombia and Ecuador (D'Croz et al., 1991; D'Croz and O'Dea, 2007). Upwelling plays a dominant role in the variability of the abundance of species which sustain the local food web (Miglietta et al., 2008), as well as fishing stocks, catches and strategy (Team, 2015). Unlike in neighboring bays, corals in the GoP have historically been at lower risk of bleaching due to the cooling influence of upwelling (Randall et al., 2020). In 2025, an exceptional weakening of winds induced a suppression of the upwelling system that led to warmest sea surface temperature (SST) readings on record over the past 40 years (O'Dea et al., 2025). The warm waters then spread throughout the tropical Eastern Pacific along the coast of Ecuador (Ormaza-González et al., 2026). The impact of the 2025 event on local ecosystems and fisheries has yet to be reported, but such oceanic conditions were unprecedented in the historical observational record.

Seasonal forecasting systems are typically reliable in the Eastern Tropical Pacific, where interannual variability is largely governed by the El Niño Southern Oscillation (ENSO), but the local-scale skill of wind and ocean upwelling forecasts in the GoP has not been assessed. An ocean biogeochemical model forced by dynamical seasonal forecasts of the atmosphere and ocean displayed significant skill in the GoP even at several months lead time (Rousseaux et al., 2021), indicating the ability to capture interannual variability in upwelling conditions. The lack of publicly available data on subsurface ocean conditions, in both the seasonal forecasting systems and ocean reanalyses often used for validation, complicates the validation of upwelling. While Ekman Pumping provides an indicative velocity for the water column influenced by winds, vertical velocity can provide an explicit indicator of the motion of subsurface waters at specific depth levels. Instead, indicators for upwelling are typically derived from local temperature, wind stress gradients and sea level pressure (Bakun, 1973; Jacox et al., 2018), and do not explore subsurface conditions. Local phenomena may override or interact with upwelling to induce warm anomalies (Berkelmans et al., 2010), potentially rendering proxy indices unreliable. Lastly, while the horizontal resolution of the atmospheric models used in seasonal forecasting systems (0.5^o-1^o) may be sufficient for capturing upwelling in the relatively large EBUS, the adequacy of the derived indicators has not yet been tested for more local-scale systems such as the GoP.

In this study, we demonstrate the reliability of an operational seasonal forecast system in capturing the driving processes of upwelling in the GoP region, and show that the unprecedented weakening of 2025 was accurately forecast. Section 2 contains descriptions of the observations and reanalyses used to represent wind, ocean temperature and upwelling, as well as the Euro-Mediterranean Centre on Climate Change Seasonal Prediction System (version 4; CMCC-SPS4). Section 3 briefly describes

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

the Ekman Pumping indicator used in the study. Section 4 presents the forecasts of 2025, a validation of the hindcast period and comparison of upwelling indicators. Finally, Section 5 summarises the study and discusses implications and needs for early warning of upwelling conditions in the GoP and beyond.

2 Datasets

2.1 ERA5 Reanalysis

ERA5 is a global atmospheric reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF) which provides hourly fields with a horizontal spatial resolution of 0.25^o (Hersbach et al., 2020). ERA5 is based on the Integrated Forecasting System (IFS) Cy41r2 (ECMWF, 2016) and uses a 4D-Var ensemble assimilation scheme for the atmosphere. Remote Sensing scatterometer data is assimilated to provide information on near-surface wind over the global oceans; multi-platform data, including ERS1 & 2, QuikSCAT, Oceansat-2, and METOP A& B ASCAT scatterometers, ensures coverage from 1993 onwards. In this study, daily and monthly means of zonal and meridional surface turbulent wind stress components, and total surface heat flux (composed of latent heat, sensible heat, longwave and shortwave radiation) are used from 1993 onwards.

2.2 Copernicus Marine Service (CMS) Wind Stress

The CMS provides a bias correction of ERA5 wind stress and derived stress-equivalent winds using Metop-B and Metop-C ASCAT scatterometer observations. Here, it is used to highlight the change in representation of upwelling indicators with resolution. The dataset includes the derived wind stress curl fields over ocean at 0.125^o resolution from November 2007 onward we use monthly fields. For brevity, this product is referred to as the “CMS".

2.3 OSTIA Sea Surface Temperature

The Operational Sea Surface Temperature and Ice Analysis (OSTIA) is a global, gap-filled record of daily foundation SST from 1993 onwards, built from in-situ and satellite data (infrared and microwave radiometers), and provided at 0.05^o resolution (Donlon et al., 2012; Good et al., 2020).

2.4 In-situ Temperature Loggers

Automated temperature loggers at Isla Pacheca, situated in the central northern area of the GoP (8.660°N, 79.050°W), provide a record of ocean temperature at 6m depth. The data was made available by O’Dea et al. (2025) and covers the period 1995 to 2025, with the exception of 2021. Here, daily values of average of nighttime temperatures was calculated to ensure fair comparison with foundation SST provided by OSTIA.

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

2.5 GLORYS12 Ocean Reanalysis

GLORYS12 (version 1) is a global ocean reanalysis built on the NEMO model, driven at surface by ECMWF ERA-Interim then ERA5 reanalyses for recent years, and uses a reduced-order Kalman filter to assimilate along-track altimeter data, SST, and in situ temperature and salinity vertical profiles (Lellouche et al., 2021). GLORYS12 has a 1/12^o horizontal resolution and 50 vertical levels, and covers the period 1993 onwards. Here, we use monthly subsurface temperature fields. GLORYS12 is the highest resolution reanalysis available globally and for the GoP, and has demonstrated accurate representation of the Californian (Amaya et al., 2023) and Benguelan EBUS (Russo et al., 2022). Vertical velocity is not a publicly available output.

2.6 CMCC Seasonal Prediction System 4

The Euro-Mediterranean Centre on Climate Change Seasonal Prediction System version 4 (CMCC-SPS4) is an operational system which provides 6-month forecasts for the Copernicus Climate Change Service. It couples several Earth system component models - atmosphere, land, ocean, sea ice and river - including CAM6 for the atmosphere at a nominal horizontal resolution of 0.5^o, and NEMO4 for the ocean at a nominal resolution of 0.25^o and with 75 vertical levels. For the hindcast period, 30 ensemble members are generated using permutations of initial conditions provided by the land, ocean and atmospheric analyses; for the operational period (2025 onwards), 50 ensemble members are generated. A comprehensive technical description and validation of global climatologies and key climate indices (e.g. ENSO) can be found in (Sanna et al., 2025).

Here, forecasts initialised in October, November and December are used to predict the upwelling season from January to March. Daily SSTs and monthly subsurface temperatures and wind stress components are taken from the ocean model. Wind speed components are instead interpolated and only available at 1 degree resolution (see Data Availability).

While multi-model ensembles are often preferred for seasonal forecasting to account for inter-model uncertainty, such an approach was not feasible for all the analysis performed here, for two reasons. First, subsurface ocean fields are not routinely available across the broader ensemble of operational forecast systems. Second, available wind-stress fields are coarse (1^o resolution) and likely to be insufficient for deriving local-scale upwelling indices (Capet et al., 2004). We therefore rely on an in-house forecast system, which provides subsurface ocean output and wind stress fields at 0.25^o resolution. To assess the reliability of this choice, we compare the skill of our system against other operational systems for available surface variables SST and meridional wind speed. ECMWF 5.1 and Meteo-France 9 from the Copernicus Climate Change Service are used, as other system were either missing data or not available in "burst" mode i.e. not initialised on the first day of the month as CMCC-SPS4 is. We find comparable performance (Section 4.2 & Appendix C) with CMCC-SPS4, which supports confidence in the system's suitability for the subsurface analysis presented here, despite the inability to directly benchmark subsurface skill across models.

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

3 Methods

3.1 Upwelling Estimation

Wind-driven upwelling may occur in two ways: Ekman Coastal Upwelling and Ekman Pumping (or suction). Ekman Coastal Upwelling is formed by the alongshore component of wind stress and is crucial in near-coastal zones, while Ekman Pumping is a response to wind stress curl and is largely responsible for open ocean upwelling.

Ekman Coastal Upwelling ($m\,s^{-1}$), is defined as:

$$W_{cu} = \frac{\tau_{\|}}{\rho_w f L} \tag{1}$$

in which ρ_w, the potential sea water density, is 1.025 kg m^{-3}, and the Coriolis parameter is $2\Omega\sin(latitude)$, with $\Omega = 7.21291 \times 10^{-5}$ rad s^{-1}, $\tau_{\|}$ indicates wind stress alongshore, and L (m) is a characteristic cross-shore length scale representing the typical offshore extent of the coastal upwelling region (e.g., the width of the upwelling plume or the distance to the shelf break). The term $\tau_{\|}/(\rho_w f)$ represents the offshore Ekman Transport per unit coastline length ($m^2\,s^{-1}$), which is converted into a vertical velocity ($m\,s^{-1}$) by dividing by L.

Ekman Pumping ($m\,s^{-1}$), meanwhile, is defined as:

$$W_{pump} = \frac{1}{\rho_w f}\nabla\tau \tag{2}$$

where $\nabla\tau$ is the wind stress curl. ERA5 and CMCC-SPS4 provide wind stress components τ_x and τ_y, corresponding to 10m winds, used to calculate the wind stress curl.

Ekman Pumping is considered to be the dominant process in the region, having been previously used to explain SST and chlorophyll patterns in the region (Xie et al., 2005). In the GoP, upwelling is caused by strong northerly jets entering the area through topographic depressions (Legeckis, 1988). Over the Gulf, the meridional wind component dominates over the zonal component, inducing positive wind stress curl in the eastern part of the GoP; this leads to upwelling via Ekman Pumping (Eq. 2). Along the Panama and Colombia coastlines to the south-east of the GoP, winds are typically weak and zonal (Fig. 1), meaning the alongshore wind stress component is negligible and therefore the coastal upwelling of cool water (Eq.1) along the coast is very weak (Legeckis, 1988). The dominance of Ekman Pumping over Ekman Coastal Upwelling is also evidenced by the location of the resulting plume of relatively cool upwelled water; the plume originates in the central part of the Gulf, extends equatorward until 2-3^{o}N, and, crucially, is disconnected from the coastlines of Panama and Colombia (Fig. 1). For these reasons, Ekman Pumping is used to quantify upwelling in this study.

3.2 Forecast Skill Metrics

The Pearson correlation coefficient between forecast ensemble means and validation data is used to quantify deterministic skill. A p-value less than 0.05 is used to indicate statistical significance. Statistical significance of the correlation coefficients was assessed following the method implemented in SciPy's pearsonr function (default settings). The p-value is obtained by

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

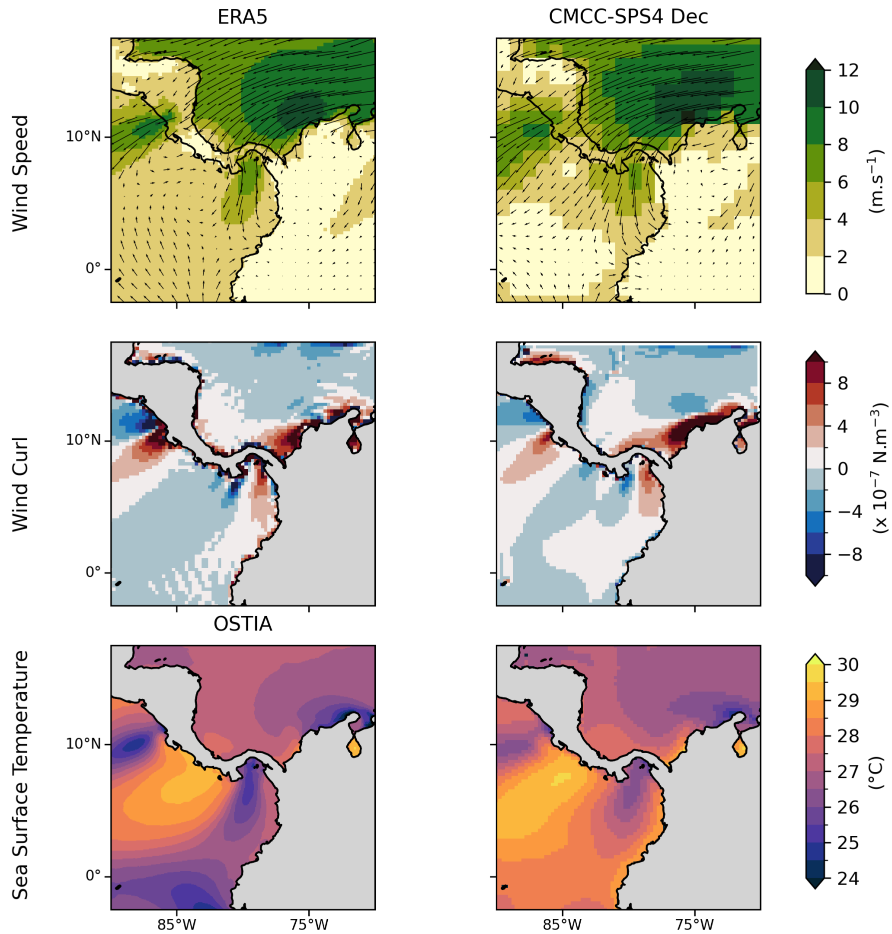

Figure 1. Regional Climatology of the Gulf of Panama. Average wind speeds, wind curl and SST for the upwelling season (January-February-March) over the period 1993-2024 in observational estimates (left) and the December initialisation of CMCC-SPS4 (right).

evaluating the probability that the correlation coefficient of an uncorrelated sample would exceed the observed correlation in magnitude.

145 The Relative Operating Characteristics Area Under Curve (AUC) is used to determine the reliability of the ensemble at capturing anomalous conditions. An AUC of 0.5 represents no skill and is equivalent to a random forecast, while 1 represents a perfect forecast. Here “events" refer to seasons in which values exceed the upper quintile for temperature or wind anomalies, and the lower quintile for upwelling. High skill means an observed event year is likely to receive a higher forecast probability than a non-event year.

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

All climatologies correspond to the period 1993 to 2024, with the exception of the in-situ temperature data, upwelling derived from CMS wind stress, and the chlorophyll, given their shorter coverage periods. Skill scores were calculated over the period 1993 (or starting date of data) to 2025.

4 Results

4.1 Accurate prediction of extreme temperatures in 2025

The 2025 upwelling season in the GoP was defined by weakened northerly winds, exceptionally warm SSTs and negligible concentrations of chlorophyll (Appendix A), confirming the weakened upwelling of cooler, nutrient-rich subsurface waters. In the GoP, as in other upwelling regions (Yu et al., 2020), air-sea coupling is initiated by upwelling: ocean heat intake generally peaks in mid-March, 2-3 weeks after upwelling as identified by climatological chlorophyll peak in February (Appendix A). In 2025, reduced upwelling led to lower-than-average heat flux into the ocean. The exceptional SSTs are therefore attributable to severely weakened upwelling, rather than atmospheric forcing.

The resulting persistent and exceptionally warm temperature anomalies are accurately captured by the CMCC-SPS4 system initialised in December (Fig. 2). In January, anomalies of SST were confined to the GoP before extending equatorward and peaking in magnitude ($> 3^oC$ in the GoP) in March. The monthly SST anomalies extending from the GoP to the coasts of South America exceed the upper quintile of temperatures experienced over the previous 32 years. The CMCC-SPS4 forecasts successfully capture the evolution of the regional SST anomalies and, while the magnitude is underestimated by the ensemble mean, the majority of ensemble members agree on the temperature anomalies exceeding the upper quintile. The ensemble also agrees strongly on the anomaly onset in early January and intensification until mid-February, after which the members begin to diverge more rapidly (Appendix B). Nonetheless, the forecasts agree on above-average SST persisting until the end of April.

Weaker-than-average winds are forecast by over 75% of ensemble members from mid-December to mid-February, while episodes of severe weakening (mid-February) and even reversals of jet direction are captured by individual ensemble members (i.e. in December, in which positive northward anomalies exceed climatological values; Appendix B). It is also noted that exceptionally warm SST anomalies in the Caribbean Sea and near-climatological conditions in the Southern Caribbean Upwelling System (SCUS) are accurately forecast (Fig. 2). Overall, the exceptionally weak winds and warm temperatures in the GoP, indicative of a weak upwelling season from January to March 2025, could have been accurately forecast a season in advance.

4.2 Validation of Hindcasts

A validation of hindcasts with OSTIA SST and ERA5 wind speeds from 1993 to 2025 highlights the reliability of CMCC-SPS4 to capture regional conditions in and around the GoP during the upwelling season. Comparing climatologies over 1993 to 2024 shows that the prevailing wind systems of the wider central American and Caribbean regions are well captured by the forecasting system (Fig. 1). The magnitude of the northerly jet over the GoP is accurate but the width is exaggerated, likely

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

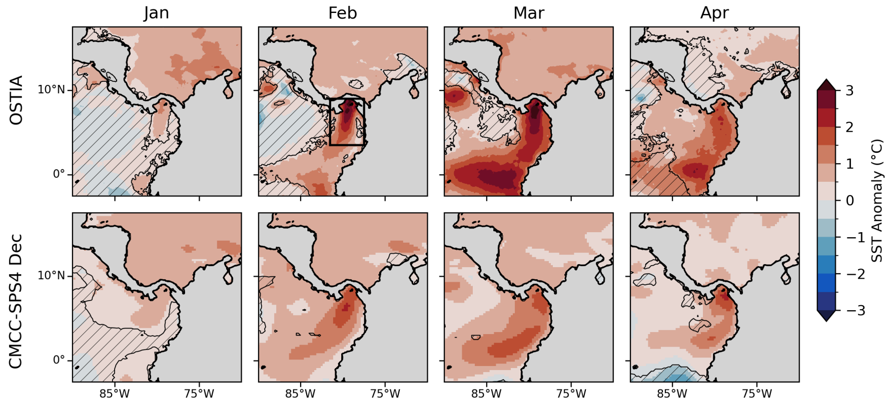

Figure 2. Forecasts of extreme sea surface temperatures anomalies in the Gulf of Panama in 2025. Top: OSTIA SST; black hatching indicates where temperatures do not exceed the upper quintile. Bottom: Ensemble mean of forecasts in the December initialisation of CMCC-SPS4; black hatching indicates where less than 50% of ensemble members predict temperatures exceeding the upper quintile. Black box: wider upwelling zone, used for time series calculations (e.g. Fig. 3). The climatology corresponds to the period 1993-2024.

due to the coarse topography in the atmospheric model representing poorly the narrowing of the jet by local mountains. For SST, the forecasts suffer from a regional warm bias in the Tropical Pacific but capture the relatively cool SST patterns caused by upwelling in the GoP and the SCUS.

When considering the potential impacts on regional fishing activities within and around the GoP, it is important to note that the larger region influenced by upwelling (Fig. 3) is indicative of conditions inside the bay, where fishing activities are likely to be concentrated; anomalies of 6m-depth temperature from the in-situ mooring at Isla Pacheca (O'Dea et al., 2025) correlate strongly with area-average SST from OSTIA (displaying a correlation of 0.83 between the period 1996-2025, excluding the missing year 2021).

Meridional wind and SST anomalies during the upwelling season are both reliably forecast over the hindcast period (Fig. 3). Correlation scores for both variables over the period 1993-2024 generally decrease with lead time between December and October, but remain statistically significant. AUC scores, which represent skill of capturing upper quintile events, remain above 0.5, indicating added-value of random forecasts. SST experiences a greater decrease in skill with lead time compared to meridional wind. A comparison with other state-of-the-art systems confirms that CMCC-SPS4 performs relatively well, and is therefore representative of current forecasting capabilities (Appendix C).

The seasonal-average wind anomalies of 2025 are correctly predicted as the maximum values on record (Fig. 3). For SST in 2025, all initialisations forecast positive anomalies but only the December initialisation forecast record values. Generally, years of strong anomalies in wind speed (1998, 2019) and SST (1998 and 2010) are well captured. The weakened northerlies in 2016 were underestimated, although the forecast anomaly stands out as relatively strong. A false alarm of warm SST anomalies was made for the same year, although the December forecast reduces the error by roughly a half compared to the October forecast.

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

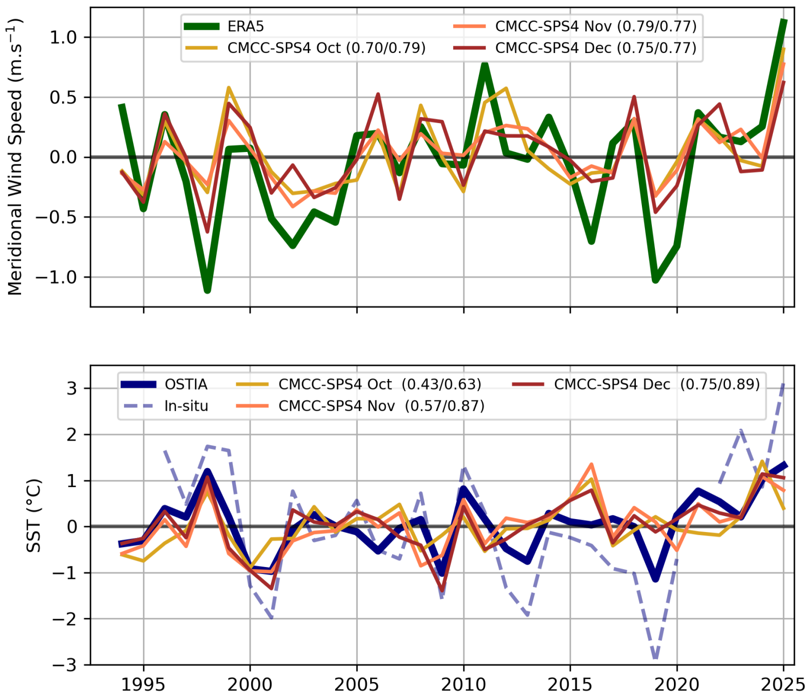

Figure 3. Hindcasts of meridional wind speed and sea surface temperature anomalies in the Gulf Of Panama upwelling region. Time series represent anomalies of area-averaged values during the upwelling season (January-March) relative to the 1993-2024 climatology. Three forecast initialisations are included: October, November and December. Wind speed convention: negative anomalies indicate stronger northerlies, while positive anomalies may indicate weaker or reversed northerlies. Values in brackets indicate correlation and AUC scores respectively.

The validation confirms the reliability of CMCC-SPS4 in the region, even at lead times of three months before the upwelling season.

While it may be expected that intensification of the northerlies (i.e. negative wind anomalies) would be linked to cooler-than-usual SSTs due to increased upwelling, this is not always observed in the GoP (Fig. 3). For example, in 1998, record intensification of the northerlies, which suggest stronger-than-average upwelling, corresponded with warm temperatures anomalies which nearly match those of 2025. Observational data confirms that 1998 experienced stronger wind speeds and positive SST anomalies from December to April, and a premature chlorophyll peak in January (Appendix D). Upwelling, therefore, did occur in 1998, but was earlier than usual and did not correspond with cool surface temperatures. The upwelling seasons in 1998 and 2025 displayed similar warm extremes in SST and, despite the different wind regimes governing the mechanics of each year, the forecast system captured both accurately.

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

4.3 Subsurface Temperature Forecasts

Given that SST is not always a reliable indicator for upwelling from the subsurface, and that wind does not directly highlight subsurface conditions, forecasts of subsurface information should be used to complement process understanding. The GLORYS12 ocean reanalysis is used here to identify the heterogeneity of seasonal anomalies throughout the water column, with the aim of providing context to surface anomalies (Fig. 4). In 2025, warm anomalies are restricted to the upper 30m and lie above relatively cool waters at climatological temperatures - a sign of weak upwelling. In 1998, conversely, warm anomalies were present throughout the water column, with peak intensity at 40m, implying the upwelling of warm waters. At the end of 1997 and beginning of 1998, ENSO was in a strong positive phase, which lead to the accumulation of warm waters throughout the upper ocean along the eastern Tropical Pacific and the GoP (Enfield, 2001). This water likely served as the source for warm upwelling in the GoP in 1998. A similarly strong positive ENSO event peaked in late 2015, but the wind anomaly for the upwelling season in 2016 was relatively weak, meaning SST remained at average conditions (Fig. 3).

The correlation skill of subsurface temperature increases with depth for October and November initialisations converging at 50m to match the skill of the December initialisations (Fig. 4). Good agreement between GLORYS12 and OSTIA at surface partially justifies the use of GLORYS12 to validate the seasonal forecast system. High skill at depth may be useful in determining the conditions of source waters for upwelling, such as detecting the exceptionally warm anomalies at 40-50 m depth in 1998 and the occurrence of warm upwelling.

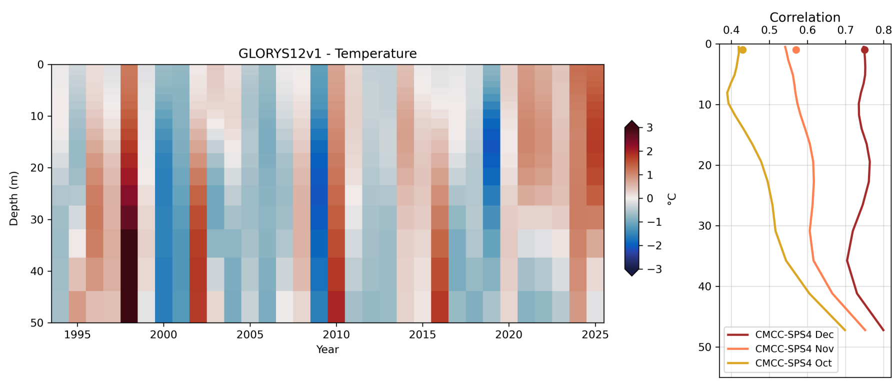

Figure 4. Subsurface temperature anomalies for Janaury-March in the upwelling region. Left: Depth-time diagram of subsurface temperature anomalies in GLORYS12. Right: Correlation skill of CMCC-SPS4 validated against GLORYS12; points indicate correlation of surface anomalies between forecasts and OSTIA SST.

4.4 Suitability of Upwelling Indicators

The CMCC-SPS4 represents accurately the driver (northerly wind jets) and the response (regional SST patterns) of upwelling, but the direct validation of upwelling is problematic due to a lack of vertical velocity data. Here, a commonly-used Ekman upwelling index derived from wind stress curl is first tested for its sensitivity to resolution, and then compared to total vertical

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

velocity only available in CMCC-SPS4. ERA5, which has a 0.25^o horizontal resolution, agrees with a 0.125^o observational-based model correction of ERA5 (Fig. 5) on the location of climatological upwelling and downwelling zones in the region, although the upwelling band is narrower in the higher-resolution product.

Wind-driven Ekman Pumping (Methods; Eq. 2), derived from ERA5 wind stress, identifies weakened upwelling in 2025 (Fig. 6) extending from the GoP to 5^{o}N. CMCC-SPS4 initialised in December, using the wind stress from the ocean model at a resolution of 0.25^o, recreates the climatological upwelling conditions within the GoP (Fig. 5). For 2025, CMCC-SPS4 correctly predicts a negative anomaly which falls into the lower quintile in January and February; the majority of ensembles members agree on the exceptional nature of the anomaly, although the ensemble mean underestimates the magnitude (Fig. 6). The persistence of the extreme negative anomaly into March is not captured by the forecast.

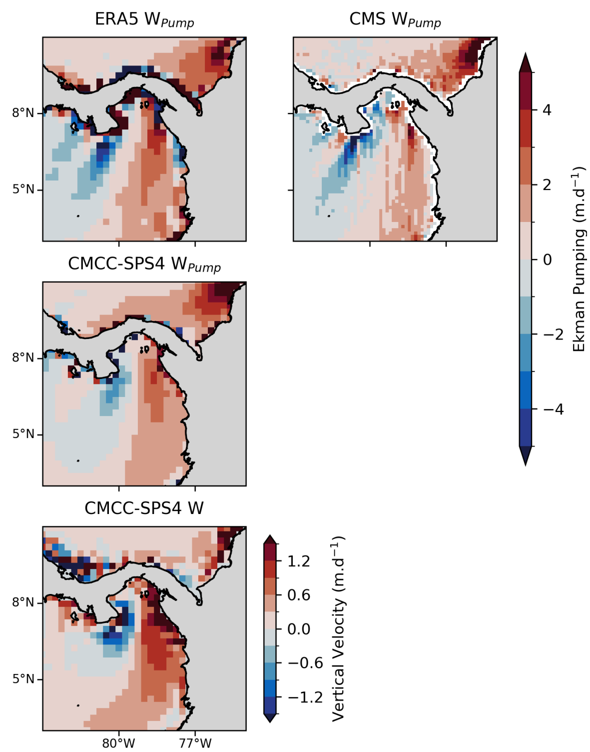

Figure 5. Regional Climatology of upwelling indicators. Climatologies correspond to the upwelling season over the period 1993-2024, with the exception of CMS which covers 2008-2024. W_{ek} represents Ekman Pumping, while W represents total vertical velocity at 10m depth. Note the different colourbar used for CMCC-SPS4 W.

Given the lack of validation data for vertical velocity, here the CMCC-SPS4 output is compared to the derived Ekman Pumping (Fig. 6, middle and bottom). Vertical velocity at a depth of 10 m is selected as indicative of upwelling into the base of the mixed layer, which is shallow during upwelling. In 2025, the forecast vertical velocity, like the derived upwelling, falls

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

below the lower quintile, which explains why the forecast temperatures exceed the upper quintile (Fig. 2). The persistence of weakened upwelling into March appears better captured by the vertical velocity forecasts, but also continues into April. While vertical motion may be induced by other processes besides wind-driven upwelling, the vertical velocity agrees with the Ekman Pumping estimation on the exceptional nature of the 2025 anomaly at onset and peak of the upwelling season.

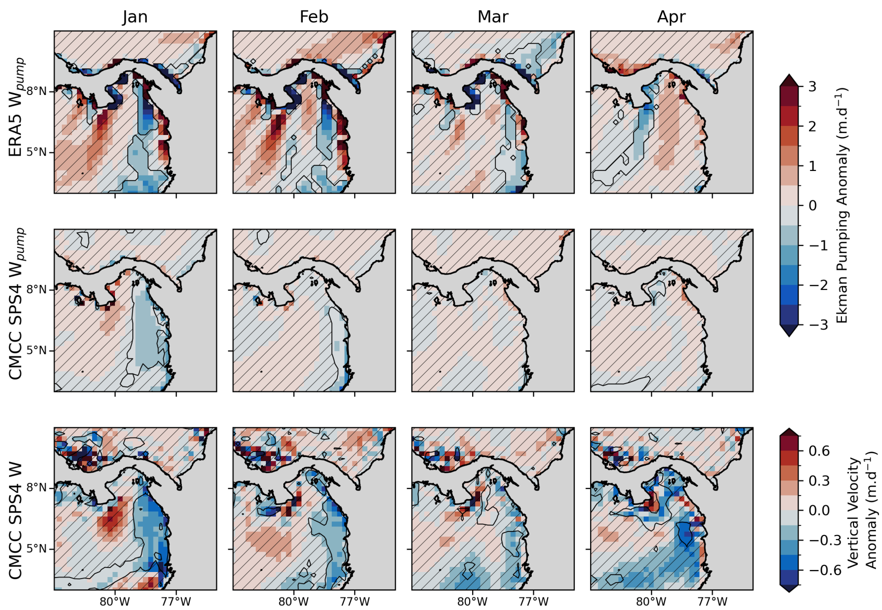

Figure 6. Comparison of upwelling indicator anomalies for 2025. Top: Ekman Pumping derived from wind stress curl, a representative velocity for the upper water column, for ERA5; black hatching indicates where values do not fall below the lower quintile. Middle: Ekman Pumping in the CMCC-SPS4 December initialisation. Bottom: vertical velocity at 10 m depth for CMCC-SPS4. For CMCC-SPS4 maps (middle and bottom), black hatching indicates where less than 50% of ensemble members predict temperatures below the lower quintile.

5 Conclusions & Discussion

Here, we show that local-scale upwelling conditions in the Gulf of Panama are predictable up to 3 months in advance, and that the unprecedented weakening of upwelling in 2025 was accurately forecast in December of 2024 (Fig. 2). Forecasts of elevated temperature and indicators relevant to nutrient concentrations are in demand from a range of end-users, from fisheries and aquaculture to ecosystem managers (Ciliberti et al., 2023; Hartog et al., 2023). This work proves the potential of operational seasonal forecasting systems to provide early warnings in the region, and suggests other local-scale or seasonal upwelling systems should be the target of future studies.

Studies on the predictability of upwelling strength on seasonal timescales have typically focused on the larger Eastern Boundary Upwelling Systems (Amaya et al., 2024; Sylla et al., 2026), in which indicators of upwelling based on wind speed and

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

temperature provide sufficient descriptions of the phenomena. For example, a widely-used indicator is the difference between coastal and open ocean temperatures, which is suitable for EBUS (Narayan et al., 2010; Sylla et al., 2026). More reliable alternatives are the Ekman Coastal Upwelling and Ekman Pumping derived from wind stress, yet these may be sensitive to horizontal resolution (Capet et al., 2004; Bonino et al., 2019). Here, we found that the wind stress fields at 0.25^o resolution provided by the ocean component of the seasonal forecast system sufficiently captured upwelling processes in the GoP (Fig. 6).

The extreme upper ocean temperatures of the GoP in 1998 highlight how upwelling may not always lead to cooler coastal waters, and suggests that indicators based solely on temperature are unreliable. Firstly, the expected inverse relationship between wind stress and SST in the GoP during upwelling cannot be assumed (D'Croz and O'Dea, 2007). Secondly, in 1998, temperature-based upwelling indicators suggested no upwelling took place, yet catches of anchovies were relatively high (Team, 2015). The apparent mismatch may lead to erroneous conclusions begin drawn about impacts and other stressors on fish stocks. Meridional wind is still a reliable indicator of Ekman Upwelling in the region, but alone does not indicate whether warm or cool waters are being upwelled. As an alternative, metrics which incorporate subsurface temperatures have been proposed in other regions, such as in the Great Barrier Reef where warm anomalies have also been linked to enhanced upwelling (Berkelmans et al., 2010). Moreover, region-specific identification of ideal indices can be based on the response of local biological indicators to various environmental conditions (García-Reyes et al., 2014; Largier, 2020). Seasonal forecasts were able to capture two types of upwelling extreme: exceptionally warm (e.g. 1998) and weak (e.g. 2025) upwelling (Fig. 3).

More generally, this work complements recent studies on the predictability of subsurface ocean conditions on seasonal timescales (McAdam et al., 2022, 2023; Amaya et al., 2024; Balmaseda et al., 2024); such findings should help boost the uptake and exploitation of seasonal forecasts of the ocean to benefit a greater range of potential users. In the GoP, temperature anomalies linked to weaker or stronger upwelling are not consistent throughout the historical record, meaning that knowledge of subsurface conditions can give further context to surface conditions. For example, the record-breaking temperatures of 2025 were restricted to the upper 30m, while in 1998 exceptionally warm anomalies were present at 40m despite strong upwelling (Fig. 4). Unseen subsurface temperature extremes may impact local ecosystems as much as surface conditions.

Appendix A: Conditions during the suppressed upwelling season of 2025

The Copernicus-GlobColour product provides daily global gap-filled chlorophyll fields from multiple ocean colour sensors at roughly 4km resolution over the period 1997-2025. In this study, it is used as a complementary biological indicator of upwelling. The exceptionally low chlorophyll concentrations throughout the season provide evidence for the impact of the upwelling suppression on local ocean health (O'Dea et al., 2025) and indciate that the extreme temepratures were not caused by interactions with the atmosphere but by a lack of cool water being upwelled.

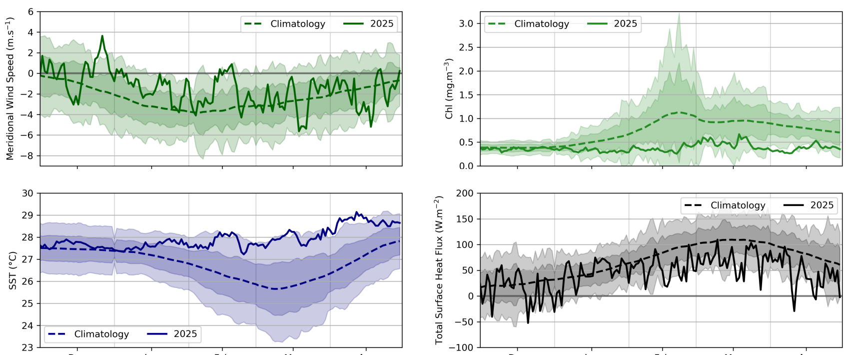

Figure A1. Oceanic and atmospheric conditions during the 2025 upwelling season. Values for meridional wind, chlorophyll concentration, sea surface temperature (SST), and net surface heat flux for the wider upwelling region (Figure 1) are shown. Climatological values from 1993-2024, or 1998-2024 in the case of chlorophyll, are represented by dashed lines. One and two levels of standard deviation of the same periods are shown by dark and light shading respectively. Heat flux convention: positive into the ocean.

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

285 ## Appendix B: Forecasts of daily conditions during 2025 upwelling season

This analysis displays the behaviour of the 40-member forecast ensemble, highlighting where members largely agree or diverge.

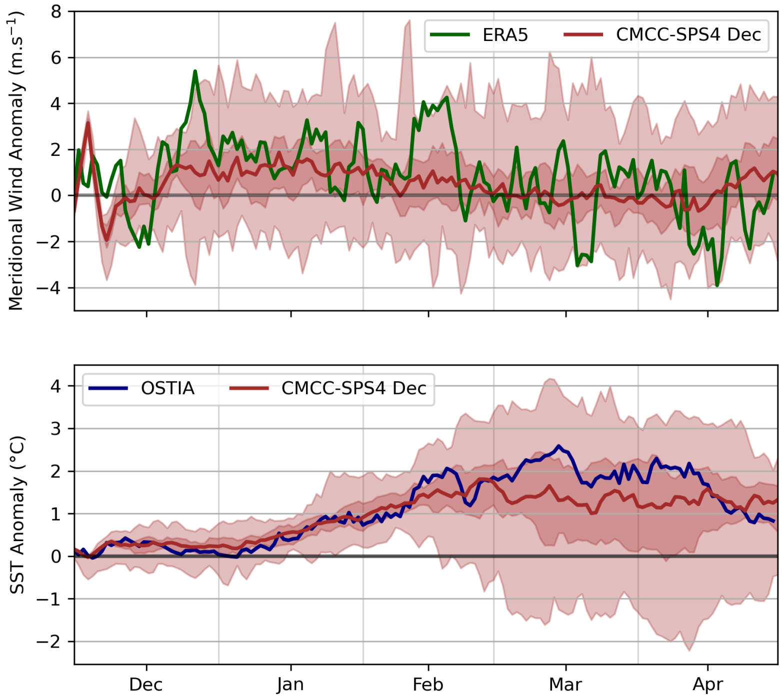

Figure B1. Forecasts and observations of daily meridional wind and sea surface temperature anomalies during the 2025 upwelling season. Dark and light shading represent the inter-quartile range and full spread of ensemble members, respectively.

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

Appendix C: Skill of surface variables in other operational forecasting systems

CMCC-SPS4 is compared to other operational systems for available surface variables SST and meridional wind speed, to demonstrate how well it represents state-of-the-art forecasting systems.

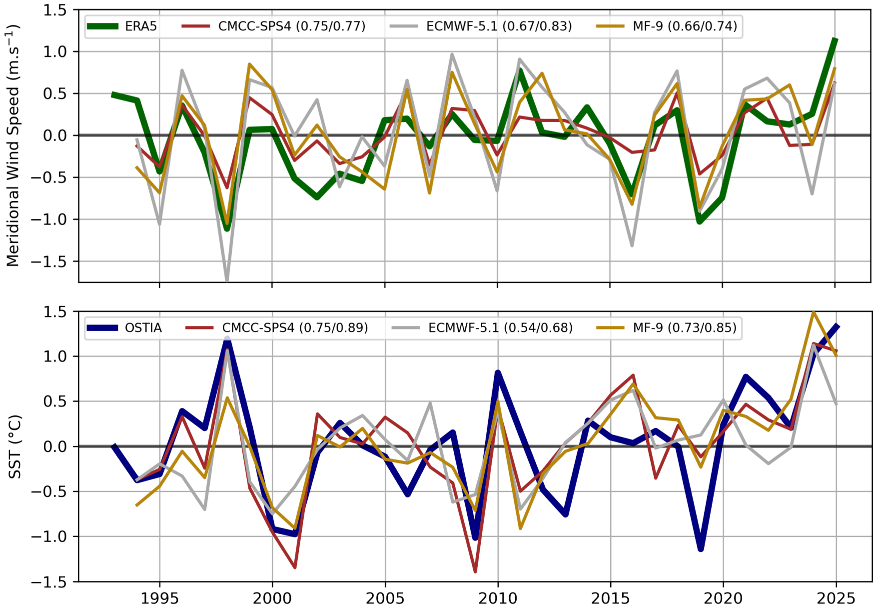

Figure C1. Hindcasts of meridional wind speed and sea surface temperature anomalies in Copernicus Climate Change Service seasonal forecast systems ECMWF version 5.1 and Meteo-France version 9. Time series represent anomalies of area-averaged values during the upwelling season (January-March) relative to the 1993-2024 climatology. Wind speed convention: negative anomalies indicate stronger northerlies, while positive anomalies may indicate weaker or reversed northerlies. Values in brackets indicate correlation and AUC scores respectively.

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

Appendix D: Conditions during the strong upwelling season of 1998

The upwelling season of 1998 experienced the most intense northerly jet and near-record temperatures on par with 2025, and was marked by premature upwelling in early Janaury.

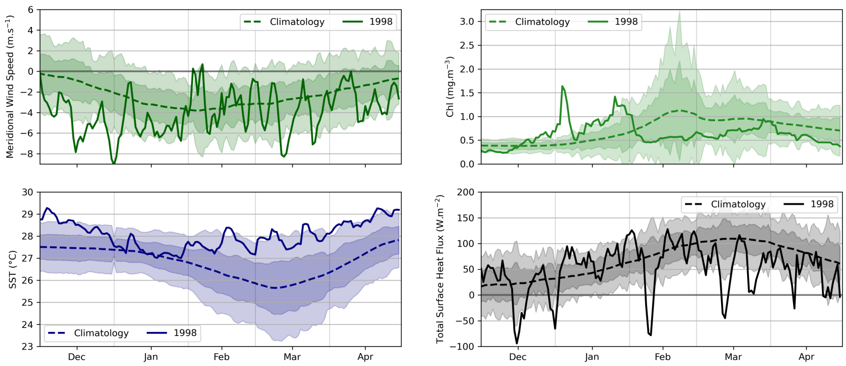

Figure D1. As in Figure A1, but for the 1998 upwelling season.

Data availability. Seasonal forecast output for wind speed and sea surface temperature are available via the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) at
https://doi.org/10.24381/cds.181d637e. ERA5 are also available on the CDs at 10.24381/cds.adbb2d47.
Forecasts of wind stress, subsurface temperature and vertical velocities for the study region are available on
Zenodo: https://doi.org/10.5281/zenodo.21723336.
This study has been conducted using E.U. Copernicus Marine Service Information: "Global Ocean Hourly Sea Surface Wind and Stress from Scatterometer and Model"
https://doi.org/10.48670/moi-00305 (Accessed on 04-04-2026).
"Global Ocean OSTIA Sea Surface Temperature and Sea Ice Analysis"
https://doi.org/10.48670/moi-00165 Accessed on DD-MM-YYYY; "Global Ocean Colour (Copernicus-GlobColour), Bio-Geo-Chemical, L4 (monthly and interpolated) from Satellite Observations (1997-ongoing)" https://doi.org/10.48670/moi-00281 (Accessed on 03-11-2025).
GLORYS12v1 reanalysis is available from the Copernicus Marine Store at 10.48670/moi-00021 (Accessed on 21-11-2025).
In-situ ocean temperature data from the Isla Pacheca mooring can be obtained from https://doi.org/10.5281/zenodo.15715993 (O'Dea, 2025).

Author contributions. RM, AS & ES conceptualised the study. RM performed the analysis and visualisation. AS curated the forecast data. RM & GB were responsible for funding acquisition. RM prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare there are no conflicts of interest for this manuscript.

Acknowledgements. We thank Dr. Aaron O'Dea and colleagues at the Smithsonian Tropical Research Institute for making the in-situ temperature data from Isla Pacheca publicly available, and for helpful correspondence regarding this work. R.M and G.B were supported by ObsSea4Clim 'Ocean observations and indicators for climate and assessments' funded by the European Union, grant agreement number: 101136548 (https://doi.org/10.3030/101136548) contribution number 58.

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

References

Amaya, D. J., Alexander, M. A., Scott, J. D., and Jacox, M. G.: An evaluation of high-resolution ocean reanalyses in the California current system, Progress in Oceanography, 210, 102 951, https://doi.org/10.1016/j.pocean.2022.102951, 2023.

Amaya, D. J., Jacox, M. G., Alexander, M. A., Bograd, S. J., and Jia, L.: Seasonal Upwelling Forecasts in the California Current System, Geophysical Research Letters, 51, e2024GL111 083, https://doi.org/10.1029/2024GL111083, 2024.

Bakun, A.: Coastal upwelling indices, west coast of North America, 1946-71, Tech. Rep. NMFS SSRF-671, Natl Ocean. Atmos. Adm Washington, DC, 1973.

Balmaseda, M. A., McAdam, R., Masina, S., Mayer, M., Senan, R., De Bosisséson, E., and Gualdi, S.: Skill assessment of seasonal forecasts of ocean variables, Frontiers in Marine Science, 11, 1380 545, https://doi.org/10.3389/fmars.2024.1380545, 2024.

Berkelmans, R., Weeks, S. J., and Steinberga, C. R.: Upwelling linked to warm summers and bleaching on the Great Barrier Reef, Limnology and Oceanography, 55, 2634–2644, https://doi.org/10.4319/lo.2010.55.6.2634, 2010.

Bograd, S. J., Jacox, M. G., Hazen, E. L., Lovecchio, E., Montes, I., Pozo Buil, M., Shannon, L. J., Sydeman, W. J., and Rykaczewski, R. R.: Climate Change Impacts on Eastern Boundary Upwelling Systems, Annual Review of Marine Science, 15, 303–328, https://doi.org/10.1146/annurev-marine-032122-021945, 2023.

Bonino, G., Masina, S., Iovino, D., Storto, A., and Tsujino, H.: Eastern Boundary Upwelling Systems response to different atmospheric forcing in a global eddy-permitting ocean model, Journal of Marine Systems, 197, 103 178, https://doi.org/10.1016/j.jmarsys.2019.05.004, 2019.

Capet, X. J., Marchesiello, P., and McWilliams, J. C.: Upwelling response to coastal wind profiles, Geophysical Research Letters, 31, 2004GL020 123, https://doi.org/10.1029/2004GL020123, 2004.

Ciliberti, S. A., Alvarez Fanjul, E., Pearlman, J., Wilmer-Becker, K., Bahurel, P., Ardhuin, F., Arnaud, A., Bell, M., Berthou, S., Bertino, L., Capet, A., Chassignet, E., Ciavatta, S., Cirano, M., Clementi, E., Cossarini, G., Coro, G., Corney, S., Davidson, F., Drevillon, M., Drillet, Y., Dussurget, R., El Serafy, G., Fennel, K., Garcia Sotillo, M., Heimbach, P., Hernandez, F., Hogan, P., Hoteit, I., Joseph, S., Josey, S., Le Traon, P.-Y., Libralato, S., Mancini, M., Matte, P., Melet, A., Miyazawa, Y., Moore, A. M., Novellino, A., Porter, A., Regan, H., Romero, L., Schiller, A., Siddorn, J., Staneva, J., Thomas-Courcoux, C., Tonani, M., Garcia-Valdecasas, J. M., Veitch, J., Von Schuckmann, K., Wan, L., Wilkin, J., and Zufic, R.: Evaluation of operational ocean forecasting systems from the perspective of the users and the experts, State of the Planet, 1-osr7, 1–6, https://doi.org/10.5194/sp-1-osr7-2-2023, 2023.

D'Croz, L. and O'Dea, A.: Variability in upwelling along the Pacific shelf of Panama and implications for the distribution of nutrients and chlorophyll, Estuarine, Coastal and Shelf Science, 73, 325–340, https://doi.org/10.1016/j.ecss.2007.01.013, 2007.

D'Croz, L., Del Rosario, J. B., and Gómez, J. A.: Upwelling and phytoplankton in the Bay of Panama, https://agris.fao.org/search/en/providers/124317/records/65119b8a511bdb9a506fee36, 1991.

Donlon, C. J., Martin, M., Stark, J., Roberts-Jones, J., Fiedler, E., and Wimmer, W.: The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system, Remote Sensing of Environment, 116, 140–158, https://doi.org/10.1016/j.rse.2010.10.017, 2012.

ECMWF: IFS Documentation CY41R2 - Part III: Dynamics and Numerical Procedures, https://doi.org/10.21957/83WOUV80, 2016.

Enfield, D.: Evolution and historical perspective of the 1997-1998 El Nino-Southern Oscillation event, BULLETIN OF MARINE SCIENCE, 69, 7–25, 2001.

García-Reyes, M., Largier, J. L., and Sydeman, W. J.: Synoptic-scale upwelling indices and predictions of phyto- and zooplankton populations, Progress in Oceanography, 120, 177–188, https://doi.org/10.1016/j.pocean.2013.08.004, 2014.

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

Good, S., Fiedler, E., Mao, C., Martin, M. J., Maycock, A., Reid, R., Roberts-Jones, J., Searle, T., Waters, J., While, J., and Worsfold, M.: The Current Configuration of the OSTIA System for Operational Production of Foundation Sea Surface Temperature and Ice Concentration Analyses, Remote Sensing, 12, 720, https://doi.org/10.3390/rs12040720, 2020.

Hartog, J. R., Spillman, C. M., Smith, G., and Hobday, A. J.: Forecasts of marine heatwaves for marine industries: Reducing risk, building resilience and enhancing management responses, Deep Sea Research Part II: Topical Studies in Oceanography, 209, 105 276, https://doi.org/10.1016/j.dsr2.2023.105276, 2023.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., De Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.: The ERA5 global reanalysis, Quarterly Journal of the Royal Meteorological Society, 146, 1999–2049, https://doi.org/10.1002/qj.3803, 2020.

Jacox, M. G., Edwards, C. A., Hazen, E. L., and Bograd, S. J.: Coastal Upwelling Revisited: Ekman, Bakun, and Improved Upwelling Indices for the U.S. West Coast, Journal of Geophysical Research: Oceans, 123, 7332–7350, https://doi.org/10.1029/2018JC014187, 2018.

Largier, J. L.: Upwelling Bays: How Coastal Upwelling Controls Circulation, Habitat, and Productivity in Bays, Annual Review of Marine Science, 12, 415–447, https://doi.org/10.1146/annurev-marine-010419-011020, 2020.

Legeckis, R.: Upwelling off the Gulfs of Panama and Papagayo in the tropical Pacific during March 1985, Journal of Geophysical Research: Oceans, 93, 15 485–15 489, https://doi.org/10.1029/JC093iC12p15485, 1988.

Lellouche, J.-M., Eric, G., Romain, B.-B., Gilles, G., Angélique, M., Marie, D., Clément, B., Mathieu, H., Olivier, L. G., Charly, R., Tony, C., Charles-Emmanuel, T., Florent, G., Giovanni, R., Mounir, B., Yann, D., and Pierre-Yves, L. T.: The Copernicus Global 1/12° Oceanic and Sea Ice GLORYS12 Reanalysis, Frontiers in Earth Science, 9, 698 876, https://doi.org/10.3389/feart.2021.698876, 2021.

McAdam, R., Masina, S., Balmaseda, M., Gualdi, S., Senan, R., and Mayer, M.: Seasonal forecast skill of upper-ocean heat content in coupled high-resolution systems, Climate Dynamics, 58, 3335–3350, https://doi.org/10.1007/s00382-021-06101-3, 2022.

McAdam, R., Masina, S., and Gualdi, S.: Seasonal forecasting of subsurface marine heatwaves, Communications Earth & Environment, 4, 225, https://doi.org/10.1038/s43247-023-00892-5, 2023.

Miglietta, M. P., Rossi, M., and Collin, R.: Hydromedusa blooms and upwelling events in the Bay of Panama, Tropical East Pacific, Journal of Plankton Research, 30, 783–793, https://doi.org/10.1093/plankt/fbn038, 2008.

Narayan, N., Paul, A., Mulitza, S., and Schulz, M.: Trends in coastal upwelling intensity during the late 20th century, Ocean Science, 6, 815–823, https://doi.org/10.5194/os-6-815-2010, 2010.

O'Dea, A.: Data and code for "Unprecedented suppression of Panama's Pacific upwelling in 2025", by O'Dea et al. [Data set]., 2025.

Ormaza-González, F. I., Martillo-Bustamante, C., Espinoza, E., Proust, J.-N., Michaud, F., and Lebrun, J.-F.: Disentangling Eastern Pacific Warming: El Niño 2023–2024 vs seasonal Panamá Bay influence, Frontiers in Marine Science, 12, 1737 039, https://doi.org/10.3389/fmars.2025.1737039, 2026.

O'Dea, A., Sellers, A. J., Pérez-Medina, C., Pardo Díaz, J., Guzmán Bloise, A., Pöhlker, C., Chiliński, M. T., Aardema, H. M., Cybulski, J. D., Heins, L., Paton, S. R., Slagter, H. A., Schiebel, R., and Haug, G. H.: Unprecedented suppression of Panama's Pacific upwelling in 2025, Proceedings of the National Academy of Sciences, 122, e2512056 122, https://doi.org/10.1073/pnas.2512056122, 2025.

Randall, C. J., Toth, L. T., Leichter, J. J., Maté, J. L., and Aronson, R. B.: Upwelling buffers climate change impacts on coral reefs of the eastern tropical Pacific, Ecology, 101, e02 918, https://doi.org/10.1002/ecy.2918, 2020.

https://doi.org/10.5194/egusphere-2026-5138
Preprint. Discussion started: 1 September 2026

Rousseaux, C. S., Gregg, W. W., and Ott, L.: Assessing the Skills of a Seasonal Forecast of Chlorophyll in the Global Pelagic Oceans, Remote Sensing, 13, 1051, https://doi.org/10.3390/rs13061051, 2021.

Russo, C. S., Veitch, J., Carr, M., Fearon, G., and Whittle, C.: An Intercomparison of Global Reanalysis Products for Southern Africa's Major Oceanographic Features, Frontiers in Marine Science, 9, 837 906, https://doi.org/10.3389/fmars.2022.837906, 2022.

Rykaczewski, R. R. and Checkley, D. M.: Influence of ocean winds on the pelagic ecosystem in upwelling regions, Proceedings of the National Academy of Sciences, 105, 1965–1970, https://doi.org/10.1073/pnas.0711777105, 2008.

Sanna, A., Gualdi, S., Benassi, M., Borrelli, A., Peano, D., Hashemi Devin, M., Cipollone, A., and Tibaldi, S.: TN0301 – The new CMCC Seasonal Prediction System SPS4, 2025.

Siedlecki, S. A., Kaplan, I. C., Hermann, A. J., Nguyen, T. T., Bond, N. A., Newton, J. A., Williams, G. D., Peterson, W. T., Alin, S. R., and Feely, R. A.: Experiments with Seasonal Forecasts of ocean conditions for the Northern region of the California Current upwelling system, Scientific Reports, 6, 27 203, https://doi.org/10.1038/srep27203, 2016.

Sylla, A., Brune, S., Losada, T., and Baehr, J.: Mechanisms and seasonal predictability of sea surface temperature in the Senegalo-Mauritanian Upwelling System, Climate Dynamics, 64, 159, https://doi.org/10.1007/s00382-026-08121-3, 2026.

Team, C. T.: Small Pelagic Fishery in Panama, Stock Assessment and Recommendations for a Management Plant, https://www.cedepesca.net/wp-content/uploads/2016/05/The_Panama_small_pelagics_fishery.pdf, 2015.

Xie, S.-P., Xu, H., Kessler, W. S., and Nonaka, M.: Air–Sea Interaction over the Eastern Pacific Warm Pool: Gap Winds, Thermocline Dome, and Atmospheric Convection*, Journal of Climate, 18, 5–20, https://doi.org/10.1175/JCLI-3249.1, 2005.

Yu, Y., Wang, Y., Cao, L., Tang, R., and Chai, F.: The ocean-atmosphere interaction over a summer upwelling system in the South China Sea, Journal of Marine Systems, 208, 103 360, https://doi.org/10.1016/j.jmarsys.2020.103360, 2020.