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Kilometer-scale trends and variability of the Adriatic present climate (1987–2017)

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Abstract
We present the Adriatic atmosphere–ocean trends and variability simulated by the kilometer-scale Adriatic Sea and Coast (AdriSC) climate model during the 1987–2017 period. As the AdriSC model has been successfully validated over the entire basin against an extensive dataset of in situ measurements and remote sensing products, the reliability of the presented results at the regional (basin-wide) and local (sub-domains) scales is high. We found that trends and variability in the atmosphere reveal strong land-sea contrasts with (1) stronger temperature trends associated with lower, mostly seasonal, variability over the Adriatic Sea than over the land and (2) positive trends of wind speed and negative trends of relative humidity associated with high, mostly seasonal, variability over the sea and vice versa over the land. While, in the ocean, the analysis highlights several processes: (1) extensive warming by the atmosphere at the surface during summer, affecting both temperature and salinity, (2) shallowing of the advection of the saline Levantine Intermediate Water inflow into the Adriatic, (3) decrease of the Adriatic deep water outflow and therefore the Adriatic-Ionian thermohaline circulation, (4) warming of near-bottom waters, in particular in the middle and northern Adriatic, and (5) shrinking and weakening of the Southern Adriatic Gyre, in particular at its center. We thus demonstrate that kilometer-scale coupled atmosphere–ocean modelling is an indispensable tool for proper quantification of climate change in complex coastal basins, as it captures local characteristics not properly reproduced by present state-of-the-art regional climate models with an order of magnitude coarser resolutions.

Keywords Adriatic Sea · Present climate · Kilometer-scale atmosphere–ocean modelling · Warming · Salinity increase

1 Introduction

The consequences of climate warming are not only a far future perspective, but also our present reality. Accelerated temperature rise has already impacted many aspects of the world we live in and, for example, melting of sea ice, accelerated sea level rise, as well as longer, more intense, heat waves are already observable (IPCC 2019; Mimura 2013; Perkins-Kirkpatrick et al. 2020). Climate change is spatially inhomogeneous, impacting different regions of the world with different severity, while the ability of these regions to adapt to and mitigate the climate risks is crucial for their management and the wellbeing of their local communities.

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Due to these observable regional changes and the interrelated risks, policy makers' and their advisors' needs for accurate regional and local information about climate warming are higher than ever. Consequently, climate studies must provide a deep understanding of physical processes governing climate trends and variability at the regional and local scale.

This is particularly true for the Mediterranean Sea, which is recognized as a "hot-spot" very sensitive to climate change with warming, in average, 20% faster than the rest of the globe (Giorgi 2006; MedECC 2020). Its northernmost basin, the Adriatic Sea (Fig. 1), is deeply incised into the European mainland, therefore its climate is strongly affected by complex orography, land–sea contrast, intense air–sea interaction, and a range of both large and small-scale complex dynamical processes which present challenges for adequate climate modelling. However, many observational studies have already documented climate trends and variability of mean and extreme atmospheric and ocean variables in the Adriatic Sea. In particular they derived (1) air

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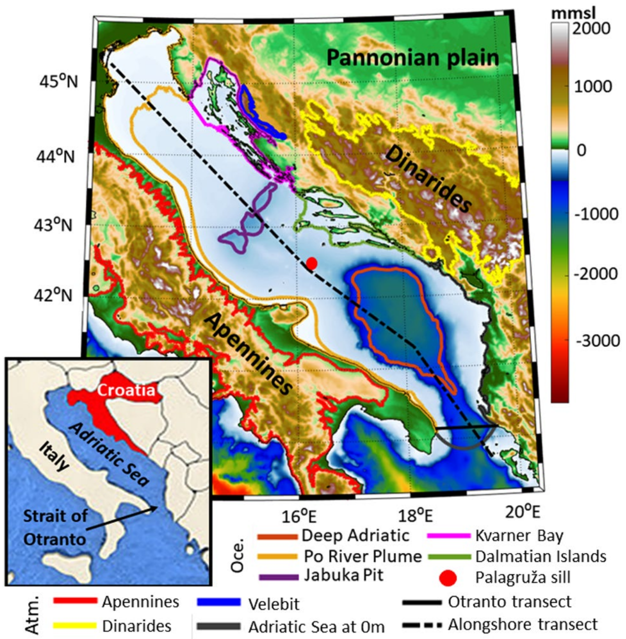


Fig. 1 AdriSC WRF 3-km domain and topography, AdriSC ROMS 1-km domain and bathymetry, along with thick black lines representing Alongshore (dotted line) and Otranto (full line) transects, as well as atmospheric (Atm.) and ocean (Oce.) sub-domains (colored full lines)

and ocean temperature trends and variability (Lipizer et al. 2014; Vilibić et al. 2019; Radilović et al. 2020), (2) trends in dry periods and rainy days (Gajić-Čapka et al. 2015; Marinović et al. 2021), (3) sea level variability and rise (Raicich 2003; Zanchettin et al. 2021), (4) surface waves (Lionello et al. 2012), (5) weakening of the thermohaline circulation (Vilibić et al. 2013), (6) trends and variability of ocean temperature and salinity from scattered long-term observations (Grbec et al. 2018; Vilibić et al. 2019; Bonacci 2012; Bonacci et al. 2021b), etc. Convincingly, it is of utmost importance to assess the future of these changes which are up to now just partially mapped by global and regional climate models (Branković et al. 2013).

As state-of-the-art coupled atmosphere–ocean Global and Regional Climate Models (GCMs, RCMs) have a relatively coarse spatial resolution (from hundreds to tens of kilometers), they are generally not suitable to assess the impacts of climate change at the local scale (Christensen et al. 2007). Therefore, the gap between large- and medium-scale modelling studies and local-scale climate impacts must be bridged (Torresan et al. 2019). Widely used kilometer-scale atmospheric climate models have been shown to provide a better representation of the topography, the coastline, and the air-sea interactions, compared to GCMs and RCMs in the Adriatic region (Kotlarski et al. 2014). In particular, they capture critical phenomena such as orographically influenced variations in precipitation, wind, and surface energy balance (Gutowski et al. 2020) extremely important in coastal (Vautard et al. 2013; Güttler et al. 2015; Estournel et al. 2021) and mountainous (Ban et al. 2014; Prein et al. 2016; Rummukainen 2016) regions like the Adriatic basin. However, previous climate studies in the Adriatic Sea were mostly based on uncoupled RCMs (Branković et al. 2013; Belušić Vozila et al. 2018a, b) while kilometer-scale models are generally more skillful in simulating extremes, such as heavy precipitation, strong winds, and severe storms (Denamiel et al. 2020a, b, 2021a), which are becoming more frequent due to climate change.

More importantly, due to their numerical costs, kilometer-scale atmospheric climate models have not been coupled to ocean models until recently, when the Adriatic Sea and Coast (AdriSC) climate model—with resolutions up to 3-km in the atmosphere and 1-km in the ocean—was set-up and thoroughly evaluated in the Adriatic region (Denamiel et al. 2019, 2021b; Pranić et al. 2021). Further, Denamiel et al. (2021a, b) have demonstrated that, contrary to the GCMs and RCMs, the chosen resolutions of the AdriSC model can represent small-scale weather and climate patterns in the Adriatic Sea. This includes the hurricane strength bora winds driving the formation of the densest waters in the Mediterranean Sea (Artegiani et al. 1989, 1997).

In this study the kilometer-scale coupled atmosphere–ocean AdriSC climate model is thus used to analyze, for the very first time, the atmosphere–ocean trends and variability of the Adriatic present climate during the 1987–2017 period which remained, till this day, partially unknown, particularly in the ocean. The article is structured as follows. The AdriSC model set-up and results as well as the methods applied in this study are described in Sect. 2, the trend and variability results are analyzed in Sect. 3 and further discussed in Sect. 4, where some conclusions are also presented.

2 Model, data, and methods

2.1 AdriSC climate model set-up and results

The Adriatic Sea and Coast (AdriSC) (sub-) kilometer-scale atmosphere–ocean modelling suite (Denamiel et al. 2019) covering the Adriatic and northern Ionian seas has been recently developed with a modular approach based on nested grids. This study analyses the daily results of the AdriSC general circulation module based on the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modelling system developed by Warner et al. (2010). It dynamically couples the Weather Research and Forecasting (WRF) atmospheric model and the Regional Ocean Modeling System (ROMS) ocean model. It is set-up with (1) two different nested grids at 15-km and 3-km resolution used in the WRF model and covering respectively the central Mediterranean area and the Adriatic-Ionian region and (2) two different nested grids at 3-km and 1-km resolution used in the ROMS model and covering respectively the Adriatic-Ionian region (similarly to the WRF 3-km grid) and the Adriatic Sea only. In the vertical, all the AdriSC grids rely on terrain following coordinates: 58 levels refined in the surface layer for the atmosphere (Laprise 1992) and 35 levels refined near both the sea surface and bottom floor for the ocean (Shchepetkin and McWilliams 2009). More details on the set-up of the AdriSC modelling suite—which is installed and fully tested on the European Centre for Middle-range Weather Forecast (ECMWF) high-performance computing facilities—can be found in Denamiel et al. (2019, 2021b) and Pranić et al. (2021).

The AdriSC climate modelling strategy follows the Pseudo-Global Warming (PGW) method (Schär et al. 1996) recently extended to the ocean (Denamiel et al. 2020a). Consequently, two 31-year long simulations are presently available: (1) an evaluation run initialized and forced at its boundaries with reanalysis products for the 1987–2017 period and (2) an extreme warming climate projection run—following the Representative Concentration Pathway (RCP) 8.5 scenario by adding climatological changes to the reanalysis products used in the evaluation run (Denamiel et al. 2020a, b)—for the far future 2070–2100 period. The evaluation of the AdriSC climate model against an extensive dataset composed of in-situ observations and remote sensing products has shown that, in the Adriatic Sea for the 1987–2017 period, the skills of the newly developed coupled atmosphere–ocean kilometer-scale climate model outperform those of the RCMs implemented in the Mediterranean Sea (i.e., Med-CORDEX; Ruti et al. 2016) in both the atmosphere (Denamiel et al. 2021b) and the ocean (Pranić et al. 2021).

Hereafter, the obtained trends and variability over different time and spatial scales in the Adriatic region are derived from the 3-km WRF daily results in the atmosphere and the 1-km ROMS daily results in the ocean extracted from the AdriSC evaluation run during the 1987–2017 period. Only four variables are analyzed for the atmosphere: air temperature at 2 m, rain, relative humidity at 2 m and wind speed at 10 m, and three for the ocean: sea temperature, salinity, and current speed.

2.2 Methods

Once the AdriSC model atmospheric and oceanic daily results are extracted for 1987–2017 period, the presented analysis is performed in two distinct ways. First globally, over the entire Adriatic region and some selected ocean transects, and then monthly, over some sub-domains of interest.

In the global analysis, anomalies and trends are first derived from the daily data: (1) horizontally, over the entire Adriatic basin (i.e., WRF 3-km domain in the atmosphere and ROMS 1-km domain in the ocean; Fig. 1) at the surface only for the atmosphere but also at the bottom and 100 m depth for the ocean; and (2) vertically, for two ocean transects (Otranto and Alongshore transects; Fig. 1). First, daily anomalies are estimated by subtracting the long term mean from each point of the 3D domain (i.e., time, latitude and longitude; hereafter daily seasonal cycles) from the detrended daily data (i.e., calculated trends removed from the model results at each point). Second, trends are calculated with the Theil-Sen method (Mondal et al. 2012) and trend significances are calculated with the Mann–Kendall test (Mann 1945; Kendall 1975; Gilbert 1987). Contrary to ordinary least squares regression (Qian et al. 2019), the Theil Sen trend is insensitive to outliers and can be significantly more accurate than simple linear regression for skewed and heteroskedastic data. It also competes well against non-robust least squares even for normally distributed data in terms of statistical power (Mondal et al. 2012). Only trends with significance over 95% are taken into consideration and presented hereafter. Then, total detrended variances are calculated from the detrended daily data (defined as the sum of the daily seasonal cycles and the anomalies), while percentages of variability caused by anomalies (hereafter percentage anomaly) are computed as the ratio (multiplied by 100) of the variance derived from the anomaly and the total detrended variance. Consequently, the more prominent the seasonal cycle is, the lower the percentage anomaly will be.

The sub-domains for atmospheric and oceanic variables are presented in Fig. 1 and selected due to their interest in terms of physical interpretation (derived either from previous studies or the global analysis). Sub-domains have been selected following well-known dynamical properties of the Adriatic region. For example, the Velebit mountain is a known location for the formation of severe bora winds, the Kvarner Bay is an area where dense water forms, while Jabuka Pit and Deep Adriatic are known collectors of dense water (Denamiel et al. 2022). In addition, some sub-domains were selected following the evaluation of the AdriSC model (Pranić et al. 2021). The sub-domains are: (1) Adriatic Sea (as a whole), Apennines (with at least 150 m in altitude), Velebit (with at least 800 m in altitude) and Dinarides (with at least 800 m in altitude) for the atmosphere, and (2) Dalmatian Islands (with less than 100 m in depth), Deep Adriatic (deeper than 800 m), Jabuka Pit (deeper than 200 m), Kvarner Bay (deeper than 55 m), and Po River Plume (with less than 40 m in depth) for the ocean. First, for each sub-domain, monthly datasets are derived for the mean, maximum, and minimum values extracted from the raw AdriSC daily data only at the surface for each atmospheric variable but also at the bottom and 100 m depth for each ocean variable. Monthly trends and variances are then determined for each variable, depth/height, dataset, and sub-domain. Finally, unique mean monthly trend value and mean monthly variance value for each sub-domain are derived as the average over all the sub-domain points for each variable, depth/height, and dataset. It should also be noted that (1) when less than 50% of the points of the sub-domain have trends with 95% of significance, the results are marked with a black diagonal line in the figures, and (2) when the sub-domain depths are all lower than 100 m, no data is displayed in the ocean figures for the 100 m depth analysis.

3 Results

3.1 Global analysis

3.1.1 Atmosphere

In the atmosphere, decadal trends and variability over the Adriatic basin (Fig. 2; left panels) reflect the impact of the significant warming that took place during the 1987–2017 period. Consequently, trends of temperature at 2 m are all significant but interestingly higher over the sea (up to 0.5–0.6 °C per decade) than over the land (only up to 0.4 °C per decade). Rain decadal trends are generally positive over the sea and along the coast, with (1) the highest values of up to 0.5 mm day^{-1} per decade over central and southern Adriatic and southern parts of the eastern coast, and (2) negative values over the Dinarides and Velebit mountains as well as further inland on the Croatian side, where values drop to − 0.4 mm day^{-1} per decade. However, for the relative humidity at 2 m and the wind speed at 10 m, large areas of the trend plots appear in light gray, meaning that trends are insignificant (i.e., significance lower than 95%). Nevertheless, significant trends show some interesting features. For the relative humidity at 2 m, they are strongly negative over the sea—about − 0.3% per decade along the Italian coast and the Po River plume and down to − 0.6% per decade in the northern Adriatic and areas in the middle and southern Adriatic far from the shore—but strongly positive over the land, varying between 0.3 and 0.5% per decade. For the wind speed at 10 m, significant trends are positive over the sea and along the Adriatic coasts (between 0.1 and 0.2 m s^{-1} per decade), but negative further inland in the Pannonian plain (about − 0.1 m s^{-1} per decade).

Concerning the total variance (Fig. 2; middle panels), the variability of the temperature at 2 m is (1) the highest over the land particularly in the Dinarides (up to 40 °C^2), (2) a bit lower over the Apennines, the northern Adriatic shallow sea and the Po River plume (up to 30 °C^2), and (3) the lowest over the rest of the Adriatic Sea (around 25 °C^2). In contrast, rain total variance is nearly homogeneous over the whole studied region (below 100 mm^2 day^{-2}), except for several areas of higher values (above 400 mm^2 day^{-2}) in the south of Italy, around Rijeka and the Kotor Bay where strong precipitations are known to occur (Marjanović et al. 2017). Further, the total variance of relative humidity at 2 m is (1) the strongest over the Adriatic Sea (above 140%^{2}), except along the Italian coast, which agrees with the trend patterns, and (2) the lowest over the land (below 80%^{2}), except on higher altitude mountain peaks in the Apennines and the Dinarides (above 120%^{2}). Finally, the highest total variances in wind speed at 10 m are found along the Velebit mountains (up to 40 m^2 s^{-2}) where the strongest Bora wind events occur (Alpers et al. 2009), but is generally below 10 m^2 s^{-2} in the rest of the Adriatic basin.

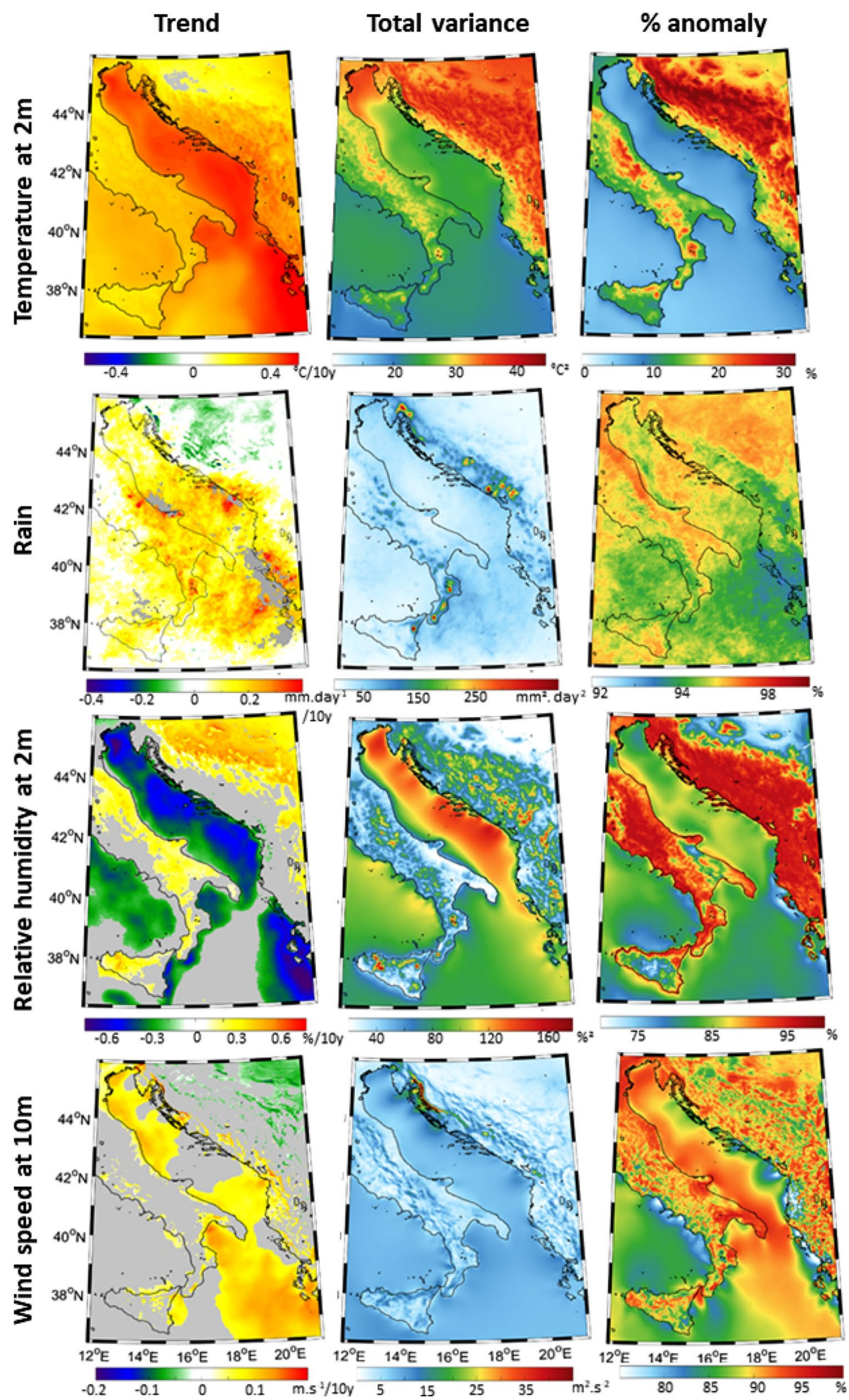
Percentage anomalies (i.e., percentage of non-seasonal variance in the total variance) are high for all variables except for temperature. Namely, over 92% of rain variability and 95% of wind speed variability are not related to seasonality over the entire domain, except for the coastal areas where these percentages vary between 75 and 80%. For the relative humidity at 2 m, a strong contrast in percentage anomaly exists between land and sea: non-seasonal variability is over 95% in most land areas but below 80% over the sea. Temperatures are, as expected, seasonally driven with low percentages of barely 10% over the sea, and an average of 25% over the land, with lower values along the coast and higher values in the mountainous areas.

3.1.2 Ocean

Decadal trends and variability in the ocean are analyzed horizontally at different depths (surface, 100 m, and bottom) in Figs. 3, 4 and 5 and vertically along the Otranto and Alongshore transects in Figs. 6 and 7. It should be noted that, in the ocean, trends are nearly always significant for temperature and salinity, but not for current speed which can display areas of insignificant trends (highlighted in light grey in the plots).

Following the results presentenced in the atmosphere, sea surface temperature trends (Fig. 3; left panels) vary between 0.4 and 0.6 °C per decade, with lowest trends over the deepest Southern Adriatic Pit, where quasi-permanent cyclonic gyre is generating an upwelling (Gačić et al. 2002), and northernmost areas of the Adriatic Sea strongly affected by freshwater load (Franco and Michelato 1992). At 100 m depth, which is roughly the maximum depth of the seasonal thermocline (Buljan and Zore-Armanda 1976; Artegiani et al. 1997), and the bottom, the differences between temperature trends above the deepest part of the Adriatic Sea and the rest of the domain are even more pronounced: 0.2 °C per decade vs. 0.4 °C per decade at 100 m depth and

Fig. 2 Trends (left panels), total variances (middle panels) and percentage anomalies (right panels) for temperature at 2 m, rain, relative humidity at 2 m and wind speed at 10 m over the entire Adriatic region. Insignificant trends (significance < 0.95) are shown in light grey in the left panels



0.1 °C per decade vs. up to 0.4 °C per decade at the bottom. Convincingly, the heating of the Adriatic deep waters is much lower than of the surface waters, like observed for the Mediterranean (Vargas-Yanez et al. 2017), while the transport of deep cold waters is lowering the heating in upper layers within cyclonic gyres.

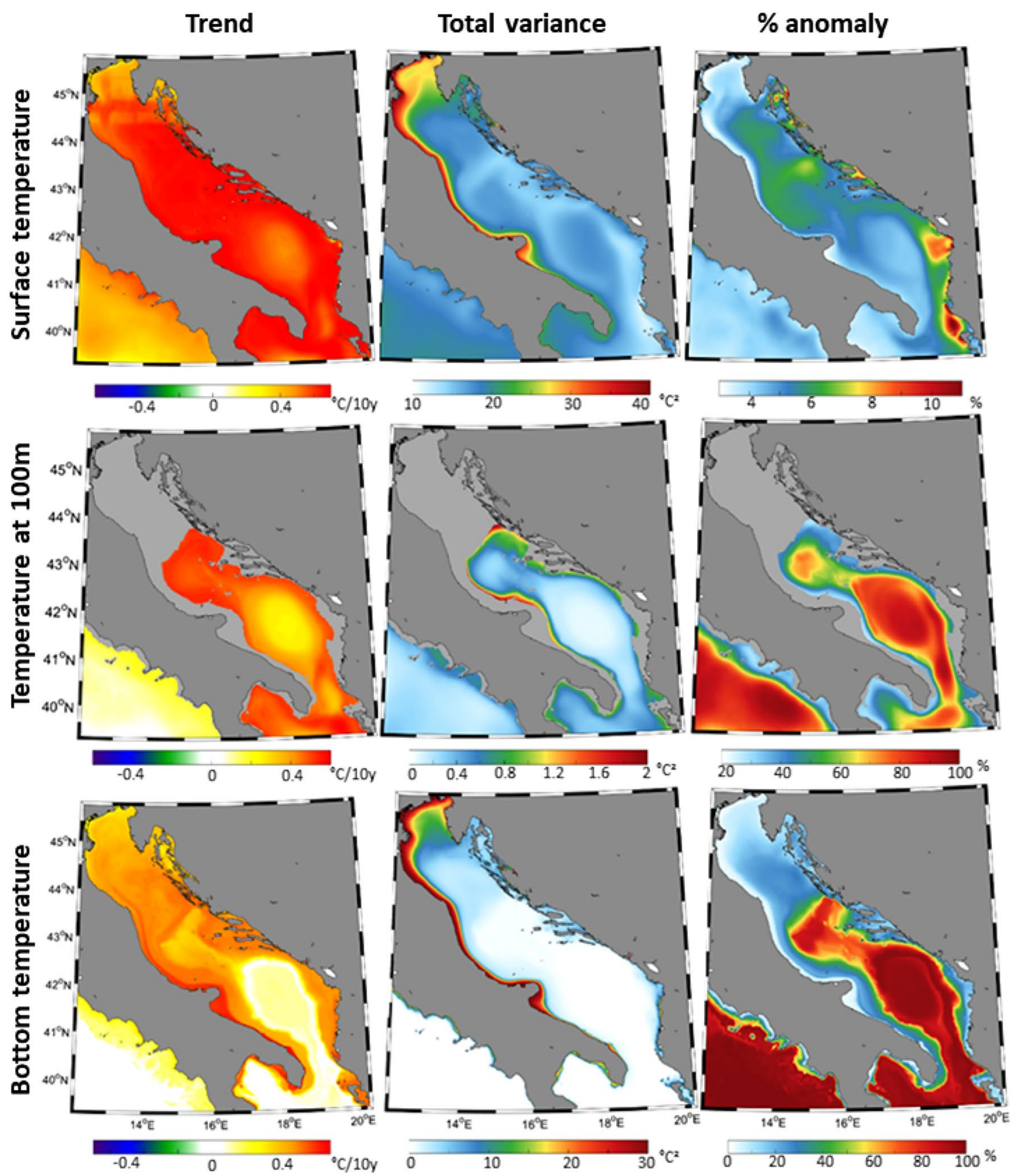


Fig. 3 Trends (left panels), total variances (middle panels) and percentage anomalies (right panels) for temperature at the surface, 100 m depth and the bottom of the sea. Insignificant trends (significance < 0.95) are shown in light grey in the left panels

Further, the temperature total variance (Fig. 3; middle panels) is (1) the highest (over 35 °C^2) along the Po River plume but generally low over the entire Adriatic Sea (below 15 °C^2) in surface, (2) mostly close to 0.1 °C^2 in the deepest areas of the Adriatic Sea at 100 m depth and the bottom, and (3) reaching up to 30 °C^2 along the Po River plume and 10 °C^2 in the shallowest part of the northern Adriatic at the bottom. Additionally, the temperature percentage anomalies (Fig. 3; right panels) mirror the patterns of the total variance at all depths. The variability is, as expected, mostly seasonally driven at depths above the seasonal thermocline, with non-seasonal values: (1) up to 10% at the surface, and particularly low in the shallow northern Adriatic and Po River plume, while (2) reaching 80–100% in the deep Adriatic region, being the largest at the very bottom of the Southern Adriatic Pit. This implies that the Po River plume is keeping the heat near the surface due to a strong haline-driven stratification and therefore exhibiting much stronger seasonal

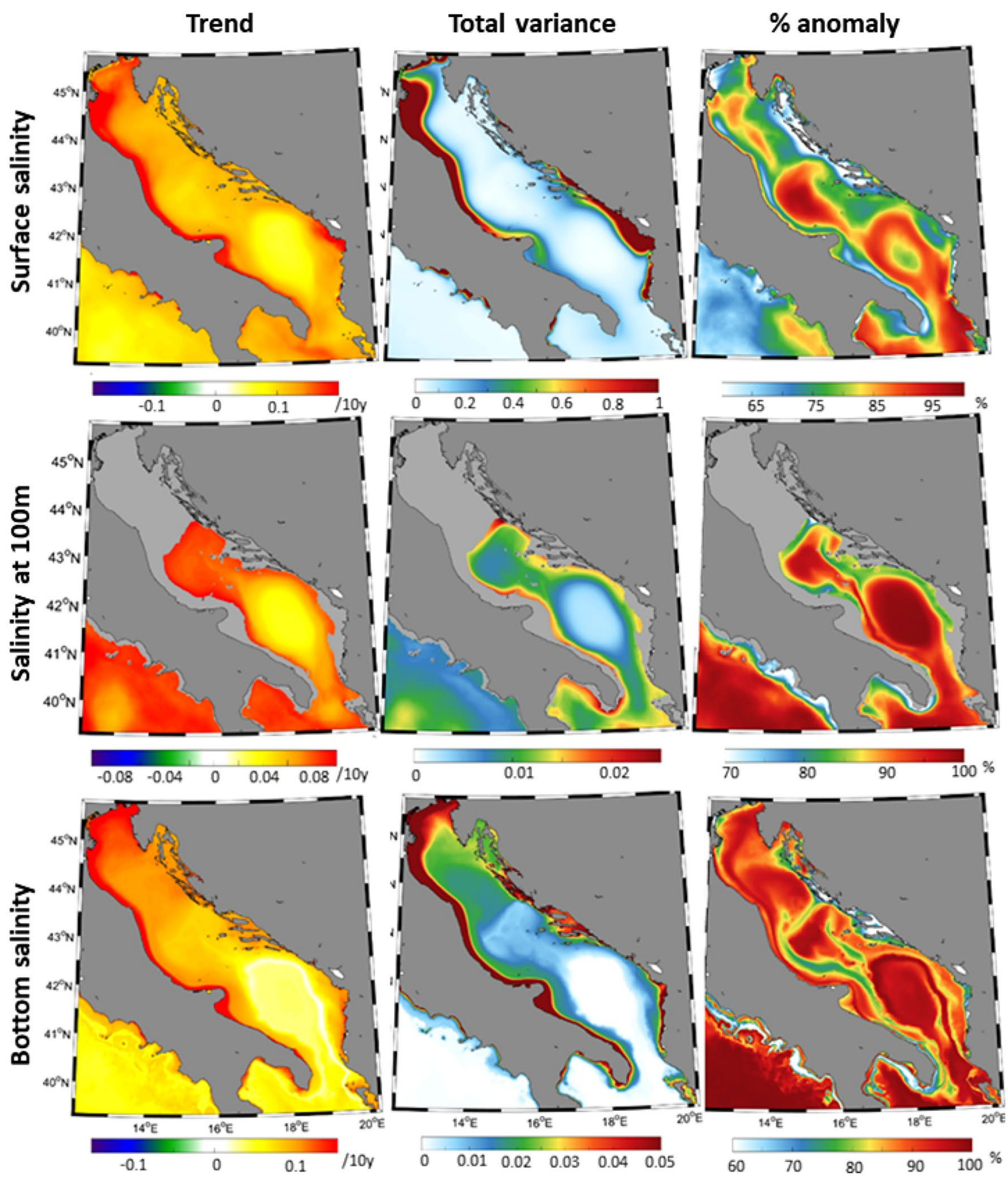


Fig. 4 Trends (left panels), total variances (middle panels) and percentage anomalies (right panels) for salinity at the surface, 100 m depth and the bottom of the sea. Insignificant trends (significance < 0.95) are shown in light grey in the left panels

variability in temperature than the rest of the Adriatic. By contrast, the deepest parts of the Adriatic, which are known to be collectors of dense waters generated on the northern Adriatic shelf during wintertime (Vilibić and Supić 2005), are exhibiting the lowest seasonal changes, in particular, in the 1200-m deep Southern Adriatic Pit where these waters are advected every few years to the very bottom (Querin et al. 2016).

Salinity trends and variability are, however, quite different (Fig. 4). On the surface, salinity percentage anomalies are the lowest along the shore, below 65%, while increasing to 90% and above when moving away from the shore and going above the deeper sea areas. Indeed, low seasonal surface salinity variability is resembling stable structures, not affected by seasonality in coastal dynamics, like the inflow of surface waters from the Ionian Sea and their recirculation

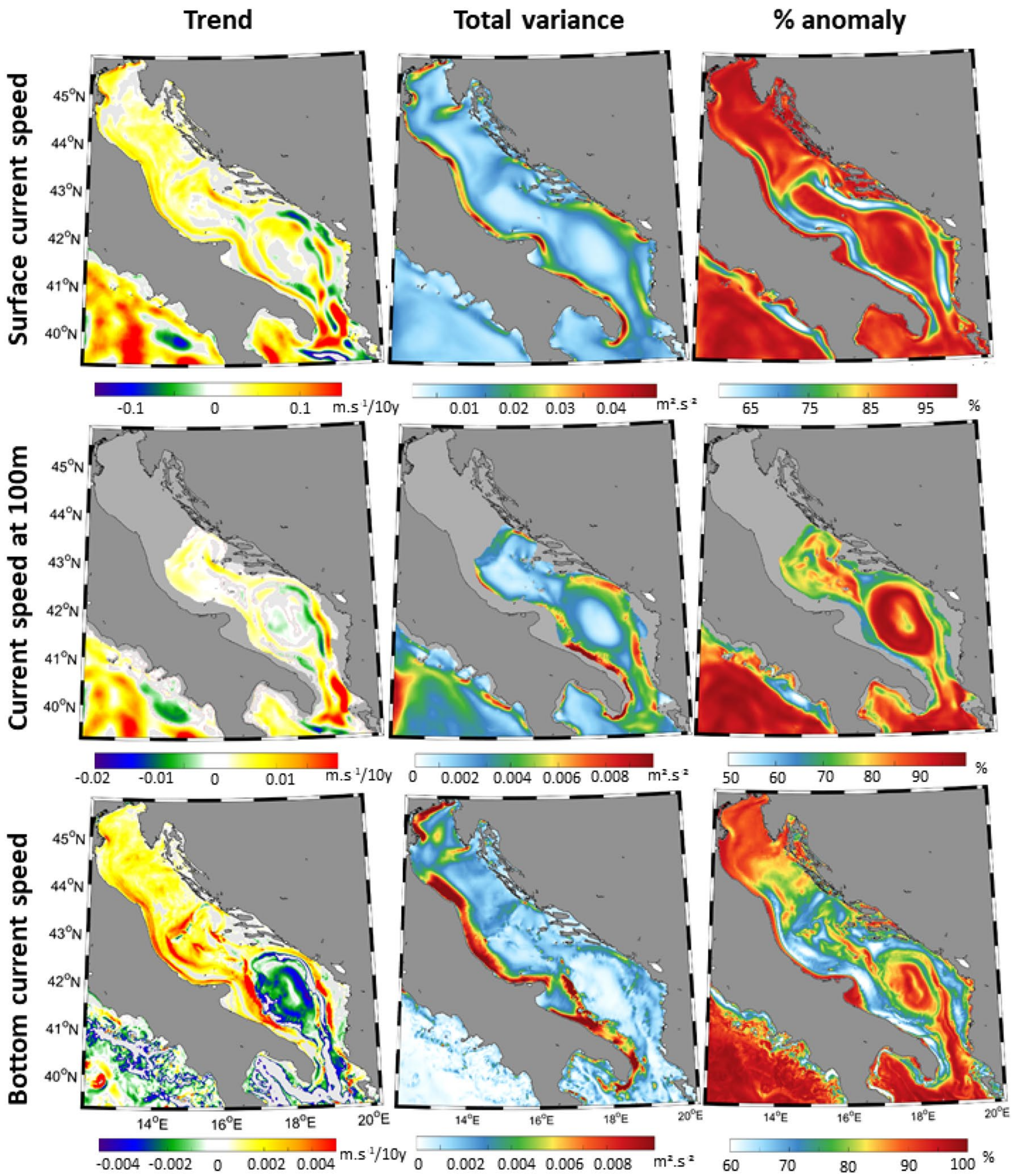


Fig. 5 Trends (left panels), total variances (middle panels) and percentage anomalies (right panels) for current speed at the surface, 100 m depth and the bottom of the sea. Insignificant trends (significance < 0.95) are shown in light grey in the left panels

within the cyclonic gyre in the Southern Adriatic Pit. Non-seasonal salinity variability is much higher at 100 m and on the bottom, with values between 80 and 100% in most areas, with the highest values at the deepest parts. Interestingly, seasonal variations have banners of lower percentage anomaly following the bathymetry, indicating the areas where near-bottom structures are seasonally modulated (e.g., depth of the Po River plume or outflow from Kvarner Bay). Further, surface salinity trends are positive, with the lowest values, down to 0.03 per decade, in the deep Adriatic area, and the highest values up to 0.2 per decade, along the Po River plume. This agrees with Vilibić et al. (2013), who found positive trends along the whole Palagruža Sill transect in the middle Adriatic Sea, but much higher in the coastal regions occupied by freshened waters. Further, positive trends in salinity are resembling reduced inflow by rivers, also in nutrients as the northern Adriatic is resembling much lower productivity in the last 10 years (Djakovac et al.

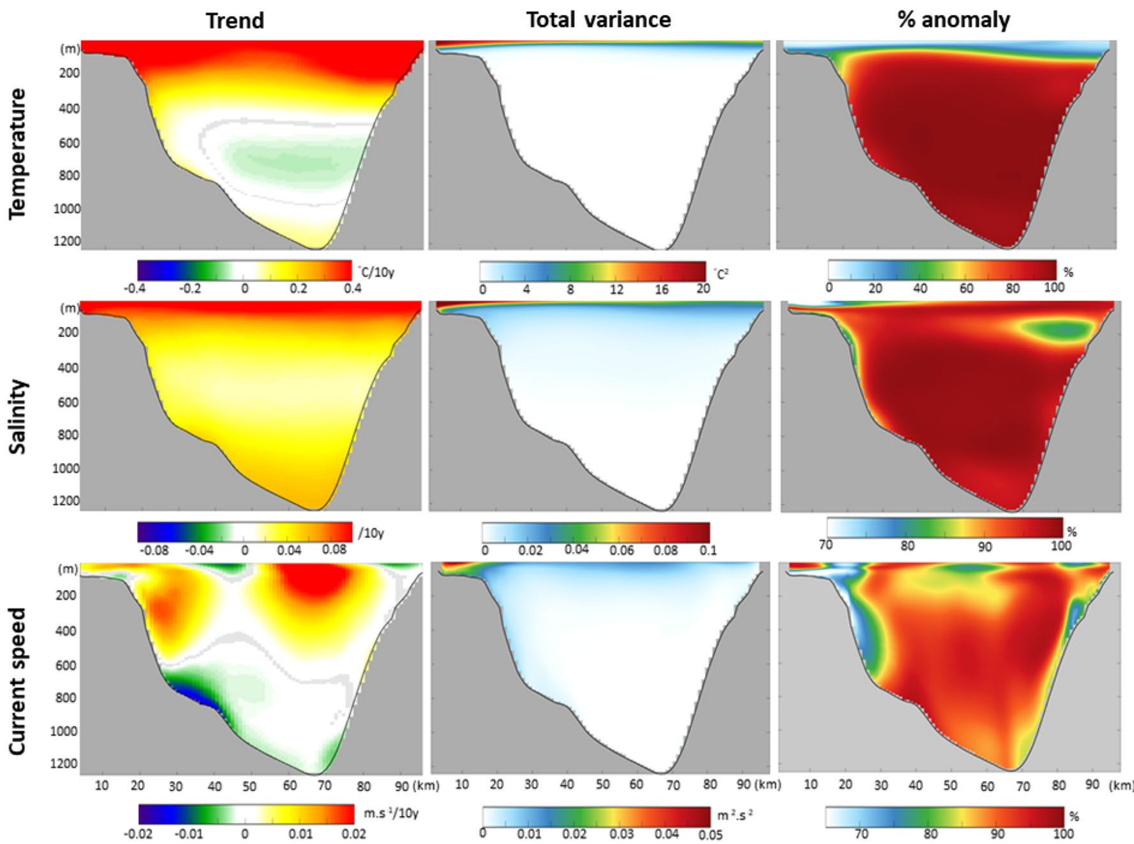


Fig. 6 Trends (left panels), total variances (middle panels) and percentage anomalies (right panels) for temperature, salinity and current speed along the Otranto transect. Insignificant trends (significance < 0.95) are shown in light grey in the left panels

2012; Totti et al. 2019). Similar patterns are found on the bottom, with slightly higher trends in the northern Adriatic, and slightly lower ones in the deepest parts, down to 0.015 per decade. At 100 m depth, trends reach up to 0.1 per decade in shallow areas but are below 0.05 per decade in the Deep Adriatic region, again presumably due to effects of upwelling from deeper layers at which salinity is lower (Lipizer et al. 2014). Total variance on the surface is, as expected, the highest along the Po River plume and in areas with freshwater flowing into the sea, like the Albanian and eastern middle Adriatic rivers, with values up to 40. At 100 m depth and at the bottom, variance values are the lowest in deepest areas, around 0.002, and are increasing with sea depth decreasing. The highest variances on the bottom are found along the west Adriatic coast, and in the middle and southern parts of the east coast along river plumes with the highest discharges (Raicich 1996; Vilibić et al. 2016).

Current speed trends and variabilities contrast with the temperature and salinity results (Fig. 5). First, it should be noted that areas with insignificant trends exist and are marked by light-gray color on the plots. Second, for the middle and northern Adriatic, surface current speed is increasing with decadal trend values mostly around 0.05 m s^{-1} and up to 0.1 m s^{-1} per decade. In the southern Adriatic and Otranto Strait, there are pronounced patchy patterns in trends all over the water column, indicating that the major dynamic features there—the southern Adriatic cyclonic gyre and the water mass exchanges through the Otranto Strait—are exhibiting spatial changes in time. For example, the negative current speed trend near the eastern coast of the southern Adriatic conjoined with positive trends off the coast are indicating shrinking of the gyre and offshore displacements of the Eastern Adriatic Coastal Current (Orlić et al. 1992) in the 2000s and 2010s. Further, the negative current speed trend at the bottom of the southern Adriatic cyclonic gyre may indicate a lower advection of dense waters from the northern Adriatic, which are indeed reflected in the observed decrease in dissolved oxygen content (Vilibić et al. 2011). This is also in agreement with the mostly negative current speed trends at the bottom of the Otranto Strait, which resemble lower production of dense waters in the southern Adriatic (Li and Tanhua 2020). In contrast, the current speed is increasing in surface and intermediate layers of the strait, indicating larger advection of saline surface and Levantine Intermediate Water to the Adriatic, following recent salinization of the Levantine Basin (Kassis and Korres 2020).

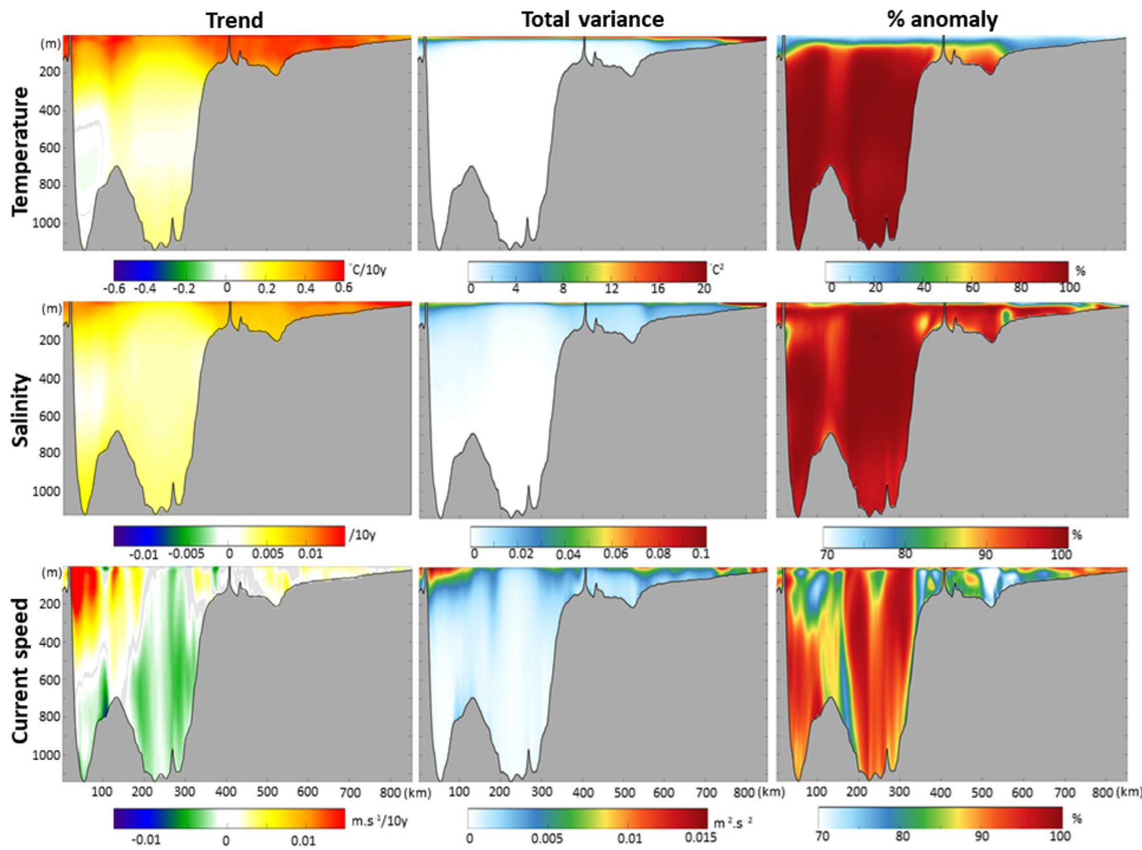


Fig. 7 Trends (left panels), variances (middle panels) and percentage anomalies (right panels) for temperature, salinity, and current speed along the Alongshore transect. Insignificant trends (significance < 0.95) are shown in light grey in the left panels

Total variances of current speeds on the surface are the highest (up to 0.06 $m^2 s^{-2}$) along the west and southwest coasts of the Adriatic Sea, following the seasonal variability of the Western Adriatic Coastal Current (Zavatarelli et al. 2002; Burrage et al. 2009). At 100 m depth, total variances are an order of magnitude lower than on the surface, being the lowest in deep waters and higher at the perimeter of the southern Adriatic cyclonic gyre and surface coastal outflow in the Otranto Strait. At the bottom, variances are of the same order of magnitude than at 100 m depth, being again the lowest in the deep Adriatic, and higher (up to 0.012 $m^2 s^{-2}$) along the west coast. Percentage anomalies at surface are over 95% everywhere but on two stripes along the west and east coast, going from the mid Adriatic to the Otranto strait, where values stay below 65%. These strips are indicating seasonal pulsations of the along-Adriatic transport, where the Western Adriatic Coastal Current is widened in summer and thereafter provoking the inflow of waters from the southeast along the eastern Adriatic coast (Poulain 2001). Similar patterns are observed at the bottom, with slightly lower percentages, varying between 75 and 95% in the rest of the domain, and being the highest in the northernmost and deep areas of the Adriatic. At 100 m depth, percentages are high, above 90% in deep Adriatic area, indicating the stability of the southern Adriatic cyclonic gyre, and are dropping to around 70% when approaching shallower areas.

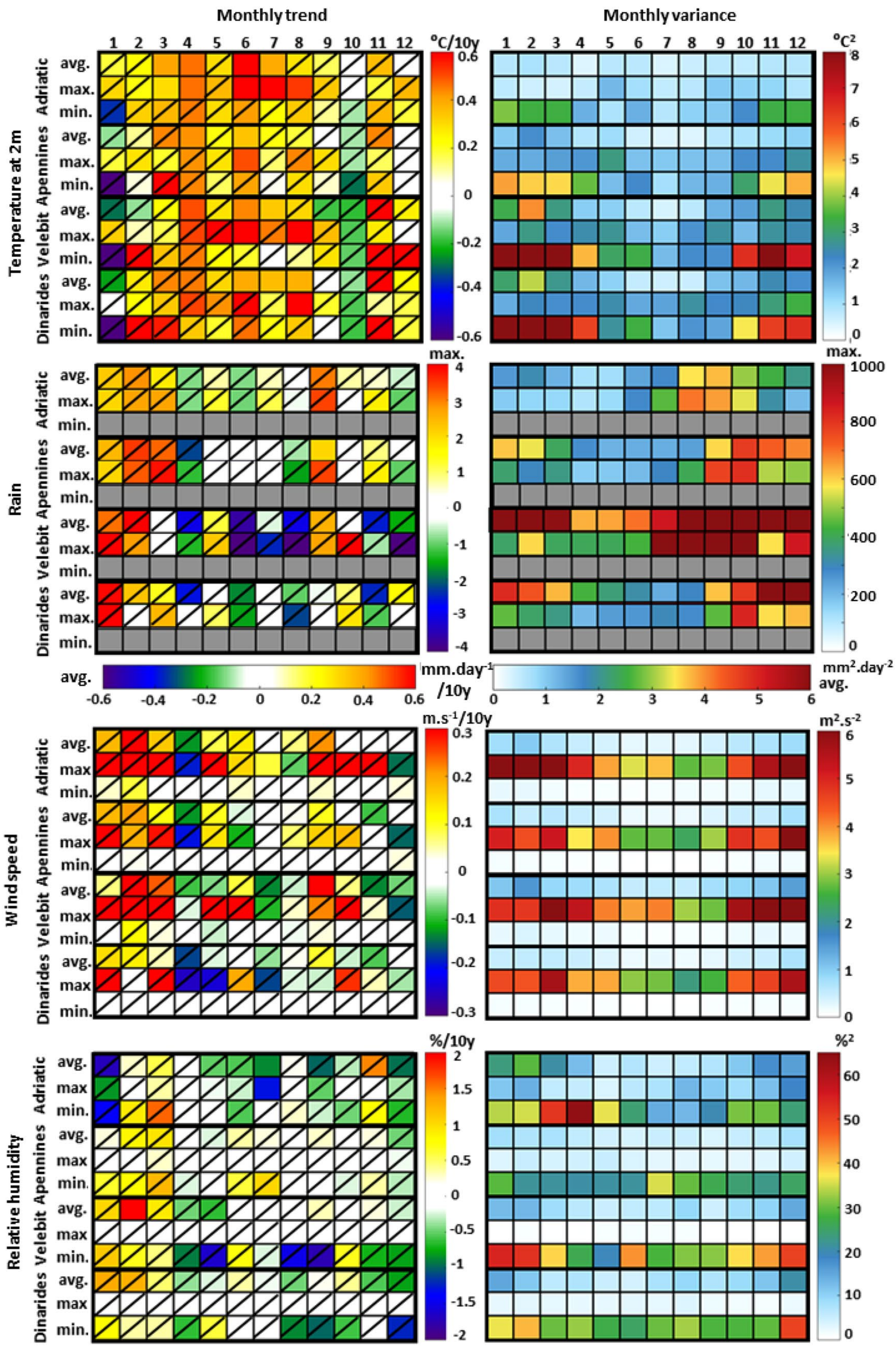
To better investigate the vertical trends and variabilities of sea temperature, salinity, and current speed in the Adriatic Sea, two transects are analyzed: (1) the Otranto transect where all the exchanges between the Adriatic and Ionian seas take place and (2) the Alongshore transect representative of the spatial variability of the Adriatic basin.

For the Otranto transect, as seen in Fig. 6, trends in temperature are generally positive, with the highest values (up to 0.4 °C per decade) in surface, but with an elliptic area of negative trends, of up to -0.1 °C per decade, between 500 and 900 m depth. Such a distribution of temperature trends—large positive trends at surface, negative trends in intermediate and deeper layers and a weak positive trend at the bottom—is already documented on long-term measurements along the Palagruža Sill transect (Vilibić et al. 2013). Although the Palagruža Sill transect is much shallower than the Otranto Strait, the temperature trends highlight similar processes: (1) strong heating of the surface layer due to an increase in vertical stratification in upper layers, (2) decrease in transport in deeper layers, seen also in current speed trends, which is decreasing the transport of warmer waters from the Ionian Sea towards the southern Adriatic at the lower section of the inflow and therefore resulting in negative temperature trends, and (3) weak warming near the bottom, where the Adriatic dense waters are outflowing (Gačić et al. 1996), indicating generation of warmer waters in the Adriatic. The latter (i.e., the positive near-bottom temperature trends) are conjoined with positive salinity and strong negative current speed trends, reflecting a decrease in dense water production in the Adriatic which is known to generate more saline waters in 2000s and 2010s than in 1980s and 1990s (Mihanović et al. 2021).

Total temperature variance is the highest in surface (up to 20 °C^2) and almost 0 below 200 m. Percentages of the non-seasonal variability are, as expected, below 10% near the surface and gradually increasing up to more than 80% below 200 m depth. Salinity trends are also overall positive, with values up to 0.1 per decade in the surface layer and down to around 0.04 per decade in the deeper areas. Variance is generally low, with the highest values (up to 0.1) on the western surface area. Percentage anomalies are over 95% almost everywhere except in the (1) west surface area inhabited by Western Adriatic Coastal Current and near-bottom between 100 and 800 m, where the dense water is outflowing, and (2) on the eastern areas between 150 and 300 m depth, where they fall to 80% exhibiting seasonality in the inflow of saline waters to the Adriatic (Yari et al. 2012). Current speed trends are positive on the western and eastern parts of the transect up to 600 m depth, indicating a strengthening of water mass exchange in surface and intermediate layers, and negative below that depth and in the surface layer between areas of positive trends. Indeed, these trends are indicating a shallowing of the Adriatic-Ionian thermohaline circulation, as projected for the future climate (Somot et al. 2006). Variance of current speed is generally low, with higher values up to 0.05 m^2 s^{-2} only in the westernmost surface layer. Percentage anomalies mostly stay above 80%, falling below that value on the western boundary of the transect, up to 700 m depth.

Alongshore transect results display the differences between trends and variances in the shallow and deep-sea areas of the Adriatic Sea. Both temperature and salinity trends are much stronger in the shallow northern Adriatic than in the deep Adriatic, going up to 0.6 °C per decade for temperature, and 0.02 per decade for salinity in shallow areas. The temperature trends correspond to the one recorded in measurements along the northern Adriatic well-surveyed transect (Vilibić et al. 2019), while salinity trends are somehow overestimated by the AdriSC model. However, the latter is following the documented overestimation in salinity of the AdriSC model off the Po River delta (Pranić et al. 2021), while the trend estimates are also found sensitive to sampling (i.e., different trends have been found at two stations off the Po River) indicating the change in plume dynamics in the last 30 years (Vilibić et al. 2019). Negative temperature trends are found in the first 150 km of the transect between 600 and 900 m depth, in agreement with the Otranto transect estimates. However, the temperature trends are positive (around 0.1 °C per decade) in the deepest part of the southern Adriatic, indicating a warming of the Adriatic deep waters coming from the northern Adriatic shelf (Cardin et al. 2020). Salinity trends at these depths are also positive (around 0.005 per decade), stretching also at the bottom of the Otranto Strait and south of it, thus indicating an increase in salinity of the deep Adriatic outflow observed recently. In the upper layers, up to 200 m, salinity trends are much larger, around 0.01 per decade (except at the center of the southern Adriatic cyclonic gyre). Still, these salinity trends are about two times lower than observed in the 1952–2010 period over the Palagruža Sill transect (Vilibić et al. 2013) probably due to the different sampling periods of the analyses. Current speed trends are mostly insignificant or slightly positive in the shallow northern Adriatic area, and strongly positive in the first 200 km of the transect, up to 500 m depth, indicating stronger water mass exchange in the Otranto Strait. In the same area but in greater depths, trends are negative, that resemble a weakening of the deep Adriatic water outflow. The weakening of the outflow is the result of weakening of the deep-water production in the southern Adriatic cyclonic gyre, as between 200 and 350 km (i.e., in the middle of the gyre) the trends are negative over the entire water column.

Variances are mostly low for both temperature and salinity, with expectedly higher values in the northernmost, and shallowest, part of the transect, and near the surface. Current speed variances are also mostly low (up to 0.005 m^2 s^{-2}) with values up to 0.015 m^2 s^{-2} in the northern Adriatic area and in the first 150 km of the transect, near the Otranto strait. Further, percentage anomalies caused by non-seasonal variations reach almost 100% for the entire transect for the salinity and for the temperature below 100–200 m depth (i.e., below the seasonal thermocline; Buljan and Zore-Armanda 1976; Artegiani et al. 1997). The temperature percentage anomalies are gradually dropping below 20% when getting closer to the surface. Interestingly, percentage values are less homogeneous for current speed than for salinity and temperature but are also high, above 70% almost everywhere. The first exception is the center of the Jabuka Pit (between 480 and 550 km of the transect), where more than 30% of the variance is ascribed by the seasonal changes, resembling the seasonal non-stationarity of the middle Adriatic cyclonic gyre that is driven by both seasonal changes in the Western Adriatic Coastal Current and the near-bottom dense water outflow (Martin et al. 2009). Another exception is the southern edge of the Palagruža Sill, where the exchange of water masses is also seasonally modulated (Martin et al. 2009; Vilibić et al. 2015). The last exception is the Otranto Strait,


Monthly trend
Monthly variance
1 2 3 4 5 6 7 8 9 10 11 12
°C/10y
°C²
Temperature at 2m
Adriatic
Apennines
Velebit
Dinarides
avg.
max.
min.
Rain
mm.day⁻¹/10y
mm².day⁻²
Wind speed
m.s⁻¹/10y
m².s⁻²
Relative humidity
%/10y
%²

◂**Fig. 8** Atmospheric monthly trends (left panels) and variances (right panels) for average (avg.), maximum (max.) and minimum (min.) values of temperature at 2 m, rain, wind speed at 10 m and relative humidity at 2 m for the four sub-domains of interest. Black diagonal lines represent insignificant trends for the sub-domain

in particular, its upper 300 m, where exchanges of surface and intermediate waters are taking place and are known to have strong seasonal pulsations (Mihanović et al. 2021).

3.2 Sub-domain analysis

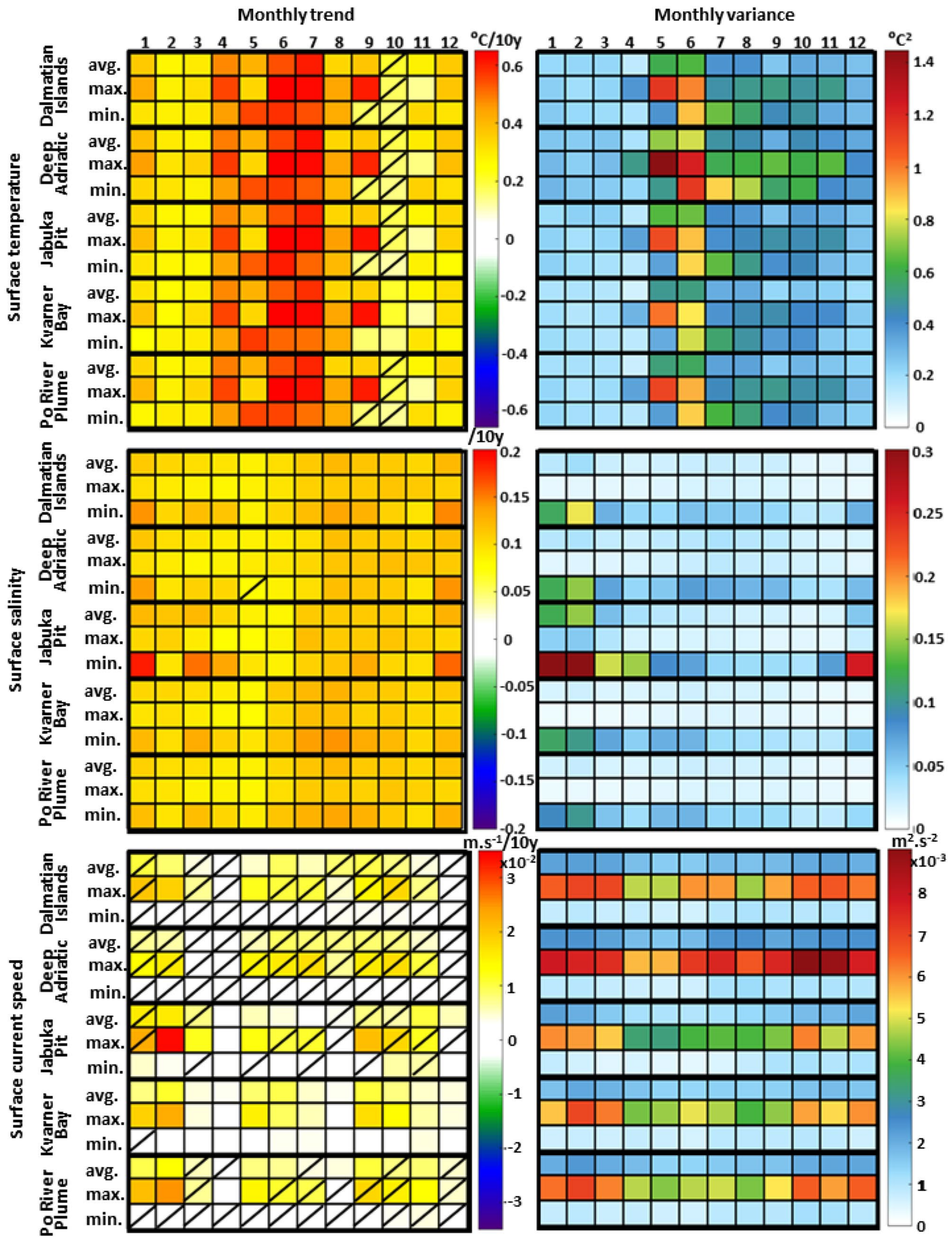
The results of the sub-domain monthly analyses are presented as tables with columns representing each month and rows representing mean, maximum and minimum daily data grouped by sub-domains (Fig. 8 for the atmospheric variables for four sub-domains and Figs. 9, 10, 11 for the oceanic variables for five sub-domains). The minimum for rain is not presented as, within the Adriatic basin, monthly rain minimums are always equal to zero. Further, insignificant trends are represented with black diagonal lines in the monthly square where they occur.

3.2.1 Atmosphere

In the atmosphere, monthly trends of temperature at 2 m, rain, wind speed at 10 m and relative humidity at 2 m are mostly insignificant (Fig. 8), implying that the atmospheric variability is much higher than the estimated trends over this 31-year interval in the Adriatic basin. However, temperature trends in June are significant and high, with values up to 0.6 °C per decade for the mean over all the sub-domains and for the maximum only over the Dinarides sub-domain. For the Adriatic Sea sub-domain, months of March, April and July also have high and significant trends for both mean and maximum temperatures, from 0.3 °C per decade in spring up to 0.6 °C per decade in summer. High and significant trends for mean temperature are also found in April for the Apennines and Velebit sub-domains (up to 0.5 °C per decade), in July for the Velebit and Dinarides sub-domains (up to 0.4 °C per decade) and in August for the Dinarides sub-domain (up to 0.4 °C per decade). Significant positive trends of temperature maximums are found for August in Velebit and Dinarides sub-domains (up to 0.6 °C per decade). These results are in good agreement with the observed trends found much stronger and significant in summer and spring than during winter and autumn months (Scorzini and Leopardi 2019; Bonacci et al. 2021b; Nimac et al. 2021). This monthly analysis also highlights that summer trends of air temperature at 2 m are generally higher above the sea (up to 0.6 °C per decade), than in the mountainous areas (up to 0.4 °C per decade). Also, trends for maximums are mostly higher than those of means, while lowest trends, down to 0.1 °C per decade, are found for the minimum datasets. Interestingly, January trends of minimum temperature are strongly negative, being lower than − 0.5 °C per decade in all four sub-domains, while mean temperature trends are negative, down to − 0.35 °C per decade, everywhere but in the Adriatic Sea sub-domain, where trends reach 0.2 °C per decade. This might be explained by cold waves, such as the one in January 2017 (Anagnostopoulou et al. 2017), and the fact that the monthly trends are only calculated with 31 values. It should be noted that January trends of minimum temperature are higher by 0.2 °C per decade in the 1987–2016 period (but stay negative) compared to the 1987–2017 period due to the absence of one cold spell. Negative temperature trends are found also in October for all sub-domains, with values between − 0.1 and − 0.3 °C per decade, following observations in the central Mediterranean (Liuzzo et al. 2017). Trends are lower in winter than in summer for the Adriatic Sea and Apennines sub-domains. While, for Velebit and Dinarides sub-domains, November mean and minimum datasets have strong positive trends with values up to 0.6 °C per decade. Intuitively, the opposing temperature trends in October and November are associated with the change in dominant synoptic and planetary conditions over Europe, that are resulting in earlier advection of cold air masses in autumn in the 2000s and 2010s which may result from climatic changes over the Arctic (Chripko et al. 2021).

Concerning the rain, only trends from mean dataset in September in Apennines sub-domain are significant with values up to 0.25 mm day^{-1} per decade. Rain trends are positive for both mean and maximum values for all the sub-domains in January, February, March, May, September, and October, but they are negative for April, June, August, and December. Strongest negative trends are found during the summer period in the Velebit sub-domain: − 0.6 mm day^{-1} per decade for the mean and about − 4 mm day^{-1} per decade for the maximum. These estimates are consistent with observations, which are documenting a redistribution of precipitation during the year with an overall decrease during summer and an increase in intensity during extreme events (Giorgi and Lionello 2008; Russo et al. 2019; Bonacci et al. 2021a).

As for the rain, insignificant trends are dominating both relative humidity and wind speed variables. However, positive trends for the mean and maximum wind speeds (up to 0.3 m s^{-1} per decade) are found for the winter months (January, February, March) in all sub-domains and in September–October for some sub-domains. Negative trends with values down to − 0.3 m s^{-1} per decade are found for all sub-domains for the mean and maximum wind speeds during April and December, and for the Dinarides and Velebit sub-domains during July. Overall, the AdriSC model results are in good agreement with the wind speed increase found over the Adriatic for different periods by different reanalysis products (e.g., 1960–1988, Cavaleri et al. 1997; 1979–2014,


Monthly trend
Monthly variance
1 2 3 4 5 6 7 8 9 10 11 12
°C/10y
°C²
Surface temperature
Surface salinity
Surface current speed
Dalmatian Islands
Deep Adriatic
Jabuka Pit
Kvarner Bay
Po River Plume
avg.
max.
min.
/10y
m.s⁻¹/10y
x10⁻²
m².s⁻²
x10⁻³

◂**Fig. 9** Ocean monthly trends (left panels) and variances (right panels) for average (avg.), maximum (max.) and minimum (min.) values of temperature, salinity and current speed at the surface for the five sub-domains of interest. Black diagonal lines represent insignificant trends for the sub-domain

Soukissian et al. 2017). Relative humidity trends are mostly negative from August to December, except during November for the Adriatic Sea sub-domain and during October for the Velebit sub-domain. In contrast, positive relative humidity trends (up to 2% per decade) are dominating during winter (January–March) in all but the Adriatic Sea sub-domain. Overall, relative humidity trends in all sub-domains, and particular in the Adriatic Sea sub-domain, are generally negative, except for February, March, and November, which is in accordance with the negative trends in relative humidity found in global analysis over most of the Mediterranean Sea (Vicente-Serrano et al. 2018).

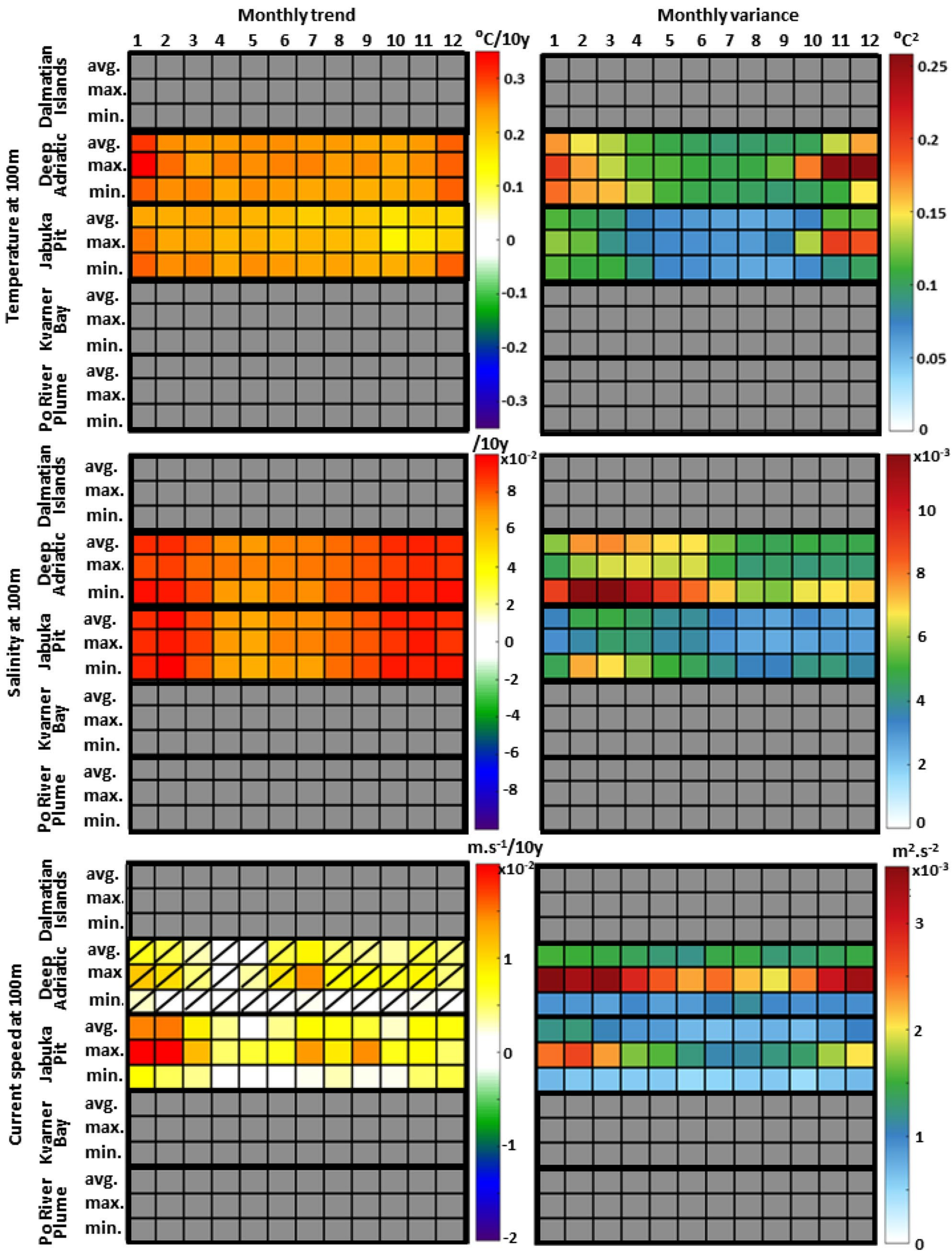
Monthly temperature variance is mostly below 2 $°C^2$ for mean and maximum values, while it is up to 4 times higher from October to April for minimum values. In more detail, during this period, minimum temperature variances go up to 4 $°C^2$ in the Adriatic Sea sub-domain, 5.5 $°C^2$ in the Apennines sub-domain, and 8 $°C^2$ in the Velebit and Dinarides sub-domains. Convincingly, minimum temperatures are strongly driven by outbreaks of continental and polar air masses that are reaching the Mediterranean during cold period, but not during warm period of the year (Saaroni et al. 1996). For the rain, minimum variance is not presented (as minimum rain is always zero) but mean and maximum variances strongly vary between the different sub-domains, reflecting the orographically-driven observed patterns (Ivušić et al. 2021). They are (1) the highest for the Velebit sub-domain with values over 1000 $mm^2\ day^{-2}$ except during the April-July period, (2) up to 1000 $mm^2\ day^{-2}$ but generally lower than those in the Velebit sub-domain for the Apennines and Dinarides sub-domains during the August-March period and (3) the lowest in the Adriatic Sea sub-domain (about 2 $mm^2\ day^{-2}$ for the mean and 300 $mm^2\ day^{-2}$ for the maximum) during the August-December period. The maximum wind speed variances (over 6 $m^2\ s^{-2}$) are found for the maximum datasets all year except during the summer, when values vary between 2 and 4 $m^2\ s^{-2}$.

Their highest values are reached within the Adriatic Sea and Velebit sub-domains. Mean wind speed variances are the highest in the Velebit sub-domain (1–2 $m^2\ s^{-2}$), then over the Adriatic Sea sub-domain, while over the Apennines and Dinarides sub-domains they are generally below 0.5 $m^2\ s^{-2}$. In contrast to the wind speed, relative humidity variances are the highest for the minimum values (up to 55$\%^2$), particularly during the winter months for the Velebit and Dinarides sub-domains, presumably reflecting the strong difference in humidity between two major Adriatic winter regimes, bora and sirocco (Belušić Vozila et al. 2021). This difference is not so large in the Apennines, as the dry bora wind is gaining moisture when crossing the Adriatic Sea (Davolio et al. 2017). For the Adriatic Sea sub-domain, the relative humidity variances are largest during the spring months, with values up to 65$\%^2$. This might be attributed to the large difference between air and sea temperatures, where cold sea has no capacity to feed the dry and warm atmosphere (relative humidity minimum is reached in March–April, Zaninović et al. 2008), while still being affected with sirocco-driven humid periods.

To summarize the monthly analysis in the atmosphere, air temperature trends are generally the strongest over the Adriatic Sea where variances are the lowest in comparison to the other sub-domains. Rain trends are insignificant but positive during winter and weakly negative over land during summer only, particularly over the Velebit sub-domain. Relative humidity trends are positive during winter overland but not over the Adriatic Sea, while mostly negative during the rest of the year. Wind speed is also following the rain trends during winter. Generally, no great difference exists between the land domains. However, the Velebit sub-domain does stand out in several cases: (1) rain variances are much higher and rain trends are more negative, (2) wind speed trends in wintertime are stronger, and (3) relative humidity variances are higher, and trends are stronger.

3.2.2 Ocean

Contrarily to the atmosphere, monthly trends of sea temperature and salinity (Figs. 9, 10, 11) are almost exclusively significant for all sub-domains and all depths, but current speed trends remain generally less significant. It should be noted that only Deep Adriatic and Jabuka Pit sub-domain results are presented at 100 m depth (Fig. 10), since other sub-domains are shallower than 100 m depth. Trends in sea surface temperature (Fig. 9) are positive in all five analyzed sub-domains, being the highest in June and July with values over 0.6 °C per decade, but also being over 0.4 °C per decade from April to August. The lowest trends are found in November and October when trends are mostly insignificant everywhere except within the Kvarner Bay sub-domain. These values agree with observational studies, either along the long-term monitored transect such as in the northern Adriatic (Vilibić et al. 2019) or with satellite-derived sea surface temperature trends (Shaltout and Omstedt 2014a; Pastor et al. 2018; Grbec et al. 2018). Trends of maximum temperatures are lower than those of mean or minimum temperatures during May and November, while they are significantly higher during September. Surface temperature variances are the lowest from January to April, and the highest in May and June. Interestingly, the highest variance values (up to 1.4 $°C^2$) are found during May for the maximum


Monthly trend
Monthly variance
1 2 3 4 5 6 7 8 9 10 11 12
°C/10y
°C²
Temperature at 100m
Salinity at 100m
Current speed at 100m
Dalmatian Islands
Deep Adriatic
Jabuka Pit
Kvarner Bay
Po River Plume
avg.
max.
min.
/10y
x10⁻²
x10⁻³
m.s⁻¹/10y
m².s⁻²

◀**Fig. 10** Ocean monthly trends (left panels) and variances (right panels) for average (avg.), maximum (max.) and minimum (min.) values of temperature, salinity and current speed at 100 m depth for the two sub-domains deeper than 100 m depth. Black diagonal lines represent insignificant trends for the sub-domain

dataset in the Deep Adriatic sub-domain. Generally, variances in the Deep Adriatic sub-domain stay higher than the ones in other sub-domains until November. This might be due to vertical processes in the southern Adriatic cyclonic gyre, which may occasionally bring or block the uplift of deep waters through upwelling, depending on its intensity and embedded mesoscale features (Cushman-Roisin et al. 2007).

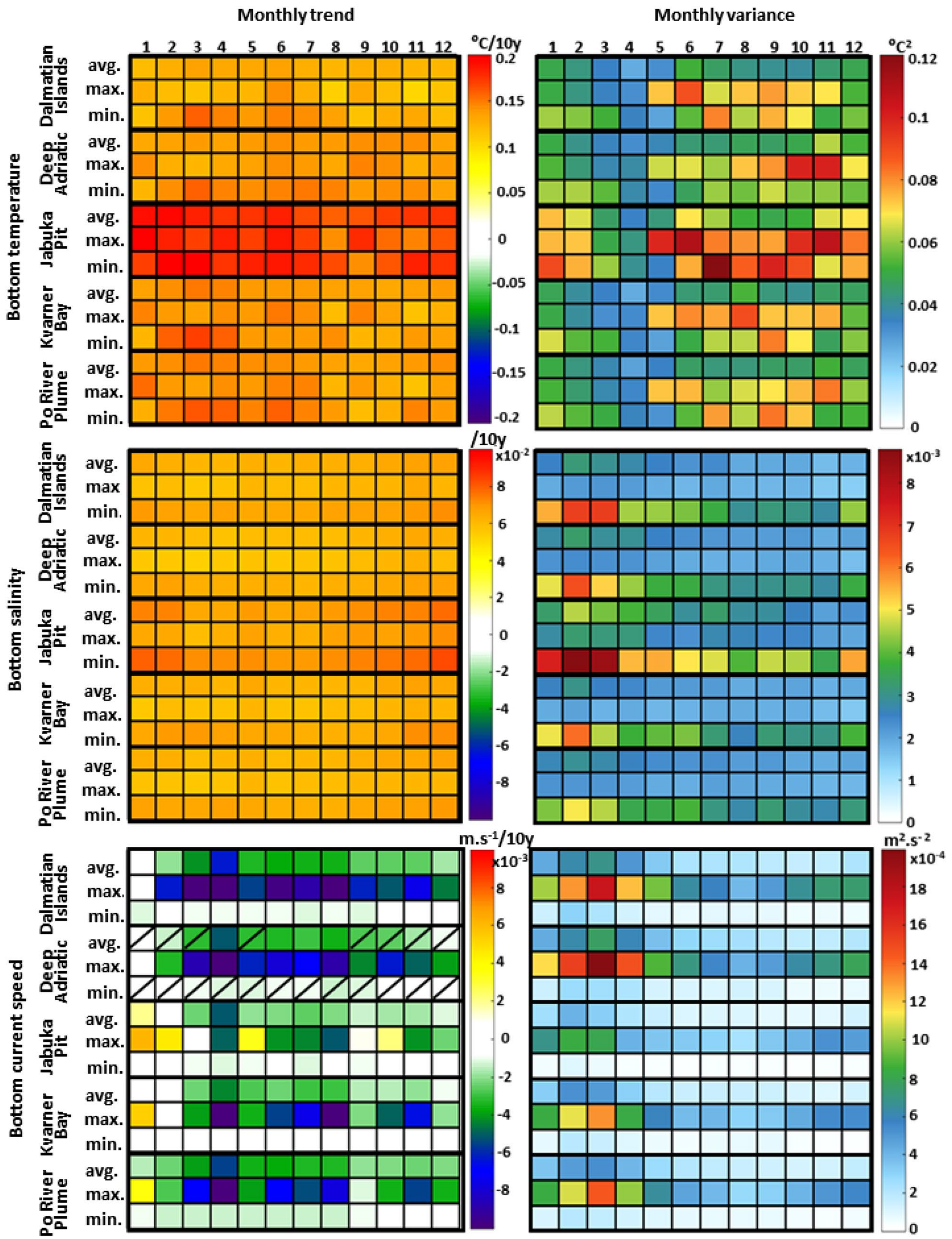
The lowest variances of sea surface temperature are found in the Kvarner Bay, with a maximum barely reaching 1 $°C^2$ in May. Indeed, the transport of waters between the Kvarner Bay and the open Adriatic is restricted by a chain of islands, while these islands are also prohibiting strong sea-breeze and Etesian wind during the warm season (Prtenjak et al. 2006; Klaić et al. 2009). Consequently, both horizontal advection and vertical mixing are presumably lower in the summer season and are not strongly affecting the surface temperature within the Kvarner Bay.

Temperature trends at 100 m depth (Fig. 10) differ from those at surface, being mostly around 0.3 °C per decade for mean, maximum and minimum datasets in the two sub-domains, slightly higher in December and the highest in January. Indeed, the 100 m depth analysis has been chosen as saline Levantine Intermediate Water is known to inflow in these depths (Buljan and Zore-Armanda 1976; Artegiani et al. 1997), and to increase in temperature and salinity in recent decades (Fedele et al. 2022). Trends in the Deep Adriatic sub-domain are slightly higher than those in the Jabuka Pit sub-domain. This relation between the sub-domains is similar for the variance values that are generally lower than at the surface. High variance values in both sub-domains are found from October until March, being the highest for November and December when the destruction of the seasonal thermocline is taking place (Buljan and Zore-Armanda 1976), followed by convection processes and a decrease in temperature acting in both deep ocean sub-domains (Gačić et al. 2002; Querin et al. 2013). Results of bottom data analysis (Fig. 11) show that the situation at the bottom highly differs from the surface. The highest temperature trends are found in the Jabuka Pit sub-domain (up to 0.2 °C per decade) indicating that the northern Adriatic dense water that are collected at the bottom of the pit (Vilibić and Supić, 2005; Mihanović et al. 2013) are rapidly warming. The warming is much smaller in the other dense water collector, the Deep Adriatic sub-domain. Trends in the Deep Adriatic sub-domain are also positive throughout the year (above 0.1 °C per decade) with slightly higher trends for the minimum datasets, especially in February, March, and April. Variances are also the highest in the Jabuka Pit sub-domain. For all sub-domains, (1) mean variances are lower than maximum and minimum variances and (2) variances are the lowest in April and the highest between May and November for the maximum datasets.

Surface salinity (Fig. 9) presents positive trends for all the sub-domains, with values mostly between 0.1 and 0.15 per decade. These values are higher than the values observed along the Palagruža Sill transect during the 1952–2010 period (Vilibić et al. 2013) but 2–3 times lower than observed between 2001 and 2019 (Fedele et al. 2022). Therefore, salinification of the Adriatic is found to rapidly increase in last decades. Highest trends are found for minimums of salinity, especially for December, January, and March, with these trends in the Jabuka Pit sub-domain being the highest. May and June trends are lower than average for all datasets and for all sub-domains. Slightly higher trends are found between July and October, indicating that higher evaporation with increased stratification may keep saline waters closer to the surface—such process is commonly observed in the Levantine Basin (Kassis and Korres 2020) and is frequently occurring in the Adriatic (Mihanović et al. 2021) in recent decades. Variances reach high values (up to 0.3) during wintertime for minimums, especially in the Jabuka Pit sub-domain, while mostly staying below 0.05 for means and maximums (except for winter in the Jabuka Pit sub-domain).

At 100 m depth (Fig. 10), salinity variances are higher for the Deep Adriatic sub-domain than for the Jabuka Pit sub-domain. The highest variances at this depth are found for February and March, when open ocean convection is taking place while the lowest ones occur in August and September. The pattern is shifted for two months in comparison to surface data. Trends in both sub-domains are the lowest during spring and summer when the Adriatic-Ionian thermohaline circulation is normally at its maximum (Orlić et al. 2007), thus indicating its weakening. The trends are much higher from October until March, with values up to 0.1 per decade.

No difference can be seen between mean, maximum, and minimum datasets, neither between the different sub-domains. At the bottom (Fig. 11), variances are again the highest for the minimum datasets, from December until March, when either vertical mixing is reaching the bottom (for all but the Deep Adriatic sub-domain) or the dense water outflow is transported downslope (for both Jabuka Pit and Deep Adriatic sub-domains, Vilibić and Supić, 2005; Rubino et al. 2012). Maximum dataset variances are generally the lowest with no great difference between months or sub-domains. Trends are positive overall, with values mostly around 0.06 per decade, being the highest for winter months in the Jabuka Pit sub-domain. Generally, at the


Monthly trend
Monthly variance
°C/10y
°C²
/10y
x10⁻²
x10⁻³
m.s⁻¹/10y
x10⁻³
m².s⁻²
x10⁻⁴
Bottom temperature
Bottom salinity
Bottom current speed
Dalmatian Islands
Deep Adriatic
Jabuka Pit
Kvarner Bay
Po River Plume
avg.
max.
min.
1 2 3 4 5 6 7 8 9 10 11 12

◂**Fig. 11** Ocean monthly trends (left panels) and variances (right panels) for average (avg.), maximum (max.) and minimum (min.) values of temperature, salinity, and current speed at the bottom for the five sub-domains of interest. Black diagonal lines represent insignificant trends for the sub-domain

bottom, trends for minimum and mean datasets are higher than those for maximum datasets.

Current speed variances and trends at surface are the highest for maximum datasets (Fig. 9). Variances are generally the highest in the Deep Adriatic and Dalmatian Islands sub-domains during the October–March period when the cyclonic activity and wind-driven circulation is the strongest (Poulain 2001). The trends are mostly insignificant in the Deep Adriatic, Dalmatian Islands and Po River Plume sub-domains, presumably related to higher variability, yet having the same rate of positive trends than the Jabuka Pit and Kvarner Bay sub-domains. In March, April, August, and December trends are generally much weaker, while they reach 0.02 m s^{-1} in the rest of the year. Some similarities between the surface current speed trends and wind speed at 10 m (Fig. 8) may be seen, indicating that surface currents are strengthening in some months largely due to the increase of wind forcing at the surface. At 100 m depth (Fig. 10), current speed variances are the highest for maximum datasets in wintertime and are higher in the Deep Adriatic sub-domain than in the Jabuka Pit sub-domain. Values are up to 3 times lower than on the surface. Trends are the highest for maximum current speeds, in particular in January, February and July, resembling stronger advection of saline waters during these months. At the bottom, negative current speed trends prevail in all the domains and for all data series (Fig. 11).

Trends obtained from maximum current speeds have much higher values than those obtained from the mean current speeds, surpassing 0.005 m s^{-1} for some months, in particular during spring and summer. This indicates much lower intensity in pulsation of waters near the bottom, which are largely coming from bottom dense currents, being in line with the decrease and shallowing of thermohaline circulation and dense water production, in particular on the northern Adriatic shelf (Somot et al. 2006; Vilibić et al. 2013).

In brief, trends of temperature and salinity are strongly significant and positive over all domains, while currents speed are less significant but positive in the surface and intermediate layers, but strongly negative at the bottom. Specifically, the trends are resembling (1) summertime extensive warming by the atmosphere at the surface, affecting both temperature and salinity (through evaporation), (2) strong salinization by Levantine Intermediate Water inflow in the intermediate layer (at about 100 m depth), (3) stronger circulation in the upper layer of the ocean due to strengthening of the vertical stratification which presumably lead to stronger baroclinicity, and (4) substantial weakening of the near-bottom circulation, which may indicate a weakening of the dense water dynamics and, consequently, of the deep thermohaline circulation in the Adriatic Sea.

4 Discussion and conclusions

The analysis of atmosphere–ocean Adriatic present climate during the 1987–2017 period using the kilometer-scale AdriSC climate model provided new insights to, previously unknown, trends and variability over the entire Adriatic basin. The reliability of these estimates is rather high, as the AdriSC climate model (1) has a kilometer-scale resolution, and therefore is capable to reproduce dynamics over most of the Adriatic, including processes in complex northeastern coastal regions (e.g., hurricane strength bora events), and (2) has been successfully validated over a great number of in situ measurements and remote sensing products, in both atmosphere (Denamiel et al. 2021b) and ocean (Pranić et al. 2021). Further, the AdriSC model is even capable of reproducing the decadal oscillations driven by the Adriatic-Ionian Bimodal Oscillating System (BiOS, Gačić et al. 2010) and is the first climate model with such a capacity (Denamiel et al. 2022). Namely, the regional Mediterranean climate models like those coming from the Med-CORDEX initiative (Ruti et al. 2016) are documented to have strong biases in the Adriatic Sea, and to underrepresent some processes like dense water generation, which are crucial for the thermohaline circulation of the Adriatic-Ionian region and the BiOS-driven quasi-decadal oscillations (Dunić et al. 2019).

The most elucidating result is the significant warming and its effect over the entire region in the last 31 years, both in the atmosphere and the ocean. While ocean trends are exclusively significant at 95%, the atmospheric trends of temperature at 2 m are dominantly insignificant, yet, the trend rates are similar, thus the difference in significance levels is probably coming from much higher variability in the atmosphere than in the ocean, but also could be affected by the use of different models and the analysis of different domains. This is also the case for other atmospheric and oceanic variables analyzed in our study. Convincingly, the trends of air temperature at 2 m go up to 0.6 °C per decade over the sea, and up to 0.4 °C per decade over the land, with higher trend and trend significance values for all atmospheric sub-domains during the March-August period than the rest of the year. Sea surface temperature trends also vary between 0.4 and 0.6 °C per decade, with lowest trends over the deepest and northernmost areas of the Adriatic Sea, the latter affected by the upwelling of colder waters that is occurring in the center of the southern Adriatic cyclonic gyre (Gačić et al. 2002). The highest temperature trend values are found in June and July. This is in accordance with the findings of Bartolini et al. (2012) and Pastor et al. (2018), who concluded in their regional climatological studies that the fastest and strongest warming trends occurred from March to August. Similarly, Bonacci et al. (2021a, b) stated that their statistical analyses performed on the time series of the mean monthly SST and air temperature in central Adriatic Sea showed that the most significant increasing trends in the SST and the air temperature occur during the warm periods of the year (i.e., during spring and summer). Pronounced warming in the summer season was also reported by Branković et al. (2013) and Bonacci (2012).

Apart from the surface, the trends in ocean temperature are behaving differently, highlighting several processes shaping the Adriatic circulation and heat transport. Negative sea temperature trends in the deeper layers of the Otranto transect (500–900 m depth), along with lowest salinity trend values and negative current speed trends, could be explained by two effects: (1) shallowing of the advection of saline and warmer Levantine Intermediate Water (LIW) inflow into the Adriatic, noticed in the last decade (Mihanović et al. 2021), and (2) a decrease of the Adriatic deep water outflow, which is now restricted more to the bottom. Therefore, the circulation in the considered layer is static, with less warm masses advected during the 2000s and 2010s than during the 1980s and 1990s. Similar effect, but on a smaller scale, has been noticed on the Palagruža Sill transect (Vilibić et al. 2013). Namely, the temperature trends there were also negative in the 1952–2010 period, but—as for the Otranto Strait—the warming was still present near the bottom of the sill. These near-bottom waters, with temperature increasing in time, are either northern Adriatic dense waters flowing over the Palagruža Sill towards deep southern Adriatic (Vilibić and Supić, 2005) or the Adriatic deep waters going over the Otranto Strait towards the deep Ionian Sea (Sisma-Ventura et al. 2021). Both types of near-bottom waters are warming in time, as having origins at the surface, thus both shelf dense water generation and open ocean convection are processes highly responsible for warming of deep waters, already observed in the Mediterranean (Llasses et al. 2018) but also globally (Ferrari and Ferreira 2011). Finally, the shallowing of the Levantine Intermediate Water inflow is in line with the regional climate simulations of the Adriatic-Ionian thermohaline circulation which is forecasted to be shallower when coming towards the end of the twenty-first century (Somot et al. 2006).

Higher trend and variance values in shallow areas compared to those in deeper ones can be explained by the presence of larger masses of water in the deep areas which are known to be more resilient to changes. In fact, warming induced by climate change propagates slowly to greater depths (Bethoux et al. 1990; Cusinato et al. 2018) and explains the decrease of sea temperature trend values from surface to the bottom. The presence of the largest variance values along the Po River plume supports the statement that surface salinity in the Adriatic Sea is mainly driven by large freshwater load in the northern Adriatic. Similarly, the highest values of salinity trends found in the coastal regions can be explained with the decrease of freshwater load in time. Indeed, Cozzi and Giani (2011) found that precipitation decrease is reflected in a decrease of the freshwater load to the Adriatic Sea, and pointed out that increased frequency of drought periods, due to ongoing climate changes, would be able to significantly change the biogeochemistry of the basin. Low values of percentage anomalies in the coastal areas and at the surface in general confirm that salinity variability is mostly driven by extreme events and daily variability. Positive salinity trends in the Jabuka Pit were also found during the 1951–1989 period by Vilibić (2004) which demonstrated that the hydrological time-series at the Jabuka Pit included an increase in salinity of 0.036 per decade. Vilibić (2004) stated that such an increase also reveals broader changes in the Mediterranean salinity caused by reduced precipitations over the entire basin.

For the atmosphere, several interesting results—aside from the increase in temperature—can elucidate the ongoing climatic changes in the Adriatic basin. Significant trends of wind speed over the sea and along the Adriatic coasts are found to be positive, which is in accordance with the results of previous studies. In the framework of the RESPONSe project, for six coastal locations in Italy and Croatia, a significant increase in wind speed intensities was found during the 1979–2018 period using the ERA5 reanalysis (DHMZ 2020). The northernmost Adriatic region was also found to be one of the areas with the fastest increase in wind speed trends over the entire Mediterranean basin (Soukissian et al. 2017). Concerning the relative humidity, the highest values are generally found over the oceans where it represents an important climate factor when associated with the evaporation rate. Negative relative humidity trends over the Adriatic Sea and somewhat positive trends over the surrounding land, in particular during winter, are found in this study which indicates that the difference between relative humidity values between land and sea is already decreasing. Previous studies yielded some contrary conclusions, several climate simulations found small increases in relative humidity over the oceans and larger decrease in relative humidity over the continents (O'Gorman and Muller 2010; Laîné et al. 2014; Fu and Feng 2014), while others (Dai 2006; Willett et al. 2008) found decreasing trends in surface relative humidity over the oceans but no significant trends over the land. Latter studies identified a bias in their data that may have caused the apparent negative trend over the oceans, while spatial differences over land may be substantial (Vicente-Serrano et al. 2018). Rain trends are found to be generally insignificant, positive during winter and generally negative during summer, which is in accordance with previous studies. For example, in the framework of the RESPONSe project, based on the E-OBS v19.0 dataset for the 1961–2018 period, linear trends of precipitations are found to be rarely significant (DHMZ 2020). Bonacci (2019) found no trends for the annual and monthly precipitation time-series during the 1948–2018 period on the small remote island of Lastovo and found only some statistically insignificant negative annual precipitation trends after 1982. However, the rain trends are contrasting when going southwards, having negative values in winter and autumn (Caloiero et al. 2018), because of the drying of the Mediterranean basin which is not reaching the middle and the northern Adriatic (Zampieri et al. 2012; Shaltout and Omstedt 2014b).

The ongoing climate change, well-documented in many studies including the presented work, has increased the scientific and policy maker's interest in climate modelling. This study explicitly shows how kilometer-scale coupled atmosphere–ocean modelling is crucial for comprehensive climate studies at the regional to local scales, as it captures some local characteristics that have not been properly reproduced by climate models up till now. For example, this includes (1) the variations in the bora wind intensities strongly affecting the transportation, energetics, etc., in coastal regions (Kozmar et al. 2012; Lepri et al. 2017) but also driving the formation of the densest waters in the Mediterranean Sea (Mihanović et al. 2013) and thus bringing oxygen to the deep ocean layers (Manca et al. 2006), or (2) the shrinking and weakening of the Southern Adriatic Gyre which is impacting the whole Adriatic Sea by transporting water masses of different temperature, salinity and oxygen concentration than the surrounding waters. Further, with the recent completion of the AdriSC future climate run (RCP 8.5, 2070–2100), the impact of extreme climate warming at the kilometer-scale can now be quantified, for the very first time, for all these processes in the Adriatic basin.

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Author contributions IV and CD designed the study and developed the concept. Material preparation was done by CD and IT. Production of the figures was done by IT. Analysis of the results was performed by CD, IV and IT. The first draft of the manuscript was written by IT and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data and material availability The model results used to produce this article can be obtained under the Open Science framework (OSF) through the FAIR data repository at https://osf.io/h8sjd/ (https://doi.org/10.17605/OSF.IO/H8SJD).

Code availability The code of the AdriSC climate model used in this article can be obtained under the Open Science Framework (OSF) FAIR data repository https://osf.io/zb3cm/ (https://doi.org/10.17605/OSF.IO/ZB3CM).

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