Acceleration of warming, deoxygenation and acidification in the Arabian Gulf driven by weakening of summer winds

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Key Points:

- Recent changes in surface winds have accelerated warming in the Arabian Gulf while dampening it in the Sea of Oman.
- The faster warming in the Arabian Gulf has reduced exchange with the Sea of Oman, leading to a buildup of nutrients and biomass in the Gulf.
- This increased productivity has caused a rise in respiration, thereby accelerating deoxygenation and acidification in the Gulf.

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Abstract

The Arabian Gulf (AG) exports hypersaline, dense waters into the Sea of Oman (SOO), replaced by fresher inflowing surface waters from the Indian Ocean. We investigate the impact of recent AG warming on its exchange with the SOO and the implications this has on the AG biogeochemistry. Using an eddy-resolving hindcast model simulation, we analyze the hydrography and biogeochemistry of the AG and the SOO from 1980 to 2018. Our study reveals that changes in summer surface winds have accelerated AG warming and weakened it in the SOO, reducing the density gradient and water exchange between the two seas during late summer. This has led to nutrient buildup, increased productivity, and heightened deoxygenation and acidification in the AG. These findings underscore how subtle wind changes can exacerbate the vulnerability of marginal seas to climate change and stress the need to properly represent regional winds in global climate models.

Plain Language Summary

The Arabian Gulf (also known as Persian Gulf) produces dense, salty water that flows into the Sea of Oman, while it receives fresher water from the Indian Ocean. This study investigates how the recent rapid warming of the Arabian Gulf affects this exchange with the Sea of Oman and its impact on the Gulf's environment. Using a computer simulation to model the Arabian Gulf's evolution from 1980 to 2018, we discovered that changes in surface winds have warmed the Arabian Gulf and weakened its connection to the Sea of Oman during summer. This led to nutrient accumulation, increased micro-algae growth, decreased oxygen levels, and increased water acidity in the Arabian Gulf. These findings highlight how minor changes in wind patterns can exacerbate the effects of climate change in specific seas, emphasizing the need to improve the representation of local winds in climate models.

1 Introduction

The Arabian Gulf, also known as the Persian Gulf (hereafter AG), is a shallow semi-enclosed sea subject to a hyper-arid climate, characterized by intense evaporation that far exceeds both precipitation and runoff (Reynolds, 1993). This results in the prevalence of large areas of hypersaline waters (Vaughan et al., 2019) and an inverse estuary circulation, in which the dense Gulf water (Gulf Deep Water) is discharged at depth along the southern side of the Strait of Hormuz (hereafter the Strait) into the Sea of Oman (hereafter SOO), and is replaced by a surface inflow of fresher, lower-density waters from the Indian Ocean (Indian Ocean Surface Water) along the northern side of the Strait (Chao et al., 1992; Reynolds, 1993; Swift & Bower, 2003). As direct observations of this exchange and its variability are scarce (Johns et al., 2003; Swift & Bower, 2003), numerous modeling studies have explored its dynamics, revealing its tight coupling to the density gradient through the Strait (Kämpf & Sadrinasab, 2006; Thoppil & Hogan, 2009; Yao & Johns, 2010; Pous et al., 2015; Lorenz et al., 2020). The recent rapid warming of the AG relative to the Arabian Sea (Al-Rashidi et al., 2009; Strong et al., 2011; Hereher, 2020; Al Senafi, 2022), which is expected to further accelerate in the future, is likely to impact the density gradient between the two seas and hence alter transport through the Strait (Swift & Bower, 2003; Kämpf & Sadrinasab, 2006; Paparella et al., 2022). Yet, little is known about the effects of such changes on the AG environment.

The AG is generally considered oligotrophic throughout most of the year because the new waters entering the Gulf mainly flow in at or near the surface, and thus are generally depleted in nutrients, except during winter when convective mixing in the northern Arabian Sea brings nutrients to the surface, triggering a winter bloom that enriches the Gulf source waters in nutrients and organic matter, fertilizing the Gulf in late winter (Al-Yamani & Naqvi, 2019). Consequently, the Gulf has been assumed to be relatively well oxygenated in its pristine state (Al-Yamani & Naqvi, 2019). Moreover, given its high levels of alkalinity, the Gulf is believed to have a high buffering capacity against ocean acidification, a process that can threaten the growth and maintenance of marine calcifiers, including coral reef calcifying organisms (Purkis et al., 2011; Izumi et al., 2022). Yet, recent observations challenge these assumptions. First, observational and modeling evidence suggests that summer near-bottom hypoxia has become regular, more intense, and widespread over recent decades (Al-Ansari et al., 2015; Saleh et al., 2021; Lachkar et al., 2022). Second, observations indicating rapid progression of ocean acidification in the AG have been reported (Uddin et al., 2012). The concomitant occurrence of ocean deoxygenation and ocean acidification may further exacerbate the vulnerability of the AG ecosystems, including its coral reefs, to ongoing warming (Burt et al., 2019; de Verneil et al., 2021; Purkis et al., 2011; Burt & Paparella, 2023).

The drivers behind these biogeochemical changes and the eventual role of the rapid warming of the AG in their emergence remain poorly understood. In particular, the role of altered exchange between the AG and the SOO in these changes remains unexplored. This paper addresses the following key questions: i) What are the implications of the rapid warming of the AG for the Gulf outflow? ii) How do these changes contribute to recently reported biogeochemical changes in the Gulf such as hypoxia expansion and acidification? and iii) what are the mechanisms responsible for the faster warming in the AG relative to the SOO? While the lack of comprehensive observational surveys of the biogeochemical properties of the Gulf waters makes documenting and understanding the ongoing biogeochemical changes challenging, here we employ a state-of-the-art coupled-physical biogeochemical model of the Gulf and the Arabian Sea region to reconstruct the evolution of the hydrography and biogeochemistry between 1980 and 2018. We demonstrate that changes in surface wind have contributed to amplifying the warming of the AG relative to the SOO, thereby reducing the density gradient across the Strait and the exchange between the two seas over the study period. Consequently, water residence times in the Gulf increased alongside respiration, leading to exacerbated deoxygenation and acidification in its deeper portions.

2 Methods

The circulation model is based on the Regional Ocean Modeling System (ROMS) (Shchepetkin & McWilliams, 2005). The model uses non-local K-profile parameterization (KPP) scheme for vertical mixing (Large et al., 1994). Covering the Indian Ocean from 31.5°S to 31°N and 30°E to 120°E, the model employs a horizontal resolution of 1/10 degree and 32 sigma-coordinate vertical layers, with enhanced resolution near the surface. Biogeochemical processes are simulated using a nitrogen-based NPZD model with two nutrient components (nitrate and ammonium), one phytoplankton, one zooplankton, and two detrital classes (Gruber et al., 2006). Additionally, the model incorporates a module describing the oxygen cycle (Lachkar et al., 2021) and a carbon module with dissolved inorganic carbon (DIC), total alkalinity (TA), and calcium carbonate state variables (de Verneil et al., 2022). A more detailed description of the model is available in the Supplementary Information (SI). The hindcast simulation is forced by ECMWF ERA-Interim 6-hourly heat fluxes, air temperature, pressure, humidity, precipitation, and winds spanning January 1980 to December 2018. Initial and lateral boundary conditions for various parameters are derived from ECMWF Ocean Reanalysis System 5 (ORAS5; Zuo et al., 2019), World Ocean Atlas 2018 (Garcia et al., 2019), and GLODAP version 2 (Lauvset et al., 2016). Atmospheric pCO_2 data is obtained from Mauna Loa (Keeling et al., 2005) and (Joos & Spahni, 2008). The model is spun-up for 69 years, after which two simulations are conducted: a control hindcast run (HR) forced with increasing atmospheric carbon and interannually varying momentum, freshwater, and heat fluxes from 1980 to 2018, and a constant climate (CC) simulation forced with climatological forcing (repeated normal year) and increasing CO_2. The CC simulation serves to quantify model drift and disentangle the roles of climate change and rising atmospheric CO_2 levels in reported acidification. Our analysis reveals a negligible model drift in the study area. Further details of the model setup and the evaluation of model drift are provided in the SI (Text S2, SI).

We evaluate the model's performance in reproducing key aspects of the region's hydrography and biogeochemistry using the limited available data (Figs S5-S7, SI). Overall, we find that despite some local discrepancies, our model generally captures the essential hydrographic features of the Gulf region, including the seasonal progression of temperature, salinity, and the Gulf outflow. Similarly, our model also aligns relatively well with available data regarding oxygen levels, vertical distribution of chlorophyll, seasonal variability in biological production, as well as the state of the carbonate system (DIC, TA, pCO_2, and pH). A detailed description of the model evaluation is provided in the SI (Text S3, Figs S1-S7).

3 Results

3.1 Seasonal and interannual variability in the AG and the SOO

To put the long-term trends in the AG in broader context, we first characterize the seasonal and interannual variability of both the physical and biogeochemical properties within the AG and the SOO. The temperature in both the AG and the SOO exhibits much stronger seasonal variability than salinity (Figs 1A-1C). Consequently, the seasonal cycle in density in both seas appears to be primarily driven by temperature fluctuations throughout the year rather than variations in salinity. While both the AG and the SOO display strong seasonal variability in temperature, the amplitude of this variability is notably stronger in the AG compared to the SOO. This leads to the amplitude of the variability in surface density being nearly twice as large in the AG relative to the SOO (Fig 1E). Furthermore, the Gulf exhibits significantly higher variability on interannual timescales vis-a-vis the SOO, with a standard deviation 3 to 4 times larger for winter temperature and 5 to 10 times larger for salinity throughout the year (Figs 1A & 1C). These differences are also reflected in surface density, which displays stronger interannual variability in the AG relative to the SOO, with a standard deviation 3 to 4 times larger in the former (Fig 1E).

The strong variability in AG water density results in notable seasonal changes in the density gradient between the AG and the SOO, with the density contrast between the two seas peaking in winter and reaching its lowest point in summer (Fig 1G). The density gradient across the Strait is the primary driver of the overturning circulation, which transports light surface waters from the SOO into the Gulf and dense, deep Gulf waters into the SOO (Swift & Bower, 2003). Consequently, fluctuations in this gradient are expected to cause fluctuations in the strength of the Gulf water outflow (e.g., Swift & Bower, 2003; Kämpf & Sadrinasab, 2006; Paparella et al., 2022). Our analysis of the Gulf outflow at the Strait indeed reveals seasonal variability similar to that of the density gradient, albeit with a time lag of 2 to 3 months (Fig 1G). Maximum outflow occurs in spring, while minimum outflow is observed in late summer and early autumn (Fig 1G). This finding aligns with evidence from previous observational and modeling studies that have investigated the seasonal variability in Gulf outflow (e.g., Johns et al., 2003; Kämpf & Sadrinasab, 2006; Lorenz et al., 2020).

The pronounced variability in hydrography is accompanied by similarly strong seasonality in biogeochemistry in both the AG and the SOO (Figs 1B-1H). Despite faster photosynthetic growth rates in summer driven by higher temperatures, the stronger winter vertical mixing and the net inflow of nutrients from the SOO result in greater biological production in the Gulf during winter than in summer (Figs 1B-1H). Similarly, in the SOO, biological production is higher in winter due to increased nutrient supply from depth because of winter convective mixing in the northern Arabian Sea (Naqvi et al., 2002). Finally, both dissolved oxygen and pH exhibit strong seasonality at depth in both seas, with maximum values occurring in late winter and minimum values in late summer when oxygen deficit and carbon excess driven by respiration accumulate at depth due to limited vertical mixing (Figs 1D-1F).

3.2 Contrasting rates of warming in the AG and the SOO

We model a rapid warming trend in both the AG and the SOO, consistent with observations (Fig 2). While much of the northern Arabian Sea has experienced warming in recent decades, the rate of warming in the AG is nearly 50% faster than in the rest of the Arabian Sea (Fig 2B). During winter, the warming in the AG is not statistically significant and is comparable in magnitude to that of the SOO (Figs 2C-2D). However, during summer the warming in the Gulf is statistically significant and up to three times faster than that observed in the SOO (Figs 2C-2D).

A more comprehensive analysis of long-term trends throughout the year reveals uneven warming patterns in both the AG and the SOO (Fig 3A). Warming is more pronounced in spring and summer and is weakest in winter in the AG. In contrast, warming peaks in spring and fall and is weakest in early summer in the SOO, due to the influence of upwelling along the coast of Oman. In addition to average temperatures, temperature extremes have also been affected by warming in the AG and SOO. Yet, important shifts towards higher extreme temperatures are observed only in summer in the AG and in winter in the SOO (Fig S8, SI). Consequently, temperature emerges from the 1980s historical variability (i.e., exceeding 2 standard deviations above the 1980s climatological means) in summer in the AG and in winter in the SOO (Fig S9, SI) Due to these disparities, along with variations in surface salinity trends between the two seas, the density gradient at the Strait also changes unevenly throughout the year (Fig 3A). Specifically, over the study period, the density contrast slightly increases in early winter but significantly decreases during summer. Consequently, the Gulf outflow strengthens slightly (+3% per decade) in winter but weakens more importantly (up to -10% per decade) in late summer and early autumn (Fig 3A).

3.3 Rapid changes in the biogeochemistry of the AG

Changes in the biogeochemical properties of the AG also display significant variations among the seasons (Fig 3B). For example, nitrogen supply to the Gulf shows a notable increase in early winter (December), coinciding with a significant intensification of water exchange (Fig 3B). However, nitrogen supply to the Gulf also experiences a significant increase during late summer and early autumn (September to October) despite a weakening of the Gulf inflow/outflow driven by warming (Fig 3B). To comprehend this apparent paradox, one must consider not only the strength of the overturning but also the vertical gradient of nutrients at the Strait (Fig S10, SI). In contrast to winter, strong summer stratification induces a pronounced vertical gradient in nitrogen at the Strait, with very low concentrations near the surface and significantly higher levels below 20 m. Consequently, the net nitrogen flux associated with the overturning circulation in summer results in a loss for the AG (outflow waters have a higher nitrogen content than inflow water). Conversely, in winter, surface inflow waters have a higher nitrogen content compared to outflowing waters (Fig S10, SI), leading to a net supply of nitrogen to the Gulf (Fig 3B). Consequently, the significant decrease in outflow during late summer, as well as the increase in early winter, both contribute to an increase in the supply of nitrogen to the Gulf. This buildup of nutrients and biomass in the AG, combined with faster photosynthetic growth rates driven by higher temperatures, leads to enhanced biological production throughout most of the year (Fig 3B). The increase in productivity enhances respiration, particularly in the benthos, resulting in increased consumption of oxygen and the release of carbon dioxide at depth near the seafloor (Fig S11, SI). As the stratification increases in summer, the supply (release) of O_2 (CO_2) from (to) the surface diminishes, causing depletion (accumulation) of O_2 (CO_2), and thus an expansion of hypoxia and low-pH waters near the bottom. This increased acidification, driven by enhanced respiration, compounds the background acidification caused by rising atmospheric CO_2 levels (constant climate), amplifying it by up to 50% in late summer (Fig 3B).

3.4 Drivers of the rapid warming of the AG

An examination of the heat budget in the AG throughout the study period indicates that most of the simulated temperature changes are driven by alterations in atmospheric fluxes, while the lateral transport of heat to and from the SOO has a minor impact (Fig 4A). To understand the processes behind changes in atmospheric forcing, we analyze changes in the individual components of the atmospheric heat fluxes (Figs 4B-4D). Positive statistically significant trends in both incoming radiation and latent heat fluxes contribute to the summer warming in the AG, while changes in sensible heat fluxes play a negligible role. Changes in downward radiation, primarily associated with longwave radiation, contribute to summer warming in both seas (Fig 4B). In contrast, changes in latent heat fluxes amplify warming in most of the AG but dampen it in the SOO (Fig

4C), thus explaining much of the differential warming between the two seas. It's important to note that the contribution of latent heat fluxes to the warming of the Gulf varies spatially and temporally due to high interannual variability. This is consistent with previous works that found that interannual fluctuations in total heat fluxes over the Gulf are dominated by fluctuations in the latent heat fluxes (e.g., Pous et al., 2015; Paparella et al., 2019). Generally, the contribution of latent heat fluxes is more pronounced in the central Gulf and during late summer (August) (Fig S12, SI). In winter, evaporative cooling decreases in both the AG and the SOO, contributing to warming trends in both seas (Fig S12, SI). These long-term trends in latent heat fluxes are primarily driven by changes in surface wind speed in the region (Fig 2E and Fig 2F). While northwesterly shamal winds have weakened over the AG during both winter and summer, surface winds over the SOO have weakened during winter and increased during summer, contributing to the differential warming in the region in recent decades (Fig 2 and Fig S13, SI).

4 Discussion

4.1 Comparison with previous works

Our study reveals significant variability in the exchange flow between the AG and the SOO, primarily driven by fluctuations in atmospheric forcing over the AG. This finding aligns with the research conducted by Lorenz et al. (2020) and Pous et al. (2015), who concluded that interannual variability in Gulf outflow is primarily influenced by surface fluxes.

We found the warming rate of the Gulf to be on average around 0.26°C per decade but with a strong spatiotemporal variability with local warming rates ranging from less than 0.2°C per decade in winter to above 0.5°C per decade during summer in much of the western Gulf. Other studies also reported important warming in the Gulf with rates varying between 0.2°C and 0.7°C depending on the region and period considered (Al-Rashidi et al., 2009; Hereher, 2020; Al Senafi, 2022). Bordbar et al. (2024) analyzed the variability in surface temperature and chlorophyll-a using MODIS-Aqua satellite data between 2003 and 2021 for the AG and the SOO region. Overall, they found no significant trend in the time series of chlorophyll in the Gulf over the study period. Interestingly, they found no major difference in the summer warming rates in the AG and the

SOO and only a slightly faster warming in the AG on an annual mean. When considering a similar period (2003-2018), we also found no significant trend in either chlorophyll-a levels, primary production or temperature gradient between the two seas. This suggests that the long-term trends reported in this study cannot be discerned from the shorter period covered by sea color satellite data.

Finally, in a recent modeling study, Vasou et al. (2024) studied the changes in the heat content of the AG over the period between 1993 and 2021. While they showed that the interannual variability in the heat content is dominated by the surface heat fluxes, they also suggested that the long-term warming of the basin is primarily driven by enhanced heat transport from the Arabian Sea because of a simulated increase in the annual mean volume of waters being exchanged at the Strait. Contrary to Vasou et al. (2024), our findings indicate that long-term warming trends in the AG are driven by changes in atmospheric heat fluxes, similar to seasonal and interannual variability. We did not observe an increase in the overturning circulation of the AG. Instead, we found a significant decrease in the volume of Gulf outflow in summer and only a slight increase in winter. This aligns with the warming-induced reduction in density contrasts between the two seas, the primary determinant of outflow strength according to theory (e.g., Bryden & Stommel, 1984; Pratt & Lundberg, 1991) and previous studies of the Gulf circulation (e.g., Swift & Bower, 2003; Kämpf & Sadrinasab, 2006; Pous et al., 2015; Lorenz et al., 2020; Paparella et al., 2022). The recent decrease in density gradient and exchange strength is further corroborated by evidence from ORAS5 reanalysis and multiple versions of the SODA reanalysis, all indicating a notable reduction in density contrast between the AG and the SOO, along with decreased Gulf outflow intensity in recent decades, particularly pronounced in summer (Fig S14, SI). It is important to mention that simulated surface temperature trends in Vasou et al. (2024) significantly underestimate observed trends in the AG and overestimate them in the SOO (refer to their Figure S1).

4.2 Caveats and limitations

While large-scale changes in atmospheric conditions in the Gulf region are relatively robust across multiple data-based products (Fig 2 and Fig S13, SI), they still harbor significant uncertainties, particularly at smaller, local scales. These uncertainties arise from the limited availability of direct observations and the relatively low spatial resolution of existing atmospheric forcing products. To enhance confidence in modeling the AG circulation and biogeochemical changes, it is important to employ better-resolved atmospheric forcing, validated via local in-situ observations, in future studies. Furthermore, the simulated alterations in Gulf outflow, productivity, and nutrient availability require confirmation through in-situ observations. Repeated measurements of critical physical parameters, such as the intensity of water exchange through the Strait, and vital biological parameters, such as chlorophyll and nutrient concentrations, are essential for documenting ongoing changes in this region, which is both under-sampled and under-studied.

4.3 Implications and recommendations

Our findings indicate that both the physical and biogeochemical properties of the Gulf exhibit significant variability across seasons and years. Consequently, measurements taken over short periods may not accurately capture the climatological conditions in the AG. This highlights the importance of employing high-resolution monitoring or continuous sampling methods, such as through the use of oceanographic moorings. Moreover, the monitoring of key variables, such as the strength of the Gulf outflow, is particularly crucial due to its critical role in the ecology and biogeochemistry of the Gulf, as evidenced in this study. The demonstrated strong relationship between Gulf outflow variability and density contrasts between the two seas underscores the potential for monitoring this gradient as a proxy to gain insights into exchange flux and its variability. The export and subsequent subduction of the Gulf waters in the northern Arabian Sea has been shown to deeply affect the intensity of the Arabian Sea oxygen minimum zone and hence the biogeochemistry of the northern Indian Ocean (Lachkar et al., 2019, 2021; Ditkovsky et al., 2023). Here, we show that a reduction of the Gulf outflow also deeply affects the biogeochemistry of the Gulf itself.

The findings of this study have important implications for biodiversity and socioeconomics in the Gulf. As a marginal marine system characterized by already extreme environmental conditions (Burt et al., 2020), further pressures such as those identified here have great potential to result in sudden, non-linear impacts on marine organisms and ecosystems (Bouwmeester et al., 2020). Marine organisms in the Gulf are considered to live very near to their thermal tolerance thresholds in summer, and we are already witnessing an increasing frequency and severity of coral bleaching and mass mortality events during summers when low wind conditions permit temperatures to rise by just 2°C above the normal summer maximum (Burt et al., 2019; Riegl et al., 2018). As ectothermic fauna whose metabolic oxygen demand is directly tied to temperature, fishes are likely to face considerable physiological strain from the need to consume more oxygen under extreme temperatures while simultaneously being challenged by the growing extent of hypoxia that has been identified in the Gulf (Vaughan et al., 2021; de Verneil et al., 2021; Lachkar et al., 2022). The physiological costs of accommodating the naturally extreme temperatures and salinity in the Gulf have previously been implicated in reducing the size and productivity of Gulf fish and therefore fisheries yields (Ben-Hasan et al., 2024); further environmental pressure may exacerbate these effects and have direct negative impacts on fisheries - a resource sector second only to oil in this region (Van Lavieren et al., 2011).

5 Summary and Conclusions

As a shallow, semi-enclosed marginal sea, the AG is notably sensitive to atmospheric forcing, leading to heightened seasonal and interannual variability compared to the SOO. Our analysis confirms that the AG has experienced rapid warming, exceeding that of the neighboring SOO. The primary driver of warming in both seas is enhanced downward radiation. However, weakening winds over the AG and strengthened southeasterly winds over the SOO contribute to accelerating warming in the former and dampening it in the latter. Consequently, this process increases the temperature gradient and reduces the density gradient between the two seas, thereby slowing down the water exchange between the Gulf and the Arabian Sea. This reduction in Gulf water outflow has led to an increased accumulation of nutrients and biomass in the Gulf over the recent decades, intensifying respiration and causing depletion of O_2 and an increase in water acidity, particularly pronounced in the deeper parts of the Gulf. Our findings underscore the importance of local changes in atmospheric conditions, particularly surface winds, in modulating global anthropogenic perturbations at regional scales, particularly for marginal and semi-enclosed seas.

6 Open Research

The ERA-Interim data used for forcing the model atmospheric boundary condition is available at: `https://rda.ucar.edu/datasets/ds627.2/dataaccess/`. The ORAS5 data used for forcing the lateral boundary condition is available at: `https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-oras5?tab=overview`. The model code (croco v1.0) can be accessed online (`https://gitlab.inria.fr/croco-ocean/croco/-/releases`). The model outputs are available online at `https://zenodo.org/records/10987332`.

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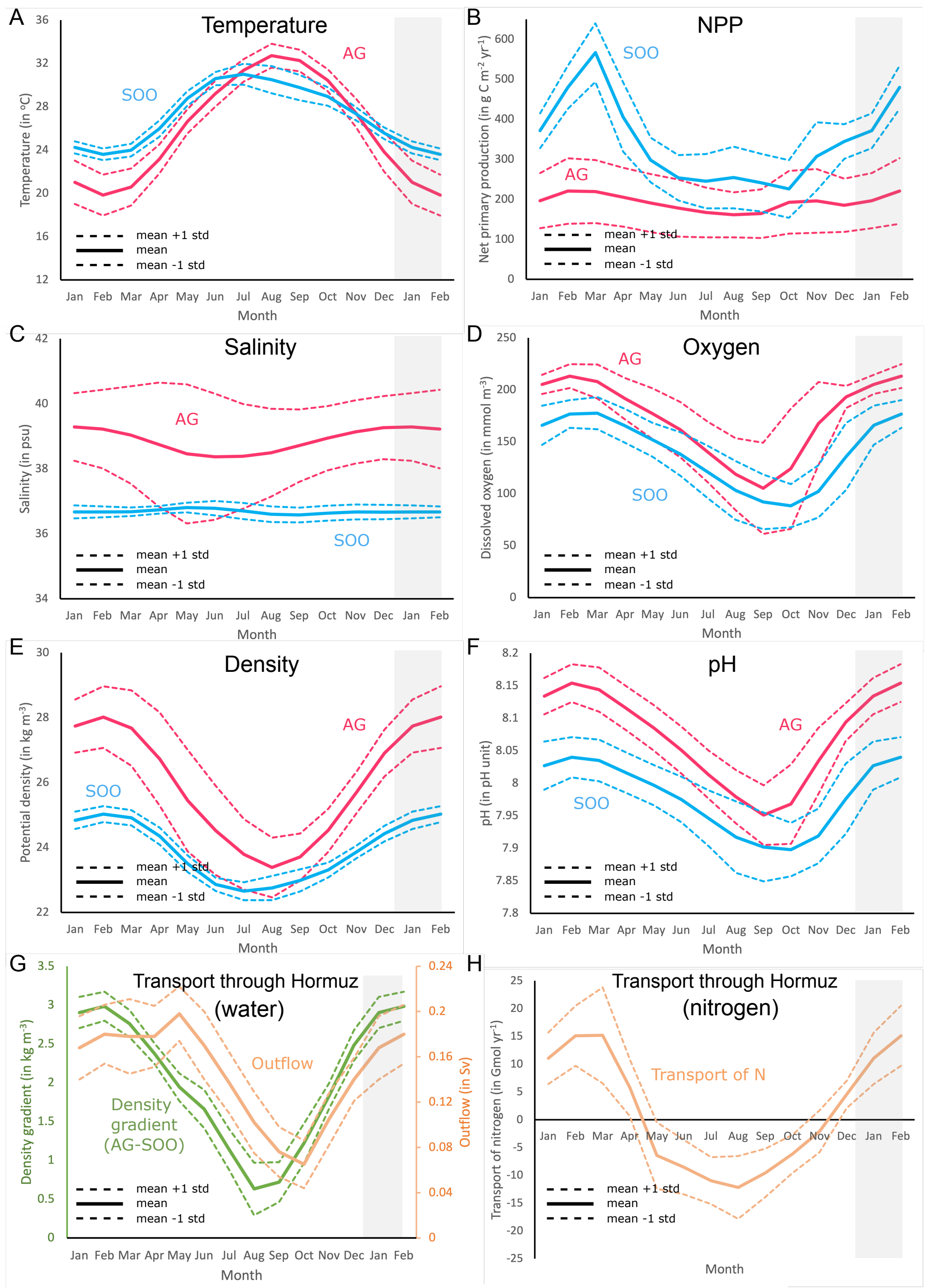

Figure 1. Seasonal variability in the AG and SOO. Seasonal cycle of sea surface (A) temperature, (B) salinity, (C) density, (D) density gradient (superimposed on the Gulf outflow at the Strait), as well as (E) net primary production, (F) dissolved oxygen, (G) pH and (H) transport of total nitrogen through the Strait. Oxygen and pH are shown near the seafloor below 40 m in the AG and at 100 m in the SOO. The solid lines depict the seasonal averages while the dashed lines show interannual variability envelope defined by ± SD. Time series in A-C and E-G are area-averaged properties (AG and SOO spatial definitions are shown in Fig 2). The shaded area depicts the first two months of the following annual cycle.

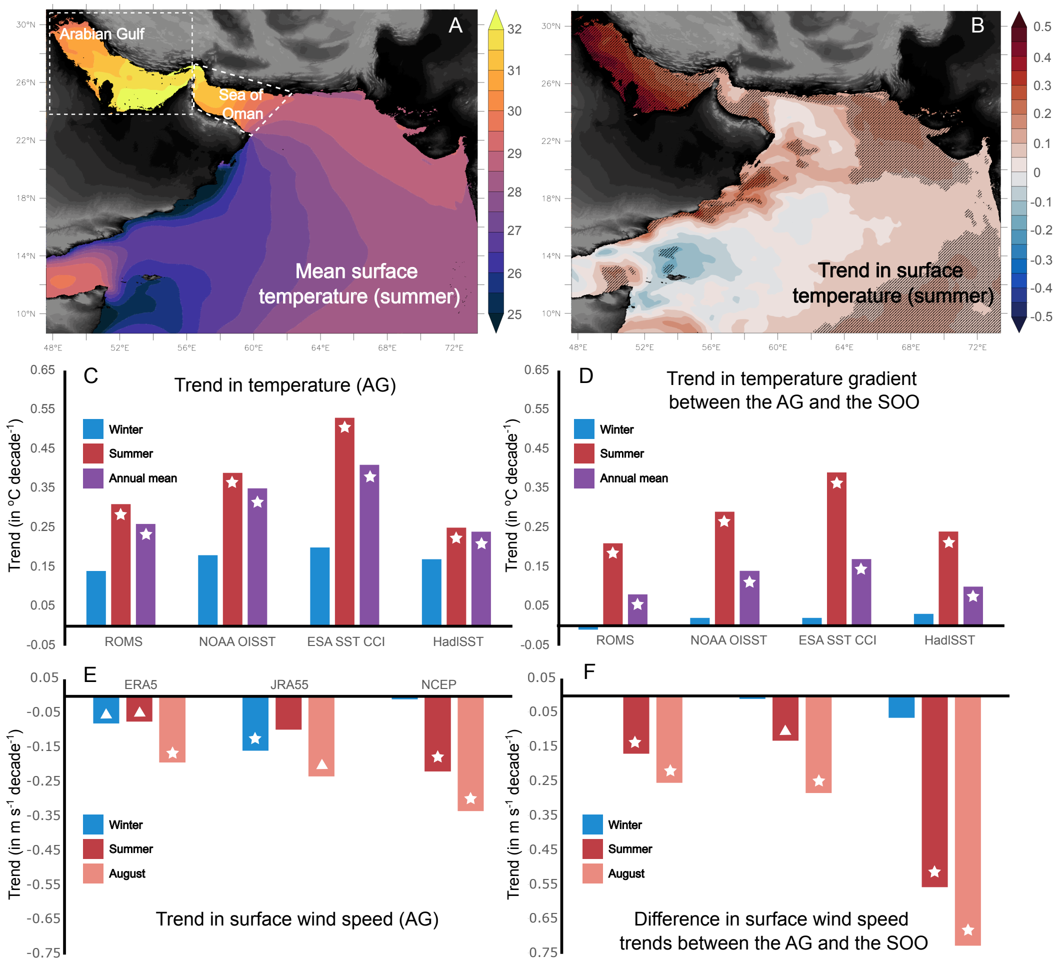

Figure 2. Warming and surface wind changes in the AG and SOO. (A) Average summer (JJA) sea surface temperature (SST; in °C) in the northern Arabian Sea as simulated in the model over the study period (1980-2018). (B) Linear trends in summer (JJA) SST (in °C per decade) in the AG and northern Arabian Sea. (C-D) Trends in AG-averaged SST (C) and SST gradient between the AG and the SOO (D) during winter (blue), summer (red) and anual-mean (purple) based on the ROMS simulation and from different data products. (E-F) Trends in AG-averaged surface wind speed (E) and the difference in surface wind speed trends between the AG and the SOO (F) during winter (blue), summer (red) and for the month of August (pink) based on different atmospheric reanalyses products. White stars and triangles indicate statistically significant trends at 95% and 90% confidence levels, respectively.

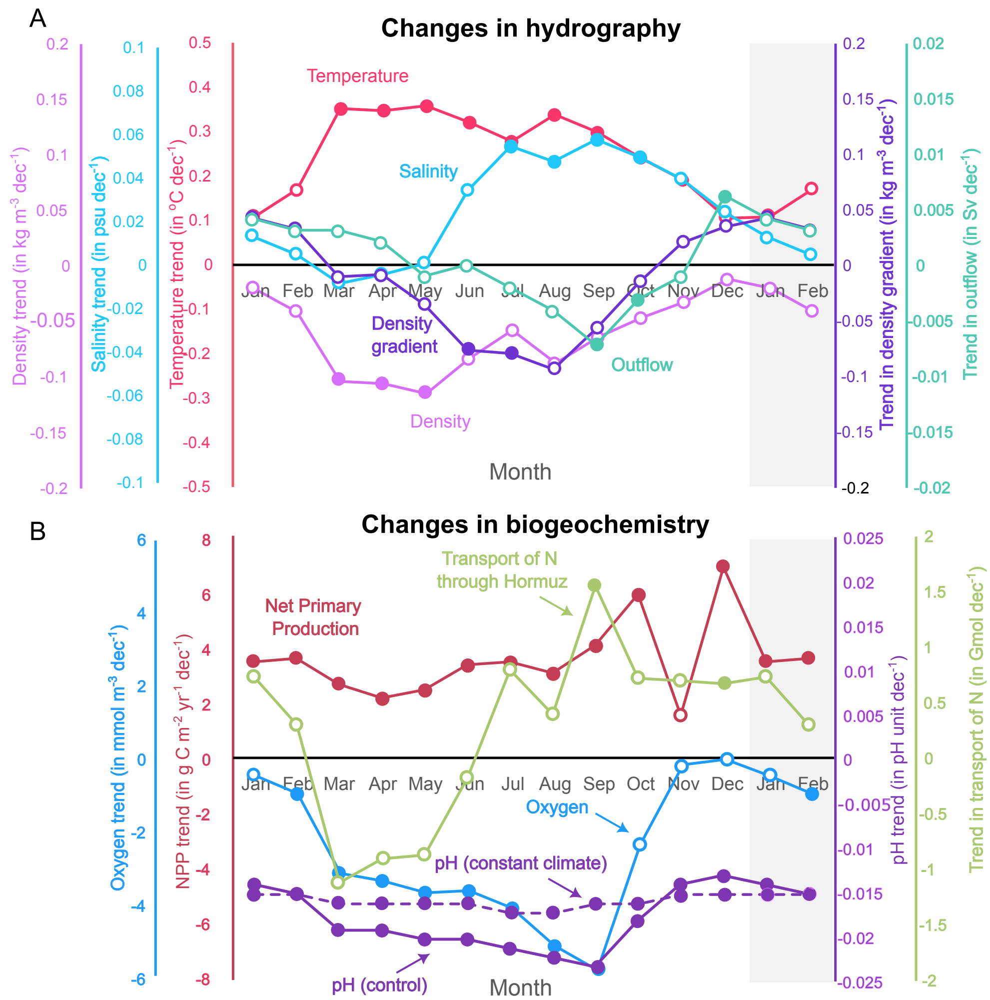

Figure 3. Long-term changes in the AG hyrography and biogeochemistry. (A) Trends (1980-2018) in AG-averaged SST (red), salinity (blue), density (purple), density gradient with the SOO (violet) and Gulf outflow (green). (B) Trends (1980-2018) in AG-averaged net primary production (red), oxygen (blue), pH (violet) and transport of total nitrogen through the Strait (green). Oxygen and pH are shown for the deepest model layer in the AG (near the seafloor). Filled (open) circles indicate statistically significant (non-significant) trends at 95% confidence interval. Multiple variables on each chart share the horizontal axis (months of the year) but are shown on different vertical axes. The shaded area depicts the first two months of the following annual cycle.

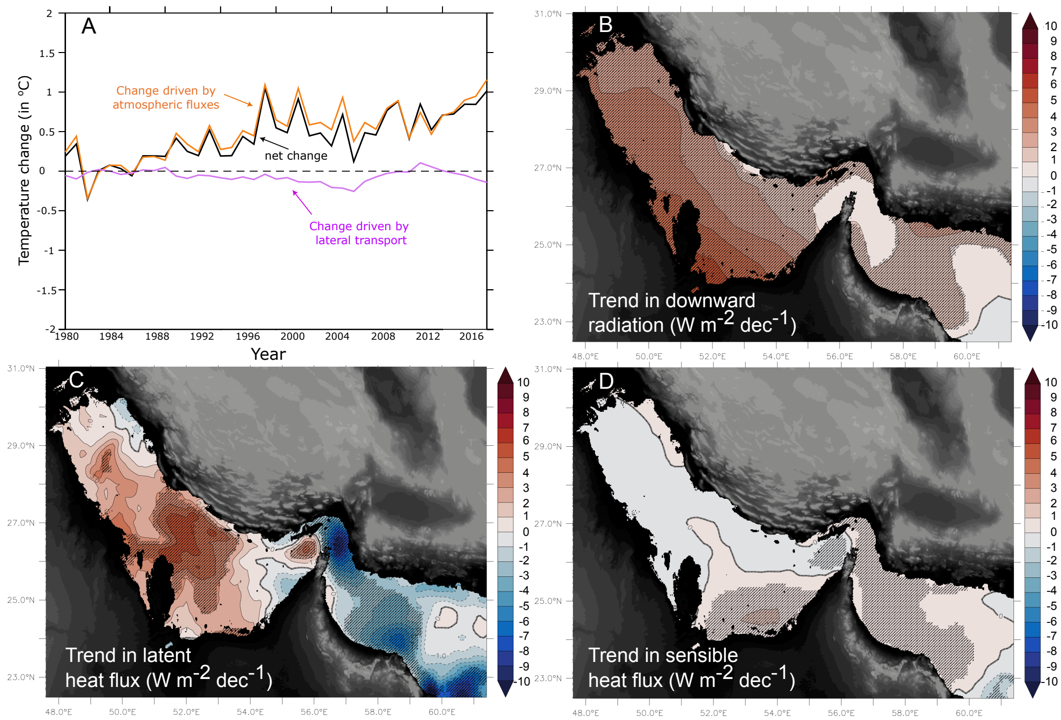

Figure 4. Drivers of AG warming. (A) Heat budget in the AG showing the contribution of atmospheric fluxes (orange) and lateral fluxes (magenta) to the net temperature change (black) over the study period. (B-D) Trends in downward radiation (B), latent (C) and sensible (D) heat fluxes over the study period (in W m^{-2} per decade; positive fluxes indicate ocean heat gain). Hatching indicates areas where trends are statistically significant at 95% confidence level.

Figure 1.

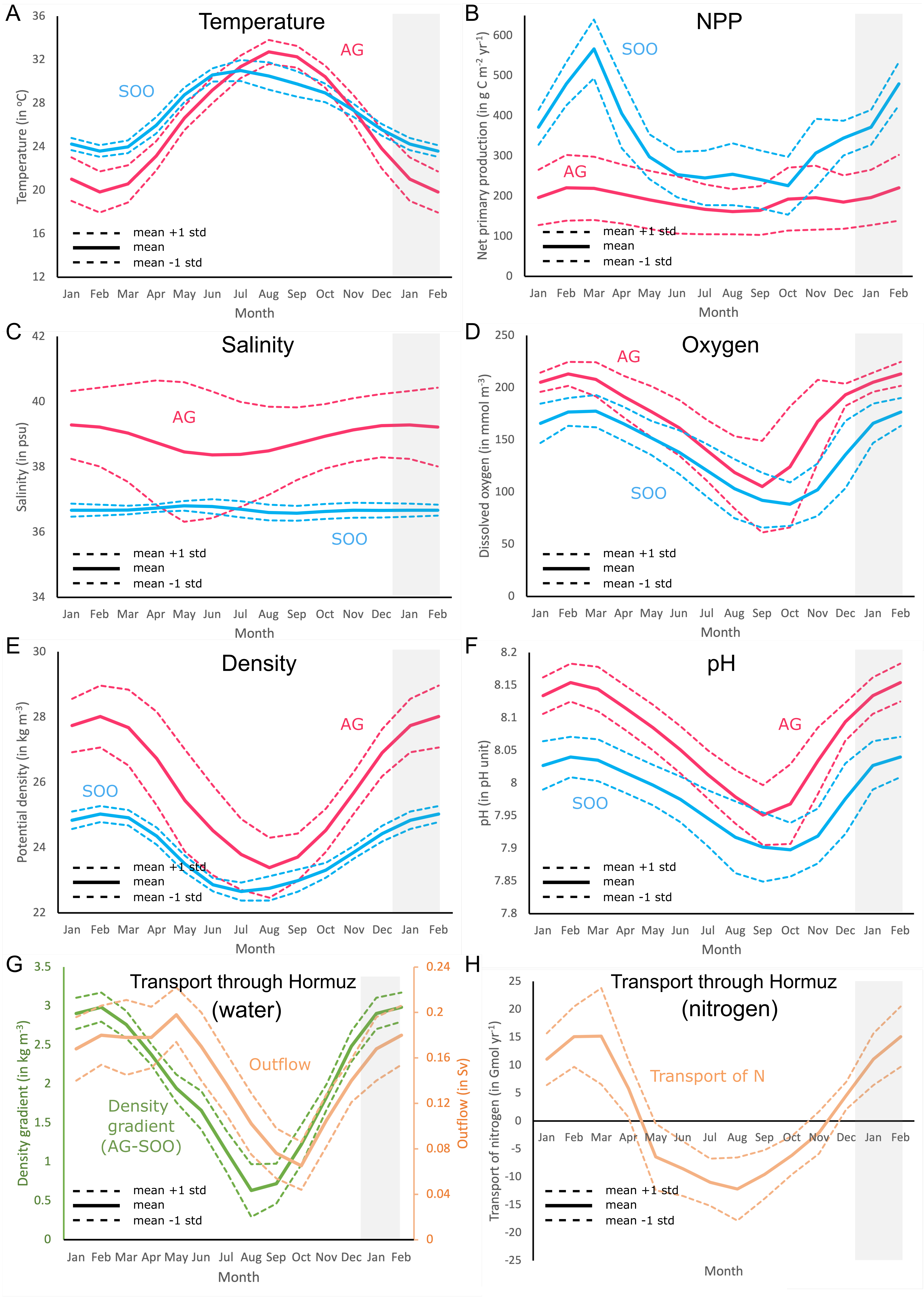
A
Temperature
Temperature (in °C)
SOO
AG
B
NPP
Net primary production (in g C m-2 yr-1)
C
Salinity
Salinity (in psu)
D
Oxygen
Dissolved oxygen (in mmol m-3)
E
Density
Potential density (in kg m-3)
F
pH
pH (in pH unit)
G
Transport through Hormuz (water)
Density gradient (in kg m-3)
Outflow (in Sv)
Outflow
Density gradient (AG-SOO)
H
Transport through Hormuz (nitrogen)
Transport of nitrogen (in Gmol yr-1)
Transport of N
mean +1 std
mean
mean -1 std
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb
Month

Figure 2.

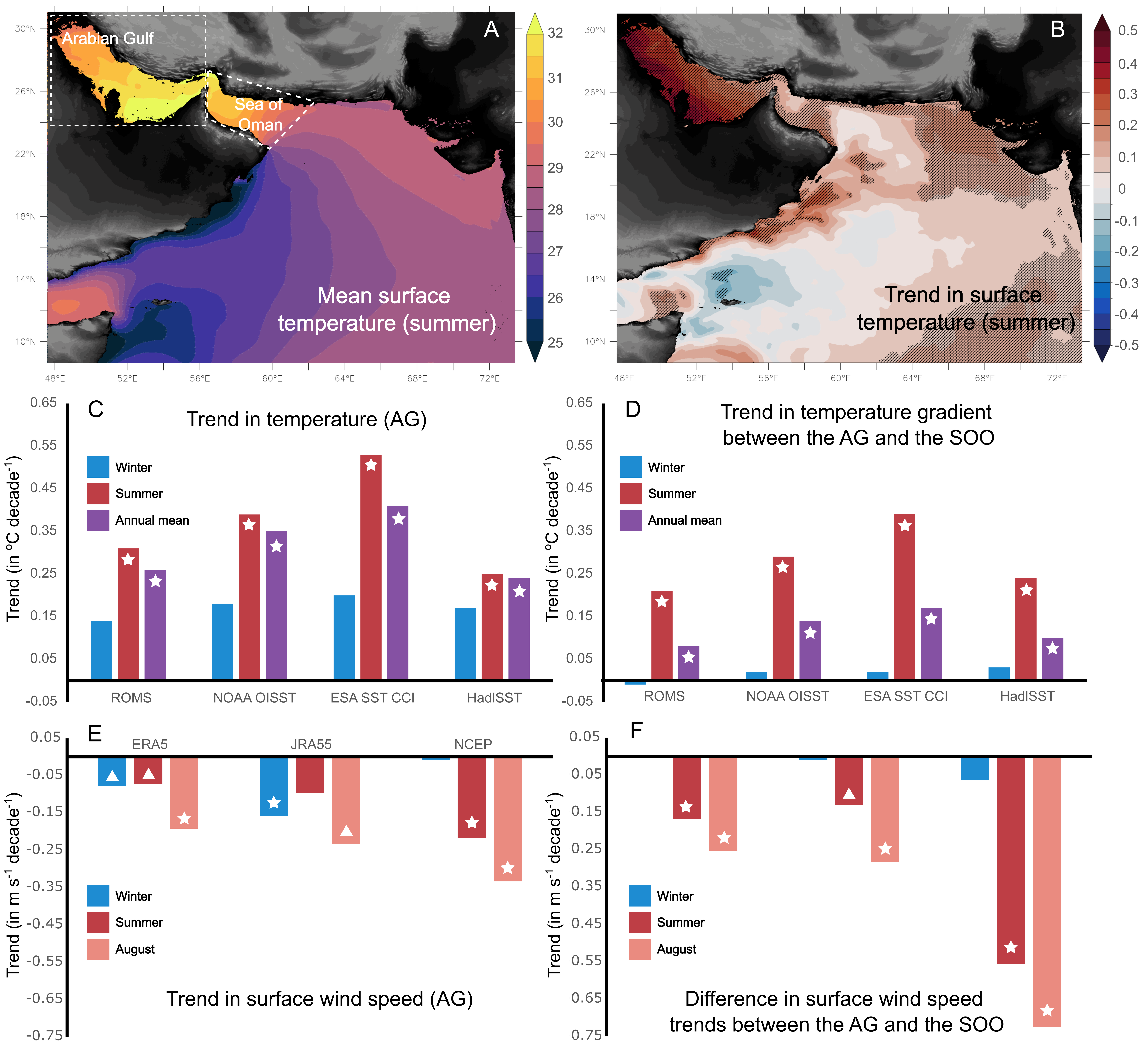
A
Arabian Gulf
Sea of Oman
Mean surface temperature (summer)
32
31
30
29
28
27
26
25
B
Trend in surface temperature (summer)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
30°N
26°N
22°N
18°N
14°N
10°N
48°E
52°E
56°E
60°E
64°E
68°E
72°E
C
Trend in temperature (AG)
D
Trend in temperature gradient between the AG and the SOO
Trend (in °C decade-1)
Winter
Summer
Annual mean
0.65
0.55
0.45
0.35
0.25
0.15
0.05
-0.05
ROMS
NOAA OISST
ESA SST CCI
HadISST
E
ERA5
JRA55
NCEP
F
Trend (in m s-1 decade-1)
Winter
Summer
August
0.05
-0.05
-0.15
-0.25
-0.35
-0.45
-0.55
-0.65
-0.75
Trend in surface wind speed (AG)
Difference in surface wind speed trends between the AG and the SOO

Figure 3.

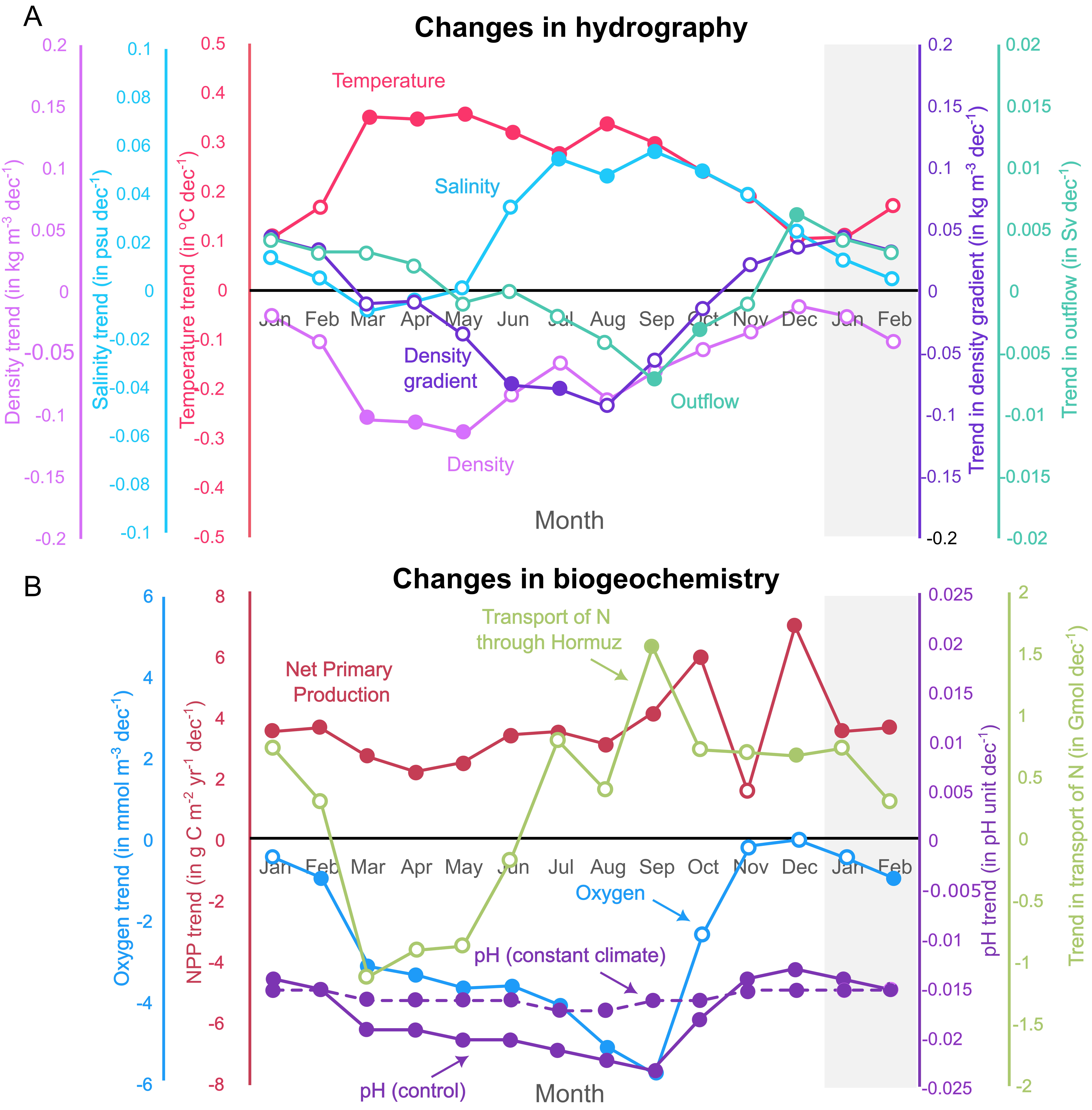
A
Changes in hydrography
Temperature
Salinity
Density gradient
Outflow
Density
Month
Density trend (in kg m-3 dec-1)
Salinity trend (in psu dec-1)
Temperature trend (in °C dec-1)
Trend in density gradient (in kg m-3 dec-1)
Trend in outflow (in Sv dec-1)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb
B
Changes in biogeochemistry
Net Primary Production
Transport of N through Hormuz
Oxygen
pH (constant climate)
pH (control)
Month
Oxygen trend (in mmol m-3 dec-1)
NPP trend (in g C m-2 yr-1 dec-1)
pH trend (in pH unit dec-1)
Trend in transport of N (in Gmol dec-1)

Figure 4.


A
Temperature change (in °C)
Year
Change driven by atmospheric fluxes
net change
Change driven by lateral transport
B
Trend in downward radiation (W m^{-2} dec^{-1})
C
Trend in latent heat flux (W m^{-2} dec^{-1})
D
Trend in sensible heat flux (W m^{-2} dec^{-1})