

The role of the Atlantic-Ionian stream in the long-term variability of the surface circulation in the Northern Ionian Sea: Results from a hindcast simulation

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ABSTRACT

We examine the long-term variability of the near-surface circulation of the Ionian Sea. Our analysis primarily focuses on a high-resolution hindcast simulation of the Mediterranean dynamics from 1981 to 2010. This time period is significant as it includes a notable near-surface circulation reversal in the Northern Ionian Sea (NIS), which shifted from anticyclonic to cyclonic at the end of 1997. This transition has been previously documented by altimeter data and Copernicus reanalysis. Our hindcast simulation accurately captures this change. Here we examine the temporal and spatial scales of the near-surface circulation during the transition and investigate the factors contributing to the observed variability of the basin dynamics, including local wind-stress, deep-water density anomalies, and the lateral current associated with the Atlantic Ionian Stream (AIS). We find that while wind stress does play a role, the primary factor driving long-term variability in the NIS near-surface circulation is the AIS. During the late 1980s to mid-1990s, the AIS was weak and local cyclonic winds were also weak, allowing the AIS to enter the NIS along the coasts of Sicily. This led to the formation of a wide anticyclonic cell in the NIS. From the mid-1990s to 2010, the AIS was stronger and, favored by stronger cyclonic winds, detached from the coasts of Sicily heading directly towards the Levantine basin without penetrating the NIS. This process led to the formation of a wide cyclonic cell over the NIS. These results highlight the role of the AIS in controlling the circulation of the NIS.

1. Introduction

The ocean circulation of the North Ionian (NI hereafter; see Fig. 1) has been the subject of many investigations in the last decades. Prolonged observational campaigns started at the end of the 80s (e.g., Malanotte Rizzoli et al., 1999) led to the discovery of the Eastern Mediterranean Transient (EMT; e.g. Roether et al, 1996) and of its propagation across the Mediterranean Sea, polarizing the attention of many scientists on the Ionian dynamics.

It is well-known that the space-time variability of the NI surface circulation controls the salt transport in the adjacent basins (South Adriatic, Levantine, and Aegean Sea), where intermediate and deep waters are formed. Therefore, studying this variability may shed light on basic aspects of the Mediterranean thermohaline circulation. Moreover, different behaviors in the Ionian Sea circulation may affect the ecosystem dynamics of the Southern Adriatic Sea (Civitarese et al, 2023).

The analysis of satellite altimeter observations, which started in 1993, has revealed the presence of reversals of the NI circulation. This is

an aspect of the Ionian Sea dynamics that has received much attention ever since its first documentation (Eusebi Borzelli et al., 2009).

From 1993 to 1997, the Atlantic-Ionian Stream (AIS) entering the Ionian Sea from the Channel of Sicily, was deflected northward, creating a wide anticyclonic cell that occupied most of the NI. This resulted in an increased supply of freshwater towards the Otranto Strait and the south Adriatic Sea. From 1998 to 2004, the NI was occupied by a wide cyclonic cell and the AIS proceeded towards the southeast, passing through the central part of the Ionian and heading towards the Levantine basin. This alternating pattern between the two configurations is usually referred to as the Northern Ionian Gyre (NIG) oscillation. After 2005, altimeter data showed the occurrence of a few other inversions of the NI circulation, characterized by shorter time scales in particular in the years 2006, 2011, and 2018 (Eusebi Borzelli and Carniel, 2023; Civitarese et al. 2023).

The NIG variability and the physical mechanisms responsible for the oscillation have been studied by several authors. Eusebi Borzelli et al (2009) first suggested that an important role in the reversal of the NIG was played by internal processes related to the anomalous outflow of

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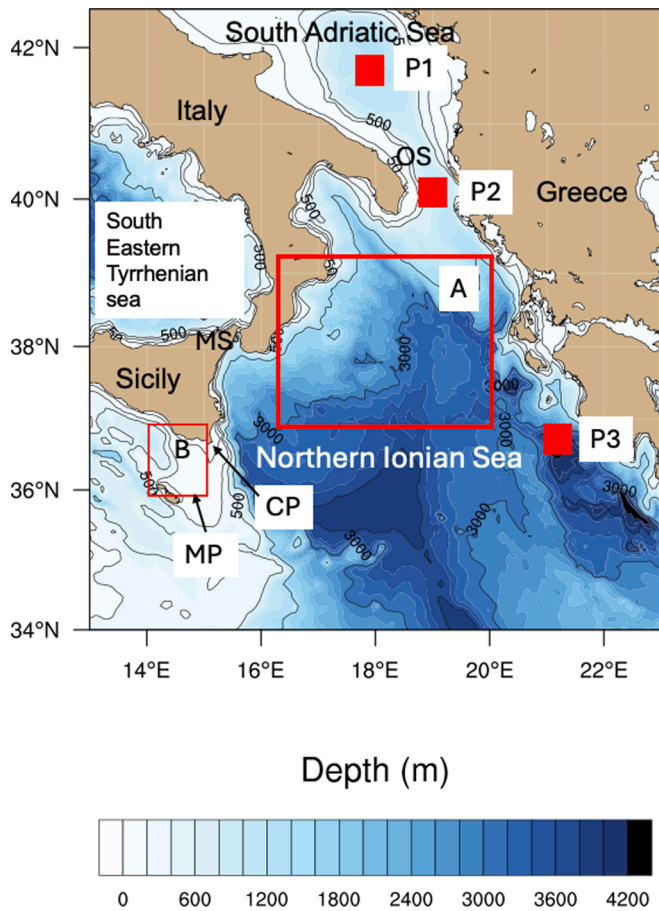


Fig. 1. The North Ionian Sea. The bathymetry is derived from the MED16 hindcast model. Boxes A, B are used for the calculation of energy and vorticity of the currents. CP: Capo Passero, MP: Malta Plateau. MS: Messina Strait, OS: Otranto Strait. Red squares (P1,P2,P3) are the regions where the Hovmöller diagrams of Fig. 8 are calculated.

deep waters from the Cretan Sea during the EMT phase. Gacić et al. (2010) proposed a feedback mechanism, working on a quasi-decadal scale (Adriatic-Ionian Bimodal Oscillating System; BiOS), that relates the NIG reversals to variations in the thermohaline properties of dense waters formed in the Adriatic Sea. Deviations from the decadal frequency were attributed to extreme atmospheric forcing over the Northern Adriatic and the consequent deep-water injection into the Ionian Sea, such as the brief inversion that occurred in 2012 (Gacić et al., 2014). Rubino et al. (2020) support this picture showing with laboratory and numerical experiments that the internal mode of oceanic variability between Adriatic and Ionian Sea is sensitive to the effects of remote atmospheric forcing. The study of the NIG inversions has also been approached by means of numerical simulations. Theocaris et al. (2014) analyzed both hydrological data and the results of a hindcast run covering 4 decades (1960–2000), concluding that the alternate production of deep water between Adriatic sea and Aegean sea determines an alteration in the upper circulation of the Eastern Mediterranean (EMed). During periods when Adriatic deep waters are denser than the Aegean waters, the AIS is shifted northward and the EMed thermohaline cell weakens. When waters of Aegean origin are denser than waters formed in the Adriatic, the AIS is directed eastward and the thermohaline cell is restored. So, the NIG oscillation and the BiOS were explained as the result of the above alternating mechanism.

Results from a Mediterranean Sea reanalysis by Pinardi et al. (2015), covering the period 1987–2006, instead indicated that the NIG oscillation could be driven by the variability of the local atmospheric forcing. It was also shown that the anticyclonic phase of the NIG revealed by

altimeter observations (1993–1997) actually started before, around 1987. Other numerical studies (Demirov and Pinardi, 2002; Korres et al., 2000) indicate that before 1987 the circulation was basically cyclonic.

A recent reanalysis covering the period 1955–2015 (Fratanni et al., 2016) was used by Kalimeris and Kassis (2020) to make an accurate analysis of the different dynamic regimes of the Ionian Sea. They found, beyond persistent seasonal signals, two major timescale components: a low-frequency at 11–17 years and a mid-frequency at 3–6 years. Liu et al. (2022) have used a long-term simulation spanning the entire XX-century to gain information on the past behavior of the Ionian Sea circulation. They found that the NI surface layer dynamics is characterized by a long-lasting cyclonic phase with weak variability and a couple of periods (including the periods covered by the observations) in which the quasi-decadal NIG reversal takes place.

In a theoretical work, Eusebi Borzelli and Carniel (2023) developed an analytical two-layer model of the NI. They demonstrated that the release of potential energy resulting from the disruption of equilibrium between internal fluid pressure and external forcing can induce a damped oscillation with timescales that align with observations.

Eusebi Borzelli et al. (2024) have focused on the role of the main baroclinic modes in determining the variability of the basin horizontal circulation. Their results indicate that the only dynamically active interface is the one between intermediate and deep waters and show that the NIG reversal is strongly linked to the circulation field associated with the first baroclinic mode.

The previous synopsis shows that the description of the NIG oscillation has changed during the years; the view of the reversal of the near surface circulation as a recurrent decadal oscillation is not consistent with the recent available observations and modeling studies. The phenomenon occurred between the 1990s and 2000s appears to be an anomalous event, both for intensity and duration, while in other periods similar events are less intense and characterized by shorter (sub-decadal) time scales. As for the driving mechanisms, the role of lateral advection has not been considered in detail until now, even though the variability of the NIG appears strongly related to that of the AIS. Indeed, Eusebi Borzelli et al. (2024) found that the region with the highest levels of kinetic energy of the first baroclinic mode is that in which the AIS outflows from the Sicily Channel. This has provided motivation for the present work, in which we pay attention not only to the dynamical effects of the atmospheric forcing and of the deep density anomalies but also to the lateral forcing associated with the AIS inflow.

To characterize the space–time variability of the NI surface circulation, we use a recent high-resolution hindcast simulation of the Mediterranean Sea circulation, described in Sannino et al. (2022). The model run covers three decades (1981–2010), including the great reversal of the 90s.

The paper is organized as follows. The Model description and validation is described in Section 2. The forcings and their relationships with the circulation variability are discussed in Section 3, and Section 4 deepens the analysis of the role played by the AIS. A diagnostics of the vorticity dynamics is analyzed in Section 5, whereas Section 6 provides a final discussion and conclusions.

2. Model description and validation

2.1. Model characteristics

The hindcast simulation used in this study covers the period 1981–2010, which includes the events of the 90s. It was conducted using the MED16 model, a new implementation of the MITgcm ocean model (Marshall et al., 1997a, b), specifically designed for climatic integrations. This model was previously utilized in Sannino et al. (2022) to analyze present and future sea-level changes in the Mediterranean Sea. It is important to note that a hindcast simulation is a run without data assimilation, and its purpose is to demonstrate the capability of the model to accurately reproduce past climatic variability.

The model solves the Navier–Stokes equations under the Boussinesq approximation for an incompressible fluid. The hydrostatic version of MITgcm has been implemented, using a finite-volume spatial discretization on a staggered Arakawa-C grid, partial step topography, rescaled vertical height (z^*) coordinate (Adcroft and Campin 2004), and an implicit non-linear free surface formulation (Campin et al. 2004).

The MED16 grid has a uniform horizontal resolution of $1/16^\circ$ (about 7 km) over most of the computational domain, which is increased to few hundred meters in the Gibraltar and Turkish Straits, to better represent the complex local dynamics. The vertical domain is discretized using 100 z -levels, with grid spacing increasing from 2 m near the surface to 62 m at a depth of 1500 m; below 1500 m a uniform grid spacing of 62 m is used down to the sea floor. The only open-boundary condition is applied at the western limit of the Gibraltar Strait. Another distinctive feature of the MED16 implementation is the inclusion of the main tidal forcing, both local and propagating from the Atlantic Ocean through the open boundary (see Sannino et al., 2015, and Palma et al., 2020).

The simulation has been forced by a dynamical downscaling of the ERA-Interim reanalysis at 0.11° resolution (i.e. approx. 12.5 km grid spacing), over the EURO-CORDEX domain (Giorgi et al. 2009), produced by the Rossby Centre regional atmospheric model RCA4 (Strandberg et al., 2014).

2.2. Validation of the North Ionian mean surface circulation

A general validation of the hindcast simulation has already been performed validated in Sannino et al. (2022). Here we present a more detailed analysis of the model behavior in relation to the object of this paper, namely the surface circulation of the NI.

The model results are compared to both satellite and reanalysis data. We use the absolute dynamic topography (ADT) obtained from altimeter observations [data processed by SSALTO/DUACS and distributed by

AVISO (<https://www.aviso.altimetry.fr>) with support from CNES (Centre national d'études spatiales; France)], and the associated geostrophic circulations. Concerning reanalysis product we use the CMEMS data product: https://data.marine.copernicus.eu/product/MEDSEA_MULTYEAR_PHY_006_004; e.g. Escudier et al., 2021), which is the accepted standard for modeling the Mediterranean Sea dynamics, thus bproviding the natural benchmark model for our simulation.

Fig. 2 shows the AVISO (geostrophic), CMEMS and MED16 near-surface circulation fields (30 mt) averaged over the periods 1993–1997 and 1998–2004. The MED16 patterns are in good agreement with both geostrophic currents and CMEMS data. In particular, the model reproduces accurately quasi-permanent structures of the region such as the Ionian Shelf Break vortex ($36^\circ\text{N}, 15^\circ\text{E}$), the Southern Gyre ($35^\circ\text{N}, 17^\circ\text{E}$) and the Pelops Anticyclone ($35.5^\circ\text{N}, 21^\circ\text{E}$) as well as the cyclonic circulation in the gulf of Taranto ($40^\circ\text{N}, 17^\circ\text{E}$).

In the MED16 simulation, during the period 1993–1997 (Fig. 2, panel C) the AIS entering the NI from the Channel of Sicily, veers northwards forming a wide anticyclonic cell. Conversely, from 1998 to 2004 (Fig. 2, panel F) the AIS stream flows zonally and the NI is occupied by a cyclonic circulation. Thus MED16 reproduces the anticyclonic and cyclonic phases of the NIG, coherently with observations and reanalysis. Moreover, the MED16 reproduces accurately the bifurcation of the surface current during the period 1998–2004 in the region at 36°N and $17^\circ\text{--}18^\circ\text{E}$.

We have sought further verification by comparing MED16 outputs with experimental results available in the literature. The only direct current measurements during that period are those of the 94–96 surveys conducted by SACLANT (NATO Center) and Harvard University, described in Robinson et al. (1999). Fig. 3 (panel c) of that work shows the velocities in the 50–70 m layer as measured by ADCP (Acoustic Doppler Current Profiler) during the campaign of October 1995. Typical AIS velocities reported are within the range 20–50 cm/s and directed

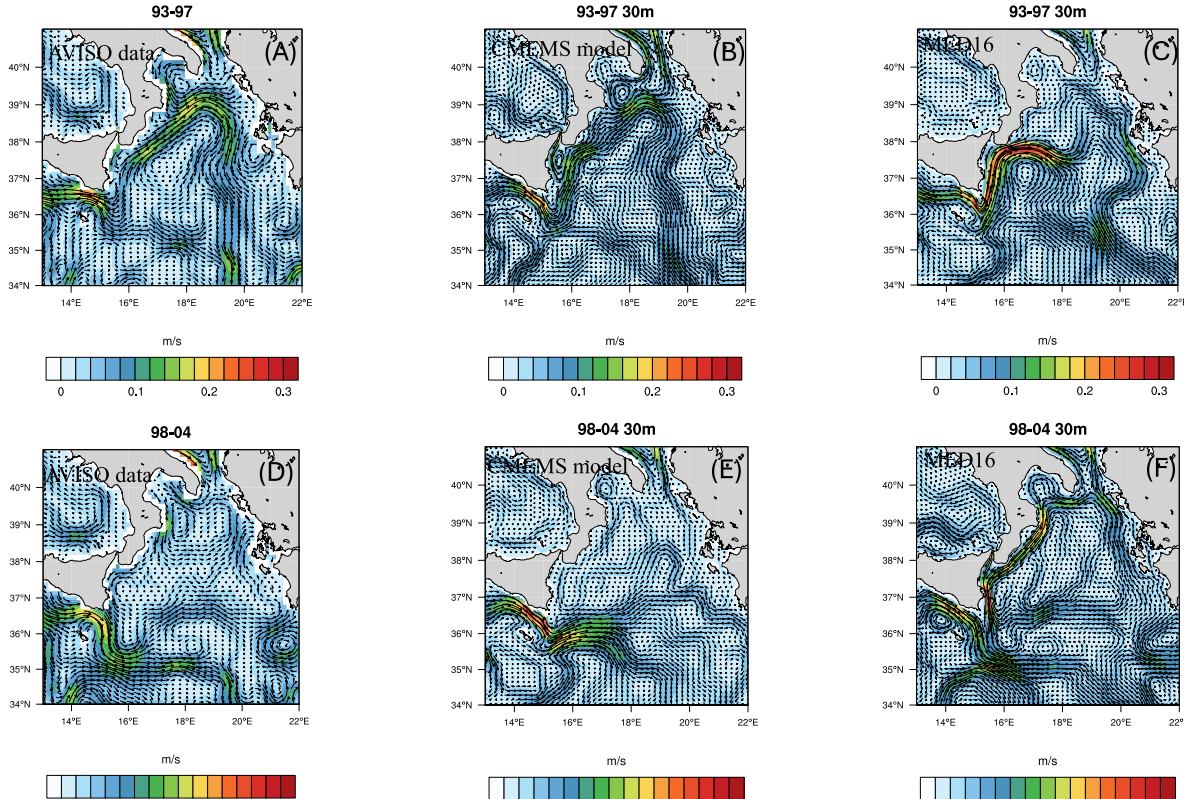


Fig. 2. The current fields averaged over the two periods 1993–1997, 1998–2004. Geostrophic velocity obtained from Aviso data (A,D), Velocity fields at 30 m depth for both CMEMS reanalysis (B,E) and MED16 hindcast (C,F).

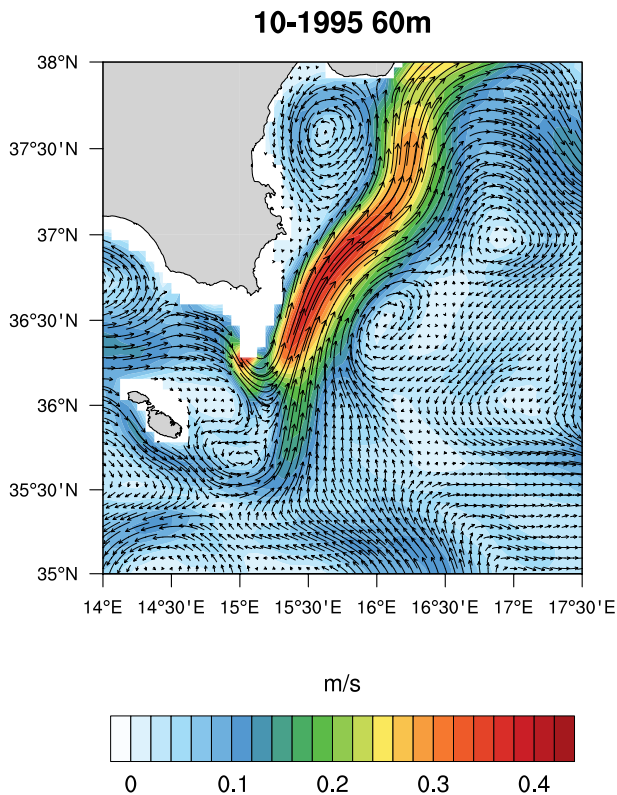


Fig. 3. Monthly average (October 1995) of currents at 60 m for Med16.

northwards along the Sicilian Coast. MED16 (Fig. 3) monthly average currents in October 1995 are in good agreement with the observations both in terms of spatial patterns and of current intensities. The model also reproduces structures such as the Ionian Shelf break vortex (35°N, 15°E) and the Messina rise vortex (37.5°N, 15.5°N).

In the next section, we characterize temporal and spatial scales of the surface long-term variability modes reproduced by MED16, and compare with those calculated from CMEMS model.

2.3. Surface space–time scales

To characterize the space–time scales of the NI circulation, we have performed an Empirical Orthogonal Function (EOF) analysis of the sea surface height (SSH), both for MED16 and for the CMEMS reanalysis. The EOF decomposition allows to identify the long-term components in the variability of the horizontal motion. Moreover, we may use the associated principal components (PCs) to define a NIG index of variability, as done by Eusebi Borzelli and Carniel (2023) and Civitarese et al (2023).

Results of the EOF analysis are shown in Fig. 4, both for MED16 (panel C, D; 1981–2010) and for the reanalysis (panels A, B; 1987–2021). The figure shows the second EOFs (A, C) and the corresponding PC coefficient time series. Note that the first EOFs (not shown) correspond to a coherent oscillation of the entire basin and are associated with the seasonal variability. For the sake of clarity, we have added vertical lines in panels B and D, to mark the initial and final years of the common period (1987–2010). The second mode of MED16 (panel C), is characterized by an extended positive area, with a main maximum centered near the Sicilian coasts, elongated toward the north. The PC time series (panel D) shows a strongly positive phase from 1989 to 1997, and then a prolonged negative phase. These phases correspond to the damped NIG oscillations (see Eusebi Borzelli and Carniel, 2023). In addition, the time series shows variability on shorter scales during the 80s. This result is consistent with that of the reanalysis; the second EOF

(panel A) has a structure similar to that of MED16, although the positive region is slightly wider and more homogeneous. The time series of the PC associated with the second EOF (panel B) is quite close to that of the MED16 hindcast in the overlapping period (1987–2010). Both models indicate that the region is characterized by sub-decadal frequencies, in agreement with the results of Liu et al. (2022), who performed a very long hindcast covering the last century.

Information derived from the decomposition may shed light on the barotropic – baroclinic response of the region. It is well-known that the SSH variability is related to the ocean first baroclinic mode (Wunsch, 1997, Wunsch and Stammer, 1997). The recent work by Eusebi Borzelli et al (2024) has highlighted the importance of the first baroclinic mode in the modulation of the long-term variability of the circulation in the NI. Therefore, it is interesting to analyze in more detail the vertical structure of the circulation. Fig. 5 displays time series of the relative vorticity (annual running means) for the surface and intermediate layers (0–150 m, 150–500 m, respectively; averages over box A of Fig. 1). The two time series are very well correlated (correlation index of 0.85), indicating that the MAW and LIW layers in the NI move in phase with each other and behave dynamically as a single layer. This is in agreement with the results of Eusebi Borzelli et al. (2024); Ioannone et al. (2011) and Klein et al. (1999), showing that the active interface associated to the first baroclinic mode is that between intermediate and deep waters, located at about 500 m. Moreover, the vorticity time series are well correlated with the time series of the principal component of the second EOF, shown in Fig. 4.

3. Analysis of the model forcings and their relationship with the circulation

The basin is represented as an open system locally forced by surface fluxes, internal processes due to deep water anomalies, and lateral boundary conditions associated with the AIS. In this section, we analyze the different forcings and their influence on the circulation.

3.1. General characteristics of processes impacting the North Ionian basin

The monthly time series of the wind stress curl used to force MED16 (see Section 2) is shown in Fig. 6 (averaged on box A of Fig. 1). The wind stress curl is almost always positive and contains a strong seasonal signal. The intensity of the winter wind stress curl is high during the first half of the 80s, decreases in 1986, remains low till 94, and then increases again.

In Fig. 7 we show a time series of the AIS Mean Kinetic Energy (MKE) provided by the model over the Malta Plateau (box B in Fig. 1), the region where the AIS enters the NI (e.g. Robinson et al. 1999). The time series shows a wide range of scales of variability, from seasonal to decadal. The MKE decreases from the end of the 80s to the mid 90s, similarly to what happens to the local wind stress curl (see Fig. 6). From the end of 1990 to mid 2000, the MKE of the AIS increases and shows a strong interannual signal.

The internal forcing acting on the basin is provided by the deep dense water anomalies. Fig. 8 shows Hovmöller diagrams of the modelled water density in the Adriatic Sea (A), the Otranto Strait (B) and the Eastern Ionian Sea (C). Values are averaged over small areas that are indicated in Fig. 1 (red boxes).

The Figure shows that the model correctly reproduces the timing of the deep water formation in the Southern Adriatic sea (e.g. Roether et al, 1996) and the corresponding outflow through the Otranto strait (Fig. 8 panel A and B) over the three decades, including the prolonged phase of decrease of Adriatic deep water (800–1000 m) from the end of the 80s to the mid 90s. The phenomenology of the EMT is instead evident in Fig. 8 panel C where the strong anomaly of dense water of Aegean origin during early 90s comes from the eastern part of the basin affecting the intermediate and deep layers of the northern Ionian and the Southern Adriatic sea (e.g. Klein et al, 1999). During the 2000s, the model shows a

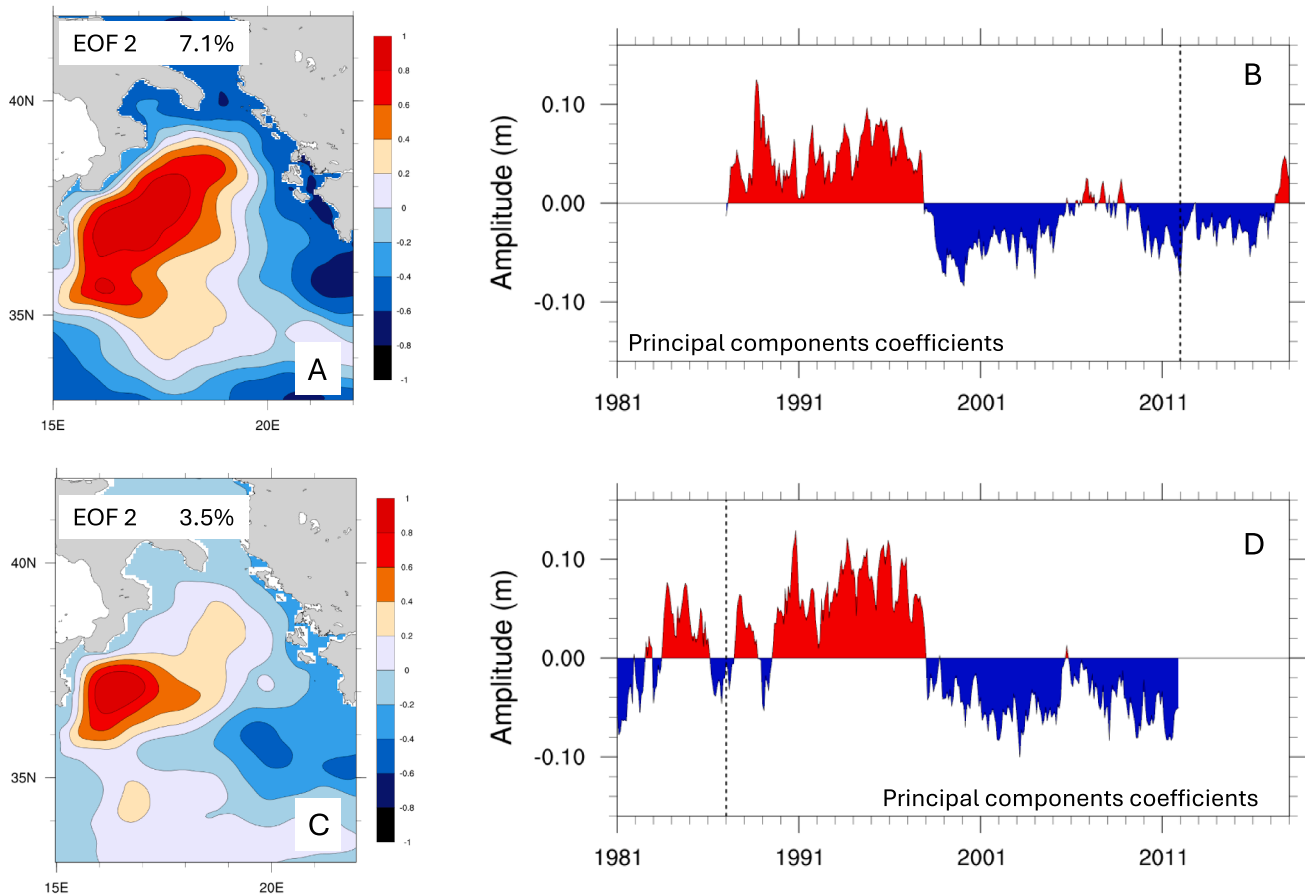


Fig. 4. EOF decomposition of the Sea Surface Height. The horizontal pattern of the second mode of variability for CMEMS (A) and MED16(C); The time series of its Principal Components coefficients for CMEMS (B) and MED16 (D). The lines indicate the overlapping period for the two models (1987–2010).

decrease of density and a stable phase up to 2010, but the system is far from returning to the pre-90s condition, in agreement with the findings by [Cardin et al. \(2015\)](#).

[Fig. 8D](#) shows the density variation over the 500–3000 m layer in box A of [Fig. 1](#) and illustrates how the local Ionian deep dense water responds to the density anomalies at the boundaries. Weak oscillations during the eighties are superimposed to the huge increase of density due to the Aegean input that started in 1992 and lasted until 2000.

To highlight the change in water column structure that occurred during the 90's, zonal transects of the model density (38° N, 16° E– 21° E) are shown in [Fig. 9](#).

From 1990 to 1992 the deep isopycnals are almost horizontal, in 1993 it is evident the intrusion of denser water input and then a progressive uplifting of the isopycnals takes place up to 1999.

To quantify the relationships between forcings and circulation variability, we show in [Table 1](#) the linear correlation coefficients between the forcings and the two quantities that can be considered as “NIG indices”: the second principal component of the SSH and the relative vorticity.

These correlations have been performed after applying a one-year running mean to the series. The highest correlation was found with the MKE over the Malta Plateau, with a coefficient of -0.68 for the second EOF PC and 0.61 for the vorticity. This suggests that the AIS has a crucial role in controlling the long-term variability of the NI.

3.2. Spectral characteristics of the forcings and of the circulation

In this section we analyze the relationship between the time scales of

the forcings and the surface circulation. In particular, we apply the Singular Spectral Analysis (SSA; a brief description is given in the Appendix A, whereas a comprehensive review can be found in [Ghil et al., 2002](#)) to the time series of the wind stress curl, the energy of the AIS over the Malta Plateau, the deep water anomalies, and the NI vorticity. This analysis requires the choice of a temporal sliding window; here a window of 7 years is chosen, so we can capture trends and periodicities as long as 7 years. This choice is a good compromise between the total length of the original time series and temporal sampling of 1 month. The trend captured over the window may be part of longer time scales oscillation as we will see through the PCs time series.

The signal to noise rate can be inferred from the eigenvalue spectra illustrated in the panels A1, C1, E1, and G1 of [Fig. 10](#) for the different variables (note that in these figures the horizontal axis goes from 1 to 84 months). The largest eigenvalues contain most of the signal and are separated by a steep slope from those related to the noisy part of the time series, which is characterized by much lower values, forming a flat floor or a very mild slope ([Ghill et al., 2002](#)). The SSA results for the vorticity are shown in [Fig. 10](#) (A, B). By analogy with the meteorological literature, the eigenvectors of the lag covariance matrix are denoted here as empirical orthogonal functions (EOFs) (e.g., [Vautard and Ghil, 1989](#)).

The EOFs corresponding to the first four eigenvalues are shown in panels a2 and a3. The first two EOFs (10a2) correspond to low frequencies, with a period of about 7 years for EOF2, and even longer for EOF1. The third and fourth EOFs also show different periodicities: about 6 years for EOF3, whereas EOF4 is associated with the seasonal cycle (10a3). We have verified that a satisfactory reconstruction of the original signal can be obtained by multiplying these 4 EOFs with their

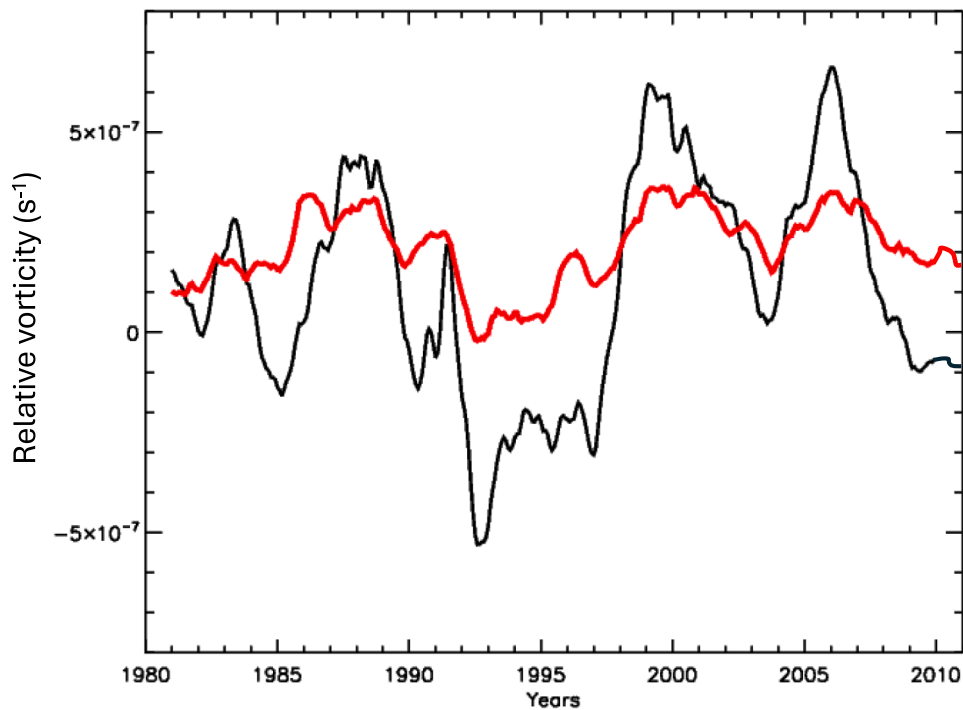


Fig. 5. Relative vorticity averaged over box A in the surface layer (0–150 m, black line) and the intermediate layer (150–500 m, red line) for MED16.

corresponding PCs time series (Fig. 10 b1, b2, b3, b4). Note that the decadal, sub-decadal and seasonal scales are also the dominant scales that were found in the EOF analysis of the SSH.

Fig. 10c and 10d show the same analysis for the time series of wind stress curl. In this case, we have two pairs of significant eigenvalues and the corresponding EOFs, shown in Fig. 10c2, c3, represent the annual and semiannual signals, respectively. The PCs show long-term changes only in the envelope of these signals. It is interesting to note that the signal of the PC corresponding to the seasonal cycle (10 d1-d2) experiences a reduction of amplitude between the late 1980s and the mid-1990s.

The SSA of the MKE of the AIS is displayed in Fig. 10 e-f. For simplicity, only the first four EOFs are shown. The first six eigenvalues, which are significant for the signal reconstruction, are shown in Fig. 10d. The main modes of variability are the seasonal mode (EOF2-3), the decadal mode (EOF4), and a subdecadal mode (EOF5), with period of about 6 years.

Finally, the SSA decomposition of the water density in the Ionian deep layer is shown in Fig. 10g, h. In this case, just two eigenvalues contribute to the reconstruction of the original signal, the first is almost constant while the second represents a linear trend. The first mode should be weighted by its PC, and it reconstructs the EMT phenomenon, whose temporal variability is represented by the decadal modulation of the coefficient time series.

Summarizing, the SSA analysis shows that only the vorticity and the MKE on the Malta Plateau have similar time scales. The wind stress curl is dominated by seasonal and sub-seasonal scales with a weak decadal modulation, while the deep-water density is characterized exclusively by long term components, without a clear periodicity. These results indicate that the energy of the AIS plays an important role in modulating the long-term variability of the surface circulation of the NI. This role will be further investigated in the next two sections.

4. The role of the Atlantic Ionian stream

Having established a strong connection between the energy of the AIS and the NIG reversal indexes, we now investigate more closely the relationship between the variability of the AIS and the NI surface circulation. Fig. 11 shows a comparison between the MKE of the AIS over the Malta Plateau and the MKE of the surface current in the NI, averaged over box A of Fig. 1. The two signals show a clear sub-decadal variability and are strongly anticorrelated (-0.79), with minima (maxima) of the AIS inflow energy corresponding to maxima (minima) of the energy in the NI. This anticorrelation suggests that an energetic AIS does not enter the NI, whereas it does when it is weak. This is consistent with the alternance of the NIG phases (see vertical lines in the Figure), showing high (low) energy over the Malta Plateau in the cyclonic (anticyclonic) circulation regime.

This interpretation is confirmed by Fig. 12, where we show maps of the surface circulation in the central and northern Ionian for the five years denoted by blue bullets in Fig. 11. The years 1984 (A) and 1994 (B) represent two cases in which the energy of the AIS has a relative minimum, while the years 1987, 2000 and 2003 correspond to relative maxima.

In the cases with minimum energy (1984 and 1994) the current entering the Ionian Sea deflects northward, follows the shelf, and forms a wide anticyclonic cell occupying the NI. It is useful to remind that the period from 1987 to 1995, where there is a strong decrease of the current over the Malta Plateau, coincides with the period when the (positive) wind stress curl is weak over the NI, facilitating the formation of a global anticyclonic cell.

On the other hand, in the high energy cases (1987, 2000, 2003) part of the flow heads towards southeast. In 1987 and 2000, the current experiences a bifurcation with a branch that flows zonally eastward and the other that goes northward forming an anticyclone centered at 36.5°N , 16.5°E . In 2003, which is the year with the maximum energy of

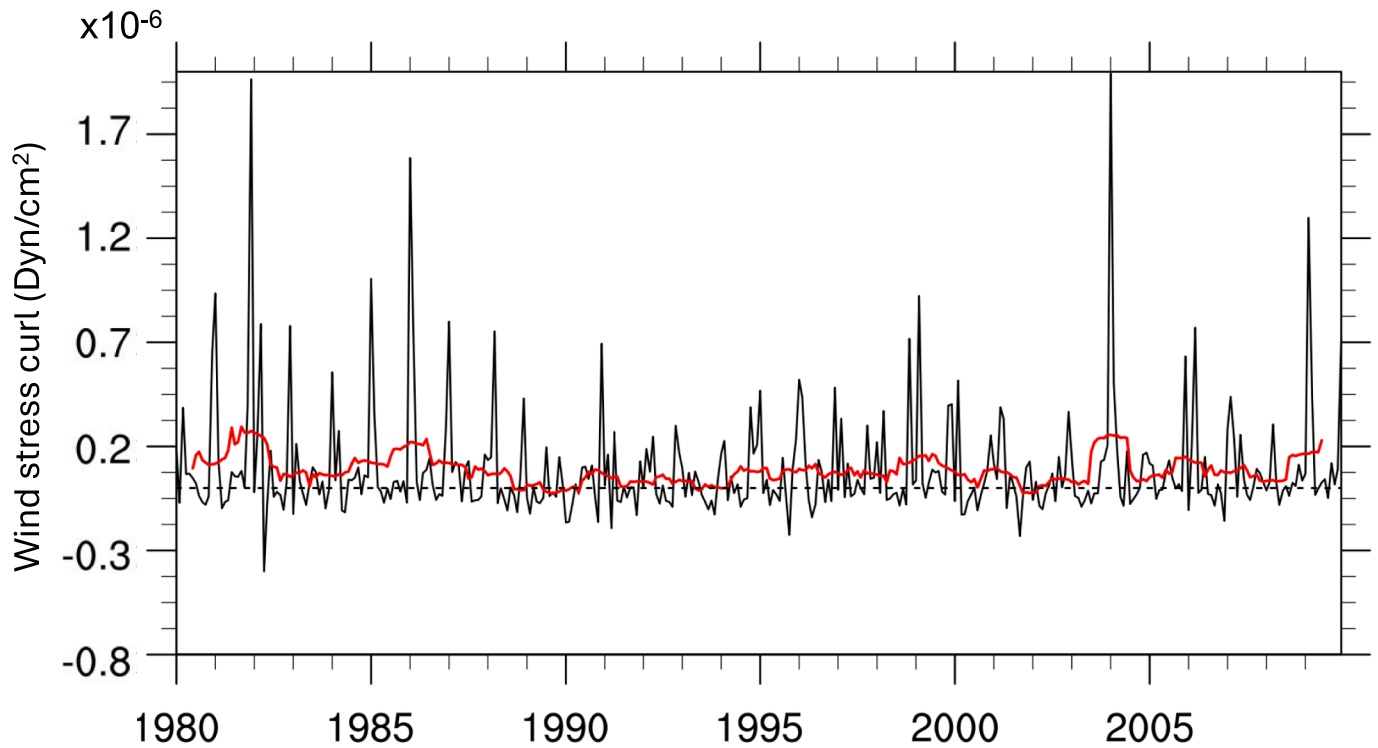


Fig. 6. Monthly time series (black curve) and 1 yr running average (red curve) of the wind stress curl (SMHI data), averaged over box A (see Fig. 1). The dashed line corresponds to 0 values.

the AIS over the 30 years, the bifurcation is not present and the strong surface current separates from the coast and proceeds eastwards inside the Ionian Sea, as a zonal flow. In this case at 36.5° N–16.5° E there is a cyclonic structure on the left side of the stream and an anticyclonic one on the right side that may be associated to instabilities of the current.

In the high energy cases, the bifurcation of the current or even its separation from the coast indicates that the local dynamics is strongly controlled by nonlinearities. There is a wide literature concerning nonlinear current separation, both in the context of very energetic boundary currents (see the review of Chassignet and Marshall, 2008) and cases of currents of moderate intensity (Barh et al, 2000; Gan et al, 1997; Gan et al. 2004).

We finally look at the relation between the variability of the MKE over the Malta Plateau and the variability of the salinity in the upper layer in the NI (0–150 m; Fig. 13). The two time series are well correlated (0.65); minima of the MKE correspond to minimum salinity, due to the input of freshwater in NI (AC phases) and maxima to higher salinity, which corresponds to the cases of current flowing more directly toward the Levantine basin.

5. The vorticity dynamics

In a system as the Ionian Sea, characterized by intense surface currents, advection may be expected to play an important role in the dynamics. To get insight on this issue, we now analyze the nonlinear vorticity equation, which, in the surface layer of a baroclinic inviscid ocean (e.g., Rhines, 1986; Pedlosky, 1986), can be written as:

$$\frac{\partial \zeta}{\partial t} + \left(u \frac{\partial \zeta}{\partial x} + v \frac{\partial \zeta}{\partial y} \right) = \frac{(\nabla p \times \nabla \rho)}{\rho^2} + f \frac{\partial w}{\partial z} + \frac{1}{\rho H} [\nabla \times \tau]_z$$

Here, the second term in the left-hand side is the nonlinear advection term (NL hereinafter). Only the horizontal components of the advection have been retained in this term, since the contribution from vertical advection is much smaller. The first term on the right-hand side is the baroclinic term (BT), which is calculated at each depth from the horizontal gradients of pressure and density. The vortex-tube stretching term (Ts: the second term on the right hand side) is calculated using the vertical variation of the vertical velocity of the model (w); if w increases (decreases) in the z -direction then the fluid lines are ‘stretched’ and the vorticity increases (decreases) (e.g., Vallis, 2006), and this can be seen as a representation of the internal mechanisms, as suggested by Eusebi Borzelli et al (2009). The last term is the wind stress curl (WSC) term, where $H = 150$ m.

We recall that in Eusebi Borzelli et al (2009), where a similar analysis was performed using a linear vorticity equation, the WSC and TS terms were found to be the dominant in the vorticity budget. It was consequently argued that internal processes are as important as the wind stress curl in setting the observed variability of the circulation.

Time series of the different terms of the nonlinear vorticity equation are displayed in Fig. 14. Data are averaged in the box A of Fig. 1 and over the first 150 m of depth, and are smoothed by applying a 4-month running average.

The Figure shows that the NL is $\sim 10^{-12}$ or more, which is an order of magnitude larger than the other terms, indicating that nonlinear advection dominates the dynamics of the region. The other terms (WSC,

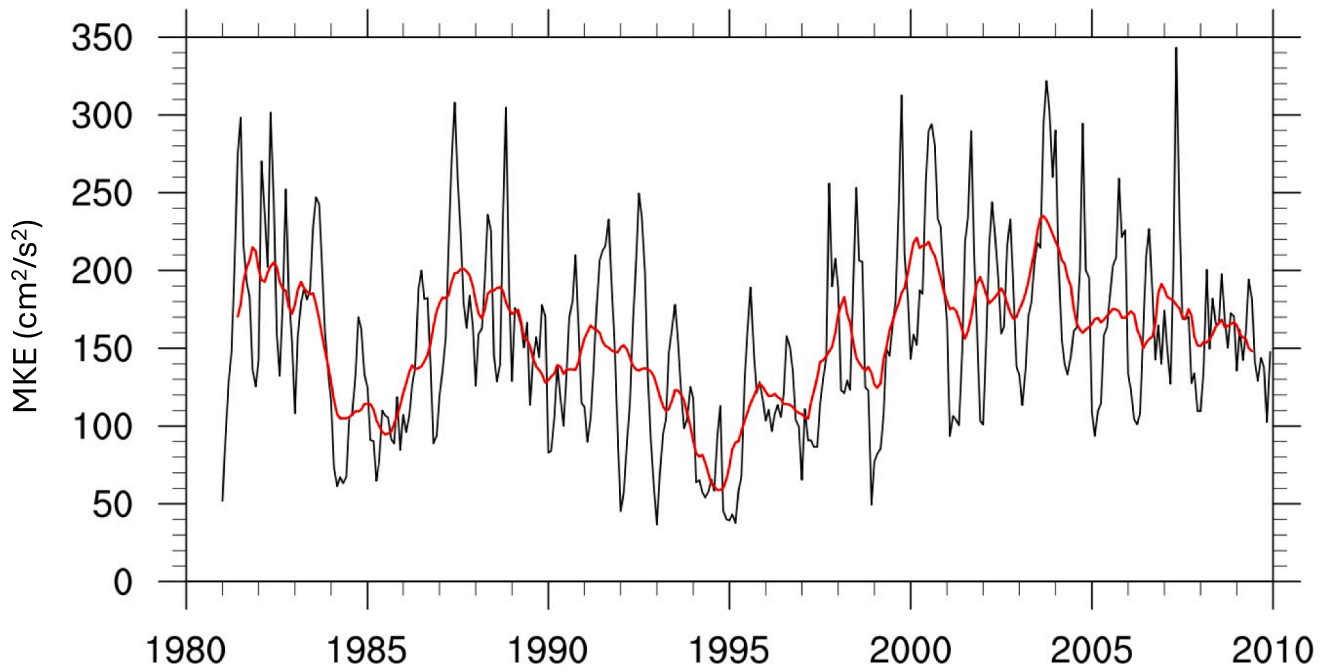


Fig. 7. Monthly Mean Kinetic Energy (obtained from MED16) over the Malta Plateau (box 2 in Fig. 1), averaged over the first 30 m. The red line is a 1 yr running average.

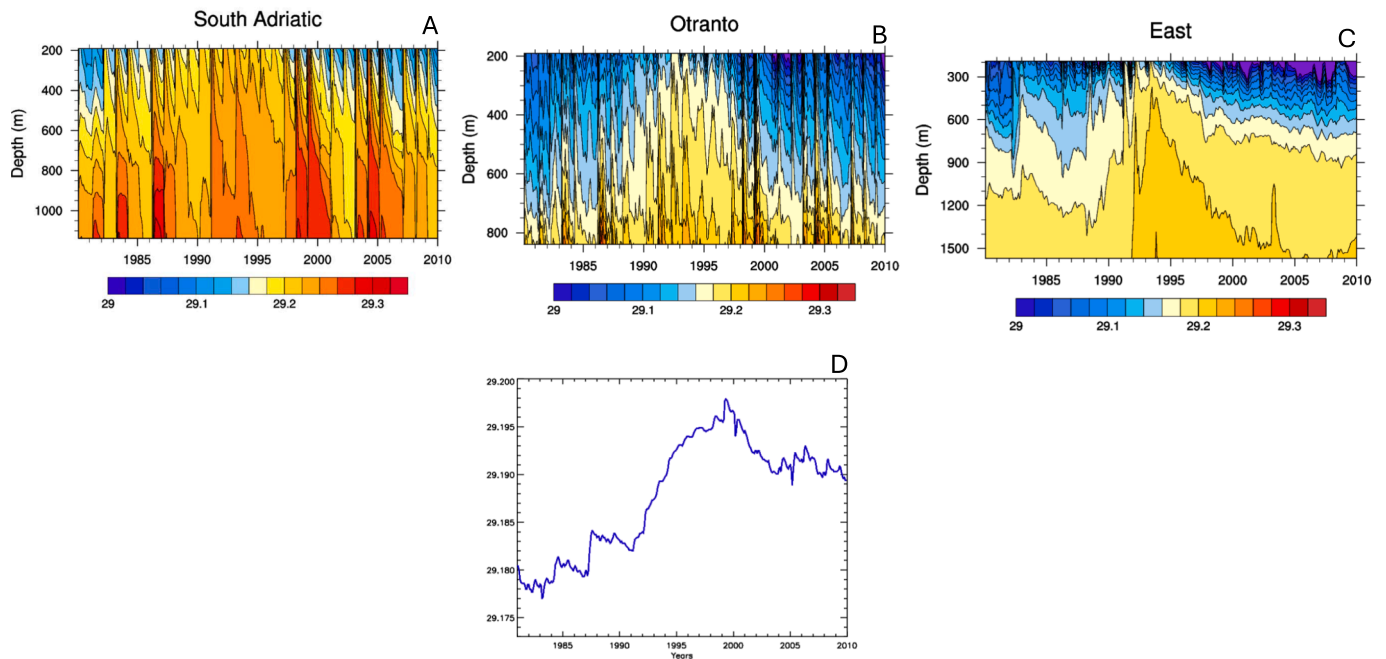


Fig. 8. Hovmöller diagrams (A, B, C) calculated in the boxes P1, P2, P3 (see Fig. 1), and (D) time series of the density (obtained from MED16 outputs) averaged in the box 1 and over the layer 500–3000 m.

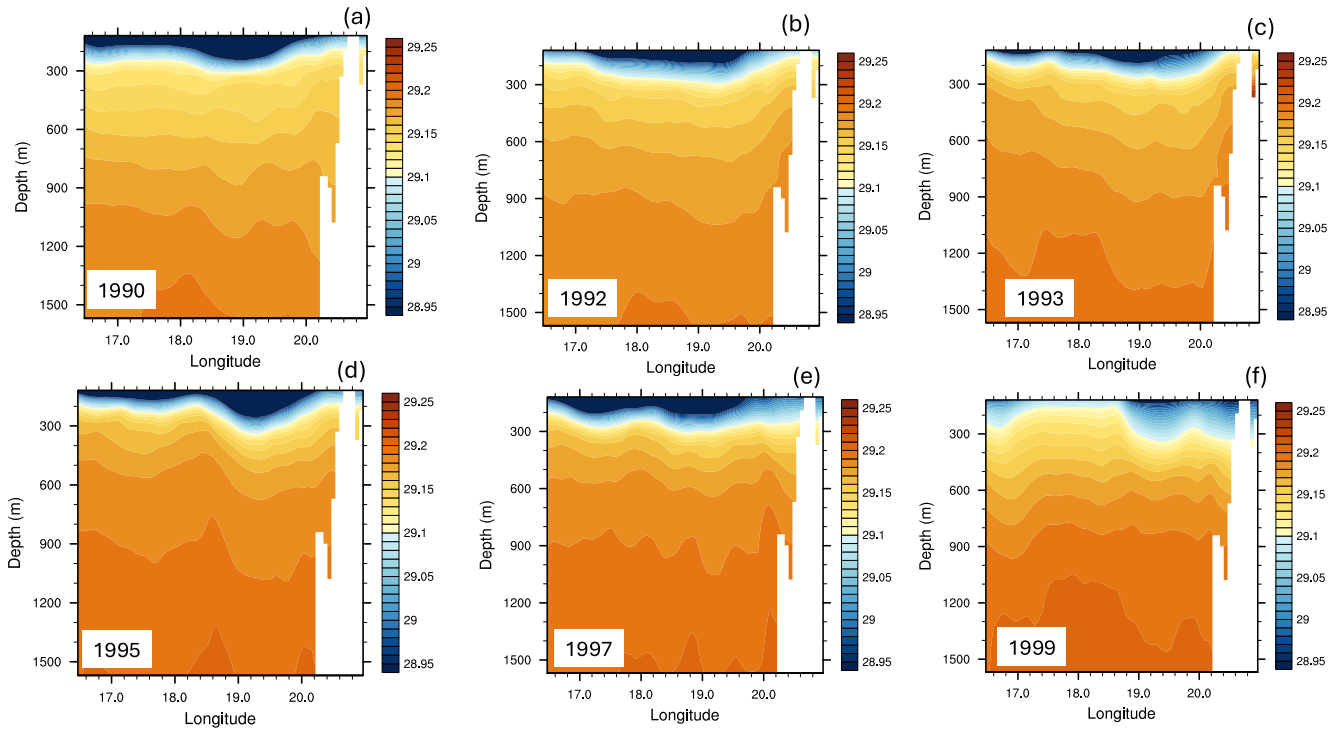


Fig. 9. Annual density (obtained from MED16 outputs) transects calculated over the horizontal section at 38° N.

Table 1

Correlation coefficients between the forcings and the Principal component signal of the EOF2, and Vorticity. The coefficients were calculated using normalized one year running averages for both time series.

Principal components (EOF2)	Wind stress curl (Northern Ionian sea)	MKE (Malta Plateau)	Deep Water density (Northern Ionian sea)
Pc2	-0.41	-0.68	0.26
Vorticity	0.36	0.61	0.17

TS and BT) are almost always positive, with the WSC being the largest term in the right-hand side and TS the smallest one. The WSC term is weak from the end of the 80s to mid 90s, as already stressed in section 4. The baroclinic term is stronger and negative during the EMT critical phase (1992–1995, see Incarbona et al. 2016), contributing to the establishment of the anticyclonic circulation in the NI (negative vorticity).

Summarizing, these results indicate that the distribution of vorticity in the NI is strongly controlled by nonlinear advection by the mean flow, which, as we have seen in the previous section, is in its turn strongly influenced by the strength the AIS entering the basin.

6. Conclusions

In this work, we have used a thirty year hindcast simulation (1981–2010) to study the long-term variability of the surface circulation of the North Ionian Sea. The simulation period includes the two decades influenced by the EMT, a striking phenomenon that has attracted much attention from the scientific community.

The long-term variability of the NI circulation has been highlighted through a EOF analysis of the outputs of both the MED16 hindcast and the CMEMS reanalysis. The 2nd mode of variability of the SSH shows a spatial structure similar to that of the NIG for both models. Moreover,

the temporal variability of this mode is in agreement with the variability observed by the altimeter. The EOF analysis, together with the SSA of the mean kinetic energy, indicates that besides the quasi-decadal scale observed from the end of the 80s to mid 2000s, the NI is characterized by sub-decadal oscillations (periods of 5–7 years), which are the dominant scales highlighted by Liu et al. (2022), with some sporadic inversions of the circulation over shorter time scales (<5 years). This suggests that the quasi-decadal oscillation of the surface currents occurred during the 90s was an anomalous phenomenon.

To determine the causes of the circulation variability, we have carefully analyzed the strength and variability of the different forcings acting over the NI. This analysis has shown that the energy input associated with the AIS (lateral advection) plays an important role that was underestimated in previous studies. We find that the strength of the AIS over the Malta Plateau is strongly anticorrelated with the energy of the surface circulation in the NI region. In periods in which the AIS energy is low, part of the stream is deflected towards north contributing to the formation of an anticyclonic cell into the NI (anticyclonic phase of the NIG); on the other hand, when the energy is high, the AIS tends to flow zonally towards the Levantine basin, without entering the NI. When the wind stress curl (always positive) is weak, the intrusion of the AIS into the NI is facilitated; this is the case of the period 1987–1995. On the other hand, when the AIS flows zonally and the wind stress curl is stronger, there are favorable conditions for the establishment of a cyclonic circulation over the whole NI; this is the case of the period 1997–2004.

Even though we have not investigated in detail the nonlinear dynamics associated with the AIS, the model indicates that the energy over the Malta Plateau controls the bifurcation and possible separation of the AIS when entering the Ionian Sea. For example, a complete separation takes place in 2003, which is the most energetic year in the simulation. This aspect is worth of further analysis in future studies. The key role of the AIS is confirmed by the vorticity diagnostics of Section 5; the nonlinear terms are found to dominate the surface layer vorticity budget whereas the internal mechanisms have a minor role, except in the period

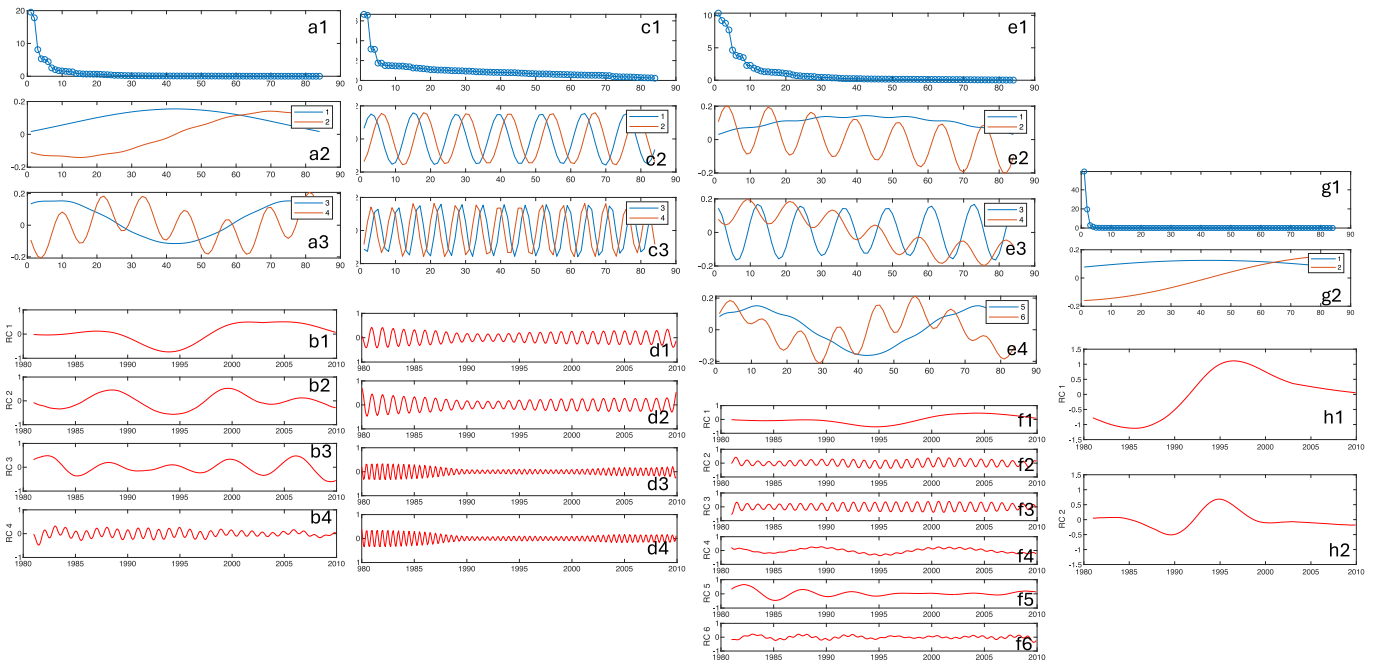


Fig. 10. Singular Spectral Analysis for vorticity (panels a-b), wind stress curl (panels c-d), MKE over Malta Plateau (panels e-f), and density in the deep NI (panels g-h).

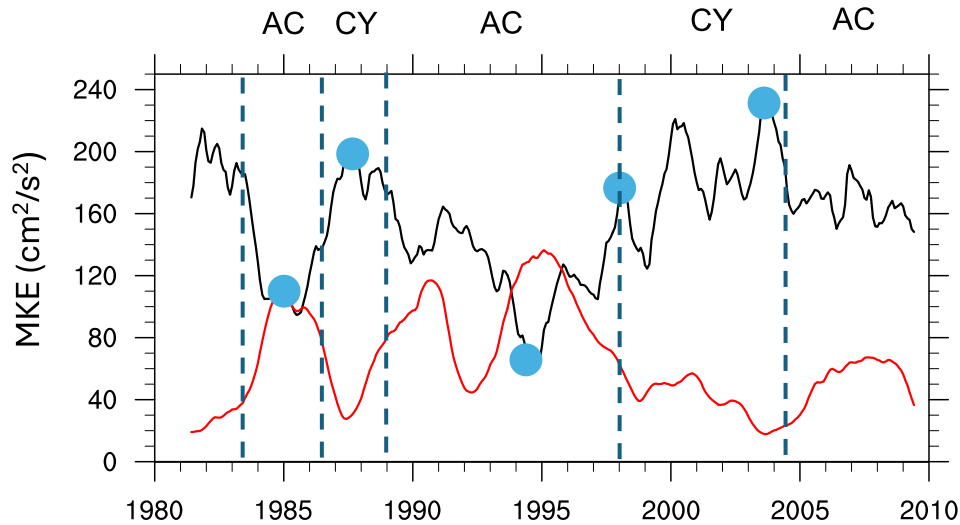


Fig. 11. Mean Kinetic Energy of the currents averaged over Malta Plateau (black line) and Northern Ionian sea (red line). For the Malta Plateau the data are averaged over the layer (0–30 m) for the Northern Ionian Sea the data are averaged over the layer (0–150 m). Blue bullets indicates the years where the annual averages of the surface circulation are shown in Fig. 12.

93–95, where they contribute to strengthen the anticyclonic NIG cell. It should be noted that these findings are consistent with the results of the recent work by Borzelli et al (2024). In that work, the long-term variability of the NI circulation was shown to be controlled by the first baroclinic mode, and the maximum energy of this mode was concentrated near the MP, in the area in which the AIS enters the Ionian Sea.

Finally, we note that to get a more complete characterization of the long-term variability of the NI circulation it would be useful to perform a longer hindcast simulation, extending both before 1981 and over the last 15 years.

CRediT authorship contribution statement

E. Napolitano: Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **A. Carillo:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M.V. Struglia:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Formal analysis, Data curation, Conceptualization. **R. Iacono:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Conceptualization. **M. Palma:** Writing – review & editing, Supervision, Investigation, Data curation. **G.L. Eusebi Borzelli:** Writing – review & editing, Writing – original draft, Formal analysis,

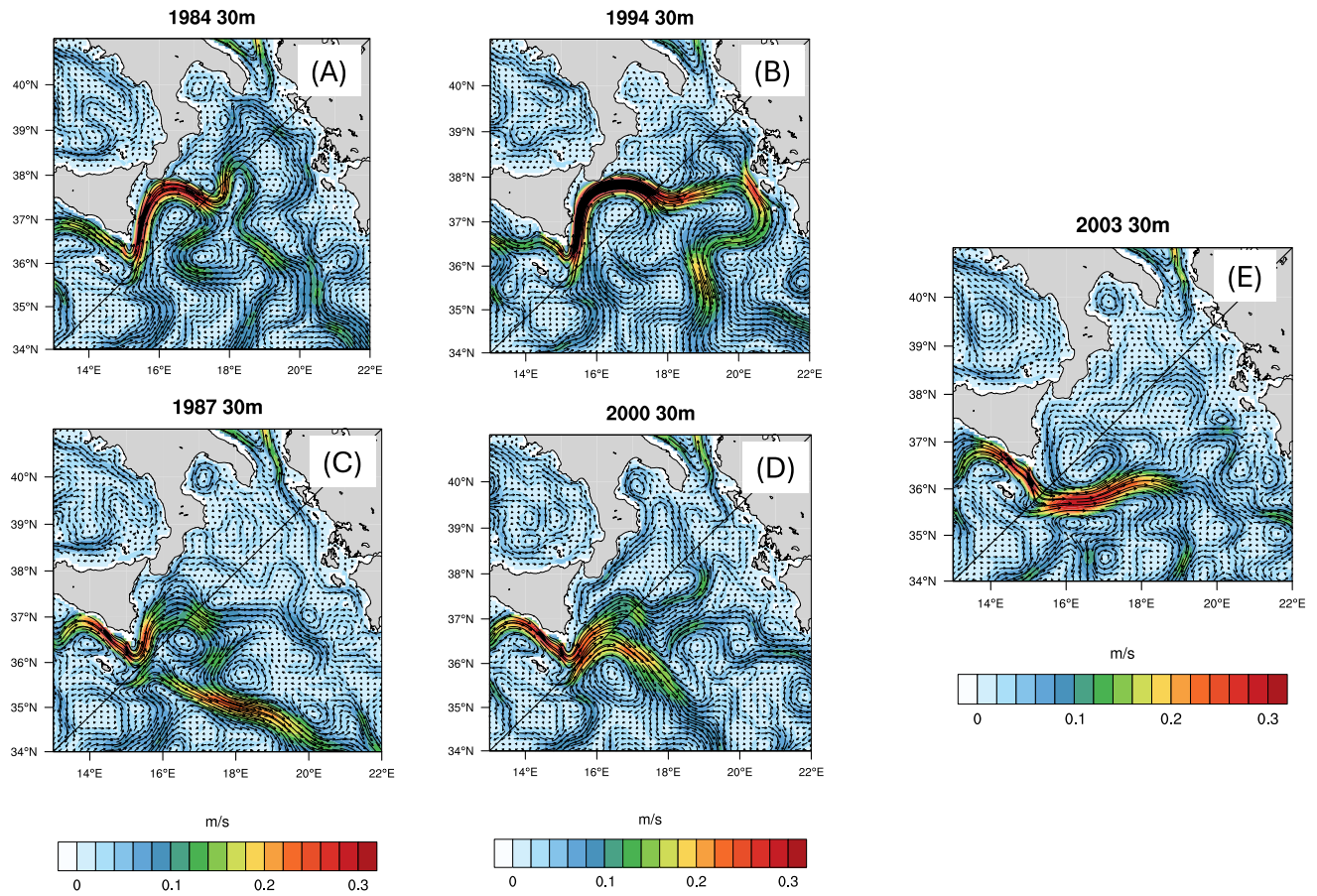


Fig. 12. Annual average of the circulation for different conditions of Mean Kinetic Energy of the surface current in the Sicily strait (cases highlighted in Fig. 14). (A) and (B) low energy cases (1984 and 1994), (C) (D) (E) high energy years (1987, 2000, and 2003).

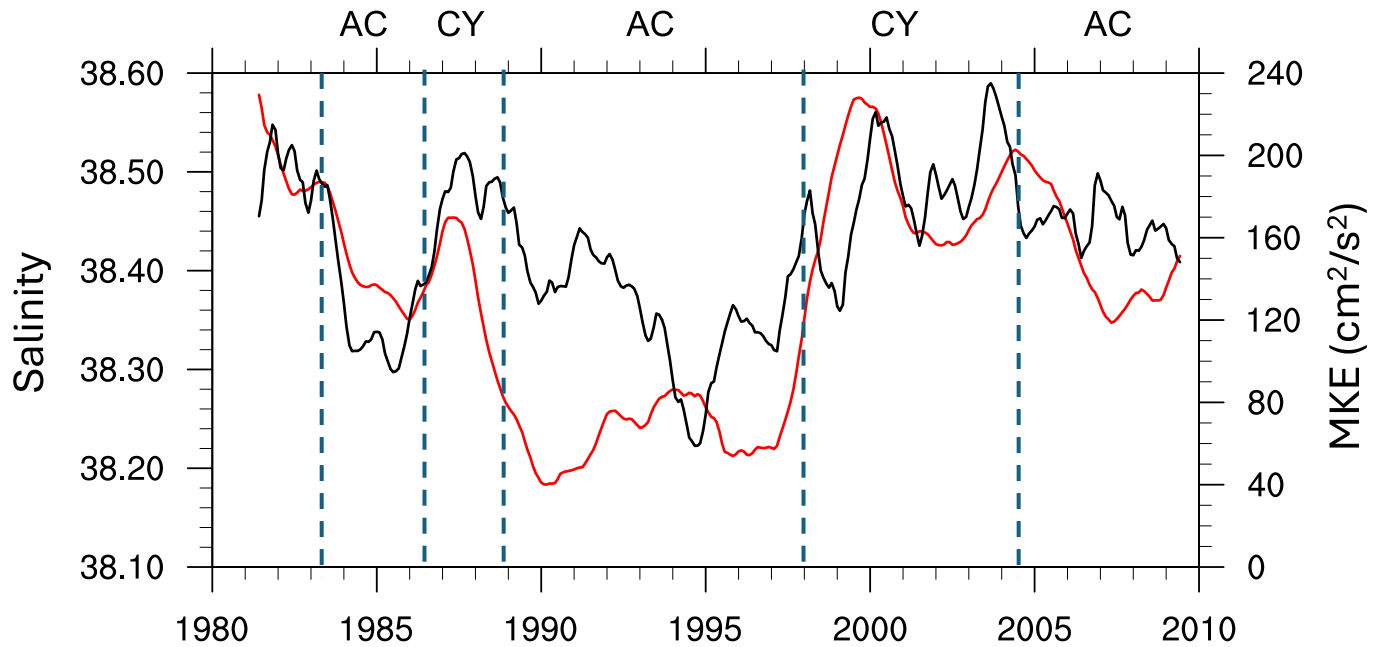


Fig. 13. MKE over the MP (red line) and salinity (0–150 m) (black line) in the Northern Ionian sea (box A of Fig. 1).

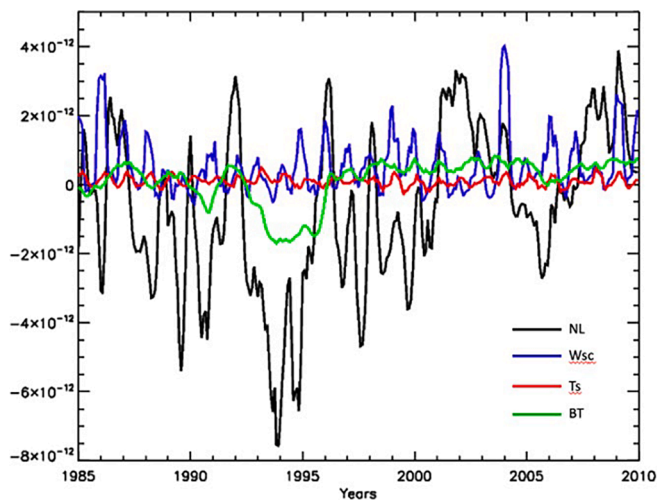


Fig. 14. Terms of vorticity equation.

Conceptualization. **G. Sannino**: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

SSA (eg [Vautard and Ghil, 1989](#)) is a temporal domain extension of the spatial empirical orthogonal function decomposition by principal component analysis (PCA) ([Preisendorfer, 1988](#)).

SSA is based on diagonalization of the time-lagged covariance matrix of univariate time series; its eigenvectors, given by the temporal empirical orthogonal functions (EOFs), are an optimal set of data-adaptive, narrowband modes for decomposing the low frequency variability. SSA is particularly efficient for quasiperiodic variability with phase and amplitude modulations. Projection of the data on each EOF yields the corresponding temporal principal component (PCs). The entire data or its components corresponding to trends, oscillatory modes, or high-frequency noise can be reconstructed by using specific linear combinations of PCs and EOFs. Since PCs do not carry phase information within the SSA time window, they simulate only spectral content and amplitude of the low frequency variability. On the other hand, low frequency variability phase information is captured by the reconstructed SSA components in the least squares sense, and the signal is found by convoluting the corresponding PCs and EOFs ([Ghil et al., 2002](#)).

Here we use a temporal sliding window $M = 7$ yrs, which is a compromise between the total length of the original time series and temporal sampling that in the present case is 1 month. It means that we capture trend and periodicity as long as 7 years. The choice of $M = 7$ is fairly safe with respect to the length of the time series because the diagonalization of the autocorrelation matrix which have $M \times M$ dimension does not introduce large numerical error ([Ghill et al., 2002](#)). The trend captured over M may be a part of longer time scales oscillation as we will see through the PCs time series.

Data availability

Data will be made available on request.

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