

UNIVERSIDAD AUTÓNOMA DE BAJA CALIFORNIA
FACULTAD DE CIENCIAS MARINAS
INSTITUTO DE INVESTIGACIONES OCEANOLÓGICAS



**VARIABILIDAD ESPACIO-TEMPORAL DE LAS CORRIENTES COSTERAS
ASOCIADA AL EFECTO DE VIENTOS SINÓPTICOS EN EL NOROESTE DEL
GOLFO DE MÉXICO**

TESIS

**QUE PARA CUBRIR PARCIALMENTE LOS REQUISITOS NECESARIOS PARA
OBTENER EL GRADO DE**

DOCTOR EN CIENCIAS EN OCEANOGRAFÍA COSTERA

PRESENTA

ANGÉLICA MARIA ROMERO ARTEAGA

**ENSENADA, BAJA CALIFORNIA, MEXICO.
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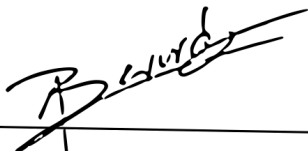
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Abstract

The primary purpose of this research was to gain a better understanding on spatio-temporal nearshore current variations during the passage of episodic synoptic-scale cold fronts. The study was undertaken along the southern Texas coast, in the northwestern Gulf of Mexico, using current and water level measurements collected over a 2-year period (November 2016 to October 2018), and local wind data in combination with synoptic wind and mean sea-level pressure (MSLP) maps. Cold fronts were identified based on local wind speeds and directions and synoptic-scale MSLP differences, and then categorized through hierarchical clustering. The flow response was primarily controlled by the wind forcing during the passage of cold fronts. A total of 38 cold fronts were identified over the two-year period. While most of the fronts reversed the alongshore current downcoast (~80 %), others were unable to completely reverse the flow throughout the entire water column or, instead, intensified the existing downcoast flow. Depending on the number of consecutive events, cold fronts were identified as *sequential*, formed by 2 to 5 events, or *individual* formed by a single event. *Sequential* fronts typically lasted 1 to 3 weeks, were associated with MSLP of ~1024 hPa and maximum along-shelf wind stresses, τ_y , of ~ -0.10 Nm⁻², and induced downcoast flows of ~-0.5 ms⁻¹ down to ~10 m depth. *Individual* fronts were classified as of high and low intensity depending on MSLP differences, and lasted 2 to 4 days (identified as short and long, respectively). Response times of the along-shelf flow to the wind forcing were analyzed through cross-correlation analysis; all events presented high correlation values (> 0.9). *Sequential* events showed comparatively smaller lags (less than 9 h) than

individual fronts (lags of 9 to 18h). Generalized lag-fitted bin-averaged velocity profiles for each cold front type showed intense surface flows of up to 0.6 ms^{-1} and milder bottom flows of up to 0.3 ms^{-1} for long-lasting events, and half the speeds for short-lasting events. Spatial variations of front-driven flows were analyzed along the 200 km southern Texas coast over a two-month period (February and March) in 2017. Strongest downcoast flows occurred in the surface in the northern (Port Aransas) and southern (South Padre Island) end, while these were weaker in the center (Port Mansfield). Time-averaged flows showed the presence of a convergence zone in the central site as a consequence of spatial variations of the along-shelf wind-stress. The northern site presented most intense surface flows (along-shelf wind speeds of $>10 \text{ ms}^{-1}$), less affected by southeasterly (upcoast) Trade winds. Instead, low-energy cold fronts (along-shelf wind speeds of $<10 \text{ ms}^{-1}$) presented stronger influence of Trade winds and were unable to completely reverse the wind direction towards the south (downcoast) in southern and central sites. Surface wind-stress and pressure gradients were the dominant terms in the along-shelf momentum budget, while the bottom stress and Coriolis terms were considered negligible. The wind-stress term was dominant in the north, while pressure gradients associated with local sea-level responses to the wind forcing were dominant in the southern site. These findings highlight the relevance of understanding pre-front wind characteristics to determine spatial variations of the along-shelf flow during cold fronts.

Resumen

El objetivo principal de esta investigación fue obtener una mejor comprensión de las variaciones de corrientes espacio-temporales cercanas a la costa durante el paso de frentes fríos episódicos de escala sinóptica. El estudio se llevó a cabo a lo largo de la costa sur de Texas, en el noroeste del Golfo de México, utilizando mediciones de corrientes, nivel del mar, datos de viento local en combinación con mapas sinópticos de viento y presión media al nivel del mar (MSLP), colectadas durante un período de 2 años (noviembre de 2016 a octubre de 2018).

Los frentes fríos se identificaron con base en la velocidad y dirección del viento local y las diferencias de MSLP a escala sinóptica, posteriormente se clasificaron mediante una agrupación jerárquica. La respuesta del flujo fue controlada principalmente por el forzamiento del viento durante el paso de los frentes fríos. Se identificaron un total de 38 frentes fríos durante el periodo de dos años. Mientras que la mayoría de los frentes invirtieron la corriente costa abajo ($\sim 80\%$), otros no pudieron invertir completamente el flujo en toda la columna de agua ó algunos frentes sólo intensificaron el flujo existente costa abajo.

Dependiendo del número de eventos consecutivos, los frentes fríos se identificaron como *secuenciales*, formados por 2 a 5 eventos, ó *individuales* formados por un único evento. Los frentes *secuenciales* duraron típicamente de 1 a 3 semanas, se asociaron con MSLP de ~ 1024 hPa y máximos esfuerzos del viento a lo largo de la costa, T_y de $\sim -0.10 \text{ Nm}^{-2}$, e indujeron flujos descendentes de $\sim 0.5 \text{ ms}^{-1}$ hasta ~ 10 m de profundidad. Los frentes *individuales* se clasificaron como alta y baja intensidad en función de las diferencias de

MSLP, y duraron de 2 a 4 días (identificados como cortos y largos, respectivamente). Los tiempos de respuesta del flujo a lo largo de la plataforma al forzamiento del viento, se analizaron mediante un análisis de correlación cruzada; todos los eventos presentaron altos valores de correlación (> 0.9). Los eventos *secuenciales* mostraron desfases comparativamente menores (menos de 9 h) que los frentes *individuales* (desfases de 9 a 18h). Los promedios generalizados de los perfiles de velocidad con desfase temporal para cada tipo de frente frío, mostraron que los eventos de larga duración presentaron flujos superficiales intensos de hasta 0.6 ms^{-1} y flujos de fondo débiles de hasta 0.3 ms^{-1} , mientras que los eventos de corta duración mostraron la mitad de las velocidades.

Las variaciones espaciales de los flujos impulsados por los frentes fríos, se analizaron a lo largo de los 200 km de la costa sur de Texas durante un período de dos meses (febrero y marzo) en 2017. Flujos descendentes intensos se produjeron en la superficie en el extremo norte (Port Aransas) y sur (South Padre Island) y débiles en el centro (Port Mansfield). Los flujos promediados en el tiempo mostraron la presencia de una zona de convergencia en la zona centro, como consecuencia de las variaciones espaciales del esfuerzo del viento a lo largo de la costa. El sitio al norte presentó los flujos superficiales más intensos (velocidades de viento a lo largo de la costa $>10 \text{ ms}^{-1}$) al ser menos afectado por los vientos alisios del sureste (costa arriba). En cambio, los frentes fríos de baja energía (velocidades del viento a lo largo de la plataforma $<10 \text{ ms}^{-1}$) presentaron una mayor influencia de los vientos Alisios y no pudieron invertir completamente la dirección del viento hacia el sur (costa abajo) en los sitios sur y centro. Los esfuerzo del viento y los gradientes de presión fueron los términos dominantes en el balance del

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Chapter 1

1 Introduction

1.1 Scientific background

In the northwestern region of the Gulf of Mexico, cold fronts, referred to synoptic-scale strong northerly winds associated with high-pressure systems ([Appendini et al., 2018](#)) and commonly originate at the Rocky Mountains ([Appendini et al., 2018](#)). These fronts, locally known as *nortes*, generate strong winds ($> 10 \text{ ms}^{-1}$) and significant temperature drops, and are the cause of operational downtimes for shipping and offshore industrial activities ([Schultz et al., 1997](#)). In the northwestern region of the Gulf of Mexico they occur more frequently than tropical cyclones ([Huang and Li, 2020](#)), and despite being typically of lower energy, they significantly modulate nearshore hydrodynamics ([Needham et al., 2012](#); [Appendini et al., 2018](#)) and drive large cumulative coastal changes that threaten population and infrastructure ([Moeller et al., 1993](#)). The occurrence of cold fronts in the Gulf of Mexico is predicted to increase in a warmer climate ([Pérez et al., 2014](#)).

The nearshore or inner-shelf (depths of a few to tens of meters) constitutes a transition zone between the continental shelf and surf zone circulation. The Texas continental shelf break acts as a barrier to the transport of material due to strong bathymetric gradients, as planetary vorticity inhibits cross-bathymetric flows (e.g., [Cushman-Roisin and Beckers, 2011](#)). While substantial amounts of nutrients, larvae, sediment and pollutants are transported shoreward from deep waters, their fate in the coastal region is less

predictable due to the variability of inner-shelf circulation processes ([Lentz and Fewings, 2012](#); [Roth et al., 2017](#); [Huguenard et al., 2020](#)). Seasonal ([Romero-Centeno et al., 2003](#); [Dzwonkowski et al., 2011](#); [Zavala-Hidalgo et al., 2014](#); [Judt et al., 2016](#)) and interannual ([Fernandez-Partagas and Mooers, 1975](#); [Magaña et al., 2003](#)) wind-stress variations are considered the principal forcing for the dominance of cross-shelf or along-shelf mass transport in the Gulf of Mexico, but buoyant plumes ([Walker et al., 2005](#)) and surface gravity waves ([Lentz et al., 2008](#)) also play a significant forcing role. While hurricanes induce large wind forces that generate strong currents, less energetic but more frequent synoptic-scale cold fronts are capable of generating alongshore currents of up to 1 ms^{-1} ([Allende-Arandía et al., 2016](#)). And these currents modulate the inner-shelf circulation ([Judt et al., 2016](#)) and interact with large surface gravity waves induced by the fronts ([Huh et al., 1984](#); [Appendini et al., 2014](#)).

Along-shelf wind stresses drive the cross-shelf circulation through Ekman transport, which diminishes closer to the shore due to shallow depths and the influence of the coastal boundary ([Dzwonkowski et al., 2011](#); [Lentz and Fewings, 2012](#); [Huguenard et al., 2020](#)). The inner-shelf circulation is primarily wind-driven and the alongshore wind stress component determines the principal current direction ([Winant, 1980](#); [Nowlin et al., 2005](#)), although it can be modified by density gradients and coastline orientation ([Schultz et al., 1997](#); [Dzwonkowski et al., 2011](#); [Horwitz and Lentz, 2014](#)). Winds along the Texas-Louisiana shelf are typically upcoast in summer and downcoast in winter, yet interannual differences in water mass transport occur ([Thyng, 2019](#)). Strong continental shelf bathymetric gradients constrain the inner-shelf mass transport alongshore,

inhibiting cross-shelf exchange (Thyng and Hetland, 2018). In addition, the southern Texas coast presents regions of seasonal convergence of winds (Zavala-Hidalgo et al, 2014) that induce material aggregation in the inner-shelf of the Port Aransas area as a consequence of along-shelf circulation variability (Thyng and Hetland, 2017). Therefore, cold fronts significantly modulate the nearshore circulation (Needham and Keim, 2012) and cause large cumulative coastal changes that threaten population and infrastructure (Moeller et al., 1993).

1.2 Research objectives and thesis outline

The primary purpose of this study is to gain a better understanding on the role of episodic synoptic-scale cold fronts in the inner-shelf circulation along 200km of coast in the northwestern Gulf of Mexico based on field measurements collected between November 2016 to October 2018. Specifically, this work aims to: 1) define a methodology to identify and categorize cold fronts; 2) analyze the vertical structure of the subtidal flow during the passage of cold fronts of different duration and intensity; 3) determine the spatial variability of currents associated with different cold fronts; and 4) quantify the relevant terms in the inner-shelf along-shelf momentum budget during the passage of the cold fronts.

The structure of the thesis is outlined as follows:

Chapter 2. Describes the field site and presents the data-set and methodology used to quantify the spatio-temporal variability of nearshore currents.

Chapter 3. Presents results on the identification and categorization of cold fronts and detailed analysis of the vertical structure of the subtidal along-shelf flows during the passage of cold fronts of different duration and intensity.

Chapter 4. Presents results on the spatial variability of along-shelf currents induced by cold fronts of different duration and intensity, and quantifies the relevant terms in the inner-shelf along-shelf momentum budget during the passage of the fronts.

Chapter 5. Provides a summary of the main research findings.

Chapter 2

2 Nearshore measurements and analytical methods

2.1 Fiel site description and research background

The research area is located in the inner Texas-Louisiana shelf, between Port Aransas and South Padre Island, along the southern Texas coast, in the northwestern Gulf of Mexico ([Fig. 2.1](#)). This site is located in a microtidal regime, with maximum annual tidal ranges of 0.45 to 0.60 m, thus, the tidal forcing is relatively weak ([Morton and McGowen, 1980](#)). The continental shelf in the field site presents large bathymetric gradients that act as a boundary for the cross-shelf mass exchange between the outer and inner regions ([Thyng and Hetland, 2018](#)). Particularly, inner-shelf gradients from the shoreface to the 100-m isobath varies from 0.5 m km^{-1} in Galveston to 1.8 m km^{-1} in South Padre Island ([Rodriguez et al., 2001](#)). Hence, the shelf break serves as a barrier between different dynamical regions of the inner and outer shelf, partially inhibiting the cross-shelf flow exchange ([Thyng and Hetland, 2018](#)). For these reasons, the inner and outer regions of the shelf present distinct dominant forcing mechanisms, and the interactions between these regions are often limited ([Nowlin et al., 2005](#)).

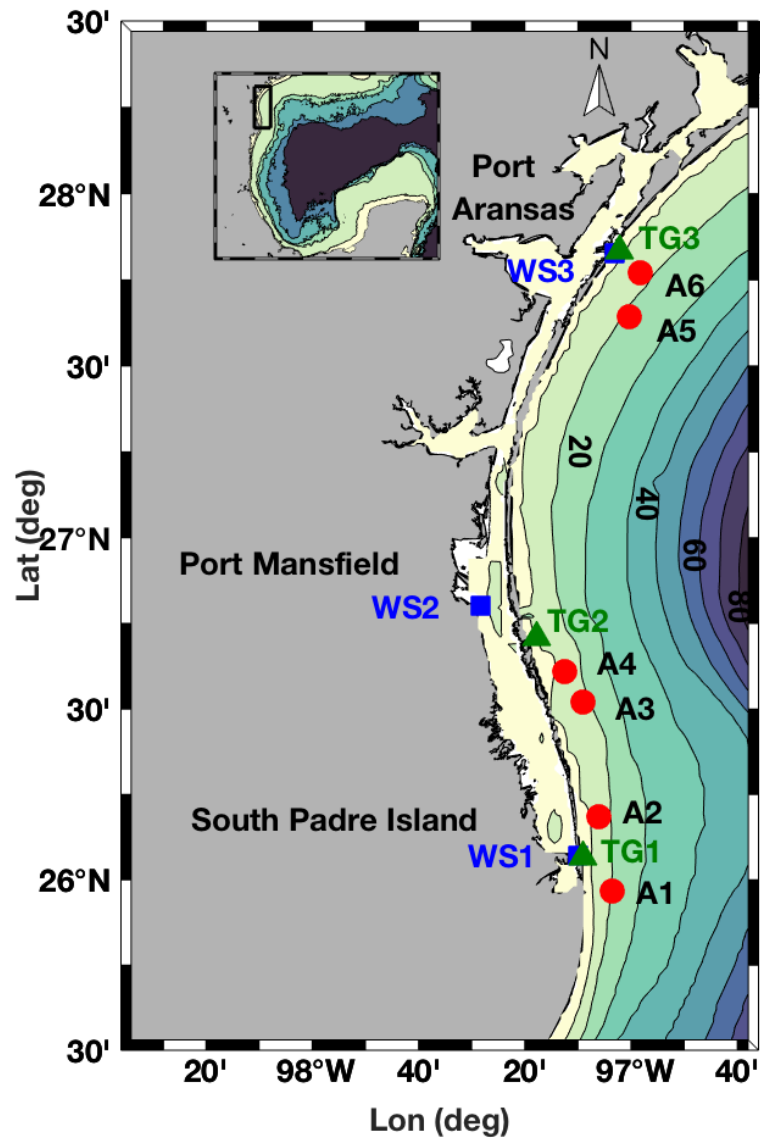


Fig. 2.1. Instrumental set-up in the southern Texas coast, northwestern Gulf of Mexico. The alongshore array of moored ADCPs is presented in red circles near to the 20-m isobath (A1 to A6, south to north). Selected NOAA weather stations (WS) and tide gauges (TG) are shown in blue squares and green triangles, respectively.

Seaward advected river plumes induce baroclinically-driven flows that can enhance cross-shelf transport in summer ([Thyng and Hetland, 2018](#)), but overall, the wind forcing is considered the dominant mechanism for inner-shelf circulation ([Nowlin et al., 1998](#)). In the field site, moderate southeast winds prevail from spring to fall, but episodic synoptic-scale cold fronts induce strong northerly winds that alter wave characteristics and current directions during the winter months ([Lohse, 1955](#)).

While along-shelf wind stresses and currents are highly-correlated in the inner-shelf ([Nowlin et al., 1998](#)), flow directions in the inner-shelf also depend on the coastline orientation relative to the dominant wind forcing. During the cold front season from October to April, along-shelf flow directions are expected to vary considerably in the southern Texas coast ([Huh et al., 1984](#)). Despite the dominance of upcoast mass transport dominates most of the year, cold fronts can reverse surface currents towards Mexico ([Thyng and Hetland, 2018](#)). Generally, downcoast currents dominate the upper and central Texas coast, while upcoast currents prevail along the southern coast; and a convergence zone is identified between Port Isabel and Port Aransas ([Cochrane and Kelly, 1986](#)). Moreover,, material aggregation has been found to occur in the inner-shelf of the Port Aransas area ([Thyng and Hetland, 2017](#)). The southern Texas coast presents regions of seasonal convergence of winds ([Zavala-Hidalgo et al, 2014](#)), and this is expected to influence the along-shelf circulation.

2.2 Currents measurements

Six upward-looking ADCPs (Acoustic Doppler Current Profilers; Nortek Aquadopp type), were moored between November 2016 and October 2018 at depths of 17–22 m covering ~200 km of the southern Texas coast (see locations from A1 to A6 south to north in [Fig. 2.1](#)) during the CIGOM project (Consortio de Investigación del Golfo de México; <https://cigom.org/>). East-west, north-south, and up-down velocity components were collected across 26 vertical bins of 0.75-1 m of resolution, with a blanking distance of 0.4 m from the seabed. The sampling rate was 1 Hz over a period of 2 min, and averaged profiles were obtained every 20 min.

Data recorded with larger instrument tilting angles than 20° were disregarded, and unreliable measurements were removed applying quality control thresholds (< 20 counts of return amplitudes). The uppermost 10% of the water column (~1.85 m) was discarded due to side-lobe interference with the water surface (< 0.60 of correlation between along-shelf current and wind speed). Therefore, average velocities for the surface and bottom layers excluded the uppermost 1.85 m and lowermost 0.4 m of the water column, respectively.

Raw current measurements were filtered applying the Lanczos low-pass filter with a cutoff frequency of 1/30 cph to eliminate high-frequency signals ([Emery and Thomson 2004](#)). The filtering procedure effectively removed most tidal and inertial motions, since

the inertial period in the region varied from 25 h in the north (A6) to 28 h in the south (A1).

Fig. 2.2 presents an example of raw depth-averaged and depth-varying along-shelf ($\bar{v}$) and cross-shelf ($\bar{u}$) flows for the southernmost A1 instrument off South Padre Island. This figure shows that specific events reversed along-shelf currents downcoast (negative V) throughout the entire water column, particularly in early and middle March 2017. Instead, a period of dominant upcoast currents (positive V) was observed in mid-to-late March 2017; and cross-shelf currents were comparatively weaker than the along-shelf. This analysis will be extended for all moorings in Chapters 3 and 4 to determine the processes that induce current reversals and understand whether this pattern is general for the southern Texas coast or rather unique for the southernmost location.

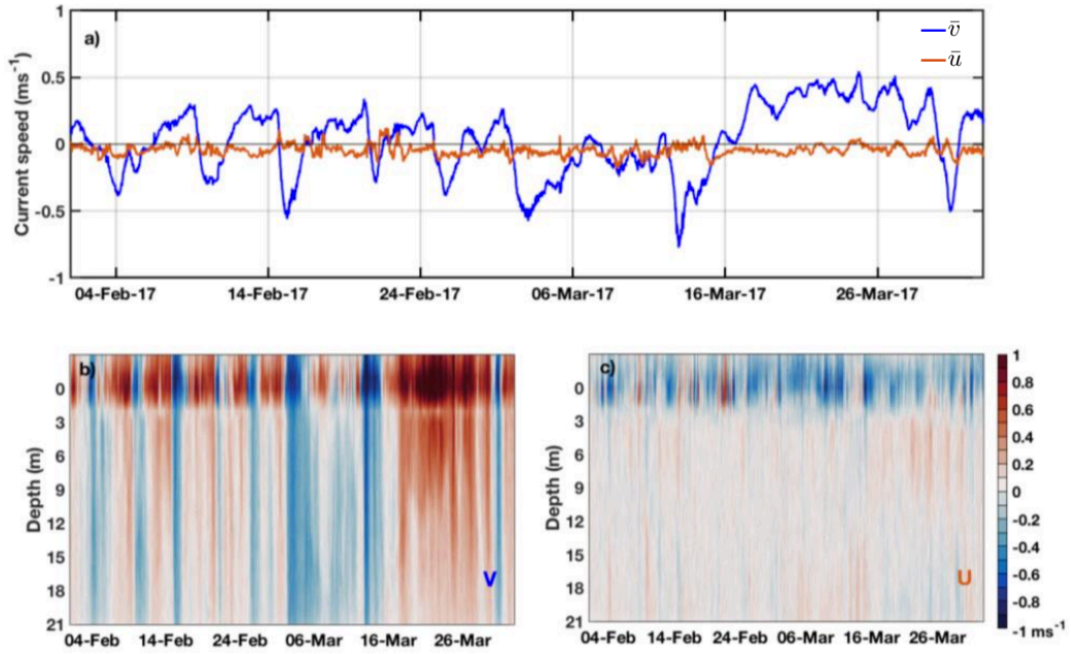


Fig. 2.2. Time series of raw measurements at A1 (southernmost site) from February to March 2017; (a) depth-averaged along-shelf ($\bar{v}$) and cross-shelf ($\bar{u}$) currents; (b) and (c) depth-varying along-shelf (V) and cross-shelf (U) currents, respectively. Negative V and U correspond to downcoast and oncoast flows, respectively. Depths are referred from the mean water level. Note side-lobbing effects in the uppermost water column.

2.3 Weather data

Hourly data of wind speed and direction and atmospheric air pressure were acquired from the WS1, WS2 and WS3 NOAA weather station (see Fig. 2.1). The wind data were filtered applying the Lanczos low-pass filter with a cut-off period of 30 h and converted to the oceanographic convention (direction toward which the wind is blowing). The cross-shelf and along-shelf wind stress components were calculated with Eq (2.1). An example of the time-series of wind speeds and directions for fifteen days in March 2017 is presented in Fig. 2.3 for WS2, the closest station to A4 in the central site (Fig. 2.1).

$$(\tau_x, \tau_y) = \rho_a C_D |\mathbf{W}| (u_w, v_w), \quad (2.1)$$

being ρ_a air density (1.2 kgm^{-3}), C_D wind drag coefficient, u_w and v_w cross-shore and alongshore wind velocity components measured at 10 m elevation and W wind speed. C_D was equal to $(0.49 + 0.065 U)10^{-3}$ and 1.14×10^{-3} for wind speeds greater or equal and lesser than 10 ms^{-1} (Large and Pond, 1981), respectively.

Synoptic weather maps were obtained from the ERA-Interim global atmospheric reanalysis dataset of ECMWF (European Centre for Medium-Range Weather Forecasts; <https://www.ecmwf.int/>). Six-hourly data of zonal and meridional wind components were acquired together with mean sea-level pressure (MSLP) over a grid of 0.75° of resolution for a region of interest from 15° to 50° N and -85° to -100° W.

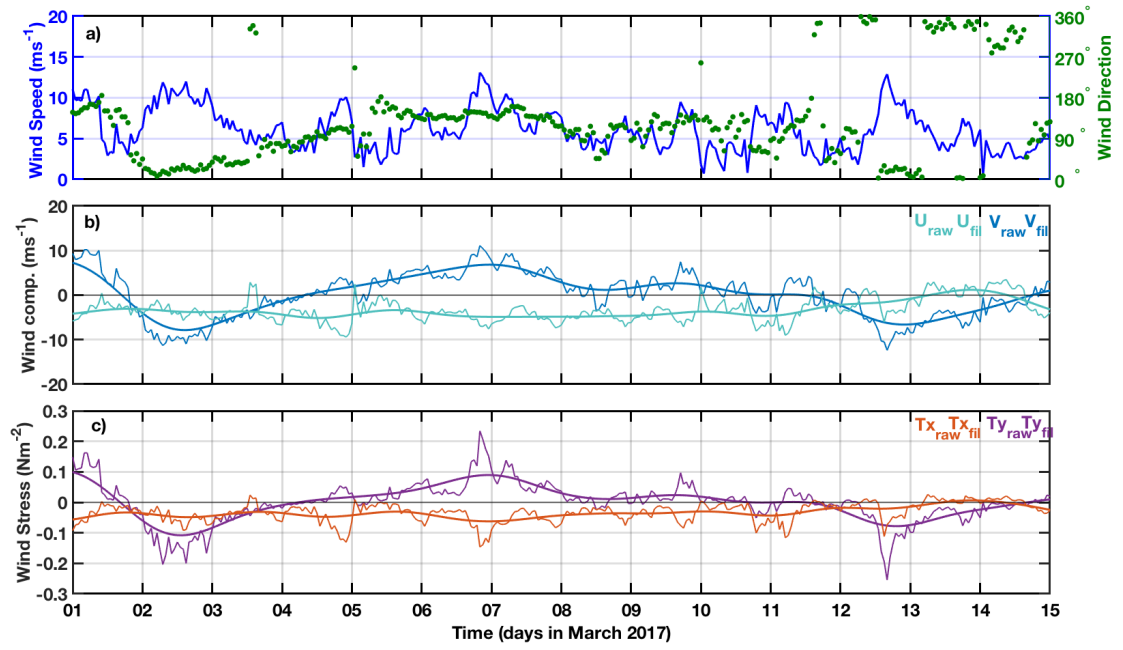


Fig. 2.3. a) Time-series from 1-15 March 2017 of: (a) Hourly wind speeds and wind directions from weather station WS2 (closest to A4 in the central site); (b) Raw (thin lines) and filtered (thick lines) wind data for along-shelf (V) and cross-shelf (U) flows; (c) Raw and filtered along-shelf (τ_y) and cross-shelf (τ_x) wind-stress components. Note that negative V and U correspond to downcoast and oncoast wind components, respectively.

Chapter 3

3 Nearshore current variations during the passage of cold fronts ¹

Yearly-average along-shelf winds were predominantly upcoast over the last two decades, but large seasonal fluctuations existed. This study provides an example of how the passage of episodic cold fronts generally induce the reversing of along-shelf flows downcoast on the southern Texas coast. A total of 819 cold fronts of 4 days of average duration were identified between 1984 and 2018, and the vertical structure of the flow was analyzed for 38 cold fronts between November 2016 and October 2018 at a location 10 km offshore of Port Aransas. Cold fronts were identified based on local wind speeds and directions and synoptic-scale mean sea-level pressure differences, and then categorized through hierarchical clustering. Theoretical flow expectation for unstratified conditions suggested that the flow response was primarily controlled by the wind forcing during the passage of cold fronts. Detailed analysis on the vertical profile of the flow demonstrated significant time-lag differences, mainly related to the front intensity and duration. Strongest downcoast flows of -0.5 ms^{-1} encompassing the entire water column (18 m depth) were associated with individual fronts of high intensity (τ_y of $\sim -0.15 \text{ Nm}^{-2}$) and long duration (at least 4 days). The most common fronts were individual of low intensity (τ_y of $\sim -0.05 \text{ Nm}^{-2}$) and short duration (up to 2 days), and induced relatively weak downcoast currents of up to -0.2 ms^{-1} , and in many cases, these were unable to completely reverse the flow downcoast. This study highlights the relevant role of episodic cold fronts in reversing and intensifying inner-shelf currents on the southern Texas coast, and emphasizes differences in the flow response related to cold front characteristics.

3.1 Introduction

¹This chapter is based on the article published in *Continental Shelf Research* 2022: Romero-

In the northwestern Gulf of Mexico, cold fronts occur more frequently than tropical cyclones, and significantly modulate nearshore hydrodynamics ([Needham et al., 2012](#); [Appendini et al., 2018](#)) and induce large cumulative coastal change that threaten population and infrastructure ([Moeller et al., 1993](#)).

In the past, cold fronts have been primarily identified using local atmospheric data ([Frankenfield, 1917](#); [Mosiño, 1964](#)) and based on resultant air temperature differences ([Hill, 1969](#); [Mecikalski and Tilley, 1992](#); [Reding, 1992](#); [Schultz et al., 1998](#)), cold air mass trajectories and rainfall patterns ([Willett, 1934](#); [Dallavalle and Bosart, 1975](#); [Klaus, 1973](#); [Mecikalski and Tilley, 1992](#)). More recently, thresholds were set to identify these fronts based on the wind characteristics and induced rainfall and air temperature drops ([Pérez et al., 2014](#)). Moreover, several cold front types were defined based on their intensity and wave generation area ([Appendini et al., 2018](#)). Nevertheless, little is still known about inner-shelf vertical flow variations induced by cold fronts of different duration and intensity.

Along-shelf wind stresses drive the cross-shelf circulation through Ekman transport, which diminishes closer to the shore due to shallow depths and the influence of the coastal boundary ([Dzwonkowski et al., 2011](#); [Lentz and Fewings, 2012](#); [Huguenard et al., 2020](#)). Thus, the inner-shelf circulation is primarily wind-driven and the alongshore component determines the principal current direction ([Winant, 1980](#); [Nowlin et al., 2005](#)). In the Texas-Louisiana shelf, strong continental shelf bathymetric gradients constrain the inner-shelf mass transport alongshore, inhibiting cross-shelf exchange ([Thyng and Hetland, 2018](#)). Winds along this shelf are typically upcoast in summer and

downcoast in winter, yet interannual differences in water mass transport occur (Thyng, 2019). The southwestern Gulf of Mexico presents regions of seasonal convergence of winds (Zavala-Hidalgo et al, 2014). In particular, the inner-shelf Port Aransas area presents locations of material aggregation, as a consequence of variations in the along-shelf circulation (Thyng and Hetland, 2017). Moreover, in this region, cold fronts are considered capable of reversing inner-shelf surface currents (Zavala-Hidalgo et al, 2014; Allende-Arandía et al., 2016). The amount of research on inner-shelf circulation patterns is fairly limited in the southwestern Gulf of Mexico compared to other locations (e.g. Rivas, 2017; Thyng and Hetland, 2018). This research contributes to the understanding of the role of episodic synoptic-scale cold fronts in the inner-shelf circulation along the southern Texas coast.

The overall goal of this Chapter is to examine the vertical structure of subtidal along-shelf flows during the passage of cold fronts of different duration and magnitude. This research contributes to the understanding of the role of episodic synoptic-scale cold fronts in the inner-shelf circulation on this coast.

3.2 Methods

Data gathered over a nearly 2-year period (2016 to 2018) were used to analyze current structure variations associated with the wind forcing during the passage of cold fronts. Hydrodynamic measurements collected with the ADCP A6 located close to the 20-m isobath offshore from Port Aransas Pass were used (Fig. 2.1). Concurrently, local meteorological observations acquired from the WS3 National Data Buoy Center weather station, and synoptic weather maps from the ERA-Interim were used.

The ADCP A6 measurements from November 2016 to October 2018 presented a few data gaps due to technical issues or the inability to replace instrument batteries during adverse weather conditions. The velocity components were rotated 45° clockwise to align them with the northeast-southwest orientation of the ~20-m isobath. A right-handed coordinate system was applied to the rotated along-shelf and cross-shelf currents; positive x (u) and y (v) indicating offcoast and upcoast directions, respectively.

The WS3 weather station provided hourly data of wind speeds and directions, atmospheric air pressures and air temperatures for the two-year period (2016 to 2018). Gaps in the time-series of WS3 were filled with the closest available node from ERA-Interim, which presented wind speed and direction correlation coefficients of 0.80 and 0.60, respectively. In addition, time sequences of maps of combined MSLP and wind data were elaborated with the ERA-Interim dataset, before, during, and after the passage of a cold front. Fig. 3.4 presents an example for the passage of a cold front in late January 2017. Available MSLP data from 1984 to 2018 will be later used to determine spatial MSLP differences for the identification of cold fronts.

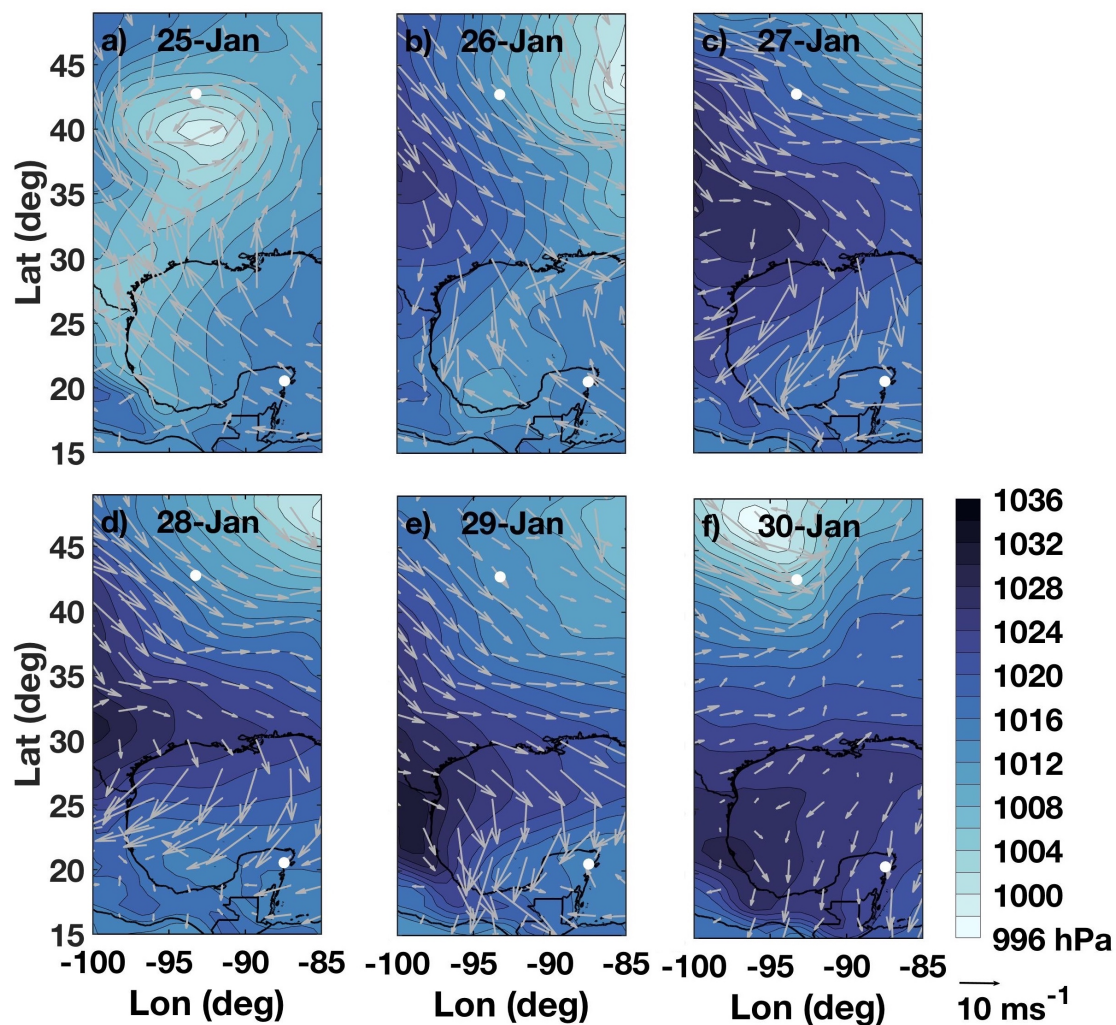


Fig. 3.4. Temporal sequence of the spatial distribution of mean sea-level pressure (colorbar) and wind speeds and directions (arrows) before (a), during (b, c, d, e), and after (f) the passage of cold front #9 in late January 2017. The dots represent the locations between which pressure differences were calculated for the cold front identification.

3.3 Cold front identification and categorization

A method to identify cold fronts was developed based on local wind speeds and directions and spatial synoptic mean sea-level pressure differences ($\text{MSLP}_{\text{Diff}}$), as being the main forcing parameters for front generation (e.g. [Appendini et al., 2018](#)). A cold front was defined as an event of wind blowing at least 24 h from the north (range of 300° to 30°) with sustained wind speeds of $\geq 5 \text{ ms}^{-1}$ for a minimum period of 15 h during which $\text{MSLP}_{\text{Diff}}$ between Iowa (-93.25°W , 42.75°N in USA) and Quintana Roo (-87.94°W , 20.51°N in Mexico) were $\geq 6 \text{ hPa}$. These locations were defined as sites of maximum and minimum MSLP variance calculated through the first mode (explains 55% of MSLP variance) of an empirical orthogonal function (EOF) decomposition of spatial MSLP anomalies from 1984 to 2018 ([Fig. 3.5](#)). Cold fronts ended when prevailing wind directions changed, and a minimum period of 15 h was established to differentiate consecutive events.

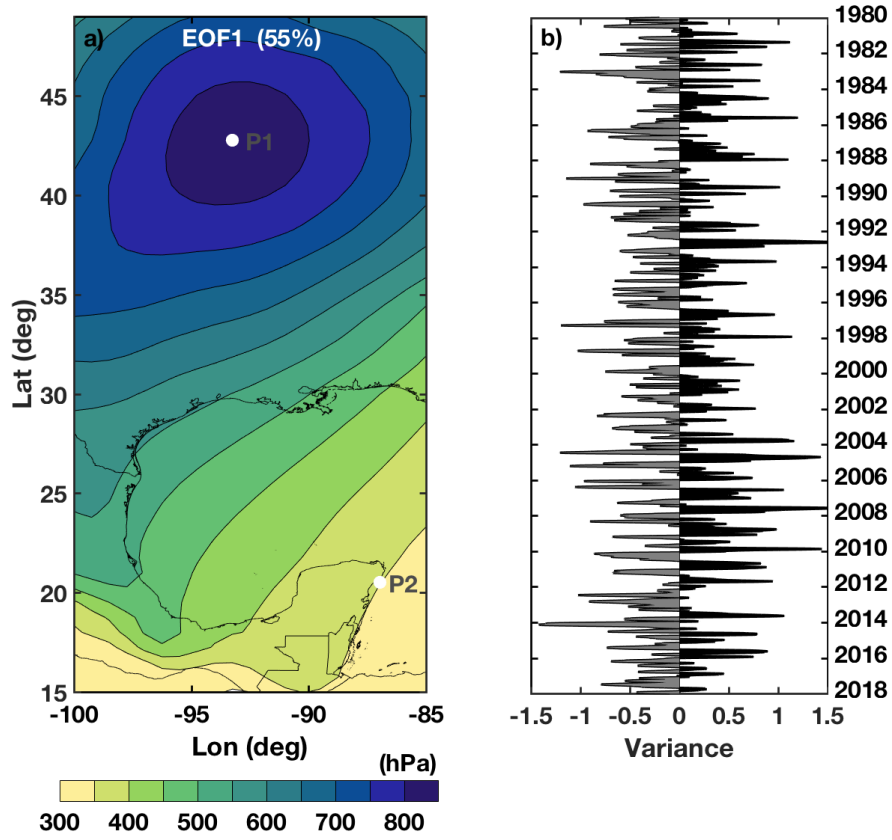


Fig. 3.5. Spatial (a) and temporal (b) components of the first EOF mode (55% of variance) for MSLP anomalies from 1984 to 2018. The dots in Iowa (P1) and Quintana Roo (P2) correspond to locations of maximum and minimum MSLP variance for the time-series.

An illustrative example of wind and flow conditions before, during, and after the passing of a cold front (#9 in Fig. 3.9) is presented in Fig. 3.6. The shifting of the wind direction towards the south (and then north) marks the starting (ending) time of the front, and that time difference is the front duration, t_f . This front started on January 25th and ended on January 30th; thus, t_f was 5 days (Fig. 3.6a, f). The period of time at which the wind speed $\geq 5 \text{ ms}^{-1}$ was represented by t_w , and it was 3 days (Fig. 3.6a). In addition, it presented a MSLP difference ($MSLP_{diff}$) of 8 hPa (Fig. 3.6c).

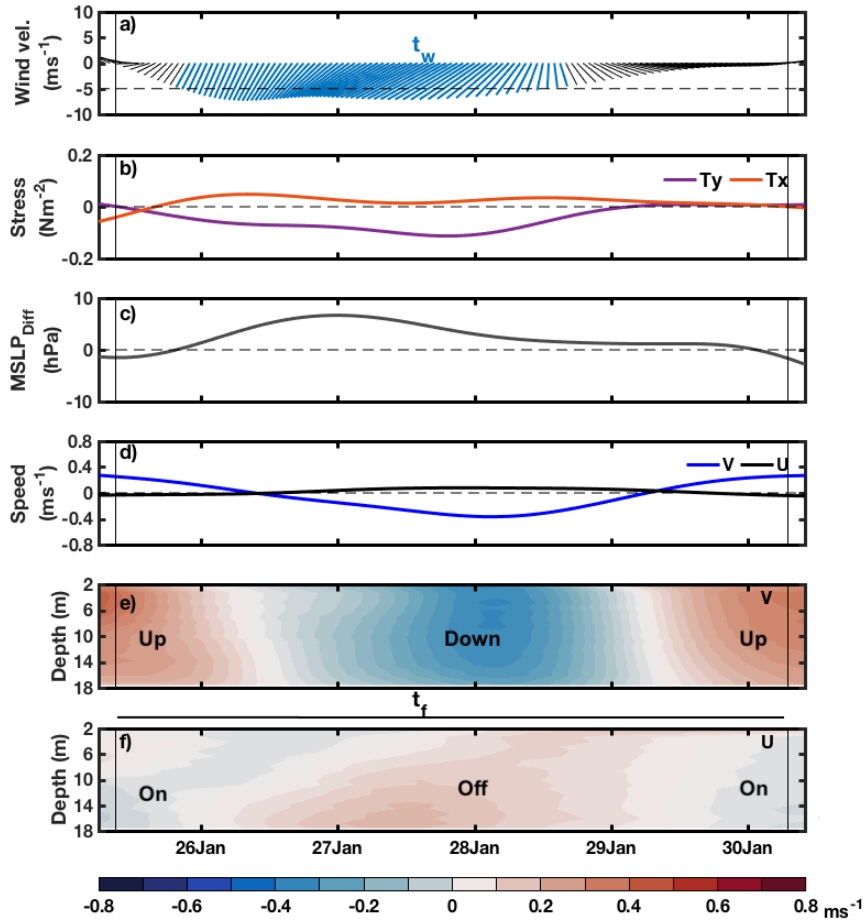


Fig. 3.6. Time-series of wind and flow characteristics for cold front #9 at the end of January 2017: a) wind velocity vectors (oceanographic convention); b) along-shelf (τ_y) and cross-shelf (τ_x) wind-stress components; c) mean sea level pressure differences ($MSLP_{diff}$), d) depth-averaged along-shelf ($\bar{v}$) and cross-shelf ($\bar{u}$) currents; and e) depth-varying along-shelf (V) and f) cross-shelf (U) velocities. Positive indicate upcoast (up) and offcoast (off) velocities. The vertical lines denote the front starting and ending times.

During the passing of the front, τ_y became negative (Fig. 3.6b) and the currents reversed downcoast, in the entire water column (Fig. 3.6d, e). Maximum downcoast current speeds of -0.6 ms^{-1} occurred in phase with maximum τ_y of -0.1 Nm^{-2} . Cross-shelf currents were comparatively weak ($< 0.2 \text{ ms}^{-1}$) and oscillated oncoast and offcoast depending on wind direction changes (Fig. 3.6f).

The identified cold fronts were assembled into several groups based on their duration (t_f), sustained wind speed duration (t_w), and MSLP differences ($MSLP_{diff}$) using a multi-dimensional scaling (MDS) analysis. This method classifies objects in full-dimensional space and represents them in fewer dimensions preserving the standardized distance relationships among the samples accurately (e.g. [Clarke, 1993](#)). The statistical significance of the cluster formation was verified using the cophenetic correlation coefficient (cop ; value of 1 is perfect match between cluster solution and input data) and a stress criterion (str ; the closer to zero the better the multidimensional is represented) was used to evaluate the dimensionality obtained from the MDS.

3.4 Results

3.4.1 Temporal wind-stress and current variations

Along-shelf wind-stress (τ_y) direction changes were examined over 35-years, from 1984 to 2018, to determine periods of dominant upcoast or downcoast winds at a seasonal scale. An average of 23 ± 3 cold fronts occurred per year, but large interannual variations existed (Fig. 3.7b). Yearly-averaged τ_y indicated significant interannual differences, with an overall dominance of upcoast winds (positive τ_y) over the past two decades (Fig. 3.7d). A seasonal signal was present in the directionality of τ_y , downcoast dominance (negative) in winter (December to February) and sometimes in spring (March to May), and upcoast (positive) in summer (June to August) and autumn (September to November) (Fig. 3.7c). The 2016–2018 period (tinted boxes in Fig. 3.7) showed net annual dominance of upcoast winds (Fig. 3.7d), and the seasonal reversing downcoast in winter (Fig. 3.7c).

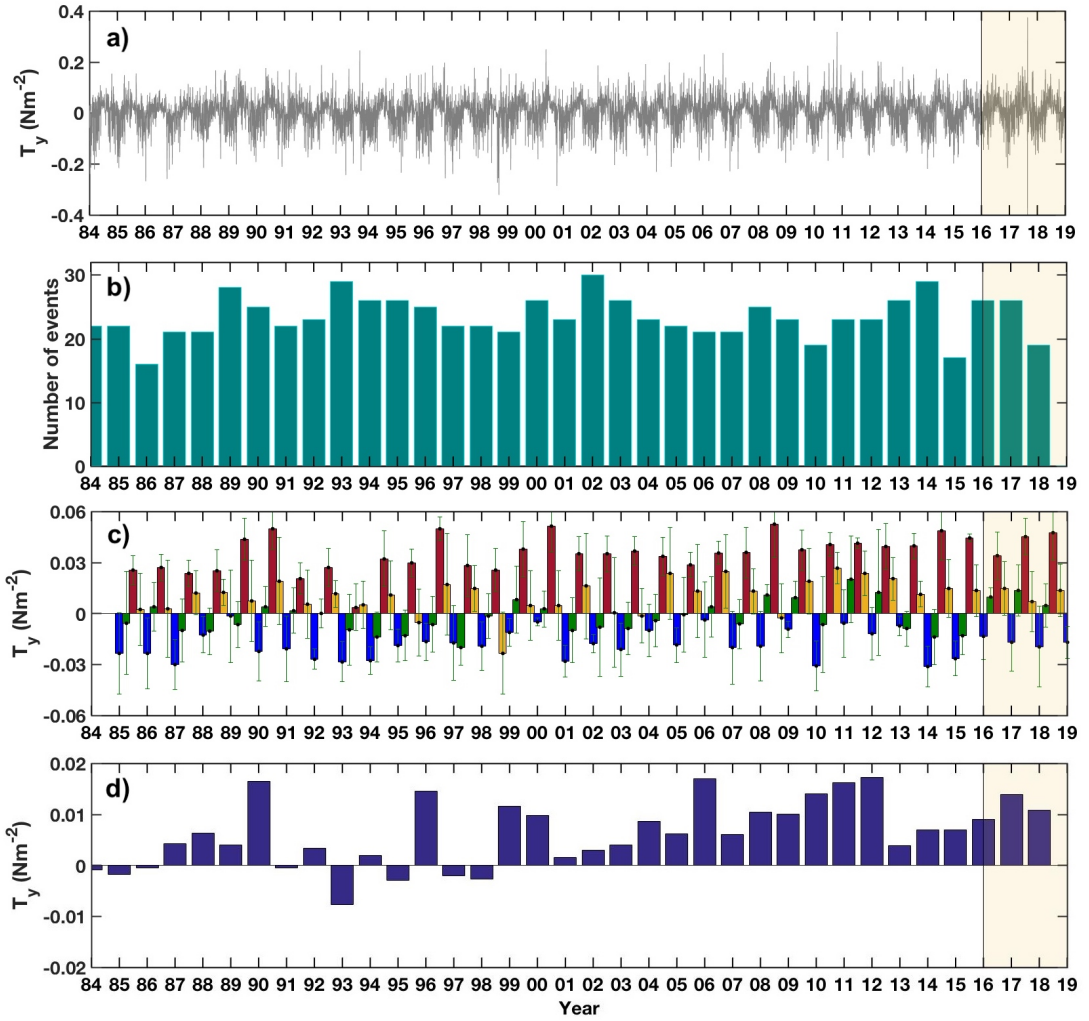


Fig. 3.7. Time-series from 1984 to 2018 of: (a) hourly along-shelf wind-stresses (τ_y); (b) number of cold fronts per year; (c) seasonally-averaged τ_y (winter, blue; spring, green; summer, red; autumn, orange); and (d) annually-averaged τ_y . The period of interest from 2016 to 2018 is highlighted with tinted boxes. Positive (negative) τ_y indicate upcoast (downcoast) winds.

3.4.2 Cold front categorization

3.4.2.1 Historical: 1984 to 2018

A total of 819 cold fronts were identified using the available historical weather data from 1984 to 2018, which presented average durations ($\overline{t_f}$) of 4 days, average sustained wind speed durations ($\overline{t_w}$) of 3 days and average MSLP differences ($\overline{MSLP_{diff}}$) of 15 hPa (Table 3.1). *Sequential* events were defined as consecutive cold fronts with more than 12 h in between. In the historical data-set cold fronts were assembled as *sequential* (more than one event) and *individual* (single event) of high, moderate and low impact at a Euclidean distance of 4.3, and with an adequate cluster solution ($str = 0.01$; $c = 0.88$) (Table 3.1; Fig. 3.8a, c).

Table 3.1. Characteristics of the assembled historical cold fronts (CF) from 1984 to 2018: event duration (t_f), sustained wind speed duration (t_w), mean sea level pressure differences ($MSLP_{diff}$) and % of occurrence.

CF Group		t_f (days)		t_w (days)		$MSLP_{diff}$ (hPa)		Occurrence (%)
		mean	std	mean	std	mean	std	
Sequential (S)	High (SH)	22	2	14	3	26	6	0.5
	Moderate (SM)	11	2	8	2	25	6	6.5
	Low (SL)	6	2	4	2	24	5	15
Individual (I)	High (IH)	4	1	3	1	17	4	20
	Low (IL)	2	1	2	1	11	3	58
CF average 1984-2018		4	3	3	2	15	7	

Sequential (S) cold fronts were 22 % of the total and presented large $\text{MSLP}_{\text{diff}}$ of 24–26 hPa (Table 3.1). Among them, *sequential-high* (SH) corresponded to 0.5 % and consisted of more than 5 consecutive events, hence, these were highly persistent, t_f of 22 days (more than five times the historical average, $\bar{t}_f$, of 4 days) with t_w of 14 days (nearly five times the historical average, $\bar{t}_w$, of 3 days) (Table 3.1). A total of 6.5 % were *sequential-moderate* (SM), consisted of up to 5 consecutive fronts, and lasted t_f of 11 days ($t_f \sim 3 \bar{t}_f$) with t_w of 8 days ($t_w \sim 3 \bar{t}_w$), and 15 % were *sequential-low* (SL), formed by 2 fronts, and had t_f of 6 days ($t_f \sim 1.5 \bar{t}_f$) and t_w of 4 days ($t_w \sim 1.5 \bar{t}_w$) (Table 3.1).

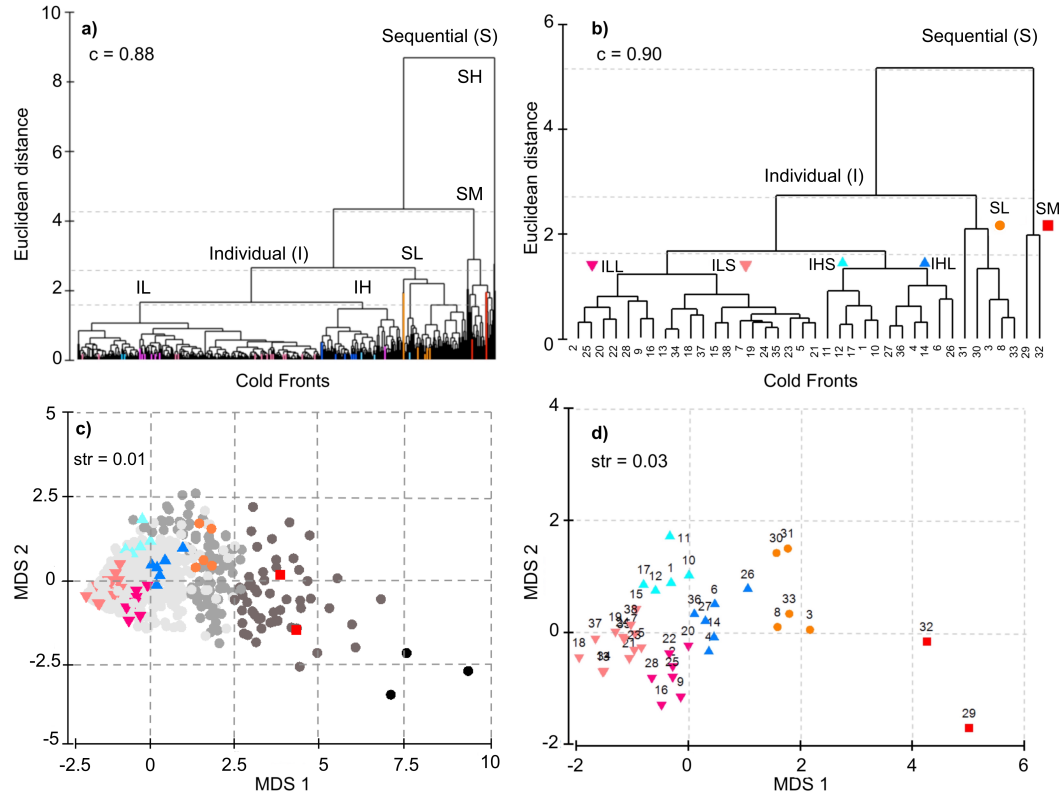


Fig. 3.8. Dendrograms of (a) historical 819 cold fronts (CF) in gray, and (b) 38 CFs from 2016 to 2018; and their respective MDS ordinations in (c) and (d). The colored lines in (a) correspond to the CFs represented in (b). Dark to light gray dots in (c) refer to the historical SH, SM, SL, IH and IL, respectively.

A total of 78 % of the fronts were *individual* (I), among which 20 % were *individual-high* (IH) with $MSLP_{diff}$ of 17 hPa and t_f of 4 days ($t_f = \bar{t}_f$) and t_w of 3 days ($t_w = \bar{t}_w$) and 58 % were *individual-low* (IL) with $MSLP_{diff}$ of 11 hPa and t_f and t_w of 2 days (both below average) (Table 3.1; Fig. 3.8a, c).

3.4.2.2 Recent: 2016 to 2018

A total of 38 cold fronts occurred from November 2016 to October 2018, and presented similar characteristics to the historical average, $\bar{t}_f$ of 4 days, $\bar{t}_w$ of 2 days and $\overline{MSLP_{diff}}$

of 16 hPa. Among these, 21 fronts occurred between early-November 2016 to early-May 2017, and the other 17 fronts from mid-October 2017 to early-April 2018. The fronts were divided as *sequential* (18 %; $MSLP_{diff} \sim 25$ hPa) or *individual* (82 %; $MSLP_{diff}$ 10–21 hPa) at a Euclidian distance of 5.1 (Fig. 3.8b). A total of 5 % were *sequential-moderate* (SM; ■), up to 5 consecutive events, with t_f of 14 days ($3\bar{t}_f$) and t_w of 7 days ($3\bar{t}_w$) (Table 3.2; Fig. 3.8b, d). And 13% were *sequential-low* (SL; ●), up to 2 consecutive events, with t_f of 7 days ($1.5\bar{t}_f$) and t_w of 4 days ($1.5\bar{t}_w$) (Fig. 3.8a, c).

Individual (I) fronts were grouped as *individual-high* (IH ▲; 29%) and *individual-low* (IL ▼; 53%) (Fig. 3.8b, d; Table 3.2), of larger and smaller $MSLP_{diff}$ of 19–21 and 10 hPa, respectively. These groups were further subdivided as *long* (IHL and ILL; ▲, ▼) and *short* (IHS and ILS; ▲, ▼), which presented t_f of 4 days) and t_w of 2-3 days ($\sim \bar{t}_w$), and t_f of 2 days ($\bar{t}_f$) and t_w of 1 day ($< \bar{t}_w$), respectively (Fig. 3.8b, d; Table 3.2). The most common cold fronts were ILS (34%, ▼), individual fronts of relatively low intensity and 2 days of duration.

Table 3.2. Characteristics of the grouped 38 cold fronts (CF) from November 2016 to October 2018: event duration (t_f), sustained wind speed duration (t_w), mean sea level pressure differences ($MSLP_{diff}$) and % of

CF Group		t_f (days)		t_w (days)		$MSLP_{diff}$ (hPa)		Occurrence (%)
		mean	std	mean	std	mean	std	
Sequential (S)	Moderate (SM) 	14	1	7	1	25	6	5
	Low(SL) 	7	2	4	1	26	4	13
Individual (I)	High-Long (IHL) 	4	1	3	1	19	3	16
	High-Short (IHS) 	2	1	1	1	21	3	13
	Low-Long (ILL) 	4	1	2	1	10	3	19
	Low-Short (ILS) 	2	1	1	0	10	3	34
CF average 2016-2018		4	3	2	2	16	7	

3.4.3 Vertical structure of the flow

3.4.3.1 Layer-averaged currents

Wind stress variations were related to current velocities at the surface, middle and bottom layers and to the average throughout the water column, to understand the effect of cold fronts on the vertical structure of the flow (Fig. 3.9). Cross-shelf velocities were generally weak $< 0.20 \text{ ms}^{-1}$, and the most frequent upcoast currents occurred in summer (i.e June 2017), up to 0.20 ms^{-1} , associated with maximum northward τ_y of 0.1 Nm^{-2} . Downcoast currents were up to -0.40 ms^{-1} over the winter and spring, when maximum southward τ_y of -0.1 Nm^{-2} occurred. All fronts induced the reversal of the current from upcoast (positive) to downcoast (negative). While downcoast currents were weaker near the bottom than at the surface, a similar vertical structure was preserved (Fig. 3.9). Specific intense and persistent events (i.e. cold front #27 in Fig. 3.9) presented

maximum downcoast surface flows of up to -0.80 ms^{-1} related to intensive downcoast winds, τ_y of -0.15 Nm^{-2} . Large periods of relatively strong downcoast currents of $\sim -0.40 \text{ ms}^{-1}$ were also observed due to the cumulative effect of dominant downcoast wind stress (i.e. January to early March 2018) (Fig. 3.9).

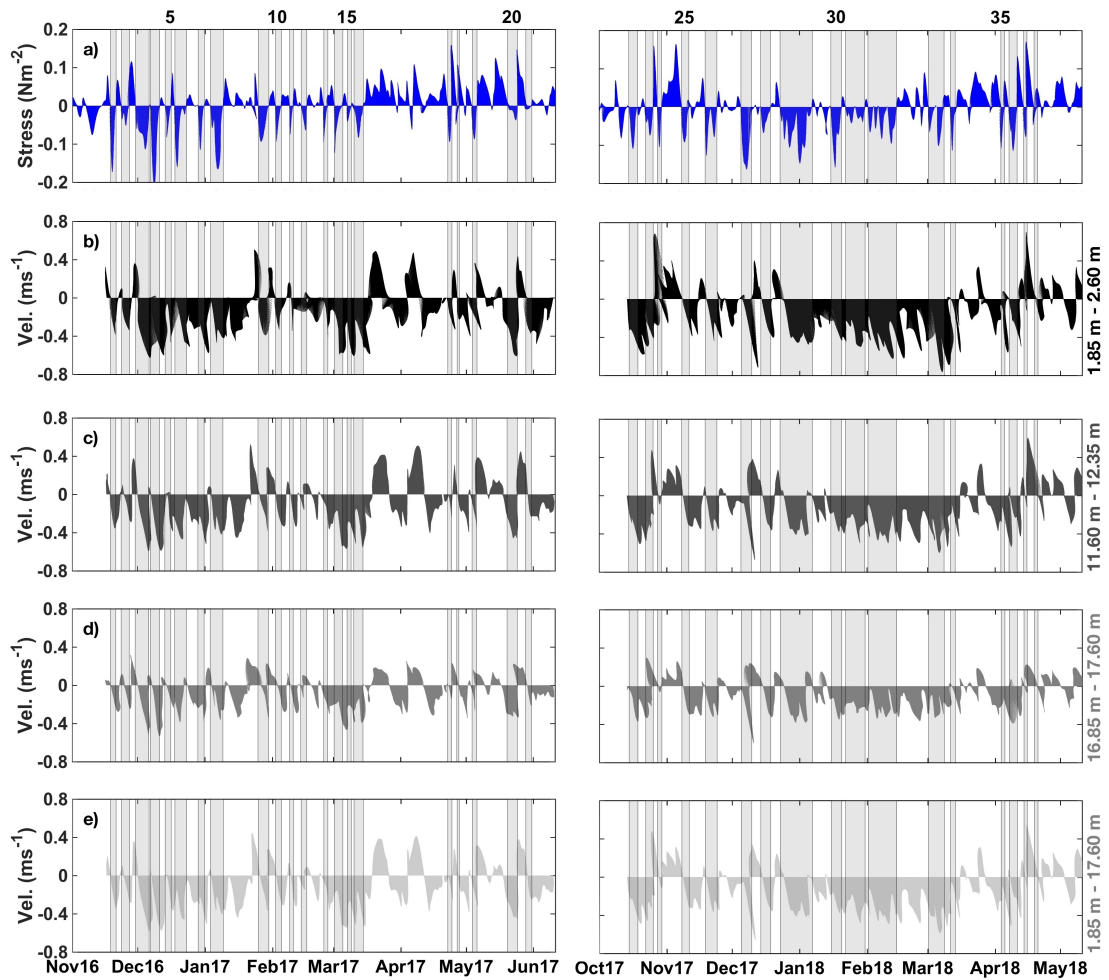


Fig. 3.9. Time-series from November 2016 to October 2018 of wind stress (a) and currents averaged at: (b) the surface layer, (c) mid-layer, (d) bottom layer, and (e) water column. The vertical shaded boxes represent each of the identified cold fronts (CF; numbered above) and described in Table 3.2.

3.4.3.2 Depth-varying currents

Along-shelf and cross-shelf velocity variations were analyzed throughout the water column in order to understand the effect of different cold front types on the structure of the flow. Representative fronts were selected from each group to analyze into detail vertical flow variations (Fig. 3.10, Fig. 3.11, Fig. 3.12). *Sequential* cold fronts SM (# 32; ■) and SL (# 33, ●) were represented in Fig. 3.10. τ_y attained significant fluctuations, and these fronts induced downcoast flows of up to -0.7 ms^{-1} and offcoast flows of 0.2 – 0.4 ms^{-1} up to $\sim 10 \text{ m}$ depth when $\tau_y \sim -0.05 \text{ Nm}^{-2}$ reached.

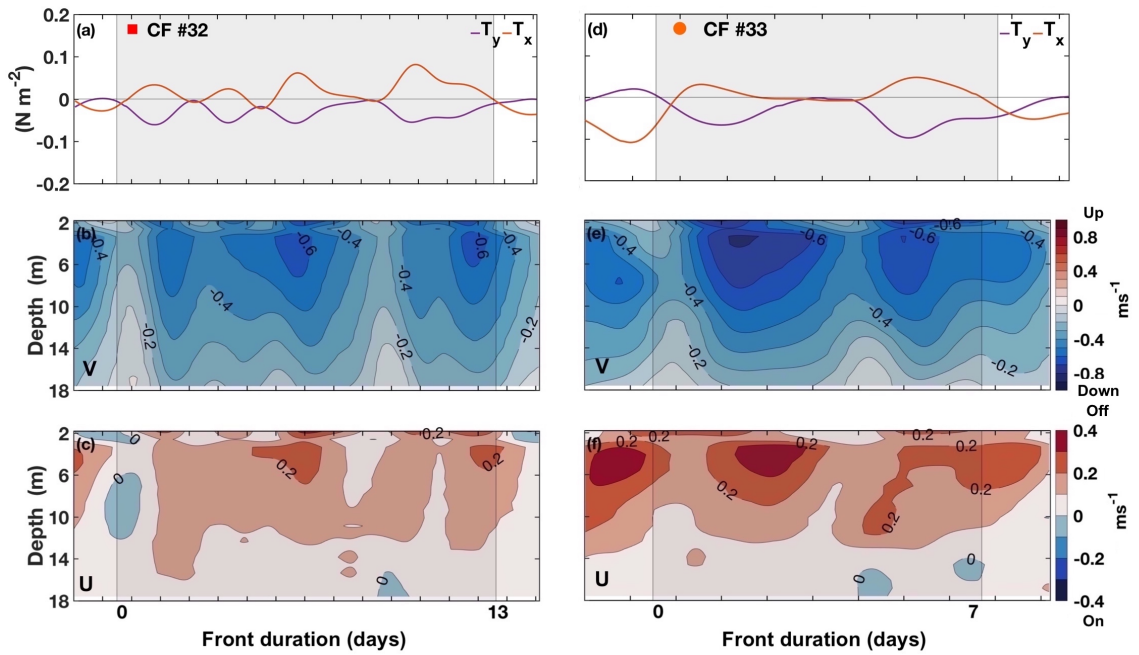


Fig. 3.10. Low-pass filtered (a, d) along-shelf and cross-shelf wind stress components (τ_y , τ_x) and vertically-varying (b, e) along-shelf and (c, f) cross-shelf current velocities for representative *sequential* (SM, ■; SL, ●) cold fronts. The shaded boxes indicate the front duration, and positive along-shelf and cross-shelf currents correspond to upcoast (up) and offcoast (off) flows.

Individual-high fronts of long (IHL, ▲) and short (IHS, ▲) duration are presented in Fig. 3.11. Intense and persistent winds (τ_y of up to -0.15 Nm^{-2}) during IHL induced strong downcoast flows of -up to -0.7 across the water column, compared to -0.3 ms^{-1} flows associated with IHS (Fig. 3.11). In both cases, cross-shelf currents were significantly weaker (0.1 to 0.2 ms^{-1}) and in some cases fluctuated oncoast/offcoast (Fig. 3.11).

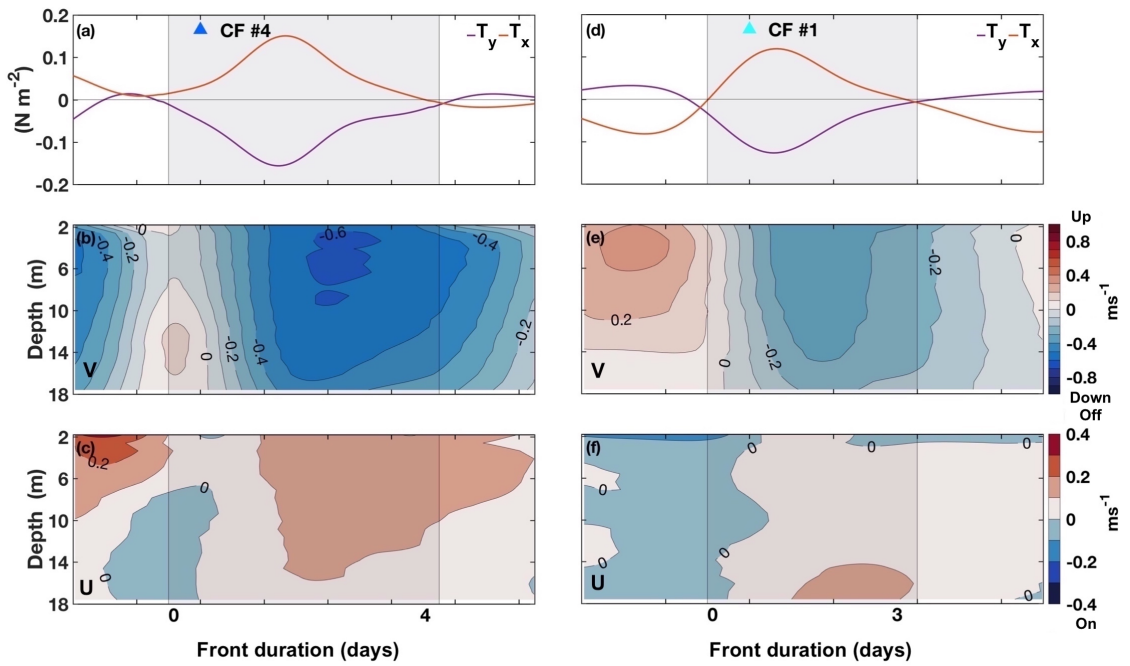


Fig. 3.11. Low-pass filtered (a, d) along-shelf and cross-shelf wind stress components (τ_y , τ_x) and vertically-varying (b, e) along-shelf and (c, f) cross-shelf current velocities for representative *individual-high* (▲) cold fronts. The shaded boxes indicate the front duration, and positive along-shelf and cross-shelf currents correspond to upcoast (up) and offcoast (off) flows.

Individual-low fronts of long (ILL, ▼) and short (ILS, ▼) duration are presented in Fig. 3.12. Overall, ILL lasted 4 days (Table 3.2) and presented downcoast currents of up to -0.4 ms^{-1} and cross-shelf currents (oncoast and offcoast) of $\sim 0.2 \text{ ms}^{-1}$ when $\tau_y - 0.05 \text{ Nm}^{-2}$ (Fig. 3.12a, b, c). ILS lasted 2 days (Table 3.2) and presented weaker downcoast and offcoast flows, typically of -0.2 ms^{-1} and 0.1 ms^{-1} , respectively (Fig. 3.12d, e, f). The latter were not always capable of reversing along-shelf currents (from upcoast to downcoast) (i.e. #18, 38; Fig. 3.9), and in most cases, the current direction reverted upcoast immediately after the passage of ILS fronts (Fig. 3.12).

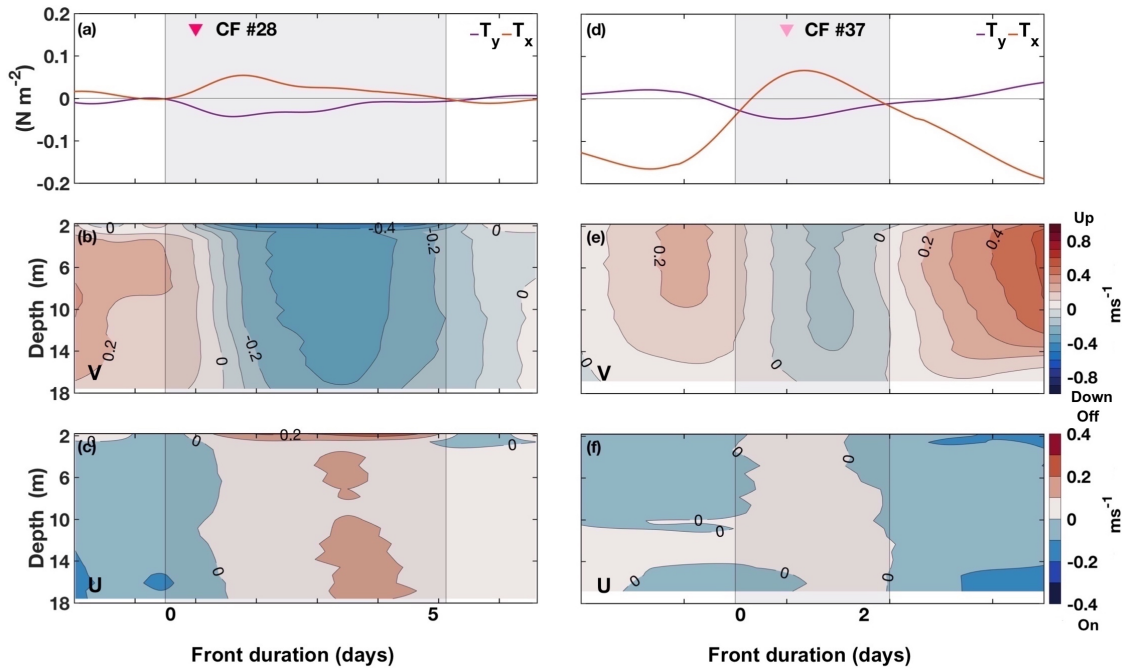


Fig. 3.12. Low-pass filtered (a, d) along-shelf and cross-shelf wind stress components (τ_y , τ_x) and vertically-varying (b, e) along-shelf and (c, f) cross-shelf current velocities for representative *individual-low* (▼) cold fronts. The shaded boxes indicate the front duration, and positive along-shelf and cross-shelf currents correspond to upcoast (up) and offcoast (off) flows.

3.5 Discussion

Yearly-average along-shelf winds were predominantly upcoast over the last two decades, but large seasonal fluctuations existed. Winds were typically upcoast in summer and fall, and sporadically intense and downcoast in spring and winter (Thyng, 2019). Along-shelf current reversals were observed over the study period (e.g. Thyng and Hetland, 2017; Rivas, 2017), and these were associated with the passage of sporadic cold fronts (Huh et al., 1984; Allende-Arandía et al., 2016; Kurczyn et al., 2020) that typically occur 20 times per year (Appendini et al., 2018). A total of 38 cold fronts were identified over the two-year period from 2016 to 2018, and the vertical flow structure was characterized based on field measurements. Interestingly, while most of the reversed the alongshore current downcoast ($\sim 80\%$), others were unable to completely reverse the flow throughout the entire water column or, instead, intensified the existing downcoast flow.

Two distinct cold front types were defined by the number of consecutive events: sequential (typically 2 to 5 events) and individual (1 event). While the number of events varied within subgroups of each type, the percentage of occurrence was consistent with historical results (Table 3.1 and Table 3.2). Wind and flow characteristics of these subgroups (Fig. 3.13a) were described in Fig. 3.13b and Fig. 3.13c, d, respectively. Group-averaged along-shelf and cross-shelf wind-stresses and flows were obtained averaging individual data from 24 h before to 72 h after the wind-stress maxima (defined as 0 h) (Fig. 3.13b and Fig. 3.13c, d, respectively).

Sequential fronts typically lasted 1 to 3 weeks (Schultz et al., 1998), were associated with mean sea-level pressures (MSLP) of ~ 1024 hPa and maximum τ_y of ~ -0.10 Nm^{-2} , and induced downcoast flows of ~ -0.5 ms^{-1} down to ~ 10 m depth (SM and SL; Fig. 3.13). *Individual* fronts were of high and low intensity (defined by MSLP differences) and presented durations of 2 and 4 days (short and long, respectively). The most intense flows of ~ -0.5 ms^{-1} throughout the entire water column (of 18 m) occurred during *individual* fronts of high intensity (MSLP of up to ~ 1018 hPa with maximum τ_y of ~ -0.15 Nm^{-2}) and long duration (IHL type; Fig. 3.13). *Individual fronts* of low intensity (ILL and ILS types; Fig. 3.13) presented stronger currents than those of higher intensity but shorter duration (IHS type; Fig. 3.13) and of similar MSLP (up to 1016 hPa). Hence, the duration of the front driven by moderate-to-strong wind-stresses (Lentz, 2001) had greater influence than MSLP on the magnitude of the flow (Shi et al., 2019). While IHS induced flows of ~ -0.3 ms^{-1} down to 8 m depth, ~ -0.4 ms^{-1} flows reached down to 10 m during ILL and ILS (Fig. 3.13). Overall, cross-shelf flows were significantly smaller than the along-shelf; and these were generally $0.1\text{--}0.2$ ms^{-1} offcoast.

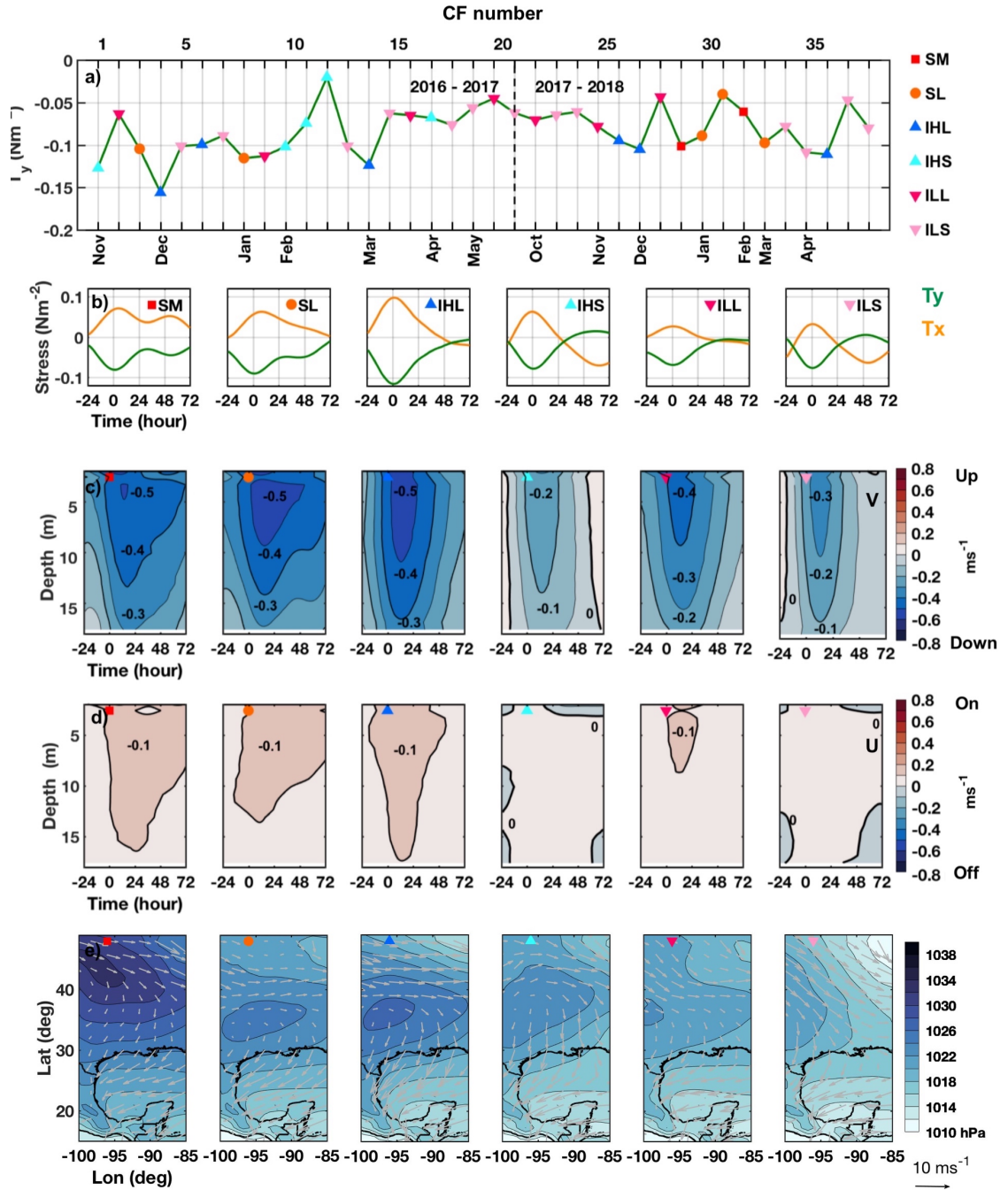


Fig. 3.13. (a) Maximum along-shelf wind stresses (τ_y) for each of the 38 cold fronts during 2016–2018. The rest of the panels represent group-averaged characteristics: (b) τ_x and τ_y 24h before and 72h after wind-stress maxima (zero value); (c) the vertical structure of along-shelf, V, and; (d) cross-shelf, U, currents (positive upcoast and offcoast); and (e) spatial distribution of MSLP. Note velocity differences of 0.1 ms^{-1} between contourlines in c) and d).

Local density gradients (Schultz et al., 1997; Dzwonkowski et al., 2011; Lentz, 2001; Horwitz and Lentz, 2014) or the presence of microeddies that move towards the inner shelf (Thyng, 2019) can modulate the response of the water column. Murray's (1975) simplified theory was applied to elucidate the potential effect of stratification on our results, on the absence of density data. As a first step, the three-component equations of motions with friction parameterized as an isotropic eddy viscosity were considered.

$$\frac{du}{dt} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + fv + K \frac{\partial^2 u}{\partial z^2} \quad (3.1)$$

$$\frac{dv}{dt} = -\frac{1}{\rho} \frac{\partial p}{\partial y} - fu + K \frac{\partial^2 v}{\partial z^2} \quad (3.2)$$

$$\frac{dw}{dt} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + g + K \frac{\partial^2 w}{\partial z^2} \quad (3.3)$$

This theory assumed a steady state, neglecting the vertical speed component and the field accelerations, and considered a homogeneous water mass permits (3.1), (3.2) and (3.3) to be combined and written,

$$K \frac{\partial^2 u}{\partial z^2} = -g \frac{\partial \zeta}{\partial x} - fv \quad (3.4)$$

$$K \frac{\partial^2 v}{\partial z^2} = -g \frac{\partial \zeta}{\partial y} + fu \quad (3.5)$$

Neglect of the Coriolis parameters in the initial equations (3.1) and (3.2) uncouples these equations and allows straightforward solutions for both u and v . Eq.(3.5) reduces to $K \frac{\partial^2 v}{\partial z^2} = 0$, implying that v is linear with z . Murray (1975) established that the vertical

structure of the along-shelf flow, v , could be calculated based on the wind forcing, as follows (Eq. 3.6 and 3.7);

$$v = \frac{\tau_{xs}}{K} z + v_b \quad (3.6)$$

$$v_b = \frac{\tau_{xb}^{1/2}}{k_b \rho} \quad (3.7)$$

being z the vertical coordinate, positive up from the bottom; v_b the near-bed bottom speed given by the quadratic bottom stress condition of $\tau_{xs} = \tau_{xb} = 2 \times 10^{-3} \sigma (Q \cos(\alpha))^2$ and assuming $k_b \approx 3 \times 10^{-3}$; Q the wind speed blowing at an angle α to the shoreline (deg); ρ the water density; and σ the air density. The eddy viscosity for a well-mixed surface layer was given by $K = 0.1825 \times 10^{-4} Q^{\frac{5}{2}}$ in $\text{m}^2 \text{s}^{-1}$.

Theoretical expectation for unstratified conditions suggested that the flow response was primarily controlled by the wind during the passage of cold fronts (Fig. 3.14), in agreement with previous research findings (Winant, 1980; Nowlin et al., 2005; Zavala-Hidalgo et al, 2014; Shi et al., 2019). Vertical flow structure differences between observed and theoretical flows were related to the simplified nature of the theory itself (i.e. v is linear with z). The most intense flows associated with maximum wind speeds were, overall, successfully captured by the theory. But flow speeds differed prior and/or after the events, particularly for fronts of short duration (i.e. IHS and ILS in Fig. 3.14).

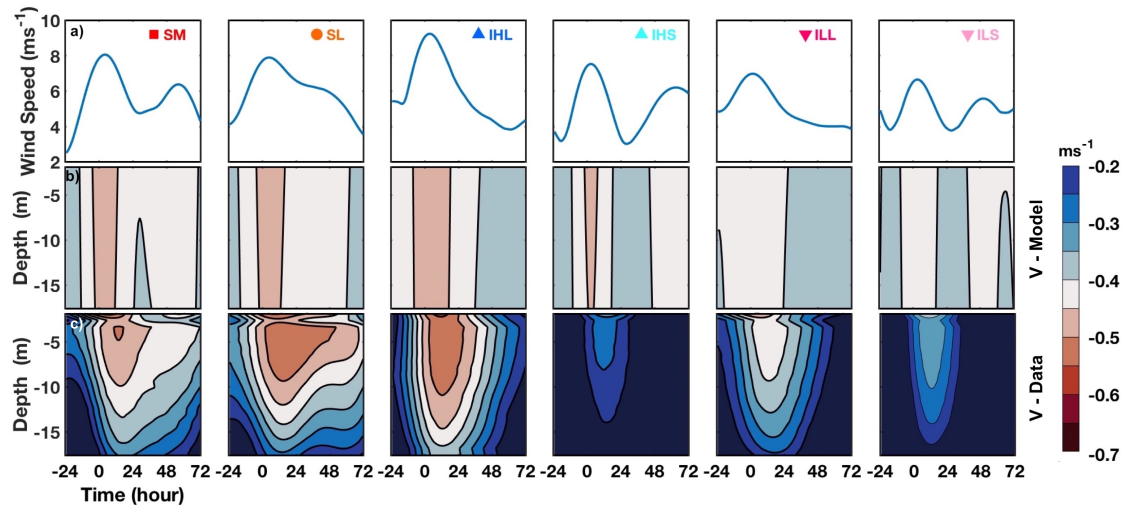


Fig. 3.14. (a) Characteristic wind speeds for each cold front group (left to right); (b) Vertical structure of the along-shelf wind-driven flow for each cold front group based on Murray's (1975) simplified theory; (c) Field measured vertical structure of the along-shelf flows characteristic for each cold front group.

Response times of the along-shelf flow to the wind forcing were analyzed through cross-correlation analysis; all events presented high correlation values (> 0.9 ; Fig. 3.15a). *Sequential* events showed comparatively smaller lags (less than 9 h) than *individual* fronts (lags of 9 to 18h). Thus, these lags were suggested to primarily depend on the time of exposure of the water column to τ_y (Fig. 3.15a). Along-shelf flow velocities were scaled with the shear velocity ($u_* = \sqrt{\frac{\tau_y}{\rho}}$; being τ_y the along-shelf wind stress and ρ the water density) to compare the flow structure among different cold front types (Fig. 3.15b). High-intensity events (i.e. SM, IHL, IHS) presented along-shelf currents of similar magnitude throughout the water column, while events of low-intensity (i.e. SL, ILL, ILS) presented larger variations of the flow throughout the water column (i.e. IHS and ILS, Fig. 3.15b). Generalized lag-fitted bin-averaged velocity profiles for each cold

front type showed intense surface flows of up to 0.6 ms^{-1} and milder bottom flows of up to 0.3 ms^{-1} for long-lasting events, and half the speeds for short-lasting events (Fig. 3.15c). These results suggest that high-intensity cold fronts induced a nearly-steady wind-driven flow, while low-intensity events presented weaker flows, and more susceptible to be influenced by other local processes.

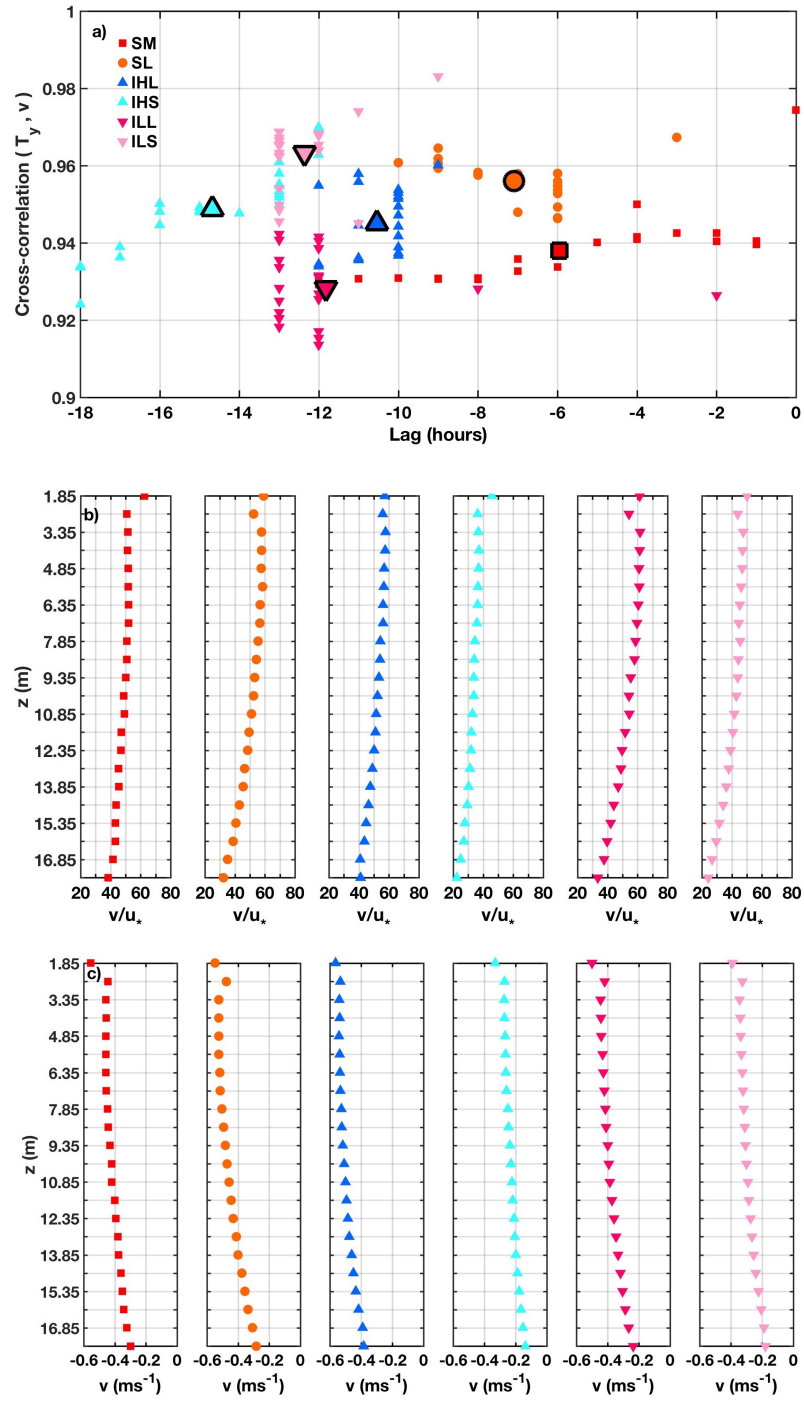


Fig. 3.15. (a) Cross-correlation coefficient (r) and lag between the along-shelf wind stress (τ_y) and depth-varying along-shelf flows (V); large symbols indicate group-averaged results. (b) Vertical profile of V (scaled with the shear velocity, u_*) for each cold front group. (c) Lag-fitted bin-averaged velocity profiles for each cold front group.

3.6 Conclusions

Yearly-average along-shelf winds were predominantly upcoast over the last two decades, but large seasonal fluctuations existed. This study focused on understanding the role of the passage of episodic cold fronts in the reversing of along-shelf flows downcoast on the southern Texas coast. A total of 819 cold fronts of 4 days of average duration occurred between 1984 and 2018, and the vertical structure of the flow was analyzed for 38 cold fronts between November 2016 and October 2018. Theoretical flow expectation for unstratified conditions suggested that the flow response was primarily controlled by the wind forcing during the passage of cold fronts. Detailed analysis on the vertical profile of the flow demonstrated significant time-lag differences, primarily related to the front intensity and duration. Strongest downcoast flows of -0.5 ms^{-1} throughout the entire water column were associated with individual cold fronts of high intensity ($\tau_y \sim -0.15 \text{ Nm}^{-2}$) and long duration (up to 4 days). The most frequent fronts were individual of low intensity ($\tau_y \sim -0.05 \text{ Nm}^{-2}$) and short duration (up to 2 days), and induced relatively weak downcoast flows of $\sim -0.2 \text{ ms}^{-1}$; some were unable to completely reverse the flow downcoast, and in most cases, the flow reverted upcoast immediately after the passage of the front. Cold fronts are potential threats to coastal environments on the western Gulf of Mexico leading to coastal erosion and flooding. This study highlights the role of episodic cold fronts in reversing and intensifying inner-shelf currents on the southern Texas coast, and emphasizes differences in the flow response related to cold front characteristics.

Chapter 4

4 Spatial variability of currents associated with different cold fronts along the southern Texas coast

Wind and current measurements collected between February and March 2017 at three sites in the southern Texas coast were used to determine along-shelf flow variations induced by episodic synoptic-scale cold fronts, and to quantify the relevant terms in the inner-shelf along-shelf momentum budget. Inner-shelf flows were wind-driven, but significant along-shelf variations existed between the northern and southern sites. Cold fronts induced downcoast mean, surface and bottom flows along the study site. Strongest downcoast flows occurred in the surface in the northern and southern end, while these were weaker in the center. Flows averaged over a longer period of time showed the presence of a convergence zone in the central site, off Port Mansfield. Spatial variations of the along-shelf wind-stress was the main cause for the flow convergence in the surface layer at the central site. Most intense surface flows occurred in the north (along-shelf wind speeds of $>10 \text{ ms}^{-1}$), less affected by southeasterly (upcoast) Trade winds. Low-energy cold fronts (along-shelf wind speeds of $<10 \text{ ms}^{-1}$) were unable to completely reverse the wind direction towards the south (downcoast) in the southern and central sites, due to the stronger influence of Trade winds. Surface wind-stress and pressure gradients were the dominant terms in the along-shelf momentum budget, while the bottom stress and Coriolis terms were considered negligible. The wind-stress term was dominant in the north, while pressure gradients associated with local sea-level responses to the wind forcing were dominant in the southern site. This study highlights the importance of pre-front wind characteristics in spatial variations of the along-shelf flow during cold fronts.²

² This chapter is based on an article published in *Ocean Dynamics*. Romero-Arteaga, A., Ruiz de Alegria-Arzaburu, A. Spatial variability of currents associated with different cold fronts along the southern Texas coast. *Ocean Dynamics*. <https://doi.org/10.1007/s10236-022-01505-z>

4.1 Introduction

The inner-shelf is dynamically defined as the region encompassing depths ranging from a few to tens of meters, and lies between the surf zone (momentum balance dominated by wave-induced terms due to wave-breaking) and the mid-shelf (along-shelf circulation usually in geostrophic balance) ([Lentz and Fewings, 2012](#)). The inner-shelf circulation is often investigated through the momentum balance across different regions, but most studies have considered conditions averaged over longer than a week ([Lee et al., 1984](#); [Lentz and Winant, 1986](#); [Lentz et al., 1999](#), [Maza et al., 2006](#); [Fewings and Lentz, 2010](#); [Grifoll et al., 2012, 2013](#)) rather than using data of higher temporal resolution (i.e. seconds to minutes).

Overall, the inner-shelf along-shelf momentum balance is simpler than the mid-shelf, where the Coriolis, wind-stress, bottom stress, acceleration and pressure gradient terms need to be considered ([Allen and Smith, 1981](#); [Lentz and Winant, 1986](#); [Lee et al., 1984, 1989](#)). Instead, the inner-shelf balance can be solved using mainly three terms, that include the along-shelf wind-stress, bottom stress and the pressure gradient ([Scott and Csanady, 1976](#); [Pettigrew, 1981](#); [Lentz and Winant, 1986](#); [Masse, 1988](#); [Lee et al., 1989](#); [Lentz, 1994](#)).

Energetic wind events associated to storms can modify continental shelf water circulation patterns. This is evidenced when sea-level slopes oppose the wind-stress in order to establish a frictional equilibrium during winter cold front events ([Lee et al., 1984](#)). Bottom friction effects associated with the proximity to the coastline prevent

the generation of inertial fluctuations, which often characterize the mid-shelf and outer-shelf regions after energetic wind pulses ([Salat et al., 1992](#); [Shearman, 2005](#)). A large fraction of the water column is usually affected by intense winds during the passage of cold fronts.

Winds are highly seasonal in the northwestern Gulf of Mexico ([Thyng and Hetland, 2018](#)), and cause along-shelf currents of different directionality. Summer winds from the southwest (June to August) induce upcoast flows while winds from the northeast during non-summer months (September to May) generate downcoast flows along the inner-shelf toward Mexico ([Thyng, 2019](#)). The frictional adjustment time is largely reduced in the nearshore during the passage of cold fronts, and this is directly and inversely proportional to the water depth and the wind-stress, respectively. For that reason, magnitude and phase changes occur in the dominant terms of the momentum balance ([Grifoll et al., 2012](#)).

The goal of this Chapter is to determine spatial variations on the along-shelf circulation throughout the water column induced by cold fronts of different duration and intensity, and to quantify the relevant terms in the inner-shelf along-shelf momentum budget during the passage of the fronts. This analysis is based on a set of wind and current measurements collected between February and March 2017, at three sites covering ~200 km of the southern Texas coast: Port Aransas in the north, Port Mansfield in the center and South Padre Island in the southern end.

4.2 Methods

Spatio-temporal variations of nearshore currents were determined throughout the water column from February to March 2017 using the data of all bottom mounted ADCPs (A1 to A6 south to north in [Fig. 4.16](#)). The northern moorings were installed off Port Aransas Pass (A6 in Boatmens Reef and A5 in MI775 Reef), two central moorings were placed off Port Mansfield (A4 in Wreck and A3 in 1047 Reef) and the southern instruments were placed off South Padre Island (A2 in Stranger Wreck and A1 in Port Isabel Reef).

A principal component analysis (PCA) was conducted between the depth-averaged current components to rotate the data into major (alongshore, V) and minor (cross-shore, U) axes of flow variability; directions were expressed in degrees clockwise from true north. Current vectors at A6 and A5 (north site) were oriented 56° counter-clockwise from depth-averaged vectors, and -54° and 88° at sites A4 and A3 (center site), and sites A2 and A1 (south site), respectively. A right-handed coordinate system was applied to the rotated along-shelf and cross-shelf currents; positive x (u) and y (v) indicating offcoast and upcoast directions, respectively.

Hourly wind data were analyzed from the three NOAA weather stations WS1, WS2 and WS3 closest to A1, A4 and A6, respectively ([Fig. 4.17](#)).

Water-level variations were obtained from the time-series of pressure data measured by the ADCPs, and referred to the local mean low water-level using local tide-gauge data

(TG1 to TG3; Fig. 4.18) operated by NOAA and located near to the ADCP moorings (see Goff et al., 2019). Along-shelf water-level gradients $\partial\eta/\partial y$ were estimate with the water-level time-series.

Depth-averaged along-shelf momentum balances were undertaken for the southern (A1) and northern (A6) sites to determine the role of different momentum terms on along-shelf current variations. The following simplified depth-averaged alongshore momentum equation (Eq. 4.1) was applied (e.g. Allen and Smith, 1981; Lentz and Winant, 1986);

$$\frac{\partial v}{\partial t} = -g \frac{\partial \eta}{\partial y} + \frac{\tau_{s,y}}{\rho_0 h} - \frac{\tau_{b,y}}{\rho_0 h} - f u \quad (4.1)$$

where $\frac{\partial \eta}{\partial y}$ indicate subtidal along-shelf water-level gradients, ρ_0 mean seawater density, $\tau_{s,y}$ alongshore wind-stress, $\tau_{b,y}$ alongshore bottom stress and h the local water depth.

The Coriolis acceleration was obtained as a product of the Coriolis parameter and subtidal depth-averaged cross-shelf currents. Terms in Eq. 4.1 represent (left to right): (1) local flow acceleration, (2) along-shelf pressure gradient, (3) and (4) along-shelf wind and bottom stresses and (5) Coriolis acceleration. Advective acceleration and horizontal momentum diffusion terms were neglected as are considered only likely to be important in shorter scales than a few weeks (e.g. Grifoll et al., 2013). The local acceleration term $\frac{\partial v}{\partial t}$ was calculated using central differencing of measured along-shelf subtidal flows. Bottom stresses $\tau_{b,y}$ were estimated assuming a quadratic drag formulation (Eq. 4. 2).

$$\tau_{b,y} = \rho_0 C_{D,b} V_b |V_b| \quad (4.2)$$

where $C_{D,b}$ is a bottom drag coefficient (3×10^{-3}), function of near-bottom along-shelf velocity.

4.3 Results

4.3.1 Cold front wind characteristics

The passage of three individual cold fronts (CF) was studied in the period of 1–16 March 2017 (Fig. 4.19), which included two CFs categorized as of mid-to-high energy and one CF of low-energy. These fronts caused energetic downcoast winds of similar speeds, which peaked around 12 ms^{-1} on the 2nd, 8th and 12th of March (Fig. 4.19), and were related to high-pressure systems near Lat 40° (see Fig. 4.19b, d, f). Relatively calm atmospheric periods occurred between cold fronts, which induced wind direction changes, towards the north (upcoast), and were associated with low-pressure systems (Fig. 4.19a, c, e, g).

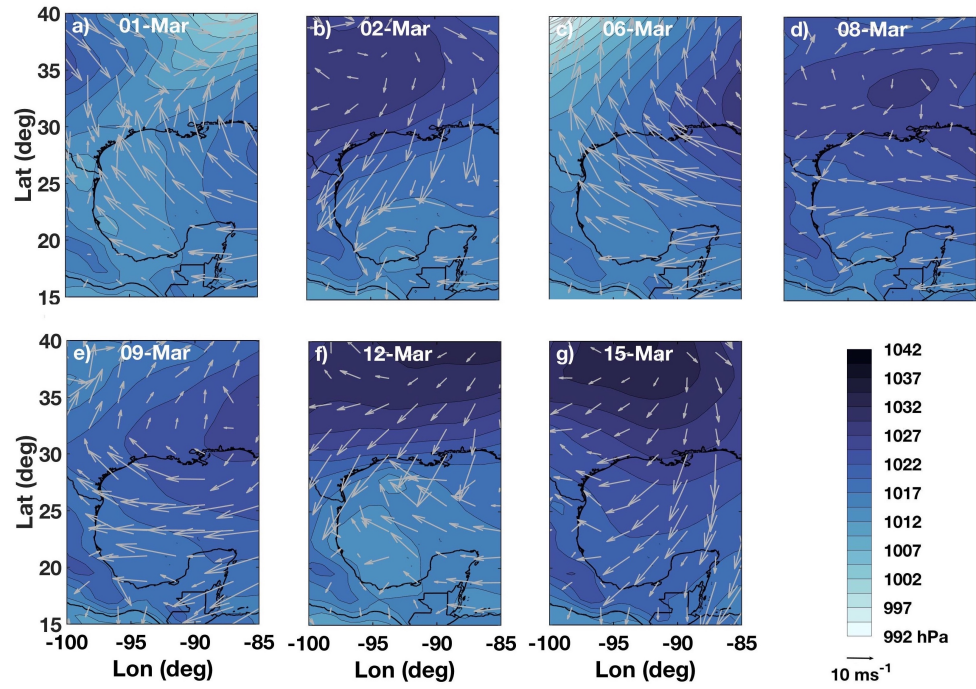


Fig. 4.19. Temporal sequence between 1-15 March 2017 of the spatial distribution of the mean sea-level pressure (MSLP; magnitude in colorbar) and wind speeds and directions (arrows); before (a, c, e, g) and during (b, d, f) the passage of cold fronts along the western Gulf of Mexico.

Low-pass filtered wind characteristics for the selected cold fronts are presented in Fig. 4.20. The first and most energetic front CF I (T_y of -0.12 Nm^{-2}) peaked on the 2nd of March and lasted 4 days (1-5 March 2017). The weakest front, CF II (T_y of -0.04 Nm^{-2}), presented maximum wind speeds on the 8th of March, and lasted 2 days (8-10 March 2017). The third front CF III, of mid-to-high energy (T_y of -0.08 Nm^{-2}), peaked on the 12th of March and lasted 4 days (10-14 March 2017) (see I, II and III in Fig. 4.20).

During the passage of the fronts, along-shelf winds increased the magnitude (up to 8 ms^{-1}) and shifted from positive (upcoast) to negative (downcoast) in all three locations, except for CF II, which was unable to turn towards the south (downcoast) in the center

and southern sites (A4 and A1) (Fig. 4.20a). The cross-shelf wind component was predominantly negative (oncoast) and remained similar or decreased in magnitude during the three events (Fig. 4.20b). Wind speed spatial variations indicated alongshore uniformity before and during the peak of CF I, but a notable speed decrease occurred in the south. Similar spatial patterns but of lower energy were presented for CF III, while weakest CF II presented significantly lower wind speeds, but highest in the north (Fig. 4.20c).

Most energetic CF I, presented maximum τ_y of around -0.12 Nm^{-2} in the northern site (A6), and -0.08 Nm^{-2} in the central site (A4) and lowest magnitudes (-0.04 Nm^{-2}) in the southern end (A1) (Fig. 4.20d). τ_x was comparatively weaker in all cases (magnitude of $< 0.05 \text{ Nm}^{-2}$) and predominantly negative (oncoast) (Fig. 4.20e). The spatial distribution of τ_y (Fig. 4.20f) and τ_x (Fig. 4.20g) indicated strong and mid-to-strong downcoast winds during CF I and III, and very weak downcoast in the north and upcoast in the central-south sections for CF II (Fig. 4.20f). Weak downcoast winds in CF II were possibly affected by strong upcoast winds prior to the front during 6-7 March (Fig. 4.20a, f).

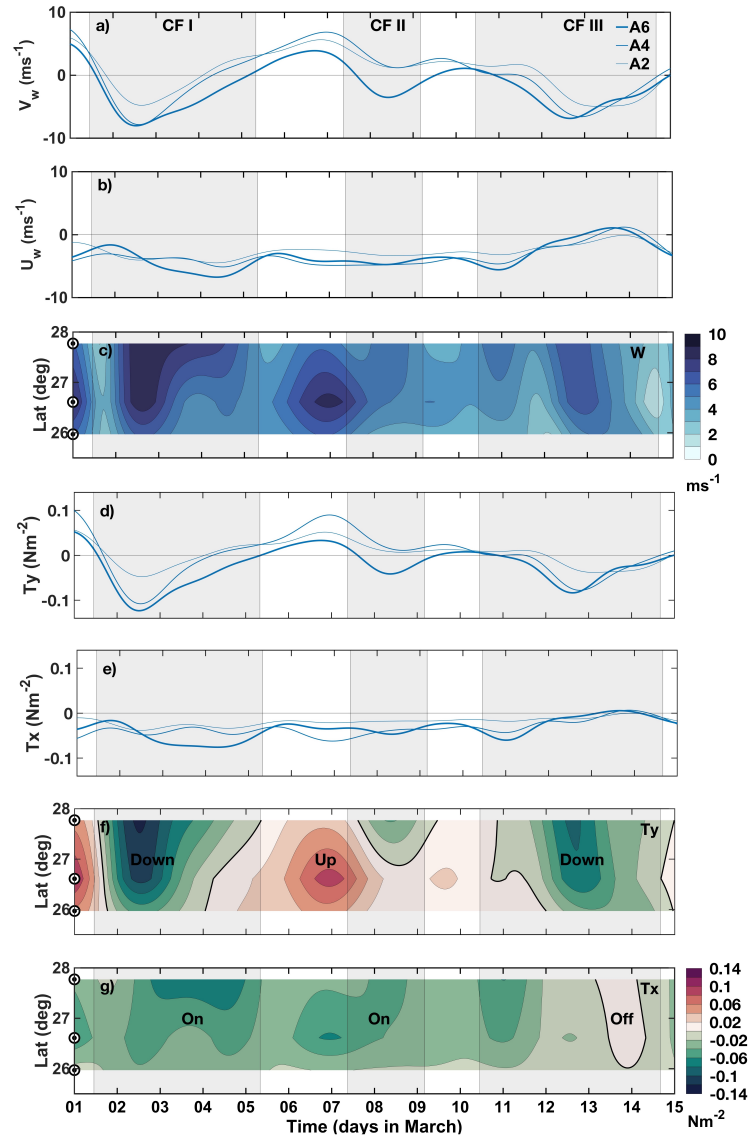


Fig. 4.20. (a) Low-pass filtered along-shelf and (b) cross-shelf wind speeds measured at the weather stations near A2, A4 and A6, and (c) the spatial distribution of the magnitude of the wind speed (W) for Lat 26-18. Subplots (d) to (g) represent wind-stress variations for the same period of time. (d) and (e) show the time-series of the along-shelf (T_y) and cross-shelf (T_x) wind-stress components calculated with the weather station data, and (f) and (g) represent the spatial distribution of T_y and T_x for Lat 26-18, respectively. Shaded sections indicate cold front (CF) durations, and circles in (c) and (g) A1, A4 and A6 locations.

4.3.2 Alongshore inner-shelf current characteristics

Currents measured at the six locations (A1 to A6) were time-averaged per vertical bin

for specific periods of time (i.e. CF period 1-15 March and two-month period 1 February to 31 March), and then depth-averaged for specific sections of the water column (surface, bottom and complete water column), (see vectors in Fig. 4.21). Currents averaged throughout the complete water column (mean; from depths of 2-m to the bottom) (Fig. 4.21a, d) were compared with surface (depth of 2-m) (Fig. 4.21b, 6e) and bottom (depth of ~20-m) flows (Fig. 4.21c, f).

During the CF period, mean (depth-averaged) currents indicated coast-aligned downcoast flows of -0.4 ms^{-1} in the north (A6 and A5) and $\sim -0.2 \text{ ms}^{-1}$ further south (A4 to A1) (Fig. 4.21a). In contrast, longer period results showed weaker downcoast flows of $\sim -0.15 \text{ ms}^{-1}$ in the north (A6 and A5), near-to-zero in the center (A4 and A3) and very weak (0.03 ms^{-1}) upcoast flows in the south (A2 and A1) (Fig. 4.21d). Considering longer period data, the magnitude of mean currents showed a reduction off Port Mansfield (between A5 and A1), which suggested the presence of a convergence zone (Fig. 4.21d). In contrast, this reduction was not evident in the CF period (Fig. 4.21a).

Downcoast flows dominated throughout the water column off Port Aransas in the north (A6 and A5 in Fig. 4.21). Strongest surface flows of $\sim -0.45 \text{ ms}^{-1}$ occurred during the CF period (Fig. 4.21b), and these were significantly weaker near to the seabed ($\sim -0.2 \text{ ms}^{-1}$) (Fig. 4.21c). Instead, during the longer period, surface flows were downcoast and oncoast, and significantly weaker ($\sim -0.3 \text{ ms}^{-1}$) (Fig. 4.21e), while bottom flows were comparatively very weak, downcoast and coast-aligned ($\sim -0.1 \text{ ms}^{-1}$) (Fig. 4.21f).

Largest discrepancies existed between surface and bottom flows in the center and southern sites. In the longer period, weak (0.15 ms^{-1}) upcoast surface currents dominated in the center (Fig. 4.21e), while these were very weak and downcoast (-0.03 ms^{-1}) near to the seabed (Fig. 4.21f). In the south, upcoast surface currents were stronger (0.25 ms^{-1}) (Fig. 4.21e), while bottom flows were as weak as in the center and predominantly downcoast (-0.02 ms^{-1}) (Fig. 4.21f). In contrast, during the CF period, surface and bottom flows in the center and southern sites were downcoast, but of different magnitude (Fig. 4.21b, c). In the central region, cold front induced relatively weak (-0.2 ms^{-1}) downcoast surface flow, and these became stronger (-0.3 ms^{-1}) and onshore further to the south (Fig. 4.21b). In contrast, downcoast near-bed flows induced by cold fronts were significantly weaker and of similar magnitude (-0.1 ms^{-1}) along the coast (Fig. 4.21c).

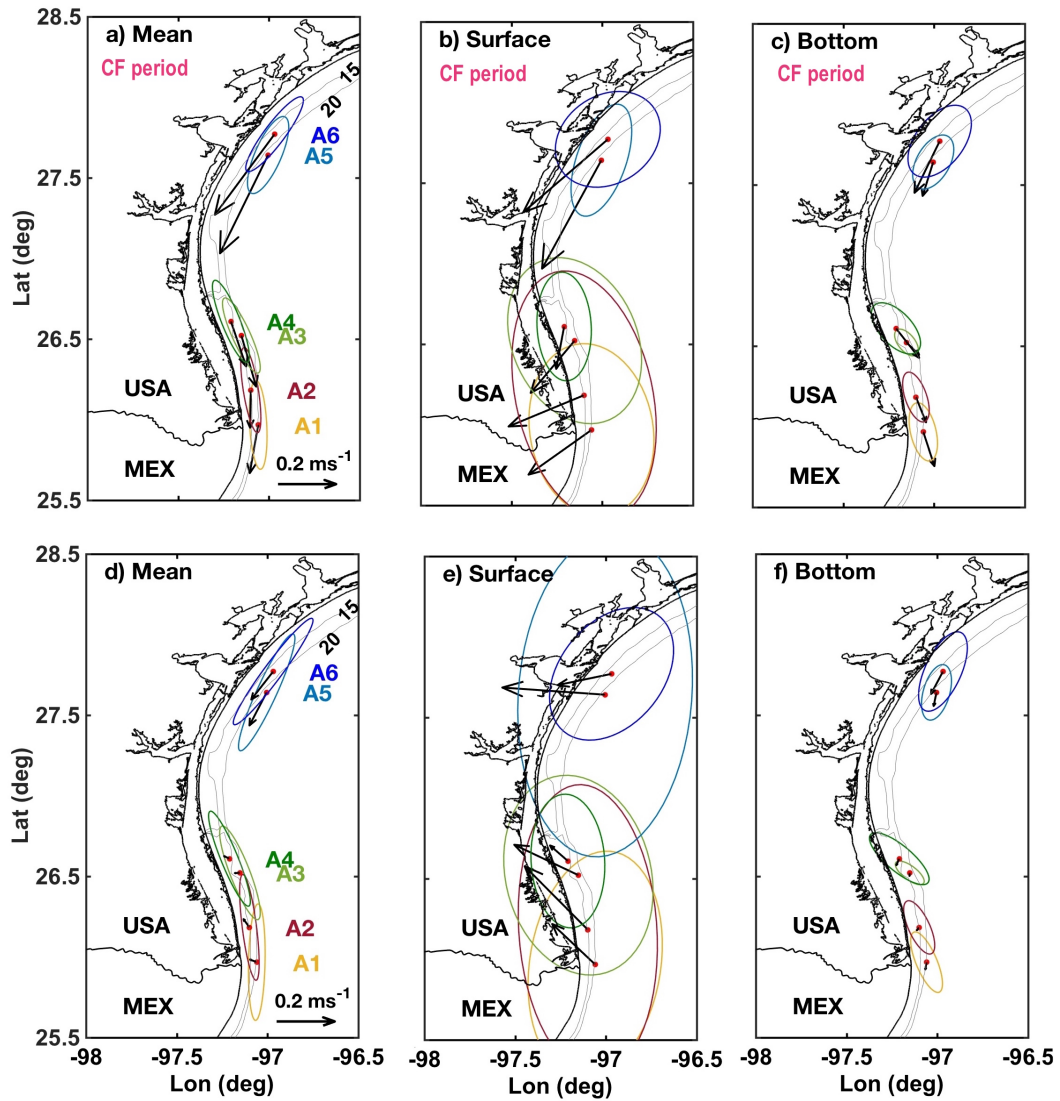


Fig. 4.21. Time-averaged current vectors and ellipses of variance at ADCP sites (red dots, A1 to A6) for the cold front (CF) period (1-15 March) (upper panels, a, b, c) and for the 2-month period (i.e. longer period; 1 February to 31 March) (lower panels; d, e, f). (a) and (d) Depth-averaged currents throughout the water column; (b) and (e) surface flow at 2-m depth; and (c) and (f) bottom flow around 20-m depth.

The convergence zone was mostly evident in the surface for flows averaged over the longer period of time (Fig. 4.21e), since near seabed currents were downcoast for all locations (Fig. 4.21f). For depth-averaged and bottom currents, the maximum flow

variance was aligned with mean current vectors, while highest variance occurred for surface flows, and mostly during the longer period of time (Fig. 4.21b, e).

Vertical current profiles in the northern (A6), central (A4) and southern (A1) locations were subjected to an empirical orthogonal function (EOF) analysis for the CF period (March 1-15) to obtain an insight into the spatio-temporal behaviour of the flow at each location. Mode 1 explained at least 80 % of the variance for all moorings, and suggested the dominance of a barotropic flow at all sites (Fig.4.22). These findings also highlight the predominance of downcoast directed flows and strongest surface flows for the CF period.

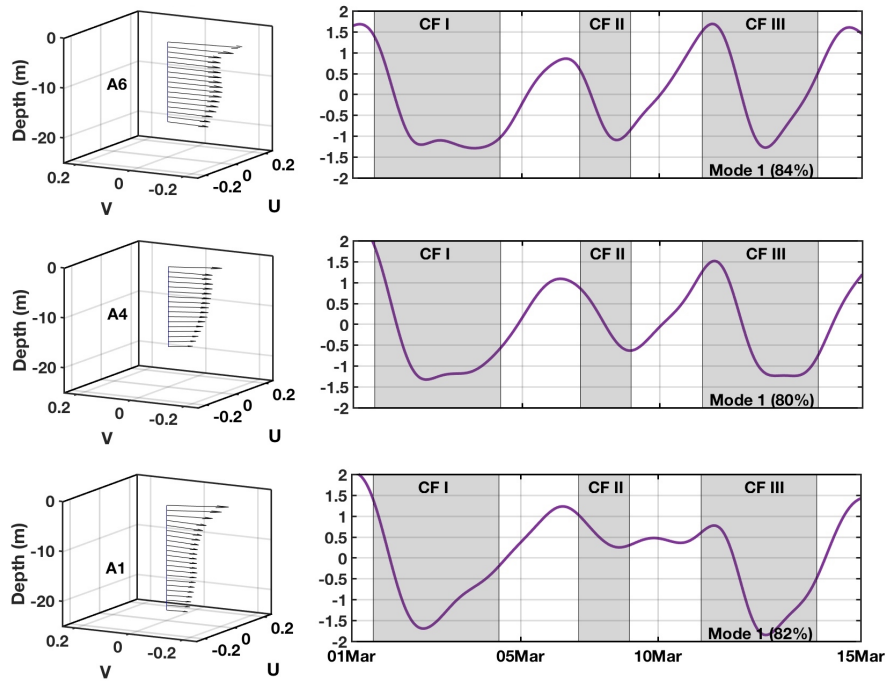


Fig. 4.22. Spatial eigenfunctions (left panels) and their associated temporal amplitudes (right panels) for the first EOF mode derived from the vertical current profiles for the northern (A6; upper panels), central (A4; middle panels) and southern (A1; lower panels) moorings.

4.3.3 Alongshore current variations induced by cold fronts

Significant alongshore variations existed in the current profiles for the northern, central and southern sites during the passage of CF I, II and III of different characteristics. Northerly (downcoast) winds induced negative along-shelf wind-stresses of different magnitude, T_y , of different magnitude of -0.04 to -0.12 Nm^{-2} , and caused depth-averaged downcoast currents of -0.6 to -0.2 ms^{-1} . Southeasterly winds (upcoast) dominated prior to CFs (Fig. 4.20d), and induced upcoast flows that partially reduced preceding downcoast current speeds (Fig. 4.23, Fig. 4.24, Fig. 4.25). Instead, cross-shelf flows were significantly weaker, remained near to zero in the northern and southern sites, but were relevant in the central site off Port Mansfield (up to 0.4 ms^{-1} near to the seabed). The fronts induced water-level increases of 0.2 to 0.3 m , and spatial variations existed along the coast (Fig. 4.23, Fig. 4.24, Fig. 4.25).

The three cold fronts induced significantly higher downcoast flows in the northern site than in the center-southern locations. Up to -0.8 ms^{-1} flows were measured in the upper water column in the north (Fig. 4.23d), while up to -0.4 ms^{-1} flows occurred in the central and southern sites (Fig. 4.24d, Fig. 4.25d). Despite CF energy differences (T_y variations of -0.04 to 0.12 Nm^{-2}), similar depth-averaged downcoast flows of $\sim -0.6 \text{ ms}^{-1}$ were measured in the northern site for the three events (Fig. 4.23a, c). However, flow structure differences existed throughout the water column. While the most intense CF I induced depth-uniform downcoast flows of -0.6 ms^{-1} over 4 days, weak near-bottom currents of -0.2 ms^{-1} occurred during CF II and III, and up to -0.6 ms^{-1} flows only

occurred in the upper half of the water column (Fig. 4.23d). When CFs ended, wind directions changed towards the north (upcoast), and relatively calm ($T_y < 0.05 \text{ Nm}^{-2}$) upcoast winds prior CF II weakened downcoast flows (Fig. 4.23d). Cross-shelf flows were considerably weaker than the along-shelf, and fluctuated oncoast/offcoast ($\pm 0.1 \text{ ms}^{-1}$) (Fig. 4.23e). Water-level increases of 0.3 m occurred after the peak of the wind in CF I, and nearly 0.2 m in CF II and III (Fig. 4.23b).

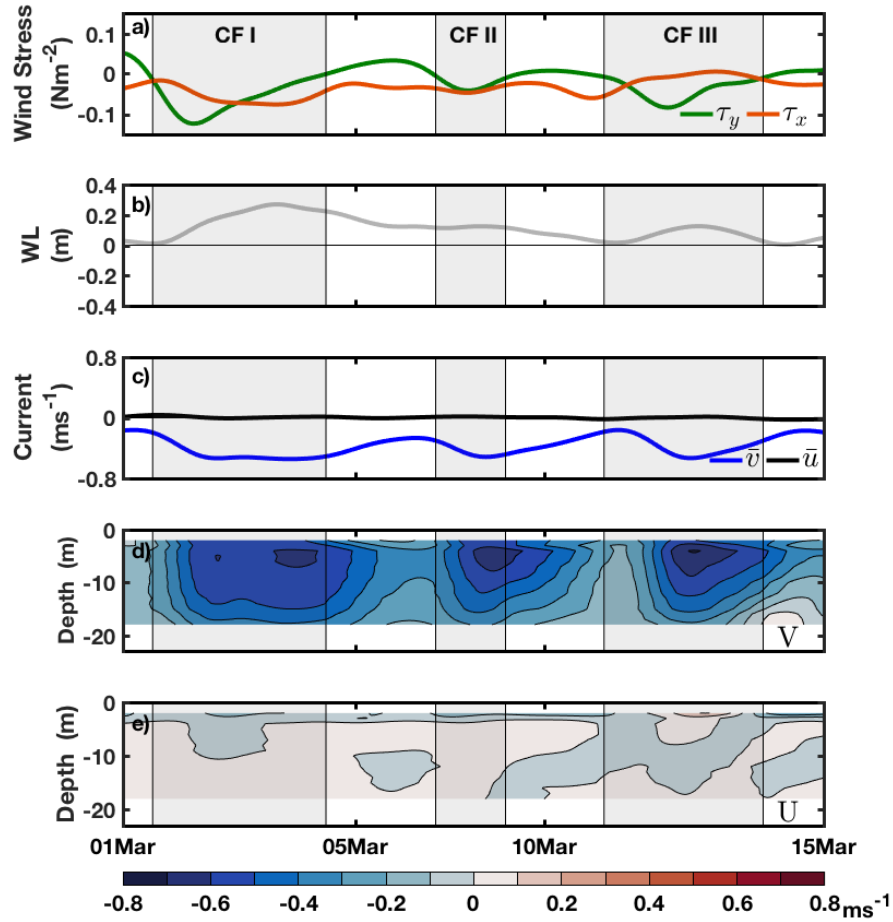


Fig. 4.23. (a) Time series of: (a) along-shelf (T_y) and cross-shelf (T_x) wind-stresses; (b) water-level variations; (c) depth-averaged along-shelf ($\bar{v}$) and cross-shelf ($\bar{u}$) velocities; and depth-varying (d) along-shelf (V) and (e) cross-shelf (U) velocities at the northern site (A6). Negative velocities indicate downcoast and oncoast flows. The shaded sections denote front durations.

In the center site off Port Mansfield (A4), the flows were slightly different to the northern site (A6). Similar downcoast winds of up to T_y of -0.1 Nm^{-2} occurred during CF I, but this event was shorter, and the wind direction reverted upcoast on the 4th of March (Fig. 4.24a). Consequently, downcoast flows were weaker here than in the north; depth-averaged flows of up to -0.4 ms^{-1} were measured in A4 compared to -0.6 ms^{-1} in A6 (Fig. 4.23c, Fig. 4.24c). Similar flow structures were observed throughout the water column for CF I, but depth-uniform downcoast flows were notably weaker than in the north (maximum of -0.4 ms^{-1}).

Downcoast flows in CF III were up to -0.4 ms^{-1} in the upper half of the water column, and -0.3 ms^{-1} near to the seabed (Fig. 4.24d, e). Weakest CF II presented largest difference with the north, the presence of strong upcoast winds in the transitional period from CF I to II inhibited CF II from reversing the wind direction towards the south. As a consequence, strongest depth-averaged downcoast flows of -0.3 ms^{-1} occurred at the end of the event, and the flow became notable weaker from the surface towards the seabed (from -0.4 to -0.2 ms^{-1}) (Fig. 4.24d).

The cross-shelf flow was stronger in the center region (Fig. 4.23e, Fig. 4.24e, Fig. 4.25e) and predominantly oncoast ($\sim -0.1 \text{ ms}^{-1}$) in the subsurface (upper 2 m of the water column), and offcoast and up to 0.3 ms^{-1} near to the seabed (Fig. 4.24e). Water-level increases were observed along the coast due to the incidence of the fronts, and these were up to 0.2 m after the wind peak of CF I, and up to 0.1 m during CF II and III (Fig. 4.24b)

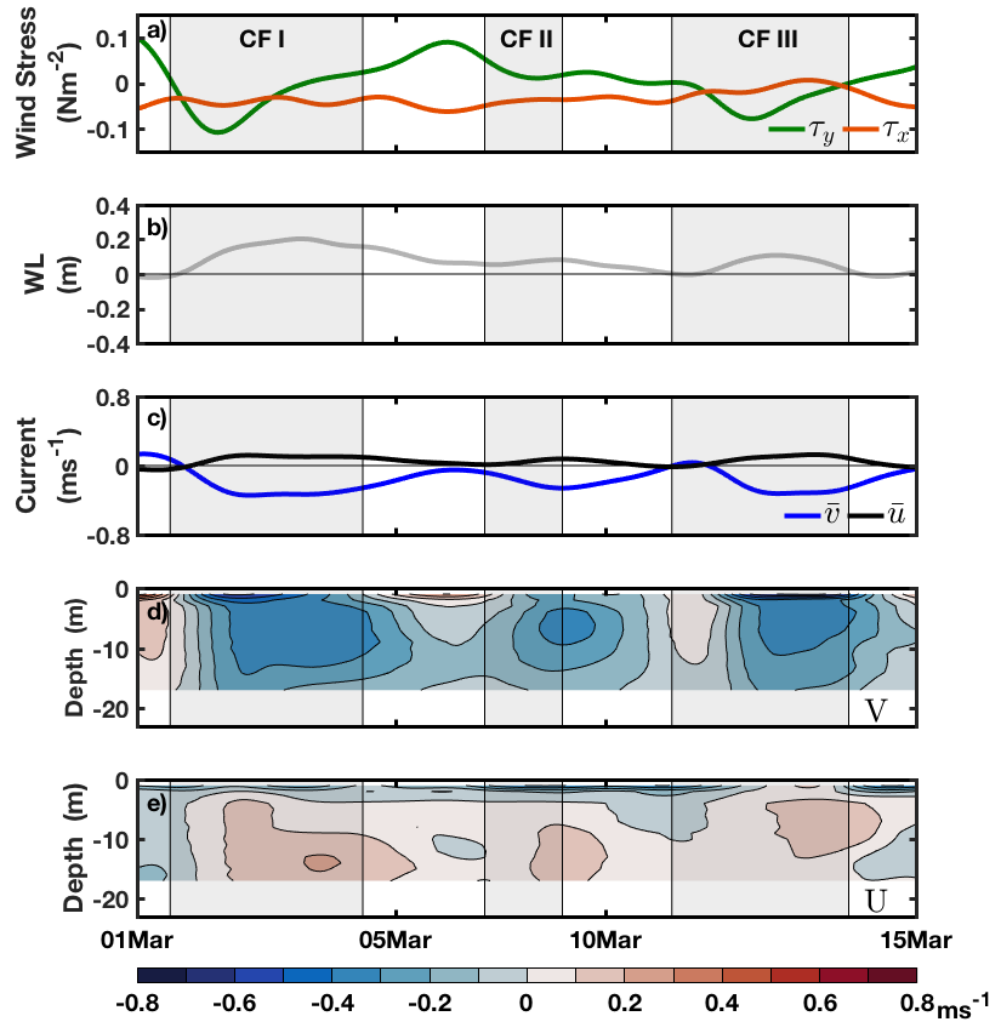


Fig. 4.24. (a) Time series of: (a) along-shelf (T_y) and cross-shelf (T_x) wind-stresses; (b) water-level variations; (c) depth-averaged along-shelf ($\bar{v}$) and cross-shelf ($\bar{u}$) velocities; and depth-varying (d) along-shelf (V) and (e) cross-shelf (U) velocities at the northern site (A4). Negative velocities indicate downcoast and oncoast flows. The shaded sections denote front durations.

Cold front wind conditions significantly changed off South Padre Island (A1) compared to the northern (A6) and center (A4) sites (Fig. 4.23a, Fig. 4.24a, Fig. 4.25a). In the south, T_y was significantly weaker for CF I and III, up to -0.04 Nm^{-2} , as a result, depth-averaged downcoast flows were also weaker (up to -0.3 ms^{-1}) (Fig. 4.25c). Strongest flow throughout the water column occurred for CF I and III, up to -0.5 ms^{-1} in the upper half of the water column and -0.3 ms^{-1} near to the seabed (Fig. 4.25d). Similar to the central site (A4), the presence of strong upcoast winds in the transitional period from CF I to II inhibited CF II from reversing the wind direction towards the south. Thus, the currents associated with CF II were significantly weaker. Depth-averaged downcoast flows were $\sim -0.1 \text{ ms}^{-1}$ (Fig. 4.25c) and strongest flows of up to -0.3 ms^{-1} occurred near the seabed (Fig. 4.25d). Similar to the northern site, cross-shelf flows were weak ($\pm 0.1 \text{ ms}^{-1}$) and fluctuated oncoast in the surface and offcoast near to the seabed (Fig. 4.25e). Water-level increases were lower than in the north and similar to the center site, up to 0.1 m for CF II and III and 0.2 m during CF I (Fig. 4.25b).

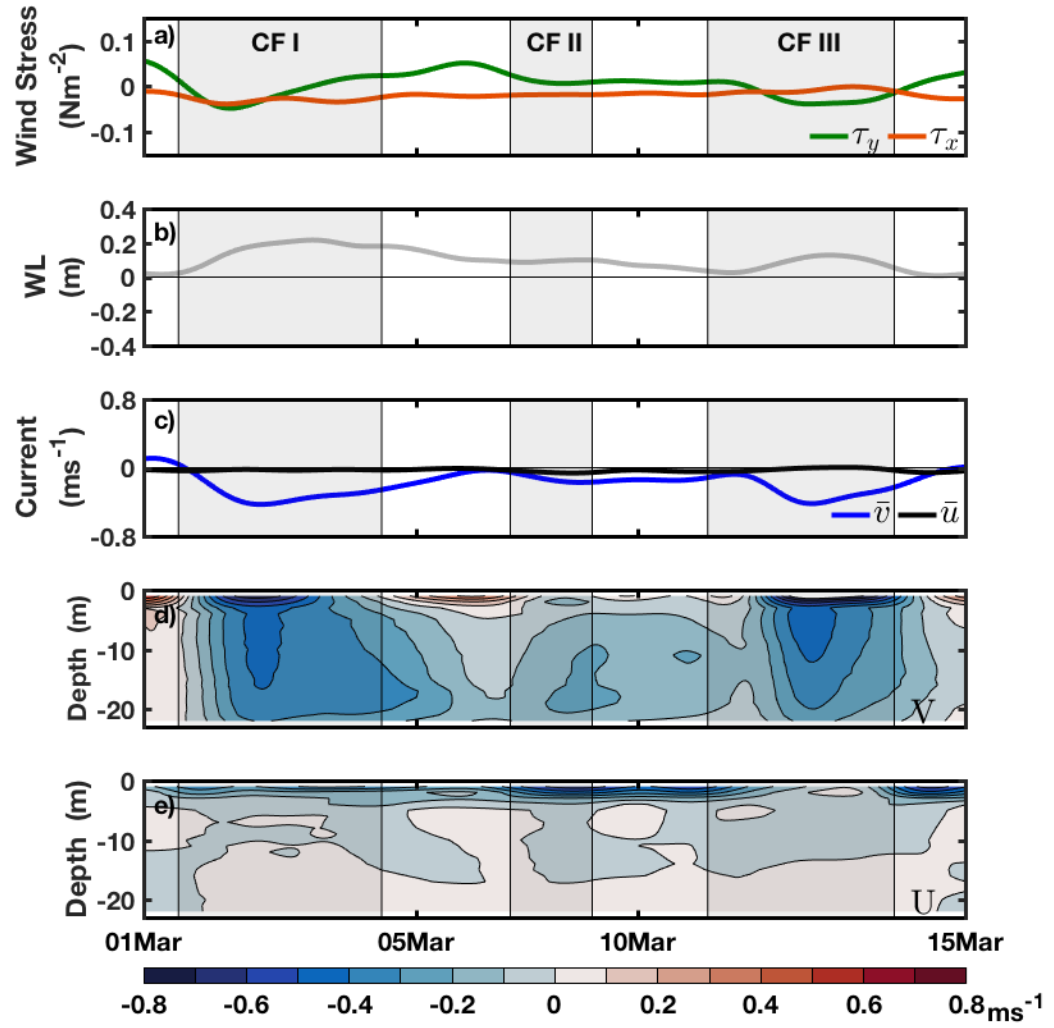


Fig. 4.25. (a) Time series of: (a) along-shelf (T_y) and cross-shelf (T_x) wind-stresses; (b) water-level variations; (c) depth-averaged along-shelf ($\bar{v}$) and cross-shelf ($\bar{u}$) velocities; and depth-varying (d) along-shelf (V) and (e) cross-shelf (U) velocities at the northern site (A1). Negative velocities indicate downcoast and oncoast flows. The shaded sections denote front durations.

4.3.4 A long-shelf momentum Budget

Depth-averaged along-shelf momentum balances were investigated at the northern (A6) and southern (A1) sites for the complete time series (1 February to 31 March 2017) including the CF period (1-15 March 2017), using along-shelf wind-stress, water-level and flow velocity measurements. The role of the different momentum terms was specifically determined for the CF period in the fluctuating momentum budget. It was found that the surface wind-stress and the pressure gradient were the dominant terms in the momentum balance (Table 4.1).

Table 4.1. Mean and standard deviations of estimated depth-averaged along-shelf momentum terms for the CF periods (expressed in 10^{-5} ms^{-2}) for A6 (north) and A1 (south) sites.

Term		Mean	Std	Mean	Std
		A6 site		A1 site	
Acceleration	$\frac{\partial V}{\partial t}$	-0.002	0.19	-0.01	0.20
Water-level gradient	$-g \frac{\partial \eta}{\partial y}$	-0.11	0.08	-0.07	0.04
Wind stress	$\frac{\tau_{s,y}}{\rho_0 h}$	-0.12	0.21	0.02	0.11
Bottom stress	$\frac{-\tau_{b,y}}{\rho_0 h}$	-0.96	0.75	-0.35	0.34
Coriolis	$-fu$	-0.02	0.09	-0.18	0.10

Time-series of decomposed momentum terms for the two-month data are presented in Fig. 4.9 for the northern and southern sites. In the northern site (A6), the pressure gradient was well correlated with the wind-stress for the CF period ($R^2 = 0.76$), while the bottom stress presented opposing fluctuations. In this location, downcoast flows accelerated during periods of strong along-shelf wind-stresses, and relaxation periods

occurred when northerly winds decayed (Fig. 4.9). This was attributed to the dominance of the pressure gradient term, which reflected water-level anomalies that propagated between both sites. In the southern site (A1), the pressure gradient was the dominant term in the momentum budget, and bottom and wind-stress terms played only a small role in the water column. The wind-stress term was more relevant than the pressure gradient term (Table 4.1), although the latter presented larger fluctuations than the wind-stress term (Fig. 4.9).

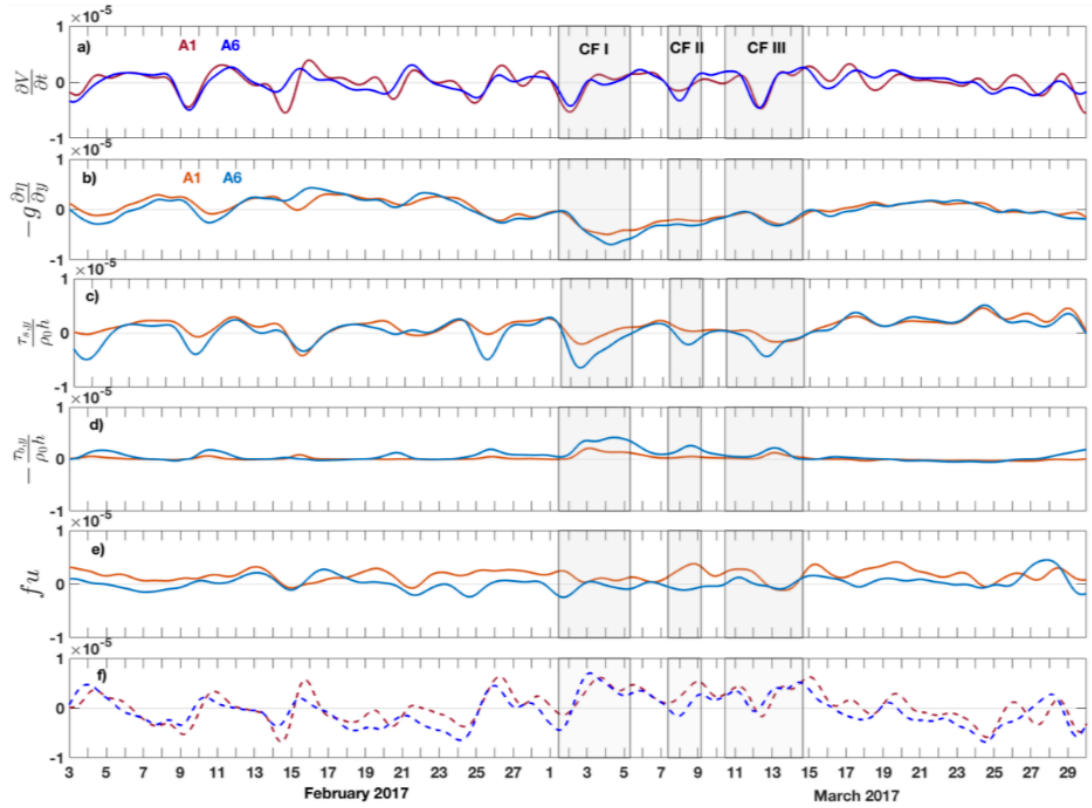


Fig. 4.27. Time-series of the along-shelf momentum terms estimated from Eq. 4.1 for the northern site in Port Aransas (A6 in blue) and southern site in South Padre Island (A1 in red). (a) Local acceleration term; (b) pressure gradient term; (c) wind-stress term; (d) bottom stress term; (e) Coriolis parameter; and (f) the difference between the local acceleration term (left side of Eq. 4.1) and the sum of all terms (a) to (e) (right side of Eq. 4.1).

4.4 Discussion

This research focused on understanding along-shelf flow variations associated with the passage of a few cold fronts of different duration (2 to 4 days) and intensity (maximum τ_y of -0.04 to -0.12 Nm^{-2}) in the southern Texas coast. The inner-shelf flow was predominantly barotropic and the circulation was primarily wind-driven; the along-shelf wind-stress component determined the principal current direction (Winant, 1980; Nowlin et al., 1998, 2005). Winds were predominantly downcoast during the incidence of episodic synoptic-scale cold fronts (Thyng, 2019) but reversed their direction upcoast after the ending of the fronts. For that reason, considerable along-shelf flow direction variations occurred during the study period (1 February to 31 March 2017), which were typical for cold front seasons (October to April) (Huh et al., 1984).

While inner-shelf currents were predominantly downcoast during the passage of cold fronts (Zavala-Hidalgo et al, 2014; Allende-Arandía et al., 2016; Thyng and Hetland, 2018), significant along-shelf current variations existed between Port Aransas (northern site) and South Padre Island (southern site). During the cold-front period, strongest downcoast flows occurred throughout the water column in the northern site, while significantly weaker flows occurred only near to the seabed in the central and southern sites. Time-averaged flows over a two-month period (February to March 2017) showed intense and downcoast (and oncoast) surface flows in the north and weaker and upcoast in the south, and a convergence zone was present in between, off Port Mansfield (Cochrane and Kelly, 1986). Thus, flow speeds were significantly reduced in the central zone due to the interaction of northerly directed downcoast currents and southerly

directed upcoast flows. At this site, the formation of convergent flows was primarily related to alongshore wind component variations ([Zavala-Hidalgo et al, 2014](#)). As a consequence of the convergence zone, material was reported to aggregate in the inner-shelf area south from Port Aransas ([Thyng and Hetland, 2017](#)).

Depth-varying alongshore discrepancies of the flow were related to variations in the strength of the downcoast winds during the cold front period ([Huh et al., 1984](#)). The most energetic cold front (CF I) generated strong winds of τ_y of -0.12 Nm^{-2} in the north, that caused depth-uniform downcoast flows of -0.6 ms^{-1} . In contrast, the same event induced τ_y of -0.04 Nm^{-2} in the south, and generated -0.5 ms^{-1} surface flows that decreased up to -0.3 ms^{-1} towards the seabed. Comparatively, the weakest cold front (CF II) induced -0.6 ms^{-1} downcoast surface flows and -0.3 ms^{-1} near to the seabed in the north, and considerably weaker surface downcoast flows of -0.1 ms^{-1} and -0.3 ms^{-1} near the seabed in the south.

Along-shelf flows presented time-lags of 6 to 11 h to longer and most energetic CFs, and 1 h to shorter and least energetic CF. While these lags were primarily considered to be related to CF intensity and duration, the presence of continental shelf waves could also contribute to the response of the flow (e.g. [Dubranna et al., 2011](#)). Vertical flow structure discrepancies were also related to spatially-varying pre-front wind characteristics. This study suggests that the central and southern sites were more influenced by southeasterly Trade (upcoast) winds, that inhibited the low-energy CF from completely reversing the wind direction towards the south (downcoast). In contrast, the northern site was less affected by Trade winds, and CFs induced strongest

downcoast flows throughout the water column.

Cold fronts induced water-level increases of up to 0.3 m in the north and 0.1 to 0.2 m in the center and southern sites. These water-level increases were similar to the generated by cold fronts in other sites in the northern Gulf of Mexico ([Huang and Li, 2020](#)), and are very relevant for the microtidal southern Texas coast. The combination of cold-front induced water-levels with high spring tides and wave set-up are expected to generate total sea surface elevations of over 1 m, which could cause relevant morphological variations and flooding in low-lying regions of the coast ([Goff et al., 2019](#)).

Generally, the along-shelf flow structure was aligned to isobaths, but the cross-shelf flow was also important in the central site due to convergent winds ([Thyng et al., 2017](#)). Surface wind-stress and pressure gradient were the dominant terms in the along-shelf momentum budget, while the bottom stress and the Coriolis terms were considered negligible ([Grifoll et al., 2016](#)). The wind-stress was the dominant term in the north, which induced isobath aligned along-shore parallel flows ([Thyng et al., 2017](#)). Instead, pressure gradients associated with local sea-level responses to the wind forcing were dominant in the southern site.

4.5 Conclusions

Weather and current measurements collected between February and March 2017 at three sites in the southern Texas coast (Port Aransas in the north, Port Mansfield in the center and South Padre Island in the south) were used to determine along-shelf flow variations induced by cold fronts throughout the water column, and to quantify the relevant terms in the inner-shelf along-shelf momentum budget. Inner-shelf flows were wind-driven, but significant along-shelf variations existed between the northern and southern sites. Cold fronts induced strongest downcoast flows throughout the water column in the northern site, and significantly weaker downcoast surface and bottom flows in the central and southern sites. Time-averaged currents over a longer period of time showed intense downcoast surface flows in the north and weaker upcoast flows in the center and southern sites; thus, a convergence zone was present in between, off Port Mansfield.

The interaction of downcoast currents induced by dominant northerly winds, and upcoast flows induced by dominant southerly winds, significantly reduced flow speeds in the central zone. Thus, spatial variations of the along-shelf wind-stresses was the main cause for flow convergence in the central site. Most intense surface flows occurred in the north, which were less affected by southeasterly (upcoast) winds. In contrast, low-energy cold fronts were unable to completely reverse the wind direction towards the south (downcoast) in southern and central sites due to the stronger influence of southeasterly Trade winds. Consequently, pre-front winds determined spatial variations of along-shelf flows during cold fronts.

Cold fronts induced significant water-level increases, which in combination with high spring tides and wave set-up could generate important sea-surface elevations for low-lying regions in the southern Texas coast. These elevations were larger in the north (up to 0.3 m) than in central and southern sites (up to 0.2 m). The along-shelf momentum budget indicated that surface wind-stress and pressure gradients were the dominant terms, while the bottom stress and Coriolis terms were negligible. The relevance of these terms, however, differed alongshore. The wind-stress was the dominant term in the north, while pressure gradients associated with local sea-level responses to the wind forcing were dominant in the southern site.

Chapter 5

5 General conclusions

The incomplete understanding of the role of episodic synoptic-scale cold fronts in the inner-shelf circulation provided the primary motivation of this research. As such, the main aim was to investigate vertical variations of the structure of subtidal along-shelf flows along the southern Texas coast. The primary dataset comprised hydrodynamic measurements collected over a nearly 2-year period with six ADCP moorings located close to the 20 m isobath. The analysis of these data in combination with local meteorological measurements and synoptic wind and mean sea-level pressure data permitted getting an understanding of the inner-shelf dynamics induced by different types of cold fronts.

This research defined a robust method to identify and categorize cold fronts based on local wind characteristics and synoptic-scale MSLPs. Cold fronts were defined as events of wind blowing at least 24 h from the north (range of 300° to 30°) with sustained wind speeds of $\geq 5 \text{ ms}^{-1}$ for a minimum period of 15 h during which MSLPDiff between Iowa (-93.25°W , 42.75°N in USA) and Quintana Roo (-87.94°W , 20.51°N in Mexico) were $\geq 6 \text{ hPa}$.

The cold fronts were then categorized into different groups through hierarchical clustering depending on their duration and intensity. Two types were defined by the number of consecutive events: *sequential* (typically 2 to 5 events) and *individual* (1 event). Moreover, detailed analysis on the vertical profile of the flow demonstrated significant time-lag differences, mainly related to the front intensity and duration. *Sequential* fronts, were associated with MSLP of ~ 1024 hPa and maximum τ_y of ~ -0.10 Nm^{-2} , and induced downcoast flows of ~ -0.5 ms^{-1} down to ~ 10 m depth (SM and SL). *Individual* fronts were of high and low intensity (defined by MSLP differences) and presented durations of 2 and 4 days (short and long, respectively).

Strongest downcoast flows of -0.5 ms^{-1} encompassing the entire water column (18 m) occurred during *individual* fronts of high intensity (MSLP of up to ~ 1018 hPa with maximum τ_y of ~ -0.15 Nm^{-2}) and long duration (IHL type). *Individual fronts* of low intensity (ILL and ILS types) presented stronger currents than those of higher intensity but shorter duration (IHS type) and of similar MSLP (up to 1016 hPa). While IHS induced flows of ~ -0.3 ms^{-1} down to 8 m depth, ~ -0.4 ms^{-1} flows reached down to 10 m during ILL and ILS. The most common fronts were individual of low intensity and induced relatively weak downcoast currents of up to -0.2 ms^{-1} , and in many cases, these were unable to completely reverse the flow downcoast. Overall, cross-shelf flows were significantly smaller than the along-shelf; and these were generally $0.1\text{--}0.2$ ms^{-1} offcoast.

Theoretical flow expectation for unstratified conditions suggested that the vertical structure of the along-shelf flow response was primarily controlled by the wind forcing during the passage of cold fronts. The most intense flows associated with maximum wind speeds were, overall, successfully captured by the theory. But flow speeds differed prior and/or after the events, particularly for fronts of short duration (i.e. IHS and ILS).

Vertical along-shelf flow variations associated with different cold fronts were analyzed along the southern Texas coast. For that purpose, weather and current measurements collected between February and March 2017 were analyzed at the three alongshore sites: Port Aransas in the north, Port Mansfield in the center and South Padre Island in the south. Time-averaged (February and March 2017) currents showed intense downcoast surface flows in the north and weaker upcoast flows in the center and southern sites; thus, a convergence zone was present in between, off Port Mansfield. Inner-shelf flows were wind-driven, but significant along-shelf variations existed between the northern and southern sites. Cold fronts induced strongest downcoast flows throughout the water column in the northern site, and significantly weaker downcoast surface and bottom flows in the central and southern sites.

The interaction of downcoast currents induced by dominant northerly winds, and upcoast flows induced by dominant southerly winds, significantly reduced flow speeds in the central zone. Thus, spatial variations of the along-shelf wind-stresses was the main cause for flow convergence in the central site. Most intense surface flows occurred in the north, which were less affected by southeasterly (upcoast) winds. In contrast, low-energy cold fronts were unable to completely reverse the wind direction towards the south

(downcoast) in southern and central sites due to the stronger influence of southeasterly Trade winds. Consequently, pre-front winds determined spatial variations of along-shelf flows during cold fronts.

Cold fronts induced significant water-level increases, which in combination with high spring tides and wave set-up, could generate important sea-surface elevations for low-lying regions in the southern Texas coast. These elevations were larger in the north (up to 0.3 m) than in central and southern sites (up to 0.2 m). The along-shelf momentum budget indicated that surface wind-stress and pressure gradients were the dominant terms, while the bottom stress and Coriolis terms were negligible. The relevance of these terms, however, differed alongshore. The wind-stress was the dominant term in the north, while pressure gradients associated with local sea-level responses to the wind forcing were dominant in the southern site.

5 Conclusiones generales

La comprensión incompleta del papel de los frentes fríos episódicos a escala sinóptica en la circulación interior de la plataforma proporcionó la motivación principal de esta investigación. Por ello, el objetivo principal fue investigar las variaciones verticales de la estructura de los flujos submareales a lo largo de la plataforma a lo largo de la costa sur de Texas. El conjunto de datos comprendía mediciones hidrodinámicas recogidas durante un período de casi dos años con seis ADCP situados cerca de la isóbata de 20 m. El análisis de estos datos en combinación con mediciones meteorológicas locales y los datos sinópticos de viento y presión atmosférica al nivel medio del mar permitió obtener una comprensión de la dinámica interior de la plataforma inducida por diferentes tipos de frentes fríos.

Esta investigación definió un método robusto para identificar y categorizar los frentes fríos basándose en las características locales del viento y presiones atmosféricas al nivel medio del mar a escala sinóptica. Los frentes fríos se definieron como eventos de viento que soplan al menos 24 h desde el norte (rango de 300° a 30°) con velocidades de viento sostenidas $\geq 5 \text{ ms}^{-1}$ durante un período mínimo de 15 h durante el cual el MSLPDiff entre Iowa (-93.25°W , 42.75°N en USA) y Quintana Roo (-87.94°W , 20.51°N en México) fue $\geq 6 \text{ hPa}$.

A continuación, los frentes fríos se clasificaron en diferentes grupos mediante una agrupación jerárquica en función de su duración e intensidad. Se definieron dos tipos según el número de eventos consecutivos: secuenciales (normalmente de 2 a 5 eventos) e individuales (1 evento). Además, el análisis detallado del perfil vertical del flujo

demostró la existencia de diferencias significativas en el tiempo, principalmente relacionadas con la intensidad y la duración del frente. Los frentes secuenciales, se asociaron con MSLP de ~ 1024 hPa y τ_y máxima de $\sim -0.10 \text{ Nm}^{-2}$, e indujeron flujos descendentes de $\sim -0.5 \text{ ms}^{-1}$ hasta ~ 10 m de profundidad (SM y SL). Los frentes individuales fueron de alta y baja intensidad (definidos por las diferencias de MSLP) y presentaron duraciones de 2 y 4 días (corta y larga, respectivamente).

Los flujos descendentes más fuertes de -0.5 ms^{-1} que abarcan toda la columna de agua (18 m) se produjeron durante los frentes individuales de alta intensidad (MSLP de hasta ~ 1018 hPa con un máximo de τ_y de $\sim -0.15 \text{ Nm}^{-2}$) y larga duración (tipo IHL). Los frentes individuales de baja intensidad (tipos ILL e ILS) presentaron corrientes más fuertes que los de mayor intensidad pero menor duración (tipo IHS) y de similar MSLP (hasta 1016 hPa). Mientras que el IHS indujo flujos de $\sim -0.3 \text{ ms}^{-1}$ hasta 8 m de profundidad, los flujos de $\sim -0.4 \text{ ms}^{-1}$ llegaron hasta 10 m durante el ILL y el ILS. Los frentes más comunes fueron individuales de baja intensidad e indujeron corrientes descendentes relativamente débiles de hasta -0.2 ms^{-1} , y en muchos casos, éstas no pudieron invertir completamente el flujo descendente. En general, los flujos transversales a la plataforma fueron significativamente menores que los longitudinales, y éstos fueron generalmente de $0.1\text{-}0.2 \text{ ms}^{-1}$ frente a la costa.

La expectativa de flujo teórico para condiciones no estratificadas sugirió que la estructura vertical de la respuesta del flujo a lo largo de la plataforma estaba controlada principalmente por el forzamiento del viento durante el paso de los frentes fríos. Los flujos más intensos asociados a las velocidades máximas del viento fueron, en general,

capturados con éxito por la teoría. Sin embargo, las velocidades de los flujos difieren antes y/o después de los eventos, particularmente para los frentes de corta duración (es decir, IHS e ILS).

Se analizaron las variaciones verticales del flujo a lo largo de la plataforma asociadas a diferentes frentes fríos a lo largo de la costa sur de Texas. Para ello, se analizaron las mediciones meteorológicas y de corrientes recogidas entre febrero y marzo de 2017 en los tres sitios a lo largo de la costa: Port Aransas en el norte, Port Mansfield en el centro y South Padre Island en el sur. Las corrientes promediadas en el tiempo (febrero y marzo de 2017) mostraron intensos flujos superficiales descendentes en el norte y flujos ascendentes más débiles en los sitios del centro y del sur; por lo tanto, había una zona de convergencia en la zona centro, frente a Port Mansfield. Los flujos internos de la plataforma eran impulsados por el viento, pero existían variaciones significativas a lo largo de la plataforma entre los sitios del norte y del sur. Los frentes fríos indujeron los flujos más fuertes hacia abajo en toda la columna de agua en el sitio norte, y flujos significativamente más débiles hacia abajo en la superficie y el fondo en los sitios del centro y del sur.

La interacción de las corrientes descendentes inducidas por los vientos dominantes del norte y los flujos ascendentes inducidos por los vientos dominantes del sur redujo significativamente las velocidades del flujo en la zona central. Así, las variaciones espaciales de los esfuerzos del viento a lo largo de la plataforma fueron la principal causa de la convergencia de los flujos en la zona central. Los flujos superficiales más intensos se produjeron en el norte, que se vio menos afectado por los vientos del sureste

(costa arriba). Por el contrario, los frentes fríos de baja energía no pudieron invertir completamente la dirección del viento hacia el sur (costa abajo) en los sitios del sur y del centro debido a la mayor influencia de los vientos alisios del sureste. En consecuencia, los vientos prefrontales determinaron las variaciones espaciales de los flujos a lo largo de la plataforma durante los frentes fríos.

Los frentes fríos indujeron aumentos significativos del nivel del agua, que en combinación con las altas mareas de primavera y la formación de olas, pudieron generar importantes elevaciones de la superficie del mar para las regiones bajas de la costa sur de Texas. Estas elevaciones fueron mayores en el norte (hasta 0.3 m) que en el centro y el sur (hasta 0.2 m). El balance del momento a lo largo de la plataforma indicó que los términos dominantes eran el esfuerzo del viento en superficie y los gradientes de presión, mientras que los términos de tensión en el fondo y Coriolis eran insignificantes. Sin embargo, la importancia de estos términos difiere a lo largo de la costa. El esfuerzo del viento fue el término dominante en el norte, mientras que los gradientes de presión asociados a las respuestas locales del nivel del mar al forzamiento del viento fueron dominantes en el sitio del sur.

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Nearshore current variations during the passage of cold fronts in NW Gulf of Mexico

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ABSTRACT

Yearly-average along-shelf winds were predominantly upcoast over the last two decades, but large seasonal fluctuations existed. This study provides an example of how the passage of episodic cold fronts generally induce the reversing of along-shelf flows downcoast on the southern Texas coast. A total of 819 cold fronts of 4 days of average duration were identified between 1984 and 2018, and the vertical structure of the flow was analyzed for 38 cold fronts between November 2016 and October 2018 at a location 10 km offshore of Port Aransas. Cold fronts were identified based on local wind speeds and directions and synoptic-scale mean sea-level pressure differences, and then categorized through hierarchical clustering. Theoretical flow expectation for unstratified conditions suggested that the flow response was primarily controlled by the wind forcing during the passage of cold fronts. Detailed analysis on the vertical profile of the flow demonstrated significant time-lag differences, mainly related to the front intensity and duration. Strongest downcoast flows of -0.5 ms^{-1} encompassing the entire water column (18 m depth) were associated with individual fronts of high intensity (τ_x of $\sim -0.15 \text{ Nm}^{-2}$) and long duration (at least 4 days). The most common fronts were individual of low intensity (τ_x of $\sim -0.05 \text{ Nm}^{-2}$) and short duration (up to 2 days), and induced relatively weak downcoast currents of up to -0.2 ms^{-1} , and in many cases, these were unable to completely reverse the flow downcoast. This study highlights the relevant role of episodic cold fronts in reversing and intensifying inner-shelf currents on the southern Texas coast, and emphasizes differences in the flow response related to cold front characteristics.

1. Introduction

Cold fronts are defined as cold air mass propagations over warmer surfaces. In the Gulf of Mexico, cold fronts are related to synoptic-scale atmospheric waves associated with high-pressure systems, and commonly originated at the Rocky Mountains (Appendini et al., 2018). These fronts, locally known as *nortes*, generate strong winds ($>10 \text{ ms}^{-1}$) and significant temperature drops, and are the cause of operational downtimes for shipping and offshore industrial activities (Schultz et al., 1997). In the northwestern Gulf of Mexico, cold fronts occur more frequently than tropical cyclones, and significantly modulate nearshore hydrodynamics (Needham and Keim, 2012; Appendini et al., 2018) and induce large cumulative coastal change that threaten population and infrastructure (Moeller et al., 1993).

In the past, cold fronts have been primarily identified using local atmospheric data (Frankenfield, 1917; Mosiño, 1964) and based on

resultant air temperature differences (Hill, 1969; Mecikalski and Tilley, 1992; Reding, 1992; Schultz et al., 1998), cold air mass trajectories and rainfall patterns (Willett, 1934; Dallavalle and Bosart, 1975; Klaus, 1973; Mecikalski and Tilley, 1992). More recently, thresholds were set to identify these fronts based on the wind characteristics and induced rainfall and air temperature drops (Pérez et al., 2014). Moreover, several cold front types were defined based on their intensity and wave generation area (Appendini et al., 2018). Nevertheless, little is still known about inner-shelf vertical flow variations induced by cold fronts of different duration and intensity.

The nearshore or inner-shelf (depths of a few to tens of meters) constitutes a transition zone between the continental shelf and surf zone circulation. The Texas continental shelf break acts as a barrier to the transport of material due to strong bathymetric gradients, as planetary vorticity inhibits cross-bathymetric flows (e.g., Cushman-Roisin and Beckers, 2011). While substantial amounts of particles are transported

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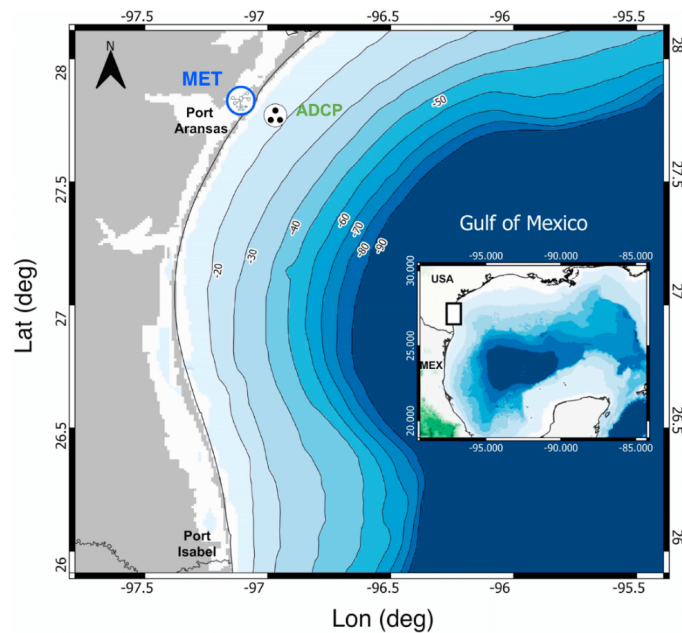


Fig. 1. Bathymetric map showing the location of the ADCP mooring close to the 20-m isobath in the inner Texas-Louisiana Shelf, NW Gulf of Mexico. The nearest weather station at Port Aransas is indicated as MET (PTAT2 from www.ndbc.noaa.gov).

shoreward from deep waters, their fate in the coastal region is less predictable due to the variability of inner-shelf circulation processes (Lentz and Fewings, 2012; Roth et al., 2017; Huguenard et al., 2020). Seasonal (Romero-Centeno et al., 2003; Dzwonkowski et al., 2011; Zavala-Hidalgo et al., 2014; Judt et al., 2016) and interannual (Fernandez-Partagas and Mooers, 1975; Magaña et al., 2003) wind-stress variations are considered the principal forcing for mass transport in the Gulf of Mexico, but in some locations, buoyant plumes (Walker et al., 2005) and surface gravity waves (Lentz et al., 2008) can also play a significant forcing role.

Along-shelf wind stresses drive the cross-shelf circulation through Ekman transport, which diminishes closer to the shore due to shallow depths and the influence of the coastal boundary (Dzwonkowski et al., 2011; Lentz and Fewings, 2012; Huguenard et al., 2020). Thus, the inner-shelf circulation is primarily wind-driven and the alongshore component determines the principal current direction (Winant, 1980; Nowlin et al., 2005). In the Texas-Louisiana shelf, strong continental shelf bathymetric gradients constrain the inner-shelf mass transport alongshore, inhibiting cross-shelf exchange (Thyng and Hetland, 2018). Winds along this shelf are typically upcoast in summer and downcoast in winter, yet interannual differences in water mass transport occur (Thyng, 2019).

The southwestern Gulf of Mexico presents regions of seasonal convergence of winds (Zavala-Hidalgo et al., 2014). In particular, the inner-shelf Port Aransas area presents locations of material aggregation, as a consequence of variations in the along-shelf circulation (Thyng and Hetland, 2017). Moreover, in this region, cold fronts are considered capable of reversing inner-shelf surface currents (Zavala-Hidalgo et al., 2014; Allende-Arandía et al., 2016). The amount of research on inner-shelf circulation patterns is fairly limited in the southwestern Gulf

of Mexico compared to other locations (e.g. Rivas, 2017; Thyng and Hetland, 2018). This research contributes to the understanding of the role of episodic synoptic-scale cold fronts in the inner-shelf circulation along the southern Texas coast. The overall goal of this paper is to examine the vertical structure of subtidal along-shelf flows during the passage of cold fronts of different duration and magnitude.

2. Field site

The research site is located offshore from Port Aransas Pass in the inner Texas-Louisiana shelf, in the northwestern Gulf of Mexico (Fig. 1). Large bathymetric gradients on the continental shelf act as a boundary for the cross-shelf mass exchange between the outer and inner regions (Thyng and Hetland, 2018). The wind forcing is considered the dominant mechanism for inner-shelf circulation (Nowlin et al., 1998), and seaward advected river plumes induce baroclinically-driven flows that can enhance cross-shelf transport in summer (Thyng and Hetland, 2018).

Moderate southeast winds prevail from spring to fall, but synoptic-scale cold fronts induce strong northerly winds that alter wave characteristics and current directions during the winter months (Lohse, 1955). Along-shelf wind stresses and currents are highly-correlated in the inner-shelf (Nowlin et al., 1998), however, flow directions also depend on the coastline orientation relative to the dominant wind forcing. As a consequence, downcoast currents dominate the upper and central Texas coast, while upcoast currents prevail along the southern coast; a convergence zone is identified between Port Isabel and Port Aransas (Cochrane and Kelly, 1986). Along-shelf flow directions are expected to vary considerably in the southern Texas coast during the cold front season from October to April (Huh et al., 1984). Upcoast mass transport

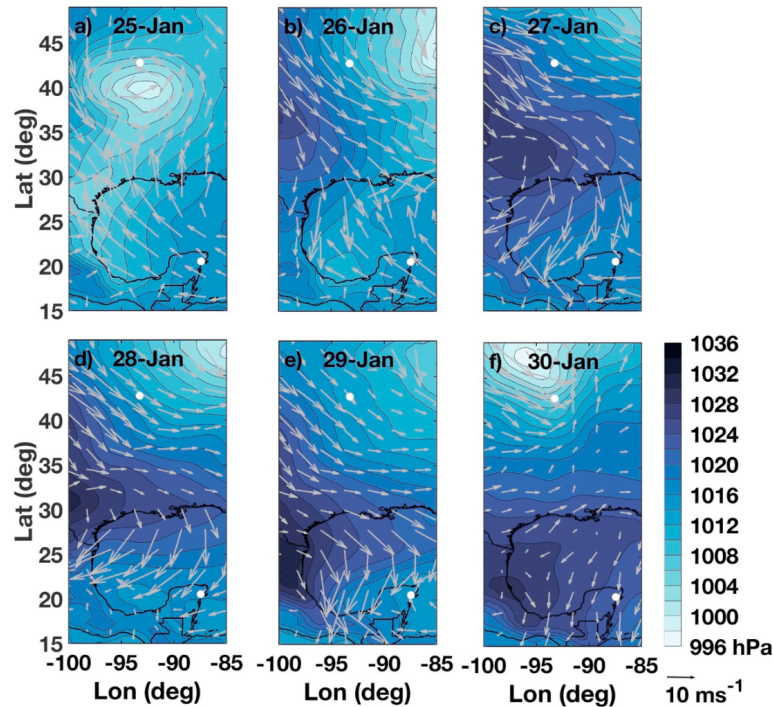


Fig. 2. Temporal sequence of the spatial distribution of mean sea-level pressure (colorbar) and wind speeds and directions (arrows) before (a), during (b, c, d, e), and after (f) the passage of cold front #9 in late January 2017. The dots represent the locations between which pressure differences were calculated for the cold front identification.

dominates most of the year, but cold fronts can reverse surface currents towards Mexico (Thyng and Hetland, 2018).

3. Methods

Data were gathered to analyze current structure variations associated with the wind forcing during the passage of cold fronts. Hydrodynamic measurements were collected in the nearshore over a nearly 2-year period during the CIGOM project (Consortio de Investigación del Golfo de México; <https://cigom.org/>) with a moored ADCP (Acoustic Doppler Current Profiler) located close to the 20-m isobath offshore of the southern Texas coast (Fig. 1). Concurrently, local meteorological observations were acquired from the PTAT2 National Data Buoy Center weather station (www.ndbc.noaa.gov), and synoptic weather maps were obtained from the ERA-Interim global atmospheric reanalysis dataset (ECMWF; <https://www.ecmwf.int/>).

3.1. Current measurements

An upward-looking 1 MHz ADCP (Nortek Aquadopp current profiler) was moored at the ~20-m isobath offshore from Port Aransas Pass from November 2016 to October 2018 (Fig. 1). A few data gaps existed in the time-series due to technical issues or the inability to replace instrument batteries during adverse weather conditions. East-west, north-south, and up-down velocity components were measured in 0.75 m bins (22 bins

within the water column) at a sampling rate of 1 Hz over a period of 2 min, and averaged profiles were obtained every 20 min. Data recorded with larger instrument tilting angles than 20° were disregarded, and unreliable measurements were removed applying quality control thresholds (<20 counts of return amplitudes). The instrument presented a blanking distance of 0.4 m from the seabed, and 10% of the uppermost velocity profile (approximately above 1.85 m depth) was discarded due to side lobe interference with the water surface (<0.60 of correlation between along-shelf current and wind speed). Therefore, average velocities for the surface and bottom layers excluded the uppermost 1.85 m and lowermost 0.4 m of the water column, respectively.

Raw current measurements were filtered applying the Lanczos low-pass filter with a cut-off period of 30 h to remove inertial, tidal and higher frequency fluctuations. The velocity components were rotated 45° clockwise to align them with the northeast-southwest orientation of the ~20-m isobath. A right-handed coordinate system was applied to the rotated along-shelf and cross-shelf currents; positive x (u) and y (v) indicating offcoast and upcoast directions, respectively.

3.2. Wind observations

Hourly data of wind speed and direction, atmospheric air pressure and air temperature were acquired from the PTAT2 NOAA weather station near Port Aransas (www.ndbc.noaa.gov) for a two-year period (2016–2018). The wind data were filtered applying the Lanczos low-

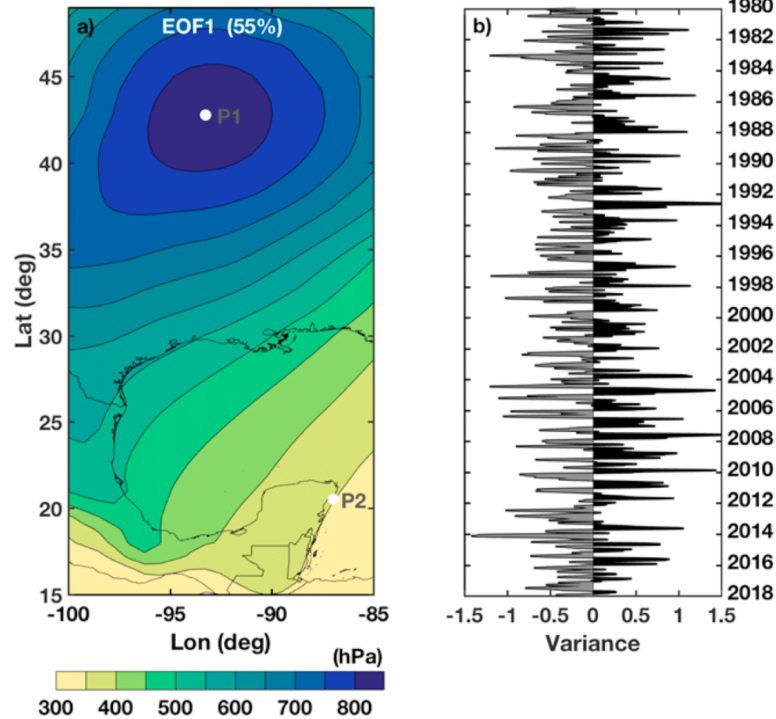


Fig. 3. Spatial (a) and temporal (b) components of the first EOF mode (55% of variance) for MSLP anomalies from 1984 to 2018. The dots in Iowa (P1) and Quintana Roo (P2) correspond to locations of maximum and minimum MSLP variance for the time-series.

pass filter with a cut-off period of 30 h and converted to the oceanographic convention (direction toward which the wind is blowing). The cross-shelf and along-shelf wind stress components were calculated as

$$(\tau_x, \tau_y) = \rho_a C_D |W| (u_w, v_w) \quad (1)$$

being ρ_a air density (1.2 kg m^{-3}), C_D wind drag coefficient, u_w and v_w cross-shore and alongshore wind velocity components measured at 10 m elevation and W wind speed. C_D was equal to $(0.49 + 0.065 U)10^{-3}$ and 1.14×10^{-3} for wind speeds greater or equal and lesser than 10 ms^{-1} (Large and Pond, 1981), respectively.

Synoptic weather maps were obtained from the ERA-Interim global atmospheric reanalysis dataset of ECMWF (European Centre for Medium-Range Weather Forecasts; <https://www.ecmwf.int/>). Six-hourly data of zonal and meridional wind components were acquired together with mean sea-level pressure (MSLP) over a grid of 0.75° of resolution for a region of interest from 15° to 50° N and 85° – 100° W. A time sequence of maps of combined MSLP and wind data, before, during, and after the passage of a cold front over the study area in late January 2017 is presented in Fig. 2. Available data from 1984 to 2018 were used to determine spatial MSLP differences, which were used to identify the cold fronts. Gaps in the local PTAT2 weather station time-series were filled with the closest available node from ERA-Interim, which presented wind speed and direction correlation coefficients of 0.80 and 0.60, respectively.

3.3. Cold front identification

A method to identify cold fronts was developed based on local wind speeds and directions and spatial synoptic mean sea-level pressure differences ($\text{MSLP}_{\text{diff}}$) as being the main forcing parameters for front generation (e.g. Appendini et al., 2018). A cold front was defined as an event of wind blowing at least 24 h from the north (range of 300° – 30°) with sustained wind speeds of $\geq 5 \text{ ms}^{-1}$ for a minimum period of 15 h during which $\text{MSLP}_{\text{diff}}$ between Iowa (-93.25° W, 42.75° N in USA) and Quintana Roo (-87.94° W, 20.51° N in Mexico) were $\geq 6 \text{ hPa}$. These locations were defined as sites of maximum and minimum MSLP variance calculated through the first mode (explains 55% of MSLP variance) of an empirical orthogonal function (EOF) decomposition of spatial MSLP anomalies from 1984 to 2018 (Fig. 3). The cold fronts ended when the prevailing wind directions changed, and a minimum period of 15 h was established to differentiate consecutive events.

An illustrative example of wind and flow conditions before, during, and after the passing of a cold front (#9 in Fig. 7) is presented in Fig. 4. The shifting of the wind direction towards the south (and then north) marks the starting (ending) time of the front, and that time difference is the front duration, t_f . This front started on January 25th and ended on January 30th; thus, t_f was 5 days (Fig. 4a, f). The period of time at which the wind speed $\geq 5 \text{ ms}^{-1}$ was represented by t_w , and it was 3 days (Fig. 4a). In addition, it presented a MSLP difference ($\text{MSLP}_{\text{diff}}$) of 8 hPa (Fig. 4c).

During the passing of the front, τ_y became negative (Fig. 4b) and the

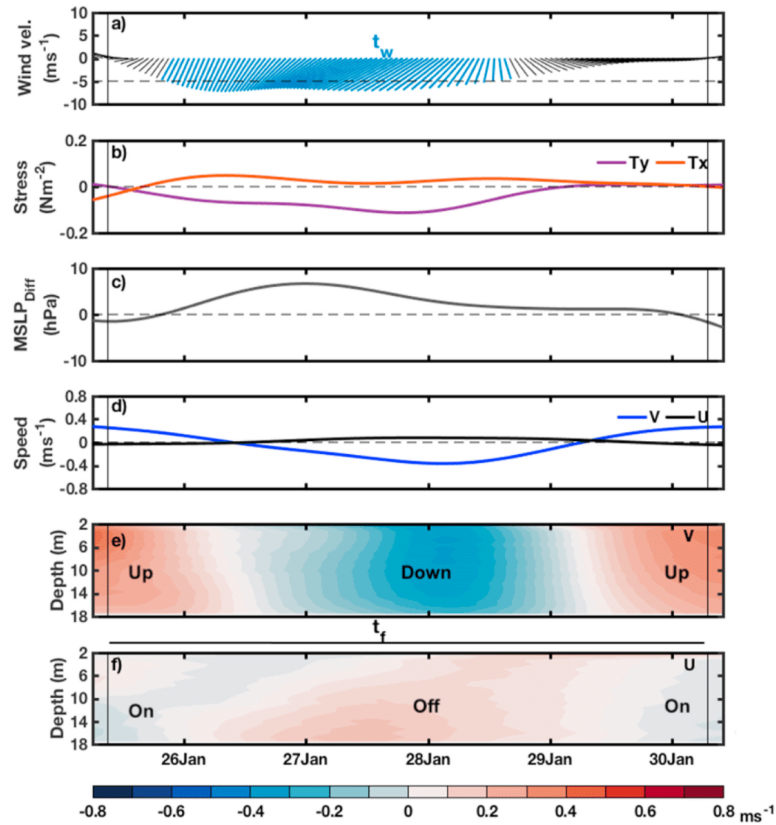


Fig. 4. Time-series of wind and flow characteristics for cold front #9 at the end of January 2017: a) wind velocity vectors (oceanographic convention); b) along-shelf (τ_y) and cross-shelf (τ_x) wind-stress components; c) mean sea level pressure differences ($MSLP_{diff}$); d) depth-averaged along-shelf (V) and cross-shelf (U) currents; and e) depth-varying along-shelf (V) and f) cross-shelf (U) velocities. Positive indicate upcoast (up) and offcoast (off) velocities. The vertical lines denote the front starting and ending times.

currents reversed downcoast, in the entire water column (Fig. 4d and e). Maximum downcoast current speeds of -0.6 ms^{-1} occurred in phase with maximum τ_y of -0.1 Nm^{-2} . Cross-shelf currents were comparatively weak ($<0.2 \text{ ms}^{-1}$) and oscillated oncoast and offcoast depending on wind direction changes (Fig. 4f).

The identified cold fronts were assembled into several groups based on their duration (t_f), sustained wind speed duration (t_w), and MSLP differences ($MSLP_{diff}$) using a multi-dimensional scaling (MDS) analysis. This method classifies objects in full-dimensional space and represents them in fewer dimensions preserving the standardized distance relationships among the samples accurately (e.g. Clarke, 1993). The statistical significance of the cluster formation was verified using the cophenetic correlation coefficient (cop ; value of 1 is perfect match between cluster solution and input data) and a stress criterion (str ; the closer to zero the better the multidimensional is represented) was used to evaluate the dimensionality obtained from the MDS.

4. Results

4.1. Temporal wind-stress and current variations

Along-shelf wind-stress (τ_y) direction changes were examined over 35-years, from 1984 to 2018, to determine periods of dominant upcoast or downcoast winds at a seasonal scale. An average of 23 ± 3 cold fronts occurred per year, but large interannual variations existed (Fig. 5b). Yearly-averaged τ_y indicated significant interannual differences, with an overall dominance of upcoast winds (positive τ_y) over the past two decades (Fig. 5d). A seasonal signal was present in the directionality of τ_y , downcoast dominance (negative) in winter (December to February) and sometimes in spring (March to May), and upcoast (positive) in summer (June to August) and autumn (September to November) (Fig. 5c). The 2016–2018 period (tinted boxes in Fig. 5) showed net annual dominance of upcoast winds (Fig. 5d), and the seasonal reversing downcoast in winter (Fig. 5c).

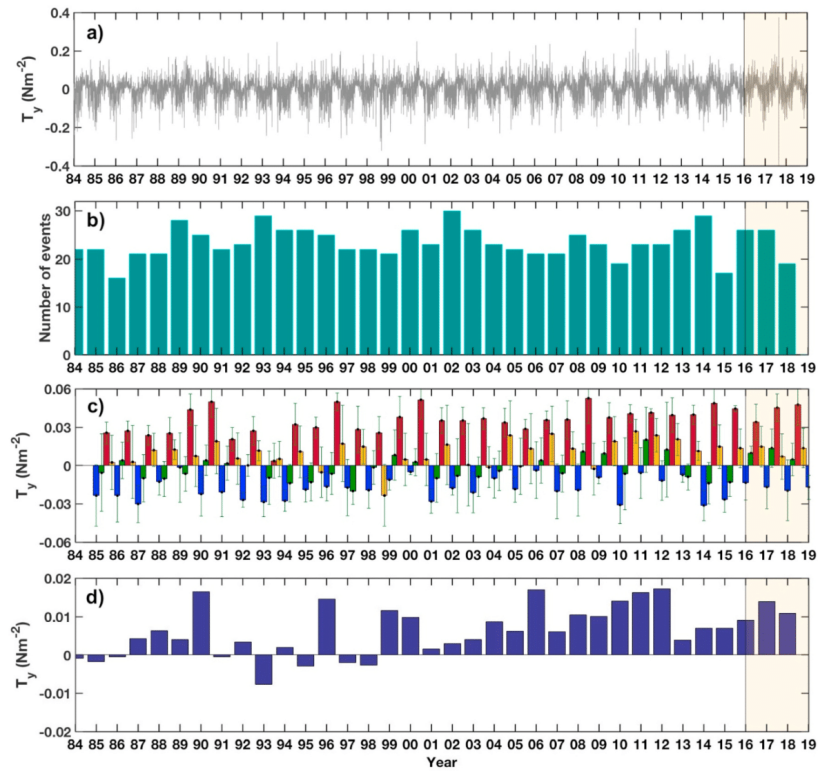


Fig. 5. Time-series from 1984 to 2018 of: (a) hourly along-shelf wind-stresses (τ_y); (b) number of cold fronts per year; (c) seasonally-averaged τ_y (winter, blue; spring, green; summer, red; autumn, orange); and (d) annually-averaged τ_y . The period of interest from 2016 to 2018 is highlighted with tinted boxes. Positive (negative) τ_y indicate upcoast (downcoast) winds.

Table 1

Characteristics of the assembled historical cold fronts (CF) from 1984 to 2018: event duration (t_f), sustained wind speed duration (t_w), mean sea level pressure differences ($MSLP_{diff}$) and % of occurrence.

CF Group		t_f (days)		t_w (days)		$MSLP_{diff}$ (hPa)		Occurrence (%)
		mean	std	mean	std	mean	std	
Sequential (S)	High (SH)	22	2	14	3	26	6	0.5
	Moderate (SM)	11	2	8	2	25	6	6.5
	Low (SL)	6	2	4	2	24	5	15
Individual (I)	High (IH)	4	1	3	1	17	4	20
	Low (IL)	2	1	2	1	11	3	58
CF average 1984–2018		4	3	3	2	15	7	

4.2. Cold front categorization

4.2.1. Historical: 1984 to 2018

A total of 819 cold fronts were identified using the available historical weather data from 1984 to 2018, which presented average durations ($\bar{t}_f$) of 4 days, average sustained wind speed durations ($\bar{t}_w$) of 3 days and average MSLP differences ($\overline{MSLP_{diff}}$) of 15 hPa (Table 1). Sequential events were defined as consecutive cold fronts with more than

12 h in between. In the historical data-set cold fronts were assembled as sequential (more than one event) and individual (single event) of high, moderate and low impact at a Euclidean distance of 4.3, and with an adequate cluster solution ($str = 0.01$; $c = 0.88$) (Table 1; Fig. 6a, c).

Sequential (S) cold fronts were 22% of the total and presented large $MSLP_{diff}$ of 24–26 hPa (Table 1). Among them, sequential-high (SH) corresponded to 0.5% and consisted of more than 5 consecutive events, hence, these were highly persistent, t_f of 22 days (more than five times the historical average, $\bar{t}_f$, of 4 days) with t_w of 14 days (nearly five times

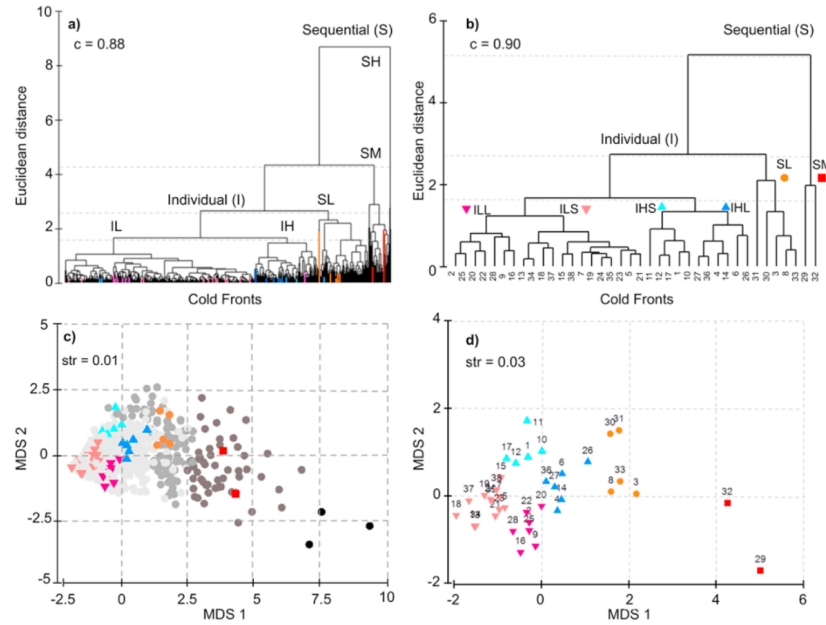


Fig. 6. Dendrograms of (a) historical 819 cold fronts (CF) in gray, and (b) 38 CFs from 2016 to 2018; and their respective MDS ordinations in (c) and (d). The colored lines in (a) correspond to the CFs represented in (b). Dark to light gray dots in (c) refer to the historical SH, SM, SL, IH and IL, respectively.

Table 2

Characteristics of the grouped 38 cold fronts (CF) from November 2016 to October 2018: event duration (t_f), sustained wind speed duration (t_w), mean sea level pressure differences ($MSLP_{diff}$) and % of occurrence.

CF Group		t_f (days)		t_w (days)		$MSLP_{diff}$ (hPa)		Occurrence (%)
		mean	std	mean	std	mean	std	
Sequential (S)	Moderate (SM)	14	1	7	1	25	6	5
	Low (SL)	7	2	4	1	26	4	13
Individual (I)	High-Long (IHL)	4	1	3	1	19	3	16
	High-Short (IHS)	2	1	1	1	21	3	13
	Low-Long (ILL)	4	1	2	1	10	3	19
	Low-Short (ILS)	2	1	1	0	10	3	34
	CF average 2016–2018	4	3	2	2	16	7	

the historical average, $\bar{t}_w$, of 3 days) (Table 1). A total of 6.5% were *sequential-moderate* (SM), consisted of up to 5 consecutive fronts, and lasted t_f of 11 days ($t_f \sim 3\bar{t}_f$) with t_w of 8 days ($t_w \sim 3\bar{t}_w$), and 15% were *sequential-low* (SL), formed by 2 fronts, and had t_f of 6 days ($t_f \sim 1.5\bar{t}_f$) and t_w of 4 days ($t_w \sim 1.5\bar{t}_w$) (Table 1).

A total of 78% of the fronts were *individual* (I), among which 20% were *individual-high* (IH) with $MSLP_{diff}$ of 17 hPa and t_f of 4 days ($t_f = \bar{t}_f$) and t_w of 3 days ($t_w = \bar{t}_w$) and 58% were *individual-low* (IL) with $MSLP_{diff}$ of 11 hPa and t_f and t_w of 2 days (both below average) (Table 1; Fig. 6a, c).

4.2.2. Recent: 2016 to 2018

A total of 38 cold fronts occurred from November 2016 to October 2018, and presented similar characteristics to the historical average, $\bar{t}_f$ of 4 days, $\bar{t}_w$ of 2 days and $MSLP_{diff}$ of 16 hPa. Among these, 21 fronts occurred between early-November 2016 to early-May 2017, and the other 17 fronts from mid-October 2017 to early-April 2018. The fronts were divided as *sequential* (18%; $MSLP_{diff} \sim 25$ hPa) or *individual* (82%; $MSLP_{diff}$ 10–21 hPa) at a Euclidean distance of 5.1 (Fig. 6b). A total of 5% were *sequential-moderate* (SM; ■), up to 5 consecutive events, with t_f of 14 days ($3\bar{t}_f$) and t_w of 7 days ($3\bar{t}_w$) (Table 2; Fig. 6b, d). And 13% were *sequential-low* (SL; ●), up to 2 consecutive events, with

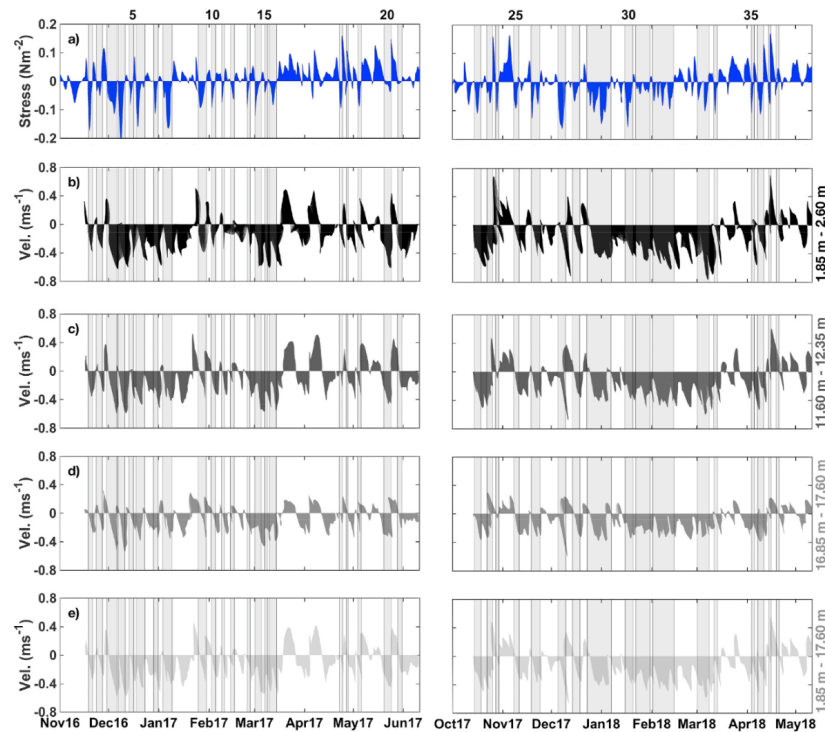


Fig. 7. Time-series from November 2016 to October 2018 of wind stress (a) and currents averaged at: (b) the surface layer, (c) mid-layer, (d) bottom layer, and (e) water column. The vertical shaded boxes represent each of the identified cold fronts (CF; numbered above) and described in Table 2.

t_f of 7 days ($1.5t_f$) and t_w of 4 days ($1.5t_w$) (Fig. 6a, c).

Individual (I) fronts were grouped as *individual-high* (IH $\blacktriangle$; 29%) and *individual-low* (IL $\blacktriangledown$; 53%) (Fig. 6b, d; Table 2), of larger and smaller MSLP_{diff} of 19–21 and 10 hPa, respectively. These groups were further subdivided as *long* (IHL and ILL; $\blacktriangle$, $\blacktriangledown$) and *short* (IHS and ILS; $\blacktriangle$, $\blacktriangledown$), which presented t_f of 4 days ($\sim t_f$) and t_w of 2–3 days ($\sim t_w$), and t_f of 2 days ($< \bar{t}_f$) and t_w of 1 day ($< \bar{t}_w$), respectively (Fig. 6b, d; Table 2). The most common cold fronts were ILS (34%, $\blacktriangledown$), individual fronts of relatively low intensity and 2 days of duration.

4.3. Vertical structure of the flow

4.3.1. Layer-averaged currents

Wind stress variations were related to current velocities at the surface, middle and bottom layers and to the average throughout the water column, to understand the effect of cold fronts on the vertical structure of the flow (Fig. 7). Cross-shelf velocities were generally weak $< 0.20 \text{ ms}^{-1}$, and the most frequent upcoast currents occurred in summer (i.e. June 2017), up to 0.20 ms^{-1} , associated with maximum northward τ_y of 0.1 Nm^{-2} . Downcoast currents were up to -0.40 ms^{-1} over the winter and spring, when maximum southward τ_y of -0.1 Nm^{-2} occurred. All fronts induced the reversal of the current from upcoast (positive) to downcoast (negative). While downcoast currents were weaker near the bottom than at the surface, a similar vertical structure was preserved (Fig. 7). Specific intense and persistent events (i.e. cold front #27 in

Fig. 7) presented maximum downcoast surface flows of up to -0.80 ms^{-1} related to intensive downcoast winds, τ_y of -0.15 Nm^{-2} . Large periods of relatively strong downcoast currents of $\sim -0.40 \text{ ms}^{-1}$ were also observed due to the cumulative effect of dominant downcoast wind stress (i.e. January to early March 2018) (Fig. 7).

4.3.2. Depth-varying currents

Along-shelf and cross-shelf velocity variations were analyzed throughout the water column in order to understand the effect of different cold front types on the structure of the flow. Representative fronts were selected from each group to analyze into detail vertical flow variations (Figs. 8–10). Sequential cold fronts SM (# 32; $\bullet$) and SL (# 33, $\circ$) were represented in Fig. 8. τ_y attained significant fluctuations, and these fronts induced downcoast flows of up to -0.7 ms^{-1} and offcoast flows of $0.2\text{--}0.4 \text{ ms}^{-1}$ up to $\sim 10 \text{ m}$ depth when $\tau_y \sim -0.05 \text{ Nm}^{-2}$ reached.

Individual-high fronts of long (IHL, $\blacktriangle$) and short (IHS, $\blacktriangle$) duration are presented in Fig. 9. Intense and persistent winds (τ_y of up to -0.15 Nm^{-2}) during IHL induced strong downcoast flows of up to -0.7 across the water column, compared to -0.3 ms^{-1} flows associated with IHS (Fig. 9). In both cases, cross-shelf currents were significantly weaker ($0.1\text{--}0.2 \text{ ms}^{-1}$) and in some cases fluctuated oncoast/offcoast (Fig. 9).

Individual-low fronts of long (ILL, $\blacktriangledown$) and short (ILS, $\blacktriangledown$) duration are presented in Fig. 10. Overall, ILL lasted 4 days (Table 2) and presented downcoast currents of up to -0.4 ms^{-1} and cross-shelf currents (oncoast

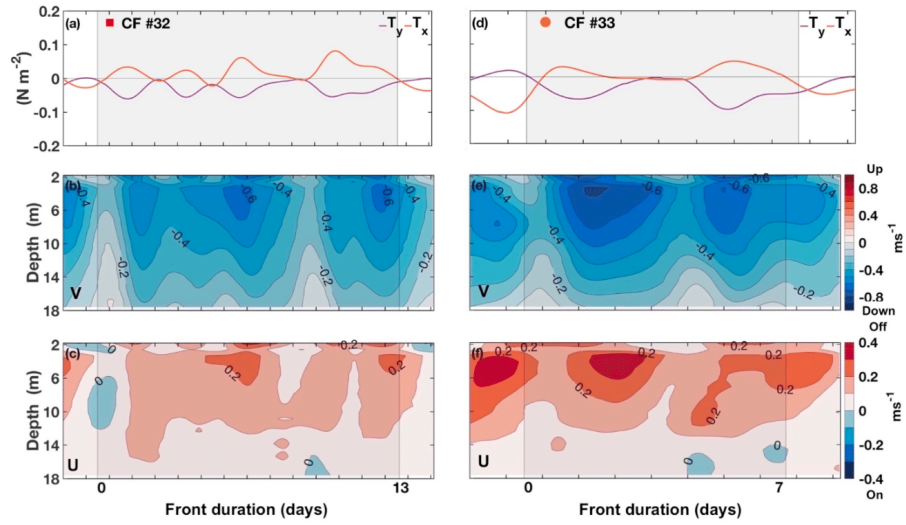


Fig. 8. Low-pass filtered (a, d) along-shelf and cross-shelf wind stress components (τ_y , τ_x) and vertically-varying (b, e) along-shelf and (c, f) cross-shelf current velocities for representative *sequential* (SM, ■; SL, ●) cold fronts. The shaded boxes indicate the front duration, and positive along-shelf and cross-shelf currents correspond to upcoast (up) and offcoast (off) flows.

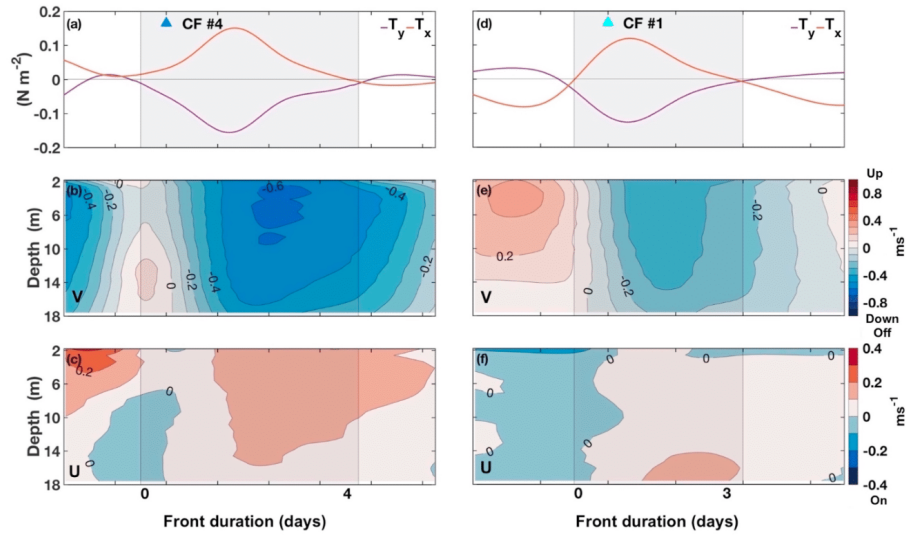


Fig. 9. Low-pass filtered (a, d) along-shelf and cross-shelf wind stress components (τ_y , τ_x) and vertically-varying (b, e) along-shelf and (c, f) cross-shelf current velocities for representative *individual-high* (▲) cold fronts. The shaded boxes indicate the front duration, and positive along-shelf and cross-shelf currents correspond to upcoast (up) and offcoast (off) flows.

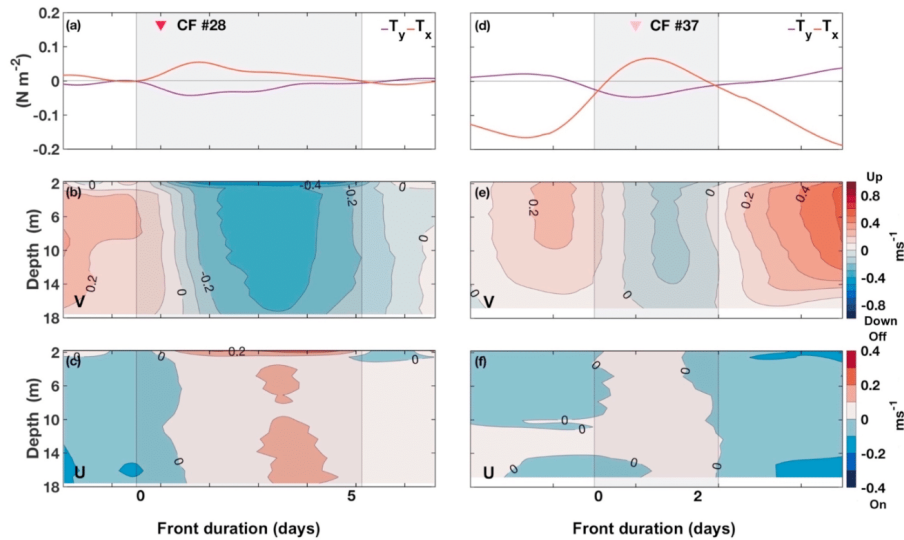


Fig. 10. Low-pass filtered (a, d) along-shelf and cross-shelf wind stress components (τ_y , τ_x) and vertically-varying (b, e) along-shelf and (c, f) cross-shelf current velocities for representative *individual-low* (▼) cold fronts. The shaded boxes indicate the front duration, and positive along-shelf and cross-shelf currents correspond to upcoast (up) and offcoast (off) flows.

and offcoast) of $\sim 0.2 \text{ ms}^{-1}$ when $\tau_y \sim 0.05 \text{ Nm}^{-2}$ (Fig. 10 a,b,c). ILS lasted 2 days (Table 2) and presented weaker downcoast and offcoast flows, typically of $\sim 0.2 \text{ ms}^{-1}$ and 0.1 ms^{-1} , respectively (Fig. 10 d,e,f). The latter were not always capable of reversing along-shelf currents (from upcoast to downcoast) (i.e. #18, 38; Fig. 7), and in most cases, the current direction reverted upcoast immediately after the passage of ILS fronts (Fig. 10).

5. Discussion

Yearly-average along-shelf winds were predominantly upcoast over the last two decades, but large seasonal fluctuations existed. Winds were typically upcoast in summer and fall, and sporadically intense and downcoast in spring and winter (Thyng, 2019). Along-shelf current reversals were observed over the study period (e.g. Thyng and Hetland, 2017; Rivas, 2017), and these were associated with the passage of sporadic cold fronts (Huh et al., 1984; Allende-Arandía et al., 2016; Kurczyn et al., 2020) that typically occurred 20 times per year (Appendini et al., 2018). A total of 38 cold fronts were identified over the two-year period from 2016 to 2018, and the vertical flow structure was characterized based on field measurements. Interestingly, while most of the fronts reversed the alongshore current downcoast ($\sim 80\%$), others were unable to completely reverse the flow throughout the entire water column or, instead, intensified the existing downcoast flow.

Two distinct cold front types were defined by the number of consecutive events: *sequential* (typically 2 to 5 events) and *individual* (1 event). While the number of events varied within subgroups of each type, the percentage of occurrence was consistent with historical results

(Tables 1 and 2). Wind and flow characteristics of these subgroups (Fig. 11a) were described in Fig. 11b and c,d, respectively. Group-averaged along-shelf and cross-shelf wind-stresses and flows were obtained averaging individual data from 24 h before to 72 h after the wind-stress maxima (defined as 0 h) (Fig. 11b and c,d, respectively).

Sequential fronts typically lasted 1–3 weeks (Schultz et al., 1998), were associated with mean sea-level pressures (MSLP) of $\sim 1024 \text{ hPa}$ and maximum τ_y of $\sim -0.10 \text{ Nm}^{-2}$, and induced downcoast flows of $\sim -0.5 \text{ ms}^{-1}$ down to $\sim 10 \text{ m}$ depth (SM and SL; Fig. 11). *Individual* fronts were of high and low intensity (defined by MSLP differences) and presented durations of 2 and 4 days (short and long, respectively). The most intense flows of $\sim -0.5 \text{ ms}^{-1}$ throughout the entire water column (of 18 m) occurred during *individual* fronts of high intensity (MSLP of up to $\sim 1018 \text{ hPa}$ with maximum τ_y of $\sim -0.15 \text{ Nm}^{-2}$) and long duration (IHL type; Fig. 11). *Individual* fronts of low intensity (ILL and ILS types; Fig. 11) presented stronger currents than those of higher intensity but shorter duration (IHS type; Fig. 11) and of similar MSLP (up to 1016 hPa). Hence, the duration of the front driven by moderate-to-strong wind-stresses (Lentz, 2001) had greater influence than MSLP on the magnitude of the flow (Shi et al., 2019). While IHS induced flows of $\sim -0.3 \text{ ms}^{-1}$ down to 8 m depth, $\sim -0.4 \text{ ms}^{-1}$ flows reached down to 10 m during ILL and ILS (Fig. 11). Overall, cross-shelf flows were significantly smaller than the along-shelf; and these were generally $0.1\text{--}0.2 \text{ ms}^{-1}$ offcoast.

Local density gradients (Schultz et al., 1997; Dzwonkowski et al., 2011; Lentz, 2001; Horwitz and Lentz, 2014) or the presence of micro-eddies that move towards the inner shelf (Thyng, 2019) can modulate the response of the water column. Murray's (1975) simplified theory

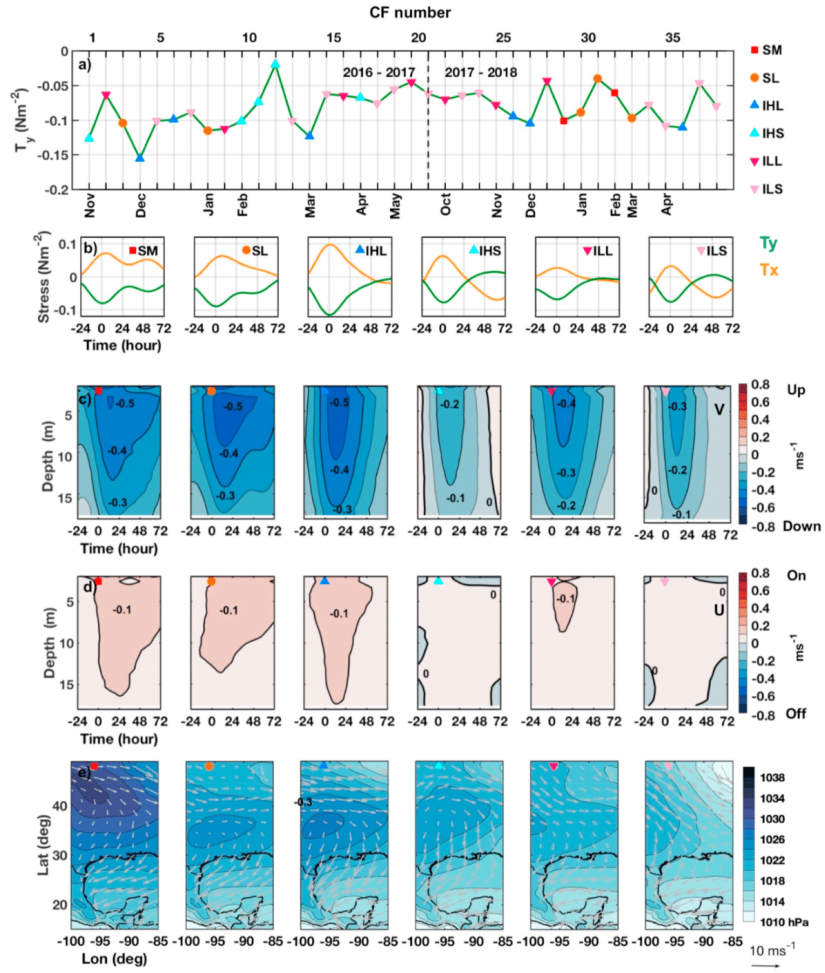


Fig. 11. (a) Maximum along-shelf wind stresses (τ_y) for each of the 38 cold fronts during 2016–2018. The rest of the panels represent group-averaged characteristics: (b) τ_x and τ_y 24 h before and 72 h after wind-stress maxima (zero value); (c) the vertical structure of along-shelf, V , and; (d) cross-shelf, U , currents (positive upcoast and offcoast); and (e) spatial distribution of MSLP. Note velocity differences of 0.1 ms^{-1} between contourlines in c) and d).

was applied to elucidate the potential effect of stratification on our results, on the absence of density data. This theory assumed a steady state, neglecting the vertical speed component, field accelerations and the Coriolis parameter, and considered a homogeneous water mass. Murray (1975) established that the vertical structure of the along-shelf flow, v , could be calculated based on the wind forcing, as follows;

$$v = \frac{\tau_{xs}}{\rho K} \tau + v_b \quad (3)$$

$$v_b = \frac{\tau_{xb}^{1/2}}{k_b \rho} \quad (4)$$

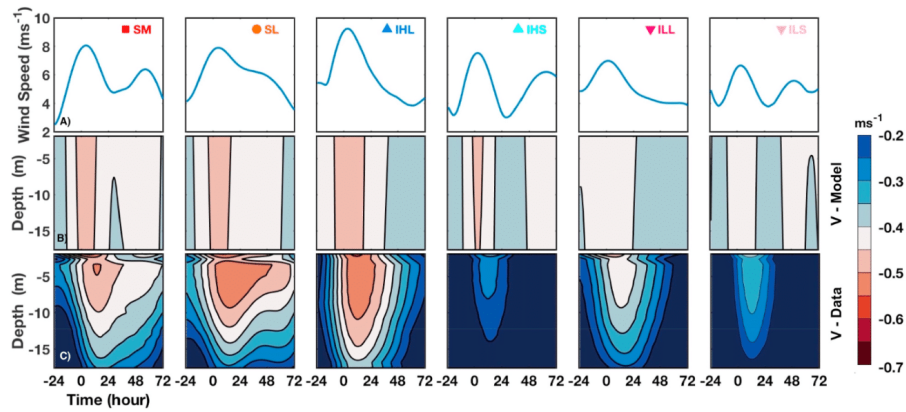


Fig. 12. (a) Characteristic wind speeds for each cold front group (left to right); (b) Vertical structure of the along-shelf wind-driven flow for each cold front group based on Murray's (1975) simplified theory; (c) Field measured vertical structure of the along-shelf flows characteristic for each cold front group.

being z the vertical coordinate, positive up from the bottom; v_b the near-bed bottom speed given by the quadratic bottom stress condition of $\tau_{xb} = \tau_{xb} = 2 \times 10^{-3} \sigma (Q \cos(\alpha))^2$ and assuming $k_b \approx 3 \times 10^{-3}$; Q the wind speed blowing at an angle α to the shoreline (deg); ρ the water density; and σ the air density. The eddy viscosity for a well-mixed surface layer was given by $K = 0.1825 \times 10^{-4} Q^{5/2}$ in $m^2 s^{-1}$.

Theoretical expectation for unstratified conditions suggested that the flow response was primarily controlled by the wind during the passage of cold fronts (Fig. 12), in agreement with previous research findings (Winant, 1980; Nowlin et al., 2005; Zavala-Hidalgo et al., 2014; Shi et al., 2019). Vertical flow structure differences between observed and theoretical flows were related to the simplified nature of the theory itself (i.e. v is linear with z). The most intense flows associated with maximum wind speeds were, overall, successfully captured by the theory. But flow speeds differed prior and/or after the events, particularly for fronts of short duration (i.e. IHS and ILS in Fig. 12).

Response times of the along-shelf flow to the wind forcing were analyzed through cross-correlation analysis; all events presented high correlation values (>0.9 ; Fig. 13a). Sequential events showed comparatively smaller lags (less than 9 h) than individual fronts (lags of 9–18 h). Thus, these lags were suggested to primarily depend on the time of exposure of the water column to τ_y (Fig. 13a). Along-shelf flow velocities were scaled with the shear velocity ($u_* = \sqrt{\tau_y / \rho}$; being τ_y the along-shelf

wind stress and ρ the water density) to compare the flow structure among different cold front types (Fig. 13b). High-intensity events (i.e. SM, IHL, IHS) presented along-shelf currents of similar magnitude throughout the water column, while events of low-intensity (i.e. SL, ILL, ILS) presented larger variations of the flow throughout the water column (i.e. IHS and ILS, Fig. 13b). Generalized lag-fitted bin-averaged velocity profiles for each cold front type showed intense surface flows of up to 0.6 ms^{-1} and milder bottom flows of up to 0.3 ms^{-1} for long-lasting events, and half the speeds for short-lasting events (Fig. 13c). These results suggest that high-intensity cold fronts induced a nearly-steady wind-driven flow, while low-intensity events presented weaker flows, and more susceptible to be influenced by other local processes.

6. Conclusions

Yearly-average along-shelf winds were predominantly upcoast over the last two decades, but large seasonal fluctuations existed. This study focused on understanding the role of the passage of episodic cold fronts in the reversing of along-shelf flows downcoast on the southern Texas coast. A total of 819 cold fronts of 4 days of average duration occurred between 1984 and 2018, and the vertical structure of the flow was analyzed for 38 cold fronts between November 2016 and October 2018. Theoretical flow expectation for unstratified conditions suggested that the flow response was primarily controlled by the wind forcing during the passage of cold fronts. Detailed analysis on the vertical profile of the flow demonstrated significant time-lag differences, primarily related to the front intensity and duration. Strongest downcoast flows of -0.5 ms^{-1} throughout the entire water column were associated with individual cold fronts of high intensity ($\tau_y \sim -0.15 \text{ Nm}^{-2}$) and long duration (up to 4 days). The most frequent fronts were individual of low intensity ($\tau_y \sim -0.05 \text{ Nm}^{-2}$) and short duration (up to 2 days), and induced relatively weak downcoast flows of $\sim -0.2 \text{ ms}^{-1}$; some were unable to completely reverse the flow downcoast, and in most cases, the flow reverted upcoast immediately after the passage of the front. Cold fronts are potential threats to coastal environments on the western Gulf of Mexico leading to coastal erosion and flooding. This study highlights the role of episodic cold fronts in reversing and intensifying inner-shelf currents on the southern Texas coast, and emphasizes differences in the flow response related to cold front characteristics.

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.

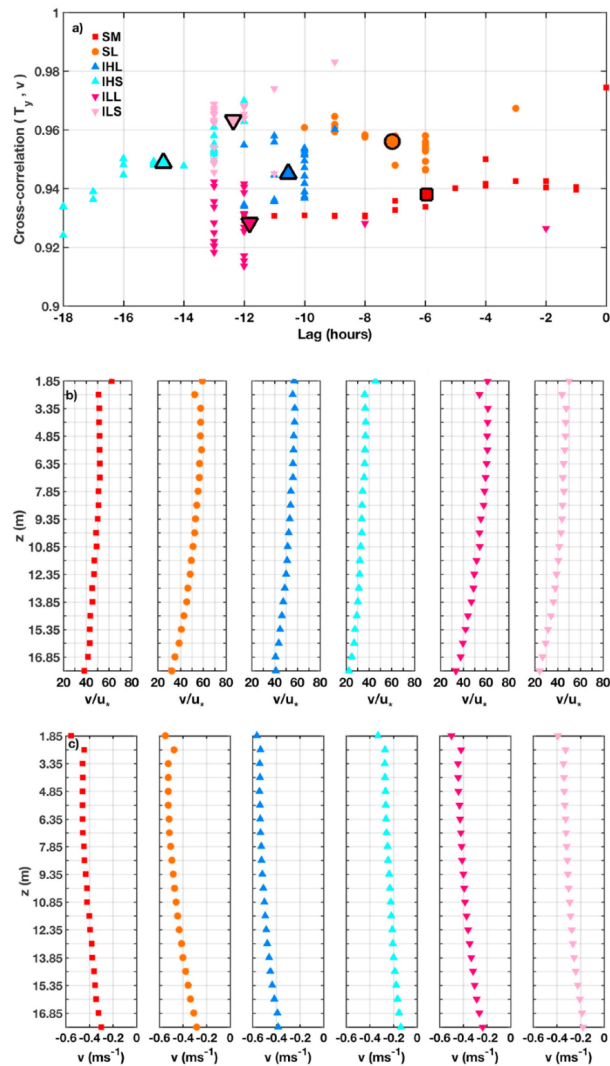


Fig. 13. (a) Cross-correlation coefficients (r) and lags between along-shelf wind stresses (τ_y) and depth-varying along-shelf flows (V); large symbols indicate group-averaged results. (b) Vertical profiles of V (scaled with the shear velocity, u^*) for each cold front group. (c) Lag-fitted bin-averaged velocity profiles for each cold front group.

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Spatial variability of currents associated with different cold fronts along the southern Texas coast

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Abstract

Wind and current measurements collected between February and March 2017 at three sites in the southern Texas coast were used to determine along-shelf flow variations induced by episodic synoptic-scale cold fronts and to quantify the relevant terms in the inner-shelf along-shelf momentum budget. Inner-shelf flows were wind-driven, but significant along-shelf variations existed between the northern and southern sites. Cold fronts induced downcoast mean, surface and bottom flows along the study site. Strongest downcoast flows occurred in the surface in the northern and southern ends, while these were weaker in the center. Flows averaged over a longer period of time showed the presence of a convergence zone in the central site, off Port Mansfield. Spatial variations of the along-shelf wind stress were the main cause for the flow convergence in the surface layer at the central site. Most intense surface flows occurred in the north (along-shelf wind speeds of $> 10 \text{ ms}^{-1}$), less affected by southeasterly (upcoast) Trade winds. Low-energy cold fronts (along-shelf wind speeds of $< 10 \text{ ms}^{-1}$) were unable to completely reverse the wind direction towards the south (downcoast) in the southern and central sites, due to the stronger influence of Trade winds. Surface wind stress and pressure gradients were the dominant terms in the along-shelf momentum budget, while the bottom stress and Coriolis terms were considered negligible. The wind-stress term was dominant in the north, while pressure gradients associated with local sea-level responses to the wind forcing were dominant in the southern site. This study highlights the importance of pre-front wind characteristics in spatial variations of the along-shelf flow during cold fronts.

Keywords Nearshore currents · Extreme events · Wind-driven circulation · Gulf of Mexico · Vertical currents. Field measurements

1 Introduction

In the northwestern Gulf of Mexico, cold fronts, referred to synoptic-scale strong northerly winds associated with high-pressure systems (Appendini et al. 2018), occur more frequently than tropical cyclones (Huang and Li 2020). The inner-shelf circulation is primarily wind driven, and the along-shelf wind-stress component defines the main current direction (Winant 1980; Nowlin et al. 2005). Therefore, cold fronts significantly modulate the nearshore circulation (Needham and Keim 2012) and cause large cumulative

coastal changes that threaten population and infrastructure (Moeller et al. 1993).

The inner shelf is dynamically defined as the region encompassing depths ranging from a few to tens of meters and lies between the surf zone (momentum balance dominated by wave-induced terms due to wave breaking) and the mid-shelf (along-shelf circulation usually in geostrophic balance) (Lentz and Fewings 2012). The inner-shelf circulation is often investigated through the momentum balance across different regions, but most studies have considered conditions averaged over longer periods of time than a week (Lee et al. 1984; Lentz and Winant 1986; Lentz et al. 1999; Maza et al. 2006; Fewings and Lentz 2010; Grifoll et al. 2012, 2013) rather than using data of higher temporal resolution (i.e. seconds to minutes).

Overall, the inner-shelf along-shelf momentum balance is simpler than the mid-shelf, where the Coriolis, wind stress, bottom stress, acceleration and pressure gradient terms need

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to be considered (Allen and Smith 1981; Lentz and Winant 1986; Lee et al. 1984, 1989). Instead, the inner-shelf balance can be solved using mainly three terms, which include the along-shelf wind stress, bottom stress and the pressure gradient (Scott and Csanady 1976; Pettigrew 1981; Lentz and Winant 1986; Masse 1988; Lee et al. 1989; Lentz 1994).

Energetic wind events associated to storms can modify continental shelf water circulation patterns. This is evidenced when sea-level slopes oppose the wind stress in order to establish a frictional equilibrium during winter cold-front events (Lee et al. 1984). Bottom friction effects associated with the proximity to the coastline prevent the generation of inertial fluctuations, which often characterize the mid-shelf and outer-shelf regions after energetic wind pulses (Salat et al. 1992; Shearman 2005). A large fraction of the water column is usually affected by intense winds during the passage of cold fronts.

Winds are highly seasonal in the northwestern Gulf of Mexico (Thyng and Hetland 2018) and cause along-shelf currents of different directionality. Summer winds from the southwest (June to August) induce upcoast flows, while winds from the northeast during non-summer months (September to May) generate downcoast flows along the inner-shelf toward Mexico (Thyng 2019). The frictional adjustment time is largely reduced in the nearshore during the passage of cold fronts, and this is directly and inversely proportional to the water depth and the wind stress, respectively. For that reason, magnitude and phase changes occur in the dominant terms of the momentum balance (Grifoll et al. 2012).

The goal of this research is to determine along-shelf circulation changes throughout the water column induced by cold fronts of different duration and intensity, and to quantify the relevant terms in the inner-shelf along-shelf momentum budget during the passage of the fronts. This analysis is based on a set of wind and current measurements collected between February and March 2017, at three sites covering ~200 km of the southern Texas coast: Port Aransas in the north, Port Mansfield in the center and South Padre Island in the southern end (Fig. 1).

2 Field site

The research area is located in the inner Texas-Louisiana shelf, between Port Aransas and South Padre Island, along the southern Texas coast, in the northwestern Gulf of Mexico (Fig. 1). The inner-shelf gradient from the shoreface to the 100-m isobath varies from 0.5 m km^{-1} in Galveston to 1.8 m km^{-1} in South Padre Island (Rodríguez et al. 2001), and the shelf break serves as a barrier between different dynamical regions of the inner and outer shelf, partially inhibiting the cross-shelf flow exchange (Thyng and Hetland

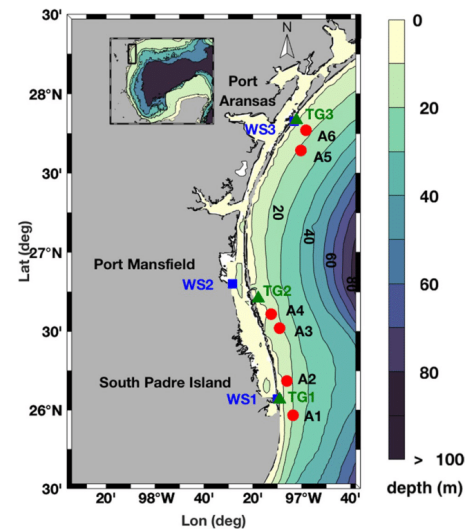


Fig. 1 Instrumental setup in the southern Texas coast, northwestern Gulf of Mexico. The alongshore array of moored ADCPs is presented in red circles near the 20-m isobath (A1 to A6, south to north). Selected NOAA weather stations (WS) and tide gauges (TG) are shown in blue squares and green triangles, respectively

2018). Thus, the inner and outer regions of the shelf present distinct dominant forcing mechanisms, and the interaction between these regions is often limited (Nowlin et al. 2005).

The southern Texas coast presents regions of seasonal convergence of winds (Zavala-Hidalgo et al. 2014) that induce material aggregation in the inner shelf of the Port Aransas area as a consequence of along-shelf circulation changes (Thyng and Hetland 2017). Tidal forcing is relatively weak, as the research site is located in a microtidal regime, with maximum tidal ranges of 0.45 to 0.60 m in the year (Morton and McGowen 1980).

3 Data and methods

3.1 Current measurements

In order to determine spatio-temporal variations of nearshore currents throughout the water column, simultaneous current velocities were measured with six bottom mounted acoustic Doppler current profilers (ADCPs; 1 MHz Aquadopp) located at 17–22-m depths at sites covering ~200 km of the southern Texas coast. The northern moorings were installed off Port Aransas Pass (A6 in Boatmens Reef and

A5 in M1775 Reef), two central moorings were placed off Port Mansfield (A4 in Wreck and A3 in 1047 Reef) and the southern instruments were placed off South Padre Island (A2 in Stranger Wreck and A1 in Port Isabel Reef). Current profiles were recorded from February to March 2017 in ENU coordinates (east–north–up), measured at 1 Hz and averaged over 120 s at 20-min intervals.

Data recorded with larger instrument tilting angles than 20° were disregarded, and unreliable measurements were removed applying quality control thresholds (<20 counts of return amplitudes). The uppermost 10% of the water column (~ 2 -m depth) was discarded due to side-lobe interference with the water surface (<0.60 of correlation between along-shelf current and wind speed). Measurements were collected across 26 vertical bins of 0.75–1 m of resolution, with a blanking distance of 0.4 m from the seabed. Therefore, average velocities for the surface and bottom layers excluded the uppermost 1.85 m and lowermost 0.4 m of the water column, respectively.

Raw current measurements were filtered applying the Lanczos low-pass filter with a cutoff frequency of 1/30 cph to eliminate high-frequency signals (Emery and Thomson 2004). The filtering procedure effectively removed most tidal

and inertial motions, since the inertial period in the region varied from 25 h in the north (A6) to 28 h in the south (A1). A principal component analysis (PCA) was conducted.

between the depth-averaged current components to rotate the data into major (alongshore, V) and minor (cross-shore, U) axes of variation; directions were expressed in degrees clockwise from true north. Current vectors at A6 and A5 (north) were oriented 56° counter-clockwise from depth-averaged vectors, and -54° and 88° at sites A4 and A3 (center), and sites A2 and A1 (south), respectively. A right-handed coordinate system was applied to the rotated along-shelf and cross-shelf currents; positive x (u) and y (v) indicate offcoast and upcoast directions, respectively.

Figure 2 presents an example of raw depth-averaged and depth-varying along-shelf (V) and cross-shelf (U) flows for the southernmost A1 instrument off South Padre Island. Specific events reversed along-shelf currents downcoast (negative V) throughout the entire water column, particularly in early and middle March 2017. Instead, a period of dominant upcoast currents (positive V) was observed in mid-to-late March 2017, and cross-shelf currents were comparatively weaker than the along-shelf. This analysis will be extended for all moorings to determine the processes that induce current reversals and

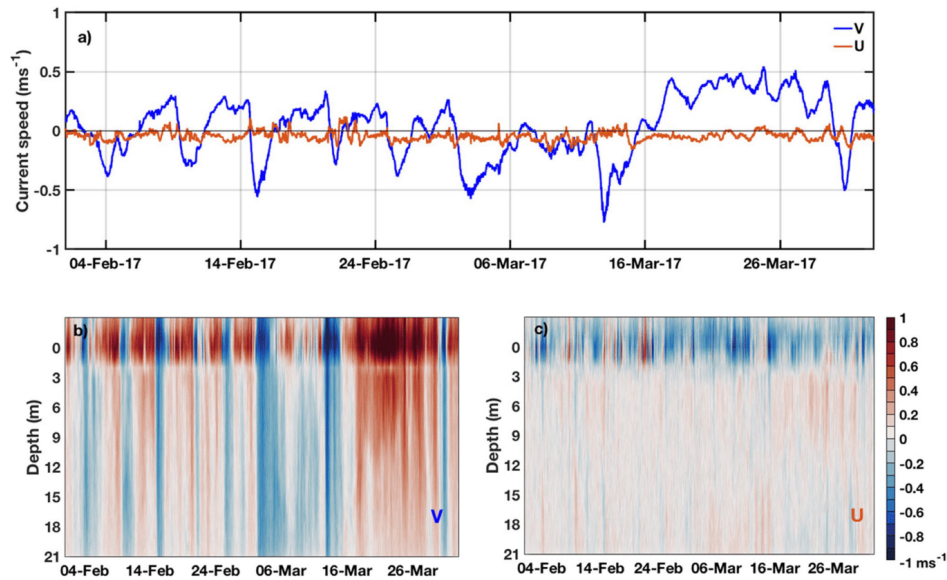


Fig. 2 Time series of raw measurements at A1 (southernmost site) from February to March 2017; (a) depth-averaged along-shelf (V) and cross-shelf (U) currents; (b) and (c) depth-varying along-shelf (V) and cross-shelf (U) currents, respectively. Negative V and U cor-

respond to downcoast and oncoast flows, respectively. Depths are referred from the mean water level. Note side-lobing effects in the uppermost water column

understand whether this pattern is general for the southern Texas coast or rather unique for the southernmost location.

3.2 Weather and water level data

Hourly wind data were obtained from three NOAA (www.ndbc.noaa.gov) weather stations (WS) closest to A1, A4 and A6 (Fig. 1). An example of the time series of wind speed and directions for fifteen days in March 2017 is presented in Fig. 3a for WS2 (closest to A4 in the center site). Synoptic wind and mean sea-level pressure (MSLP) maps were additionally obtained every 6 h from the ERA-Interim global reanalysis product by the European Centre for Medium Range Weather Forecasting (ECMWF) over a grid of 0.75° of resolution.

Surface wind stresses were calculated from local wind measurements (Fig. 3) using a quadratic friction law based on wind speeds and empirical drag coefficients (Eq. 1):

$$(\tau_{x,x}, \tau_{x,y}) = \rho_a C_D |W| (u_w, v_w) \quad (1)$$

being ρ_a air density (1.2 kg m^{-3}), C_D wind drag coefficient, u_w and v_w cross-shore and alongshore wind velocity

components measured at 10-m elevation and W wind speed. $C_D = (0.49 + 0.065 U) 10^{-3}$.

for wind speeds $> 10 \text{ ms}^{-1}$ and $C_D = 1.14 \times 10^{-3}$ for wind speeds $\leq 10 \text{ ms}^{-1}$ (Large and Pond 1981). Wind data were converted to oceanographic convention (direction toward which the wind blows).

Water-level variations were obtained from the time series of pressure data measured by the ADCPs and referred to the local mean low water level using local tide-gauge data (TG; Fig. 1) operated by NOAA and located near to the ADCP moorings (see Goff et al. 2019). The time series of water-level variations was used to estimate along-shelf water-level gradients $\partial\eta/\partial y$.

3.3 Along-shelf momentum budget

Depth-averaged along-shelf momentum balances were undertaken for the southern (A1) and northern (A6) locations in order to determine the role of the different momentum terms on along-shelf current variations. For that purpose, the following simplified depth-averaged alongshore momentum equation (Eq. 2) was applied (e.g. Allen and Smith 1981; Lentz and Winant 1986):

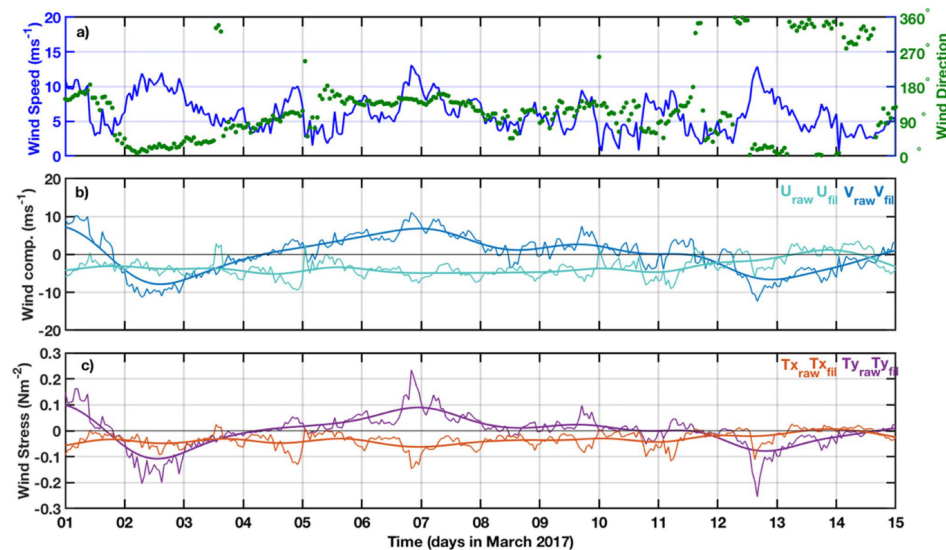


Fig. 3 Time series from 1 to 15 March 2017 of: (a) hourly wind speeds and wind directions (0° refers to winds approaching from the north) from weather station WS2 (closest to A4); (b) raw (thin lines) and filtered (thick lines) wind data for along-shelf (V) and cross-shelf

(U) flows; (c) raw and filtered along-shelf (τ_y) and cross-shelf (τ_x) wind-stress components. Note that negative V and U correspond to downcoast and oncoast wind components, respectively

$$\frac{\partial V}{\partial t} = -g \frac{\partial \eta}{\partial y} + \frac{\tau_{s,y}}{\rho_0 h} - \frac{\tau_{b,y}}{\rho_0 h} - f u \quad (2)$$

where $\frac{\partial \eta}{\partial y}$ indicates subtidal along-shelf water-level gradients, ρ_0 mean seawater density, $\tau_{s,y}$ alongshore wind stress, $\tau_{b,y}$ alongshore bottom stress and h the local water depth.

The Coriolis acceleration was obtained as a product of the Coriolis parameter and subtidal depth-averaged cross-shelf currents. Terms in Eq. 2 represent (left to right): (1) local flow acceleration, (2) along-shelf pressure gradient, (3) and (4) along-shelf wind and bottom stresses and (5) Coriolis acceleration. The advective acceleration and horizontal momentum diffusion terms were neglected in Eq. 2 as are considered only likely to be important in shorter scales than a few weeks (e.g. Grifoll et al. 2013).

The local acceleration term, $\frac{\partial V}{\partial t}$, was calculated using central differencing of measured along-shelf subtidal flows. And bottom stresses $\tau_{b,y}$ were estimated assuming a quadratic drag formulation represented in Eq. 3.

$$(\tau_{b,x}, \tau_{b,y}) = \rho_o C_{D,b} V_b |V_b| \quad (3)$$

where $C_{D,b}$ is a bottom drag coefficient (3×10^{-3}) as a function of the near-bottom along-shelf velocity.

4 Results

4.1 Cold-front wind characteristics

Cold fronts (CF) were defined as events of wind blowing at least 24 h from the north (range of 300° to 30°) with sustained wind speeds of $\geq 5 \text{ ms}^{-1}$ for a minimum period of 15 h during which MSLP differences between Iowa (-93.25°W , 42.75°N in USA) and Quintana Roo (-87.94°W , 20.51°N in Mexico) were $\geq 6 \text{ hPa}$. The passage of three individual CFs was studied in the period of 1–16 March 2017 (Fig. 4), which included two CFs of mid-to-high energy and one CF of low energy. These fronts caused energetic downcoast winds of similar speeds, which peaked around 12 ms^{-1} on the 2nd, 8th and 12th of March (Fig. 3), and were related

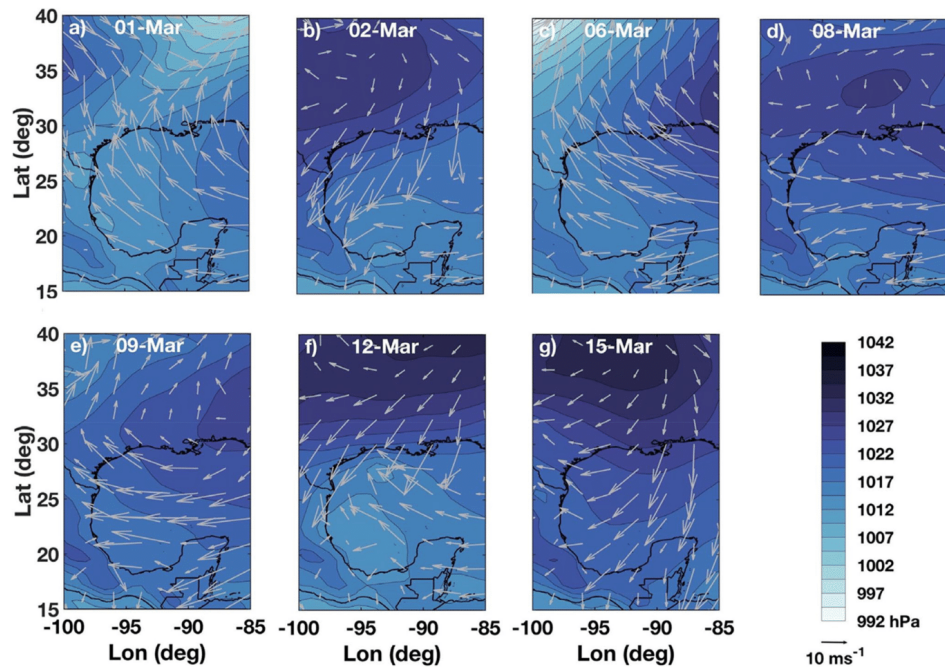


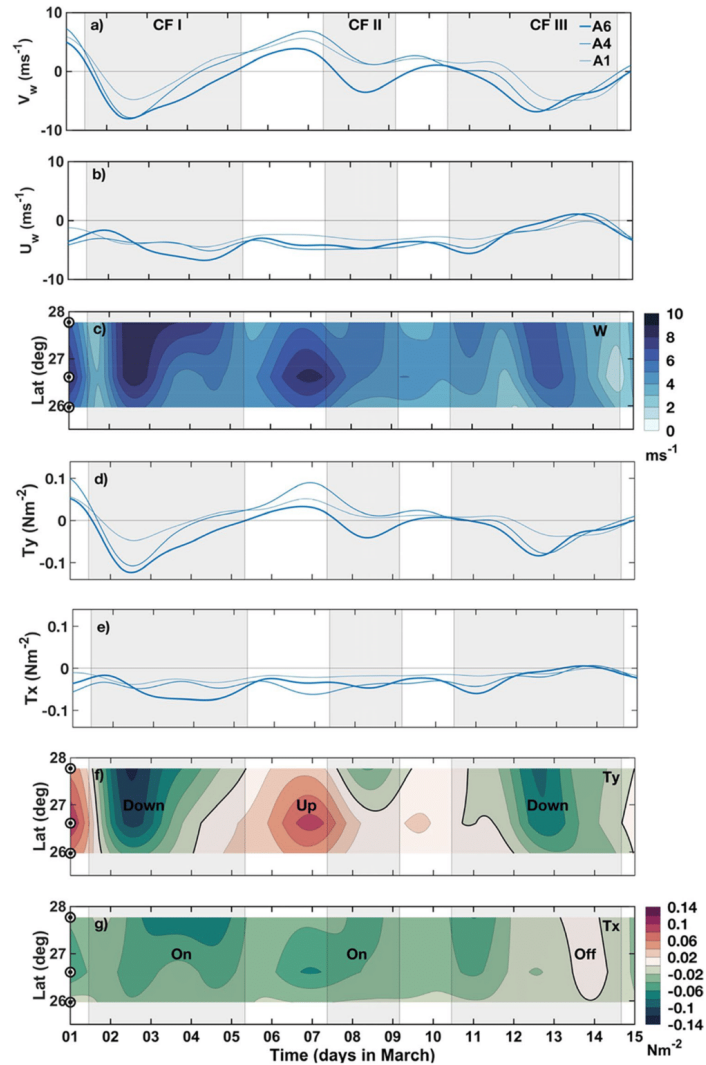
Fig. 4 Temporal sequence between 1 and 15 March 2017 of the spatial distribution of the mean sea-level pressure (MSLP; magnitude in color-bar) and wind speeds and directions (arrows); before (a, c, e, g) and during (b, d, f) the passage of cold fronts along the western Gulf of Mexico

to high-pressure systems near Lat 40° (see Fig. 4b, d, f). Relatively calm atmospheric periods occurred between cold fronts, which induced wind direction changes, towards the north (upcoast), and were associated with low-pressure systems (Fig. 4a, c, e, g).

Low-pass filtered wind characteristics for the selected cold fronts are presented in Fig. 5. The first and most

energetic front CF I (T_y of -0.12 Nm^{-2}) peaked on the 2nd of March and lasted 4 days (1–5 March 2017). The weakest front, CF II (T_y of -0.04 Nm^{-2}), presented maximum wind speeds on the 8th of March, and lasted 2 days (8–10 March 2017). The third front CF III, of mid-to-high energy (T_y of -0.08 Nm^{-2}), peaked on the 12th of March and lasted 4 days (10–14 March 2017) (see I, II and III in Fig. 5).

Fig. 5 (a) Low-pass filtered along-shelf and (b) cross-shelf wind speeds measured at the weather stations near A1, A4 and A6, and (c) the spatial distribution of the magnitude of the wind speed (W) for Lat 26–18. Subplots (d) to (g) represent wind-stress variations for the same period of time. (d) and (e) show the time series of the along-shelf (T_y) and cross-shelf (T_x) wind-stress components calculated with the weather station data, and (f) and (g) represent the spatial distribution of T_y and T_x for Lat 26–18, respectively. Shaded sections indicate cold-front (CF) durations, and circles in (c) and (g) A1, A4 and A6 locations



During the passage of the fronts, along-shelf winds increased the magnitude (up to 8 ms^{-1}) and shifted from positive (upcoast) to negative (downcoast) in all three locations, except for CF II, which was unable to turn towards the south (downcoast) in the center and southern sites (A4 and A1) (Fig. 5a). The cross-shelf wind component was predominantly negative (oncoast) and remained similar or decreased in magnitude during the three events (Fig. 5b). Wind speed spatial variations indicated alongshore uniformity before and during the peak of CF I, but a notable speed decrease occurred in the south. Similar spatial patterns but of lower energy were presented for CF III, while weakest CF II presented significantly lower wind speeds, but highest in the north (Fig. 5c).

Most energetic CF I presented maximum τ_y of around -0.12 Nm^{-2} in the northern site (A6) and -0.08 Nm^{-2} in the central site (A4) and lowest magnitudes (-0.04 Nm^{-2}) in the southern end (A1) (Fig. 5d). τ_x was comparatively weaker in all cases (magnitude of $< 0.05 \text{ Nm}^{-2}$) and predominantly negative (oncoast) (Fig. 5e). The spatial distribution of τ_y (Fig. 5f) and τ_x (Fig. 5g) indicated strong and mid-to-strong downcoast winds during CF I and III, and very weak downcoast in the north and upcoast in the central-south sections for CF II (Fig. 5f). Weak downcoast winds in CF II were possibly affected by strong upcoast winds prior to the front during 6–7 March (Fig. 5a, f).

4.2 Alongshore inner-shelf current characteristics

Currents measured at the six locations (A1 to A6) were time-averaged per vertical bin for specific periods of time (i.e. CF period 1–15 March and 2-month period 1 February to 31 March), and then depth-averaged for specific sections of the water column (surface, bottom and complete water column) (see vectors in Fig. 6). Currents averaged throughout the complete water column (mean; from depths of 2 m to the bottom) (Fig. 6a, d) were compared with surface (depth of 2 m) (Fig. 6b, e) and bottom (depth of ~ 20 m) flows (Fig. 6c, f).

During the CF period, mean (depth-averaged) currents indicated coast-aligned downcoast flows of -0.4 ms^{-1} in the north (A6 and A5) and $\sim -0.2 \text{ ms}^{-1}$ further to the south (A4 to A1) (Fig. 6a). In contrast, longer period results showed weaker downcoast flows of $\sim -0.15 \text{ ms}^{-1}$ in the north (A6 and A5), near-to-zero in the center (A4 and A3) and very weak (0.03 ms^{-1}) upcoast flows in the south (A2 and A1) (Fig. 6d). Considering longer period data, the magnitude of mean currents showed a reduction off Port Mansfield (between A5 and A1), which suggested the presence of a convergence zone (Fig. 6d). In contrast, this reduction was not evident in the CF period (Fig. 6a).

Downcoast flows dominated throughout the water column off Port Aransas in the north (A6 and A5 in Fig. 6).

Strongest surface flows of $\sim -0.45 \text{ ms}^{-1}$ occurred during the CF period (Fig. 6b), and these were significantly weaker near to the seabed ($\sim -0.2 \text{ ms}^{-1}$) (Fig. 6c). Instead, during the longer period, surface flows were downcoast and oncoast, and significantly weaker ($\sim -0.3 \text{ ms}^{-1}$) (Fig. 6e), while bottom flows were comparatively very weak, downcoast and coast-aligned ($\sim -0.1 \text{ ms}^{-1}$) (Fig. 6f).

Largest discrepancies existed between surface and bottom flows in the center and southern sites. In the longer period, weak (0.15 ms^{-1}) upcoast surface currents dominated in the center (Fig. 6e), while these were very weak and downcoast (-0.03 ms^{-1}) near to the seabed (Fig. 6f). In the south, upcoast surface currents were stronger (0.25 ms^{-1}) (Fig. 6e), while bottom flows were as weak as in the center and predominantly downcoast (-0.02 ms^{-1}) (Fig. 6f). In contrast, during the CF period, surface and bottom flows in the center and southern sites were downcoast, but of different magnitude (Fig. 6b, c). In the central region, cold fronts induced relatively weak (-0.2 ms^{-1}) downcoast surface flows, and these became stronger (-0.3 ms^{-1}) and onshore further to the south (Fig. 6b). In contrast, downcoast near-bed flows induced by cold fronts were significantly weaker and of similar magnitude (-0.1 ms^{-1}) along the coast (Fig. 6c).

The convergence zone was mostly evident in surface flows averaged over the longer period of time (Fig. 6e), since near seabed currents were downcoast for all locations (Fig. 6f). For depth-averaged and bottom currents, the maximum flow variance was aligned with mean current vectors, while highest variance occurred for surface flows, and mostly during the longer period of time (Fig. 6b, e).

Vertical current profiles in the northern (A6), central (A4) and southern (A1) locations were subjected to an empirical orthogonal function (EOF) analysis for the CF period (March 1–15) to obtain an insight into the spatio-temporal behavior of the flow at each location. Mode 1 explained at least 80% of the variance for all moorings and suggested the dominance of a barotropic flow at all sites (Fig. 7). These findings also highlight the predominance of downcoast directed flows and strongest surface flows for the CF period.

4.3 Alongshore current variations induced by cold fronts

Significant alongshore variations existed in the current profiles for the northern, central and southern sites during the passage of CF I, II and III of different characteristics. Northerly (downcoast) winds induced negative along-shelf wind stresses, T_y , of different magnitude of -0.04 to -0.12 Nm^{-2} , and caused depth-averaged downcoast currents of -0.6 to -0.2 ms^{-1} . Southeasterly winds (upcoast) dominated prior to CFs (Fig. 3) and induced upcoast flows that partially reduced preceding downcoast current speeds (Figs. 8, 9, 10). Instead, cross-shelf flows were

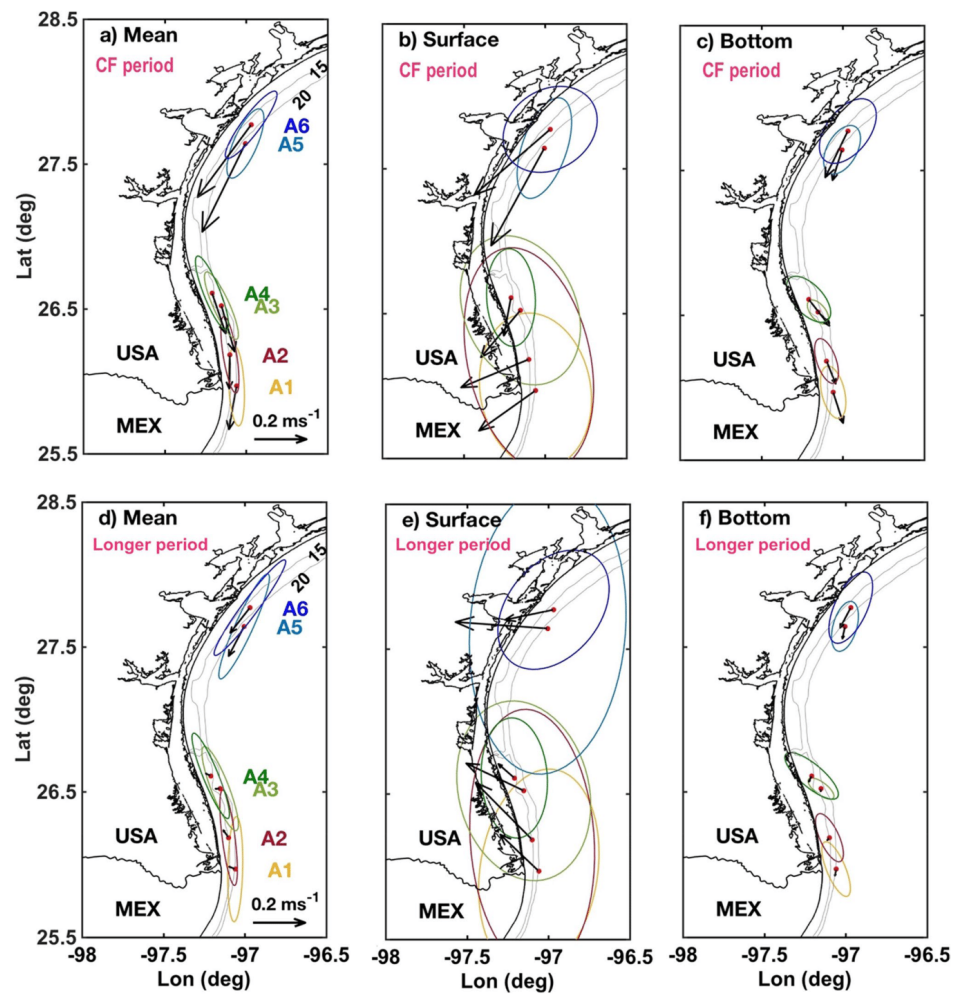


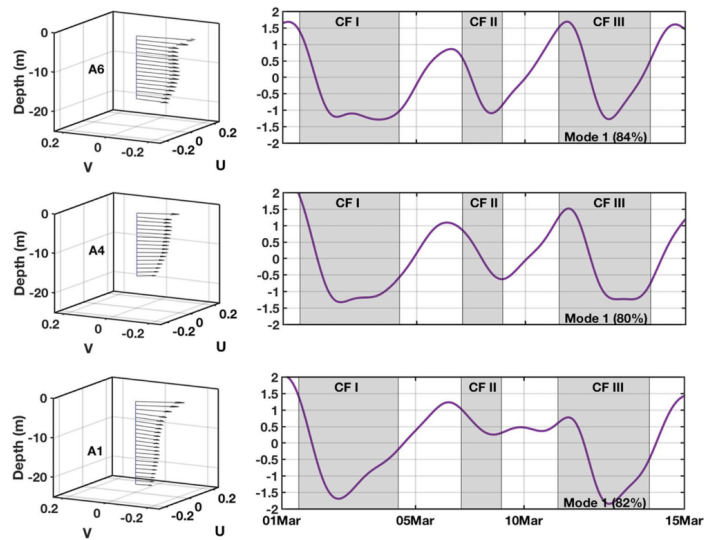
Fig. 6 Time-averaged current vectors and ellipses of variance at ADCP sites (red dots, A1 to A6) for the cold-front (CF) period (1–15 March) (upper panels; **a**, **b**, **c**) and for the 2-month period (i.e. longer period; 1 February to 31 March) (lower panels; **d**, **e**, **f**). (**a**) and (**d**)

Depth-averaged currents throughout the water column; (**b**) and (**e**) surface flows at 2-m depth; and (**c**) and (**f**) bottom flows around 20-m depth

significantly weaker, remained near to zero in the northern and southern sites, but were relevant in the central site off Port Mansfield (up to 0.4 ms^{-1} near to the seabed). The fronts induced water-level increases of 0.2 to 0.3 m, and spatial variations existed along the coast (Figs. 8, 9, 10).

The three cold fronts induced significantly higher downcoast flows in the northern site than in the center-southern locations. Up to -0.8 ms^{-1} flows were measured in the upper water column in the north (Fig. 8d), while up to -0.4 ms^{-1} flows occurred in the central and southern

Fig. 7 Spatial eigenfunctions (left panels) and their associated temporal amplitudes (right panels) for the first EOF mode derived from the vertical current profiles for the northern (A6; upper panels), central (A4; middle panels) and southern (A1; lower panels) moorings



sites (Figs. 9d, 10d). Despite CF energy differences (T_y variations of -0.04 to 0.12 Nm^{-2}), similar depth-averaged downcoast flows of $\sim -0.6 \text{ ms}^{-1}$ were measured in the northern site for the three events (Fig. 8a, c). However, flow structure differences existed throughout the water column. While the most intense CF I induced depth-uniform downcoast flows of -0.6 ms^{-1} over 4 days, weak near-bottom currents of -0.2 ms^{-1} occurred during CF II and III, and up to -0.6 ms^{-1} flows only occurred in the upper half of the water column (Fig. 8d). When CFs ended, wind directions changed towards the north (upcoast), and relatively calm ($T_y < 0.05 \text{ Nm}^{-2}$) upcoast winds prior CF II weakened downcoast flows (Fig. 8d). Cross-shelf flows were considerably weaker than the along-shelf and fluctuated oncoast/offcoast ($\pm 0.1 \text{ ms}^{-1}$) (Fig. 8e). Water-level increases of 0.3 m occurred after the peak of the wind in CF I and nearly 0.2 m in CF II and III (Fig. 8b).

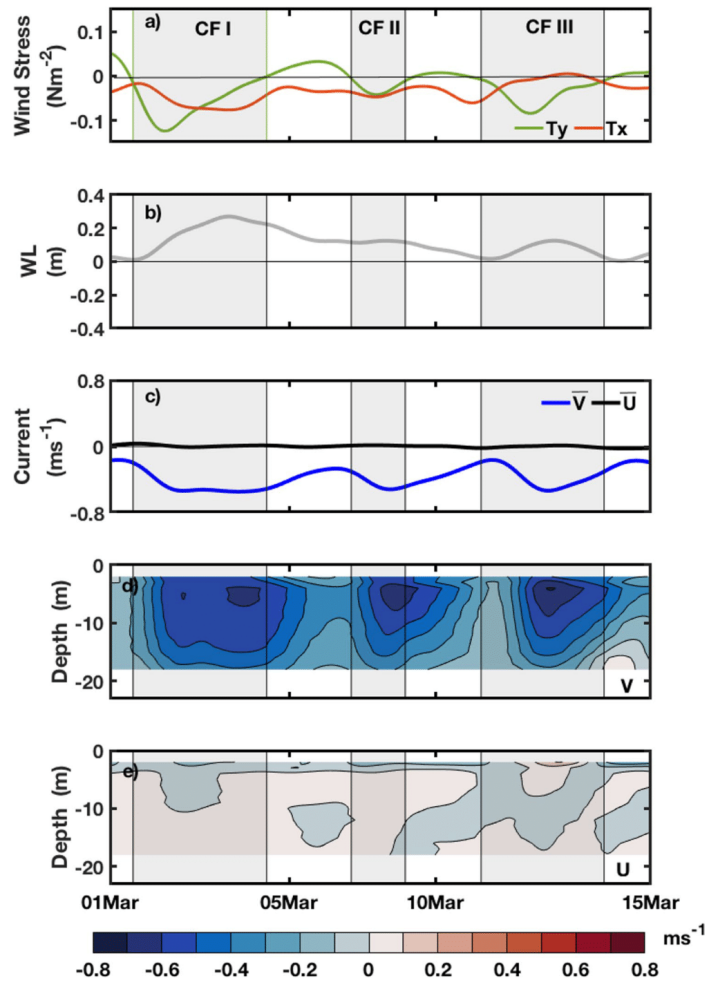
In the center site off Port Mansfield (A4), the flows were slightly different to the northern site (A6). Similar downcoast winds of up to T_y of -0.1 Nm^{-2} occurred during CF I, but this event was shorter, and the wind direction reverted upcoast on the 4th of March (Fig. 9a). Consequently, downcoast flows were weaker here than in the north; depth-averaged flows of up to -0.4 ms^{-1} were measured in A4 compared to -0.6 ms^{-1} in A6 (Figs. 8c, 9c). Similar flow structures were observed throughout the water column for CF I, but depth-uniform downcoast flows were notably weaker than in the north (maximum of -0.4 ms^{-1}).

Downcoast flows in CF III were up to -0.4 ms^{-1} in the upper half of the water column and -0.3 ms^{-1} near to the seabed (Fig. 9d, e). Weakest CF II presented largest difference with the north; the presence of strong upcoast winds in the transitional period from CF I to II inhibited CF II from reversing the wind direction towards the south. As a consequence, strongest depth-averaged downcoast flows of -0.3 ms^{-1} occurred at the end of the event, and the flow became notably weaker from the surface towards the seabed (from -0.4 to -0.2 ms^{-1}) (Fig. 9d).

The cross-shelf flow was stronger in the center region (Fig. 8e, 9e, 10e) and predominantly oncoast ($\sim -0.1 \text{ ms}^{-1}$) in the subsurface (upper 2 m of the water column), and offcoast and up to 0.3 ms^{-1} near to the seabed (Fig. 9e). Water-level increases were observed along the coast due to the incidence of the fronts, and these were up to 0.2 m after the wind peak of CF I, and up to 0.1 m during CF II and III (Fig. 9b).

Cold-front wind conditions significantly changed off South Padre Island (A1) compared to the northern (A6) and center (A4) sites (Figs. 8a, 9a, 10a). In the south, T_y was significantly weaker for CF I and III, up to -0.04 Nm^{-2} ; as a result, depth-averaged downcoast flows were also weaker (up to -0.3 ms^{-1}) (Fig. 10c). Strongest flows throughout the water column occurred for CF I and III, up to -0.5 ms^{-1} in the upper half of the water column and -0.3 ms^{-1} near to the seabed (Fig. 10d). Similar to the central site (A4), the presence of strong upcoast winds in the transitional period from CF I to II inhibited CF II from reversing the wind direction towards the south. Thus, the currents associated with CF

Fig. 8 Time series of: (a) along-shelf (T_y) and cross-shelf (T_x) wind stresses; (b) water-level variations; (c) depth-averaged along-shelf ($\bar{v}$) and cross-shelf ($\bar{u}$) velocities; and depth-varying (d) along-shelf (V) and (e) cross-shelf (U) velocities at the northern site (A6). Negative velocities indicate downcoast and oncoast flows. The shaded sections denote front durations

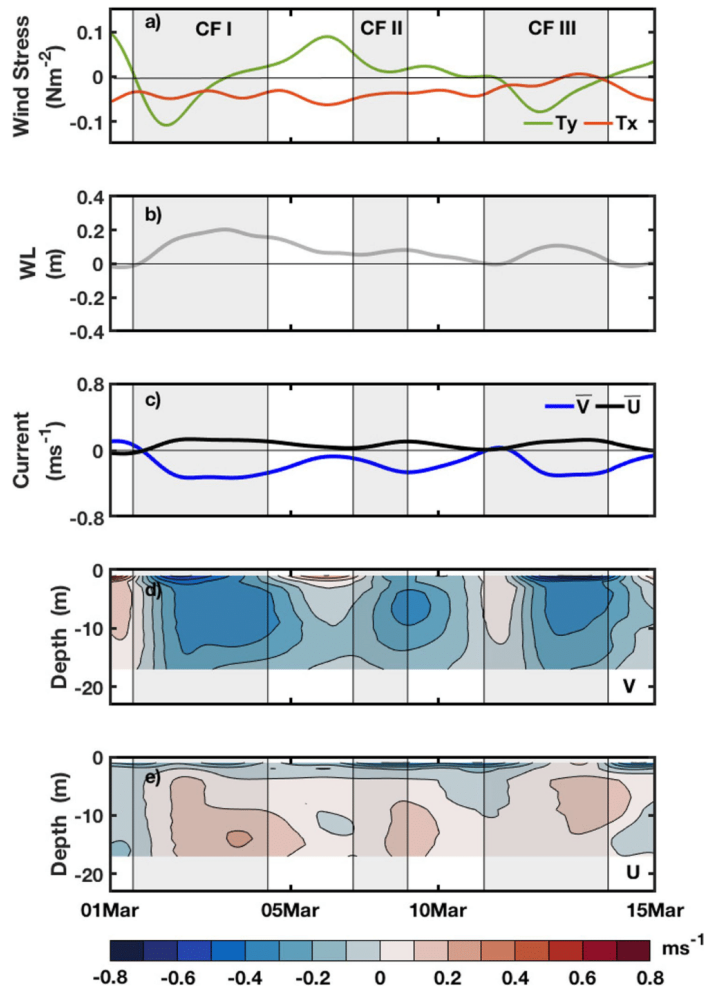


II were significantly weaker. Depth-averaged downcoast flows were $\sim -0.1 \text{ ms}^{-1}$ (Fig. 10c) and strongest flows of up to -0.3 ms^{-1} occurred near the seabed (Fig. 10d). Similar to the northern site, cross-shelf flows were weak ($\pm 0.1 \text{ ms}^{-1}$) and fluctuated oncoast in the surface and offcoast near to the seabed (Fig. 10e). Water-level increases were lower than in the north and similar to the center site, up to 0.1 m for CF II and III and 0.2 m during CF I (Fig. 10b).

Time lag responses of the flow to different CFs were analyzed for the northern site (A6) through cross-correlation

analysis between the maxima of along-shelf wind stresses and along-shelf surface flows (Fig. 11a). Surface flows presented lags of 6 to 11 h during most energetic and longer CFs (i.e. CF I and III), and 1 h for the least energetic and shorter CF II (Fig. 11b). In addition, a cross-correlation analysis was performed between surface flows along the coast (Fig. 11c, e). Time lags of 0 h were obtained between northern (A6) and central (A4) surface flows (Fig. 11d), and lags of 0 to 3 h between the northern (A6) and southern (A1) flows (Fig. 11f).

Fig. 9 Time series of: (a) along-shelf (T_y) and cross-shelf (T_x) wind stresses; (b) water-level variations; (c) depth-averaged along-shelf ($\bar{v}$) and cross-shelf ($\bar{u}$) velocities; and depth-varying (d) along-shelf (v) and (e) cross-shelf (u) velocities at the central site (A4). Negative velocities indicate downcoast and oncoast flows. The shaded sections denote front durations



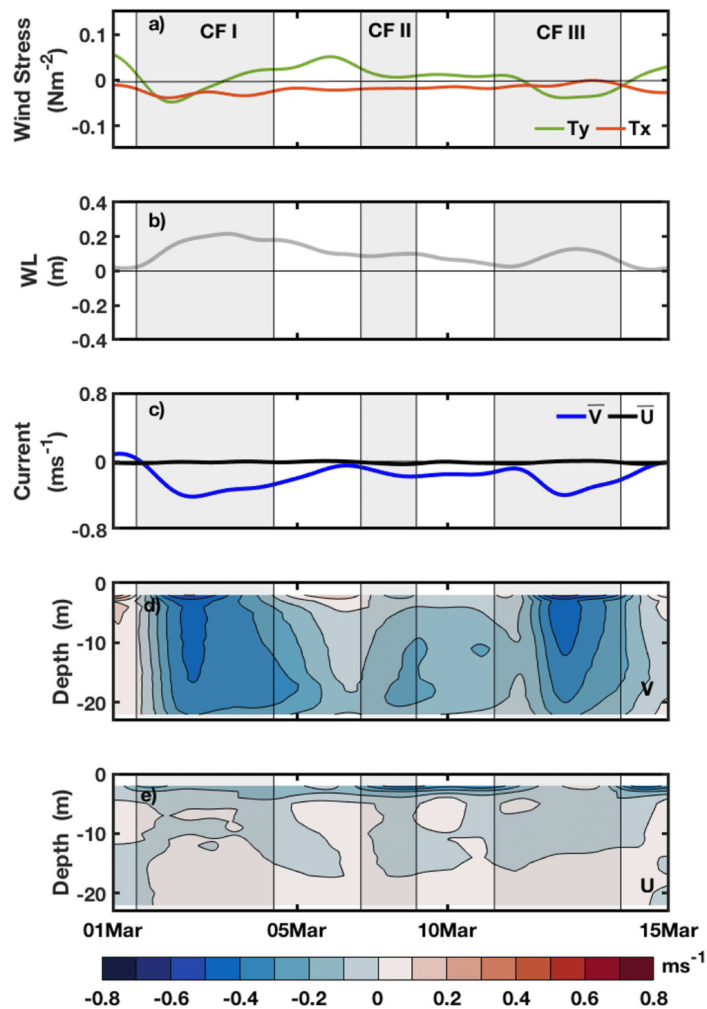
4.4 Along-shelf momentum budget

Depth-averaged along-shelf momentum balances were investigated at the northern (A6) and southern (A1) sites for the complete time series (1 February to 31 March 2017) including the CF period (1–15 March 2017), using along-shelf wind stress, water-level and flow velocity measurements. The role of the different momentum terms was specifically determined for the CF period in the fluctuating momentum budget. It was found that the surface wind stress and the

pressure gradient were the dominant terms in the momentum balance (Table 1).

Time series of decomposed momentum terms for the 2-month data are presented in Fig. 12 for the northern and southern sites. In the northern site (A6), the pressure gradient was well correlated with the wind stress for the CF period ($R^2=0.76$), while the bottom stress presented opposing fluctuations. In this location, downcoast flows accelerated during periods of strong along-shelf wind stresses, and relaxation periods occurred when northerly winds decayed

Fig. 10 Time series of: (a) along-shelf (T_y) and cross-shelf (T_x) wind stresses; (b) water-level variations; (c) depth-averaged along-shelf ($\bar{v}$) and cross-shelf ($\bar{u}$) velocities; and depth-varying (d) along-shelf (v) and (e) cross-shelf (u) velocities at the southern site (A1). Negative velocities indicate downcoast and oncoast flows. The shaded sections denote front durations



(Fig. 12). This was attributed to the dominance of the pressure gradient term, which reflected water-level anomalies that propagated between both sites. In the southern site (A1), the pressure gradient was the dominant term in the momentum budget, and bottom and wind-stress terms played only a small role in the water column. The wind-stress term was more relevant than the pressure gradient term (Table 1), although the latter presented larger fluctuations than the wind-stress term (Fig. 12).

5 Discussion

This research focused on understanding along-shelf flow variations associated with the passage of a few cold fronts of different duration (2 to 4 days) and intensity (maximum τ_y of -0.04 to -0.12 Nm^{-2}) in the southern Texas coast. The inner-shelf flow was predominantly barotropic, and the circulation was primarily wind driven; the along-shelf wind-stress component determined the principal current

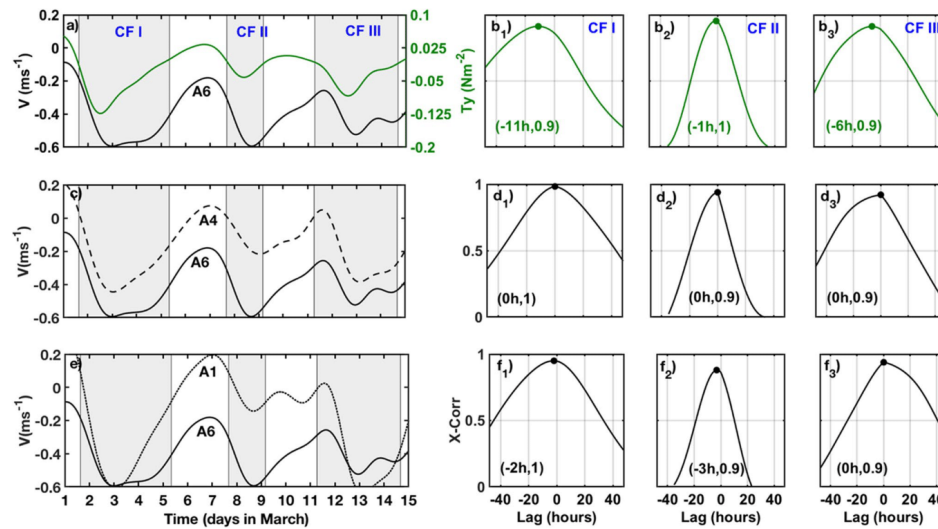


Fig. 11 **a** Time series of the along-shelf surface flow (black lines) and along-shelf wind stress (green line) for the northern site (A6), and **b** cross-correlation results between the wind stress and surface flow for each cold front (CF I, CF II and CF III). Panels **c** and **e** represent

time series of along-shelf surface flows for the three sites (A1, A4 and A6), and **d** and **f** show cross-correlation results between A6–A4 and A6–A1, respectively. Time lags (hours) and correlation values are represented in brackets for each correlation in panels **b**, **d** and **f**

Table 1 Mean and standard deviations of estimated depth-averaged along-shelf momentum terms for the CF period (expressed in 10^{-5} ms^{-2}) for A6 (north) and A1 (south) sites

Term		Mean	Std	Mean	Std
		A6 site		A1 site	
Acceleration	$\frac{\partial V}{\partial t}$	−0.002	0.19	−0.01	0.20
Water-level gradient	$−g \frac{\partial \eta}{\partial y}$	−0.11	0.08	−0.07	0.04
Wind stress	$\frac{\tau_{xy}}{\rho_0 h}$	−0.12	0.21	0.02	0.11
Bottom stress	$−\frac{\tau_{bx}}{\rho_0 h}$	−0.96	0.75	−0.35	0.34
Coriolis	$−f u$	−0.02	0.09	−0.18	0.10

direction (Winant 1980; Nowlin et al. 1998, 2005). Winds were predominantly downcoast during the incidence of episodic synoptic-scale cold fronts (Thyng 2019) but reversed their direction upcoast after the ending of the fronts. For that reason, considerable along-shelf flow direction variations occurred during the study period (1 February to 31 March 2017), which were typical for cold-front seasons (October to April) (Huh et al. 1984).

While inner-shelf currents were predominantly downcoast during the passage of cold fronts (Zavala-Hidalgo et al 2014; Allende-Arandía et al. 2016; Thyng and Hetland 2018),

significant along-shelf current variations existed between Port Aransas (northern site) and South Padre Island (southern site). During the cold-front period, strongest downcoast flows occurred throughout the water column in the northern site, while significantly weaker flows occurred only near to the seabed in the central and southern sites. Time-averaged flows over a 2-month period (February to March 2017) showed intense and downcoast (and oncoast) surface flows in the north and weaker and upcoast in the south, and a convergence zone was present in between, off Port Mansfield (Cochrane and Kelly 1986). Thus, flow speeds were significantly reduced in the central zone due to the interaction of northerly directed downcoast currents and southerly directed upcoast flows. At this site, the formation of convergent flows was primarily related to variations of the alongshore wind component (Zavala-Hidalgo et al 2014). As a consequence of the convergence zone, material was reported to aggregate in the inner-shelf area south from Port Aransas (Thyng and Hetland 2017).

Depth-varying alongshore discrepancies of the flow were related to variations in the strength of downcoast winds during the cold-front period (Huh et al. 1984). The most energetic cold front (CF I) generated strong winds of τ_y of $−0.12 \text{ Nm}^{-2}$ in the north, which caused depth-uniform downcoast flows of $−0.6 \text{ ms}^{-1}$. In contrast, the same event induced

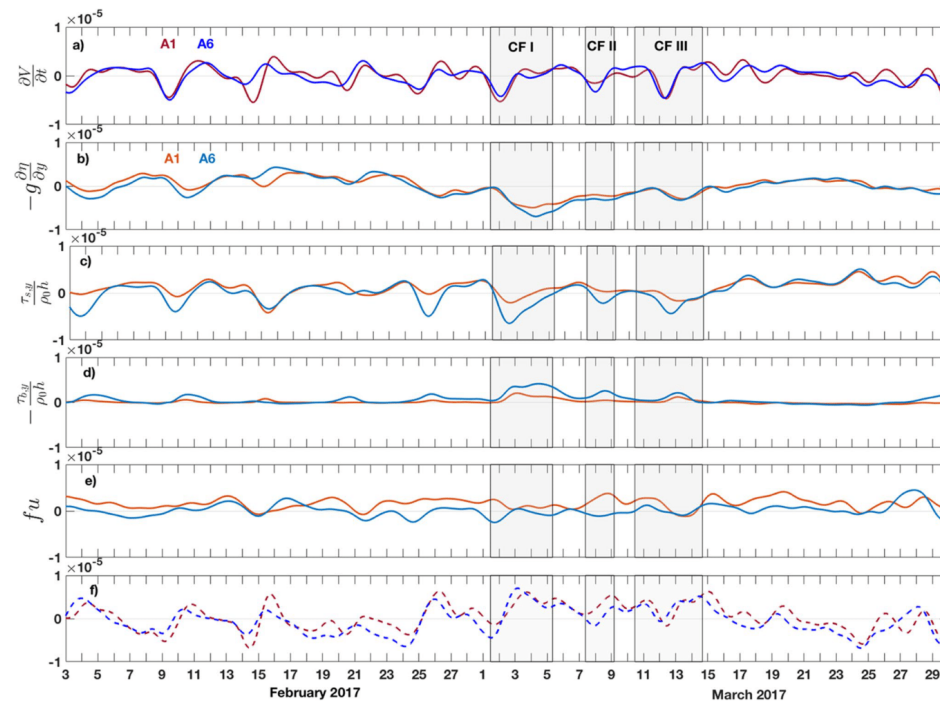


Fig. 12 Time series of the along-shelf momentum terms estimated from Eq. (2) for the northern site in Port Aransas (A6 in blue) and southern site in South Padre Island (A1 in red). (a) Local acceleration term; (b) pressure gradient term; (c) wind-stress term; (d) bottom

stress term; (e) Coriolis parameter and (f) the difference between the local acceleration term (left side of Eq. 2) and the sum of all terms (a) to (e) (right side of Eq. 2)

τ_y of -0.04 Nm^{-2} in the south and generated -0.5 ms^{-1} surface flows that decreased up to -0.3 ms^{-1} towards the seabed. Comparatively, the weakest cold front (CF II) induced -0.6 ms^{-1} downcoast surface flows and -0.3 ms^{-1} near to the seabed in the north, and considerably weaker surface downcoast flows of -0.1 ms^{-1} and -0.3 ms^{-1} near the seabed in the south.

Along-shelf flows presented time lags of 6 to 11 h to longer and most energetic CFs, and 1 h to the shorter and least energetic CF. While these lags were primarily considered to be related to CF intensity and duration, the presence of continental shelf waves could also contribute to the response of the flow (e.g. Dubranna et al. 2011). Vertical flow structure discrepancies were also related to spatially varying pre-front wind characteristics. This study suggests that the central and southern sites were more influenced by southeasterly Trade (upcoast) winds, which inhibited the low-energy CF from completely reversing the wind direction

towards the south (downcoast). In contrast, the northern site was less affected by Trade winds, and CFs induced strongest downcoast flows throughout the water column.

Cold fronts induced water-level increases of up to 0.3 m in the north and 0.1 to 0.2 m in the center and southern sites. These water-level increases were similar to the generated by cold fronts in other sites in the northern Gulf of Mexico (Huang and Li 2020) and are very relevant for the microtidal southern Texas coast. The combination of cold-front induced water levels with high spring tides and wave setup are expected to generate total sea surface elevations of over 1 m, which could cause relevant morphological variations and flooding in low-lying regions of the coast (Goff et al. 2019). Generally, the along-shelf flow structure was aligned to isobaths, but the cross-shelf flow was also important in the central site due to convergent winds (Thyng and Hetland, 2017). Surface wind stress and pressure gradient were the dominant terms in the along-shelf momentum

budget, while the bottom stress and the Coriolis terms were considered negligible (Grifoll et al. 2016). The wind stress was the dominant term in the north, which induced isobath aligned alongshore parallel flows (Thyng and Hetland 2017). Instead, pressure gradients associated with local sea-level responses to the wind forcing were dominant in the southern site.

5.1 Conclusions

Weather and current measurements collected between February and March 2017 at three sites in the southern Texas coast (Port Aransas in the north, Port Mansfield in the center and South Padre Island in the south) were used to determine along-shelf flow variations induced by cold fronts throughout the water column and to quantify the relevant terms in the inner-shelf along-shelf momentum budget. Inner-shelf flows were wind driven, but significant along-shelf variations existed between the northern and southern sites. Cold fronts induced strongest downcoast flows throughout the water column in the northern site, and significantly weaker downcoast surface and bottom flows in the central and southern sites. Time-averaged currents over a longer period of time showed intense downcoast surface flows in the north and weaker upcoast flows in the center and southern sites; thus, a convergence zone was present in between, off Port Mansfield.

The interaction of downcoast currents induced by dominant northerly winds, and upcoast flows induced by dominant southerly winds, significantly reduced flow speeds in the central zone. Thus, spatial variations of the along-shelf wind stresses were the main cause for flow convergence in the central site. Most intense surface flows occurred in the north, which were less affected by southeasterly (upcoast) winds. In contrast, low-energy cold fronts were unable to completely reverse the wind direction towards the south (downcoast) in southern and central sites due to the stronger influence of southeasterly Trade winds. Consequently, pre-front winds determined spatial variations of along-shelf flows during cold fronts.

Cold fronts induced significant water-level increases, which in combination with high spring tides and wave setup could generate important sea-surface elevations for low-lying regions in the southern Texas coast. These elevations were larger in the north (up to 0.3 m) than in central and southern sites (up to 0.2 m). The along-shelf momentum budget indicated that surface wind stress and pressure gradients were the dominant terms, while the bottom stress and Coriolis terms were negligible. The relevance of these terms, however, differed alongshore. The wind stress was the dominant term in the north, while pressure gradients associated with local sea-level responses to the wind forcing were dominant in the southern site.

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Author contribution Both authors contributed to the study conception and design. A.R.A.A. led the research. Data collection was undertaken by the CIGOM-UABC group, and analysis was performed by A.R.A. The first draft of the manuscript was written by A.R.A. with the support of A.R.A.A. Both authors read and approved the final manuscript.

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Data availability The datasets generated during and/or analyzed during the current study are not publicly available due internal policy of the CIGOM project, but may be available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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