Meteorological Influence on Summertime Baroclinic Exchange in the Straits of Mackinac

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Key Points:

- Exchange flow in the Straits of Mackinac is governed by a Helmholtz mode and summer baroclinic mode
- Seasonal variability in flow is driven by thermal stratification and is marked by a shift from regional- to local-scale meteorology
- Flow due to the baroclinic mode is controlled by the local wind forcing

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Abstract

Straits flows can impose a complex hydrodynamic environment with high seasonal variability and significant impacts to nearby water bodies. In the Straits of Mackinac, exchange flow between Lake Michigan and Lake Huron influences water quality and ecological processes, as well as the transport of any contaminants released in or near the Straits. Although previous work has shown that a Helmholtz mode is responsible for the barotropic flow oscillations in the Straits, baroclinic effects impose opposite surface and subsurface flows during the summer months. In this study, we use observations of currents and water temperatures from instruments deployed in the Straits to validate a hydrodynamic model of the combined Lake Michigan-Huron system and then use the model results to investigate the baroclinic flow and determine the forcing mechanisms that drive exchange flow in the Straits of Mackinac. Analysis shows that although the Helmholtz mode drives a 3-day oscillation throughout the year, thermal stratification in the summer establishes a bi-directional flow that is governed by a shift from regional- to local-scale meteorological conditions. These results detail the seasonal variability in the Straits, including the barotropic and baroclinic contributions to exchange flow and the influence of local atmospheric forcing on transport through the Straits of Mackinac.

1 Introduction

The dynamic exchange flow through straits can have significant impacts on the characteristics of the connected water bodies. Large fluctuations in volume transport, seasonal variation, and bi-directional currents can result in water quality differences and a physical influence that can span large distances. Transport within straits is dictated by fluctuations in water level, local atmospheric conditions, and changing thermal structure, making transport prediction a difficult task. Straits flows have been investigated in several regions around the world [*Whitehead*, 1974;

Miyake 1988; *Sayin and Krauss*, 1996] and earlier work has focused on aspects of geostrophic control [*Garrett and Toulany*, 1982; *Toulany and Garrett*, 1984; *Wright*, 1987; *Pratt*, 1991], seasonal variability [*Isobe*, 1994], meteorological influence [*Garrett and Toulany*, 1982], Helmholtz resonance [*Svansson*, 1980; *Stigebrand*, 1980], and rotational effects [*Garrett and Petrie*, 1981; *Whitehead*, 1986; *Lawrence*, 1990; *Oguz et al.*, 1990; *Farmer and Møller*, 1990].

Recent work by *Anderson and Schwab* [2013] investigated Helmholtz-driven barotropic flow in the Straits of Mackinac, the connecting waterway between Lakes Michigan and Huron, and the location of two 60 year-old underwater oil pipelines that cross the Straits (Figure 1). On their own, Michigan and Huron are two of the Earth's largest sources of surface freshwater, however if considered as a single lake due to a shared resting lake level, they form the world's largest lake by surface area. Exchange between the two lakes occurs through the Straits of Mackinac, a 6-km wide channel with depths between 30 and 80 m that experiences volumetric fluxes up to 80,000 m^3/s (0.08 Sv). *Anderson and Schwab* [2013] suggested that flow oscillations in the Straits of Mackinac are driven by a Helmholtz mode that is constantly forced by regional meteorological conditions, resulting in an oscillatory barotropic exchange flow that exists continually throughout the year, with a period given approximately by

$$T = 2\pi\sqrt{\frac{Al}{2A_c g}} \tag{1}$$

where T is the oscillation period, A is the surface area of either lake (assumed to be equal), l is the length of the straits channel, A_c is the cross-sectional area of the straits, and g is the gravitational constant. Using approximate values of A=6x10^{10} m^2, A_c=1.2x10^5 m^2, and l=60 km, (1) gives a period, T, of 2.8 days. Measurements have confirmed a dominant oscillation period between 2 and 3 days associated with flow through the Straits [*Saylor and Sloss*, 1976; *Saylor* *and Miller*, 1991]. However, observations and model results have suggested that local meteorological conditions can play an important role in the exchange flow in the Straits during summer months (June – September).

In the Great Lakes, the annual heating cycle results in alternating periods of well-mixed conditions in the winter and a thermally stratified (or two-layer) system in the summer [*Csanady*, 1967]. Thermocline development in the spring and summer is followed by thermocline deepening to peak depths of 15-30 meters in August, and a fall turnover in September or October. The thermal cycle of the lakes leads to distinct barotropic and baroclinic periods that can be observed in the Straits of Mackinac where a bi-directional exchange flow forms in mid- to late-June and lasts until the lake overturns.

If we assume rotational effects are important, given a Rossby radius of approximately 3 km [*Beletsky et al.*, 1997], we can consider a two-layer exchange flow between the lakes where the pressure gradient is in geostrophic balance with the Coriolis force (Figure 2). For the case of a steady flow setup by a prior impulse, where the cross-straits wind and bottom stresses are negligible, transport is aligned with the along-straits (x) direction ($v = 0$), the along-straits pressure gradient is negligible, and using the Boussinesq approximation ($\rho_1 \approx \rho_2 \approx \rho$), the shallow water equations for the upper and lower layers can be written as

$$-fu_1 = g\frac{\partial n_1}{\partial y}$$

$$-fu_2 = g\frac{\partial n_1}{\partial y} + g\frac{\Delta\rho}{\rho}\frac{\partial \eta_2}{\partial y} \qquad (2)$$

where u and v are the along-straits and cross-straits velocity components, respectively, in the upper (u_1) and lower (u_2) layers, f is the Coriolis parameter (10^{-4} s^{-1}), ρ is the density, η_1 is the surface displacement, η_2 is the interface displacement, and y is the cross-straits coordinate.

In the Straits, an eastward (along-straits) flow of warmer surface waters, with a colder subsurface return flow from Lake Huron to Lake Michigan, would result in the surface displacement and thermocline tilt illustrated in Figure 2, which is the typical condition given by the dominant west or southwest wind direction in the summer and is confirmed by observations. However, variation in the wind field can induce a change in thermal structure due to Ekman transport, resulting in changes to the thermocline angle in the Straits and impact on the baroclinic currents.

How these baroclinic processes are controlled by local meteorological conditions and to what extent they impact exchange in the Straits of Mackinac is the primary focus of this paper. Ultimately, this work gives insight into straits flows under strong seasonal variability, particularly differences between seasonal barotropic and baroclinic modes, and the impacts to transport. These complex hydrodynamic conditions can have important implications for water quality, ecology, and spill response in the event of a pipeline rupture. As a result, furthering our understanding of straits flows can enable an improvement to model forecast skill and help protect important resources while building resilient coastal communities.

2 Model

Investigations into the exchange flow in the Straits of Mackinac are carried out using the hydrodynamic model described in *Anderson and Schwab* [2013]. The model is based on the Finite Volume Community Ocean Model (FVCOM v3.2) [*Chen et al.*, 2006], a three-dimensional oceanographic model that solves the governing equations on an unstructured grid with sigma (terrain-following) vertical coordinates, which has been used successfully for several studies of the Great Lakes [*Anderson et al.*, 2010; *Bai et al.*, 2013; *Rowe et al.*, 2015; *Anderson et al.*, 2015]. The model domain covers the entire Lake Michigan-Huron system including the Straits of Mackinac at 100 m resolution and broadening out to 2.5 km in the offshore region of each lake (31,054 elements, 21 sigma layers). The model is the basis for the next-generation Lake Michigan-Huron Operational Forecast System (LMHOFS) being implemented by the National Oceanic and Atmospheric Administration (NOAA) for real-time nowcast and forecast prediction of water levels, currents, and water temperatures.

For this study, boundary conditions are limited to surface meteorological forcing (wind, air temperature, dew point, cloud cover) and do not include lateral boundary conditions such as tributary inflows and outflows, which do not have a significant impact on flow conditions in the Straits. Surface forcing conditions are prescribed by the NOAA National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR; *Saha et al.*, 2010), which has hourly reanalysis data at 0.2^{o} horizontal resolution. Recent work has demonstrated the successful simulation of Great Lakes water temperatures [*Xue et al.*, 2015] and storm surge [*Jensen et al.*, 2012] using CFSR forcing conditions. Given the focus of this study on exchange flow, thermal structure and water level fluctuations are critical to understanding differences between barotropic and baroclinic modes in the Straits, and thus CFSR provides the most appropriate set of forcing conditions to carry out this work.

The model simulation encompasses the period April 1 – Dec 31, 2014, which overlaps with the period of instrument deployment in the Straits of Mackinac and is chosen specifically to investigate meteorological influence on baroclinic flow. Initial conditions for water temperature were set to 1^{o}C uniformly over the entire domain. Model results are compared to hourly current measurements from two in-line Acoustic Doppler Current Profilers (ADCP; Teledyne RDI 300 kHz) located at 45.8145° N and 84.8218° W. The ADCPs were arranged such that one was at mid-depth facing upward to measure currents in the top half of the water column, and the second was located at the lake bottom to measure currents in the bottom half of the column. Adjacent to the ADCP location, a thermistor string was deployed with 21 temperature sensors (Seabird SB56) uniformly distributed throughout the top 40 meters of the water column.

Simulations are carried out for two cases, (*i*) a barotropic (uniform density) condition and (*ii*) a baroclinic condition with the full 3-dimensional density calculated by FVCOM. Each case covers the entire simulation period. Comparisons to observations are carried out using the baroclinic results, however both cases are analyzed for current velocity and volumetric flow calculated along a longitudinal transect across the Straits (Figure 1). We also analyze the difference in flow conditions between the two cases by subtracting the barotropic currents from the baroclinic simulation, highlighting the contributions to exchange flow from the summertime baroclinic mode only. As discussed in previous work, the barotropic mode drives exchange flow throughout the annual cycle, however the differences between these two simulations enables an investigation into the effects of local meteorological forcing on summertime baroclinic transport in the Straits. To understand the influence of local meteorology in the baroclinic case, focus is placed on epilimnetic and hypolimnetic flow, which we define as net transport above (epilimnetic) and below (hypolimnetic) the 12°C isotherm.

3 Exchange flow in the Straits of Mackinac

3.1 Observations

Hydrodynamic conditions in the Straits were measured from June 11, 2014 to May 21, 2015, at a location in the western end of the Straits near the Mackinac Channel, a submerged river channel that once drained Lake Michigan waters into Lake Huron and now serves as the deepest feature in the Straits of Mackinac. The chosen point of observation is a compromise between locations away from shipping traffic and the pipeline area but close enough to the Straits to detect the oscillatory and bi-directional phenomena in the channel. As such, the ADCPs and thermistor chain lie just outside of the narrowest reaches of the Straits, at the point where the channel widens into Lake Michigan, and as a result experiences a mixture of the oscillatory currents in the Straits and the effects of an open-lake gyre that exists in the northern end of Lake Michigan.

Current observations reveal a dominant along-straits component, reaching velocities up to 0.85 m/s at the surface (Figure 3). The cross-straits component is roughly an order of magnitude smaller under most conditions. A plot of the energy spectrum confirms the primary period of oscillation near 3.3 days, which is attributed to a Helmholtz mode in the Lake Michigan-Huron system [*Anderson and Schwab*, 2013]. The largest amplitudes in the along-straits component occur in October and November, when weather conditions in the Great Lakes bring frequent and intense storm fronts.

A time-averaged plot of the subsurface currents (Figure 4) shows the bi-directional flow established during the summer months, in which the warmer surface layer flows toward the east (positive) and the cooler subsurface layer flows toward the west (negative). After the fall turnover, when water column densities equilibrate and result in a well-mixed condition, the along-straits component of velocity reveals a net westward flow throughout the column. Examination of the spatial structure of modeled average currents in this region indicates that the net westward flow is a function of ADCP location. Areas to the north or south or further east in the Straits may have dominant eastward or neutral velocities, respectively, to balance the exchange and result in the net eastward flux from Lake Michigan to Lake Huron. Modeled currents are able capture both the high amplitude oscillations in the Straits ($\text{RMSD}_{\text{along-straits}}$ = 0.10 m/s, $\text{RMSD}_{\text{cross-straits}}$ = 0.03 m/s) and the bi-directional flow profile observed throughout the water column, though peak amplitudes are often underpredicted in the fall (Figures 3 and 4).

A thermistor chain deployed near the ADCP location captures the onset of stratification in the Straits which begins to form in late June and lasts until mid-September when the lake overturns and mixes throughout the water column (Figure 5). The development of the thermocline enables the bi-directional flow (shown in Figure 4), which is driven by wind forcing and has been discussed previously by *Anderson and Schwab* [2013]. Modeled water temperatures agree well with the start of stratification, thermocline depth, and overturn, though the metalimnion is slightly more diffuse in the FVCOM model, consistent with other Great Lakes modeling studies [*Beletsky and Schwab*, 2001; *Beletsky et al.*, 2013]. The mean RMSD in the water column between thermistor observations and the corresponding model sigma-layer temperature is 1.34 ^{o}C.

3.2 Barotropic and baroclinic contributions

The exchange flow between Lake Michigan and Lake Huron is investigated along a longitudinal transect (A-A’) at the narrowest reach in the Straits for barotropic and baroclinic cases (Figure 1). The Helmholtz mode is easily discernable in the barotropic case, illustrated by a time-series plot of the surface along-straits current taken at a location midway across the transect, near the center of the Straits (Figure 6). The 3-day oscillation is present throughout the entire model period, driven by continual regional atmospheric forcing. Monthly-averaged plots of the along-straits current profile at this location (center of the Straits) reveal a mean westward current in most months (Figure 7), as was found at the ADCP location. With the absence of thermal structure, a contour plot of the averaged barotropic along-straits velocity across the entire transect shows westward currents are laterally stratified and bound to northern-center region of the Straits, with dominant eastern flows in the southern region (Figure 8).

In the baroclinic case, thermal stratification begins in June and lasts through September (Figures 5 and 8d,e,f). During this period, surface currents are primarily eastward, transporting the warmer epilimnion waters from Lake Michigan into Lake Huron even though the Helmholtz oscillations are still dominant (Figure 6). A compensating subsurface return flow (westward) sets up during this period, with peak amplitudes centered along the Straits though slightly north of the deepest region of the channel (Figure 8b).

By subtracting case *i* results from case *ii* results, the contribution of the baroclinic mode is made apparent and clearly reveals the bi-directional flow that persists throughout the summer period (Figures 6, 7, 8c). The exchange flow for the baroclinic case reaches 80,000 m^3/s, with largest amplitudes in the late fall, but differences between the two cases (*i* and *ii*) are relatively small, owing to the barotropic Helmholtz mode that is the primary mechanism behind the oscillatory flow (Figure 9a,b).

3.3 Impact of local meteorological forcing

Except for two periods in late June and late August, a consistent eastward surface flow and westward subsurface return flow are present in the Straits during stratified conditions (Figure 9b,c). However, during these two excursions, a reversal or near-reversal in flow direction occurs in the surface and subsurface layers, persisting for a few days in each case. From (2), we expect a geostrophic balance between the currents in the hypolimnion and the pressure gradient that results from the thermocline slope and surface displacement across the straits, given in Table 1.

Plotting the difference in water temperature between the northern and southern shorelines, we see the majority of the summer period experiences a thermocline that is tilted up toward the northern shore (shown as negative temperature; Figure 9d). However, in late June the thermocline angle reverses for an extended period with northern boundary temperatures increasing to nearly 4°C higher than the southern shore, resulting in the reversal of surface and subsurface flows in the Straits. Similarly, in mid- to late-August, two additional spikes in water temperature difference occur, timed with the near-reversal and reversal of currents in the Straits. Wind observations from a nearby NOAA National Ocean Service (NOS) C-MAN station (MACM4) reveal dominant west winds (positive values of the along-straits wind, U_w) during the summer months with notable excursions at the time of the thermocline angle reversal (Figure 9e).

Scatter plots of the along-straits wind component (U_w) from MACM4 versus the surface volumetric flow and mid-channel currents from the baroclinic, barotropic, and difference cases are shown in Figure 10. If we consider a momentum balance in the along-straits direction,

$$\frac{\partial U}{\partial t} - fV = -gH\frac{\partial \eta}{\partial x} + F_x - B_x$$

where U and V are the depth-integrated along- and cross-straits velocity, H is depth, F_x is the wind stress, and B_x is the bottom stress, and assuming the along-straits pressure gradient and cross-straits velocity are negligible, the along-straits transport equation reduces to

$$\frac{\partial U}{\partial t} = F_x - B_x$$

If the stresses are written as $F_x = u_*^2$ and $B_x = C_D\left(\frac{U}{H}\right)^2$, and after some frictional adjustment time scale, the solution yields an along-straits current which is governed by

$$U = \frac{u_*}{\sqrt{C_D}} \tag{3}$$

where U is the depth-averaged along-straits transport, $u_*$is the friction velocity and C_D is a drag coefficient [*Csanady*, 1982]. For $u_* = \sqrt{\tau/\rho_{water}} = \sqrt{\rho_{air}C_{Da}(U_w)^2/\rho_{water}}$, we can compare the model results with estimated along-straits current from (3) using observed wind (U_w) and approximate values (C_{Da} = 0.0025, ρ_{air} = 1.22 kg/m^3, ρ_{water} = 1000 kg/m^3, C_D = 0.002). Model results show the effect of the local wind field on the surface baroclinic flow (R^2 = 0.60), where eastward surface flows tend to follow sustained westerly winds and compare well with the relationship from (3). Though not shown in this plot, subsurface flows have a similar correlation with opposite flow direction. The surface current from the baroclinic case located midway across the channel has a weaker correlation (R^2 = 0.20; Figure 10b), which can be expected since any single location may not represent the integrated flow across the Straits transect. However, much of the reasoning for the poor correlation is due to the underlying barotropic mode, which does not correlate well with the local wind field (R^2 = 0.08; Figure 10c). This influence is clearly illustrated in the current difference between the baroclinic and barotropic cases, where the correlation with the along-straits wind velocity is nearly as strong as the baroclinic surface flow and also agrees well with the predicted transport from (3) (R^2 = 0.51; Figure 10d).

4 Discussion

The Straits of Mackinac may be a smaller system in terms of depth and channel width relative to many ocean straits reported in the literature, however these straits exhibit much of the same behavior as found in larger marine systems. Aspects such as meteorological influence, rotational effects, seasonal variation, and Helmholtz resonance all play an important role in governing the exchange flow between Lake Michigan and Lake Huron. In this study, we explore the seasonal variability in the Straits that arises from barotropic and baroclinic modes, and the role of local surface forcing on the baroclinic mode.

For the barotropic mode, exchange flow though the Straits oscillates with a 3-day period and persists throughout the year, forming the underlying volumetric exchange flow between the lakes. This barotropic flow results from a Helmholtz mode that is constantly reinforced by passing weather systems (i.e. wind stress and/or atmospheric pressure gradient) that act on all parts of both lakes. Historically, this relationship between weather systems and flow in the Straits was not well understood, as neither local meteorology nor the bi-lake seiche could explain the oscillation, making current prediction in the Straits a difficult task. *Anderson and Schwab* [2013] showed that a hydrodynamic model of the combined Michigan-Huron system using hourly, spatially explicit wind forcing was required to accurately predict flow in the Straits. However, the Helmholtz mode alone cannot fully account for the bi-directional exchange flow observed during the stratified season, as previous studies have demonstrated.

Differences between the Helmholtz flow and the summertime flow conditions are attributed to the baroclinic mode, during which stratification in the water column establishes a bi-directional current field. By subtracting the barotropic simulation from the baroclinic run, we isolate the baroclinic contribution to flow and reveal the resultant flux that occurs during the summer months. Comparison with observed wind conditions from a nearby location yields a strong correlation with the baroclinic flow direction, signifying a shift from a paradigm where regional meteorology drives the barotropic Helmholtz flow to one where local meteorology plays an equally important role in controlling the baroclinic flow signal. The mechanism behind this shift is the development of a two-layer system in the Straits during the summer season.

During the stratified period, a geostrophic balance exists between the surface and thermocline slope across the Straits and the Coriolis force. The angle of the thermocline tilt is dictated by the local wind field, where, for instance, sustained westerly winds would result in a thermocline that is tilted upward toward the north. In this case, warmer surface waters would be transported toward the east into Lake Huron with subsurface return flow of colder waters into Lake Michigan. However, as the local wind field changes, the exchange flow is altered, which changes the pressure gradient across the Straits. In 2014, two notable changes in the bi-directional flow occurred in late June and late August, during which sustained easterly winds reversed the thermocline angle and the flow direction in the surface and subsurface layers. Using the same meteorological forcing, the Helmholtz mode alone fails to explain these conditions, underscoring the paradigm shift and the increasing role of local meteorology during the stratified season.

Overall, the baroclinic mode enables local meteorology to control the exchange flow between the lakes and affect transport in the surface and subsurface layers, which can have important implications for water quality, ecology, and contaminant transport. With respect to the pipelines in the Straits, a release from the lake bottom will experience different flow regimes during stratified and unstratified seasons as buoyancy carries the oil toward the lake surface. The bi-directional currents during the summer will introduce a significant amount of shear into the water column that could substantially increase dispersion in the early minutes or hours after the release. Although the strong correlation between sustained wind and flow directions is known, which may increase predictive skill, significant variability in meteorology can still complicate response efforts. Certainly, further investigation into the implications of barotropic and baroclinic flow on spill transport is necessary, though it is beyond the scope of this work. Another limitation of this work is that simulations were carried out for the ice-free period only. Additional questions remain about flow conditions in the Straits during the winter season when ice formation may inhibit exchange flow, and therefore should be the subject of further study.

5 Conclusions

The Straits of Mackinac is an important resource that connects two of the Earth's largest lakes. Currents in the Straits exhibit a complex hydrodynamic picture that entails seasonal variability, Helmholtz resonance, and bi-directional flow. This study shows that the annual lake thermal cycle results in a shift from winter to summer conditions in which a two-layer system develops with bi-directional currents in the Straits. Although the Helmholtz mode drives a 3-day flow oscillation that is present throughout the year, this work illustrates the relationship between the baroclinic transport in a straits system and the local meteorological conditions, a feature which can dictate flow direction in the summer months in the Straits of Mackinac and play an important role in contaminant transport and water quality.

Acknowledgments and Data

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	July	August	September
$\boldsymbol{u_1}$ (m/s)	0.091	0.023	0.053
$\boldsymbol{u_2}$ (m/s)	-0.065	-0.014	-0.047
$\boldsymbol{u_1'}$ (m/s)	0.059	0.019	0.045
$\boldsymbol{u_2'}$ (m/s)	-0.062	- 0.016	- 0.044

Table 1. Upper and lower layer along-straits currents (*u*) estimated using monthly-averaged modeled conditions in the Straits given geostrophic balance according to (2) as compared with the model-simulated currents ($\boldsymbol{u'}$).

Figure 1. In the Great Lakes, the Straits of Mackinac (top right, bottom) connects Lake Michigan and Lake Huron (top left). The unstructured model grid and location of 2014-2015 ADCP and thermistor chain deployment location in the Straits is marked, including a meteorological station (MACM4, top right). Two underwater oil pipelines cross the straits, as depicted by the red dashed lines (top right). The bathymetry of the Straits (3 arc-second) is shown in the lower panel, including a cross-straits transect (A-A') used for transport analysis (bottom).

Figure 2. Schematic of the Straits of Mackinac as a steady two-layer system during the summer stratified period, from the perspective looking east into Lake Huron, with the northern (N) and southern (S) shorelines depicted. The thermocline tilt and surface deflection are assumed to be in geostrophic balance with the currents in the bottom layer, driving flow into (depicted) or out of Lake Michigan with an opposite return flow at the surface layer.

Figure 3. (**a**) Scatter plots, (**b**) energy spectra, and (**c**) times-series plots of the observed hourly surface currents are shown in red for the 2014 period at a location in the western region of the

Straits of Mackinac. Model output is shown in black. Time-series plots (**c**) of the surface along-straits and cross-straits components of velocity are shown with 24-hour smoothing to highlight the flow oscillation, relative magnitude, and model validity. Positive and negative values of the along-straits current depict eastward and westward flows, respectively.

Figure 4. Time-averaged currents from ADCP observations (red) and model simulation (black) during the stratified (left) and unstratified (right) periods in 2014 for along-straits (solid) and cross-straits components (dashed) of velocity.

Figure 5. Thermistor measurements (top) and modeled (bottom) water temperatures in the Straits of Mackinac during June – December 2014.

Figure 6. Modeled surface currents (along-straits component) near the center of the Straits transect (A-A’) for the (i) barotropic case, (ii) baroclinic case, and the difference between the two simulations (bottom). Hourly model output is shown in red, with 10-day smoothed currents over-plotted in black. In the difference plot (bottom), the blue line represents the along-straits velocity at a depth just below the thermocline, which represents the subsurface current (10-day smoothed).

Figure 7. Modeled monthly-averaged along-straits velocity profiles near the centerline of the Straits along transect (A-A’). Barotropic velocity is shown in blue and the difference between the baroclinic and barotropic cases is shown in black.

Figure 8. Summer average along-straits velocity (July-September; **a-c**) along the Straits transect (A-A’), shown as a function of distance from the northern to southern coastline. Warmer colors represent eastward currents that flow toward Lake Huron and colder colors depict westward

currents that flow into Lake Michigan (subsurface return flow in the baroclinic case). Monthly-averaged water temperatures (**d-f**) for July, August, and September 2014.

Figure 9. (**a**) Baroclinic exchange flow through the Straits of Mackinac, and the (**b**) difference in flow between the baroclinic and barotropic cases (black line), flow difference above the 12^{o}C isotherm (red line), and flow difference below the 12^{o}C isotherm (blue line). (**c**) The development and depth of the 12^{o}C isotherm is shown for reference as stratification sets up in the summer months, (**d**) with differences in water temperature between the northern and southern coastlines, and (**e**) the along-straits wind component from a nearby NOAA C-MAN station (MACM4). All plots are shown with 5-day smoothing.

Figure 10. Scatter plot of the along-straits wind component (U_w) from the NOAA C-MAN MACM4 station versus model results (red circles) for the along-straits (**a**) surface baroclinic exchange flow, as well as a mid-channel surface current from the (**b**) baroclinic case, (**c**) barotropic case, and (**d**) the difference between the baroclinic and barotropic cases. Transports given by (3) are shown as dashed black lines in (a) and (d). Observed wind data and model output are plotted using 10-day smoothing.

Figure 1.


48°
46°
44°
42°
-90°
-85°
-80°
0
90
180
km
N
2014
MACM4
ADCP/Therm.
5 km
A
A'
0
20
40
60
80
100
120
140
meters

Figure 2.

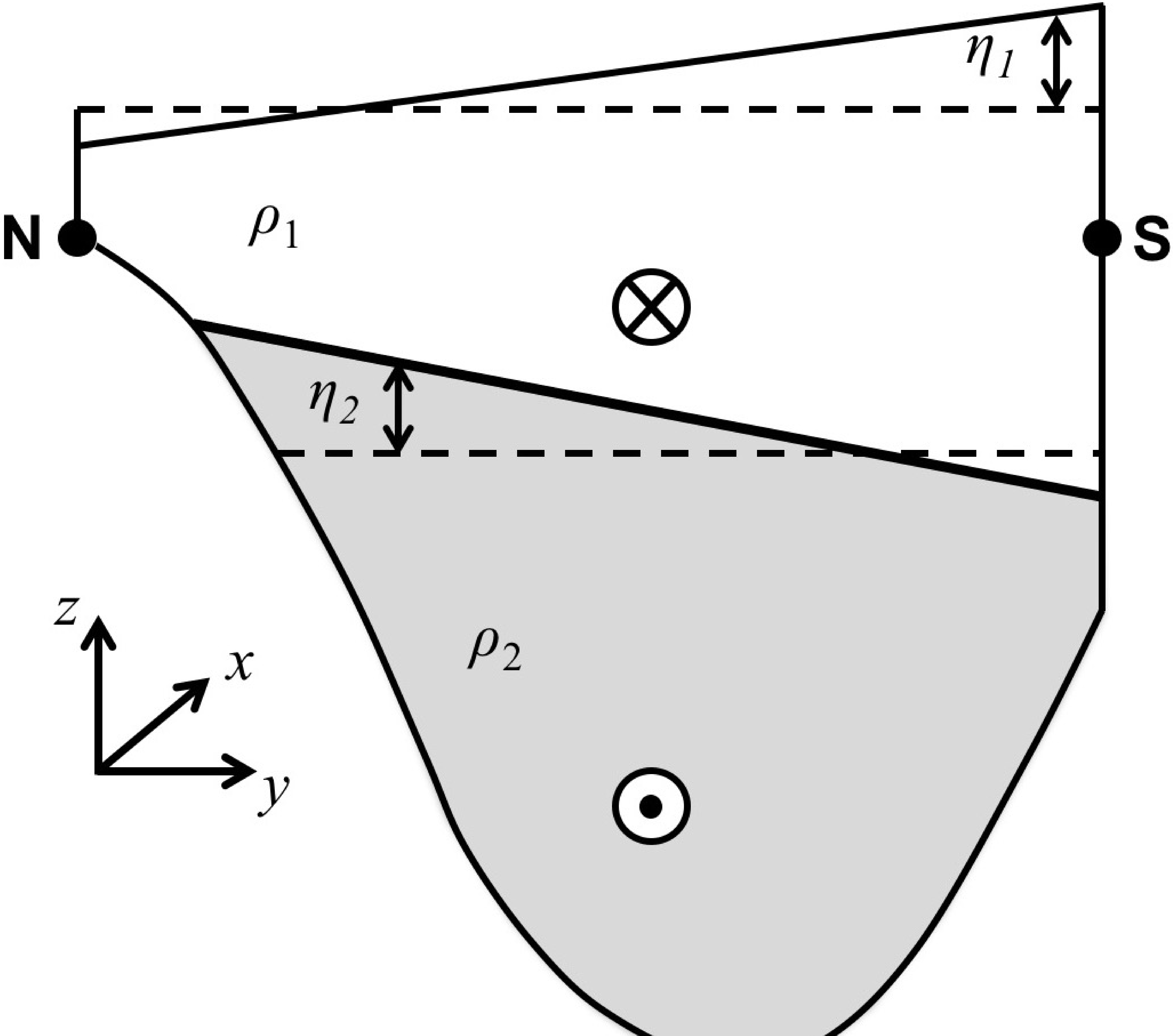

η_1
N
ρ_1
S
$\otimes$
η_2
z
x
ρ_2
y
$\odot$

Figure 3.

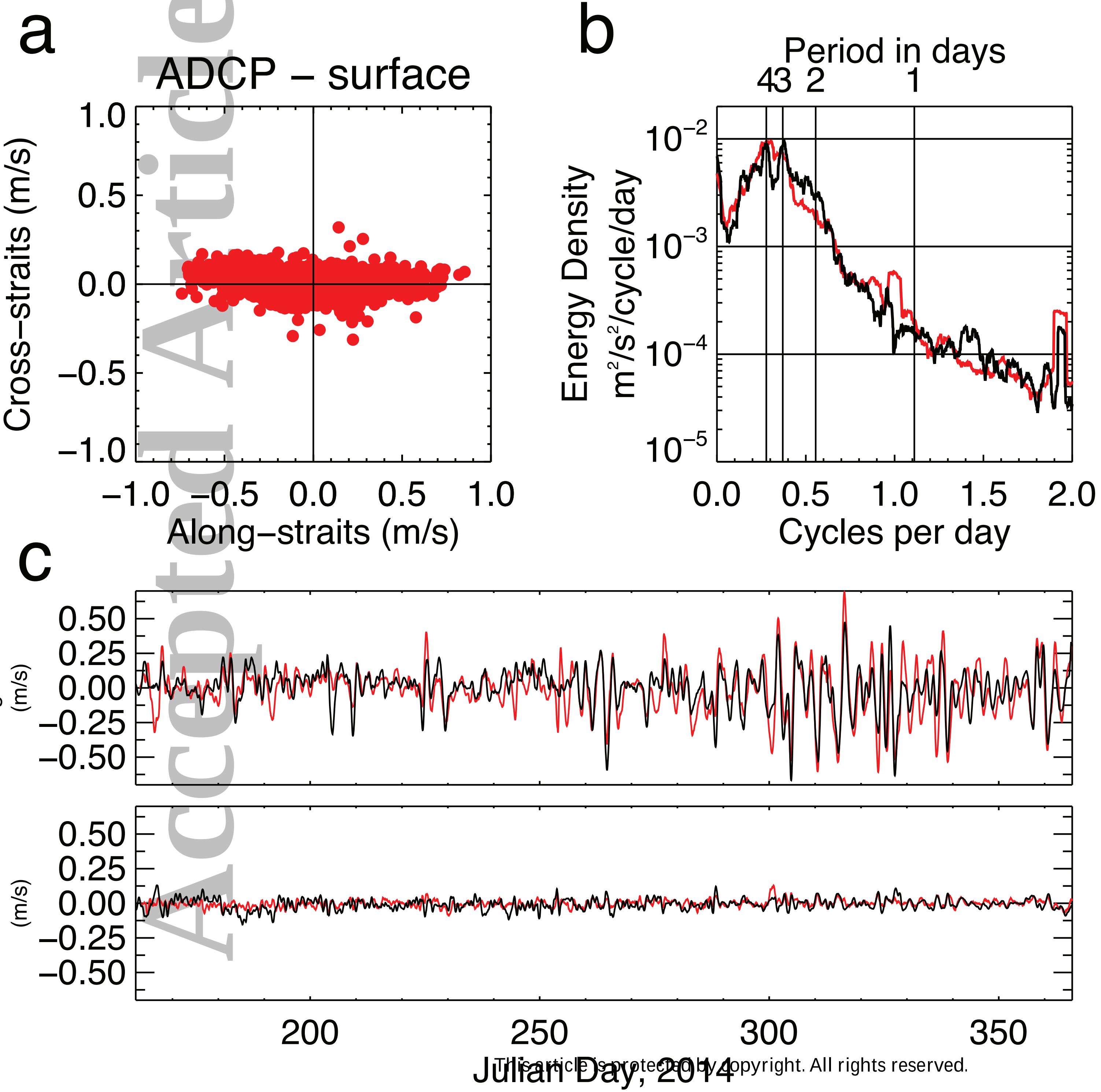

a
ADCP – surface
1.0
0.5
0.0
−0.5
−1.0
Cross–straits (m/s)
−1.0
−0.5
0.0
0.5
1.0
Along–straits (m/s)
b
Period in days
4
3
2
1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Energy Density
m^2/s^2/cycle/day
0.0
0.5
1.0
1.5
2.0
Cycles per day
c
0.50
0.25
0.00
−0.25
−0.50
Along–straits (m/s)
0.50
0.25
0.00
−0.25
−0.50
Cross–straits (m/s)
200
250
300
350
Julian Day, 2014

Figure 4.

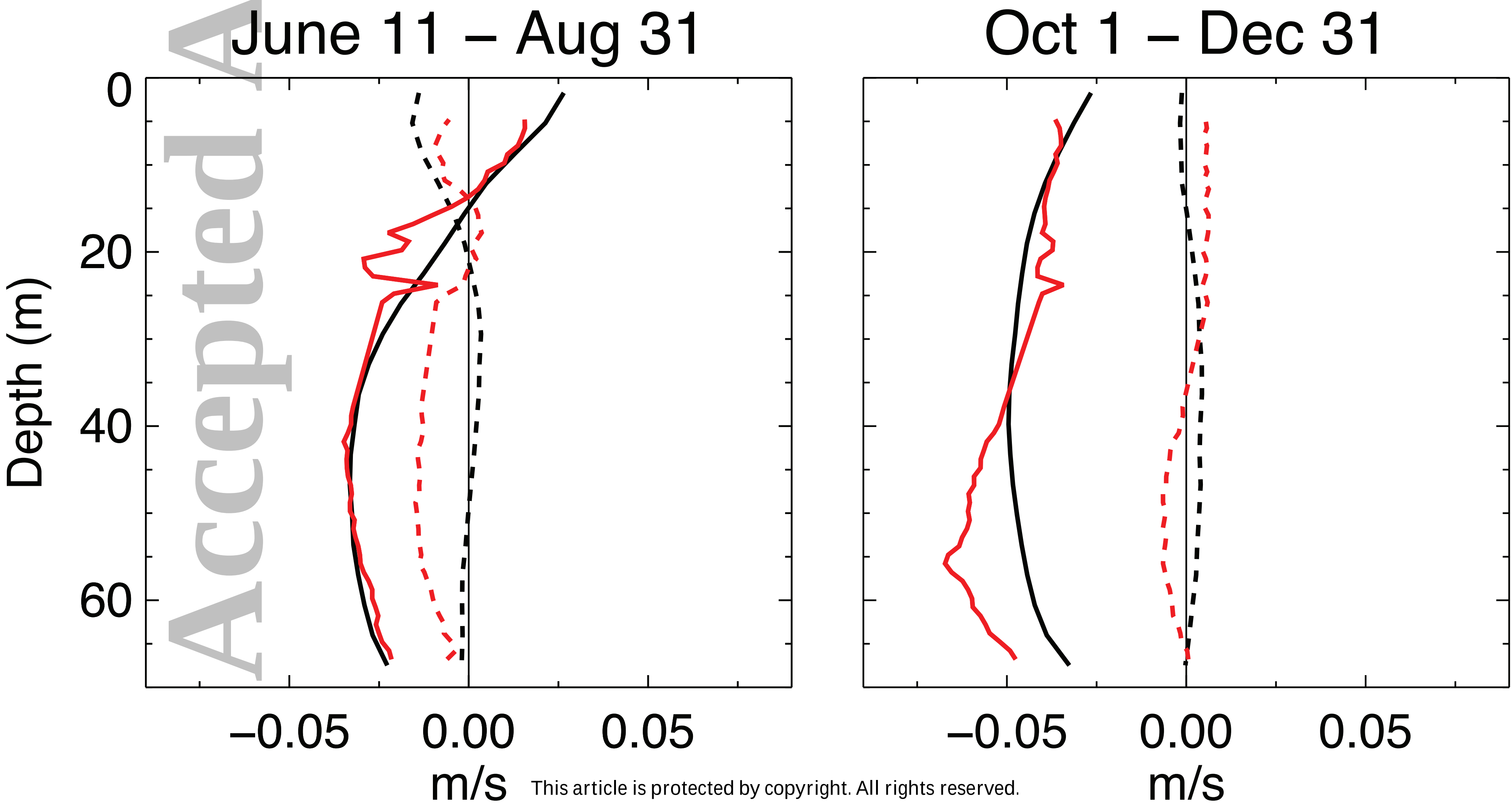

June 11 – Aug 31
Oct 1 – Dec 31
Depth (m)
0
20
40
60
–0.05
0.00
0.05
m/s
–0.05
0.00
0.05
m/s

Figure 5.

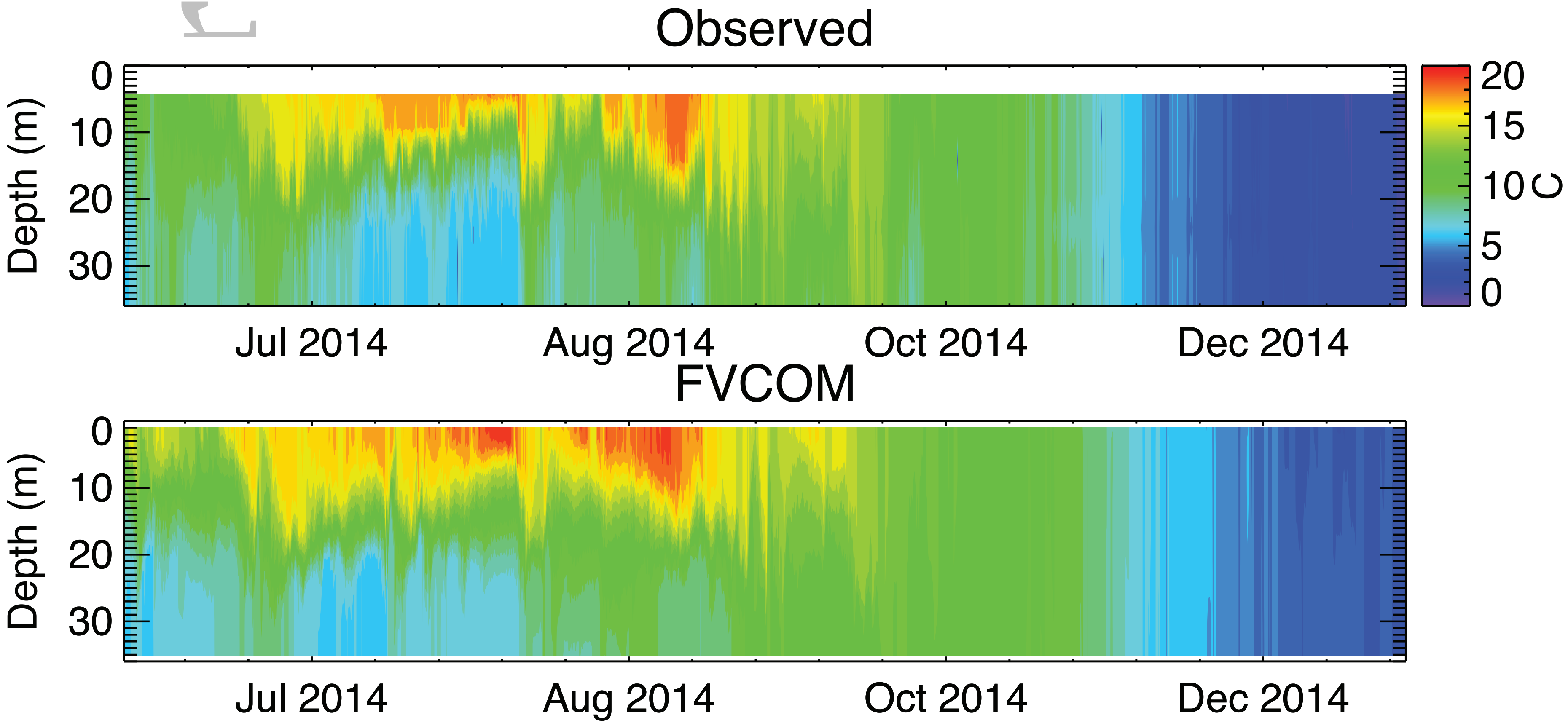

Observed
Depth (m)
0
10
20
30
Jul 2014
Aug 2014
Oct 2014
Dec 2014
20
15
10
5
0
C
FVCOM
Depth (m)
0
10
20
30
Jul 2014
Aug 2014
Oct 2014
Dec 2014

Figure 6.

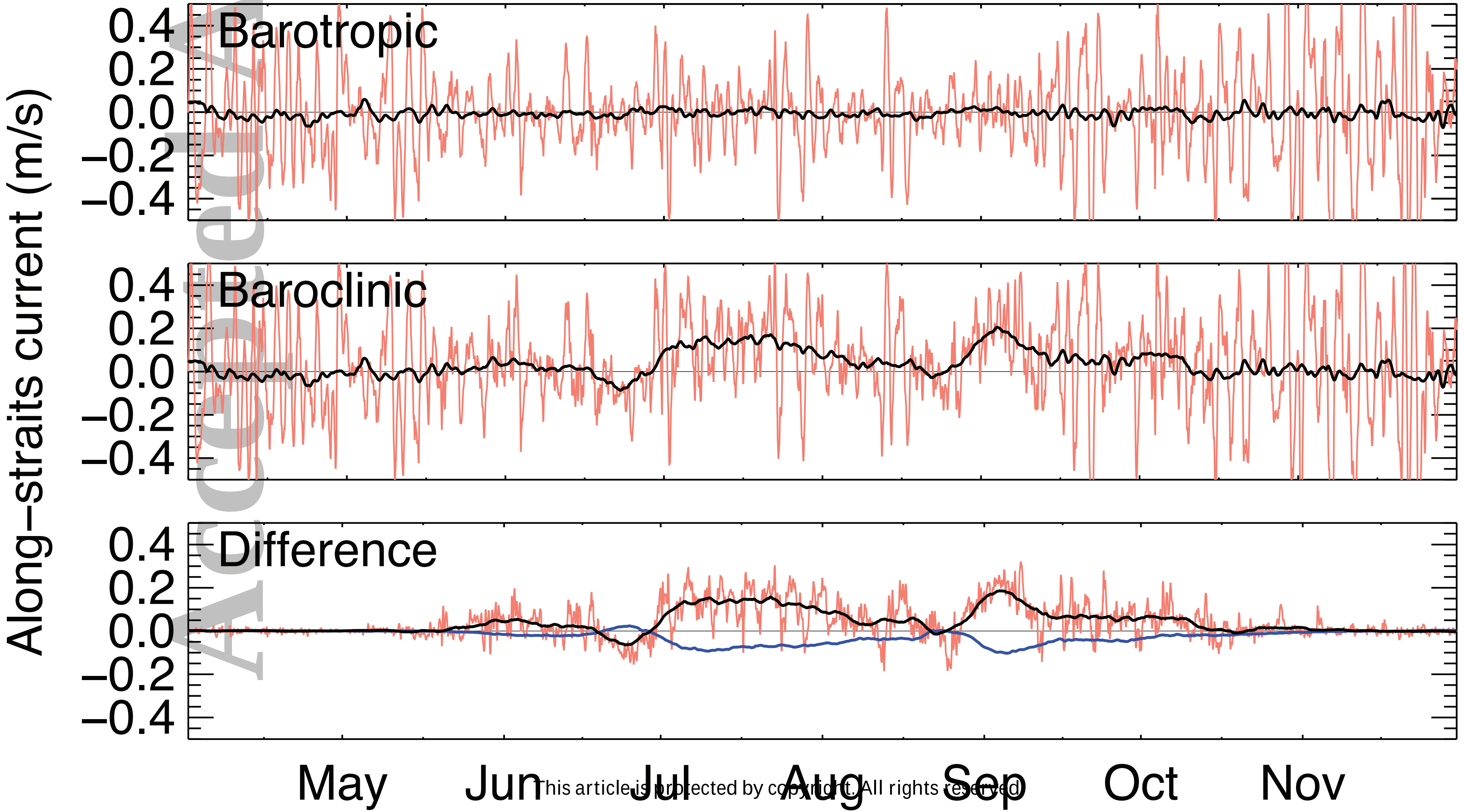

Along–straits current (m/s)
Barotropic
Baroclinic
Difference
0.4
0.2
0.0
−0.2
−0.4
May
Jun
Jul
Aug
Sep
Oct
Nov

Figure 7.

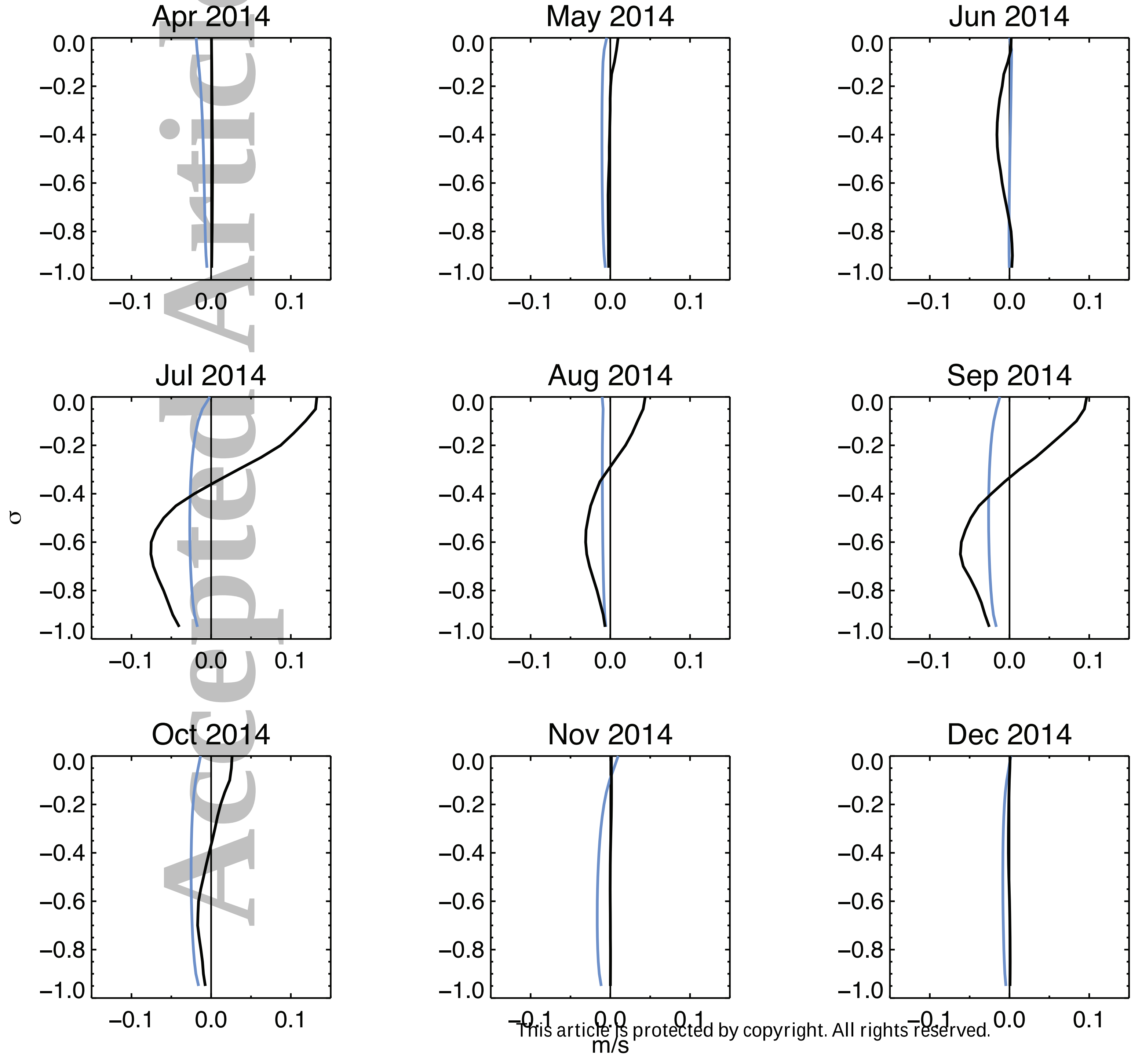

Apr 2014
May 2014
Jun 2014
Jul 2014
Aug 2014
Sep 2014
Oct 2014
Nov 2014
Dec 2014
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−0.1
0.0
0.1
σ
m/s

Figure 8.

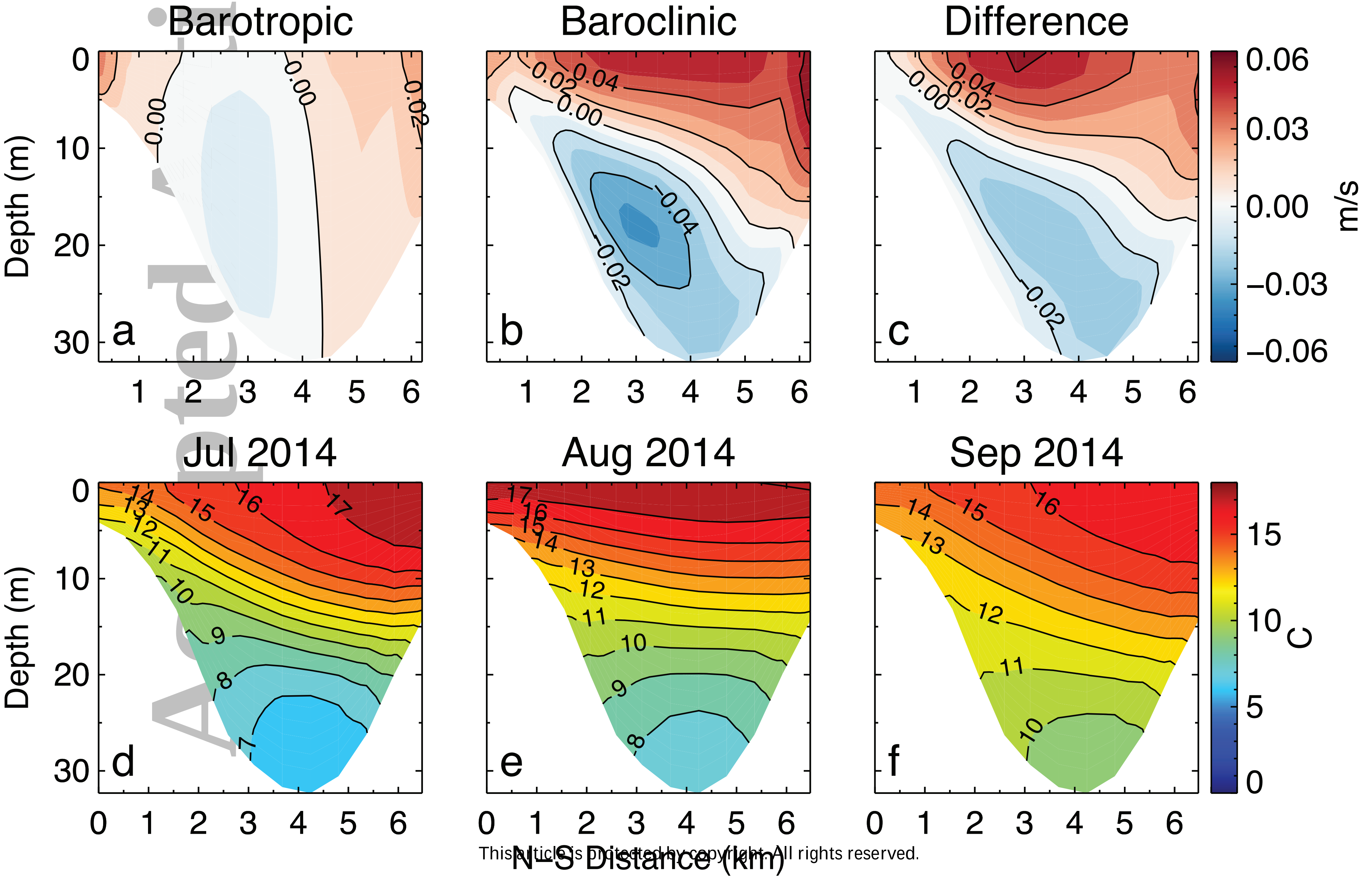

Barotropic
Baroclinic
Difference
Depth (m)
0
10
20
30
a
b
c
0.00
0.02
0.04
−0.02
−0.04
1
2
3
4
5
6
0.06
0.03
0.00
−0.03
−0.06
m/s
Jul 2014
Aug 2014
Sep 2014
d
e
f
7
8
9
10
11
12
13
14
15
16
17
0
5
10
15
C
N–S Distance (km)

Figure 9.

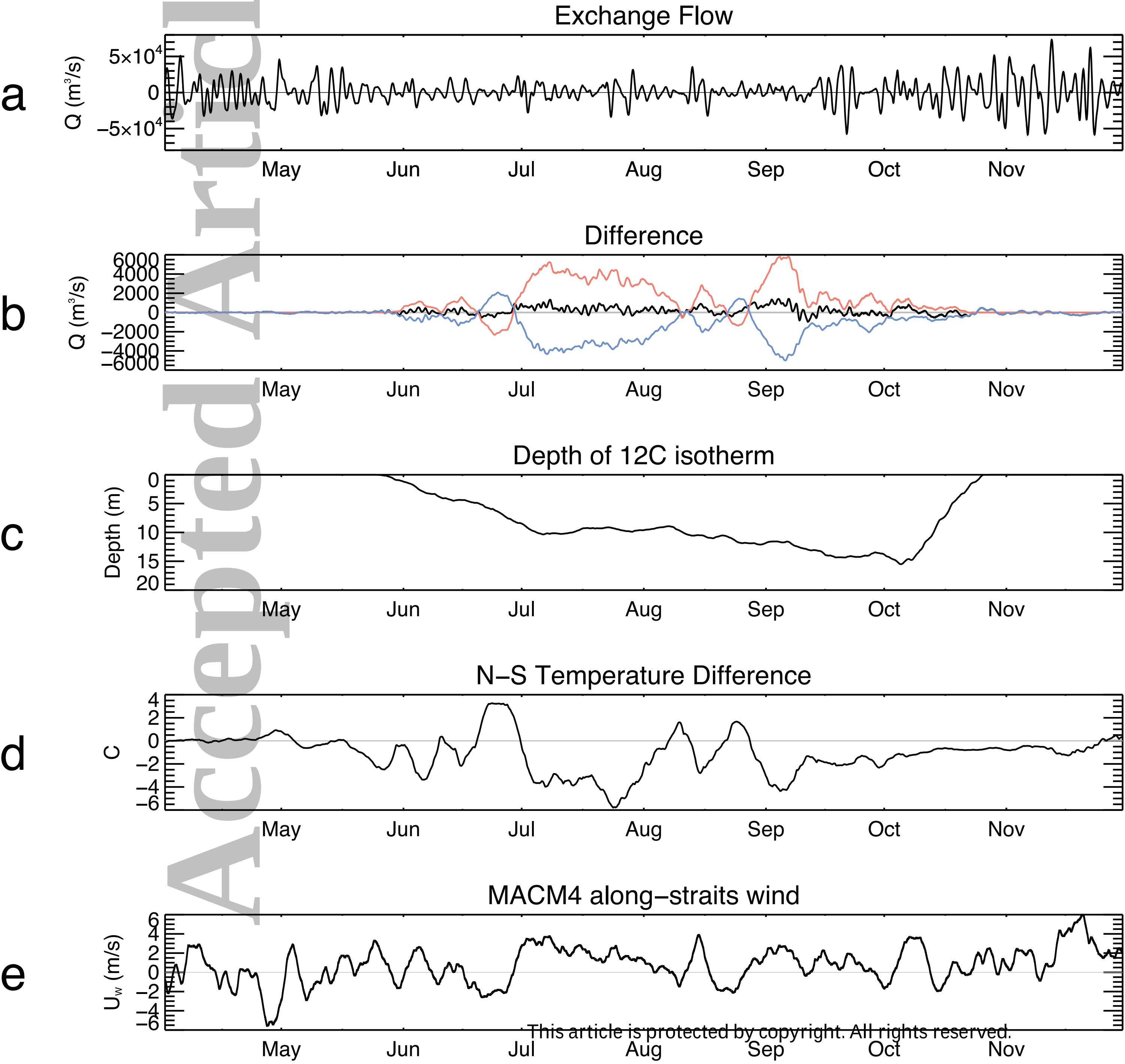
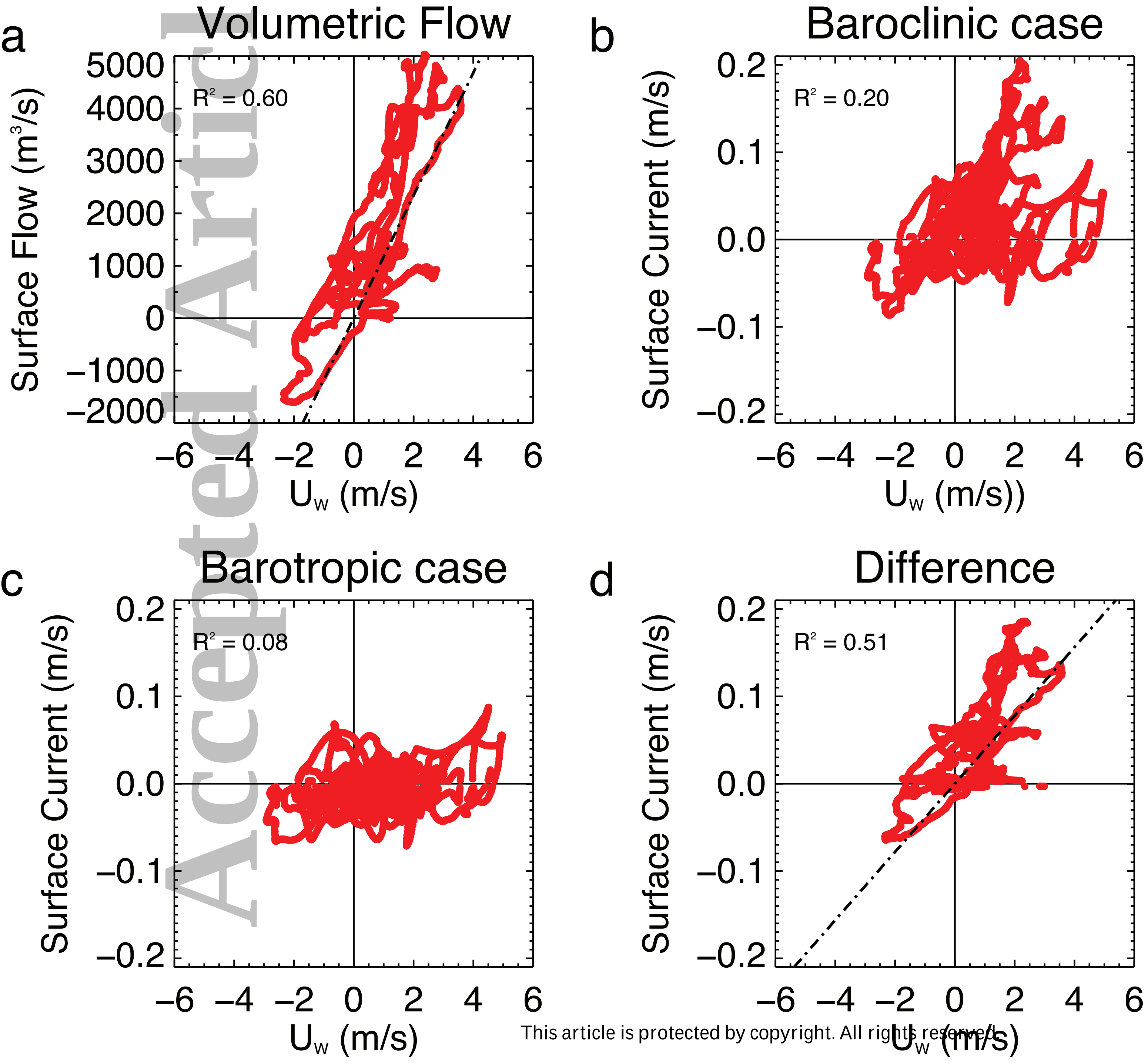

a
Exchange Flow
Q (m³/s)
5×10⁴
0
−5×10⁴
b
Difference
Q (m³/s)
6000
4000
2000
0
−2000
−4000
−6000
c
Depth of 12C isotherm
Depth (m)
0
5
10
15
20
d
N−S Temperature Difference
C
4
2
0
-2
-4
-6
e
MACM4 along−straits wind
U_W (m/s)
6
4
2
0
-2
-4
-6
May
Jun
Jul
Aug
Sep
Oct
Nov

Figure 10.


a
Volumetric Flow
Surface Flow (m^3/s)
5000
4000
3000
2000
1000
0
−1000
−2000
R^2 = 0.60
−6
−4
−2
0
2
4
6
U$_w$ (m/s)
b
Baroclinic case
Surface Current (m/s)
0.2
0.1
0.0
−0.1
−0.2
R^2 = 0.20
−6
−4
−2
0
2
4
6
U$_w$ (m/s))
c
Barotropic case
Surface Current (m/s)
0.2
0.1
0.0
−0.1
−0.2
R^2 = 0.08
−6
−4
−2
0
2
4
6
U$_w$ (m/s)
d
Difference
Surface Current (m/s)
0.2
0.1
0.0
−0.1
−0.2
R^2 = 0.51
−6
−4
−2
0
2
4
6
U$_w$ (m/s)