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Key Points:

- We provide the first analysis of intraseasonal circulation variability on the western Antarctic Peninsula shelf based on ocean data
- The major pattern of circulation variance is nearly barotropic, is wind driven, and is strongly influenced by Marguerite Trough

Supporting Information:

Supporting Information S1

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Spatially Coherent Intraseasonal Velocity Fluctuations on the Western Antarctic Peninsula Shelf

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Abstract We analyze several year-long moored current meter records collected on the midshelf and shelf break of the western Antarctic Peninsula in order to describe the major features of the intraseasonal circulation. An empirical orthogonal function (EOF) analysis of all current meter records in any given year reveals that over 49% of the circulation variance follows a spatially coherent, nearly depth-invariant anticyclonic cell in the downstream vicinity of Marguerite Trough, qualitatively consistent with flow-topography interaction with the canyon. An analysis of kinetic energy spectra supports the interpretation that the shelf break current is diverted shoreward at the location of the canyon and generates substantial counterclockwise energy at periods shorter than ~10 days as the flow is compressed by a downstream bank. The circulation is well correlated with the long-shore wind stress both local and remote. Composite velocity profiles under upwelling and downwelling winds show that the change in the barotropic current under different wind states is comparable to or larger than the shear of the mean profile in all years. The barotropic velocity fluctuations are generally not coherent with subpycnocline heat content.

Plain Language Summary Owing to scarcity of time series of observations on the western Antarctic Peninsula shelf, it has been difficult to diagnose how the currents below the ocean surface vary on time scales of days to weeks. Here we collect an array of ocean velocity measurements from several point locations across and along the shelf at various depths and study the properties of the currents at each site and how the currents at the different sites covary with each other. We find that over half of the circulation variance is nearly depth independent and is spatially coherent over a scale of several hundred kilometers. The circulation's spatial variability is related to the ocean bathymetry, and its temporal variability is related to the winds, both local and far away.

1. Introduction

The western Antarctic Peninsula (WAP) is undergoing rapid climate change including strong wintertime atmospheric warming (Turner et al., 2013). The ocean is a primary heat source and presumably plays some role in the changing environment. For example, shelf waters along the WAP have warmed and shoaled (Martinson et al., 2008; Schmidtko et al., 2014), and these warmed subpycnocline waters have been directly implicated in ice mass loss on the WAP as glaciers in contact with warm subpycnocline waters are in retreat, while those in contact with colder waters of the Bransfield Strait are not (Cook et al., 2016). WAP hydrography is dominated by the influence of Upper Circumpolar Deep Water (UCDW), which is a mid-water column temperature maximum (T_{max}) several degrees above the in situ freezing point (Gordon, 1971). As the southern boundary of the Antarctic Circumpolar Current (ACC) flows adjacent to the WAP shelf (Orsi et al., 1995), UCDW is readily available at shelf depths.

The importance of column heat content motivates an understanding of the circulation, which dictates its transport. The physical setting, major bathymetric features, and an overview of the circulation are presented in Figure 1. Recent reviews of the WAP circulation and of shelf-slope exchange along western Antarctica are given by Moffat and Meredith (2018) and Gille et al. (2016), respectively, but we provide a summary here. The mean circulation is broadly characterized by a northeastward flow along the shelf break associated with the southern boundary of the ACC (the Shelf Break Jet; SBJ) and a southwestward flow along the coast (the Coastal Current; CC). Long-shore winds south of the Bransfield Strait are coastal downwelling (Figure 1a) which act to drive the southward flow, although a baroclinic component is seasonally enhanced by introduction of near-surface melt water (Moffat et al., 2008). The prevailing cyclonic circulation induced by these two





Figure 1. Overview of physical setting, mean circulation, and sampling. (a) Regional map showing the Pal LTER grid (blue box), the 1,500 m isobath (black contour), and time-averaged SLP from ERA-Interim 12-hourly data (orange contours). (b) Inset showing the Pal LTER grid. The seven mooring sites are indicated with large black squares, and the time mean currents are shown with white lines where the thickest lines (terminating in "v" symbols) are currents below the pycnocline, medium (terminating in diamond symbols) within, and thinnest (terminating in "^" symbols) above. Color contours indicate time mean geopotential height anomalies at 80 dbar relative to 330 dbar from Pal LTER annual January CTD sampling (stations at black dots). Binned, depth- and time-averaged shipboard ADCP currents are shown as gray lines emanating from small black squares. The location of the Southern ACC Boundary (SACCB; the 0.35 dyn m contour from Orsi et al. (1995)) is indicated. The 3,750, 3,000, 1,500, 480, and 375 m isobaths are shown as gray contours with the 1,500 m contour outlined in bold black. (c) Inset showing the regional bathymetry in greater detail, emphasizing the major bathymetric features. The same isobaths are shown as line contours with additional color contours at 2,250, 750, 300, and 200 m. The x's indicate ship stations where CTD profiles were taken. The section along the 100 station was occupied in June 1999, and the section along the 300 line was occupied completely in January 1993–2008 and incompletely since then.

currents is captured in the geopotential height fields calculated from ship surveys, as in Figure 1b. Eulerian mean absolute currents from a database of shipboard Acoustic Doppler Current Profiler (ADCP) profiles corroborate many of the same features (Savidge & Amft, 2009). On smaller scales (tens of kilometers), numerical models (Dinniman et al., 2011) and isolated moorings (Martinson & McKee, 2012; Moffat et al., 2009) suggest the circulation is primarily barotropic with cyclonic flow over depressions and anticyclonic flow over shoals. In fact, drifter observations imply some imprint of the bathymetry near the surface (Beardsley et al., 2004). Cross-cutting canyons also serve as conduits for UCDW to penetrate the shelf and be steered shoreward (Klinck, 1998; Klinck et al., 2004; Smith et al., 1999). For example, the time mean mooring currents in Figure 1b indicate along-isobath flow and onflow along the northeastward extension of Marguerite Trough. Much less is known of the time-varying circulation, though. UCDW has been shown to flow along isobaths in the form of mesoscale eddies along the downstream wall of Marguerite Trough (Couto et al., 2017; McKee et al., 2019) with temporal frequency of about four per month (Martinson & McKee, 2012; Moffat et al., 2009). In general, either eddies or the mean flow may interact with a canyon (St-Laurent et al., 2013), but heat transport through Marguerite Trough is thought to be due primarily to the mean flow (Graham et al., 2016).



Observations thus far have often needed to make a trade-off between spatial and temporal coverage, and no observational study has yet revealed how the large-scale circulation of the WAP shelf varies on intraseasonal time scales or how such circulation is related to the wind stress. In this study we present the first simultaneous measurements of intraseasonal subsurface current variability on the WAP shelf and shelf break as sampled by an array of moored current meters that spans a spatial extent of ~427 km along shore and ~72 km across. These data were collected over several years (2008–2017) as part of the Palmer Long Term Ecological Research (Pal LTER) project (Smith et al., 1995). Here we identify a spatially coherent circulation pattern via empirical orthogonal function (EOF) analysis and study the spatial variability of kinetic energy spectra to complement our understanding of the pattern. Time variability of the long-shore flow is compared to reanalysis wind stress. Finally, we discuss the circulation pattern in the context of flow-topography interaction and its associated heat transport.

2. Data

2.1. Coordinate System

Locations in this paper use the Pal LTER coordinate system and are given as GGG.SSS where GGG is the grid line (distance parallel to the mean coast; units of kilometers) and SSS the grid station (distance perpendicular to the mean coast; units of kilometers). The grid has origin 000.000 at ~69.0°S, 73.6°W and is oriented 50° counterclockwise from east. Therefore, the long-shore dimension is quantified by the *x* coordinate with velocity component *u* (positive to the northeast), and the cross-shore dimension is quantified by the *y* coordinate with velocity component *v* (positive offshore). Accordingly, velocity vectors are rotated by 50° from their compass coordinates. For convenience, mooring sites are numbered 1 through 7 in order of increasing grid line and grid station and will be referred to as such (see Figure 1b for the correspondence between site name and grid station).

2.2. Mooring Data

2.2.1. Overview

Moorings containing thermistor arrays and one or more current meters have been deployed each year since 2007 as part of the Pal LTER project (Martinson, 2020). Between one and four moorings are deployed on each annual January Pal LTER cruise (usually at the end) and recovered on the following cruise (usually at the beginning), making each record about 350 days in length. It is important to note that the array is not static and that different locations are occupied in different years. The most frequently occupied sites (M3 at station 300.100, M4 at station 300.160, and M6 at station 400.100) were chosen because conductivity-temperature-depth (CTD) sampling revealed a large fraction of oceanic UCDW was consistently present there (Martinson et al., 2008). Of those, M3, which is located above the downstream wall of Marguerite Trough, is occupied most regularly and has been indicated as a site of shelf-slope exchange (Martinson & McKee, 2012). As it became increasingly apparent that canyons play an important role in steering the circulation, sites M5 (station 347.088) and M7 (station 500.120), each on the western flanks of two other submarine depressions, were sampled in 2014. Site M2 (station 200.140) is located on the shelf break in about 420 m of water and was deployed to sample the SBJ upstream of where it impinges on Marguerite Trough canyon. Site M1 (station 073.108) was added in 2017 to sample the SBJ even farther upstream. Since our focus in this study is on circulation on the midshelf, three coastal records near Palmer Deep (station 600.040) and one coastal record at station 460.046 are not included, and since our focus is on spatially coherent circulation patterns, nor are years with only one noncoastal mooring (2007 and 2015-2016, with the exception of 2013).

Current meters are placed nominally at the temperature maximum (~250 dbar) and at the temperature minimum (~80 dbar), though for individual process studies (e.g., M2 year 2013) or due to instrument failure, there may be more or fewer in the vertical. Current meters referred to as "deep" are deeper than 225 dbar, current meters referred to as "pycnocline depth" are between 100 and 225 dbar, and current meters referred to as "shallow" are shallower than 100 dbar. We primarily use JFE Advantech Alec Infinity EM current meters, though a few InterOcean S4 current meters were used in the early years. An overview of data coverage is given in Table 1, and the mooring locations and time mean currents are shown in Figure 1b.



List of Current Meters Used in This Study Along With Their Nominal Pressures in Decibars

5		<i>y</i> 0					
	2008	2010	2011	2012	2013	2014	2017
M1	_	_	_	_	_	_	289
M2	—	—	—	—	44, 95, 145, 196, 246, 348	—	—
M3	279 (S)	189, 288	91, 193	95, 180, 279	—	74, 263	236
M4	323 (S)	188	94, 280	287	—	—	_
M5	_	_	_	_	_	69, 247	—
M6	299 (S)	89, 233	265	_	_	_	—
M7	_	_	—	_	—	72, 275	—

Note. "S" indicates InterOcean S4 whereas all other instruments are Alec EM current meters.

2.2.2. Sampling and Data Processing

All current meters sample at least once per hour which is sufficient to avoid aliasing any major tidal constituent. Records that sampled faster are subsampled at that interval. Each Alec instrument was programmed to employ burst sampling, measuring and averaging 25 (M4 year 2010), 64 (all other sensors prior to 2012), or 81 (all sensors after 2012) samples at each increment. By invoking the Central Limit Theorem, this means nominal instrument uncertainties of ± 1 cm s⁻¹ for speed and $\pm 2^{\circ}$ for angle are reduced by a factor of 5, 8, or 9. The few S4 sensors have an accuracy of ± 1 cm s⁻¹.

Accuracy of the Alec current meters decreases when they are tilted by more than 15° from the vertical under strong currents. While the Alec instruments do not have an onboard tilt sensor, they are each situated within ~25 m of an SBE39 pressure sensor so we have knowledge of their approximate displacement at each time step. The S4 instruments, on the other hand, do have a tilt sensor, so we use the few S4-derived records to construct an empirical relationship between sensor displacement from its nominal depth (in dbar) and current meter tilt angle by binning tilt angles into 1 dbar pressure displacement bins and extracting the maximum angle. Assuming spatial and temporal invariance, this method suggests that on average less than 4% of time steps at M3 and M7 are critically tilted (less than 1% at all other sites).

Tidal variability was assessed with a harmonic analysis (Pawlowicz et al., 2002) and comparison with a barotropic tide model (Padman et al., 2002). Removal of short-period (diurnal and semidiurnal) tides by harmonic analysis is straightforward, simply removing any constituents that pass a signal-to-noise ratio (SNR) threshold of 1, where SNR is quantified as the square of the ratio of the fitted major axis amplitude to its uncertainty. However, the long-period tides are more difficult to assess. These include the fortnightly (Mf, Msf), monthly (Mm, Msm), and longer (Ssa) harmonics. The tide model includes only (Mf, Mm), which are also the only two long constituents identified in coastal Antarctic tide gauges by Aoki (2002). Analysis of a multiyear time series at nearby Vernadsky (formerly Faraday) tide gauge (described below) reveals that only Ssa, Mm, and Mf have SNR greater than 1. Oceanic variability is large at the fortnightly and monthly periods, yielding low SNR fits at Ssa, Mm, and Mf with much larger amplitude than predicted by the tide model. For example, of the six time series at M2, none have a SNR > 1 for any of Ssa, Mm, or Mf, and of all time series at M3, between 0 and 2 (out of 11) exhibit a SNR > 1 for any of those tides. Thus, while we can conclude that Ssa, Mm, and Mf are likely present in our time series, because we are interested in nontidal variance at long periods and because the amplitudes predicted by the tide model and the multivear tide gauge analysis are so low, we determine that any attempt to remove long-period tides by harmonic analysis would likely do more harm than good and we do not remove them. All analyses were repeated with forced removal of Ssa, Mm, and Mf, and there is no systematic or significant difference in results.

After subsampling once per hour and detiding, the residual is low-pass filtered to remove variability with periods shorter than 2 days. We use an ideal filter which zeroes out amplitude of the Fourier transformed signal above the cutoff frequency. Unless otherwise specified, all time series are filtered in such a manner, with the exception of "intraseasonal variability" which is band-pass filtered with an ideal filter with passband 3–100 days.

2.3. Other Data Sources

2.3.1. Reanalysis Data

We use surface pressure, mean sea level pressure (SLP), and surface stress (wind stress) from the European Centre for Medium-range Weather Forecast (ECMWF) ERA-Interim reanalysis (European Centre for



Medium-range Weather Forecast, 2011). The data are reported on a $0.75 \times 0.75^{\circ}$ grid at a 12 hr interval. Note that the surface stress is technically a forecast variable, representing the downward turbulent stress at the surface accumulated over a 12 hr forecast. As such, we divide the surface stress by the time step and assign each value a new time stamp corresponding to the middle of the forecast window.

2.3.2. Faraday/Vernadsky Tide Gauge Data

We acquire hourly, Research Quality tide gauge data from Faraday/Vernadsky station from the University of Hawaii Sea Level Center (Caldwell et al., 2015). Short-period tidal constituents are removed via harmonic analysis (Pawlowicz et al., 2002). To correct for the inverse barometer effect, the reanalysis surface pressure data are spatially interpolated onto the tide gauge site (with a bicubic spline) at each reanalysis time step and then interpolated in time (with a linear interpolant) onto the hourly tide gauge grid. Then, the interpolated surface pressure data are multiplied by the correction factor (1 cm sea level)/(1 mbar atmospheric pressure) and combined with the tide gauge signal. To enhance SNR for the long-period tides, we analyze the multi-year, inverse barometer-corrected record which reduces noise by distributing the nontidal variance among more Fourier harmonics. We find Ssa, Mm, and Mf to exhibit SNR > 1, and they are removed by harmonic analysis (Pawlowicz et al., 2002). Finally, small gaps are filled with linear interpolation, and a low-pass filter with cutoff period of 2 days is applied.

2.3.3. Shipboard Data

Shipboard data from the Pal LTER program are used to define the climatological physical environment in the vicinity of the mooring sites. CTD profiles are collected as part of the standard sampling on each annual January cruise since 1993 (Jannuzzi, 2018; see details in Martinson et al., 2008). The standard grid locations are spaced 20 km in the cross-shore dimension and 100 km in the long-shore dimension (Figure 1b). Additional data from the June 1999 cruise, which densely sampled across Marguerite Trough, are analyzed (see cast locations in Figure 1c). Processed, high-resolution (5 min in time, 8 m in vertical) velocity profiles from the ARSV *L. M. Gould*'s hull-mounted RDI 150 kHz narrowband instrument were obtained from the Joint Archive for Shipboard ADCP (SADCP; Caldwell et al., 2010). The instrument provides velocity profiles good to about 300 m (depending on weather and sea state) when the vessel is on station. These data are used to quantify the mean circulation along the sections in Figure 1c and are not detided. Time- and depth-averaged currents are shown in Figure 1b.

3. Results

3.1. Velocity Spectra

In order to give an overview of the velocity variance, component and rotary spectra were calculated for every current meter record and the depth-averaged current using the multitaper method (Thomson, 1982) with seven DPSS functions for 14 degrees of freedom. These spectra compared favorably to spectra calculated by partitioning the time series into seven nonoverlapping segments (again yielding 14 degrees of freedom) and averaging the spectra of each segment; however, the multitaper method does not suffer from decreased frequency resolution. Selected spectra essential to the findings of this paper are shown in Figure 2. Component and rotary spectra for all sites are shown in supporting information Figures S1 and S2, respectively.

The long-shore power is substantially greater than the cross-shore power at M2, M3, and M5 (Figures 2a, 2b, and S1e). At the former two sites, the long-shore power is greater at all frequencies (as much as 10 times the cross-shore power below 0.1 cpd). The cross-shore power is similar at all sites, other than at M6, which has more cross-shore power at high frequencies compared to all other sites (Figure S1f). Spectra are generally red to some degree, at least up to ~0.2–0.25 cpd, although M3 maintains a steep slope over all frequencies and M6 is unusually flat. Many sites have more power at depth for low frequencies (mainly in the long-shore component) and comparable or less power at depth for high frequencies (e.g., Figure 2a). The slope stations M2 and M4 have an interesting divergence in long-shore versus cross-shore power at ~0.28 cpd (Figures 2a and 2c).

Regarding the rotary spectra, most records are approximately equipartitioned between positive (counterclockwise) and negative (clockwise) frequencies up until 0.15–0.25 cpd. Beyond that, M3, M5, and M7 have more power in the clockwise spectrum (they are in canyons), M6 and M1 have much more power in the counterclockwise spectrum (the former is on a bank), M4 is still approximately equipartitioned, and M2





Figure 2. Selected kinetic energy spectra for one year of sampling. The year with the vertically densest current meter array is shown. Spectra are colored by depth, and the bold black spectrum corresponds to the depth-averaged current. For component (rotary) spectra, the long-shore (counterclockwise) spectra are solid and the cross-shore (clockwise) spectra are dashed. An error bar at the 5% significance level is indicated. Component spectra for (a) M2, 2013; (b) M3, 2012; (c) M4, 2011; and rotary spectra for (d) M6, 2010.

has slightly more counterclockwise power (Figures 2d and S2). Some of the spectra indicate a peak near ~ 0.12 cpd (e.g., Figure S2a), while others indicate a divergence in counterclockwise versus clockwise power at ~ 0.28 or ~ 0.35 cpd (e.g., Figure S2e). Frequencies of ~ 0.12 , ~ 0.28 , and ~ 0.46 cpd may correspond to the topographically trapped modes associated with the East Pacific Rise, the Mid-Atlantic Ridge, and the Kerguelen Plateau, respectively, that can be resonantly excited by the wind. Excitation of these modes may yield signal propagation around the Antarctic coastline as Kelvin waves (see discussion in Weijer & Gille, 2005).

While both M2 and M4 are situated on the shelf break at similar bottom depth, the spectrum at M2 resembles those at M3 and M5 more so than it does that at M4. Particularly so, all but M4 demonstrate a significant elevation in long-shore variance, primarily at frequencies lower than about 0.25 cpd (Figures 2a–2c and S1e). The similarity of the spectra suggests the possibility that the slope flow that passes M2 diverts onto the shelf prior to encountering M4. It would be natural, then, to ask why the spectrum at M6 is so different from those immediately upstream. Recall that while M6 is close to a cross-shelf depression ("Channel" in Figure 1c), it is actually on a bank downstream of Marguerite Trough ("Bank" in Figure 1c) with bottom depth ~337 m, substantially shallower than the other midshelf sites. As the strong long-shore flows near the slope impinge on Marguerite Trough and then the shallow bank an anticyclonic (counterclockwise)





Figure 3. Maps of the first circulation EOF vector weights. (a–g) Maps for each current meter, for each year. Vectors are color coded by depth as indicated in the legend, and the percentage of the total variance explained by the pattern is given in the title. The bathymetry line contours are the same as in Figure 1, with the 480 m isobath plotted in black to distinguish it from the shallower 375 m isobath. (h) Schematic circulation induced by regional winds on WAP in the presence of Marguerite Trough. An anticyclonic cell is generated downstream of the canyon which pinches off the large wind-generated cyclone. The SBJ and its intrusion (solid red line) is inferred from the EOF analysis and the SADCP data. The circulation above the 450 line (dashed red line) is inferred from the single mooring and is more speculative. The CC (blue line) is inferred from observations published elsewhere (e.g., Moffat & Meredith, 2018). Only the 480 m isobath surrounding Marguerite Trough is shown.

vortex forms over the bank due to compression of the water column (Fennel & Schmidt, 1991; St-Laurent et al., 2013). As to why the polarization is greatest at high frequencies (Figure 2d), note that at periods longer than the spindown time the flow would be able to adjust to any perturbation before one cycle. The spindown time for barotropic motions (Pedlosky, 1987) is $\tau = H/\sqrt{2A|f|}$, which at 65.9°S in 337 m depth, and assuming $A = 5 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ is about 10.7 days, which is close to where the two spectra diverge.

3.2. Spatial Pattern of Circulation

In order to identify a spatially coherent pattern in the WAP circulation, we use empirical orthogonal function (EOF) analysis to decompose all current meter records in a given year into orthogonal patterns that maximize temporal covariance. For each year we construct the augmented data matrix **X** whose rows are all of the long-shore velocity time series followed by all of the cross-shore velocity time series, allowing us to diagonalize the covariance matrix $\mathbf{C} = \mathbf{X}\mathbf{X}^{T}$ that includes covariability across site, depth, and velocity component. To avoid contamination by the seasonal cycle, we band-pass filter all signals into the intraseasonal band before decomposing.

Maps of the first EOF weights for every year of analysis are shown in Figure 3. In each year with multiple sites, over half (49–81%) of the total variance can be explained by the first pattern. To the extent it is



Table 2

Correlation Coefficient of EOF1's Principal Component Against Each Current Meter Record

00	v 1	1 0					
	2008	2010	2011	2012	2013	2014	2017
M1, deep	_	—	—	—	—	—	0.72 (0.79)
M2, 44 dbar	_	_	—	_	0.91 (0.44)	_	_
M2, 95 dbar	_	_	—	_	0.95 (0.39)	_	_
M2, 145 dbar	—	—	—	—	0.98 (0.59)	—	—
M2, 196 dbar	—	—	—	—	0.99 (0.55)	—	—
M2, 246 dbar	—	—	—	—	0.98 (0.48)	—	—
M2, 348 dbar	—	—	—	—	0.94 (0.74)	—	—
M3, shallow	—	—	0.97 (-0.15)	0.98 (-0.23)	—	0.89 (0.03)	—
M3, pycnocline	—	0.98 (-0.44)	0.98 (-0.43)	0.99 (-0.41)	—	—	—
M3, deep	0.99 (-0.15)	0.98 (-0.55)	—	0.99 (-0.63)	—	0.94 (-0.34)	0.98 (-0.46)
M4, shallow	—	—	0.23 (0.07)	—	—	—	—
M4, pycnocline	—	0.05 (0.21)	—	—	—	—	—
M4, deep	0.06 (0.02)	—	0.11 (0.17)	0.19 (0.16)	—	—	—
M5, shallow	—	—	—	—	—	0.73 (-0.31)	—
M5, deep	—	—	—	—	—	0.82 (-0.68)	—
M6, shallow	—	-0.61 (0.63)	—	—	—	—	—
M6, deep	-0.50 (0.62)	-0.53 (0.49)	-0.40 (0.55)	—	—	—	—
M7, shallow		_	_		_	0.36 (-0.57)	_
M7, deep	—	—	—	_	—	0.57 (-0.68)	—

Note. The correlation for long-shore component is followed by correlation for cross-shore component in parentheses. Those significant with $p \le 0.05$ are emphasized in bold.

possible to determine (given different sampling each year), the pattern is qualitatively the same each year. This consistency is a testament to it truly being a spatially coherent pattern. More specifically, the orientation and magnitude of the weight vectors are always similar, even if the decomposition involved covariances with different sets of locations.

In the positive state, the pattern (Figures 3a–3g) consists of an upgrid flow along the shelf edge (M1, M2), an anticyclonic cell in the downstream vicinity of Marguerite Trough (M3, M5, M6), and an upgrid flow along the western wall of a second canyon downstream of Marguerite Trough (M7). Importantly, the one location that consistently does not covary with the others is M4, which is located on the downstream wall of Marguerite Trough, but seaward of M3 (Figures 3a–3d). As implied by the spectral analysis, this argues for Marguerite Trough playing a role in the emergence of the pattern and essentially diverting the SBJ onto the shelf once it passes the 200 line, through the anticyclonic pathway, and bypassing site M4 on the shelf break.

The vectors suggest that the pattern is quasi-barotropic, perhaps somewhat bottom intensified (e.g., Figure 3f). Consistent with this, the vectors at each site are aligned along isobaths. There is also little veering with depth. The weights for M3 are largest each year, but that is partially compensating for the larger total variance at M3 compared to M6. To get a better sense of the spatial coherency than can be provided by the EOF weights alone, we correlate the time variability of the pattern with each velocity component (Table 2). Correlations between the pattern and each current meter record are all strong along the component(s) most aligned with major variability, except at site M4, where correlations are always low for both components (|r| < 0.23). Significance of correlation coefficients is evaluated using a bootstrapping approach by generating 1,000 simulated versions of the time series that each preserve spectral amplitude (but randomize phase), repeating the correlation analysis, and counting the number of synthetic correlation coefficients that exceed the observed (see A2.4 of Martinson, 2018). For sites other than M4, in the majority of cases no simulated time series had a correlation coefficient greater than that observed. Note that the correlations tend to decrease with increasing distance from Marguerite Trough.

3.3. Relation to the Wind

Regional models of the WAP point to the importance of the local long-shore wind stress in driving shelf-slope exchange and onshore flux of UCDW (Dinniman et al., 2011, 2012) with a potential role for the wind stress curl as well (Graham et al., 2016). As a first test of the influence of the wind in forcing the circulation pattern we construct velocity composites under positive (northeastward) and negative

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Figure 4. Composite intraseasonal velocity vectors under positive (red) and negative (blue) long-shore wind stress for each year of analysis. Each panel (a–g) is for a different year. Bathymetry contours are as in Figures 1 and 3. Insets in (b), (d), and (e) are selected total velocity profile composites under the same wind states. Long-shore currents are solid with circles at nominal depths, and cross-shore currents are dashed with squares. Red profiles are under positive wind state, blue profiles are under negative wind state, and black profiles are averages over all time.

(southwestward) long-shore wind stress. At this stage we make no assumptions about the spatial scale of the wind and only assume that the influence occurs via barotropic dynamics: Northeastward (southwestward) wind stress induces an Ekman transport away from (toward) the coast which induces a coastal sea surface height drop (rise) and a stronger (weaker) northeastward flow along the slope and shelf. We isolate the reanalysis surface stress signal nearest to mooring site M3, extract the component parallel to the coast, and identify all time steps where it exceeds ± 1 standard deviation beyond the 2007–2016 mean. After determining an appropriate lag time (the lag that yields maximum correlation between M3 depth-averaged *U* and the long-shore wind stress series; 20 hr), the ocean velocity vectors are averaged at corresponding time steps to create positive and negative composites, respectively. The wind and velocity series are first band-pass filtered in the intraseasonal band.

The results are shown in Figure 4 and mirror the first EOF pattern: positive long-shore winds yield a strong shelf break flow and strong anticyclonic cell while negative long-shore winds the opposite. Again, the pattern is approximately depth invariant, and again, M4 does not respond in a consistent manner (and the composite anomalies there are relatively smaller). In addition to maps, composite profiles are shown as insets in Figure 4, constructed by averaging the total velocity profiles instead of the filtered profiles. Variance at M2 and M3 is stronger in the long-shore component, and the total shear between the shallowest and deepest current meter is less than the barotropic offset between the two wind states (Figures 4d and 4e). At M6 the barotropic offset between the two wind states is less than, but of the same order of magnitude as, the shear (Figure 4b).



Figure 5. Heterogeneous correlation maps at zero lag for the long-shore barotropic velocity at M3 (year 2012; gray square) against the reanalysis sea level pressure (contours) and zonal and meridional surface stresses (subsampled vectors). The location of maximum correlation with the long-shore stress is indicated with a gray triangle. For orientation, the 1,500 and 0 m isobaths are plotted, and for reference a vector scale is given.

The correspondence between the composites and the first EOF suggests that the dominant circulation variability on the WAP is wind driven. Further, the spatial coherence suggests that the scale of the wind forcing is at least as large as the array length (427 km). To evaluate what atmospheric forcing is responsible, we compute heterogeneous correlation maps between the depth-averaged long-shore current at M3 and the reanalysis data at zero lag (Figure 5). The spatial pattern of the correlations with the SLP is approximately like the spatial pattern of the Southern Annular Mode (SAM; Thompson & Wallace, 2000) with negative values near the Antarctic continent and positive values toward the midlatitudes, which, broadly speaking, means that more southern and/or stronger westerlies are associated with a stronger WAP circulation. Correlations with SLP are statistically significant at a 5% level around the entire continent, particularly near the coast and the continent itself. An important deviation from the SAM-like pattern is the center of alternating positive and negative correlation on opposite sides of the Antarctic Peninsula. The western center of correlation, which is the largest positive correlation in the domain, is distinct from the nonannular component of the SAM that projects onto the Amundsen Sea Low (Lefebvre et al., 2004) and appears to be spatially coincident with the ridge associated with the Pacific-South America (PSA) wave train that operates on intraseasonal time scales (Mo & Higgins, 1998). Note that the location of maximum correlation with the long-shore stress is actually several hundred kilometers northeast of the mooring site as opposed to directly over it (gray triangle versus square in Figure 5).

3.4. Mean State

The circulation variance is relative to a mean state. The time-averaged mooring velocity vectors in Figure 1b reveal that the mean circulation has the same sense as the spatially coherent pattern identified through the EOF and wind composite analyses, meaning that the dominant pattern of variance represents an enhancement or suppression of the mean. For better spatial resolution than can be provided by the mooring data it is useful to introduce time-averaged SADCP data near the mooring array (Figures 6 and 7; also overlain in Figure 1b). While these data are insufficient to study intraseasonal variability they generally provide a good estimate of the mean (data coverage shown in Figures 6d and 7d; data uncertainty shown in Figures 6e and 7e).

The general sense of the circulation pattern, with onflow along the downstream wall of Marguerite Trough and outflow through the channel at the 400 line, is apparent in the cross-shore direction (Figures 6a and 6b). There is also clearly cyclonic vorticity introduced over Marguerite Trough. Assuming the impinging current has no relative vorticity, an upper bound to the amount of barotropic stretching vorticity introduced as a current descends from a shelf depth of $H_1 \sim 400$ m to mean canyon depth of $H_2 \sim 550$ m is

$$\zeta_{\text{stretch}} = \left(\frac{H_2}{H_1} - 1\right) f,\tag{1}$$

which is ~0.38 *f*. The actual cyclonic vorticity over the canyon as implied by the depth-averaged currents in Figure 6a, though, is about an order of magnitude less. The anticyclone over the downstream bank is also well pronounced in the mean. The mean SADCP currents in the bin centered at 400.100 (which partially





Figure 6. Overview of circulation as sampled by SADCP on the 100 stations. (a) Depth-averaged (0–300 m) cross-shore current from all SADCP profiles on Pal LTER cruises (2000–2015). The anticyclonic pinch circulation pattern, with onflow in Marguerite Trough and outflow on the 400 line, is indicated. (b) The bin-averaged cross-shore profiles (8 m depth, 25 km long-shore bins; contours) along with labels for major bathymetric and circulation features. (c) Potential density sampled in June 1999. Profile locations indicated with black triangles are synoptic, while the two profiles indicated by stars were sampled a few weeks later. The 27.64 and 27.76 kg m⁻³ surfaces which carry UCDW are indicated. (d) Counts of SADCP profiles and cruises represented in each long-shore bin. Note that the standard LTER stations are much better sampled than the intermediate bins. (e) Standard error in each SADCP velocity bin.

spans the channel) are more directly seaward while the mean mooring currents at M6 have a downgrid component (Figure 1b), suggesting the mooring is only capturing the edge of this flow.

The section in the long-shore dimension (300 line) was sampled multiple times, allowing a robust estimate of the geostrophic shear for comparison with the absolute SADCP currents. There is clearly anticyclonic vorticity generated over the Marguerite Trough Fork (MT Fork) which manifests in both the geostrophic shear (referenced to the seafloor) and the SADCP currents (Figures 7b and 7c). The long-shore flow over the continental slope is also well represented in the geostrophic currents, but it appears distinct from the SBJ upstream of Marguerite Trough on the 200 line as it no longer straddles the shelf (labeled "Slope Current" instead of SBJ). Instead, the diversion of the SBJ onto the 300 line at M3 associated with the circulation pattern is apparent, and it is clearly barotropic (and/or ageostrophic) as it is prominent only in the SADCP data.

4. Discussion

4.1. Role of Marguerite Trough

We identified a pattern in our current meter records on the WAP shelf that explains over 49% of the total variance. The pattern suggests that an acceleration of the along-slope flow upstream of and over Marguerite Trough is accompanied by the strengthening of an anticyclonic circulation pattern downstream of Marguerite Trough and of the flow on the western flank of another canyon ~200 km downstream. The





Figure 7. Overview of circulation as sampled by SADCP on the 300 line. (a) Depth-averaged (0–300 m) long-shore current from all SADCP profiles on Pal LTER cruises (2000–2015). (b) The bin-averaged long-shore profiles (8 m depth, 10 km cross-shore bins; contours) along with labels for major bathymetric features and currents. (c) Geostrophic currents calculated from first differencing the station average of all historic Pal LTER CTD data (stations at black triangles). The same isopycnals from Figure 6 are labeled. (d) Counts of SADCP profiles and cruises represented in each cross-shore bin. (e) Standard error in each SADCP velocity bin.

pattern does not covary with the current on the shelf break immediately downstream of Marguerite Trough, suggesting that the pattern emerges as an upwelling of the shelf break current upon interacting with the canyon. The velocity spectrum from a current meter on a bank downstream of the canyon shows enhanced anticyclonic rotation consistent with vortex compression of an incident flow. Composites of the velocity records under positive and negative long-shore wind states suggest that on intraseasonal time scales the pattern is strongest under positive winds and is weaker (or reversed) under negative winds. An idealized schematic of the circulation is given in Figure 3h. As suggested in that figure, the upwelling current effectively "pinches" the shelf-scale cyclone (formed by the SBJ and the CC) by inducing onflow of oceanic water near Marguerite Trough and outflow on the 400 line. We hereafter refer to the pattern as the "pinch pattern."

Theories for flow interaction with a canyon suggest that when a right-bounded flow in the Southern Hemisphere (as is the SBJ against the WAP) impinges upon a submarine canyon, cyclonic vorticity is induced into the water flowing over the canyon, steering flow up-canyon along the downstream wall (Allen et al., 2001; Allen & Hickey, 2010; Kämpf, 2006, 2007). The initial interaction (inertial overshoot of the impinging slope flow) sets up a cross-canyon pressure gradient which is balanced by the Coriolis and inertial terms (the latter being smaller but influential), yielding a nearly geostrophic flow up the canyon (Kämpf, 2006). Because it is the cross-canyon pressure gradient that initiates the upwelling and not an along-canyon pressure gradient, the upwelling flux is not very sensitive to the canyon width (Kämpf, 2007) and wide canyons (canyon width is wider than the Rossby radius) such as Marguerite Trough are able to support upwelling. The Canyon Rossby number (taking into account curvature of isobaths) reflects the notion that canyons decrease the relevant length scale and that metric may be large

even if the Rossby number is not, allowing up-canyon flow to cross isobaths and upwell onto the shelf proper at a location shoreward of the impinging flow. Once on the shelf, vortex compression will steer the flow again seaward in the downstream direction, generating an anticyclonic counterpart to the canyon cyclone (St-Laurent et al., 2013).

Stratification tends to diminish the response in the upper ocean which is consistent with our observed pattern being somewhat bottom intensified (most apparent in Figure 3f). The upwelling-favorable current orientation must persist as deep as the shelf break depth which it certainly does along the WAP under positive long-shore winds since the barotropic variance in the current is strong and larger than the mean shear (Figure 4e). St-Laurent et al. (2013) show that the proximity (or width) of the incident SBJ has a strong bearing on the flow interaction with topography. If the jet is wide (straddles the slope), the mean flow itself interacts with the canyon and generates a cyclone over the canyon and an anticyclone on the shelf proper (as in Figure 6b); otherwise eddy-topography interaction ensues. The latter point might partially explain why Marguerite Trough is such an important site for shelf-slope exchange. Regional modeling suggests that the SBJ near Marguerite Trough is wider than it is farther south (Graham et al., 2016), and it clearly straddles the slope since it is sampled by our mooring M2 which is about 10 km inshore of the shelf break. The SBJ farther south is either held over the slope or is nonexistent as velocity spectra at M1 are different from those at M2 (supporting information Figures S1a, S1b, S2a, and S2b), and fields of geopotential height have little gradient there (Figure 1b).

In contrast to the theories on canyon-induced dynamics, a more general explanation for flow-topography interaction was considered by Dinniman and Klinck (2004) who found a significant spatial correlation between isobath curvature and the time-averaged cross-shore volume transport with shoreward flux strongest ~10 km downstream of curvature. In analyzing the time mean momentum budget, the nonlinear momentum advection term was found to have strong bearing on the cross-shelf break transport. Thus, in their model, much of the cross-isobath advection is just due to curvature of isobaths. There is a large seaward bend in the continental slope between the 000 and 200 grid lines which would act to bring the SBJ onto the shelf edge (as sampled by mooring M2), but this alone is not enough to cause the flow to penetrate far onto the continental shelf. To yield transport farther shoreward on the shelf, the circulation on the inner shelf must act to pull the SBJ onshore. This would require simultaneous acceleration of the long-shore flow at both the shelf break and inner shelf downstream of the canyon, which is consistent with the pinch pattern's scale.

Enhancement of the flow over M3 allows the barotropic current to leave Marguerite Trough, and flow enhancement suggests potential importance of the momentum advection terms. While we noted that the velocity at M6 is highly rotary, that property is time dependent. Under strong long-shore flow and upwelling (positive circulation pattern) conditions, the strong flow funneled seaward along the 400 line tends to force rectilinear variations and suppress the free anticyclonic, potential vorticity conserving motions. This is illustrated through time variability of the rotary coefficient evaluated in 75% overlapping 15 day windows,

$$r(\omega,t) = \frac{P_+(\omega) - P_-(\omega)}{P_+(\omega) + P_-(\omega)},$$
(2)

where P_+ and P_- are the counterclockwise and clockwise power spectra, respectively. The frequency-time series of the rotary coefficient can be collapsed into a single time series by averaging over the most rotary band of 2–5 days (Figure 8),

$$r_c(t) = \frac{1}{N_{\omega}} \int_{\omega_1}^{\omega_2} r(\omega, t) d\omega.$$
(3)

This metric, which is +1 (-1) for purely anticyclonic (cyclonic) motions and 0 for rectilinear motions, reveals that motions at M6 are almost always anticyclonic to some degree but become more rectilinear when the long-shore flow at M3 (and hence the circulation pattern) is more positive. The two time series are weakly anticorrelated (r = -0.34, p = 0.02 in 2010; r = -0.45, $p \approx 0$ in 2011).

Thus, an interpretation of the pinch circulation is as follows. The basic state time mean circulation mimics that of EOF1 (compare Figure 3 to Figures 1b, 6, and 7). When the EOF is in its positive state (upwelling





Figure 8. Rotary coefficient time series for barotropic current at M6. (a) Time series of band-averaged rotary coefficient $r_c(t)$ at M6 for both years of sampling (black) along with the depth-averaged long-shore current at M3 (gray), where each sample of the latter is the time average within each window used to compute the moving spectra. (b) Time average of all of the 15 day rotary coefficient spectral windows. The band used in the integration to compute $r_c(t)$ is indicated with black triangles.

wind stress), the long-shore flow is accelerated, the SBJ is pulled shoreward (through some combination of continuity at the northern limb out of Marguerite Trough and through canyon-induced cyclonicity and momentum advection over the Trough), the midshelf anticyclone is enhanced, and flow at M6 is rectilinear and seaward. When the EOF is in its negative state (downwelling wind stress), the circulation relaxes, flow at M3 falls to f/H contours, a cyclonic circulation remains in Marguerite Trough, and flow at M6 falls to free potential vorticity conserving anticyclonic motions.

Proper exploration of these ideas would require evaluation of momentum and vorticity budgets in a numerical model. We emphasize that the role of the wind in driving the circulation on the WAP appears to be related to modulating the incident flow speed at the shelf break and inner shelf. This is in contrast to the role of the wind observed elsewhere in West Antarctica, for example, in the Amundsen Sea where up-trough flow was related to the long-shore wind stress in an Ekman upwelling sense (Wåhlin et al., 2013). This suggests that the close proximity of the ACC southern boundary and/or the width of the SBJ along the WAP near the trough may make the circulation there more "ACC-like" than that on other shelves around the continent.

4.2. Scale of the Pattern

If the pinch circulation pattern is induced by continuity of the impinging SBJ with an accelerated inner shelf flow, a necessary condition is that variations are of large enough spatial extent to accelerate both flows simultaneously. Our results reveal (1) the scale is at least as large as the array length of several hundred kilometers, (2) the fluctuations are nearly barotropic, and (3) the long-shore wind stress that is significantly correlated to the fluctuations has influence along the coastline. Inspection of subsurface pressure at nearby Faraday/Vernadsky tide gauge reveals very good agreement with the barotropic long-shore current at M3 in the time and frequency domains (supporting information Figure S3). The two are significantly correlated at zero lag (r = -0.75, $p \approx 0$), coherent at a 5% level over most frequencies, and approximately antiphased in accordance with geostrophic balance. Interestingly, the correlation improves to r = -0.82 when the Faraday/Vernadsky signal leads by 18 hr, which requires phase propagation in the coastal trapped wave direction.





Figure 9. Heat transport time series for one year at M3. (a) Heat content Q (black) and T_{max} (gray). (b) Long-shore U (black) and cross-shore V (gray) barotropic current. (c) Heat transport components UQ (black) and VQ (gray) with time mean of each component presented as thin horizontal lines, colored in the same manner. (d) Cross-wavelet coherency time-period spectrum between U and T_{max} . The threshold for significance at a 5% level based on generation of 500 bootstrapped time series is indicated with a thin black line, and the cone of influence is indicated with a thick black line. The arrows indicate the relative phasing, with arrows to the right (left) meaning in-phase (antiphased) and arrows upward (downward) meaning T_{max} leads (lags) U. The wavelet calculations use a Morlet mother wavelet, 0.125 octaves per scale, 80 total scales, and a minimum scale of 2 hr (analogous to a Nyquist period for our sampling). (e) As in (d) but for V against T_{max} .

Intraseasonal variability in Antarctic tide gauges is dominated by wind-driven fluctuations in coastal sea surface height in accordance with a wavenumber zero mode (Aoki, 2002; Hughes et al., 2003) and barotropic shelf waves (Kusahara & Ohshima, 2009). Curiously, there are energetic, geostrophically balanced fluctuations at ~40 day period in both time series. Variability at that period has been shown to affect ACC transport in Drake Passage through the projection of tropical-forced variability onto the SAM with wavenumber zero signature (Matthews & Meredith, 2004). Variability at that period is also associated with the PSA wave train



Table 3

Subpycnocline (WMLD to 350 dbar) Heat Transports and T_{max} -Weighted Velocities at Site M3

	2008	2010	2011	2012
\overline{UQ} (×10 ⁸ J m ⁻¹ s ⁻¹)	+2.30	+2.99	+2.07	+1.63
\overline{VQ} (×10 ⁸ J m ⁻¹ s ⁻¹)	-1.17	-1.26	-0.99	-0.74
\overline{UT} (×10 ⁻² °C m s ⁻¹)	+7.06	+9.83	+7.18	+5.67
\overline{VT} (×10 ⁻² °C m s ⁻¹)	-3.59	-4.14	-3.45	-2.53
$\overline{uq} (\times 10^6 \mathrm{J \ m^{-1} \ s^{-1}})$	+2.58	+1.71	-0.07	-0.58
$\overline{\nu q} (\times 10^6 \text{ J m}^{-1} \text{ s}^{-1})$	-2.27	-1.70	+0.81	-0.93
\overline{ut} (×10 ⁻⁴ °C m s ⁻¹)	-6.30	-15.30	+0.21	-5.15
\overline{vt} (×10 ⁻⁴ °C m s ⁻¹)	+0.29	+4.02	+2.27	+3.28

Note. Because several thermistors were lost in 2014 and 2017, heat content cannot be calculated for those years.

(Iijima et al., 2009) that may carry the teleconnection to high latitudes. The latter should have a pronounced influence in the southeast Pacific, and the high correlation with SLP there could reflect wind-driven barotropic shelf waves with finite damping scale. An analysis of wind-driven velocity fluctuations and coastal trapped wave dynamics is considered in detail in a companion study (McKee & Martinson, 2020).

4.3. Heat Transport

While the focus of this paper is on the circulation, we briefly comment on the heat transport since its variability sheds some light on the former. From thermistors on the moorings, heat content from the winter mixed layer depth (WMLD) down to 350 dbar can be calculated as

$$Q(t) = \rho_0 c_p \int_{350 \text{ db}}^{\text{WMLD}} (T(z, t) - T_{\text{freeze}}) dz$$
(4)

with an average bias of under 0.1% (Martinson & McKee, 2012). Thermistor data are interpolated onto 1 dbar profiles as described in Martinson and McKee (2012) before integrating. From those interpolated profiles we also obtain the temperature maximum T_{max} . These are used to define heat transports in the long-shore (similar in the cross-shore)

dimension as $UQ = (U_0+u)(Q_0+q)$ and T_{max} -weighted velocities $UT = (U_0+u)(T_0+t)$, where subscript 0 indicates the time mean and lower case letters represent fluctuations about that mean. Mean total transports are defined as the time mean of the transports over a mooring year (e.g., $\overline{UQ} = U_0Q_0 + \overline{uq}$). Figures 9a–9c show time series of Q, T_{max} , U, V, and their associated transports for one year at M3, and Table 3 shows the time mean transports for all years at that site.

Overall, mean total transports \overline{UQ} and \overline{VQ} and mean total temperature-weighted velocities \overline{UT} and \overline{VT} are large and shoreward in a manner consistent with the circulation pattern (shoreward and out of Marguerite Trough). However, closer inspection reveals that this quantity is driven almost entirely by the mean terms. The time mean eddy term, on the other hand, is <2% of the total mean magnitude and is always offshore (or near 0) for \overline{ut} but of varying sign for \overline{uq} (Table 3). Hence, in a surprising result, velocity fluctuations are generally uncorrelated to temperature (or heat content) fluctuations. This is also true in a spectral sense: evaluating $\overline{U(\omega)Q(\omega)}$ or $\overline{U(\omega)T(\omega)}$ via a coherency analysis reveals no frequencies significant at any reasonable α level. As the fluctuations are intermittent, some additional detail is gained from a cross-wavelet coherency analysis (Grinsted et al., 2004) of U(s)T(s) for wavelet scale *s* (Figures 9d and 9e). There are fluctuations with periods 2–16 days that are variously in and out of phase, but these are intermittent and the squared coherency averaged over the entire year is less than 50%. On the other hand, at scales *s* of ~40–60 days, there is generally significant coherency for the months May–July in U(s)T(s).

As discussed by Martinson and McKee (2012), the *Q* series is dominated by episodic warming events in the T_{max} record that are consistent with eddies with weak azimuthal velocity. Slightly farther south, Moffat et al. (2009) found similar eddy-like signatures with weak rotation. The importance of mesoscale eddies in dominating the thermal variance on the WAP has been corroborated by recent glider surveys (Couto et al., 2017; McKee et al., 2019), though the studies cited thus far point to a weak velocity signature. All of this is consistent with the findings of Graham et al. (2016) who ran a model of the WAP under 1.5 km (eddy resolving) and 4 km (non-eddy resolving) resolution and found that the upstream temperature and onshore heat transport were significantly correlated only when eddies were not resolved. The transport fluctuations UQ and VQ (and UT and VT) are significantly correlated with U and V, respectively, and not with Q (or T). This is also consistent with Graham et al. (2016) who identified the incident SBJ flow speed as the major determinant of onshore heat transport in the vicinity of Marguerite Trough. Thus, mesoscale eddies may dominate the thermal variance, while intraseasonal velocity fluctuations dominate the velocity variance and heat transport.



It is worth noting that the pinch pattern is in close proximity to the location of strong wintertime atmospheric warming identified by Turner et al. (2013), downstream of the onflow at Marguerite Trough. Those authors identified a region near Faraday/Vernadsky station that demonstrated a strong delayed sea ice advance and wintertime warming over 1979–2007 associated primarily with a loss of days with surface air temperature < -15 °C. The mean heat transports at the Marguerite Trough Fork are shoreward and upgrid, toward the Faraday/Vernadsky area. As observed mixed layer warming (Meredith & King, 2005) is likely not enough to explain the entire trend in delayed sea ice advance in the WAP area (see discussion in Stammerjohn et al., 2012), an additional deep ocean heat source may be necessary to precondition the upper ocean and that heat may be sourced by the pinch circulation pattern.

5. Conclusions

We present the first observational view of intraseasonal circulation variability on the WAP shelf as measured by an array of current meters that spans the two layers of the water column in the vertical, ~427 km in the long-shore dimension, and samples continuously for up to a year. Through EOF analysis of those records we identify a pattern that explains over 49% of total variance and that remains the same across years regardless of which current meters were sampling. The pattern is related to the long-shore wind stress in accordance with barotropic dynamics and is qualitatively consistent with flow-topography interaction near Marguerite Trough for the following reasons: (1) Under positive long-shore wind stress, the SBJ upstream of Marguerite Trough is accelerated and emerges on the shelf shoreward of the shelf break after encountering the canyon, bypassing another mooring along the slope downstream of the canyon, and continuing along an anticyclonic pathway before returning seaward; (2) the pattern is quasi-barotropic but somewhat bottom intensified; (3) velocity spectra on a bank downstream of the canyon are anticyclonically polarized, indicating vortex compression downstream of the canyon; (4) correlation coefficients between the circulation EOF's principal component and individual velocity records decrease with increasing distance from the canyon. The circulation pattern enhances or shuts down the mean flow pattern, with momentum advection carrying flow out of Marguerite Trough toward its northward extension at the MT Fork and suppressing potential vorticity conserving anticyclonic rotation over a downstream bank when the pattern is in its positive state. With the prevailing circulation on the WAP shelf being cyclonic, composed of the northward SBJ and the southward CC, the circulation pattern effectively "pinches" the WAP midshelf into a northern and a southern half.

Heterogeneous correlation maps suggest that the wind influence is SAM-like but also point to major influence from the PSA wave train in the Southeast Pacific. The relation to the long-shore wind stress in accordance with barotropic dynamics and the spatially coherent nature of the pattern over hundreds of kilometers points to large-scale (potentially remote) variability in the atmosphere, as suggested by other authors (Kusahara & Ohshima, 2009; Spence et al., 2017). In a companion study (McKee & Martinson, 2020) we investigate in detail the dynamics by which the long-shore wind stress drives the long-shore flow via a wavenumber zero mode and barotropic shelf waves.

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referenced in section 2 of this paper.

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