SPECIAL U.S. CLIVAR/SeaFlux COLLECTION



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ABSTRACT

High-resolution underway shipboard atmospheric and oceanic observations collected in Drake Passage from 2000 to 2009 are used to examine the spatial scales of turbulent heat fluxes and flux-related state variables. The magnitude of the seasonal cycle of sea surface temperature (SST) south of the Polar Front is found to be twice that north of the front, but the seasonal cycles of the turbulent heat fluxes show no differences on either side of the Polar Front. Frequency spectra of the turbulent heat fluxes and related variables are red, with no identifiable spectral peaks. SST and air temperature are coherent over a range of frequencies corresponding to periods between ~10 h and 2 days, with SST leading air temperature. The spatial decorrelation length scales of the sensible and latent heat fluxes calculated from two-day transects are 65 ± 6 km and 80 ± 6 km, respectively. The scale of the sensible heat flux is consistent with the decorrelation scale for air-sea temperature differences (70 ± 6 km) rather than either SST (153 ± 2 km) or air temperature (138 ± 4 km) alone. These scales are dominated by the Polar Front. When the Polar Front region is excluded, the decorrelation scales are 10-20 km, consistent with the first baroclinic Rossby radius.

These eddy scales are often unrepresented in the available gridded heat flux products. The Drake Passage ship measurements are compared with four recently available gridded turbulent heat flux products: the European Centre for Medium-Range Weather Forecasts high-resolution operational product in support of the Year of Coordinated Observing Modeling and Forcasting Tropical Convection (ECMWF-YOTC), ECMWF interim reanalysis (ERA-Interim), the Drake Passage reanalysis downscaling (DPRD10) regional product, and the objectively analyzed air-sea fluxes (OAFlux). The decorrelation length scales of the air-sea temperature difference, wind speed, and turbulent heat fluxes from these four products are significantly larger than those determined from shipboard measurements.

1. Introduction

The Antarctic Circumpolar Current (ACC) is the dominant zonally oriented flow of the Southern Ocean. It consists of multiple deep-reaching circumpolar jets, which are geostrophic and coincide with sharp frontal gradients in water properties. These narrow fronts separate the subantarctic water mass to the north from the colder Antarctic water to the south and are thought to be important for Subantarctic Mode Water formation and the meridional overturning circulation (Nowlin et al. 1977; Nowlin and Clifford 1982; Orsi et al. 1995; Gille 1999; Rintoul et al. 2001; Sprintall 2003; Lenn et al. 2007; Sallée et al. 2008; Cerovecki et al. 2011). The fronts produce energetic mesoscale eddies and rings (Lutjeharms

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and Baker 1980; Daniault and Ménard 1985; Chelton et al. 1990; Gille 1994; Morrow et al. 1994; Gouretski and Danilov 1994) that play an important role in the redistribution of momentum and buoyancy (Bryden 1979; McWilliams et al. 1978; Johnson and Bryden 1989; Ivchenko et al. 1996; Marshall 1997; Gille 1997; Gille et al. 2001; Sprintall 2003).

The Southern Ocean's contribution to the climate system is mediated through air–sea heat fluxes. Air–sea heat fluxes are important because of their influence on water mass transformation and on the oceanic uptake of heat (e.g., Speer et al. 2000; Dong et al. 2007; Gille 2008). Despite the importance of surface fluxes, at present there is little agreement about the choice of products for Southern Ocean applications, and the surface heat flux products for the Southern Ocean can differ by 50 W m⁻² (e.g., Dong et al. 2007). Ocean heat flux studies often rely on surface fluxes from numerical weather prediction (NWP) reanalyses. These have typically been released at

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2° resolution, although the decorrelation scale of the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis turbulent heat fluxes was found to be around 600 km (Dong et al. 2007).

The atmospheric and oceanic mesoscale eddies in the Southern Ocean vary on different spatial scales. The atmospheric mesoscale cyclonic vortices can be from 500 to 1000 km in diameter (e.g., Mansfield 1974; Businger and Reed 1989; Rasmussen et al. 1992; Turner et al. 1993) and are consequently reasonably well resolved by NWP products. In contrast, the first baroclinic Rossby radius L_d can be as short as 10–20 km in the Southern Ocean (Chelton et al. 1998). Since eddy variability has a wavelength $2\pi L_d$ (e.g., Williams et al. 2007), correspondingly typical Southern Ocean eddies are between about 60 and 120 km in diameter (e.g., Sprintall 2003; Kahru et al. 2007). This large difference between atmospheric and oceanic mesoscale variability leads to the question of whether SST variations on the scale of the oceanic Rossby radius can have a substantive impact on basin-averaged air-sea heat fluxes. Alternatively, heat fluxes might instead be dominated by the large-scale meteorological mesoscale variations that are resolved in NWP fields. If oceanic mesoscale eddies and fronts play an important role in air-sea heat exchanges, then this implies that air-sea heat flux products need to resolve variations that occur over these oceanic eddy length scales, which have not been resolved in standard NWP products.

To date there have been only a few opportunities to calibrate or validate gridded flux fields for the Southern Ocean (e.g., Dong et al. 2007; Lenn et al. 2007) or to assess their spatial structure (e.g., Dong et al. 2007). The Southern Ocean has not benefited from an array of upperocean flux moorings, of the type used for the Tropical Ocean and Global Atmosphere (TOGA)- Tropical Atmosphere Ocean (TAO) in the tropical Pacific, for example. In contrast to the Southern Ocean, in the Arctic Ocean turbulent heat fluxes and meteorological variables were collected from October 1997 to October 1998 during the Surface Heat Budget of the Arctic Ocean (SHEBA) experiment ice camp deployed in the Beaufort gyre (Andreas et al. 1999; Persson et al. 2002; Uttal et al. 2002). However, no equivalent measurements were made in the open ocean of the Arctic. The first two flux moorings in the Southern Ocean were deployed in 2010, and to date there exist only a few studies that use relatively shortterm shipboard measurements of flux-related variables in the Southern Ocean (e.g., Rouault et al. 2000; Pezzi et al. 2005).

The paucity of in situ observations in the Southern Ocean leaves open a host of questions about the true nature of surface fluxes at high latitudes, and our objectives are to address some of these most basic unknown aspects of Southern Ocean air–sea fluxes. We focus specifically on the turbulent fluxes of sensible and latent heat, which depend strongly on air–sea temperature differences and on specific humidity. In our analysis, we make use of yearround high-resolution shipboard measurements of the flux-related variables across Drake Passage from 2000 to 2009. Our first objective is to assess the spatial scales over which the turbulent fluxes vary and to ask what physical processes are likely to control small-scale variations in turbulent fluxes.

As part of our analysis, we also compare the shipboard data with recent flux estimates including objectively analyzed air-sea fluxes (OAFlux) (Yu et al. 2008), which blend satellite retrievals and NWP reanalysis. New reanalysis efforts offer some prospect for resolving smaller scale features than the older NWP products. Recently the European Centre for Medium-Range Weather Forecasts released more than two years (May 2008-present) of data from their high-resolution operational product in support of the Year of Coordinated Observing Modeling and Forcasting Tropical Convection (YOTC) (Waliser and Moncrieff 2008), hereafter referred to as ECMWF-YOTC. Dynamical downscaling (Kanamitsu and Kanamaru 2007) offers another strategy for obtaining small-scale fluxes for specific study regions. Our second objective is thus to evaluate the success of these recent higher resolution products at representing smallscale variations in surface fluxes.

A final objective in assessing spatial scales of variability of surface fluxes is to consider criteria for improving the observation of surface fluxes in the future. High-quality direct observations of turbulent fluxes would be useful for validating future NWP reanalyses of surface fluxes and future satellite-derived turbulent flux fields, and these in situ observations in turn are likely to improve the accuracy of flux products (Bourassa et al. 2011, manuscript submitted to *Bull. Amer. Meteor. Soc.*). Before new observing systems are established (whether from ships of opportunity or from moored flux arrays), observing system designers will benefit from knowing not only the wind and temperature conditions that each mooring must withstand, but also appropriate spatial sampling between moorings and critical temporal sampling rates.

2. Data

a. Shipboard observations

Shipboard meteorological and near-surface oceanographic parameters were obtained from the R/V *Lawrence M. Gould (LMG)*, which traverses Drake Passage approximately 20 times yr^{-1} in all seasons (e.g., Chereskin et al. 2000; Sprintall 2003). The *LMG* began providing regular underway atmospheric and oceanic measurements in 2000 and by mid-2009 had completed 202 transects. We retained only the 166 transects that have a northern end point near 55°S, 65°W and eliminated those transects that fall outside of the Drake Passage triangle with vertices at 65°W, 55°S; 65°W, 62°S; and 57°W, 62°S (Fig. 1). We limited our analysis to the region north of 62°S to avoid regions with persistent wintertime sea ice. For this work, we further narrowed our dataset by requiring a relatively constant ship speed so that time series data collected from the ship sensors could be used consistently to infer spatial structure. Of the 166 transects that start or end near point 55°S, 65°W, $25 (\sim 15\%)$ either did not follow straight trajectories or had a nonconstant ship speed (likely due to field work or severe weather). In addition, 33 transects ($\sim 20\%$) have big chunks of erroneous data (abnormally noisy measurements, outliers, or missing data) due to sensor malfunction, and 13 transects ($\sim 8\%$) have steplike humidity measurements, especially during the period from 2004 to 2008. Ultimately 95 transects were analyzed for this study, among which there are 47 north-to-south transects and 48 south-to-north transects (Fig. 1).

The *LMG* takes about two days to complete the open ocean crossing of Drake Passage. Meteorological instruments sample at 1-min intervals, thus providing about 2880 continuous measurements for each crossing. The shipboard measurements include the upper-ocean temperature (4 m below the surface), near-surface air temperature (T_{air}) , wind speed (U_w) , and atmospheric relative humidity, which was converted to specific humidity (q_{air}) using the Buck (1981) algorithm. Dong et al. (2006) showed that there is little bias in the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) ocean temperature (measured at 1-2mm depth) relative to in situ temperature measured by the LMG in Drake Passage. The observed ocean temperature is therefore referred to as SST in this study although it is not formally a skin temperature. In this study we used the wind measurements from an anemometer 30 m above the reference waterline on the port side of the ship. Wind measurements were corrected to 10 m using the bulk formulae embedded in the Coupled Ocean-Atmosphere Response Experiment version 3.0 (COARE 3.0) algorithm (Fairall et al. 1996).

From these shipboard observations of the state variables, the COARE 3.0 algorithm is used to calculate the turbulent (latent and sensible) heat fluxes. The COARE 3.0 algorithm was developed for wind speeds up to 20 m s⁻¹, in contrast to the earlier COARE 2.5 algorithm that was valid only for wind speeds below 10 m s⁻¹. In the 95 transects that we use, approximately 1% of the ship wind speed data exceeded 20 m s⁻¹ (and approximately



FIG. 1. Cruise tracks of the 95 shipboard transects (black lines) in Drake Passage from 2000 to 2009. The shaded area shows the position of the Polar Front determined from XBT observations with its standard deviation (Sprintall 2003). Note that the mean Polar Front is located around 58.5°S.

3% of observations for the 202 total transects since 2000). For latent heat flux, $Q_l = \rho_a L_v C_E U_w (q_{air} - q_s)$, where ρ_a is the density of air, L_v is the latent heat of evaporation, C_E is the turbulent coefficient of latent heat, and U_w is the 10-m wind speed. The surface specific humidity q_s is calculated from the saturation humidity q_{sat} for pure water at SST, $q_s = 0.98q_{sat}$ (SST), where a factor of 0.98 is used to take into account the effect of a typical salinity of 34 psu. For sensible heat flux, $Q_s = \rho_a C_p C_h U_w$ (SST – θ), where C_p is the specific heat capacity of air at constant pressure, C_h is the turbulent coefficient of sensible heat, and θ is a linear function of air temperature T_{air} (Liu et al. 1979; Yu et al. 2004).

b. Surface flux products

We compare the shipboard measurements with four recent gridded products: 1) The 3-hourly ECMWF-YOTC state variables and the turbulent heat fluxes from May 2008 to April 2009, which are on a $0.5^{\circ} \times 0.5^{\circ}$ horizontal grid (Waliser and Moncrieff 2008). We analyze only one year of this product to simplify the reconstruction of the 95 transects (described below); 2) 6hourly ECMWF reanalysis ERA-Interim state variables and turbulent heat fluxes from January 2000 to August 2009, which are on a $0.5^{\circ} \times 0.5^{\circ}$ horizontal grid (Uppala 2007; Simmons et al. 2007); 3) hourly Drake Passage reanalysis downscaling (DPRD10) state variables and turbulent heat fluxes on a 10 km \times 10 km grid that we computed for this study for a 12-month period from 1 May 2008 to 30 April 2009; and 4) daily OAFlux state variables and turbulent heat fluxes from January 2000 to

August 2009, which are on a $1.0^{\circ} \times 1.0^{\circ}$ horizontal grid (Yu et al. 2008). The OAFlux products blend satellite retrievals and three NWP reanalysis [NCEP–NCAR, NCEP reanalysis 2, and the 40-yr ECMWF Re-Analysis (ERA-40)]. Note that gridded products 1) and 3) do not cover the full time period covered by the ship measurements.

The DPRD10 is similar to the California Reanalysis Downscaling at 10 km (CARD10) produced for the California current region with some improvement in the boundary conditions and model physics (Yoshimura and Kanamitsu 2009; Kanamitsu et al. 2010). Small-scale features are generated by forcing a high-resolution regional atmospheric model with large-scale NCEP-NCAR reanalysis fields on the domain boundaries. For the California downscaling CARD10, daily SSTs from ECMWF reanalysis $(1^{\circ} \times 1^{\circ})$ were used (Fiorino 2004; Kanamitsu and Kanamaru 2007). Here, to improve the resolution of the SST forcing in the DPRD10 reanalysis, we employed daily $0.25^{\circ} \times 0.25^{\circ}$ resolution optimum interpolation SST analysis version 2 (Reynolds et al. 2007). This SST product uses both the Advanced Very High Resolution Radiometer infrared satellite, which has good coverage in cloud-free regions near land, and the AMSR-E satellite, which can see through the year-round clouds in the Southern Ocean. This high-resolution SST product was shown to agree with observations (Reynolds and Chelton 2010) and in our tests it improves the small-scale resolving skill in DPRD10 relative to SST from the ECMWF reanalysis.

While the SST fields used by surface flux products come from the same sources, they are released as part of the NWP and OAFlux products—hereafter referred to as ECMWF-YOTC SST, ERA-Interim SST, DPRD10 SST, and OAFlux SST, respectively.

c. Satellite measurements

We also compare the shipboard observations with satellite measurements of SST and winds. For SST we consider the daily $0.25^{\circ} \times 0.25^{\circ}$ AMSR-E microwave SST product from June 2002 to August 2009 (http://www.ssmi.com). AMSR-E is a multichannel, multi-frequency, passive microwave radiometer system. It was launched on the National Aeronautics and Space Administration *Aqua* spacecraft on 4 May 2002 and provides sea surface temperature through almost all types of clouds.

For wind we use two products. The first is four times daily $1^{\circ} \times 1^{\circ}$ Center for Ocean-Atmospheric Prediction Studies (COAPS) Quick Scatterometer (QuikSCAT) wind speed from January 2000 to August 2009 (Pegion et al. 2000), hereafter referred to as Q-COAPS. Q-COAPS wind speed at 10 m utilizes a direct minimization

approach with tuning parameters determined from generalized cross-validation and QuikSCAT satellite observations filtered by the normalized objective function (NOF) rain flag. The second wind product is twice daily (morning and evening passes) $0.25^{\circ} \times 0.25^{\circ}$ Physical Oceanography Distributed Active Archive Center (PODAAC) Level-3 QuikSCAT wind speed from January 2000 to August 2009, hereafter referred to as Q-PODAAC. The Q-PODAAC wind speed determines rain probability by using the multidimensional histogram (MUDH) rain flagging technique (Huddleston 2000).

d. Constructing transects from gridded products

Gridded products provide synoptic Eulerian maps, while ship transects are not strictly synoptic, because the ship takes approximately two days to cross Drake Passage. To make them comparable, we linearly interpolated the gridded flux products to the longitude, latitude, and time of the ship measurements to construct 95 transects. Note that linear interpolation preserves the decorrelation scales of the gridded products. For gridded products that roughly cover the same 10-yr period (January 2000 to August 2009) as the ship measurements, such as ERA-Interim, OAFlux, Q-COAPS, and AMSR-E (which starts only in June 2002 but is otherwise complete), these 95 transects were constructed to coincide exactly in time with the ship measurements. For gridded products available only for the 12-month period from May 2008 to April 2009 (ECMWF-YOTC and DPRD10), the 95 transects were constructed to match only the day-hour of the ship observations in any individual year, under the assumption that the year-to-year variability in ECMWF-YOTC and DPRD10 has no significant effect on the mean and variance or decorrelation scales. This assumption is later evaluated in section 3 by using a subset of 11 ship transects concurrent with the exact period when ECMWF-YOTC and DPRD10 are available.

3. Results

a. Mean differences and the variance

To evaluate the shipboard data in comparison to gridded flux and satellite products, we first present the mean differences. In this study, we use the ship-measured state variables and the calculated turbulent fluxes from these variables as reference data. In our discussion, the differences are reported as the flux or satellite product minus the shipboard measurement.

The ship-derived fluxes are generally thought to be reliable, but there are two issues that could limit their fidelity. First, the relative difference between wind and ocean current should be used to calculate the turbulent heat fluxes, and this is effectively what a scatterometer does (Kelly et al. 2001; Bourassa 2006). The impact of the ocean current on the turbulent heat fluxes depends on the ratio of the ocean current component in the direction of the wind to the wind speed itself. In the tropical Pacific near the intertropical convergence zone, where the ocean currents are strong and winds are weak, the ocean currents can have a significant impact on accuracy of the turbulent heat flux calculation (e.g., Kelly et al. 2001; Jiang et al. 2005). In contrast, in Drake Passage both ocean currents and winds are strong. Lenn et al. (2007) found that the depth-averaged ocean currents in Drake Passage are dominantly zonal with speeds of up to 40 cm s⁻¹. Assuming this maximum ocean current occurs at all locations and at all times across Drake Passage, then the maximum influence of the ocean currents is 2.0 \pm 0.4 W m $^{-2}$ for latent heat flux and -0.7 \pm 0.4 W m^{-2} for the sensible heat flux. These upper bounds on errors due to ocean currents are within the uncertainties of the turbulent heat fluxes derived from the in situ measurements. We also note that flux products in this study do not take the ocean currents into account in computing wind stress. Therefore, the effect of ocean currents is not included in the turbulent heat flux calculation. Second, as noted above, the COARE 3.0 algorithm was developed for wind speeds up to 20 m s⁻¹, and for the 95 transects we employed here, approximately 1% of the wind speed data exceed this 20 m s⁻¹ wind speed limit, with maximum observed winds reaching up to 27 m s⁻¹. In contrast to winds, other flux-related variables are within the tested ranges of the COARE 3.0 algorithm. For instance, within the ensemble of 95 transects, specific humidity values range from 1.4 to 7.3 g kg⁻¹. The air-sea temperature difference ($\delta T = SST - T_{air}$) ranges from -6.4°C to 9.9°C, and turbulent heat fluxes range from -289.9 to 154.0 W m⁻².

The mean differences between the 95-transect-averaged turbulent heat fluxes and the flux-related variables are shown in the top section of Table 1. The constructed SSTs show no significant differences from ship measurements. Differences between ship and constructed air temperature, air-sea temperature difference, and specific humidity are near zero for ECMWF-YOTC, DPRD10, and OAFlux, while ERA-Interim has a cold bias in air temperature, a warm bias in the air-sea temperature, and a dry bias in the specific humidity (Table 1). The wind speeds of the ECMWF-YOTC and DPRD10 compare well with the ship measurements, while other constructed products, including the two gridded scatterometer winds, have weaker winds than the observations. QuikSCAT winds have been evaluated at high wind speeds at Macquarie Island in the Southern Ocean (Yuan 2004), but to our knowledge they have not been evaluated using high-resolution (1-min interval) in situ measurements from Drake Passage. We carried out orthogonal linear regression (Deming 1943), which minimizes the orthogonal distance from the shipboard data points to the regression line, assuming that both scatterometer and shipboard winds might include error sources. We did not use ordinary linear regression because it assumes that only the scatterometer measurements are associated with random measurement errors. If the scatterometer winds agreed perfectly with the shipboard measurements, the linear regression slopes would be expected to be 1 (zero bias). The orthogonal linear regression slopes calculated for the constructed 1-min interval Q-COAPS (0.53 ± 0.01) and Q-PODAAC ($0.67 \pm$ 0.01) wind field are lower than the 1:1 zero-bias lines.

Several factors may contribute to the low linear regression slopes of the gridded satellite products including random errors in the ship measurements, high-frequency shipboard measurements that resolve wind gusts unresolved by the scatterometer, and low spatiotemporal resolution in the gridded scatterometer wind products. Typically, there are only four to eight satellite passes during the two-day ship crossing. As a result, the linear interpolation of the sparsely sampled gridded products to the 1-min interval ship transects results in horizontal "stripes" (not shown), where a single scatterometer wind value is associated with many shipboard wind values. To examine the effect of the temporal linear interpolation used to match the scatterometer winds to the high-resolution ship data, we select shipboard wind measurements that are less than 1 min away from the morning and evening passes of Q-PODAAC along each transect. This yields 568 coincident data points (Fig. 2a). The linear regression slope for Q-PODAAC against these now twice-daily shipboard measurements is $0.80 \pm$ 0.18 (Fig. 2a), and the correlation coefficient improves from 0.60 \pm 0.10 for the interpolated values to 0.71 \pm 0.11. This suggests that the temporal linear interpolation used for the scatterometer wind products contributes to the low linear regression slopes. To further examine the effect of the mapping procedure imposed on the gridded wind products, we use the QuikSCAT Level 2B swath winds at 25-km resolution, selecting satellite observations that are within 0.2° in distance and 2 min in time from the ship measurements. This collocated dataset has 512 points (black dots in Fig. 2b). The linear regression slope for the QuikSCAT 25-km resolution swath winds against the collocated shipboard measurements is now 0.71 ± 0.17 (black line in Fig. 2b), and the correlation coefficient increases from 0.56 \pm 0.10 to 0.75 \pm 0.16. Collectively, these comparisons suggest that the interpolation, especially the temporal interpolation that is used for the scatterometer wind

TABLE 1. Mean and the standard error of 95-transect-averaged (top section) and 11-transect-averaged (bottom section) turbulent fluxes and flux-related state variables from the ship measurements (row 1). The standard error equals the standard deviation divided by square root of the number of the observations (95 or 11). Bias and standard error of the difference of transect averaged seven state variables from ECMWF-YOTC, ERA-Interim, DPRD10, OAFlux, AMSR-E, Q-COAPS, and Q-PODAAC relative to ship measurements (rows 2–8). Bias and standard error of the difference of the turbulent heat flux estimations from ECMWF-YOTC, ERA-Interim, and DPRD10 using COARE 3.0 algorithm (rows 9–11). Variables include SST, air temperature T_{air} , specific humidity q_{air} , 10-m wind speed U_w , air-sea temperature difference SST- T_{air} , latent heat flux Q_b and sensible heat flux Q_s .

	SST(°C)	$T_{\rm air}$, (°C)	$\delta T(^{\circ}C)$	$q_{\rm air}({\rm g~kg^{-1}})$	U_w , (m s ⁻¹)	$Q_l(W m^{-2})$	$Q_{\rm s}({\rm W~m^{-2}})$
			95-transect a	veraged			
Ship	2.7 ± 0.2	2.9 ± 0.3	-0.2 ± 0.2	4.1 ± 0.1	9.7 ± 0.5	-17.7 ± 3.3	1.4 ± 3.2
ECMWF-YOTC	-0.1 ± 0.1	-0.2 ± 0.3	0.1 ± 0.3	-0.1 ± 0.1	-0.5 ± 0.6	-6.0 ± 4.7	1.8 ± 3.9
ERA-Interim	-0.1 ± 0.1	-0.3 ± 0.1	0.2 ± 0.1	-0.1 ± 0.0	-0.9 ± 0.4	-4.4 ± 1.9	-0.4 ± 1.9
DPRD10	0.1 ± 0.1	-0.0 ± 0.3	0.1 ± 0.3	-0.1 ± 0.1	-0.4 ± 0.6	-9.3 ± 4.5	3.6 ± 3.8
OAFlux	-0.1 ± 0.1	0.0 ± 0.2	-0.1 ± 0.2	0.1 ± 0.1	-0.9 ± 0.5	0.7 ± 2.7	2.9 ± 2.7
AMSR-E	-0.0 ± 0.1						
Q-COAPS					-1.5 ± 0.5		
Q-PODAAC					-1.4 ± 0.5		
ECMWF-YOTC(C)						-5.5 ± 4.6	1.1 ± 3.9
ERA-Interim(C)						-1.5 ± 1.8	-0.3 ± 1.9
DPRD10(C)						-2.5 ± 4.4	2.3 ± 3.8
			11-transect a	veraged			
Ship	2.7 ± 0.4	3.4 ± 0.5	-0.7 ± 0.5	4.2 ± 0.2	10.8 ± 1.1	-16.0 ± 8.9	7.2 ± 6.8
ECMWF-YOTC	-0.2 ± 0.2	-0.8 ± 0.4	0.6 ± 0.3	-0.4 ± 0.1	-1.1 ± 1.1	-10.8 ± 5.2	-4.7 ± 5.3
DPRD10	0.0 ± 0.3	-0.4 ± 0.5	0.4 ± 0.5	-0.1 ± 0.2	-1.1 ± 1.3	-10.2 ± 7.9	0.2 ± 7.5
ECMWF-YOTC(C)						-10.3 ± 5.1	-5.6 ± 5.4
DPRD10(C)						-3.2 ± 7.9	-1.2 ± 7.3

products to the ship measurements, is probably a factor in the discrepancies between the shipboard measurements and the gridded scatterometer wind products. Because scatterometer winds cannot resolve the strong wind gusts that the ship measurements do, the linear regression slopes for the two gridded scatterometer wind products are lower than the zero-bias lines, and consequently the 95-transect-averaged scatterometer



FIG. 2. Scatterplots of wind speed from (a) Q-PODAAC winds against twice daily shipboard observations and (b) QuikSCAT 25-km resolution Level 2B swath winds against the collocated shipboard measurements. The thin black line is the zero bias line (1:1 line); the thick black lines are their orthogonal linear regression slopes. The regression slopes, correlation coefficient (ρ) between satellite and shipboard winds, the ratios (δ) of their variance, the number of data points, and their corresponding values for 95% significance intervals are listed in the right lower corners. See the text for details.

TABLE 2. Standard deviation of 95-transect-averaged (top section) and 11-transect-averaged (bottom section) turbulent fluxes and fluxrelated state variables from the ship measurements (row 1). The standard deviation, σ , is computed for each transect, and reported values represent the mean and standard error of σ for the ensemble of transects. Variables and datasets are as specified in Table 1.

	SST(°C)	$T_{\rm air}(^{\circ}{\rm C})$	$\delta T(^{\circ}C)$	$q_{\rm air}({ m g~kg}^{-1})$	$U_w(\mathrm{m~s}^{-1})$	$Q_l(W m^{-2})$	$Q_s(W m^{-2})$
			95-transect	averaged			
Ship	2.2 ± 0.4	2.1 ± 0.6	1.1 ± 0.4	0.6 ± 0.2	2.9 ± 0.9	19.3 ± 9.8	15.7 ± 8.1
ECMWF-YOTC	0.7 ± 0.2	1.2 ± 0.5	1.3 ± 0.5	0.5 ± 0.3	3.6 ± 1.2	27.2 ± 13.7	19.9 ± 9.3
ERA-Interim	0.7 ± 0.2	0.8 ± 0.2	0.9 ± 0.2	0.2 ± 0.1	2.2 ± 0.8	13.6 ± 6.4	12.6 ± 5.8
DPRD10	0.8 ± 0.2	1.3 ± 0.5	1.3 ± 0.5	0.6 ± 0.2	3.7 ± 1.1	28.5 ± 11.1	20.8 ± 9.2
OAFlux	0.6 ± 0.2	0.9 ± 0.3	1.0 ± 0.3	0.3 ± 0.2	2.8 ± 0.9	17.1 ± 8.9	14.7 ± 7.6
AMSR-E	0.5 ± 0.1						
Q-COAPS					2.6 ± 0.8		
Q-PODAAC					2.4 ± 0.8		
ECMWF-YOTC(C)						26.4 ± 12.9	20.0 ± 9.4
ERA-Interim(C)						13.6 ± 6.2	12.9 ± 5.7
DPRD10(C)						27.0 ± 10.9	20.3 ± 9.1
			11-transect	averaged			
Ship	2.3 ± 0.5	2.3 ± 0.3	1.0 ± 0.4	0.6 ± 0.2	2.7 ± 1.0	20.1 ± 10.8	15.8 ± 7.7
ECMWF-YOTC	0.5 ± 0.2	0.7 ± 0.4	0.9 ± 0.3	0.2 ± 0.1	2.1 ± 0.5	15.5 ± 6.7	12.9 ± 4.5
DPRD10	0.7 ± 0.2	1.0 ± 0.4	1.0 ± 0.5	0.5 ± 0.2	2.9 ± 0.9	22.3 ± 8.2	16.5 ± 8.8
ECMWF-YOTC(C)						15.3 ± 6.9	12.9 ± 4.6
DPRD10(C)						21.3 ± 9.2	16.3 ± 8.5

wind speeds are weaker than the ship observations (Table 1).

The latent heat flux for OAFlux agrees well with the flux derived from ship measurements. In contrast, the latent heat fluxes for three NWP products are strong compared to the latent heat flux derived from the ship data, indicating greater heat release from the ocean to atmosphere. The possible reasons for this will be addressed in more detail below.

Only 11 ship transects are available during the year for which we consider ECMWF-YOTC and DPRD10 data. To illustrate the effect of the unresolved interannual variability, the bottom section of Table 1 shows mean differences for the 11 ship transects that are coincident in time with the 2008–09 reanalysis. The smaller number of transects results in larger error bars compared to the mean differences for the averaged 95 transects, and hence the mean differences of the state variables and fluxes of these NWP products are not significantly different and are also within the accuracy of the ship measurements.

Table 2 shows the standard deviation of the differences between ship data and the reconstructed transects. Standard deviations σ are computed for each transect, and values reported are the mean σ and standard error of σ for the full ensemble of 95 transects (top section) or the 11 transects in 2008–09 (bottom section). The reconstructed products are much smoother than the ship measurements, especially for the turbulent heat fluxes, and hence their variances are significantly different from the ship measurements (Table 2). Compared to OAFlux and higher-resolution NWP products (ECMWF-YOTC and DPRD10), ERA-Interim variances agree well with the ship data. AMSR-E SST compares the best with the variability of the ship SST measurement. Scatterometer wind products Q-COAPS and Q-PODAAC appear to have variances comparable to that of the ship measurements but slightly smoother than ECMWF-Interim.

The COARE 3.0 algorithm for the turbulent heat fluxes is not identical to the effective bulk flux algorithms used in NWP models. To examine the effect of using the COARE 3.0 algorithm on the mean differences (Table 1) and the variability of turbulent heat fluxes (Table 2), we substituted the NWP flux-related variables into the COARE 3.0 algorithm. In all cases using the COARE 3.0 algorithm with NWP products [here defined as ECWMF-YOTC(C), ERA-Interim(C), and DPRD10(C)] results in less mean latent heat release from the ocean than was found from the NWP-derived turbulent heat fluxes (Table 1). Use of the COARE 3.0 algorithm did not appear to impact the variability (Table 2). A similar result was reported in the tropical Pacific (Jiang et al. 2005). In general, the reduced mean latent heat release from the ocean when using the COARE 3.0 algorithm might result from two possible factors. First, the built-in turbulent flux parameterization used by the NWP models differs from the COARE 3.0 algorithm (Renfrew et al. 2002; Dong et al. 2007). Second, the turbulent heat fluxes from the COARE 3.0 algorithm are calculated from 6-hourly averages and not from the state variables computed at each model time step. However, even though the NWP-satellite blended state variables for OAFlux show

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statistics similar to those of NWP products (Tables 1 and 2), the OAFlux latent heat flux derived from the COARE 3.0 algorithm compares well with the ship measurements. This implies that using the COARE 3.0 algorithm can reduce the latent heat release from the ocean to the atmosphere in the three NWP products (Tables 1 and 2).

b. Seasonal cycle

Drake Passage expendable bathythermograph (XBT) temperature measurements from the top 100 m of the water column show a distinct seasonal cycle (Sprintall 2003). The temperature tendency and net heat flux (the sum of the shortwave, longwave, and turbulent heat fluxes) in the area-averaged heat budget also show significant seasonal cycles in the Southern Ocean (Sallée et al. 2006; Dong et al. 2007). However, to our knowledge there has been no systematic examination of the seasonality of the turbulent heat fluxes or flux-related state variables using the in situ measurements in Drake Passage. Here we present the seasonal cycles of the shipboard measurements and the constructed products.

Figure 3 shows the time series of the derived turbulent fluxes and the observed flux-related state variables for two transects: one from a warm season (March 2003, solid lines) and one from a cold season (September 2002, dashed lines). Note that variables in Fig. 3 are plotted as a function of time but could also be plotted as a function of distance. The sea surface temperature and air temperature show a distinct drop of 4°-6°C from north to south (Fig. 3a) beginning after about 20 h, indicating the ship's crossing of the Polar Front. The mean latitude of the Polar Front is around 58.5°S (shaded area in Fig. 1). Unlike SST and air temperature, the air-sea temperature difference (Fig. 3d) shows much smaller-scale variability with a less pronounced drop at the Polar Front. Wind speed for these two transects also show an obvious change at the position of the Polar Front, and this is true for the mean wind speed observations from all transects. However, wind speed also varies abruptly as a result of storms or gusts, and wind speed variance is higher north of the Polar Front than south, a result found by Thompson et al. (2007).

On average March temperatures are $2.94^{\circ} \pm 0.03^{\circ}$ C warmer than September temperatures (Fig. 4), but the SST gradient is sharper around the Polar Front in September compared to March when the cold Antarctic surface water is capped by summer heating. Temperatures in March and September for the whole data period are presented in Fig. 4 to show the contrast. XBT data show that the temperature drop at the location of the Polar Front is often detectable through at least the top 800 m of the ocean (Sprintall 2003). For the two transects shown in Fig. 3, the air–sea temperature difference shows more smaller-scale variability than either SST or



FIG. 3. Time series of (a) SST and T_{air} (°C), (b) specific humidity q_{air} (g kg⁻¹), (c) 10-m wind speed U_w (m s⁻¹), (d) air – sea temperature difference $\delta T = \text{SST} - T_{air}$ (°C), and (e) latent heat flux Q_t and sensible heat flux Q_s (W m⁻²) for two transects in a typical summer (March 2003, solid lines) and a typical winter (September 2002, dotted lines). The x axis shows the time (h) of the transect with t = 0 at the north end point 65°W, 55°S to t = 44 h at the southerm point 62°S.

air temperature. The SST $-T_{air}$ drops more abruptly across the Polar Front in winter than in summer (Fig. 3d), with correspondingly greater winter sensible heat flux (Fig. 3e). Both summer and winter specific humidity decrease from north to south across Drake Passage, and the decrease in winter specific humidity is sharper at the front (Fig. 3b). This results in an abrupt increase in winter latent heat flux (Fig. 3e), while summer latent heat flux seems to be closely related to the stronger winds that occurred during this transect (Fig. 3c).

Figure 3 suggests that the state variables and turbulent heat fluxes both undergo some seasonal variability. To examine their seasonality in detail, we least squares fitted the 1° latitude-binned observations to a sinusoidal seasonal cycle. The amplitudes of the seasonal cycle of the shipboard sensible (Fig. 5) and latent (Fig. 6) heat fluxes and the flux-related variables vary with latitude (black lines, left panels). The amplitude of the seasonal cycle of SST (Fig. 5a) south of the Polar Front is twice the



FIG. 4. Time series of SST (°C) of all late summer (March, solid lines) and late winter (September, dotted lines) transects. The x axis shows the time (hour) of the transect with t = 0 at the north end point 55°S to t = 44 h at the southern point 62°S.

amplitude north of the front (about 2°C compared to 1°C). The stronger seasonal cycle of SST south of the front is because of the surface water capping by summer heating (Sprintall 2003). South of the Polar Front the amplitude of the air temperature and SST seasonal cycles are comparable. In contrast, north of the Polar Front air temperature has a larger seasonal cycle than does SST (Figs. 6a,b). The cause for this is likely related to the much deeper mixed layer north of the Polar Front. None of the other atmospheric variables in Figs. 5 and 6 show the sharp transition in the amplitude of seasonal cycle at the Polar Front, implying that oceanic processes likely govern the seasonal cycle of SST around the Polar Front.

The amplitude of the seasonal cycle of the shipboard air – sea temperature difference (δT) varies from 0.5° to 1.2°C (Fig. 5c) but does not show the same latitudinal structure as SST or T_{air} . The amplitude of the seasonal cycle of the sensible heat flux is similar to δT and ranges from 3 to 21 W m⁻² (Fig. 5d). The seasonal cycle of sensible heat flux peaks around 57°–58°S, where the Polar Front is located, suggesting that the front likely plays a significant role in the air–sea interaction and water mass formation in the Southern Ocean.

The amplitude of the seasonal cycle of specific humidity varies from ~0.8 g kg⁻¹ in the north to ~0.6 g kg⁻¹ in the south (Fig. 6b). The seasonal cycle of the wind speed is weak compared with the mean wind speed, with an amplitude less than 1.5 m s⁻¹ at all latitudes (Fig. 6a), in agreement with scatterometer winds (Gille 2005). The amplitude of the seasonal cycle of latent heat flux (Fig. 6c) shows a similar magnitude and pattern to the sensible heat flux (Fig. 5d), except for latitudes around the sea ice edge where the latent heat flux shows a slightly smaller amplitude.

In contrast to the amplitudes, phases of the shipboard turbulent heat fluxes and flux-related variables vary little with latitude (Figs. 5 and 6, black lines, right panels), with the exception of wind speed (Fig. 6a). Wind speed has a small seasonal cycle (within one standard deviation) and can peak at any month of the year. For the different wind products, the phases agree within two standard deviations. The SST seasonal cycle peaks mainly in April and May (Fig. 5a), consistent with the upper 100-m XBT temperatures (Sprintall 2003). Both the seasonal cycle of air temperature (Fig. 5b) and specific humidity (Fig. 6b) peak in May, just after the ocean temperature peaks. This provides further evidence to support the hypothesis that the seasonal cycle of ocean temperature is mainly controlled by oceanic processes rather than being driven by atmospheric processes. Unlike SST and air temperature, the air - sea temperature difference peaks from December to January (Fig. 5c). The turbulent heat fluxes peak from May to August and show a distinct dependence on latitude (Figs. 5d and 6d).

Compared to the ship measurements, OAFlux and all three NWP products show the same 2°C amplitude in the seasonal cycle of SST south of the Polar Front; however, they show larger amplitudes north of the front (Fig. 5a). In addition, south of the Polar Front the amplitudes of the seasonal cycle of air temperature in the NWP and OAFlux data are smaller than in the ship measurements (Fig. 5b). The amplitude of the specific humidity in DPRD10 is smaller than the ship measurements around and south of the Polar Front (Fig. 6b). For the air – sea temperature difference (Fig. 5c) and the turbulent heat fluxes (Figs. 5d and 6c), the amplitudes of OAFlux and the three NWP products are significantly smaller than the ship measurements around the Polar Front. The phases of the three NWP and OAFlux turbulent heat fluxes differ greatly from the ship measurements at and south of the Polar Front (Figs. 5d and 6c).

c. Temporal and spatial scales

The autocorrelation function (ACF) allows us to determine the predominant temporal and spatial scales over which a variable x(t) ($t_1 < t < t_2$) decorrelates, where *t* can be interpreted either as the time or along-track distance away from the northern end point 55°S. We compute ACFs as a function of *m*, ACF (m) = $1/(t_2 - t_1 - m) \int_{t_1}^{t_2 - m} x'(t)x'(t + m) dt$, where *m* is the time or distance lag, and the prime indicates deviations from the time or along-track mean value. The ACF therefore describes the correlation between values of *x* at different times or along-track locations.

Published studies have used a variety of definitions for determining the decorrelation scale. One simple definition is the time or space lag τ_0 at which the ACF crosses zero. As illustrated in Fig. 7, the first zero crossing (τ_0) is not always a robust indicator of the ACF. In Fig. 7, ACF1 3

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(a)SST

³(b)T_{air}



0 11 (d)Q (d)Q 20 9 7 ²⁻² 10 5 3 1 -11 62S 55S 56S 57S 58S 59S 60S 61S 62S 55S 56S 57S 58S 59S 60S 61S ECMWF-YOTC ----- ERA-INTERIM DPRD10 Shipboard OAFlux FIG. 5. The (left) amplitudes and (right) phases of the seasonal cycles of sensible heat fluxes (Q_s) and the flux-

FIG. 5. The (left) amplitudes and (right) phases of the seasonal cycles of sensible heat fluxes (Q_s) and the fluxrelated variables: (a) SST, (b) T_{air} , (c) air – sea temperature difference δT , and (d) sensible heat flux Q_s . Error bars denote the standard error of the means (N = 95). The phases indicate the month of the maximum in the annual cycle of each variable.

and ACF2 represent the autocorrelation functions for the two-day sensible heat fluxes from ship measurements and ERA-Interim, which we will address in more detail below in Fig. 8. Although ACF1 and ACF2 have the same zero crossing scales (τ_0), they decorrelate at different rates before crossing zero. The integral scales τ_1 and τ_2 more precisely distinguish ACF1 and ACF2, where ACF2 of ERA-Interim indicates a larger temporal or spatial decorrelation scale than ACF1 of the ship measurements (Fig. 7). For this study, we therefore use the integral scale, τ , derived by integrating the ACF with respect to the time/space lags from a lag of zero to the first zero crossing; that is, $\tau = \int_0^{\tau_0} ACF(t) dt$.

The ACFs and decorrelation scales are determined using two approaches for the datasets in this study. First, we use the complete two-day transects that include the Polar Front (Fig. 8). The presence of the Polar Front can influence the ACF, therefore, we also computed ACFs and decorrelation scales using shorter data segments that exclude the fronts (Fig. 9). Table 3 shows the transect and segment-averaged decorrelation scales of the state variables from different products. Uncertainties in the decorrelation scales were estimated using a boot-strapping method with 500 subsamples (Diaconis and Efron 1983).

The ACFs of the two-day shipboard SST (Fig. 8a) and air temperature (Fig. 8b) are similar in shape, with ACFs of air temperature decreasing at slightly larger rates before crossing zero. However, the ACF for air – sea temperature difference (Fig. 8c) drops more abruptly. The Polar Front results in a substantial large-scale temperature drop from north to south in both SST and air temperature (e.g., Fig. 3a), which is then partially cancelled in the air – sea temperature difference (e.g., Fig. 3d). In addition, the removal of the along-track mean when computing the ACFs of the shipboard variables such as SST, air temperature, and specific humidity, which are more clearly influenced by the

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FIG. 6. As in Fig. 5 but of the latent heat fluxes (Q_l) and the flux-related variables: (a) wind speed U_w , (b) air specific humidity q_{air} , and (c) latent heat flux Q_l .

front, results in positive anomalies north of the Polar Front with similar magnitude negative anomalies to the south. This results in larger negative ACFs (~ -0.5) at long lags for these variables compared to the ACFs of the air - sea temperature difference, wind speed, and the turbulent heat fluxes (~ -0.2) (Fig. 8). Table 3 summarizes the decorrelation scales for each product; consistent with Fig. 8, the shipboard wind speed (72 \pm 8 km) and the air - sea temperature difference (70 \pm 6 km) have the smallest decorrelation scales of the four state variables, while SST, T_{air} , and q_{air} , which are impacted by the location of the Polar Front, all have scales larger than 120 km (Table 3). The decorrelation scales of the latent (80 ± 6 km) and sensible (65 ± 6 km) heat fluxes are strongly influenced by the shortest scales in the input variables, that is, the wind speed and the air - sea temperature difference.

The decorrelation scales of the satellite products are generally comparable with the shipboard measurements (Table 3 top section). The scale of the QuikSCAT wind speed Q-PODAAC is 89 ± 8 km, which is smaller than the scale of Q-COAPS (112 ± 8 km). Both Q-PODAAC and DPRD10 wind speeds show scales comparable with the in situ measurements.

Compared to the ship-derived ACFs, OAFlux and NWP-derived ACFs of air – sea temperature difference (Fig. 8c) and wind speed (Fig. 8e) decrease more slowly before crossing zero and have larger negative autocorrelations at large lags, meaning much larger decorrelation scales (Table 3, top section). These long scales appear to translate into long decorrelation scales for latent and sensible heat fluxes (Figs. 8d,g). The fact that the OAFlux and the three NWP products have large negative autocorrelations at large lags (Fig. 8) implies that their actual decorrelation scales may be even greater than the scales shown in Table 3.

To examine the effect of the year-to-year variability in ECMWF-YOTC and DPRD10, the decorrelation scales for the 11 transects with exactly concurrent shipboard and NWP products are shown in Table 3 (middle section). Again the smaller numbers of transects result in larger error bars compared to the averaged 95 transects



FIG. 7. Definition of the decorrelation scales: integral time scales. Note that ACF1 (black) and ACF2 (gray) have the same zero crossing scales (τ_0) but their integral time scales τ_1 and τ_2 precisely measure how ACFs change on small scales. ACF1 and ACF2 represent the 95-transect-averaged autocorrelation functions for the sensible heat fluxes from ship measurements and ERA-Interim. The 95% confidence intervals for their true mean ACFs are calculated using a Student's *t* distribution (N = 95).

decorrelation scales (Table 3, top section). The decorrelation scales derived from the concurrent transects (Table 3, middle section) largely agree with those reported for the 95-transect average (Table 3, top section), suggesting that year-to-year variability for ECMWF-YOTC and DPRD10 has little significant effect on the scales.

To exclude the effect of the front in determining the decorrelation length scales, our second approach is to calculate the ACFs and decorrelation scales using data segments from north and south of the Polar Front (Fig. 9). Based on the shipboard SST measurements, we select from each transect one segment between the Subantarctic Front (SAF) and the Polar Front and one segment between the Polar Front and the Southern Antarctic Circumpolar Current Front (SACCF). This selection resulted in 40 shipboard segments north of the Polar Front ranging from 331 to 1249 min in duration and 72 segments south of the Polar Front ranging from 421 to 1480 min in duration. The reason for there being fewer segments north of the Polar Front is that the SAF and Polar Front sometimes meander too close together, resulting in too few data points from which to compute the ACFs. The ACFs of shipboard SST (Fig. 9a) show much smaller negative autocorrelation coefficients at large lags than those determined using the complete two-day transects (Fig. 8a). The segment-averaged decorrelation length scales (Table 3, bottom section) show that the decorrelation length scales for all shipboard state variables are O(10-20 km), consistent with the first baroclinic Rossby deformation radius in the Southern Ocean (Chelton et al. 1998). The length scales south of the Polar Front are slightly larger than the scales north of the Polar Front. This finding is inconsistent with the first baroclinic Rossby radius in Drake Passage reported by Chelton et al. (1998), who calculated the vertical integral of buoyancy frequency from climatological temperature and salinity profiles. Using high-resolution XBT/expendable CTD (XCTD), Thompson et al. (2007) found the stratification to be stronger south of the Polar Front than north of the Polar Front. The impact of the stratification appears to dominate the impact of the β effect, resulting in slightly larger length scales south of the Polar Front than those north of the front (Table 3, bottom section).

We also find the corresponding segments for the NWP and satellite products. Compared to the shipboard measurements, the time series of ECMWF-YOTC SST segments have fewer small-scale features both north and south of the Polar Front. The magnitudes of the negative ACFs for ECMWF-YOTC (Fig. 9b) are larger at large lags than those for the shipboard measurements (Fig. 9a). The OAFlux and other NWP products exhibit similar large negative autocorrelation at large lags.

The two approaches used to calculate the decorrelation length scales indicate that the OAFlux and the three NWP flux products have larger decorrelation scales than the scales determined from high-resolution shipboard measurements (Table 3). Two factors might contribute to the larger length scales found in OAFlux and the NWP products: 1) atmospheric models fail to resolve the small scale features driven by mesoscale SST variations and/or 2) atmospheric models fail to respond to the mesoscale SST variations as rapidly as the true atmosphere does. Compared to ECMWF-Interim, ECMWF-YOTC does a better job at representing the small-scale variability. The decorrelation scale of the air – sea temperature difference and wind speed of DPRD10 are the smallest among OAFlux and the three recent NWP products (Table 3 top section), which indicates that the highresolution atmospheric model does indeed resolve smaller-scale features than the coarse-resolution NWP products.

d. High-frequency variability

To determine if there is a preferential scale in the higher frequency and wavenumber domain (<2 days and <800 km) in the turbulent heat fluxes and the flux-related variables, we computed frequency/wavenumber spectra (Figs. 10a,b). We also calculated the coherence between SST and air temperature to examine their interrelations (Figs. 10c,d).



FIG. 8. Transect-averaged autocorrelation functions for (a) SST (°C), (b) air temperature T_{air} (°C), (c) air – sea temperature difference $\delta T = \text{SST} - T_{air}$ (°C), (d) sensible heat flux Q_s (W m⁻²), (e) wind speed U_w (m s⁻¹), (f) air specific humidity q_{air} (g kg⁻¹), and (g) latent heat flux Q_s (W m⁻²) for shipboard (black), ECMWF-YOTC (red), ERA-Interim (blue), DPRD10 (green), and OAFlux (magenta). The 95% confidence intervals for their true mean ACFs are calculated using a Student's *t* distribution (N = 95).



FIG. 9. The segment-averaged autocorrelation functions for SST north (solid line) and south (dash-dotted line) of the Polar Front for (a) shipboard measurements and (b) ECMWF-YOTC. There are 40 segments north of the Polar Front and 72 segments south of the Polar Front. The 95% significance levels are calculated using a Student's *t* distribution.

To calculate the spectra we first compute a time mean as a function of latitude by averaging all transects. From each transect we then subtract the time mean to obtain a spatially detrended transect and apply a fast Fourier transformation. The frequency spectrum is then the sum of the squares of the Fourier components at each frequency divided by 95. In constructing the error bars, each of the 95 transects is treated as an independent realization. This assumption of independence is justifiable because the transects cover all seasons of the year with consecutive transects typically separated in time by 2–6 weeks, and each transect takes about two days to complete.

The spectra of the derived turbulent fluxes and the flux-related variables from shipboard measurements are fairly smooth, in agreement with that suggested for highresolution spectra by Haren and Gostisux (2009). The spectra for the two-day transects are red, even for high frequencies (not shown). This implies that the spatially detrended records still include some effect of the Polar Front, leading to energy leakage from low frequencies to high frequencies. In this case, to effectively remove the Polar Front, we apply a first-difference filter to prewhiten the shipboard segments north and south of the Polar Front and then apply a fast Fourier transformation. The frequency spectra of shipboard SST, air temperature, and air – sea temperature differences north and south of the Polar Front are still red except at very high frequencies (Figs. 10a,b). Their energy level is two orders of magnitude smaller than that of the complete two-day transects. There is no significant difference in spectra north (Fig. 10a) and south (Fig. 10b) of the Polar Front. Although the shipboard shortwave radiation has a significant diurnal cycle, there are no significant diurnal peaks in the energy power density of the turbulent fluxes and the other flux-related variables (not shown). Using Argo float temperatures and AMSR-E SSTs, Gille (2009) also found the diurnal cycle to be small in the Southern Ocean.

The slopes of the spectra for the turbulent fluxes (not shown) and flux-related variables are very similar to those shown for SST and air temperature (Figs. 10a,b). The power spectral density of sensible heat flux is generally higher than the latent heat flux at all frequencies.

We carried out the coherence analysis in two ways: first using the 95 transects ordered temporally in the way the measurements were collected and second using the 95 transects ordered geographically, with the first record beginning at the northernmost point at 55°S. We found that the temporal ordering produced higher coherence; therefore results presented here are based on that analysis. Because the reported temporal resolution of OAFlux, ERA-Interim, ECMWF-YOTC, and DPRD10 variables are daily, 6 hourly, 3 hourly, and hourly respectively, they can only resolve frequencies lower than 0.5, 2, 4, and 12 day⁻¹, respectively. The daily OAFlux data are therefore not included in Figs. 10c and 10d because they provide only two flux values during the two-day crossing of Drake Passage. The segments north and south of the Polar Front show the same coherence at high frequencies as the two-day transects, but they are too short to provide coherence at low frequencies, so only the coherence analysis for the two-day transects is shown in Fig. 10.

SST and T_{air} are coherent over a range of frequencies corresponding to periods between ~10 and 24 h (Fig. 10c) with SST leading air temperature (Fig. 10d). For the 47 north-to-south transects, SST always leads air temperature for periods between ~10 and 24 h. In contrast, for the 48 south-to-north transects, SST always leads air temperature for periods between ~12 and 16 h. The phase lag between SST and air temperature at the daily cycle is close to zero (not shown). Similarly, SST and air temperature for all three NWP products are significantly coherent for frequencies <1 cycle in 12 h, although the coherence between DPRD10 SST and air temperature drops off more slowly, between 12-h and 6-h time periods (Fig. 10c). Air temperature and SST for the three

TABLE 3. Decorrelation scales (in kilometers) for 95-transect-averaged (top section), 11-transect-averaged (middle section), and 40 segments north of the Polar Front and 72 segments south of the Polar Front (bottom section) averaged turbulent fluxes and flux-related state variables. Error bars are two standard deviation of 500 subsamples using a bootstrapping method. Variables and datasets are as specified in Table 1.

	SST	$T_{\rm air}$	$q_{\rm air}$	$U_{ m w}$	$SST-T_{air}$	Q_l	$Q_{ m s}$
		95	-transect averag	ed			
Ship	153 ± 2	138 ± 4	124 ± 8	72 ± 8	70 ± 6	80 ± 6	65 ± 6
ECMWF-YOTC	165 ± 2	152 ± 4	130 ± 8	92 ± 6	105 ± 8	111 ± 8	96 ± 8
ERA-Interim	165 ± 2	151 ± 4	135 ± 6	108 ± 6	111 ± 6	112 ± 6	109 ± 8
DPRD10	163 ± 2	153 ± 4	117 ± 6	85 ± 6	96 ± 6	100 ± 8	94 ± 6
OAFlux	160 ± 2	154 ± 4	147 ± 4	118 ± 6	116 ± 6	125 ± 6	118 ± 6
AMSR-E	160 ± 4						
Q-COAPS				112 ± 8			
Q-PODAAC				89 ± 8			
		11	-transect averag	ed			
Ship	159 ± 6	147 ± 10	145 ± 14	63 ± 16	60 ± 14	98 ± 18	59 ± 20
ECMWF-YOTC	166 ± 6	156 ± 16	152 ± 16	88 ± 14	100 ± 18	125 ± 24	95 ± 22
DPRD10	164 ± 6	160 ± 6	129 ± 16	85 ± 24	74 ± 18	98 ± 26	68 ± 18
		Polar Front nor	th and south-tra	ansect averaged	l		
Ship (Polar Front north)	13 ± 2	13 ± 2	12 ± 2	12 ± 2	11 ± 2	12 ± 2	11 ± 2
Ship (Polar Front south)	18 ± 2	19 ± 2	19 ± 2	18 ± 2	17 ± 2	19 ± 2	18 ± 2

NWP products are coherent at low frequencies, with air temperature leading SST for ECMWF-YOTC and ECMWF-Interim, unlike that found for the shipboard data.

4. Summary

This study evaluates the small-scale variations in the air-sea turbulent heat fluxes and flux-related state variables near eddies and fronts in Drake Passage. The scales of the turbulent heat fluxes and flux-related state variables are determined using shipboard measurements from 2000 to 2009 in the passage. These meteorological observations are unique as the transects are near repeating and provide the only multiyear, year-round time series in the Southern Ocean. The in situ data are compared against four recent surface flux products and three satellite products all resolving different scales.

The magnitude of the observed SST seasonal cycle south of the Polar Front is twice that north of the front. This strong SST seasonal cycle south of the front appears to be associated with the mixed layer depth variability. In summer, warm surface water forms on top of the yearround cold Antarctic Surface Water, likely resulting in the larger variability of the mixed layer depth south of the Polar Front. No dependence on latitude was found in other observed variables or in the derived turbulent heat fluxes, which supports the speculation that ocean physical processes govern the seasonal cycle of SST around the location of the Polar Front. Frequency spectra of the turbulent heat fluxes and the flux-related variables are red, with no identifiable spectral peaks. Air temperature and SST are coherent for periods between ~ 10 h and 2 days, with SST leading air temperature.

The constructed mean SSTs from the gridded and satellite products show no significant differences from ship measurements. Compared to the ship measurements, ERA-Interim has a cold bias in air temperature, a warm bias in the air - sea temperature, and a dry bias in the specific humidity. The wind speeds of the ECMWF-YOTC and DPRD10 compare well with the ship measurements, while the other constructed products have weaker winds than the observations. The three NWP products show that the ocean loses greater latent heat to the atmosphere compared to the latent heat flux derived from the ship data. In contrast, the OAFlux latent heat flux which is derived using the COARE 3.0 algorithm, agrees well with the flux derived from ship measurements. We also find that replacing the NWP built-in bulk algorithms with the COARE 3.0 algorithm appears to reduce the differences between the mean turbulent heat fluxes from in situ data and the NWP data. However, we do not have sufficient validation data to assess whether the COARE 3.0 algorithm is more accurate than those built into the NWP products since few direct flux observations have been collected in the Southern Ocean.

OAFlux and all three recent NWP products show a larger amplitude of the SST seasonal cycle north of the Polar Front than south, which results in a smaller north– south difference in amplitude of the SST seasonal cycle than in the ship measurements. OAFlux and the NWP products also show smaller amplitude of the seasonal



FIG. 10. The power spectrum of shipboard SST (black), air temperature T_{air} (red), and air – sea temperature difference $\delta T = SST - T_{air}$ (blue) (°C) for (a) north and (b) south of the Polar Front. The (c) coherence and (d) phase difference between SST and air temperature for shipboard measurements (black), ECMWF-YOTC (blue), ERA-Interim (green), and DPRD10 (red). Positive phase difference corresponds to SST leading air temperature. The black line in (c) shows the 95% significance level.

cycle of air - sea temperature difference and turbulent heat fluxes than the ship measurements near the Polar Front. The spectra of the products are similar to those from ship measurements. Air temperature and SST for the three NWP products are coherent for low frequencies, with air temperature leading SST for ECMWF-YOTC and ECMWF-Interim, unlike what was found with the shipboard data. Compared to the ship measurements, OAFlux and all three NWP products have larger length scales, especially for wind speed, air – sea temperature difference, and turbulent heat fluxes. The satellite SST product generally agrees with the ship data, while the constructed scatterometer winds are weaker than the ship observations, probably owing to the unresolved wind gusts in the gridded scatterometer products.

For two-day transects, the decorrelation length scale of the latent heat flux is found to be 80 ± 6 km, and the decorrelation length scale of the sensible heat flux is 65 ± 6 km. These scales appear to covary with the smallest scales of the flux-related state variables, that is, the wind speed (72 \pm 6 km) and the air – sea temperature difference (70 \pm 6 km). The decorrelation scales calculated from the shipboard measurements segmented north and south of the Polar Front are 10-20 km. This has important implications. First, the 10-20 km scales of the turbulent heat fluxes without the effect of the Polar Front are consistent with the first baroclinic Rossby radius in the Southern Ocean (Chelton et al. 1998). This finding implies that the oceanic eddies have the potential to influence the overlying atmosphere through air-sea turbulent heat fluxes in the Southern Ocean. Future work aims to investigate the physical mechanisms that control the SST-wind interaction at the Polar Front in Drake Passage using both a regional atmospheric model and an ocean-atmosphere coupled model. Second, these scales provide important numbers to evaluate the surface flux products used for air-sea interaction studies in the Southern Ocean to gain a better understanding of air-sea interaction mechanisms. To improve the small-scale features in the existing NWP flux products, we need to place emphasis on improving small-scale resolving skills and the response time to mesoscale surface forcing in the NWP products. Finally, the spatial scales of variability of surface fluxes assessed from this study provide useful criteria for best observing surface fluxes in the future. For example, moorings spaced as closely as 10-20 km apart are likely to have fully uncorrelated turbulent heat fluxes.

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