HIGH-RESOLUTION UNDERWAY UPPER OCEAN AND SURFACE ATMOSPHERIC OBSERVATIONS IN DRAKE PASSAGE

SYNERGISTIC MEASUREMENTS FOR CLIMATE SCIENCE

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ABSTRACT. This article highlights recent and ongoing studies that analyze in situ underway upper ocean and surface atmospheric observations from frequently repeated transects by the Antarctic Research and Supply Vessel *Laurence M. Gould* in Drake Passage. High-resolution measurements of upper ocean temperature, salinity, and velocity, along with concurrent shipboard meteorological, surface water CO_2, and nutrient sampling have been routinely acquired aboard the *Gould* since the late 1990s. There are significant benefits and synergy of air-sea observations when they are measured at similar temporal and spatial scales from the same platform. The multiyear measurements have been used to examine seasonal and spatial variability in upper ocean heat content, Antarctic Circumpolar Current transport variability, eddy heat and momentum fluxes, frontal variability, validation of satellite and model-based air-sea fluxes, and the upper ocean response to climate variability. At present, the *Gould* provides the only year-round shipboard air-sea measurements in the Southern Ocean. Collectively, the measurements in Drake Passage have provided much insight into the characteristics, mechanisms, and impacts of the processes and changes that are occurring within the Southern Ocean.

INTRODUCTION

Drake Passage, lying between Cape Horn at the tip of the Tierra del Fuego archipelago and the western Antarctic Peninsula (Figure 1), has long had a reputation as one of the roughest stretches of water in the global ocean. Strong westerly winds and currents that flow without interruption around the Southern Ocean are directly funneled into the relatively narrow Drake Passage choke point. As part of the homeward stretch of the circumpolar "Clipper Route" for trading vessels between Europe and the southern antipodes, the fierce winds and huge waves gave Drake Passage a notorious reputation among sailors. In fact, sailors eponymously referred to any gigantic waves encountered during their sea voyages as "*Cape Horners.*" Even the intrepid sailor Sir Francis Chichester, who in 1966 was the first solo circumnavigator in his 16 m ketch *Gypsy Moth IV*, implored after his adventure in 15+ m waves that flooded his cockpit five times while in Drake Passage: "Wild horses could not drag me down to Cape Horn and that sinister Southern Ocean again in a small boat. There is something nightmarish about deep breaking seas and screaming winds…"

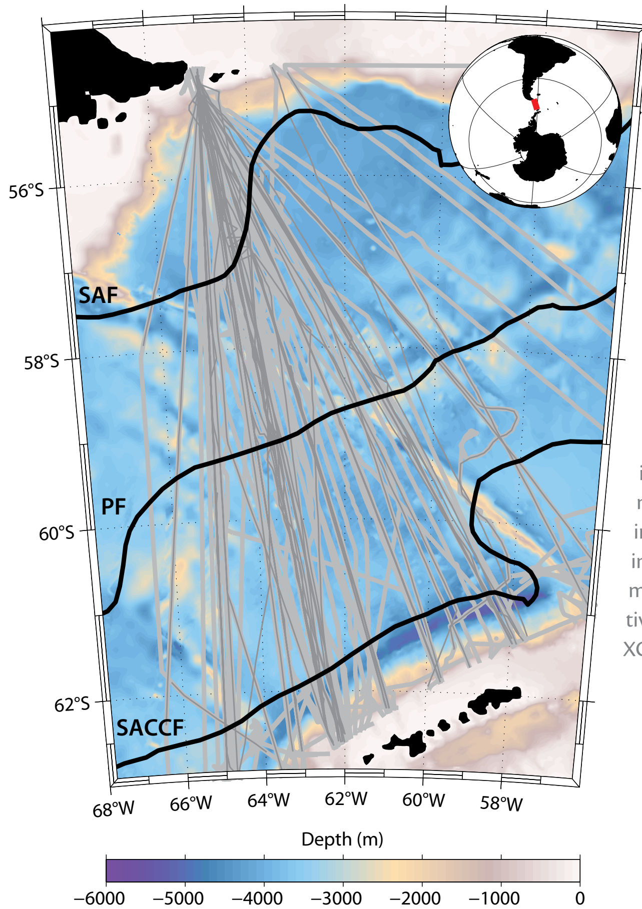

Figure 1. Bathymetry (m) of Drake Passage with Orsi et al. (1995) climatological front positions. From north to south: Subantarctic Front (SAF), Polar Front (PF), and Southern Antarctic Circumpolar Current Front (SACCF). Light gray lines indicate ARSV *Laurence M. Gould* Drake Passage transects using the underway acoustic Doppler current profiler and including carbon and meteorological measurements. Dark gray lines indicate those transects that include expendable bathythermograph/expendable conductivity-temperature-depth (XBT/XCTD) sampling.

While Chichester's sentiment may still ring true for many modern-day sailors who venture into the Southern Ocean—whether for recreational, commercial, or research purposes—for oceanographers, Drake Passage fills a unique role for increasing our understanding of the connections of the large-scale global circulation. Drake Passage provides direct linkages for the interocean exchange of waters between the Pacific and Atlantic Oceans. This interocean pathway via Drake Passage is known as the "cold-water" route for the surface to intermediate-depth water that, upon entering the South Atlantic, flows northward to ultimately participate in the Atlantic meridional overturning circulation. The leakage of waters from the Indian Ocean via the Agulhas Current system south of South Africa forms the "warm-water" route that also contributes to the overturning circulation.

Drake Passage is the narrowest constriction (~ 800 km) through which the Antarctic Circumpolar Current (ACC) must pass on its global journey around the Southern Ocean. This feature has historically made Drake Passage an ideal location for monitoring the full meridional width of ACC transport, water masses, and properties. In particular, the pioneering International Southern Ocean Studies (ISOS) program that began in the mid-1970s deployed a picket-fence mooring array and conducted numerous hydrographic surveys designed to resolve the structure and transport of the ACC (Nowlin et al., 1977). Analyses of the ISOS data led

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to establishment of the canonical ACC mean volume transport of 134 ± 11.2 Sv (Whitworth and Peterson, 1985), which has subsequently remained fairly robust (Cunningham et al., 2003).

In the modern era, the logistical convenience of the Antarctic Peninsula has led to the establishment of many international bases, and frequent visits by supply ships have fostered many opportunities for oceanographic surveys of Drake Passage. In 1993, the UK initiated sampling on the near-repeat World Ocean Circulation Experiment (WOCE)-designated SR1b transect that crosses Drake Passage, making use of the crossings to or from British Antarctic Survey bases. Meredith et al. (2011) provide a review of scientific studies of these full-depth SR1b hydrographic sections (some with lowered acoustic Doppler current profiles [ADCPs]). Similarly, underway in situ measurements of upper ocean temperature, salinity, and velocity, along with concurrent shipboard meteorological and CO_2 sampling, have been routinely acquired aboard US Antarctic research and supply vessels since the late 1990s. As the principal supply ships for the US base at Palmer Station, Antarctica, the ARSVs cross Drake Passage on average twice a month, thus providing underway measurements at high temporal and spatial resolution on a year-round basis.

Our paper highlights the results from recent analyses of the in situ underway shipboard observations from these near-repeat transects in Drake Passage. Our motivation is to demonstrate the significant benefits and synergy of air-sea observations when they are measured at similar temporal and spatial scales from the same platform. As we will show, the multiyear high-resolution measurements are useful for examining seasonal and spatial variability in upper ocean heat content, surface ocean CO_2, ACC transport, eddy heat and momentum fluxes, and frontal variability. The simultaneous, comprehensive suite of air-sea shipboard data enabled one of the very few data-based evaluations of air-sea heat fluxes in the Southern Ocean, as estimated from satellites, models, and the reanalysis flux products. This long history of measurements makes Drake Passage the most observed region in the Southern Ocean and provides much insight into the characteristics and mechanisms of the changes that are occurring within the Southern Ocean.

> "COLLECTIVELY, THE MEASUREMENTS IN DRAKE PASSAGE HAVE PROVIDED MUCH INSIGHT INTO THE CHARACTERISTICS, MECHANISMS, AND IMPACTS OF THE PROCESSES AND CHANGES THAT ARE OCCURRING WITHIN THE SOUTHERN OCEAN."

ARSV *LAURENCE M. GOULD* UNDERWAY MEASUREMENT SYSTEMS

In 1996, Ray Peterson (Scripps Institution of Oceanography) had the foresight to suggest inclusion of an expendable bathythermograph (XBT) sampling program in Drake Passage as part of the existing, broader, Pacific-wide network of high-resolution XBT transects. Ray had undertaken his PhD at Texas A&M University with Worth Nowlin measuring the transport and dynamics of the ACC through Drake Passage based on the ISOS observations (Whitworth and Peterson, 1985; Peterson, 1988) and had a fine appreciation for the high value of well-managed, sustained measurement programs. The near-bimonthly, high-resolution XBT sampling transect of upper ocean temperature in Drake Passage was initiated in September 1996 aboard the then R/V *Polar Duke*, and continued when ARSV *Laurence M. Gould* came online in September 1999.

XBTs are free-falling instruments that measure temperature profiles of the ocean's upper ~ 850 m. They are readily deployed from a moving ship, making them ideal for operation in the high sea states of the Southern Ocean. Typically, six to seven XBT transects are completed per year in Drake Passage, with 102 XBT transects undertaken through December 2011. The nature of these Antarctic ships means that the track is not always exactly repeating (Figure 1). During the two- to three-day Drake Passage crossing, about 70 XBTs are dropped between the coastal boundary 200 m isobaths, with probe separations of about 6–10 km across the Subantarctic Front (SAF) and Polar Front (PF), and

10–15 km elsewhere. The dense sampling is designed to resolve the structure of frontal systems and mesoscale eddies that are predicted by theory to have minimum length scales of ~ 10 km (Chelton et al., 1998). In fact, the sharp transition at the PF often occurs within two to three XBT drops (~ 10–20 km). The XBT data are corrected for the systematic fall rate error following Hanawa et al. (1995). Since 2001, most XBT transects have also included 10–12 expendable CTD (XCTD) profiles, spaced 25–50 km apart, that return temperature and conductivity (and hence allow calculation of salinity and density) to ~ 1,100 m. Small spikes in temperature and conductivity, characteristic of the XCTD profiles, are removed through filtering (Gille et al., 2009). The individual XBT and XCTD profiles are carefully quality controlled to allow proper representation of the subtle property fluctuations within Drake Passage. Fine-scale structure of interleaving water masses is evident in many of the profiles, particularly in the frontal regions. All profile data are archived at the National Oceanographic Data Center (NODC) for public distribution, and are also available at a Scripps Institution of Oceanography-maintained website (http://www-hrx.ucsd.edu) on a transect-by-transect basis.

Continuous upper ocean current profiling from a 150 kHz shipboard ADCP commenced in September 1999 on the *Gould*, with 274 transects of Drake Passage completed as of December 2011. A ship-mounted ADCP measures the velocity of the water relative to the ADCP's transducer by transmitting a pulse of high-frequency sound along multiple acoustic beams and estimating the Doppler shift in the frequency of the sound reflected from scatterers in the water. Estimating the Doppler shift over successive time intervals, corresponding to increasing vertical distance from the transducer, results in a vertical profile of measured currents. The navigation of the ship over the ground must be estimated with high accuracy in order to estimate absolute ocean currents. A basic assumption of the technique is that scatterers are present and are passively advected by the currents. Scatterers in the ocean are not uniformly distributed but rather vary geographically and with depth. For ADCPs operating at 150 kHz, the main sound scatterers are zooplankton and other small particles. Although the primary use of the ADCP is to measure ocean currents, the measured acoustic backscatter has provided valuable insights into the depth distributions, vertical migration behaviors, and even life cycles of dominant biological scatterers (e.g., Flagg and Smith, 1989; Zhou et al., 1994; Chereskin and Tarling, 2007). The *Gould*'s 150 kHz ADCP provides velocity and backscatter measurements at 8 m vertical resolution over a 300 m depth range. A second deep-profiling 38 kHz ADCP was added in late 2004, with 147 transects completed as of December 2011. It provides velocity and backscatter measurements at 24 m vertical resolution over a 1,000 m depth range. Typical processing for both ADCPs includes editing of profiles, averaging, and removal of the barotropic tide (Firing et al., 2012, in this issue). The horizontal resolution of the final data set is about 5 km along track, and the accuracy of absolute ocean currents is about 1 cm s^{-1} (Chereskin and Harding, 1993). The *Gould* underway ADCP measurements are made on all crossings (about 20 per year). Public access to the data is provided through the NODC Joint Archive for shipboard ADCP data and through a project website (http://adcp.ucsd.edu).

Starting in March 2002, underway measurements of the partial pressure of CO_2 (pCO_2) have been made for surface waters and the overlying atmosphere, collected through the ship's uncontaminated seawater and atmospheric air intake lines, respectively. The pCO_2 in seawater is measured in a 30 L airtight equilibration chamber that allows the pCO_2 of surface waters flowing at ~ 5 L min^{-1} to equilibrate with a head space of air (15 L) in a thermally isolated (within 0.3°C of sea surface temperature [SST]) environment. Every three minutes, ~ 150 cc of an equilibrated air sample is extracted from the head space, dried, and measured with an infrared gas analyzer (LICOR 6262). These measurements are directly compared every two hours to five different standards traceable to the World Meteorological Organization (WMO) that have known CO_2 mixing ratios (mol CO_2/mol air). *Gould* pCO_2 measurements can be found at http://www.ldeo.columbia.edu/CO2. In addition to the continual sampling of pCO_2, discrete samples for total CO_2, salinity, NO_3, SiO_4, PO_4, and ^{13}C of total CO_2 (TCO_2) are also taken from the uncontaminated seawater at 15 different locations across Drake Passage during each XBT transect.

Regular underway atmospheric and near-surface oceanic measurements began on the *Gould* in 2000. The complete meteorological package consists of dual sensors, including R.M. Young anemometers on both port and starboard sides for wind speed and direction, barometers, humidity/wet temperature sensors, and PAR

(Photosynthetically Available Radiation), PIR (Precision Infrared Radiometer, to measure longwave radiation), and PSP (Precision Spectral Pyranometer, to measure shortwave radiation) sensors. A hull-mounted thermosalinograph (TSG) and fluorometer provide continuous measurements of surface temperature, salinity, and fluorescence (chlorophyll *a* proxy measurement).

UPPER OCEAN VARIABILITY IN DRAKE PASSAGE

The shipboard underway measurements in Drake Passage provide concurrent transect information about air-sea variability at high temporal and spatial resolution on a year-round basis—an unmatched achievement in the Southern Ocean. Figure 2 provides an example of the data collected during a typical transect in March 2002. During this late summer transect, the PF, defined by the northern extent of the 2°C isotherm at 200 m depth from the XBT temperature section (Figure 2d), is located at 59°S. A surface salinity gradient is also evident at the PF location (Figure 2b). The PF separates the colder, fresher Antarctic water masses to the south from the warmer, saltier sub-Antarctic waters masses to the north (Nowlin et al., 1977; Sprintall, 2003).

Just south of the PF lies the subzero Antarctic Surface Water (Sprintall, 2007) that forms a temperature minimum layer centered at ~ 100 m; it is capped by warmer surface waters during spring and summer (Figure 2d). In winter, air-sea fluxes erode the summer cap, and the Antarctic Surface Water extends from ~ 150 m depth up to the surface. The Upper Circumpolar Deep Water (UCDW) that lies below the surface water is characterized by temperatures of 1.8°–2°C and exhibits the least temporal variability in temperature of all the upper ocean water masses found in Drake Passage (Sprintall, 2003). The Southern ACC Front (SACCF), which marks the southernmost eastward core of the ACC, is better defined by velocity than temperature (Lenn et al., 2007). For example, the temperature-defined SACCF (Orsi et al., 1995) lies at 61°S, while the strongest velocity core is centered at ~ 62°S (Figure 2e). Clearly, the velocity-defined SACCF also corresponds to gradients in underway ΔpCO_2, fluorescence, and salinity (Figure 2).

Two deep cores of relatively warm water lie north of the PF (Figure 2). The northernmost core of the warmest water is found north of the SAF located at 55.6°S on this transect. The southern core, centered on 58°S, is separated

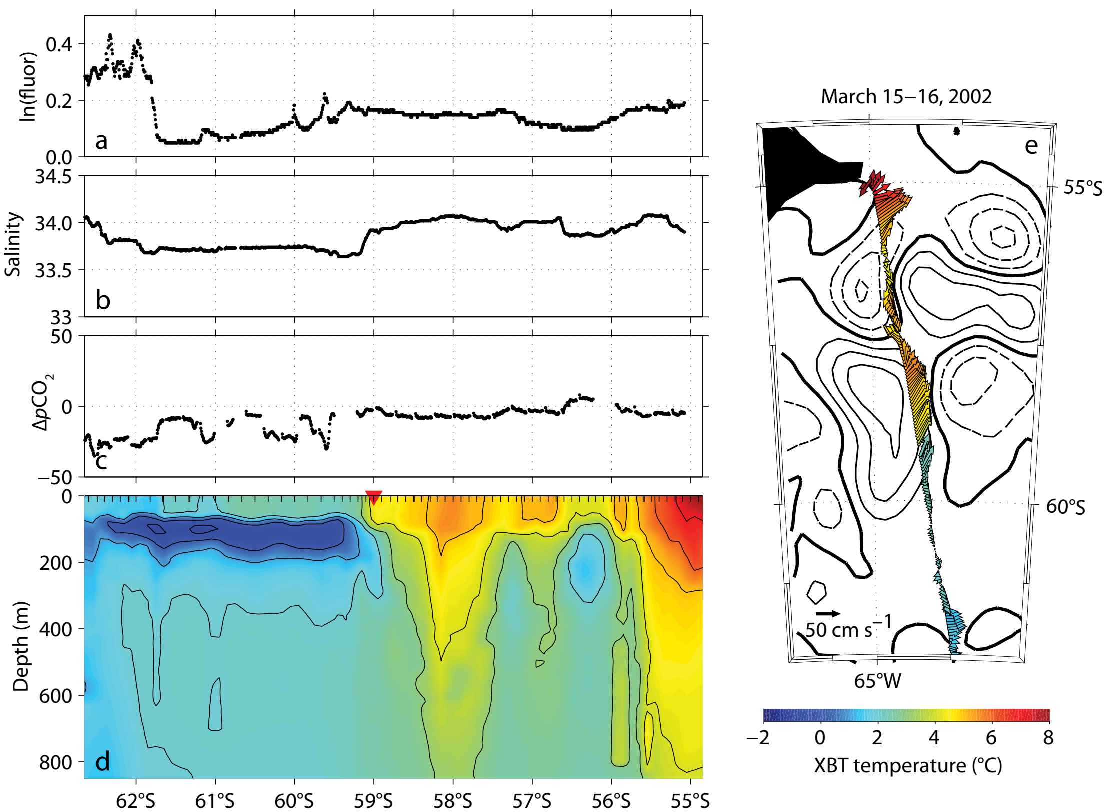

Figure 2. Concurrent underway measurements of (a) fluorescence, (b) thermosalinograph (TSG) salinity, (c) ΔpCO_2 (μatm), (d) XBT temperature (°C), and (e) ADCP velocity at 100 m depth, color-coded by XBT surface temperature, overlying altimetric sea surface height anomaly (SSHA) contours, during a March 2002 ARSV *Laurence M. Gould* crossing of Drake Passage. In (d), XBT drop locations are indicated by tick marks along the top axis, and the latitude of the Polar Front is denoted by the downward red triangle. In (e), the SSHA contour interval is 5 cm, and the type of line denotes zero (bold), negative (dashed), and positive (solid) SSHA values, respectively.

from the SAF by a deeper core of colder water that is capped by warmer waters at the surface. This cold-core feature corresponds to a slight elevation in $\Delta p CO_2$, a decrease in fluorescence, and a decrease in surface salinity (Figure 2), properties that are more characteristic of levels found south of the PF. The slight increase in surface pCO_2 could be driven by warming of surface waters as the cold core moves north, and it suggests that these cold core rings help move CO_2 from south to north of the PF and further enhance the flux of CO_2 from the surface ocean to the atmosphere. The ADCP vector velocities clearly show the jets associated with the main ACC fronts, with peak speeds of 85 cm s^{-1} in the SAF, 65 cm s^{-1} in the PF, and 40 cm s^{-1} in the SACCF (Figure 2e). Contours of sea surface height anomaly (SSHA) from altimetry show good correspondence with ADCP velocity vectors (Figure 2e). The ship track crosses a northward-meandering PF and slices through the eastern side of the deep cold core eddy found between the SAF and the PF. High mesoscale variability north of 60°S is evident in the SSHA field.

Distinct bands of alternating cores of warm and cool waters that correspond to eddies and frontal meandering are ubiquitous in the XBT transects (Sprintall, 2003) and confirmed in the ADCP velocity measurements (Lenn et al., 2007). Geostrophic velocity anomalies estimated from altimetric SSHA tend to underestimate directly observed currents due in part to the lack of a mean geostrophic reference and also due to the coarser resolution of the altimetry (Lenn et al., 2007), but the patterns generally show good agreement. An Eulerian gridded mean updated from Lenn et al. (2008) and based on a longer 11.5 year interval (262 transects) clearly shows the three main frontal jets of the ACC relative to climatology (Figure 3a). The apparent northward displacement by about 50 km of the SAF and the PF from their climatological positions (Orsi et al., 1995) agrees with front locations determined from XBTs (Sprintall, 2003) and is likely due to uncertainty in determining front locations from the coarser sampling (~ 50 km station spacing) of the climatology. In this region of Drake Passage, the eddies seem to be exclusively confined to the Antarctic Polar Frontal Zone between the PF and the SAF (Sprintall, 2003), and standard deviation ellipses show elevated eddy kinetic energy in this zone (Figure 3b; Lenn et al., 2007). The combined data set contributes useful information on the mesoscale eddy features in Drake Passage and for computations such as estimating eddy heat fluxes (Lenn et al., 2011).

Direct velocity observations are useful in determining total transport over the profiling range of the ADCPs. Only a subset of transects are considered suitable for transport calculation, using the criteria that the Drake crossing needs to be at least 700 km in length and 90% good coverage. Gaps smaller than these are interpolated. A slab layer extrapolates

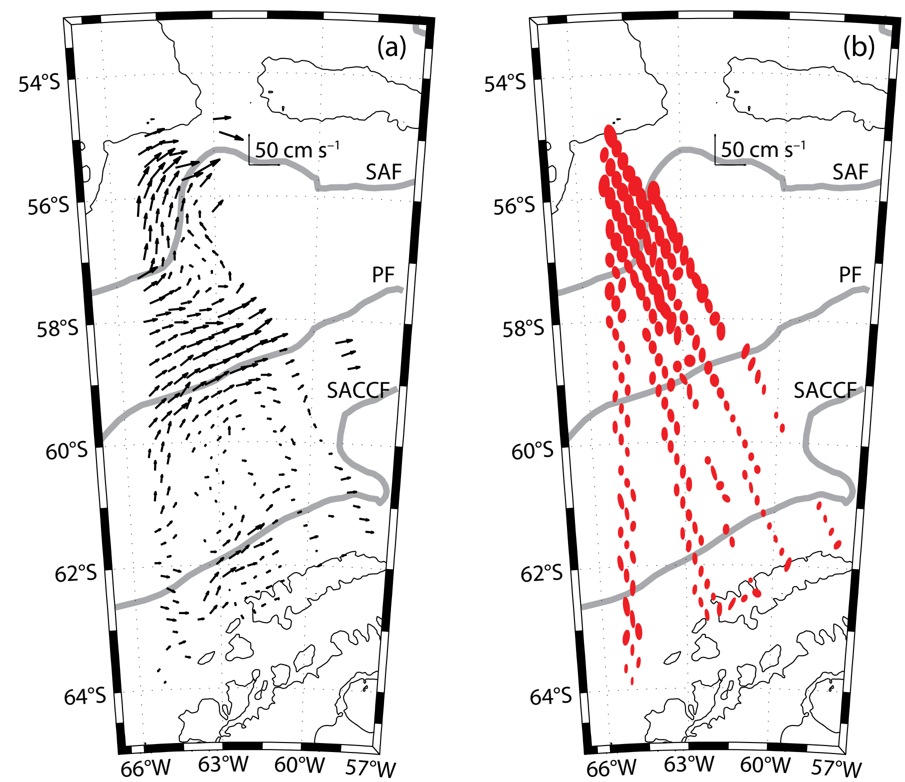

Figure 3. (a) Gridded (25 km x 25 km), depth-averaged (26–298 m), time-averaged currents from 262 Drake Passage transects between September 1999 and April 2011, and (b) standard deviation ellipses. Gridded velocities are shown in each grid box crossed three times or more; standard deviation ellipses are shown for each grid box crossed 15 times or more. Climatological locations of the Subantarctic Front (SAF), Polar Front (PF), and Southern ACC Front (SACCF; Orsi et al., 1995) are shown as thick gray lines. *Updated from Lenn et al. (2008)*

to the surface. The mean observed transport of the ACC in the upper 1,000 m based on 51 38-kHz ADCP transects over 4.5 years is 95 ± 2 Sv, or 71% of the canonical full-depth value of 134 Sv (Firing et al., 2011). The remarkable stability of the five-year transport estimate is also seen in the 16-year mean from the SR1b transect (Meredith et al., 2011); additionally, the *Gould*'s near-bimonthly sampling avoids potential aliasing of the annual signal and thus is suitable for examining variability at seasonal to annual timescales. It has been postulated that the ACC is presently in an almost eddy-saturated state (see Meredith et al., 2011), whereby strengthening winds change the eddy intensity more than the ACC transport changes it. The *Gould* transport time series provides an extremely important baseline for comparing the response of the ACC to any future changes in wind forcing, whether due to natural or anthropogenic impacts on the environment.

In the Southern Ocean, the zonally integrated Ekman transport is estimated to be 25–30 Sv and constitutes the shallowest limb of the meridional overturning circulation, a key component of the coupled ocean/atmosphere climate system. Wind-driven Ekman currents have been difficult to observe directly because, even when forced by strong winds as in the Southern Ocean, their magnitudes are small compared to the background geostrophic circulation. While Ekman currents can be inferred from the wind, direct measurements are required in order to determine Ekman layer depth, mean temperature, eddy viscosity, and associated Ekman layer heat fluxes. The shipboard ADCP has been a valuable tool in describing Ekman currents because it provides velocity profiles that span the ocean surface layer, from the level of direct wind influence down into the geostrophic interior. Lenn and Chereskin (2009) describe the characteristics of the Ekman layer in Drake Passage. The mean Ekman currents decay in amplitude and rotate anticyclonically with depth, penetrating to 100 m, above the base of the annual mean mixed layer at 120 m. The rotation depth scale exceeds the e-folding scale of the speed by about a factor of three, resulting in a current spiral that is compressed relative to predictions from theory. The mean temperature of the Ekman layer is not distinguishable from temperature at the surface. Turbulent eddy viscosities estimated from the time-averaged stress are O(100–1,000) $m^2\ s^{-1}$. The eddy viscosity is not constant; it decreases in magnitude with depth, and the time-averaged stress is not parallel to the time-averaged vertical shear. These differences from the simplest theory are likely due to nonconstant eddy viscosity and to time averaging over the cycling of the stratification in response to diurnal buoyancy fluxes, although the action of surface waves and the oceanic response to high-frequency wind variability may also contribute.

Many of the processes most relevant to climate change occur in the oceanic surface layer where there is direct heat, freshwater, and gas exchange with the atmosphere. In many studies of air-sea exchange, the limit of the upper ocean is defined by the mixed layer; the low stratification in Drake Passage, however, makes identification of the mixed-layer depth problematic (Stephenson et al., 2012). Consequently, mixed layers are often ill defined and display considerable variability over very short distances. In contrast, upper ocean heat content has been shown to provide a much more robust measure of upper ocean variability, with a first-order heat balance between heat content and air-sea heat fluxes matching in both phase and amplitude over the seasonal cycle (Stephenson et al., 2012). There was no similar agreement between the mixed layer integrated heat content and air-sea fluxes, and, in particular, the seasonal phasing differed significantly. However, the simple one-dimensional heat budget balancing the upper ocean heat content and surface heat fluxes (Stephenson et al., 2012) does not provide a complete picture of the processes governing upper ocean variability in the Southern Ocean—for example, frontal meanders and eddies frequently found north of the PF (Figure 2) can redistribute heat through horizontal and vertical advection and so complicate the one-dimensional heat exchange balance. Nonetheless, the relationship between upper ocean heat content and surface forcing accounts for most of the variance on seasonal timescales.

EVALUATION OF SOUTHERN OCEAN AIR-SEA FLUXES

The sensitivity of the Southern Ocean to the climate system is largely dependent on the exchanges of heat, freshwater, and momentum that occur at the air-sea interface. Southern Ocean air-sea fluxes are particularly important because of their influence on water mass formation and transformation, and also through the oceanic uptake of heat. Significant changes have occurred in observed Southern Ocean heat content and water mass properties over the past few decades (e.g., Gille, 2002, 2008; Purkey and Johnson, 2010). Yet, the magnitude and variations of air-sea fluxes in the Southern Ocean are poorly known, and this has led to great uncertainties in Southern Ocean heat budgets and the climate system (Dong et al., 2007; Cerovecki et al., 2012). For many physical (e.g., high winds and sea states) and logistical (e.g., remoteness) reasons, routine meteorological measurements are problematic in the Southern Ocean (Mark Bourassa, Florida State University, and colleagues, *pers. comm.*, July 2012, based on a recent review). These difficulties make the unique data set from the multiyear, year-round, high-resolution shipboard measurements of flux-related parameters from *Gould*'s Drake Passage transects invaluable for assessing remotely sensed and National Weather Prediction (NWP) air-sea flux products (e.g., those from the National Centers for Environmental Prediction/National Center for Atmospheric Research [NCEP/NCAR] and the European Centre for Medium-Range Weather Forecasts [ECMWF]).

The May 2002 launch of the NASA Earth Observing System (EOS) Aqua satellite offered new possibilities for obtaining a suite of remotely sensed, flux-related state variables. However, validation of the satellite retrievals of these state variables, mainly relevant to the latent and sensible heat components of the net air-sea heat flux, are mostly based on data that have been collected in the tropics or mid-latitudes. Dong et al. (2006b) presented one of the first attempts to evaluate the performance of the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) sea surface temperatures using the *Gould* ship-based SST measurements from XBTs and TSG. Compared to the EOS Moderate Resolution Imaging Spectroradiometer (MODIS) infrared retrievals of SST, the AMSR-E provides SST measurements with little bias relative to in situ observations. The distinction is important because, unlike the infrared instrument, the AMSR-E microwave sensor is capable of penetrating cloud cover, which is perpetual in the Southern Ocean. This better temporal and spatial coverage improves the application of the AMSR-E measurements for Southern Ocean heat budget studies (Dong et al., 2007), frontal variability (Dong et al., 2006a), and potentially for determining Ekman heat transport (Lenn and Chereskin, 2009).

The EOS Atmospheric Infrared Sounder (AIRS) surface air temperature and specific humidity sensors were also assessed by comparing their data to *Gould* shipboard meteorological measurements in Drake Passage (Dong et al., 2010). The objective was to evaluate whether the AIRS retrievals, in conjunction with the AMSR-E SST, could provide sufficiently accurate parameters to estimate the sensible and latent heat fluxes in the data-poor Southern Ocean. The colocated data show that both AIRS-derived SST and air temperature are colder, and the specific humidity measurements lower, than the shipboard measurements. Nonetheless, compared to several NWP products, the remotely sensed variables showed the small-scale spatial structure that is typical of the *Gould* observations. Consequently, the turbulent fluxes derived from the AIRS and AMSR-E data using bulk algorithms were better able to represent the full range of flux values estimated from the shipboard data compared to the NWP products (Dong et al., 2010).

> “SOUTHERN OCEAN AIR-SEA FLUXES ARE PARTICULARLY IMPORTANT BECAUSE OF THEIR INFLUENCE ON WATER MASS FORMATION AND TRANSFORMATION, AND ALSO THROUGH THE OCEANIC UPTAKE OF HEAT.”

In a recent paper, Jiang et al. (2012) used the underway *Gould* measurements to examine the spatial scales of the turbulent heat fluxes and the flux-related state variables. The spatial decorrelation scales of sensible and latent heat fluxes calculated from the two-day transects were respectively 65 ± 6 km and 80 ± 6 km. However, when the PF region was excluded from the calculations, the decorrelation scales reduced to 10–20 km, consistent with the first baroclinic Rossby radius (Chelton et al., 1998). These eddy scales are often unrepresented in the available NWP gridded heat flux products. To gain a better understanding of air-sea exchange processes and their relevance to the climate system, it is important that the small-scale resolving skills and the response time to mesoscale forcing be improved in the NWP products.

LONG-TERM CHANGES IN DRAKE PASSAGE

Many recent studies have documented changes in Southern Ocean water mass properties, the coupled ice-ocean system, the marine ecosystem, and atmospheric forcing on timescales of relevance to climate (e.g., Thompson and Wallace, 2000; Yuan and Martinson, 2000; Le Quéré et al., 2002; Gille, 2002, 2008; Vaughan et al., 2003). The relatively extensive long-term hydrographic data coverage in Drake Passage means the number of available observations greatly exceed those used in other studies of climate change in the Southern Ocean. Using data from Drake Passage starting in 1963, Sprintall (2008) found statistically significant trends in upper ocean temperature using linear robust regression analysis. Because most of the winter observations are associated with the more recent year-round, high-resolution XBT program, Sprintall (2008) also presented trends determined only from summer transects (November to March) to avoid any seasonal sampling bias. As for the full data set, using the seasonally adjusted data resulted in statistically significant trends of ~ 0.02°C yr^{-1} observed north of the PF below the surface, with smaller significant trends of ~ 0.005°C yr^{-1} observed south of the PF. The time series of temperature anomalies were highly correlated with climate indices of the Antarctic Oscillation (AAO) and the El Niño-Southern Oscillation (ENSO). The annual temperature anomalies both north and south of the PF lagged El Niño variability in the Pacific, with phasing consistent with the cyclical patterns in SST and sea ice associated with the Antarctic Circumpolar Wave or the Antarctic Dipole Mode (White and Peterson, 1996; Yuan and Martinson, 2000). The temperature anomalies north of the PF were primarily coincident with the AAO, and largely consistent with a southward shift in the PF due to the strengthening and poleward shift of the band of westerly winds in the Southern Ocean (Thompson and Wallace, 2000; Dong et al., 2006a).

Changes in water column stratification and properties in the Southern Ocean are also likely to have important consequences to primary production and the structure of the marine ecosystem in Antarctic waters. The 150 kHz ADCP data have been used to look at variability in backscattering in Drake Passage (Chereskin and Tarling, 2007), a measurement that is correlated with planktivore biomass (e.g., Zhou et al., 1994). Diel vertical migration in the upper 150 m was the dominant variability observed in any single transect. When averaged over depth, there was a well-defined annual cycle in backscattering strength, with a factor of four increase from a late-winter minimum to a spring-summer maximum over a period of four months. The diel and seasonal variability suggest that the scattering is dominated by biological scatterers. A significant decline in backscatter was observed south of the PF over the six years examined (1999–2004), peaking in 1999 and dropping to the lowest levels in 2004. Most notably, the largest decline was seen south of the SACCF, where the biomass is dominated by Antarctic krill (*Euphausia superba*), the keystone species in Southern Ocean food webs (Siegel, 1988).

Also notable in this regard is that populations of planktivorous higher predators (e.g., Adélie penguins, *Pygoscelis adeliae*) have been declining in nearby islands over a number of years (Forcada et al., 2006). Long-term declines in population size point to a more significant environmental shift. The fact that both planktivores and acoustic backscatter have declined over similar periods suggests that the wider zooplankton community is currently in a phase of decline in this region of the Southern Ocean. This decline is occurring especially in regions where Antarctic krill dominates, for example, south of the SACCF. Such a decline may be a result of recent warming trends in the surface waters of this region (Meredith and King, 2005) as well as changing ice dynamics (Vaughan et al., 2003).

Finally, changes in the marine ecosystem structure and in the ice-ocean-atmosphere system will likely also have significant implications for the role of the Southern Ocean as a sink for the increasing anthropogenic atmospheric CO_2. Recent modeling studies and observations made aboard the *Gould* suggest that the stronger westerlies in the Southern Ocean will lead to increased upwelling and subsequent degassing of the carbon-rich UCDW found at depth south of the PF (e.g., Lovenduski et al., 2008; recent work of author Sweeney and colleagues). The models further suggest that the response of seawater pCO_2 to wind-driven long-term changes in temperature and photosynthesis is relatively small (Lovenduski et al., 2008; Le Quéré et al., 2007). The relationship between the underway *Gould* surface CO_2 and temperature measurements sheds light on some of the processes that may be controlling this variability (Figure 4). Here, we examine the correlation of the time series of underway measurements of the ΔpCO_2 (Figure 4a) with the concurrent time series of XBT temperature profiles. We use the ΔpCO_2 (i.e., the difference between the underway measured atmospheric pCO_2 and the measured ocean surface pCO_2) to account for the observed trends in atmospheric pCO_2. Both XBT and surface ΔpCO_2 time series have been binned to the same 10 km along track grid in winter (Figure 4b) and spring (Figure 4c). A significant negative correlation of the surface ΔpCO_2 (air-sea) and the concurrent XBT temperature profiles is found just south of the PF in winter (Figure 4b). A negative correlation corresponds to higher temperatures and lower ΔpCO_2 such that the flux is from the ocean to the atmosphere or, conversely, that lower temperatures enhance the flux from atmosphere to ocean. Southern Ocean pCO_2 is strongly controlled by the thermodynamic relationship between temperature and pCO_2: every 1°C increase in temperature is equivalent to a 4.23% increase in pCO_2. The negative correlation pattern is therefore in agreement with the thermodynamic relationship and, furthermore, is consistent with the winter upwelling of the warmer and higher oceanic pCO_2 UCDW waters that drive the ΔpCO_2 (and air-sea flux) to be more negative. During the spring months, the positive correlation found in the near-surface layer north of the PF suggests that temperature is driving a biological relationship for the increased ΔpCO_2 (Figure 4a,c). The warmer waters of spring enhance near-surface stratification, and trapping of increased sunlight will drive biological production and thus lower the oceanic pCO_2 and enhance the air-to-sea flux.

CONCLUSIONS

Our review highlights some new and ongoing scientific studies of upper ocean processes in Drake Passage using the ARSV *Laurence M. Gould* suite of underway air-sea measurements. With decades of data now available, the Drake Passage air-sea measurement programs have reached a point where they can be maintained with a minimum of personnel and resources while generating high-quality data that are publicly available in a prompt manner. Oceanographic time series such as this are carefully considered prior to their implementation

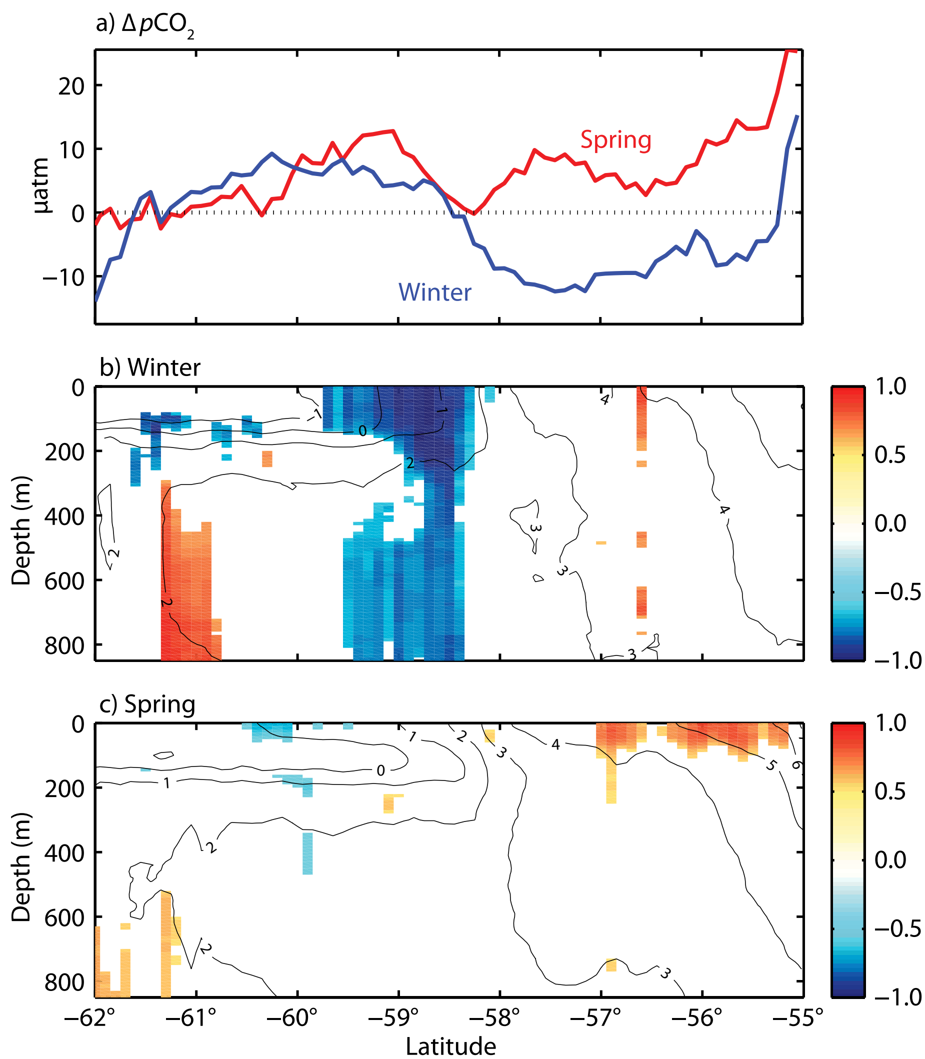

Figure 4. (a) Mean ΔpCO_2 (μatm) during winter (blue) and spring (red) from ARSV *Laurence M. Gould* underway measurements in Drake Passage. Correlation of the time series of surface ΔpCO_2 measurements and the XBT-temperature sections at concurrent along track bins (10 km) in (b) winter and (c) spring. Only those correlations that are significant at the 95% confidence level are colored. Background solid contours show the mean XBT temperature structure during the corresponding seasons.

because their usefulness is in their longevity. Interrupting or disbanding them seriously degrades the potential usefulness of the data already collected. The programs involve a small financial outlay for a huge scientific benefit. Automated underway observations on supply ships provide an extremely cost-effective method for obtaining high-quality data at the air-sea interface that has benefits for a broad range of climate-related research questions. Simultaneous high-resolution repeat transect information of upper ocean temperature and velocity, air-sea gas fluxes, and meteorological measurements cannot presently be obtained any other way. At present, the *Gould* provides the only year-round repeat shipboard air-sea measurements in the Southern Ocean. Encouraging the routine collection of underway concurrently measured air-sea data from vessels operating in the Southern Ocean is a critical recommendation of the community-supported Southern Ocean Observing System (Rintoul et al., 2012). Future observation systems would benefit from expanding vessel recruitment in this region of importance to global climate.

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