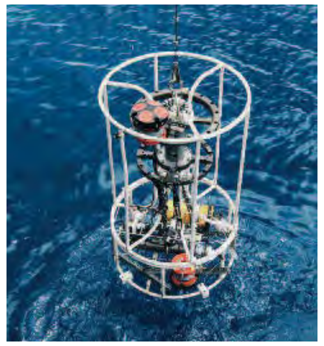

Uncovering secrets of the Southern Ocean

By Peter Spain PhD, Teledyne RDI, Poway, California, USA

Varied studies show versatility of ADCPs

Circling the globe in the high latitudes of the southern hemisphere, the Southern Ocean has seen an upsurge in scientific attention. This remote region is now understood to have global influence on both ocean circulation and Earth's climate. As well as its unique physical environment, the Southern Ocean provides essential oceanic connections. These are geographical – between Pacific, Atlantic and Indian Ocean basins – and vertical, between upper and deep layers of the ocean.

The Southern Ocean separates chilly Antarctic waters from warmer tropical oceans. The region's well-known aspects include strong zonal winds, deep Antarctic Circumpolar Current and surficial outcropping of deep, nutrient-rich waters. Recent results from the Southern Ocean have clarified its important global role in absorbing CO_2 and heat, which would otherwise reside in the atmosphere.

For ocean circulation, the region's influence is equally pervasive. Consequential findings include widespread intense oceanic mixing and disproportionate uptake of energy from the wind. These reinforce the Southern Ocean's pivotal role in the global overturning circulation. Furthermore, the Southern Ocean has been studied as a sensitive indicator of the global ocean's response to changing climate, especially shifting winds and warming.

Taking advantage of modern technology, oceanographers are now better equipped to surveil the Southern Ocean. Their observational programmes have examined different facets of this remote region.

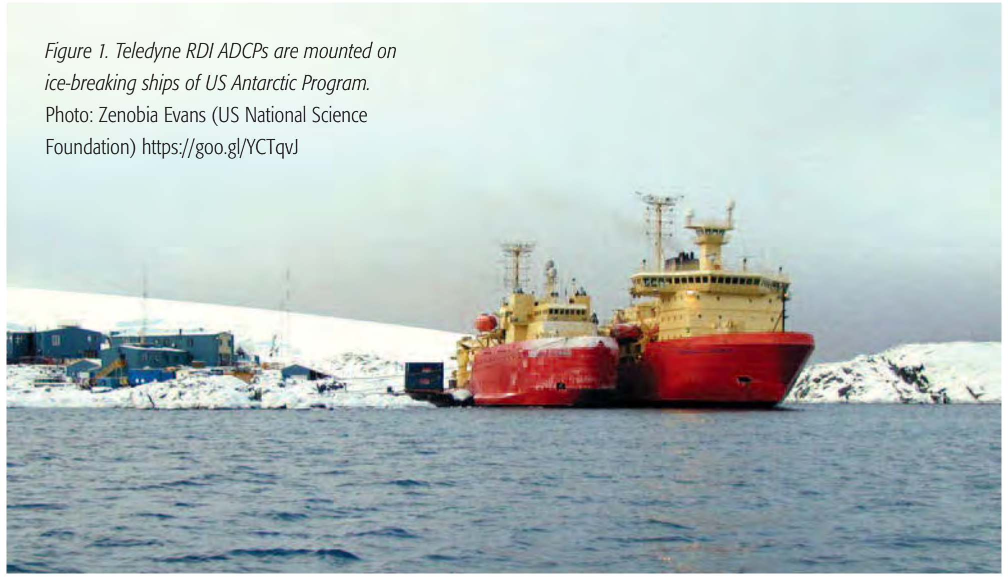

Figure 1. Teledyne RDI ADCPs are mounted on ice-breaking ships of US Antarctic Program. Photo: Zenobia Evans (US National Science Foundation) https://goo.gl/YCTqvJ

In studies looking at circulation and mixing, acoustic Doppler current profilers (ADCPs) have seen action in various guises. For two decades, ADCPs aboard US Antarctic supply ships have monitored currents through Drake Passage. Moored ADCPs provided French researchers with multi-year observations for merging with satellite data to construct a 20-year record of transport of the Antarctic Circumpolar Current. And lowered ADCPs (LADCP) have aided various UK and international programmes studying oceanic mixing.

DRAKE PASSAGE ADCP TRANSECTS

Since 1999, two supply ships of the US Antarctic Program have repeated ADCP transects while crossing Drake Passage about twice per month. Driving this effort are researchers from the Scripps Institution of Oceanography, USA, and the University of Hawaii, USA. They seek to measure any sustained changes in the speed, transport and distribution of the prevailing currents.

A hull mounted 150kHz ADCP was initially employed, profiling currents to 300 metres depth. Five years later, a second 38kHz ADCP was added to reach 1000 metres depth. The two frequencies offer complementary range/resolution capabilities. Unique aspects of these installations are the ADCP's immersion in anti-freeze solution, and their protection for ice breaking operations.

A range of scientific studies have used these ADCP transects to explore features of the Southern Ocean, particularly the Antarctic Circumpolar Current. The Drake Passage presents the narrowest constriction to this flow – 800 kilometres wide. As a result, numerous upstream frontal filaments that separate different water masses converge into predominant fronts – e.g., Subantarctic (SAF) and Polar (PF) Fronts.

As well as jets associated with these fronts, the current field is enriched with motions due to eddies, frontal meandering and strong winds. Some zonation is observed; for example, eddy energy is greater northward of the Polar Front.

> ### Shipboard ADCPs
> From the mid-1980s, ADCPs on research ships provided a new 2D view of upper-ocean currents: along-track and through depth.
>
> Over the next two decades, the scientific value of this data type was boosted by two technological improvements. One was advancing GPS capability, which supplied more accurate ship's heading. The other was far deeper current profiling, which came from Teledyne RDI's phased-array acoustic Doppler current profilers using much lower frequency.
>
> Researchers at University of Hawaii and other institutions developed best practices for extracting high-quality ADCP sections (https://goo.gl/zxB5Pk). As well, they improved understanding of environmental influences on the vertical reach of shipboard ADCPs.

The ADCP-based current fields have better along-track resolution than previously available. Two advantages result. Current speeds in narrow frontal regions are more accurate. Also spatial structure of the flow field is more sharply defined, unmasking quiet regions near frontal jets.

The longevity of the ADCP programme permits more reliable statistical calculations and has produced notable results.

One was to evaluate important wind-driven effects: characteristics of the mean Ekman layer and its associated heat flux. These features tend to be masked in mid-latitude oceans. Second, eddies were seen to produce a momentum convergence that reinforces the frontal zones. And third, combining ADCP data with XBT temperature profiles, scientists found a large poleward heat flux in the near-surface layer.

Various forcing mechanisms produce currents in the upper ocean. For unravelling the mix in Drake Passage, the set of shipboard ADCP transects has two advantages: duration and depth. The latter comes from 38kHz ADCP.

Scientists at the Scripps Institution of Oceanography studied dynamical features. One was the persistent structure of the Antarctic Circumpolar Current. In particular, they identified some interesting contrasts from examining vertical structure of the upper kilometre. For example, the energy levels of eddy motions showed marked changes in depth whereas average current conditions did not. In fact, speeds to 20 centimetres per second persisted at one kilometre depth. Further, the dominant vertical direction of energy propagation was opposite in the upper ocean compared with greater depths. Internal waves are known to be generated by storms at the surface and by submarine ridges at depth.

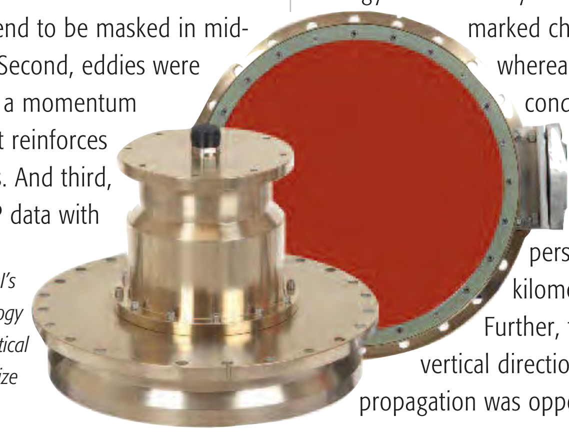

Figure 2. Teledyne RDI's phased-array technology pushed back the practical limits for transducer size and frequency.

MOORED ADCP TIME SERIES

For almost three decades, satellite altimetry has aided studies of ocean circulation. The method has been especially productive for studying remote, sparsely-observed regions. As well, the satellite-based record provides long time series. This is a much-desired attribute for evaluating interannual and decadal changes in Earth's systems.

One recurring use of satellite altimetry has been to examine ocean transport variability. Yet the interpretation of these satellite-based results can be equivocal. Hence a validation period with in situ observations is essential before scientists use the altimeter data as a long-term index of ocean transport.

For long-term monitoring of the Antarctic Circumpolar Current, French scientists opted for satellite altimetry. The satellite data provided a time series of volume transport over two decades. But first the scientists collected hydrographic and moored measurements to provide ground-

> ### Volume Transport
> The amount of water carried by strong currents – volume transport – is a prime choice for ocean monitoring. It reveals the pulse of the ocean. Besides, this property is a common output from models of ocean circulation; hence predictions of volume transport are often used for validating model performance.

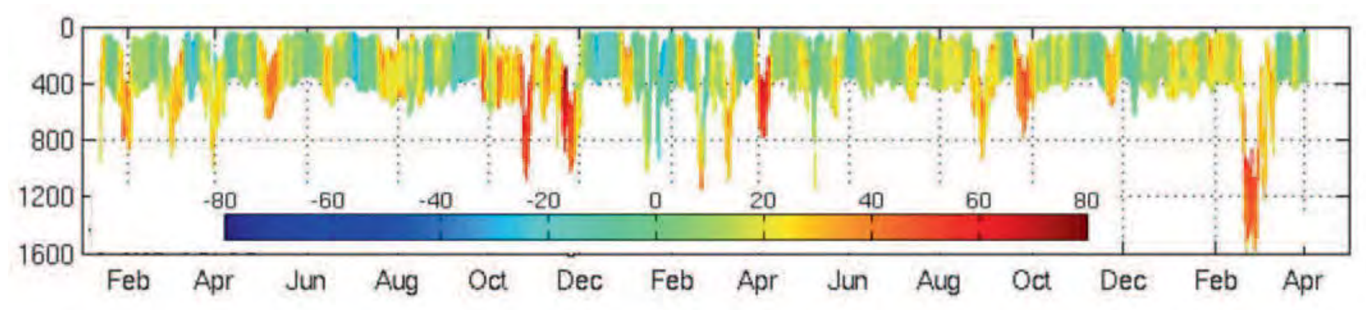

Figure 3. North-south flow in ADCP time series for 27 months in northern Drake Passage. Depth (m), Speed (cm/s).
Image: Z. Koenig, *et al.* (2014) https://doi.org/10.1002/2014JC009966. https://goo.gl/sWQo7C

truth during a three-year validation period. Both lowered ADCP transects and moored ADCPs were used. The moorings were set along the ground track of the satellite. In addition to quantifying the volume transport of the current, the mooring data revealed how that transport changed.

Included in the moored section were two moorings topped with uplooking Teledyne RDI ADCPs. These were deployed astride the Subantarctic Front on the northern end of the section. In the first deployment, higher frequency ADCPs were used to capture with better resolution the structure of strong currents in the upper ocean. At times, mooring blow-down due to strong frontal jets was marked. You can see these effects in Figure 3. In the later deployment, moorings were terminated deeper. They carried uplooking 75kHz Long Ranger ADCP to measure currents in the upper 400 metres.

Lowered ADCP sections were collected when moorings were serviced. In particular, two LADCP sections with high along-track resolution were performed within three weeks for a detailed intercomparison with spatial structure reported by satellite altimetry.

OCEANIC MIXING IN THE SOUTHERN OCEAN

Understanding how and where energy is dissipated has been a long-standing challenge in the physics of ocean circulation. Better observational tools allowed closer study of the role of rough bottom topography in this process.

Scientists looked for signatures of energy transfer where strong, deep flows meet submarine mountain ranges. A favoured signature is the turbulent mixing created by breaking underwater 'internal waves'. These waves arise where deep horizontal motions must move up and over subsea ridges. The resulting waves are internal like those you've seen inside a bottle holding layers of oil and water.

These internal waves follow distinct pathways, sometimes slanting beams across the ocean. Upon hitting the seabed, some of the waves break and dump the energy they carry. The ensuing turbulent action is thought to create deep mixing in the ocean. These events can be identified by locally-elevated dissipation focused near the sea floor. As well as heat transfer, this process also causes vertical exchange of other water properties, e.g., nutrients.

The Southern Ocean offers expansive regions where strong, deep flows meet rough bottom topography. Thus several international teams have mounted field programmes looking for these deep signatures. Both lowered and moored ADCPs have been used. These data are used in an indirect method for estimating mixing. This approach needs to be applied prudently in weakly-stratified waters, such as the Southern Ocean

For two decades, research cruises through various domains of the Southern Ocean have lowered ADCPs during hydrographic casts. Transects of full-depth current

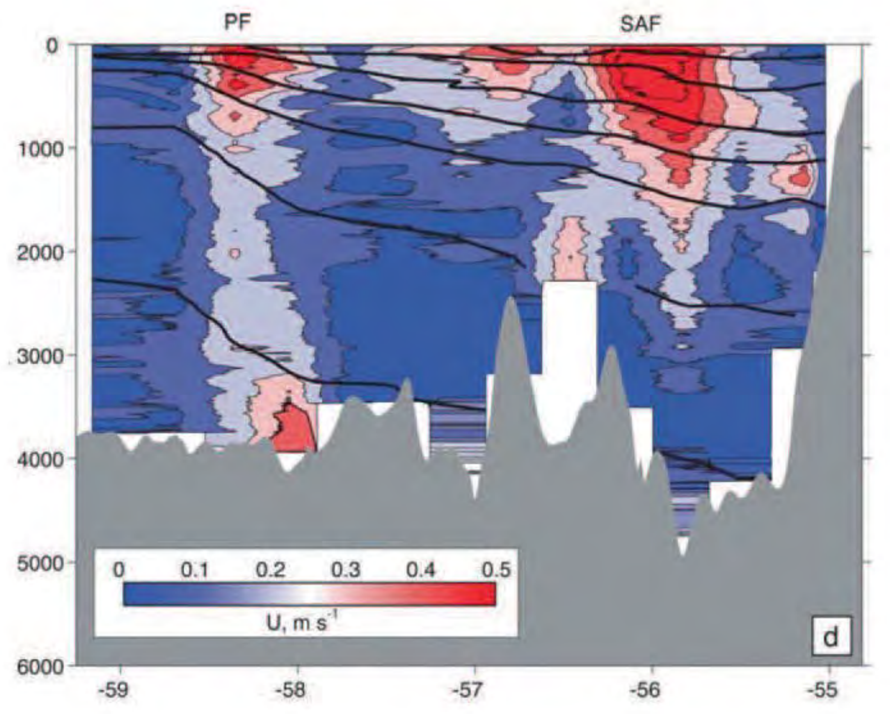

Figure 4. East-west currents in Drake Passage from LADCP profiles. Speed (m/s), Depth (m), Distance (deg) with S. America on RHS. Image: K. Sheen, *et al.* (2013). https://doi.org/10.1002/jgrc.20217. https://goo.gl/UHhWw7

> Considered together, these studies reveal the remarkable versatility of the ADCP. It provides a powerful tool for assessing the fascinating characteristics of this remote oceanic region

profiles have provided revealing slices of the spatial distribution of the region's strong, deep currents. Plus the measured current shear held additional information.

In the late 1990s, scientists tested LADCP profiles as input to a statistical description of mixing in the ocean. The calculation uses current shear – vertical change in water speed. The method blends the LADCP profiles with complementary data from concurrent CTD profiles. Although results from widespread regions have now been reported, some of the most riveting came from the Southern Ocean.

Initial tests had shown intriguing results for profiles near rough topography in the Southern Ocean. Motivated by this success, an international team made a more expansive study. They reported results of widespread intense mixing near Drake Passage. High rates were reported over rough topography for great distances. The implication is that mixing is an essential factor in the large-scale overturning circulation at high southern latitudes.

Subsequent investigators found these indirect fine-structure-based results tend to overestimate mixing in weakly stratified waters. Yet the qualitative value of this approach for identifying sites of enhanced mixing remained.

Those groundbreaking studies created an upsurge in broader use of LADCP data. In the Southern Ocean, several projects worked around Drake Passage. Another busy site is located farther west – south of the Indian Ocean. Using LADCP transects, UK researchers mapped a large-scale region around Kerguelen Plateau. East-west currents show a stationary meander due to a subsea ridge. The same LADCP data also aided study of much smaller spatial scales. The scientists looked at energetics of features excited when the current field interacts with peaks on the ridge.

PROTEAN PROFILER

Considered together, these studies reveal the remarkable versatility of the ADCP. It provides a powerful tool for assessing the fascinating characteristics of this remote oceanic region. In varied applications from circulation to mixing – and sometimes both at once – ADCP profiles have been a sound resource. They have supported research from Antarctic supply ships and multi-year moorings to full-depth hydro casts. And ADCPs have been applied across a wide range of issues. Although conducted by scientists from different countries, these research programmes share a common intent – uncovering secrets of the Southern Ocean. ■