Conclusions

As ocean waves propagate into the shoaling waters of the nearshore, they undergo a wide range of changes. Most people are familiar with the refraction, shoaling and eventual breaking of waves in a near-shore surf zone. However, this same energy can drive strong secondary flows. Wave breaking pushes water shoreward, yielding a super-elevation at the shoreline that can accentuate flooding and erosion. Waves arriving at an angle to the beach will drive strong currents along the beach that can transport large amounts of sediment. Often these currents form circulation cells, with strong rip currents spaced along the beach.

Natural waves occur in groups, with heights that vary. The breaking of these fluctuating groups drives waves and currents at the same modulation timescale, called infragravity waves. These can be trapped in the nearshore by refraction as edge waves. Even long shore currents can develop instabilities called shear waves that drive meter-per-second fluctuations in the current strength with timescales of several minutes.

The apparent physics that dominates different beaches around the world often appears to vary. For example, on low-sloping energetic beaches, infra-gravity energy often dominates the surf zone, whereas shear waves can be very important on barred beaches. In fact, the physics is unchanging in these environments, with only the observable manifestations of that physics changing. The unification of these diverse observations through parameters such as the Iribarren number is an important goal for future research.

See also

Breaking Waves and Near-surface Turbulence. Coastal Circulation Models. Coastal Trapped Waves. Beaches, Physical Processes Affecting. Sea Level Change. Surface, Gravity and Capillary Waves. Wave Generation by Wind.

Symbols used

E	wave energy density
H	wave height
H_s	significant wave height
L	wavelength
L_0	deep water wave length
P	wave power or energy flux
R_s	significant swash height
RMS	root mean square statistic
S	radiation stress (wave momentum flux)
T	wave period
$\bar{V}$	mean longshore current
X	distance coordinate in the direction of wave propagation
a	wave amplitude
a_s	wave amplitude at the shoreline
c	wave celerity, or phase velocity
c_g	wave group velocity
g	acceleration of gravity
h	water depth
k	wavenumber (inverse of wavelength)
n	ratio of group velocity to celerity
m	ratio of infragravity swash height to offshore wave height
n	edge wave mode number
u	water particle velocity under waves
v	long-shore component of wave particle velocity
x	cross-shore position coordinate
y	long-shore position coordinate
z	vertical coordinate
β	beach slope
γ	ratio of wave height to local depth for breaking waves
η	sea surface elevation
θ	angle of incidence of waves relative to normal
ξ_0	Iribarren number
ρ	density of water
σ	radial frequency ($2\pi/T$)
φ	cross-shore structure function for edge waves
$\bar{\eta}_{\max}$	mean set-up at the shoreline
∇	gradient operator

WEDDELL SEA CIRCULATION

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Introduction

The Weddell Sea is an area of intense air–sea interaction and vertical exchange. The resulting cold water masses participate in the global thermohaline circulation as deep and bottom waters.

The large-scale horizontal circulation in the Weddell Sea is dominated by a cyclonic (clockwise) gyre conforming to the coastline and topographic features like midocean ridges and submarine escarpments. The flow is driven by both wind and thermohaline forcing. The meridional component at the eastern edge of the gyre transports upper ocean water from the Antarctic Circumpolar Current to the Antarctic Continent, where its density increases by ocean–ice–atmosphere interaction processes. Part of this newly formed water leaves the inner Weddell Sea northward and escapes through gaps and passages and thus ventilates the deep world ocean. Upwelling in the Antarctic Divergence and sinking plumes along the continental slope cause a large-scale overturning motion. Intermittently, open ocean deep convection might also play a role in deep water renewal. The observational database of direct current measurements is rather weak. Consequently, the most reliable basin-wide estimates of ocean currents are obtained from adequately validated numerical models.

Limits of the Weddell Sea

Geographically, the Weddell Sea is a southern embayment of the Atlantic Ocean, bounded to the west by the Antarctic Peninsula up to Joinville Island, to the east by Coats Land on the Antarctic Continent with the north-eastern limit at 73°25′S, 20°00′W, and to the south by the Filchner–Ronne Ice Shelf. In these limits it covers an area of 2 800 000 km^2.

From an oceanographic point of view, however, it is more adequate to consider the closed cyclonic circulation cell as one dynamically connected regime; hence the Weddell Sea is often considered as the area of the Weddell Gyre which extends eastward as far as 30°E or 40°E (**Figure 1**). Then, the Weddell Sea is bounded to the north by the South Scotia, the North Weddell and the Southwest Indian Ridges where the Weddell Front marks the transition from the water masses of the Weddell Gyre to the Antarctic Circumpolar Current. At the eastern boundary no obvious front separates the Weddell and the Circumpolar water masses which leaves the eastern boundary diffuse. Obviously, limits based on water mass properties and current branches are time dependent.

The Effect of Ice–Ocean Interaction on the Currents

Ocean currents are wind-driven and thermohaline-driven; the particular situation in the Weddell Sea is even more complex due to the presence of the seasonally variable sea ice belt. During the winter months, sea ice covers almost all of the Weddell Sea (exceptions are the occurrences of coastal or, less frequently, open ocean polynyas); during summer, only a relatively small area in the southwestern Weddell Sea remains ice covered.

The presence of sea ice affects the ocean currents both through the modification of the momentum transfer from the wind to the ocean and through

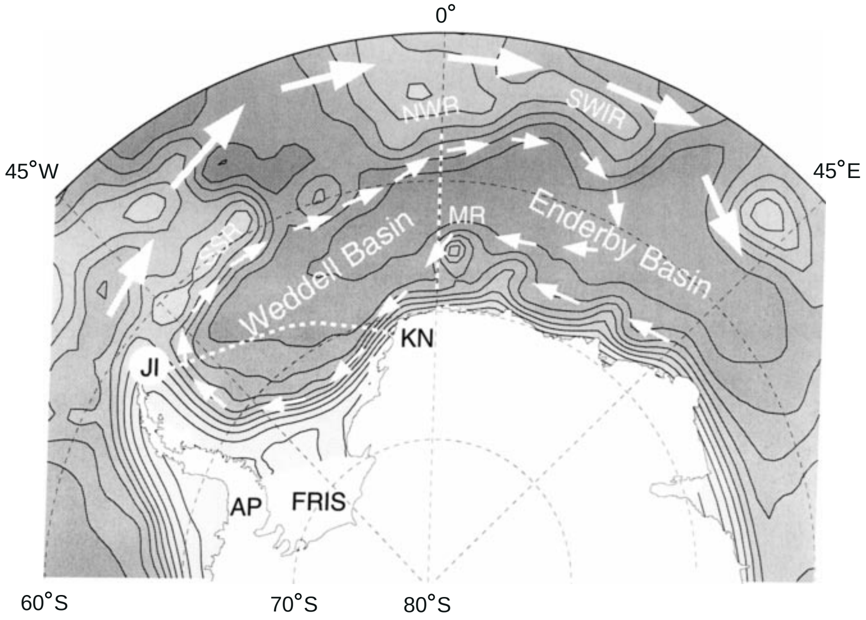

Figure 1 Schematic representation of the Weddell Gyre and the Antarctic Circumpolar Current in the Atlantic and Indian sectors of the Southern Ocean. The locations of the two transects with direct current measurements are indicated by lines. AP, Antarctic Peninsula; FRIS, Filchner–Ronne Ice Shelf; JI, Joinville Island; KN, Kapp Norvegia; MR, Maud Rise.

density changes caused by the salt gain during the freezing phase and the fresh water release during melting. In areas of stagnant sea ice the internal ice stresses balance the momentum supplied by the wind and the momentum input into the ocean is largely reduced; this situation is typical for the western Weddell Sea. The freeze and melt cycle of sea ice (and the corresponding freshwater fluxes) is an equally important component in the thermohaline forcing of the currents in the Weddell Sea; as freezing and melting regions are not identical, the sea ice drift with wind and ocean currents causes a net northward freshwater transport. This leads to a salt gain in the interior Weddell Sea and a freshwater gain at its northern boundary.

The Database on Ocean Currents in the Weddell Sea

The database to derive ocean currents in the Weddell Sea is small compared to other ocean areas. This is due to a number of reasons.

- The uninhabited Antarctic Continent does not require intensive shipping traffic and consequently no long-term records of ship observations are available.
- The sea ice cover restricts shipping traffic to selected areas and part of the year (austral summer).
- The sea ice does not move exactly with the surface ocean currents; consequently ice buoys or satellite-derived ice motion do not represent surface ocean currents.
- The weak stratification in polar and subpolar oceans implies a strong barotropic component of the currents. This restricts the reliability of current estimates by use of geostropic currents with unknown reference velocities or the geopotential anomaly (dynamic topography) with a fixed reference level.
- In large areas of the Weddell Sea the time-mean currents are relatively weak. They are therefore masked by high frequency motion (tides and inertial motion), especially when the period of observations is short.

Most of the current patterns in the Weddell Sea are derived indirectly either by tracking water mass properties or from the geopotential anomaly (dynamic topography) measurements. Water mass properties (**Figure 2**) give good qualitative results because water masses of circumpolar origin enter the Weddell Gyre in the north and the major modification areas are in the southern parts of the Weddell Sea. The modified water leaves the Weddell Sea to the north. However, the regional variations in the water mass characteristics do not allow quantitative estimates of current velocities and volume transport. Because of the strong barotropic component, the current pattern derived from water mass properties holds for most of the water column except for the bottom water plumes and the boundary layers.

In certain areas information on currents is available from moored instruments. They are concentrated on transects between Joinville Island and Kapp Norvegia, along the Greenwich Meridian and off the Filchner-Ronne Ice Shelf (**Figure 3**). The data allow to determine the horizontal and vertical structure of the currents on the basis of records which are at least several months long. However, moored instruments can not be used in the upper ocean layer due to the effect of sea ice and icebergs which might damage the moorings. In the eastern Weddell Gyre current information is available from ALACE floats drifting at approximately 750 m depth (**Figure 3**).

Information on the surface currents (i.e., within the Ekman layer) can be obtained indirectly, if wind and sea ice motion is known. For example, weather center (e.g., European Centre for Medium-Range Weather Forecasts (ECMWF), National Centers for Environmental Prediction (NCEP) surface winds are used to calculate sea ice drift. Differences in observed and calculated ice buoy drift are then attributed to the surface currents. Iceberg drift data can be included in this analysis.

Uncertainties in these estimates arise from the highly variable contribution of internal ice forces (ice pressure). Furthermore, buoy observations are rare and require extensive interpolation or extrapolation in both time and space. The resulting flow fields are rather smooth and do not contain much detail. Some improvement may be gained from satellite-derived sea ice drift.

As a direct consequence of the sparse observational data, the most consistent estimates of large-scale ocean currents in the Weddell Sea stem from numerical models, which have been validated rigorously against available observations. They extend into regions without observational data, include the upper ocean layers which are not accessible by moored instruments and cover time periods when no measurements are made. This is of particular interest because of the wide range of variability detected in the measurements.

Current state-of-the-art numerical tools to simulate the large-scale circulation and water mass structure in the ocean are coupled sea ice-ocean models, which are driven by atmospheric data sets from weather center analyses. They allow for ocean and

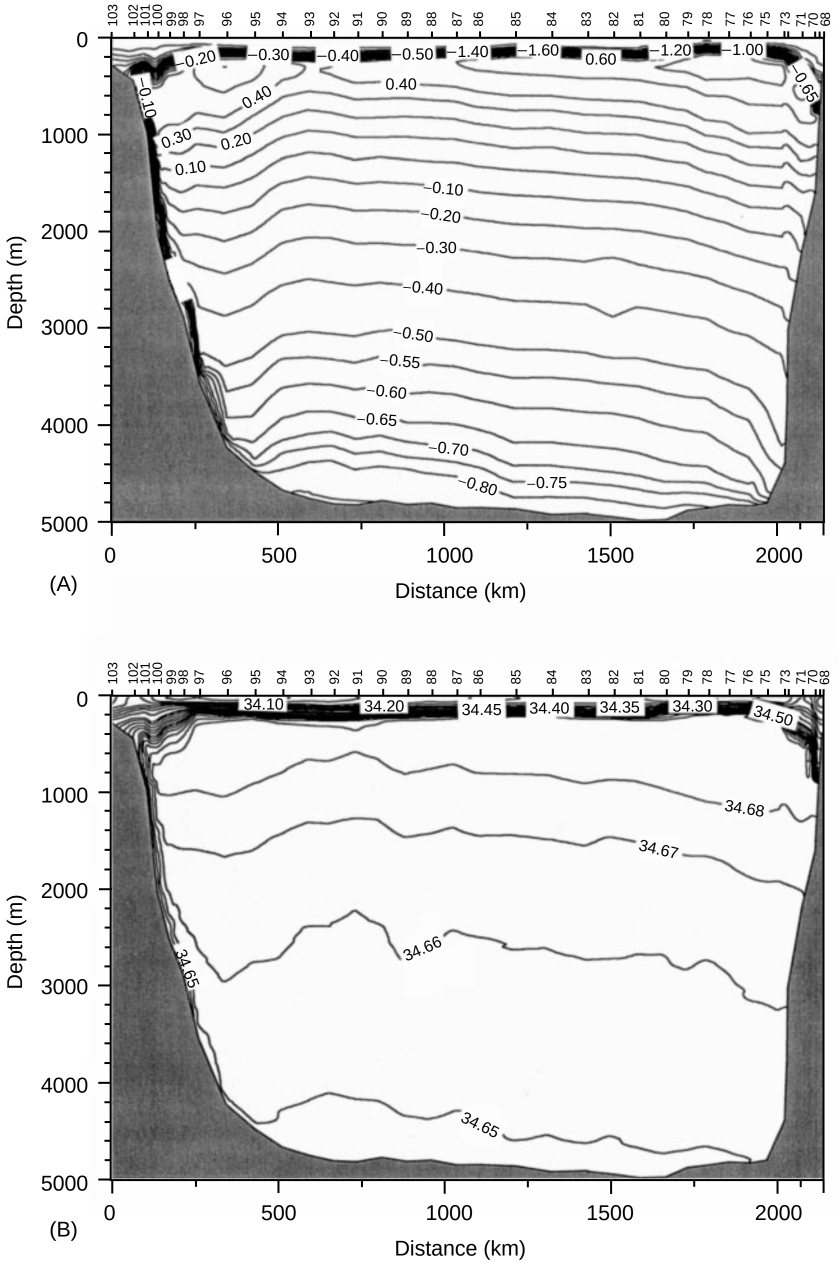

Figure 2 Distribution of the potential temperature (°C) (A) and salinity in PSU (B) on a vertical transect from the northern tip of the Antarctic Peninsula (left) to Kapp Norvegia (right) obtained with RV *Polarstern* in 1996.

ice dynamics and thermodynamics, as well as the feedback between both components of the climate system. Advanced models of the Weddell Sea also include the ice shelf cavities (Filchner–Ronne Ice Shelf, Larsen Ice Shelf and the ice shelves in the eastern Weddell Sea). The ocean component is based on the hydrostatic primitive equations. For an optimal representation of ocean dynamics in shallow shelf areas and over a sloping bottom a terrain-following vertical coordinate is useful. The sea ice component describes sea ice as a viscous-plastic medium. The model computes temperature, salinity, horizontal and vertical motion in the ocean as well as ice and snow thickness, and ice concentration. The horizontal resolution varies between 20 and 100 km horizontally and 10 and 400 m vertically. This excludes many details of coastline and topography but preserves the ability to capture the main features necessary to simulate the large-scale features. Multiyear integrations are carried out with these models and averaged in time to obtain a picture of the general circulation.

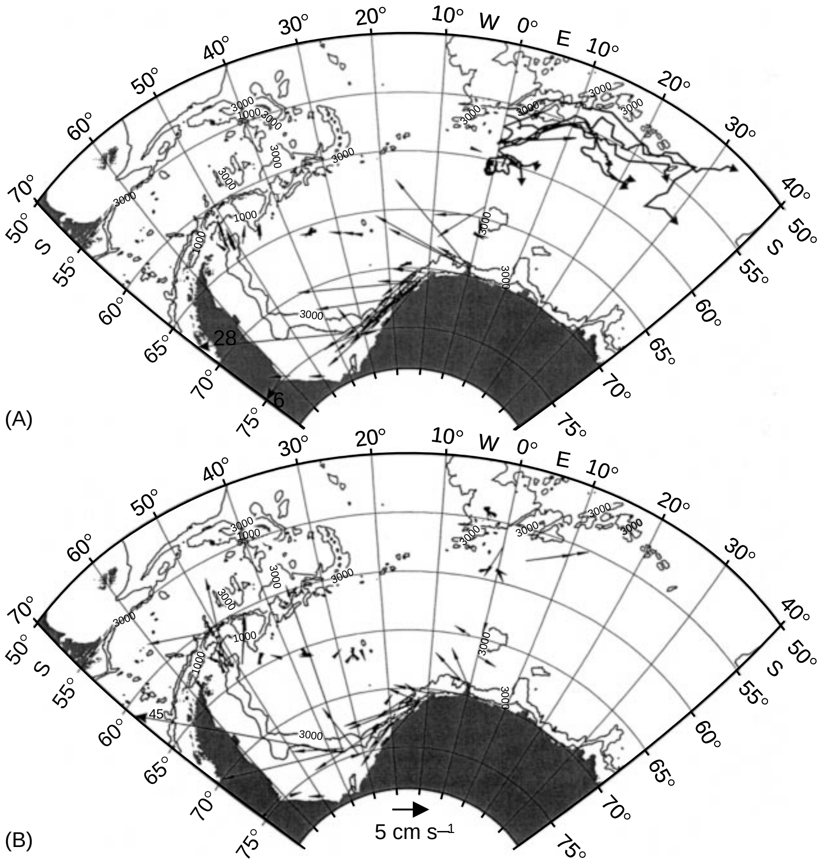

Figure 3 Ocean currents in the Weddell Sea obtained by direct measurements with recording periods between several months and two years. The currents in the upper ocean layer to a depth of 750 m (A) include data from moored instruments and subsurface floats. Those in the near bottom layer (B) include data up to 200 m from the bottom.

A validation of the coupled model system has to take into account oceanic transport estimates along selected sections (see **Figure 1**), satellite-based observations of the annual cycle of sea ice concentration, pointwise measurements of sea ice thickness and Lagrangian observations of sea ice drift. In all four categories, agreement within the limits of measurement uncertainty can be achieved.

A consistent picture of the three-dimensional ocean circulation in the Weddell Sea is obtained from multiyear simulations of the circumpolar ocean, using ECMWF atmospheric data for the late 1980s and early 1990s. The model indicates that the wind-driven and thermohaline components are of similar importance in forcing the barotropic flow.

The Structure of the Ocean Currents in the Weddell Sea

The dominant feature of the currents in the Weddell Sea is the cyclonic gyre. It appears clearly in the time-mean streamlines and barotropic currents (**Figure 4A**) of the numerical model. There is a pronounced double cell structure, caused by either the presence of Maud Rise, a seamount with its center at 65°S, 2°30′E or/and the inflow from the north of water of circumpolar origin at about 20°W. The volume transport across sections along the Greenwich Meridian amounts to 50 Sv. The transport across the section from the northern tip of the Antarctic Peninsula to Kapp Norvegia is 30 Sv (**Figure 1**). The velocities in the boundary currents are relatively high, up to 50 cm s^{-1} and in the interior almost stagnant conditions prevail (**Figure 3**).

The surface circulation in the eastern Weddell Gyre is characterized by the Antarctic Divergence, which divides the onshore flow south of 63°S from the predominantly equatorward flow to the north (**Figure 4B**). This pattern is disrupted in the western Weddell Sea, where the presence of the Antarctic Peninsula causes a generally northward flow. The observed sea ice drift patterns reflect both this

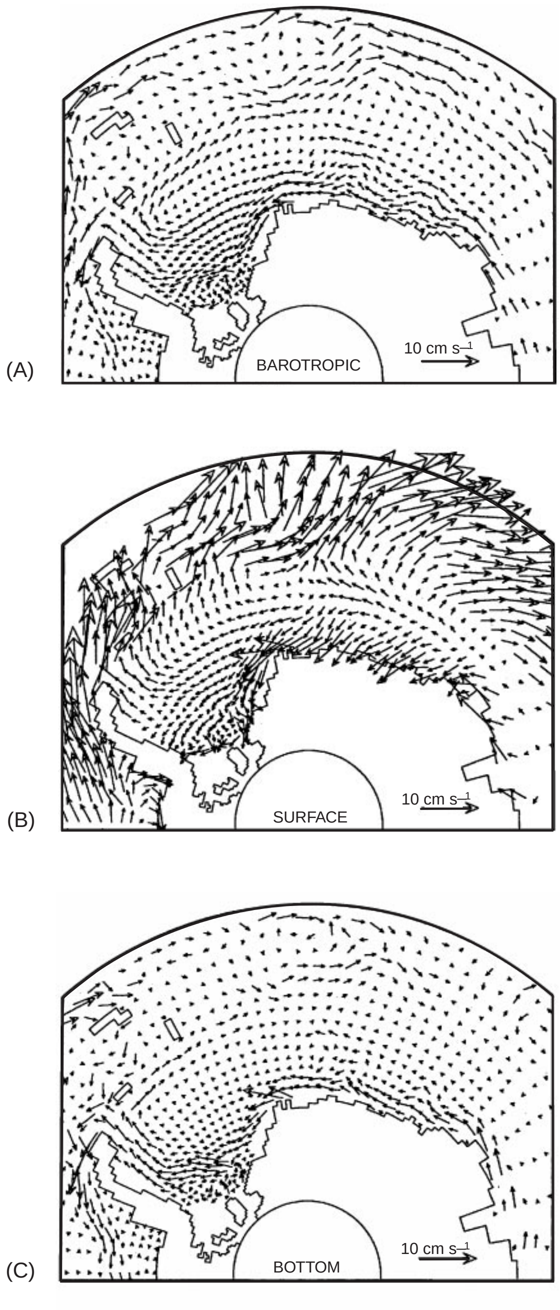

Figure 4 Annual mean current field in the Weddell Sea from a numerical simulation of the circumpolar ocean; (A) barotropic; (B) surface velocity vectors, and (C) bottom.

wind-driven surface velocity field, and the barotropic flow, through the sea surface inclination.

The wind-driven flow in the surface Ekman layer leads to coastal downwelling, with a corresponding offshore (downslope) component in the bottom boundary layer (**Figure 4C**). The near-bottom flow is clearly concentrated along the continental slope and numerical results suggest that part of it continues westward past the tip of the Antarctic Peninsula.

The best-known part of the ocean current system in the Weddell Sea is the Antarctic Coastal Current which follows the Antarctic coastline from the east to the west. It is partly driven by the persistent Antarctic east winds and partly by thermohaline forcing evidenced by the differences between shelf and open ocean water masses. The east winds force an onshore Ekman transport which is balanced by an upward sea level inclination towards the coast which leads to westward currents along the coast.

Its seaward extent is defined in various ways; either, it includes all westward flow between the coast and the center of the cyclonic gyre, or it is limited to the near-shore part including the 'shelf front' which is formed by differences between the water mass characteristics of the shelf waters and the open ocean surface layer. The near-shore water is seasonally highly variable and can be less or more saline than the open ocean water, depending on the relative importance of the melt water input from the continent and the salt release due to sea ice formation. Enhanced (vertical) mixing on the shelf also contributes to the horizontal water mass differences. The density gradient-related shelf front gives rise to a frontal jet. The frontal jet forms a local maximum of the coastal current.

The path of the coastal current roughly follows the depth contours, i.e., is mainly along-slope. It is mainly barotropic, but a baroclinic component is superimposed which causes a decrease of the flow with depth but in certain areas the flow is bottom-intensified.

The flow speed in the coastal current averaged over weekly or monthly periods ranges between 10 and 50 cm s^{-1}. The corresponding volume transport amounts to 10 to 15 Sv. In some areas, the current may separate into two (or more) quasiparallel branches. This is often triggered by the bottom topography, e.g., near Kapp Norvegia where a relatively flat plateau interrupts the continental slope at 1500–2500 m depth. Eventually, an undercurrent towards the east is found on the upper slope.

The core of the offshore branch of the coastal current (200–1500 m) transports warm deep water westward which originates from Circumpolar Deep Water (**Figure 2**). This warm and saline water mass can be used to trace the gyre flow along the coast. The westward-decreasing temperature and salinity anomaly reveals the exchange with the ambient water masses. In addition to the along-slope flow, cross-slope circulation cells transport modified warm deep water up the continental slope and on to the shelf, where it either loses its heat to the atmosphere or melts sea or shelf ice. The heat supply by warm deep water is the major heat source for shelf ice melt. In the open ocean it controls the sea ice thickness, because haline convection due to sea ice formation can bring the heat from the warm deep water into the surface mixed layer and control sea ice growth.

In the southern Weddell Sea where the shelf widens to several hundred kilometers the Antarctic Coastal Current splits into two branches; one follows the coastline onto the shelf and the other continues along the continental slope. Both branches join again at the Antarctic Peninsula.

The shelf areas in the southern and western Weddell Sea with a depth up to 500 m are the origin of downslope plumes of dense water. These water masses usually descend gradually down the slope as they follow the general along-slope path of the water masses of the coastal current. Alternatively, they may be guided directly downslope at topographical features like ridges or canyons. They form either Weddell Sea Deep Water by mixing with adjacent water masses or interleaving in intermediate depths, or Weddell Sea Bottom Water which mixes afterwards with the layers on top of it to form again Weddell Sea Deep Water, which fills most of the Weddell Basin.

The northward flow along the Antarctic Peninsula is relatively well studied. It ranges between 25 and 30 Sv whereas the transport of newly formed Weddell Sea Bottom Water amounts only to a few Sv.

At the tip of the Antarctic Peninsula, the Weddell Sea shelf waters are injected between those from the Antarctic Circumpolar Current and the Weddell Sea proper. By this process two fronts are formed: the Weddell Front in the south and the Scotia Front in the north which enclose the 'Weddell–Scotia Confluence' zone. Water masses from the Weddell–Scotia Confluence are dense enough to sink and to contribute to the renewal of the global oceans deep water. The location of the flow band is strongly controlled by bottom topography. Mixing and local atmosphere ocean exchange can cause further modifications.

The Weddell Front follows the North Weddell and the Southwest Indian Ridges to the east. The related northern current band follows those structures and is strongly affected by their irregularities which generate meridional perturbations of the zonal field. It is most likely that Circumpolar Deep Water enters the Weddell Gyre in such excursions and that Weddell Sea Deep Water leaves it. Horizontal structures in the Warm Deep Water core in the gyre suggest this exchange and affect the gyre structure. A separation into two adjacent subgyres, as indicated earlier, might be due to those intrusions.

The trapping of the gyre flow along the midocean ridge ends at the eastern edge of the Southwest Indian Ridge. There, the northern part of the gyre flow seems to split into an eddy field, consisting of cold eddies with water from the Weddell Gyre and warm eddies with a core of Circumpolar Deep Water. The eddies drift in the remnant flow field to the south-west and merge into the southern band of the gyre supplying the Warm Deep Water flow in the gyre.

Variability of the Circulation

Seasonal variations in the Weddell Sea circulation have been observed in the Antarctic Coastal Current, which reaches a maximum in the austral winter. A similar cycle is superimposed on the flow of bottom water in the north-western Weddell Sea. However, outside the boundary currents the seasonal cycle can only be derived from numerical model results and appears to be relatively small. The Weddell Gyre transport is larger in winter than in summer, due to stronger winds. Thermohaline effects on the large-scale circulation are not felt on a seasonal scale but on longer timescales.

This interannual variability is dominated by variations in sea ice cover and formation. Numerical studies indicate that the signal of the Antarctic Circumpolar Wave (with a typical period of four years) influences the whole Weddell Sea. A four-year periodicity can be detected, mainly in response to meridional wind stress anomalies; strong southerly winds in the western Weddell Sea lead to increased ice export causing more ice formation and deep water production during the following winter. With a time lag of about one year, this newly formed bottom water will begin to cross the South Scotia Ridge northward and spread into the global ocean.

Circulation fluctuations on longer timescales certainly exist, but they have not been investigated conclusively.

The Role of the Weddell Gyre in the Global Ocean Circulation

A significant part of the water mass transformation in the Southern Ocean occurs in the Weddell Sea. A census of the water colder than 0°C south of the Polar Front revealed that 66% of it was from Weddell Sea Bottom Water, 25% from Adélie Land Bottom Water and 7% from Ross Sea Bottom Water.

Whereas the quasi-zonal Antarctic Circumpolar Current system is a barrier for meridional exchange, the subpolar gyres in the Ross and Weddell Seas have sufficiently strong meridional flow components to allow for significant meridional heat and freshwater transports. The eastern branch of the cyclonic circulation of the Weddell Gyre advects water masses from the subantarctic water belt towards the Antarctic coast where intense atmosphere–ocean interaction will lead to a decrease in temperature and an increase in salinity.

This occurs mainly in coastal polynyas, induced by a strong offshore wind component with cold air from the continent. The irregular structure of the coastline forming capes and embayments leads regionally to offshore winds even if the large-scale directions of the winds is parallel to the coast. In the coastal polynyas the oceanic heat loss to the atmosphere can exceed $500\,\mathrm{W\,m^{-2}}$. The salt gain due to sea ice formation has to compensate the fresh water gain by glacial melt water from the continent and precipitation which had desalinated the previously upwelled Circumpolar Deep Water. The relative importance of melting icebergs as a regional enhancement of the freshwater gain is still unclear. If the salt release is strong enough, the density increases until the water sinks and forms bottom water directly by plumes sinking down the continental slope or by further cooling during the circulation under the ice shelves. Both forms of dense shelf water form plumes on the continental slope which either reach the bottom of the Weddell Basin or enter the open ocean at a depth level according to their own density by interleaving. Due to the nonlinearity of the equation of state of sea water, descending plumes can be formed or enhanced by the thermobaric effect.

Eventually the regime of the deep water renewal by plumes along the continental slopes can switch to deep open ocean convection. This was most likely happening during the 1970s when a large open ocean polynya was observed west of Maud Rise. The polynya and open ocean convection are in intensive interaction, because the heat loss due to open water in winter cools the water column sufficiently to form deep water whilst on the other hand, the normal supply of Warm Deep Water from deeper layers can maintain the polynya. The polynya formation could be caused by advection of warmer water from the north or by changing atmospheric forcing.

Weddell Sea Deep Water leaves the Weddell Sea to the north and represents the major cold source of water for the globally spreading bottom water. The water mass formation in the Weddell Sea, therefore, represents a major part of the global thermohaline overturning circulation. The combined effects of wind-induced downwelling and thermohaline driven sinking of dense water masses from the shelves of the inner Weddell Sea generate a large-scale overturning motion in the Southern Ocean. Circumpolar ice–ocean model simulations indicate maximum overturning transports of about 20 Sv, half of which originate in the Weddell Sea sector. At the same time, estimates from observations show that only a relatively small part (2–3 Sv) seems to be directly in contact with the surface, thus ventilating the deep ocean.

See also

Antarctic Circumpolar Current. Bottom Water Formation. Deep Convection. Ekman Transport and Pumping. General Circulation Models. Ice–Ocean Interaction. Non-rotating Gravity Currents. Open Ocean Convection. Polynyas. Rotating Gravity Currents. Sea Ice: Overview. Sub Ice-shelf Circulation and Processes. Thermohaline Circulation. Water Types and Water Masses.

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WET CHEMICAL ANALYZERS

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Introduction

Since the early 1960s there has been a requirement for seawater laboratories to carry out increasing numbers of routine analyses, many of which were performed by traditional manual methods. The performance of standard manual methods was generally variable due to human error and the efficiency was poor. Method automation has since enabled increased numbers of samples to be analyzed with improved efficiency and reduced the risk of human error. Air-segmented continuous flow analyzers (CFA) and flow injection analyzers (FIA) have handled the bulk of this automation. Instrument manufacturers have continued to improve both hardware and software over the years, which has resulted in better reliability and analytical performance.

Air-Segmented Continuous Flow Analyzers

These instruments are in widespread use for the determination of nutrient concentrations in natural waters. The technique is based on the fundamental principles developed in 1957 and converts a series of discrete samples into a continuous flowing carrier stream by a pumping system. Reagents are added by continuous pumping and merging of the sample carrier and reagent streams. The sample carrier stream is segmented with air before reagent addition, which typically allows between 20 and 80 samples to be processed in an hour. The insertion of standards in the sample carrier stream provides regular datum points during a particular analysis. There is usually no problem with distinguishing between the samples at the detection stage as the regular timing between stages is controlled. However, unless precautions are taken to prevent carryover, interaction can occur in a continuous system causing loss in discrimination between successive samples at the detection stage.

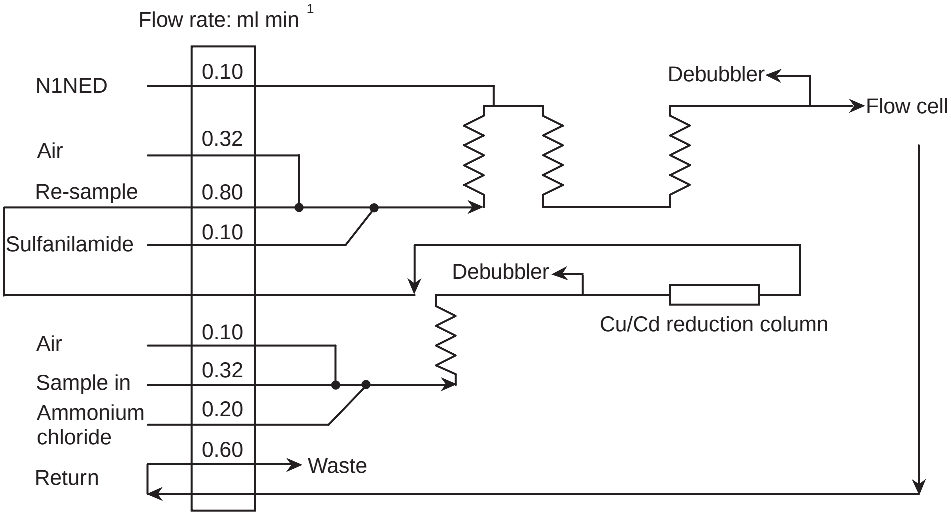

Figure 1 Schematic diagram of a typical air-segmented continuous flow analyzer manifold (for total oxidized nitrogen).