Note to readers:

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A knowledge of the key water masses and currents that affect New Zealand is invaluable to understanding near-shore and coastal processes, and the chemistry and biology of oceanic and coastal waters. This chapter introduces ocean circulation around New Zealand and discusses features and processes that are relevant to a broad understanding of the ocean and its impact on New Zealand. There is a brief introduction to the driving forces of oceanic circulation, followed by a short review of the geology and bathymetry of New Zealand waters. A synopsis of Antarctic and Pacific Ocean circulation patterns that affect the New Zealand ocean environment is discussed before the general and localised circulation is presented in some detail, with special attention given to unique features of New Zealand's ocean environment. The relevance of oceanic circulation to sedimentary processes, biological processes and ecosystem function (including fisheries) is discussed. Finally, the ability to detect spatial and temporal changes in ocean processes is reviewed in the context of climate change issues.

**Historical perspective**

In the early 1960s physical oceanographers relied upon the water bottle and reversing thermometers to measure the temperature and salinity characteristics of water masses (referred to as T–S characteristics). The main components of ocean currents were computed from water column profiles of temperature and salinity using geostrophic methods, where flows occur along isobars. At this time ocean circulation was thought to be a combination of a steady response to wind-induced pressure gradients in geostrophic balance with the Coriolis force, and thermohaline-driven mechanisms (density-driven convective forces). Advances over the last four decades have seen the development of recording current meters, satellite-tracked ocean drifters, fast-response ocean sensors, ocean acoustic instruments, satellite imagery (enabling the calculation of satellite-derived sea surface temperature—SST—and surface currents), and computer models able to generate simulations of oceanic circulation patterns. Immediate and fine-scale observations have revealed that, far from being a stable, predictable system, the oceans are intensely dynamic, much like the atmospheric weather system, with time and space scales that range from seconds to years, and millimetres to
kilometres. Physical oceanography has advanced such that the early-derived patterns of world oceanic circulation and water masses are now being continually updated.

**Driving forces of oceanic circulation**

The atmosphere and the ocean are strongly linked by an interplay of planetary, meteorological, and oceanographic processes with complex feedback loops. In order to understand global oceanic circulation, and for the purpose of modelling ocean processes, the ocean and atmosphere are frequently treated as a coupled system. The fundamental driving forces of ocean circulation are differential heating, convection, and wind stress. Surface currents are principally driven by atmospheric circulation and global wind patterns, and are primarily horizontal movements, while deep ocean currents are mainly driven by differential heating and convective processes, and often have a horizontal and a vertical component. The paths and intensity of both the surface and deep ocean currents are modified by the rotation of the Earth and by the morphology of the ocean basins.

Atmospheric circulation is principally caused by solar heating (resulting in transfer of momentum, heat, and mass) and is influenced by the rotation of the Earth (as described in Chapters 4 and 5). Energy is then transferred via the atmospheric wind system to the upper 100–200 m of the ocean through frictional coupling at the sea surface, resulting in similar pathways of the wind field and surface current system. The ocean, in turn, influences the atmosphere by its distribution of SST and ice coverage, and its effect on atmospheric moisture content and atmospheric stability. The ocean has the ability to absorb heat in one region and to restore it to the atmosphere, maybe decades or centuries later, in a different location.

Convergences and divergences of wind-driven surface currents result in the circulation of large bodies of water known as oceanic gyres. The dynamic response to the prevailing Southeast Trades at low latitudes (0–20°S) and southwesterlies at high latitudes is an anticyclonic rotation that is more intense on the western side, as first described by Stommel (1948). These anticyclonic gyres have fast, narrow, deep, and intense currents along the western boundaries, and slow, shallow, broad, and more diffuse currents in the interior. Western intensification, for example, results in the Gulf Stream in the North Atlantic, the Kuroshio Current in the North Pacific, and the East Australian Current in the South Pacific.

The vertical density-driven circulation of the deep ocean is referred to as a thermohaline circulation. Density changes in sea water result from changes in temperature and salinity, which are directly or indirectly related to solar radiation. Temperature variations are caused by fluxes of heat across the air–sea boundary, mixing, and advection, while changes in salinity result from evaporation, precipitation, and freezing and melting of ice. If surface water becomes denser than underlying water, instability arises and the denser surface water sinks, contributing to the thermohaline circulation. In simple terms, cold saline bottom waters form in the polar regions, fill the deep ocean basins, and flow towards lower latitudes. Eventually, the deeper waters upwell or diffuse at the equator, warming as they move towards the surface. The rising deep water
slowly mixes with the warm upper layer and eventually flows back towards the poles, where it is eventually cooled to form deep water again to complete the convection cell. The oceans thus carry heat from the tropics to polar latitudes and, at deeper levels, carry cold water from the poles to the equator. This process of heat transfer by the oceans has been described as the 'Great Ocean Conveyor Belt' (Broecker 1991), a concept that clearly demonstrates the importance of the location of New Zealand in terms of world oceanic circulation. New Zealand is located right in the path of one of the largest deep-water ocean currents, the Pacific Deep Western Boundary Current (DWBC), which moves northwards to fill the Pacific basin.

Surface and deep-water ocean currents are very dynamic features, often exhibiting large spatial and temporal variability and responding to a variety of influences such as meteorology (Sun's radiation, wind stress, heating and cooling, evaporation, and precipitation), tides, bathymetry, and land-ocean interactions. The mean motion of long-term large-scale current systems is sometimes considered the oceanic equivalent of 'climate'. Oceanic variability over shorter time scales has only been studied relatively recently and, under the same analogy, can be viewed as oceanic 'weather'.

It is outside the scope of this chapter to go into detailed specifics of the mechanisms and driving forces of oceanic circulation. For more information on these issues and general oceanic circulation patterns, the reader is advised to refer to basic oceanographic texts such as Gill (1982), Mann & Lazier (1996), Neumann & Pierson (1966), Open University Course Team (1989a, b), Pickard & Emery (1993), Pond & Pickard (1995), Tomczak & Godfrey (1994) and Warren & Wunsch (1987).

New Zealand: location, geology, and bathymetry

To understand the local circulation around New Zealand, one must first have an appreciation of the location, geology, and topography of New Zealand and its surrounding oceanic waters (see Chapter 2). New Zealand is particularly isolated, located in the southwest Pacific Ocean at approximately 41°S 174°E, with the nearest continental landmasses being Australia and Antarctica, at respective distances of 2000 and 2500 km (Figures 12.1 and 12.2). The country consists of two main islands situated on an isolated continental platform at the intersection of a series of moving tectonic plates along the Australian and Pacific crustal plate boundary (refer to Figure 2.18). To the north and east of the North Island the Pacific Plate is actively subducting beneath the Australian Plate at an annual rate of 40–50 mm. South and west of the South Island the Australian Plate is being subducted under the Pacific Plate at an annual rate of 30–40 mm. The collision of the two crustal plates causes strong deformation and seismic activity, producing a landscape that is scattered with faults, elevated land masses, scarps, and volcanoes, as described in Chapters 2 and 3. This landscape extends underwater to the seabed around New Zealand, which is marked by vast submarine plateaus, volcanic seamounts, submarine canyons, troughs, ridges, and highly irregular shelf slopes, all of which contribute to a complex regime of ocean currents and fronts.
The width of the continental shelf around New Zealand varies greatly and exerts a strong control on the resultant current flows around the islands. The total shelf area around New Zealand is 300,000 km², encompassing three extensive broadly sloping areas shallower than 200 m: Greater Cook Strait, the Canterbury Bight, and the Stewart Island region (Figure 12.3). In some areas the continental shelf is almost nonexistent, producing steep underwater scarps close to the coastline where the sea floor drops sharply to greater than 1000 m in less than 5 km distance offshore (e.g. off the west Fiordland coast). In other places submarine canyons extend well into the coastal zone (e.g. Kaikoura Canyon extends to within 2 km of the shore), and in many locations around New Zealand these canyons are thought to play an important role in the shelf-edge current dynamics (e.g. along the eastern section of Cook Strait, the Otago...
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Figure 12.3  Bathymetry of the New Zealand region. Contours are in metres. EEZ (dashed line) represents the extended economic zone of New Zealand. (After CANZ 1997)

cost, and the west coast of the South Island). The narrow aspect of much of the continental shelf and the numerous near-shore canyons means that there is great potential for oceanic water to influence the New Zealand coastal environment.
The bathymetry to the west of New Zealand is dominated by the Lord Howe Rise, which is 500–1500 m above the surrounding sea floor and begins as part of the broad continental shelf of New Zealand around 42°S then runs northwest to 20°S. Southwest of the Lord Howe Rise is the Tasman Basin, with abyssal depths of 4500–5000 m and comparatively smooth topography. Northeast of the rise a series of parallel troughs and ridges with elevations of 1000–2000 m give way to the 4000 m deep abyssal plain of the South Fiji Basin. East of this the active tectonic and volcanic activity of the Kermadec Arc has produced a complex series of parallel ridges alternating with deep oceanic troughs. The ridges are dotted with seamounts and frequently reach elevations of 1000–2000 m above the sea floor, while the Kermadec Trench drops to depths of 7000–8000 m. This ruggedly aligned topography acts as an effective barrier to near-surface (intermediate) and deep-water flows, greatly restricting the east-west interchange of waters between the Tasman Sea and the Pacific Ocean and steering the DWBC northwards (Warren et al. 1994).

East of the North Island the complex bathymetry of the Kermadec Arc gives way to Hikurangi Plateau, which is a 300–400 km wide block of thin continental crust or over-thickened oceanic crust at about 3500 m depth, and separated from the North Island by Hikurangi Trough. To the south of Hikurangi Plateau lies Chatham Rise, a broad continental crustal block that rises to 300 m water depth and protrudes about 1100 km into the southwest Pacific Ocean, acting as an effective barrier to northward transport of intermediate depth waters. Marking the southern edge of Chatham Rise is Bounty Trough, a 300 km wide depression from an ancient rift separating Chatham Rise and Campbell Plateau, and which spreads 1000 km eastward into the Southwest Pacific Basin. Campbell Plateau, at 500–1000 m depth, is a submerged block that extends the continental slope of the South Island nearly 1000 km offshore. The plateau itself has a relatively smooth topography, possessing the occasional volcanic seamount or volcanic island, while the margins of the plateau are particularly rugged and drop abruptly from 1000 m depth to 4500 m, forming the Subantarctic Slope into the Southwest Pacific Basin. West of Campbell Plateau, Macquarie Ridge represents an extension of the transform Alpine Fault with underwater relief ranging from 2000 to 3000 m and increasing to 5000 m off Macquarie Island. Macquarie Ridge constrains the path of the Antarctic Circumpolar Current (ACC) and the DWBC until they are deflected northeastwards around Campbell Plateau. Both Macquarie and Kermadec Ridges are underwater features exceeding the length of the New Zealand continent, and it is not surprising that both exert a strong influence on the deep-water circulation.

Water masses and circulation of the Antarctic and Pacific Oceans

New Zealand is located in the south of the Pacific Ocean and on the fringe of the Antarctic Ocean. The water masses and circulation of both these oceans have significant impacts on the flow of waters around the country.
The Antarctic Ocean

The Antarctic Ocean and its circulation has some unique features. It is the only region where water can flow around the globe uninterrupted and where there is communication with all other oceans (Figure 12.1). In addition, Antarctic waters exhibit small density variations with depth, and strong currents therefore extend to great depth rather than being restricted to the upper layers of the ocean. The Antarctic Ocean is also a major region of bottom-water formation.

Antarctic Bottom Water

In both the Weddell Sea and the Ross Sea, surface waters that are very saline due to sea-ice formation, cool, increase in density, and sink to form Antarctic Bottom Water (AABW) with a temperature of $-0.5^\circ$C and salinity of 34.7. During the sinking process the final properties of the AABW emerge during intense mixing with water from the ACC. Most of the AABW is formed in the Weddell Sea and enters the Pacific Ocean, travelling in an eastwards path around Antarctica. A small proportion of AABW, however, enters through Drake Passage via a depression in the South Scotia Ridge (Tomczak & Godfrey 1994). The major route of entry of AABW from the Ross Sea into the Southwest Pacific Basin is east of the New Zealand Plateau and Chatham Rise. AABW then subsequently travels eastward and northward into all oceans, and can be detected as bottom waters below 3000 m even in the Northern Hemisphere.

Antarctic Intermediate Water

Antarctic Intermediate Water (AAIW) is a major northward-spread ing water mass. It has T–S values of 3–7°C and 34.3–34.5, respectively, and is characterised by an intermediate depth salinity minimum (Deacon 1933, 1937; Wüst 1935) and, at or above this depth, a dissolved oxygen maximum (Wyrtki 1962). The core of AAIW lies near the surface, north of the Polar Front (PF), and deepens northwards to depths of 600–1500 m in mid latitudes. It can still be recognised as far north as the equator and beyond (Gordon 1975; Gordon & Molinelli 1986; Piola & Georgi 1982; Whitworth 1988). AAIW is most likely formed through a combination of mixing across the polar front and the subduction of deep winter mixed layer waters at the convergence of the PF (Gordon et al. 1977; Sverdrup 1940; Sverdrup et al. 1942) and by winter convective overturning of waters west of South America (England et al. 1993). Large-scale instabilities of the ACC are also thought to have a significant impact on the properties of AAIW (Joyce et al. 1981). The several theories as to the exact method and location of formation of AAIW are summarised by Piola and Georgi (1982). Movement of the AAIW in the Southwest Pacific Ocean is strongly influenced by topography. The position of New Zealand results in AAIW entering the Tasman Sea along two paths. AAIW with minimum salinity of less than 34.4 enters from the south, whereas a second source enters the Tasman Sea from the north and leaves via the Tasman Front (TF), an extension of the East Australian Current (EAC), along the northern tip of New Zealand.
Circumpolar Deep Water

Underlying AAIW below 1500 m is by far the most voluminous water mass in the Antarctic, the Circumpolar Deep Water (CDW). North Atlantic Deep Water (NADW) from the South Atlantic (temperature 2°C, salinity 35.0) becomes entrained in the ACC and mixes with AABW to form CDW. CDW is characterised by a salinity maximum of 34.7 at a depth of about 2800 m at 55°S, which deepens as it travels northwards to 3400 m at 28°S. This water mass is commonly subdivided into three main layers: lower CDW (LCDW), below 4000 m, which is a mixture of AABW and NADW; middle CDW (MCDW), occurring approximately between 2700 and 4000 m, where the salinity maximum occurs representing the NADW core; and upper CDW (UCDW), occurring approximately between 1500 and 2700 m, which has an oxygen minimum and T−S properties of 1.8–3.0°C, 34.5–34.7. UCDW appears to have a variable mixing history, not only incorporating NADW, AABW, and AAIW, but also mixing with subtropical Indian and Pacific deep waters (Charles & Fairbanks 1992; Oppo et al. 1990).

Circumpolar fronts and the Antarctic Circumpolar Current

There are three main circumpolar fronts in the Southern Ocean: the PF, the Subantarctic Front (SAF), and the Subtropical Front (STF) (Figure 12.1). The STF represents the northernmost demarcation of the Southern Ocean. Between the SAF and the PF lies the ACC, which is driven by the 50°S westerly windbelt and extends to the ocean bottom.

The ACC is the Earth’s only circumglobal current flowing eastwards unimpeded around Antarctica and has the largest mass transport of any ocean current. It has a transportation rate of about 130 x 10^6 m^3 s^-1 (Gordon 1975) with an average flow 400 times greater than the Mississippi River (Whitworth 1988). The current consists of two or more relatively narrow jets that run parallel to the mid-ocean ridge system that rings the Antarctic. The jets do not remain in fixed locations and appear to meander hundreds of kilometres north and south of the region marked ACC on Figure 12.1 (Whitworth 1988). In two places, to the east of South America and east of New Zealand, the flow of the ACC turns northwards, where it temporarily behaves as a boundary current before resuming its eastward path.

Most of the waters carried in the ACC do not acquire their T−S and chemical characteristics locally in the Southern Ocean but from waters formed in other parts of the world. For example, waters from the Arctic Ocean combine with Mediterranean Sea outflow and move south across the equator to form the major water mass of CDW in the ACC. Waters from within the ACC spread both northwards, to form bottom waters of the Pacific Ocean, and southwards, where they become the primary constituent of AABW within the Weddell Sea and Ross Sea Gyres (Whitworth 1988). Current rings and eddies frequently occur along the ACC and transport envelopes of Antarctic water to the north, or subantarctic water to the south, facilitating the exchange of waters with adjacent oceans.
The Pacific Ocean

The Pacific Ocean is the largest of all oceans, comprising 40% of the total surface area of the world ocean and covering the same area as the combined continental landmasses. The main surface currents of the Pacific Ocean are illustrated in Figure 12.2. New Zealand is situated in the western section of the South Pacific Subtropical Gyre, where western boundary currents occur along the coasts of Australia and the North Island of New Zealand, and the STF marks the southern edge of the gyre. In the western South Pacific Ocean the currents illustrated are for the period April–November, when the dominant winds are the trades. From December to March the region is influenced by the northwest monsoon and the following changes are observed: flow reverses along the Australian coast north of 18°S and along the New Guinea Coastal Current (NGCC), the Halmahera Eddy (HE) reverses direction, and the South Equatorial Current joins the North Equatorial Countercurrent east of the eddy.

Circulation in the western Pacific Ocean is very sluggish below 2000 m depth, and more than 1000 years has elapsed since the deep water was in contact with the atmosphere. AABW is slowly advected from the South Pacific, mixing with the water masses above it as it flows northwards producing deep water with uniform characteristics. Pacific Deep Water (PDW) has T–S characteristics of 1.1–2.2°C and 34.7, and lies about 1000–3000 m between AABW and AAIW. PDW is very similar in characteristics to 'oceanic common water' in the Indian Ocean. It results from the mixing of AABW, AAIW, and, in the vicinity of the Southern Ocean, the inclusion of remnants of NADW. As PDW spreads northwards and eastwards, the deep and bottom waters homogenise, showing a slight rise in temperature and decrease in salinity, and the NADW salinity maximum signal gradually disappears. For more information on individual current systems and water masses in the Pacific Ocean, the reader is referred to Pickard and Emery (1993) and Tomczak and Godfrey (1994). For more specific details of ocean circulation around New Zealand, Carter and McCave (1994), Heath (1985), and Neil (1997) are recommended.

Physical oceanography of New Zealand waters

Heath (1973, 1985) gave a comprehensive review of the progression of physical oceanography in New Zealand from the 1960s to the early 1980s. Heath’s collection of publications dating from 1968 to 1985 (see bibliography of Heath 1985) is an impressive database relating to the circulation of New Zealand waters. Publications of Roemmich and Sutton (1998), Stanton et al. (1997), and Whitworth et al. (1999) provide more up-to-date perspectives on aspects of New Zealand physical oceanography. In addition, the National Institute of Water and Atmospheric Research (NIWA) has recently compiled new charts of bathymetry, surface and abyssal flow regimes, and associated water masses around New Zealand (Figures 12.3–12.5) (Garlick et al. 1997, 1998). The new charts illustrate the relationship between ocean-floor topography and ocean currents, showing the spatial variability in positions of frontal systems and
Figure 12.4 The main surface currents, oceanic fronts, and water masses around New Zealand. The main currents around New Zealand are: Antarctic Circumpolar Current (ACC), East Auckland Current (EAUC), North Cape Eddy (NCE), East Cape Eddy (ECE), East Cape Current (ECC), Wairarapa Eddy (WE), Southland Current (SC), Southland Front (SF), Westland Current (WC), and D'Urville Current (DC). (After Carter et al. 1998)
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Figure 12.5 The abyssal circulation around New Zealand, including the Deep Western Boundary Current (DWBC) and deep parts of the Antarctic Circumpolar Current (ACC). (After Carter et al. 1998)
associated currents, and provide new details of current flow regimes. For a comprehensive summary of the features relating to these charts, the reader is referred to Garlick et al. (1998). The updated physical oceanographic features presented in the charts are compiled from a combination of physical oceanographic data, geological studies of the shelf and deep-sea bathymetry, satellite-derived sea surface temperatures, and output from a high-resolution global circulation model (GCM). Utilisation of the GCM enables a detailed picture of the circulation to be derived in areas or at times, where observations may be insufficient. The combined satellite images and observations show that the fronts and surface currents have a high degree of spatial and temporal variability and are extremely dynamic.

There are several factors that contribute to the dynamic and unique circulation in New Zealand waters: the strong winds of the Roaring Forties and higher latitudinal wind belts result in marked meteorological forcing of the circulation (Heath 1985; Hofmann 1985); New Zealand's highly variable submarine topography, which interacts with major current systems to produce general flow displacements, large-scale eddy fields, zonal jets, and boundary currents (Carter & McCave 1997; Gordon 1975; Morrow et al. 1992; Roemmich & Sutton 1998); the New Zealand microcontinent lies across three oceanic fronts separating waters with subtropical to polar characteristics; and inter-annual variability (e.g. El Niño and La Niña events).

### Oceanic fronts and water masses

Around New Zealand there are five main water masses, including two surface water masses: Subtropical Water (STW) and Subantarctic Water (SAW); and from the surface down, AAIW, CDW, and AABW. STW is characterised by high-salinity (35.7), nutrient-depleted, warm (temperature >15°C in summer) water sourced from the north. SAW is derived from the south of New Zealand and is cooler (temperature <14.5°C), fresher (salinity 34.5), and relatively nutrient-rich.

An oceanic front is a narrow region (50–100 km wide) of strong horizontal gradients of temperature and/or salinity that often marks the boundary between two distinct water masses. Vertical temperature and salinity gradients may also be very high, producing stratified waters within the front. The highly variable bathymetry around New Zealand has a strong influence on current pathways and the location of oceanic fronts, with the result that New Zealand is positioned in an extremely dynamic oceanographic environment. There are four main oceanographic fronts that influence the physical and biological oceanography of New Zealand. Moving from south to north, these are the PF, the SAF, the STF, and the TF. East of New Zealand is a locally significant feature, the Southland Front.

#### Polar Front

The PF (formerly called the Antarctic Convergence) is identified by a rapid change in surface temperature. Located around 62°S and 170°E (Figure 12.1), the PF marks the junction between cold surface water from the Antarctic and Circumpolar Surface
Water (CSW). It is a zone of convergence where the deep winter mixed layer becomes capped by surface waters and subducts to form AAIW.

**Subantarctic Front**

The SAF separates SAW and CSW and marks the northernmost limit of the ACC (Figures 12.1 and 12.4). The location of the SAF is strongly influenced by Macquarie Ridge and Campbell Plateau (Burling 1961; Gordon 1975), and interactions with these features produce large-scale meanders and deep eddies (Morrow et al. 1992). These eddies progress northeast along the flanks of Campbell Plateau and, combined with the main ACC-DWBC flow, produce significant scouring of the plateau margin (Carter & McCave 1997; Gordon 1975). The SAF passes through gaps to the north and south of Macquarie Island and around the southern tip of Macquarie Ridge, and then follows the Subantarctic Slope off the southeast of New Zealand. From there it moves eastwards and branches into two paths around 46°S and 51°S to continue its passage around the globe (Bryden & Heath 1985; Carter & Wilkin 1999; Orsi et al. 1995).

**Subtropical Front**

The STF (sometimes also referred to as the Subtropical Convergence) defines the northern limit of the Southern Ocean. It is a highly energetic ocean front and a major circumpolar ocean boundary that separates warm, high-salinity STW to the north, and cold, fresher SAW to the south (Chiswell 1994a, b; Heath 1981; Stramma et al. 1995). Figures 12.1 and 12.4 illustrate the location of the STF, which follows approximately the 15°C and 10°C surface isotherms in summer and winter, respectively, and the 34.7-34.8 surface salinity isohaline (Garner 1959). It can be traced both to the west and east of New Zealand (Burling 1961; Heath 1972; Jillett 1969). To the west of New Zealand the STF occurs around 45°S. As it passes south of New Zealand it follows the upper continental slope around the southeastern coastline of the South Island and, just south of Kaikoura, is known as the Southland Front, marking the boundary between the warm saline STW of the Southland Current and SAW (Burling 1961; Chiswell 1996; Heath 1985). At this point SAW is entrained over the upper slope and STW onto the continental shelf. The Southland Front continues northeastwards until reaching the Chatham Rise, where once again it is referred to as the Subtropical Front. From here the STF moves eastwards, closely following the bathymetry of the southern flank of the rise around 44°S before becoming broader and extending further south to 47°S close to the SAF (Gordon & Molinelli 1986; Uddstrom & Oien, 1999). Along the Chatham Rise the STF has been shown to be a complex and irregular front comprising large meanders and eddies with associated upwelling (Chiswell 1994b; Vincent et al. 1991). Jeffrey (1986) and Stanton and Ridgeway (1988) identified an additional front north of the STC to the west of New Zealand between 40 and 42°S and 152 and 160°E. This front lies within the STW mass near Tasmania, where STW from the EAC system meets SAW from south of Australia. Jeffrey (1986) considered the front to be a wind-derived feature, while Stanton and Ridgeway (1988) suggested the front may be associated with old East Australian Current (EAC) eddies.
Tasman Front
The TF occurs in the north Tasman Sea between 30 and 35°S and was first described by Stanton (1976) and Denham and Crook (1976), and later discussed by Andrews et al. (1980), Stanton (1981), and Stramma et al. (1995). The front marks a meandering zonal jet originating in the outflow from the EAC, and links the EAC to the other western boundary currents in the Pacific Subtropical Gyre (Stanton 1981). The front is the result of geostrophic motion and is a dynamic feature rather than a water mass boundary. Meanders and other disturbances in the thermocline develop along the front because of the variability in the EAC system and the irregular underwater topography of the north Tasman Sea. The TF loses some of its definition over the topographic highs of the ridge system and interacts with the Lord Howe Rise and the Norfolk Ridge (Uddstrom & Oien, 1999). The meanders and consequent disturbances produce westward-travelling waves that separate from the main eastward-flowing current forming eddies along the East Australian coast. These eddies are generally long-lived and are characteristic of the upper 500 m of the Tasman Sea. Remnants of them, in the form of subsurface layers of uniform temperature and salinity, are abundant south of the TF (Tomczak & Godfrey 1994). There is some evidence from SST satellite imagery that a component of the TF flows down the west coast of the North Island, possibly as the West Auckland Current, and that on the shoreward side of this current a northward flow (or upwelling) is indicated (Uddstrom & Oien, 1999).

Currents
One of the main reasons for New Zealand’s varied oceanographic environment is that it is a large system, isolated from other continental landmasses situated in the main flow of global oceanic current systems (Figures 12.1 and 12.2). There are three main current systems affecting the circulation of New Zealand waters which have a mean west to east zonal flow (Figure 12.2). Two of these are surface currents: the western boundary current of the South Pacific Subtropical Gyre, and the ACC; and the third is the deep-water Pacific DWBC (Figure 12.5).

Surface circulation
The South Pacific Subtropical Gyre is a vast anticlockwise movement of relatively warm water around the Pacific. The water within the gyre moves south down the eastern margin of Australia and then travels eastwards towards New Zealand for several months as an extension of the EAC within the TF (Heath 1980; Stanton 1976; Stanton et al. 1997) (Figure 12.2). The circulation in northern New Zealand is dominated by the extension of the EAC on the TF, which is a highly energetic, variable, and meandering flow transporting STW (temperature 18–20°C, salinity ~35.7) eastwards across the Tasman Sea to New Zealand at around 32°S (Cresswell 1987; Sharples 1997; Stanton 1981). Anticyclonic eddies with diameters of about 250 km are a permanent feature of the EAC (Hamon 1970), and individual eddies may exist for up to
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a year and intermittantly drift south (Cresswell & Golding 1979). On reaching New Zealand the extension of the EAC splits into three main flows: a continuation of the eastward flow across the Pacific, a smaller flow down the western coastline of the North Island, and a large flow down the eastern side of the North Island, which becomes the East Auckland Current (EAUC). Current speeds in the EAUC are typically 15–30 cm s⁻¹ (Booth 1974; Bradshaw et al. 1991; Brodie 1960; Denham et al. 1984). The strength and position of the current is highly variable (Roemmich & Sutton 1998; Stanton et al. 1997). It is likely that the presence of the continental platform of New Zealand may determine the separation point of the EAUC. Three semi-permanent eddies—the Northland Eddy, Bay of Plenty Eddy, and Wairarapa Eddy—occur offshore of the EAUC and are part of the complex eddy field between the two eastward flowing branches of the EAUC (Greig & Gilmour 1992; Roemmich & Sutton 1998). Beyond 38°S, part of the EAUC becomes the East Cape Current (ECC), which continues south to join the STF in an eastward flow.

The warm, saline initially STW of the Southland Current (SC) flows eastwards through Foveaux Strait and south of Stewart Island before turning northwards along the east coast of the South Island continental slope, mixing with cool, low-salinity SAW north of Banks Peninsula (Burting 1961; Heath 1972; Jillet 1969). On meeting Chatham Rise the current splits, with part of it flowing east along the southern flank of the rise and part flowing through the Mernoo Saddle crossing the rise. North of the saddle the SC splits again into a northward flow along the continental slope (which continues along the east coast of the North Island) and an eastward flow along the northern flank of the Chatham Rise. Both of these flows eventually merge with the ECC along the east coast of the North Island. There is also a small offshoot from the northward flow that enters the southwestern side of Cook Strait near Cape Campbell. The strength of the SC appears to be quite variable along its length and its various offshoots. North of Kaikoura the current strength depends on the amount of water that turns eastward, and further north, along the east coast of the North Island, it is dependent on the relative strength of the currents exiting from Cook Strait (Heath 1972).

The wind-driven ACC dominates the circulation to the south of New Zealand transporting SAW, Antarctic Surface Waters, and Deep Circumpolar Waters into the region (Gordon 1975; Whitworth 1988). The ACC passes through and around Macquarie Ridge before being steered northeastward by the steep flanks of Campbell Plateau along the Subantarctic Slope to the eastern end of Bounty Trough. At this point the northernmost jet of the ACC is associated with the SAF, which veers eastward to traverse the Pacific. Eddies within the ACC are frequent east of the Scotia Ridge and in the region of Macquarie Ridge. The northward movement of cold eddies within the ACC is compensated by the southward movement of warmer water and represents a net flux of heat towards the South Pole (Tomczak & Godfrey 1994).

Deep Water Circulation

The Pacific DWBC is the main inflow of deep water into the Pacific Ocean, with an estimated volume transport to the north of 20 x 10⁶ m³ s⁻¹ (Warren 1973, Warren & Wunsch 1987) and is one of the largest deep water flows. A sill at 2850 m in the north of the Tasman Basin prevents the passage of the Pacific DWBC northward through
the basin, and because of this the effective western boundary for the deep South Pacific is not Australia, but New Zealand and the Tonga–Kermadec Ridge (Warren & Wunsch 1987). A salinity maximum within the DWBC represents the last traces of NADW that has been carried eastward around Antarctica in the ACC and northward within the CDW into the Pacific (Warren 1973). The deep-water circulation of New Zealand is thus dominated by the northward flow of the Pacific DWBC, which transports deep Antarctic waters to the eastern margin of the New Zealand microcontinent and then onward through the Valerie Passage between Chatham Rise and Louisville Seamount Chain (Carter & McCave 1994) into the central Pacific Ocean (Figure 12.5). New Zealand is unique in that it is the only major region of continental shelf that intercepts a western boundary current in midocean (Sharples 1998).

As the DWBC moves to the east of New Zealand, it encounters the steep topography of Macquarie Ridge and Campbell Plateau and comes into contact with the shallower ACC, which serves to reinforce and modify its flow (Carter & McCave 1994, 1997). The combined flows of the ACC and the DWBC move northeastwards along Macquarie Ridge and the Subantarctic Slope to about 56°S, where the SAF diverges to the east. Two offshoots of the ACC depart eastwards, at about 56°S and 50°S, at the SAF and rejoin each other further east in the Pacific, while the DWBC continues its northward journey. The ACC departure from the main flow of the DWBC reduces the velocity of the deep-water current, and further north within the Bounty Trough where the bathymetry shallows, the DWBC spreads and slows down. Here, and further north, as the current flows northwestward from the Chatham Rise towards the Kermadec Trench, the DBWC may be up to 1000 km wide and has the largest volume transport of any boundary current. Once it reaches the steep sides of the Kermadec Ridge the current narrows and intensifies. The Pacific DWBC exerts an extremely strong influence on the global heat-transfer system and ocean/climate change (Warren 1973, Warren & Wunsch 1987).

**Sediment transport and deposition**

An understanding of bottom current movements and wave action is critical to predicting and monitoring the movement and deposition of sediments. The type and quantity of sediment moved and the direction of movement will depend on factors such as the shelf and break slope, coastline configuration, estuarine or riverine inputs, the energy of waves, the tidal range, and tidal current movements and their direction of motion. In near-shore areas, waves and currents, particularly under wind-storm forcing, often act together to enhance sediment transport, with the waves lifting sediment into suspension, which is then transported by currents. Understanding sediment transport and deposition can have a significant economic and political impact, since this information is critical to many organisations, including harbour authorities, city and regional councils, the tourist industry, shipping traffic, the fishing industry, and, in particular, the marine construction industry (see also Chapter 16).

Large-scale and often sudden underwater movements of large amounts of sediment are known to occur around the coast of New Zealand. Such features are termed
'turbidity currents' and represent sporadic deep-ocean flows of water that are extremely heavily laden with suspended sediment. They occur either as a result of the direct discharge of sediment-laden rivers into the ocean, or are due to terrestrial or submarine slides caused by wave action or earth movements where large amounts of sediment are rapidly transported offshore. They are particularly prevalent in New Zealand waters, where conditions for their formation are ideal, owing to high levels of seismic activity and the fact that the rapidly uplifting hinterland increases the riverine input of sediments to the continental margin (Carter 1975; Griffiths & Glasby 1985). Eastern and southern New Zealand account for about 1% of the sediment input to the world’s oceans. The main pathways of turbidity currents around New Zealand are marked on Figure 12.5, which shows the prevalence of these submarine features. Once turbidity currents find a submarine trough or channel, they may flow for distances up to 1000–1400 km before finally fanning out on the abyssal ocean floor (Carter et al. 1996; Lewis 1994). These sedimentological events, and any rapid changes in seabed morphology as a direct result of seismic activity, can have a marked effect on the continental margin, affecting potential current circulation speeds and patterns.

The impact of ocean circulation on biological processes

Large-scale and local ocean circulations have a profound effect on ocean chemistry, biological systems, and ecosystem dynamics in New Zealand’s marine environment, and just a few examples will be presented here. For instance, upwelling of deep water enriched in nutrients can encourage high levels of primary production and allow complex food webs and ecosystems to be supported. Upwelling, both wind-driven and forced by shelf-edge currents, is a common feature of much of New Zealand’s coastline. For example, the Farewell Front is a response to bottom friction-induced upwelling driven by the northward flowing Westland Current and reinforced by westerly winds and the curvature of the Cape Farewell coastline (Stanton 1971). These upwelled nutrient-rich waters along the Farewell Front support an economically important squid fishery to the west of Cook Strait.

The STF represents the boundary between warm, saline, nutrient-poor STW and cool, less saline, nutrient-rich, low-chlorophyll SAW. Although the SAW is rich in macronutrients, it is low in iron, an essential micronutrient for phytoplankton growth, and is therefore relatively unproductive water. In contrast, the STW north of the front, tends to be higher in iron at all times. Nitrate levels in the STW are high enough to support a spring bloom, after which exhausted nitrate levels limit further production. Within the STF both nitrate and iron have intermediate concentrations between the STW and SAW, and phytoplankton thrive in waters that are highly stratified with steep nutrient gradients. In the winter and spring the STF over Chatham Rise has higher plankton and net biological production throughout the food web, compared with the open-ocean STW or SAW (Bradford-Grieve et al. 1997, 1999). Chatham Rise also supports an important nursery for hoki (Macruronus novaezelandiae) and is a major deep-water fishery. The transport of nutrients across the front is presumed to be an important factor in determining the total biological production.
The higher levels of production in the STF can produce increased sedimentation rates of organic matter, and hence carbon export, from the surface waters to the deep ocean. Measurements of the partial pressure of CO$_2$ in surface waters show that the STF to the east of New Zealand acts as a sink for atmospheric CO$_2$, owing to the enhanced biological activity in the front (Curry & Hunter, 1998). It is possible that the STF is a major Southern Hemisphere sink for atmospheric CO$_2$ in the ocean, and that it may have an important role in the global carbon cycle. It is clear that oceanic fronts can have a large impact on ocean biology and geochemistry.

Along the northeast coast of New Zealand during late spring and summer it has been observed that a combination of southeasterly winds driving warm STW from the EAUC towards the coast and strong thermal stratification of the water can produce cross-shelf exchange of coastal and oceanic waters (Sharples 1997; Sharples et al. 1998). During these conditions intrusions of warmer, more saline oceanic water move onto and across the Hauraki Gulf Shelf and mix with the shelf waters. These oceanic intrusions fluctuate in intensity both seasonally and annually, and have the potential to introduce alien oceanic species into near-shore waters. For example, subtropical oceanic toxic phytoplankton blooms in 1993–94 produced shellfish poisoning (Chang et al. 1995), and oceanic salps have also been introduced into the Hauraki Gulf (Zeldis et al. 1995). The oceanic intrusions may also be responsible for variations in the recruitment of fish species in the Hauraki Gulf, owing to the sporadic introduction of waters carrying fish larvae (Francis & Evans 1992; Kingsford 1989). Toxic algal blooms may not occur every year that oceanic intrusions are noted. Over four years the timing of the intrusions has varied from late November to early January (Sharples et al. 1998), and it seems that the introduction of alien species is dependent on the characteristics and constituents of the oceanic water at the time of the intrusion. It is possible that nutrient and hence phytoplankton characteristics of the oceanic water could change from year to year in relation to fluctuations in the ocean–atmosphere system. A knowledge and prediction of intrusion timing and the biology and chemistry of the oceanic waters is critical to understanding changing biological processes in the near-shore waters and is important for the commercial viability of local fisheries.

**Climate change**

The upper 2.5 m depth of surface ocean water has the same heat capacity as the entire depth of the atmosphere (Gill 1982). This means that the oceans have a large capacity to act as a damping mechanism for rapid fluctuations in climate. Conversely, much of the long-term variability in climate may be related to the ocean as it slowly releases heat stored from earlier rapid climate changes (Tomczak & Godfrey 1994). Over the last 20 years there has been an increased effort in the study of inter-annual and climate-scale changes in the ocean, which has been recently accelerated by the issue of potential global warming because of increased atmospheric greenhouse gas concentrations (IPCC Working Group 1 1990). It is not only important to understand the atmosphere’s role in ocean circulation, but it is becoming increasingly important to understand the role of the oceans in moderating climate and climate change. The large
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Advection of heat by the oceans appears to have a strong influence on New Zealand’s climate, either equal to or greater than the role of the atmosphere on inter-annual to decadal time scales (Sutton 1996). Two aspects of particular importance in New Zealand are: the El Niño Southern Oscillation (ENSO), the effects of which are felt particularly strongly in the South Pacific; and the fact that the maritime influence on New Zealand is very strong, owing to a higher surface area of ocean compared to land in the Southern Hemisphere than in the Northern. This means that the effects of global warming in the two hemispheres may be markedly different, as indicated by coupled ocean–atmosphere models (Bryan et al. 1988).

El Niño manifests itself in fluctuations of rainfall, winds, ocean currents, and SST in the tropical oceans, in particular the Pacific Ocean. The phenomenon occurs because of a disruption of the ocean–atmosphere system in the tropical Pacific, and was first noted off the coast of Peru when periodic influxes of warm tropical water suppressed the upwelling of cold water and nutrients, ruining the local anchovy (Engraulis mordax) fishery. Fluctuations of the barometric pressure difference between the east and west sides of the South Pacific Ocean are associated with El Niño, which occurs when pressure is higher than average over Indonesia and lower than average near Easter Island. El Niño appears as an anomalous warming in the equatorial Pacific, associated with reversals of the general trade wind pattern (i.e. weakened Southeast Trade Winds with stronger westerlies to the south). La Niña occurs when there are stronger Southeast Trades (and weaker westerlies to the south), with resulting cool water (<25°C) extending much further westward along the equator than usual. The effects on New Zealand’s climate are discussed further in Chapter 8.

New Zealand’s position in the southwest Pacific Ocean means that it is significantly influenced by the ENSO phenomenon. However, there are only a few long-term coherent data sets with which to assess the detailed response of New Zealand shelf waters to El Niño events. Since El Niño events have a quasi-periodicity of four years, observations need to span decades in order to observe features related to El Niño. From a long-term data set of monthly mean temperatures from Leigh and Portobello marine laboratories, Greig et al. (1988) were able to make some deductions. They showed that the warmer SST in the central and eastern tropical Pacific that are associated with El Niño years are accompanied by lower SST throughout New Zealand coastal waters. This is likely to be caused by a combination of, first, a stronger southerly component in the prevailing winds introducing a cooling effect (Gordon 1986), and second, an El Niño-related reduction in tropical waters to the Australasian region inducing large-scale upwelling from deep waters. These combined processes not only reduce SST but also have the potential to increase surface nutrients in New Zealand waters during El Niño years.

SST exhibits an almost instantaneous response to the SOI. Recent information from the NIWA satellite-derived SST archive (1993–present) and hydrographic observations indicate that the Tasman Sea was in a warming phase between December 1996 and April 1998 (Kidson & Uddstrom 1998, Uddstrom & Oien 1999). This is in contradiction of the expected negative value for the 1997–98 El Niño SST anomaly in the New Zealand region as observed by Greig et al. (1988). It illustrates the variability and complexity of the ENSO phenomenon, and the problems associated with
predicting oceanic responses to the cyclic event. It is clear that the use of a variety of monitoring techniques may be advisable to derive short-term and long-term changes. It is also essential when investigating low-frequency variability to aim for a long-term time series upward of 10 years.

Since 1986 a time-series record of subsurface sea temperatures down to 800 m in a transect between Auckland and Suva has been collected, which promises to provide valuable long-term deeper water temperature variations, particularly in the EAUC (Sutton 1996). Already, El Niño events in 1987 and 1992–93 have been identified by cooler water temperatures penetrating to deeper than 100 m. Cooler winters for 1992–93 are also indicated by a 1.5°C drop in surface water temperatures compared with La Niña years.

Sea-level changes have also been observed at inter-annual scales in relation to the ENSO, with a lag of up to nine months between the SOI and the monthly mean sea level anomaly (Bell & Goring 1996). Sea-level measurements at Moturiki (Mt Maunganui) from 1973 and Port of Auckland from 1947 show that El Niño years produce a drop in sea level of up to 10–12 cm, while a similar rise occurs during La Niña episodes (Bell & Goring 1997; Goring & Bell 1999). Interestingly, these response patterns are similar to those in the equatorial western Pacific (although fluctuations are smaller in New Zealand), despite there being no simple teleconnection between the two zones. The recent introduction of satellite radar altimetry, which provides an accurate estimate of the height of the sea surface compared with a reference level, and a new NIWA network of 10 open-coast sea-level gauges will considerably widen the temporal and spatial scope of sea-level change measurements and interpretations in relation to ENSO events.

It is encouraging that there appears to be a coherent relationship between spatial patterns in SST and deeper oceanographic features. SST data have the potential to put hydrographic data in context and, in addition, to spatially and temporally extend deductions made from those data (Uddstrom & Oien, 1999). The availability of SST satellite imagery composite maps, the introduction of satellite radar altimetry, the increasing deployment of long-term current recorders and meteorological buoys, and the availability of continually improving technology will enhance the study of ocean variability and enable features to be more accurately monitored on daily to inter-annual time scales. As the time frame of data-base collection increases, more detailed and accurate pictures of variations can be built up, thus facilitating a greater understanding of the ocean's role in driving inter-annual to decadal variability and global change events.

**Summary**

This chapter has provided an overview of the driving forces of oceanic circulation, and then discussed local circulation around New Zealand. Background on the location, geology, and topography of New Zealand led to a discussion of water masses and circulation of the Antarctic and Pacific Oceans. The factors that contribute to New Zealand's dynamic and unique circulation include the strong winds of the Roaring
Forties, highly variable submarine topography, the location of New Zealand across three oceanic fronts separating waters with subtropical to polar characteristics, and inter-annual variability such as El Niño and La Niña events. The currents around New Zealand were discussed in some detail, including consideration of surface and deep-water circulation. The impact of these circulations on both sediment transport and deposition, and biological processes was then considered. Finally this chapter discussed the relationships between oceans and climate change, and related the increased understanding of atmosphere–ocean interactions resulting from advances in technology.

Further reading