Chapter 4

Physical oceanography

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"The *Nansen* played an important role in describing the physical oceanographic processes of the Western Indian Ocean – often from a perspective of how they would affect fish distribution and abundance patterns."

Abstract

Data on the physical properties (water temperature, salinity and oxygen profiles, fluorescence) and ocean processes (ocean circulation, heat transfer, upwelling, riverine outflow) have been collected since the early RV *Dr Fridtjof Nansen* surveys in the Western Indian Ocean. These physical processes influence ocean productivity on spatial and temporal scales, and thus determine the distribution and abundance of fisheries resources. *Nansen* surveys between 1975 and 1990 focussed on fisheries exploration, with routine hydrographic observations made, using the Nansen reversing bottle to sample temperature, salinity and oxygen in the water column. The Nansen bottle was replaced by a CTD with Niskin bottles in 1994, when the first RV *Dr Fridtjof Nansen* was replaced with a more modern second vessel. Recent surveys (post-2007) used technologically more advanced sensory techniques – such as satellite imagery and high resolution underway sensors. The later surveys followed a broader multi-disciplinary strategy, in which the collection and analysis of oceanographic information received far more attention. Chapter 4 reviews the *Nansen's* contributions to oceanographic discovery in the Western Indian Ocean, with a focus on the Somali Coast and East Africa Coastal Current subregions (surveys in 1975–1984), Mozambique and Madagascar (1977–2014), and the Mascarene subregion (1978–2010). Whereas many of the early observations were inconclusive at the time, more recent studies during the "satellite era" have corroborated earlier findings. For instance, *Nansen* data contributed to the first identification of eddies in the Gulf of Aden, and in the Mozambique Channel. *Nansen* data from a 2008 survey described the flow structure of the Southeast Madagascar Current. Upwelling events were observed near Angoche in Mozambique and off southeast Madagascar. Surveys to the Mascarene subregion in 2008 and 2010 suggested sub-surface (approximately 60–100 m depth) maximum phytoplankton densities – a major factor in explaining the functioning of local marine ecosystems. In retrospect, the *Nansen* played an important role in describing the physical oceanographic processes of the Western Indian Ocean – often from a perspective of how they would affect fish distribution and abundance patterns.

Previous page: Coastal ocean off southeast Madagascar. © Johan Groeneveld

4.1 Introduction

Initial surveys by the RV *Dr Fridtjof Nansen* in the Western Indian Ocean (1975–1990) focussed primarily on fisheries research, but oceanographic observations were routinely made. Following on a 17 year absence, renewed surveys with the *Nansen* after 2007 used far more advanced sampling techniques – such as satellite imagery and high resolution underway sensors – to map oceanographic features. The latter era (2007–2016) was characterized by a multi-disciplinary survey strategy to support broader ecosystems approaches to fisheries research. Within this set-up, oceanographic studies received far more attention, and in some cases, such as the 2008 survey of east Madagascar, focussed on studying the physical oceanography of specific ocean current systems. Post-2007 *Nansen* surveys in the Western Indian Ocean were restricted to the waters of Mozambique, Madagascar, Comoros and the Mascarene Plateau, well south of areas affected by piracy.

Chapter 4 presents an overview of oceanographic information collected by the *Nansen*, with a focus on the Somali Coast and East Africa Coastal Current subregions (EACC; surveys in 1975 to 1984); Mozambique and Madagascar subregions (surveys in 1977 to 2014); and the Mascarene subregion (surveys in 1978 to 2010). The contributions of the *Nansen* surveys to regional knowledge of the Western Indian Ocean are highlighted. Further, Chapter 4 outlines the known oceanographic features of the region – such as ocean circulation, temperature, salinity and oxygen profiles, water masses, upwelling areas and riverine input. These features influence ocean productivity on spatial and temporal scales (Chapter 5), and thus they also determine the distribution and abundance of pelagic (Chapter 6) and demersal (Chapter 7) fisheries resources. The strong link between physical oceanography, ocean productivity and fish resources is demonstrated in a Western Indian Ocean context. In addition, selected oceanographic information from pioneering surveys to eastern Somalia, Kenya and Tanzania was reanalysed, to assess the influence of monsoon seasons on water column structure (see Appendix 4.1).

4.2 General circulation of the Western Indian Ocean

The South Equatorial Current (SEC) is the principal pathway along which eastern and central Indian Ocean water masses move towards the African continent (Figure 4.1). East of Madagascar, at about 17 °S, the SEC branches into a southward flowing Southeast Madagascar Current (SEMC) and a northward flowing Northeast Madagascar Current (NEMC). At the southern tip of Madagascar, the SEMC sheds a sequence of eddies and dipoles that propagate southwestwards, towards the coasts of southern Mozambique and eastern South Africa (de Ruijter *et al*., 2002; Quartly *et al*., 2006; Ridderinkhof *et al*., 2013).

The NEMC branch passes the northern tip of Madagascar, where a portion of its flow becomes unsteady and sheds eddies into the Mozambique Channel (MCE). These eddies propagate southwards through the channel, to feed into the upper Agulhas Current, off eastern South Africa. The remainder of the NEMC continues westwards after passing northern Madagascar, feeding into the EACC; this current flows northwards off Tanzania, but off Kenya (north of 4 °S), its flow direction changes with alternating monsoon seasons.

During the Southwest (SW) monsoon (June to September), the EACC feeds into the northward-flowing Somali Current (SC). At about 3 °N, a part of it retroflects to the south of the equator, where it feeds into the South Equatorial Counter Current (SECC). The Somali Current flows northwards along the Somali coast during this time, forming a gyral circulation, or Great Whirl (GW) in the north (Figure 4.1a). An upwelling centre forms at the lee side of the Somali Current branch towards the Great Whirl (Schott, 1983). Further north, Gulf of Aden Eddies (GAE) dominate the upper layer circulation year-round (Al Saafani *et al*., 2007; Fratantoni *et al*., 2006). During the Northeast (NE) monsoon (December to March), the Somali Current flows southwards (Figure 4.1b), colliding with the northwards flowing EACC off Kenya; their confluence feed into the SECC. The dominant northeasterly winds induce downwelling

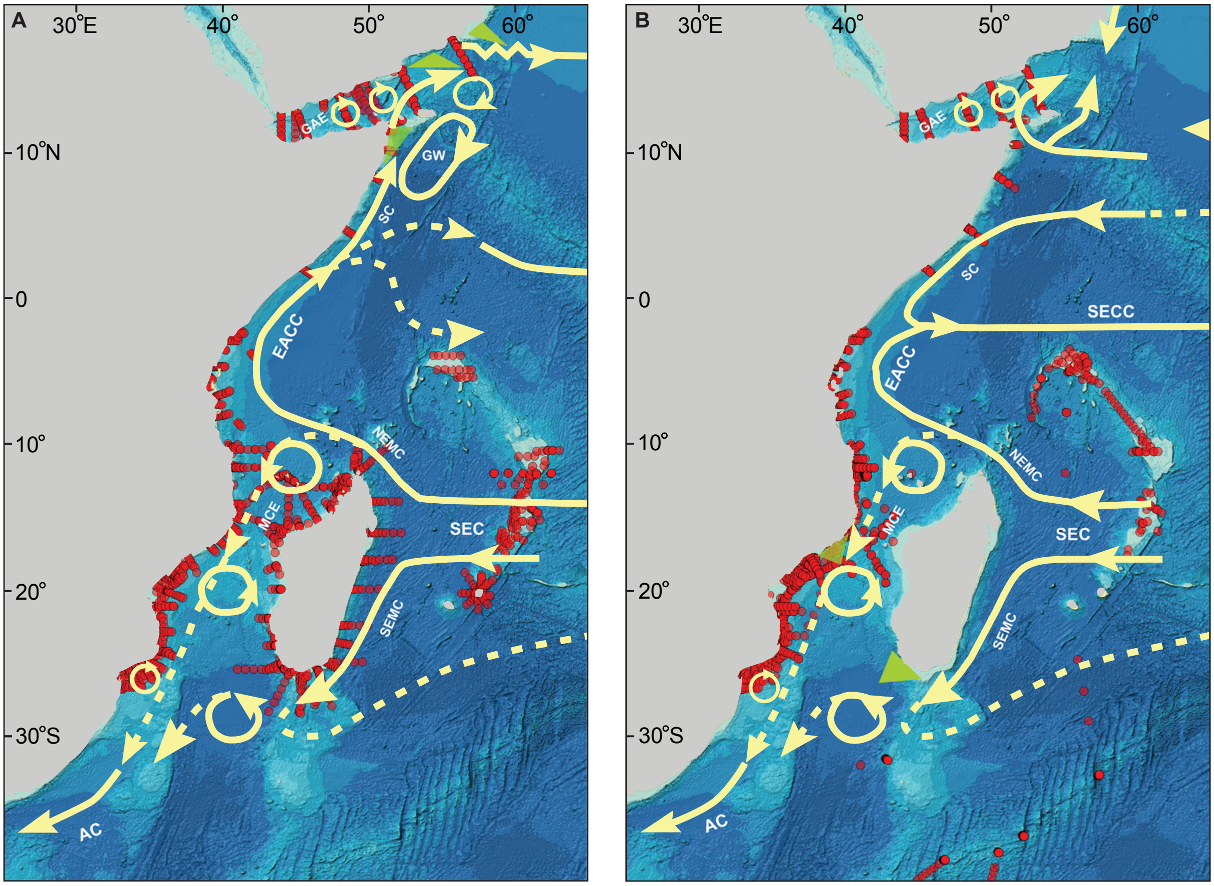

Figure 4.1 Schematic circulation in the Western Indian Ocean: (A) the Southwest monsoon season (June–September) and (B) Northeast monsoon season (November–March). Ocean currents are the South Equatorial Current (SEC), South Equatorial Counter Current (SECC), Northeast and Southeast Madagascar Current (NEMC and SEMC), Agulhas Current (AC), East Africa Coastal Current (EACC), Somali Current (SC), Great Whirl (GW), Mozambique Channel eddies (MCE) and Gulf of Aden Eddies (GAE). The red dots indicate stations sampled by the RV Dr *Fridtjof Nansen*. The green areas denote upwelling centers. Adapted from Schott *et al*. (2009).

off Somalia, but upwelling has been observed off northern Kenya during monsoon transition periods (October to November and April to May); likely because of accelerating eastward flow near the equator, called Wyrtki jets (Düing and Schott, 1978).

South of the equator, the NE monsoon favours wind-induced coastal upwelling in southern Tanzania and northern Mozambique. In the Mozambique Channel, the monsoon winds, eddies and rings collide with coastal and seafloor outcrops, to form the Angoche upwelling cell (Malauene *et al*., 2014; Figure 4.1b). A similar interaction of favourable winds, eddies and local topography induces upwelling at the southernmost tip of Madagascar (Machu *et al*., 2002). A quasi-permanent cyclonic lee-eddy in the Delagoa Bight (southern Mozambique), with enhanced chlorophyll concentrations, suggests a year-round upwelling cell.

4.3 Early days – *Nansen* surveys in Somalia and the EACC

The first observations off Somalia coincided with the *Nansen's* maiden surveys in 1975 and 1976, followed by a survey in 1984. Fish resources of

Kenya and Tanzania were surveyed in 1982 and 1983, when more oceanographic observations were made (Iversen, 1984; Iversen *et al*., 1984). Initial surveys using the first *Nansen* measured near-surface temperature distributions using an underway thermograph. The vertical structure of temperature, salinity and dissolved oxygen in the water column was measured by lowering Nansen reversing bottles to collect water from a stationary vessel, often at a series of sampling stations along transects perpendicular to the coast (Sætersdal *et al*., 1999). During surveys, currents were evaluated qualitatively, either from the ship's surface drift observations (IMR, 1976), or by inferring the geostrophic current direction from isopycnal slopes (vertical distribution of water density layers) observed in hydrographic sections (Iversen *et al*., 1984).

Nansen data collected during the 1975–1976 surveys contributed to the identification of cyclonic and anticyclonic eddies in the Gulf of Aden (Sandven, 1979). It was not until 30 years later, when satellite altimetry observations were available, that these dominant westward-traveling eddies in the surface waters of the Gulf of Aden could be fully confirmed (Al Saafani *et al*., 2007; Fratantoni *et al*., 2006). These eddies likely originate from instabilities of the Somali Current. Sandven's (1979) analysis, based on *Nansen* data, was one of the first studies from the pre-satellite era to show the existence of Gulf of Aden eddies (Al Saafani, 2008).

An important rationale for conducting *Nansen* surveys during the 1970s and 1980s was to identify how fish biomass and distribution patterns were affected by seasonal changes in the water column, resulting from various stages of monsoon circulation (Kesteven *et al*., 1981; Venema, 1984).

The observations were briefly summarized in the respective survey reports, but have not been used further to advance general oceanographic knowledge. Hence, Behrman (1981), describing the results from the IIOE, remarked on the role of the surveys by the *Nansen* and the Soviet RV *Professor Mesyatsev* in the following way: "Such vessels are a far cry from the general purpose research ships that sailed in the IIOE. *Dr Fridtjof Nansen*, for example, is equipped to hunt fish acoustically and then trawl in promising areas. Her

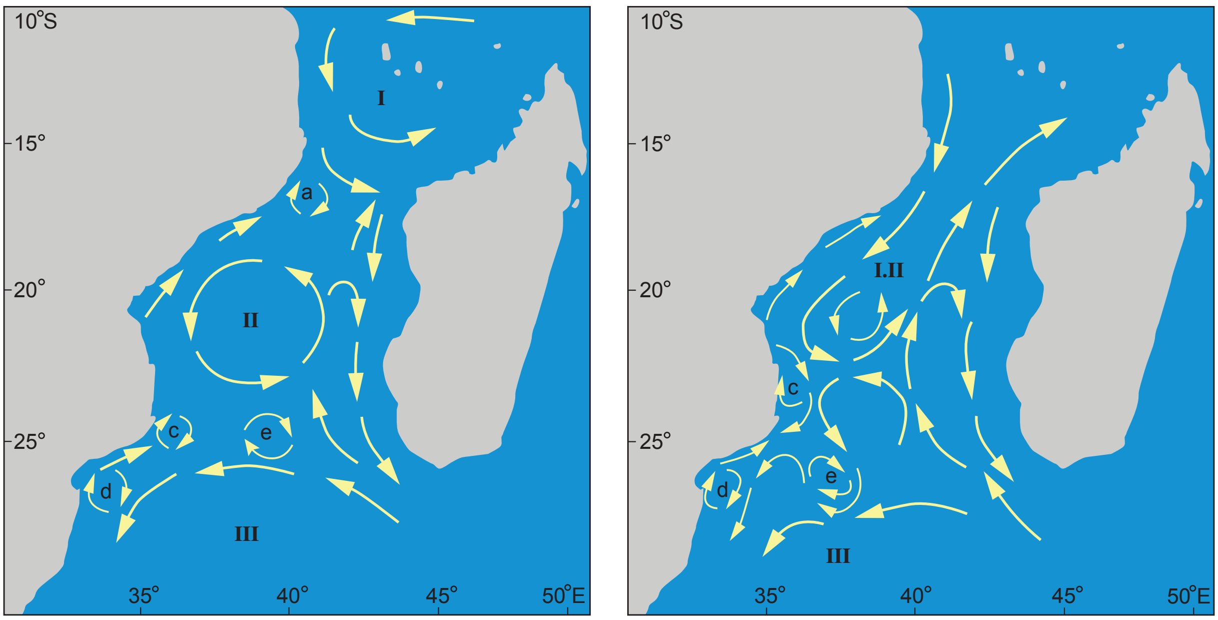

Figure 4.2 Location of quasi-geostationary anticyclonic cells in the Mozambique Channel and cyclonic cells over the shelf, showing seasonal variation. Adapted from Sætre and da Silva (1984).

survey was a particularly useful follow-up to the expedition, in that it identified specific concentrations of harvestable species."

The *Nansen* did, however, participate in general purpose oceanographic work at that time, by deploying moorings off the Kenyan coast to study the confluence between the EACC and Somali Current (Düing and Schott, 1978). A selection of observations, obtained from *Nansen* survey reports, is used to illustrate oceanographic conditions during opposing monsoon seasons off Tanzania, Kenya and Somalia (Appendix 4).

4.4 Mozambique subregion – the channel and coastal waters

The Mozambique Channel (deep ocean between the African shelf-break and Madagascar) and Mozambique coastal waters (broad continental shelf up to the shelf-break) have very different oceanographic features, and were sampled at different times by the *Nansen*. A total of 14 surveys took place in this subregion between 1977 and 2014 (see Chapter 3), and although they were mostly targeted at fisheries development objectives, most surveys also collected oceanographic data – especially those after 2007.

Mozambique Channel

Circulation and eddies

Early *Nansen* surveys (IMR, 1977, 1978a, b, c) used hydrographic data to investigate ocean circulation, and even though the surveys lacked offshore coverage, they contributed to a composite field of circulation patterns in the Channel (Sætre and da Silva, 1984). The composite description showed that large anticyclonic (anti-clockwise circulation) features dominate Mozambique Channel circulation (see also Harris, 1972). Sætre and da Silva (1984) proposed a circulation pattern of three quasi-geostationary anticyclonic cells, in the northern, central and southern parts of the channel. In winter, the northern and central cells apparently merged, suggesting seasonal variability in the northern channel, influenced by monsoon conditions. Smaller cyclonic (clockwise circulation) eddies occurred closer to the Mozambique coast (Figure 4.2).

The *Nansen* returned to the Mozambique Channel in November 2008, and the hydrographic observations made at that time confirmed the presence of eddies depicted from satellite altimetry data (AVISO). The vertical structure of an anticyclonic eddy showed downwelling in its core, as seen from depressed temperature, salinity and oxygen isolines (Figure 4.3). Moreover, the chlorophyll maxima, as derived from fluorescence measurements, were deeper in the central, downwelled anticyclonic eddy, than in adjacent cyclonic eddies. The vertical structure of cyclonic eddies was confirmed (see Schouten *et al*., 2003), with upward doming of temperature, salinity and oxygen isolines in the north and south of a transect (see domes to left and right in Figure 4.3), indicating deep, cool, low oxygen and enhanced Chl-a waters upwelled in their cores (Kaehler *et al*., 2008). The shipboard ADCP (S-ADCP or Acoustic Doppler Current Profiler, used to measure water current velocities) observations also confirmed the presence of the eddy fields seen in the AVISO satellite altimetry, in terms of their horizontal and vertical structure, and rotational velocities (Kaehler *et al*., 2008).

The eddy fields challenged the notion that the Mozambique Channel circulation consisted of a continuous western boundary current, the Mozambique Current. From the early 2000s, using modern oceanographic observation equipment and methods, new studies confirmed the dominant train of eddies (de Ruijter *et al*., 2002; Schouten *et al*., 2003) and rings (Halo *et al*., 2014), and concluded that a continuous Mozambique Current does not exist.

Vertical structure and water masses

Vertical temperature, salinity and oxygen profiles, collected by the *Nansen* since 1977, have been used to describe water masses up to 1 500 m depth (Figure 4.4). Surface waters near the coast comprise of two typical water masses: Tropical Surface Waters (TSW) and Subtropical Surface Water (STSW) (Sætre and da Silva, 1984; IMR, 1990b; Johnsen *et al.*, 2007). TSW consists of warm (>26 °C) low salinity (<34.5) water, caused by higher precipitation than evaporation in the tropical Indian Ocean. STSW consists of relatively cooler water with higher salinity (>34.5), because evaporation exceeds precipitation in the southern Indian Ocean. The transition from TSW to STSW is around 22 °S (Johnsen *et al.*, 2007).

The South Indian Central Water (SICW), below the thermocline depth, can be depicted by a quasi-linear decreasing relationship between temperature and salinity, and the presence of an oxygen maximum (Sætre and da Silva, 1984; IMR, 1990b; Johnsen *et al.*, 2007). At intermediate depths, Red Sea Water (RSW) was observed, with cool (4–7 °C) saline waters (>34.5), and low oxygen concentration of 2 m.l^{-1} (Sætre and da Silva, 1984). This water mass originates in the Arabian Sea, with contributions from the Red Sea and Gulf of Aden, and enters the Mozambique Channel from the north, propagating southwards. Antarctic Intermediate water (AAIW) with low salinity is evident in the south of Mozambique, transported northwards by the Mozambique Undercurrent. The AAIW is unlikely to penetrate further north into the Comoros Basin (IMR, 1978b; Johnsen *et al.*, 2007; Krakstad *et al.*, 2015).

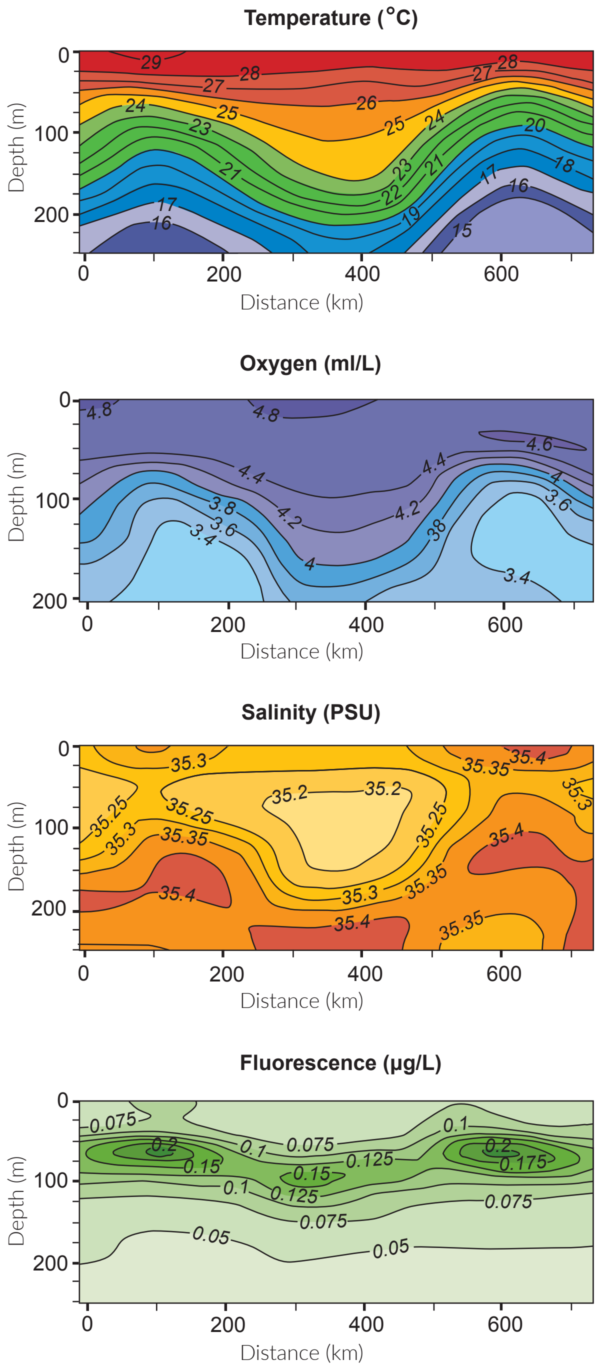

Figure 4.3 Seawater property distribution plots of the vertical structure of the water column across three eddies in the Mozambique Channel, based on *Nansen* samples along a mid-channel transect between 15 and 20 °S. Cyclonic eddies (left and right in each panel) show upwelling in eddy cores, and the anti-cyclonic eddy (centre of each panel) shows downwelling. After Kaehler *et al.*, (2008).

Mozambique coastal waters

Circulation and eddies

Sætre and da Silva (1984) identified four cyclonic eddies along the Mozambican shelf edge (Figure 4.2): a) near Angoche (16 °S); b) north of the Zambezi River mouth on the Sofala Bank (18 °S); c) off Inhambane (24 °S); and d) in the Delagoa Bight (26 °S). The Angoche eddy was not apparent during the winter monsoon (Figure 4.2), and is likely caused by topography. The Sofala Bank eddy may result from recirculation of Zambezi River outflow. The eddies at Inhambane and in the channel e) were apparently transient structures. The Delagoa Bight eddy appeared to be quasi-stationary and topographically induced.

Information from vessel drift during the early *Nansen* surveys suggested that circulation consists of weak northward counter-currents

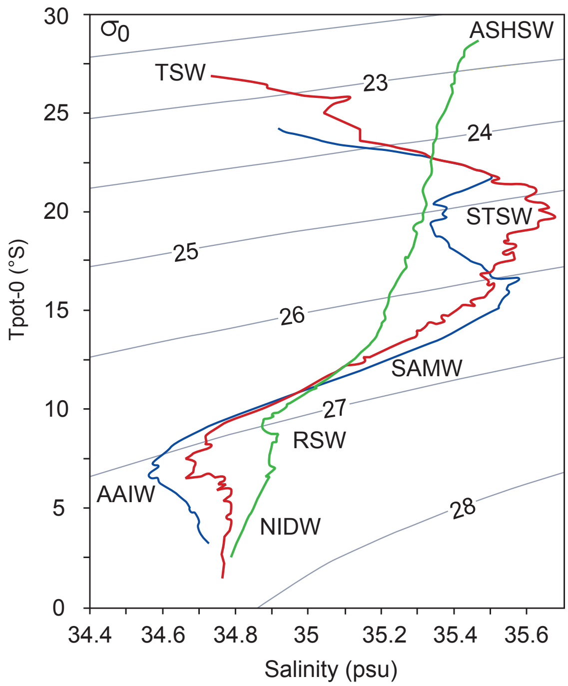

Figure 4.4 Temperature, salinity and oxygen profiles used to describe water masses: Arabian Sea High Salinity Water (ASHSW); Tropical Surface Water (TSW); Subtropical Surface Water (STSW); Subantarctic Mode Water (SAMW); Red Sea Water (RSW); Antarctic Intermediate Water (AAIW); North Indian Ocean Water (NIDW).

(approximately 0.28 m.s^{-1}), along the Sofala Bank (16–20 °S) and Delagoa Bight (24–26 °S) coasts (IMR, 1977; 1978c; Sætre and da Silva, 1984). The short duration of surveys and long intervening periods between them did not allow for definite conclusions on the persistence of the countercurrents. Moreover, they have not yet been confirmed by more recent studies.

River runoff

Freshwater river runoff was noticeable as low salinity values in measurements made near river mouths. Based on salinity variations, coastal waters have been categorized into three parts: a) north of 18 °S, with small salinity variations because of few large rivers; b) central (18–22 °S), with large salinity variations because of large rivers discharging into the ocean, particularly the Zambezi River (IMR, 1977, 1978a); and c) south of 24 °S, with moderate variations.

The influence of Zambezi River freshwater extended from the sea surface to 30 m water depth (IMR, 1977; Brinca *et al.*, 1981) and to approximately 50 m depth during the rainy season (IMR, 1978b, c). Plumes were observed up to 60 km offshore (IMR, 1977, 1978a, b, c; Brinca *et al.*, 1981; Nehama, 2012; Malauene, 2015), with the latter two studies also describing the bi-directional nature of the Zambezi River plume.

Temperature and salinity structures

Sea surface temperature (SST) decreased gradually from north to south along the coast, reaching a minimum near Maputo (IMR, 1977, 1978a, b, c; Johnsen *et al.*, 2007). SST over the northern Sofala Bank (<16 °S) indicated quasi-homogenous warm tropical surface waters (IMR, 1978b; Johnsen *et al.*, 2007), but south of the bank (>16 °S) water temperature decreased at a rate of 0.5 °C per 1 ° latitude (IMR, 1978b; Johnsen *et al.*, 2007; Krakstad *el al.*, 2015). A difference of 4 °C was measured between winter and summer temperatures (IMR, 1977c, 1978b). Cells of cool water with a temperature below 16 °C at a water depth of 150 m were observed near Angoche and the Delagoa Bight (IMR 1977c, 1978a, b, c, 1990a). The cool Delagoa Bight cell has been associated with upwelling of water from around 1 000 m deep, at the core of a quasi-permanent cyclonic lee-eddy (Lutjeharms and da Silva, 1988).

Angoche upwelling

The *Nansen* surveyed Angoche (northern Sofala Bank; 16 °S) four times in 1977–1978 (IMR 1977, 1978a, b, c) and again in 2009 (Olsen *et al.*, 2009). Temperature and oxygen isolines moved up the continental slope and onto the shelf during the NE monsoon (September to February), indicating upwelling of deep, cool and low oxygen waters into the upper mixed layer (Figure 4.5).

The deep cool waters did not always reach the surface, as seen from high oxygen concentrations (>4.7 ml.l^{-1}) in surface layers in September and November. In February, however, strong cooling and low oxygen concentrations extended to nearshore surface waters (to left of panels in Figure 4.5) whereas high-oxygen concentrations remained at the surface, further from the shore (to right of panels). The 2009 summer survey confirmed that deep, cool water, upwelled off Angoche, had enhanced chlorophyll-a concentrations (Olsen *et al*., 2009; Malauene *et al*., 2014).

The SW monsoon sample in April showed a decline of nearshore temperature and oxygen isolines over the continental shelf (Figure 4.5), suggesting downwelling. The seasonal nature of the Angoche upwelling, partly coupled with prevailing monsoon winds, has since been confirmed, based on SST satellite images, chlorophyll-a, altimetry geostrophic velocities and wind regime (Malauene *et al*., 2014). The NE monsoon wind (polewards, alongshore and parallel to the coast off Angoche) is favourable for an offshore surface Ekman transport, leading to wind-induced coastal upwelling, similar to Somalia.

4.5 Madagascar subregion

The *Nansen* surveyed the Madagascar coast on three occasions: June 1983 (southeast and southern coasts; Brinca *et al*., 1983); August and September 2008 (entire east coast; Krakstad *et al*., 2008); and August to October 2009 (west coast; Alvheim *et al*., 2009). A map of surveys and sampling positions is shown in Chapter 3.

East Madagascar Current

The S-ADCP readings along the track of the 2008 *Nansen* survey showed a bi-directional

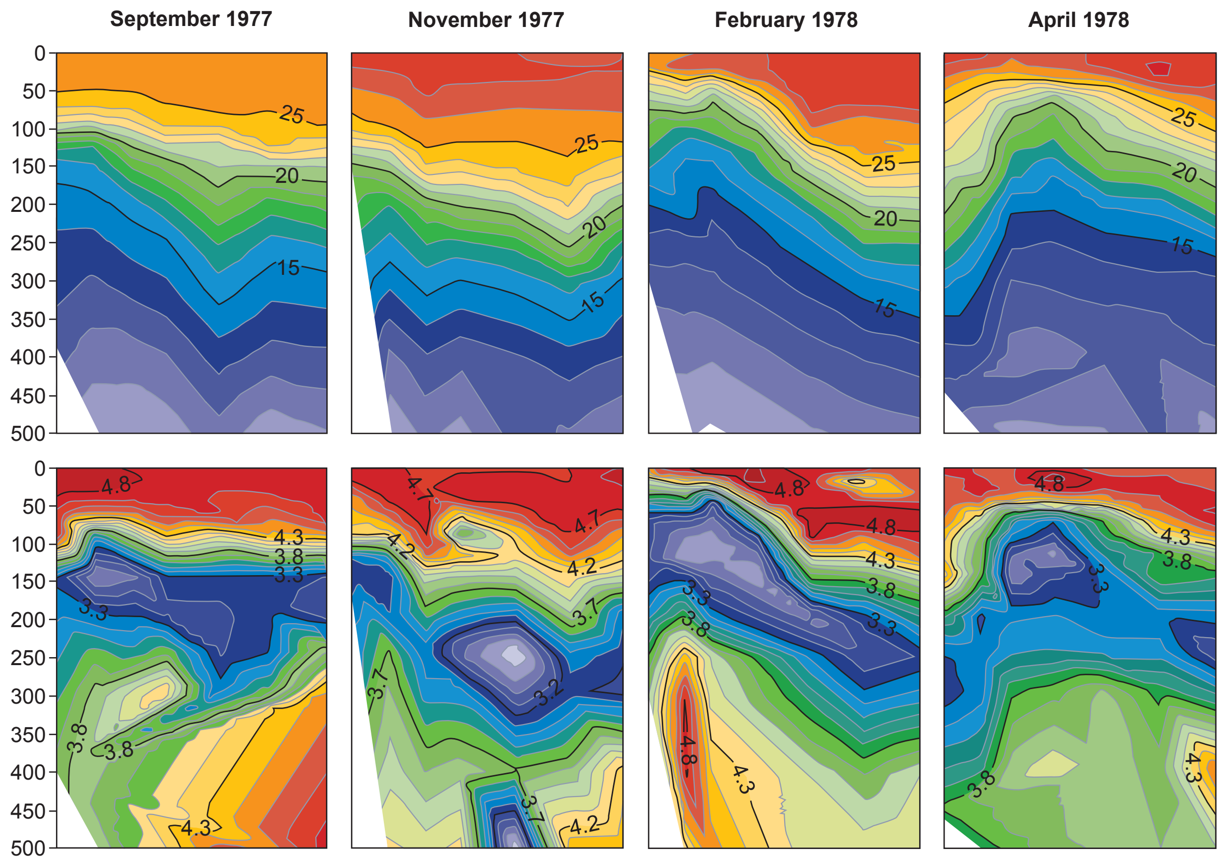

Figure 4.5 Seawater property distribution plots (by depth) off Angoche (16 °S) in the west Mozambique Channel. Vertical axis shows the oceanic vertical depth. Temperature (top row) and oxygen (bottom row) are ordered according to monsoon seasons: September 1977 – intermonsoon leading up to the NE monsoon; November 1977 and February 1978 – early and late NE monsoon; April 1978 – onset of SW monsoon.

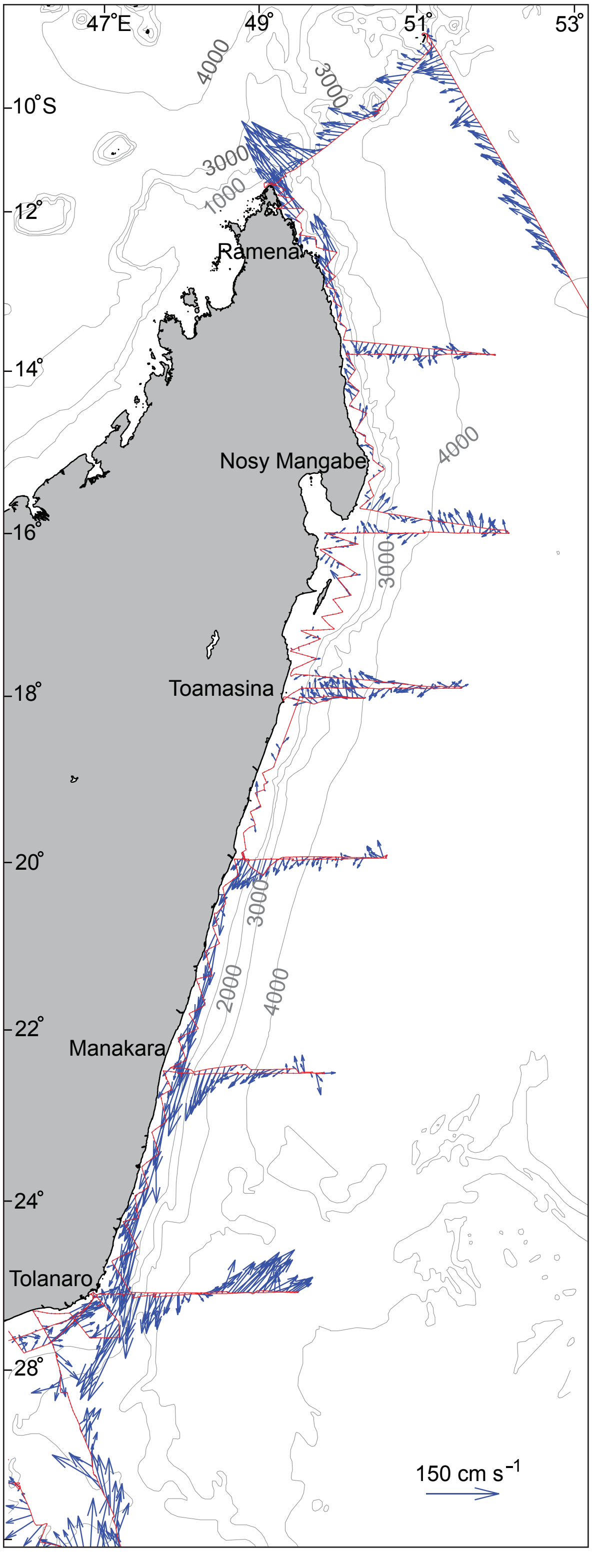

Figure 4.6 S-ADCP current velocity along the east coast of Madagascar as observed with the RV *Dr Fridtjof Nansen* in 2008. Adapted from Voldsund (2011).

East Madagascar Current (EMC) with northward (NEMC) and southward (SEMC) branches (Figure 4.6). The transition zone between the two branches – or bifurcation of the South Equatorial Current into SEMC and NEMC – lay between 18 and 20 °S, where the shelf current was weakly defined (Voldsund, 2011). The NEMC is weak (<50 cm.s^{-1}), but increases and steadies as it propagates northwards along the Madagascar coast (Figure 4.6; Voldsund, 2011). At the northeastern tip of Madagascar (12–13.5 °S) it accelerates and veers into the Mozambique Channel. The increased current velocities may be related to an incoming branch of the SEC in the north (Schouten *et al.*, 2003). The NEMC exhibits relatively strong vertical velocities (<40 cm.s^{-1}) propagating northwards along the coast and over the inner-shelf, limited to the upper 100 m water depth (Voldsund, 2011). Below 100 m depth, the NEMC is weak and irregular, nearing zero around 200 m.

Older technologies used during the 1970s and 1980s, such as ship's surface drift and geostrophic approximation from isopycnal slopes, first characterized the SEMC as a southward filament of high SST (>25 °C) and salinity (35.2–35.3), branching from Equatorial Surface Waters (Brinca *et al.*, 1983). Advanced current measurements using ADCPs after 2000 indicated that the SEMC is steady and strong, increasing southwards to ~150 cm.s^{-1}. Therefore it is a well-defined western boundary current following the continental shelf and slope (Voldsund, 2011). The southward net water volume transport was estimated at approximately 26 Sv (Voldsund, 2011). Vertical current profiles showed a strong, jet-like, southward current from the coast to 150 km offshore, peaking at 30 to 50 km offshore (Figure 4.6). The 2008 *Nansen* survey showed that the strong southward flow extended down to 200 m water depth (Voldsund, 2011), indicating that the SEMC is a robust feature.

Southeast Madagascar upwelling

A cell of cool (<23 °C) surface water along the inshore edge of the SEMC off southeast Madagascar indicated upwelling during the 1983 survey (Brinca *et al.*, 1983), and this was confirmed by vertical temperature and oxygen measurements at that time. Satellite imagery and a hydrographic survey carried-out in March 2001 on board of the Dutch RV *Pelagia* (DiMarco *et al*., 2000; Machu *et al*., 2002) confirmed the upwelling – probably resulting from a combination of topography-induced eddies and upwelling-favourable wind conditions (Machu *et al*., 2002).

4.6 Mascarene subregion

The *Nansen* surveyed the Mascarene subregion on three occasions: Seychelles in 1978 (IMR, 1978d), when few physical oceanography observations were made; an oceanographic survey of Mauritius and the Mascarene Plateau in 2008 (Strømme *et al*., 2010); and a multi-disciplinary survey of Mauritius and the southern Mascarene Plateau in 2010 (Strømme *et al*., 2010).

The submerged Mascarene Plateau is one of the most prominent topographic features of the Western Indian Ocean seafloor (Parson and Evans, 2005). It has volcanic origin, is crescent-shaped along a north-south axis between 4 and 24 °S, and is 2 200 km long (Spencer *et al*., 2005; Weijer, 2008). The plateau is bounded to the north and south by the Seychelles Bank and Mauritius Island, respectively (see Figure 4.1). Shallow banks on the plateau, such as Saya de Malha, Nazareth, and Cargados Carajos (20–100 m deep) rise steeply from about 4 000 m depth in the Mascarene (west) and Central Indian (east) basins (Parson and Evans, 2005). The plateau may have significant impact on meteorological and oceanographic circulation, including the distribution of heat, nutrients, and biological material (Spencer *et al*., 2005). On its southern edge, Mauritius is also of volcanic origin, with no southern or western shelf areas. The fundamental physical processes that control ocean currents and water mass properties in the region are not yet well understood (Spencer *et al*., 2005; New *et al*., 2007; Weijer, 2008; Pous *et al*., 2014).

Oceanic circulation

The large-scale circulation around the Mascarene Plateau is complex, with a westwards-flowing equatorial current and eastward counter-currents dominating the time-averaged flow field. The equatorial dynamics of the region is further influenced by monsoonal climate wind systems, which modulate the latitudinal placement of the South Equatorial Current (SEC). The SEC is a branch of the South Indian Ocean anticyclonic gyre circulation, which also include waters from the Indonesian Throughflow (ITF; Stramma and Lutjeharms, 1997). The complexity of the upper ocean circulation is further influenced by the meridional and shallow Mascarene Plateau, which obstructs the westwards flow of the SEC almost perpendicularly, between roughly 9 and 20 °S. This obstruction splits the broad SEC into several narrow branches, which flow through gaps in the plateau (Figure 4.7). The southern branch of the SEC dominates circulation and water mass characteristics around Mauritius (New *et al*., 2007; Pous *et al*., 2014).

From a physical oceanography perspective, research questions asked during the 2008 survey of the Mascarene Plateau were as follows (Strømme *et al*., 2009): i) How is the SEC flow affected by the gaps in the Mascarene Plateau? ii) What is the effect of the Mascarene Plateau between Seychelles and Madagascar on the overall flow of SEC waters? iii) Does the Mascarene subregion between Seychelles and Madagascar differ from the section between Mauritius and Seychelles, and what are the linkages?

Atmospheric circulation

Meteorological information (wind direction and speed, air temperature and pressure, relative humidity, and near-surface temperature at 5 m depth) were logged automatically on a WIMDA ship-mounted meteorological station during the 2008 and 2010 surveys. To the south of 10 °S, the Mascarene subregion was characterized by steady southeast trade winds, but north of 10 °S, the winds varied considerably in response to the reversal of the monsoons (Schott *et al*., 2009).

Hydrographic measurements

The hydrographic measurements made by the *Nansen* during the 2008 survey corroborate the

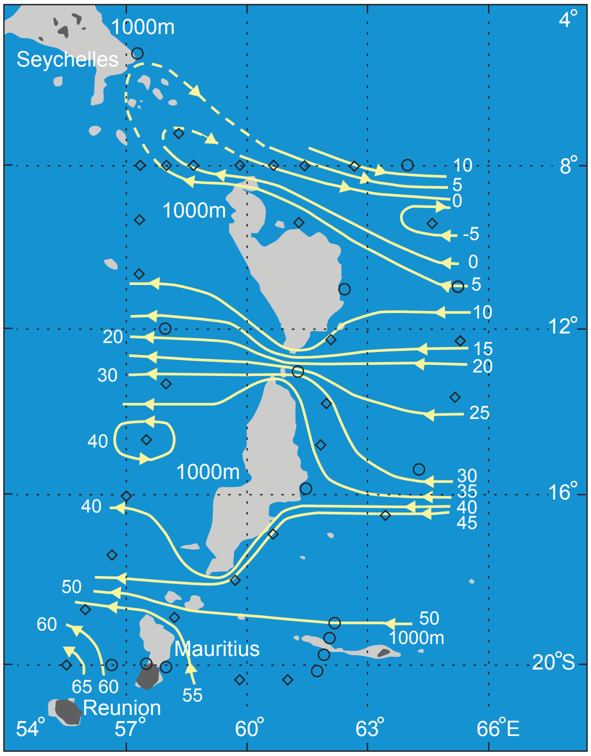

Figure 4.7 Geostrophic transports (Sv) accumulated from a reference depth of 2 000 m to the sea surface. After New *et al*. (2007).

findings published by New *et al*. (2007). Before reaching the Mascarene Plateau, the SEC transports about 50–55 Sv (1Sv = 106 m^3s^{-1}), of which about 25 Sv passes through a gap of roughly 100 km wide between Saya de Malha and Nazareth Banks. The remaining volume either passes over the northern tip of Saya de Malha (also a gap of 100 km wide) or through a relatively wider gap of 200 km between Mauritius and the Cargados-Carajos Banks.

The flow field in the three main SEC branches is, however, variable (Figure 4.7; New *et al*., 2007). The westward currents in the 7–20 °S latitudinal band are consistent with the SEC as described in the literature (Stramma and Lutjeharms, 1997; Tomczak and Godfrey, 2003; New *et al*., 2007; Schott *et al*., 2009), but reversal of the currents suggest that several processes are involved, increasing variability. One of these would be the interaction of the mean SEC flow with the topography of the Seychelles Bank, apparently inducing an eastward flow or mesoscale eddies. Secondly, it is important to bear in mind that this region is also dominated by mesoscale westward propagation of Rossby waves (planetary westward-traveling waves driven by the meridional gradient of Coriolis forces). The *Nansen* survey data also suggests that flow intensifies (>0.5 $m.s^{-1}$) between 11 and 13 °S, concordant with the narrow gap between Saya de Malha and Nazareth Banks. This is also consistent with the gap of maximum westward geostrophic transport (about 25 Sv; New *et al*., 2007).

Water masses

CTD casts performed during the *Nansen's* survey in 2008 provided unprecedented high-resolution vertical profiles of temperature, salinity, oxygen, and pathways of matter across the Mascarene Plateau. Various water masses were identified, most obviously Tropical Surface Waters (TSW), Subtropical Surface Waters (STSW), Arabian Sea High Salinity Waters (ASHSW) and potentially Indonesian Throughflow (ITF). Below 750 m depth, Red Sea Water (RSW), Antarctic Intermediate Water (AAIW) and Subantarctic Mode Water (SAMW) were inferred (Figure 4.4; Strømme *et al*., 2009).

The presence of the ASHSW around Seychelles (near 5 °S, Figure 4.8) is attributed to its transport by the eastward flowing South Equatorial Counter Current (SECC). It has a northern origin in the Arabian Sea, where evaporation rates exceed precipitation, and hence has a high salinity of 35.5–35.45. ASHSW water near Seychelles had a temperature of 24–28 °C, and oxygen concentration of 4.3–4.5 $m.l^{-1}$ (Strømme *et al*., 2009; Vianello, 2015). Nearly at the same location, but at intermediate depths, Red Sea Water (RSW), with a temperature of 4–7 °C, salinity of >34.5, and oxygen concentration of 1.6–2 $m.l^{-1}$ (Vianello, 2015) was identified. In the sector between Seychelles and Saya de Malha, there was evidence of North Indian Ocean waters (NIDW). Analysis of *Nansen's* dataset by Vianello (2015) showed a temperature of 3 °C and salinity of 34.8. The temperature/salinity diagram presented by Strømme *et al*. (2009) also verified this water mass (Figure 4.8).

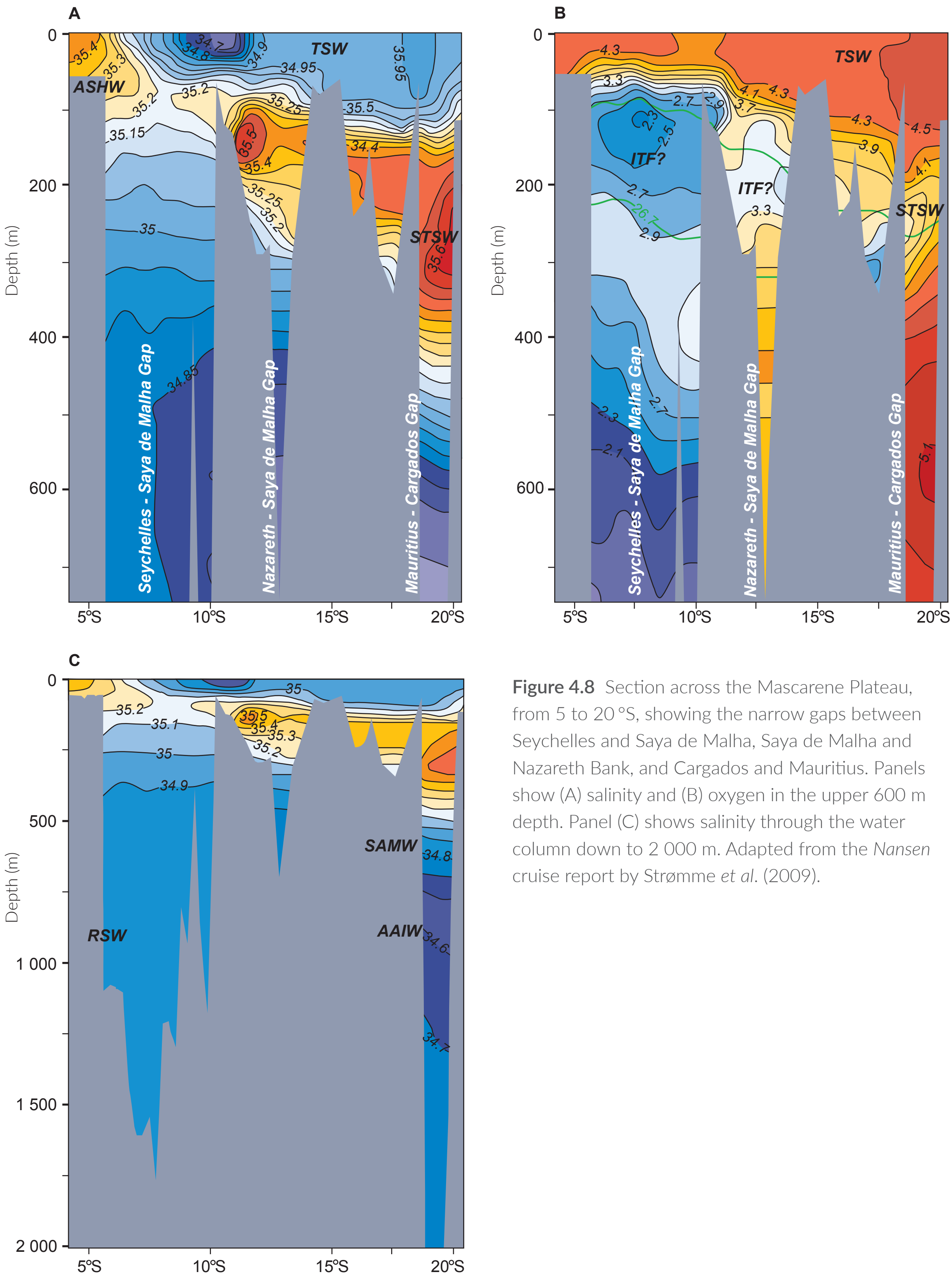

Figure 4.8 Section across the Mascarene Plateau, from 5 to 20 °S, showing the narrow gaps between Seychelles and Saya de Malha, Saya de Malha and Nazareth Bank, and Cargados and Mauritius. Panels show (A) salinity and (B) oxygen in the upper 600 m depth. Panel (C) shows salinity through the water column down to 2 000 m. Adapted from the *Nansen* cruise report by Strømme *et al.* (2009).

Tropical Surface Waters (TSW) with low salinity were present at nearly all stations across the plateau; this layer has been linked to the westward propagation of the SEC (New *et al*., 2007). Subtropical Surface Water (STSW), with high salinity, induced by higher evaporation than precipitation in the subtropical South Indian Ocean, occurred in subsurface layers. In the gap (channel) between Mauritius and the Cargados-Carajos Bank, STSW had a temperature of >23 °C, a subsurface salinity maximum of 35.6 and oxygen minimum of 3 m.l^{-1} (Vianello, 2015).

AAIW, with a typical salinity minimum below 34.6 and temperature range of 5–7 °C, was found between Saya de Maya and Nazareth Banks, and between Mauritius and Cargados-Carajos Bank. Vianello (2015) also observed ITF water in the gaps between Seychelles and Saya de Malha; Saya de Malha and Nazareth Banks; and Cargados-Carajos and Mauritius (Figure 4.8). The ITF layer occurred at 100–250 m depth, with salinity of 35.2, and a subsurface oxygen minimum of 2.5 m.l^{-1} (Strømme *et al*., 2009). ITF originates from the west Pacific, has typical high temperature and low salinities induced by high precipitation rates, and its presence around the Mascarene Plateau relies on the westward progression of the SEC (Tomczak and Godfrey, 2003).

4.7 Conclusions

Physical oceanography research was often approached from the perspective of explaining the distribution and abundance of fisheries resources. Nevertheless, its importance grew from mainly routine observations conducted during the era covered by the first *Nansen* (1975–1990 in the Western Indian Ocean), to the use of technologically far more advanced on-board sensory equipment and satellite imagery in surveys undertaken after 2007, by the second *Nansen*. Recent surveys followed a multi-disciplinary approach, and in some cases even focussed on describing large scale oceanographic systems (for example the 2008 and 2010 surveys of east Madagascar and the Mascarene subregion).

The role of the *Nansen* in describing the physical oceanography of the Western Indian Ocean cannot be overstated, with many of its earlier findings being confirmed by later, more detailed studies, or by subsequent satellite imagery data. More detailed exploration of the stored *Nansen* data is recommended, to investigate oceanographic processes that remain enigmatic – for instance, the Southeast Madagascar Current retroflection, or the Mozambican coastal counter-currents. ■

References

Al Saafani, M.A., Shenoi, S.S.C., Shankar, D., Aparna, M., Kurian, J., Durand, F. & Vinayachandran, P.N. 2007. Westward movement of eddies into the Gulf of Aden from the Arabian Sea. *Journal of Geophysical Research: Oceans*, 112(C11): doi:10.1029/2006JC004020.

Al Saafani, M.A. 2008. *Physical Oceanography of the Gulf of Aden*. Dona Paula, Goa 403 004, Goa University (PhD Thesis).

Alvheim, O., Torstensen, E., Fennessy, S., MacKay, F., Zaera, D. & Bemiasa, J. 2009. *West Madagascar: Pelagic Ecosystem Survey SWIOFP/ASCLME/FAO 2009 Cruise 2, 25 August–03 October 2009. Preliminary report*. Bergen, Norway, Institute of Marine Research.

Behrman, D. 1981. *Assault on the largest unknown; the International Indian Ocean Expedition 1959–65*. Paris, France, The Unesco Press.

Brinca, L., Rey, F., Silva, C. & Sætre, R. 1981. *A Survey on the Marine Fish Resources of Mozambique, October–November 1980*. Bergen, Norway, Institute of Marine Research.

Brinca, L., Jorge da Silva, A., Sousa, L., Sousa, I. & Sætre, R. 1983. *A Survey on the Fish Resources at Sofala Bank – Mozambique, September 1982*. Bergen, Norway, Institute of Marine Research.

de Ruijter, W.P.M., Ridderinkhof, H., Lutjeharms, J.R.E., Schouten, M.W. & Veth, C. 2002. Observations of the flow in the Mozambique Channel. *Geophysical Research Letters*, 29(10): 1502–1504.

DiMarco, S.F., Chapman, P. & Nowlin, W.D. 2000. Satellite observations of upwelling on the continental shelf south of Madagascar. *Geophysical Research Letters*, 27(24): 3965–3968.

Düing, W. & Schott, F. 1978. Measurements in the source region of the Somali Current during the monsoon reversal. *Journal of Physical Oceanography*, 8(2): 278–289.

Fratantoni, D.M., Bower, A.S., Johns, W.E. & Peters, H. 2006. Somali Current rings in the eastern Gulf of Aden. *Journal of Geophysical Research: Oceans*, 111(C9): doi:10.1029/2005JC003338.

Halo, I., Backeberg, B., Penven, P., Ansorge, I., Reason, C. & Ullgren, J.E. 2014. Eddy properties in the Mozambique Channel: A comparison between observations and two numerical ocean circulation models. *Deep Sea Research Part II: Topical Studies in Oceanography*, 100: 38–53.

Harris, T.F.W. 1972. Sources of the Agulhas current in the spring of 1964. *Deep Sea Research and Oceanographic Abstracts*, 19(9): 633–650.

IMR. 1976. *Report on Cruise No. 3 of R/V Dr Fridtjof Nansen. Indian Ocean Fishery and Development Programme, Pelagic Fish Assessment Survey North Arabian Sea*. Bergen, Norway, Institute of Marine Research.

IMR. 1977. *Cruise Report No. 1 of R/V Dr Fridtjof Nansen. Joint NORAD/Mozambique/FAO Project to Investigate the Fish Resources off the Coast of Mozambique*. Bergen, Norway, Institute of Marine Research.

IMR. 1978a. *Cruise Report No. 2 of R/V Dr Fridtjof Nansen. Joint NORAD/Mozambique/FAO Project to Investigate the Fish Resources off the Coast of Mozambique, October–December 1977*. Bergen, Norway, Institute of Marine Research.

IMR. 1978b. *Cruise Report No. 3 of R/V Dr Fridtjof Nansen. Joint NORAD/Mozambique/FAO Project to Investigate the Fish Resources off the Coast of Mozambique, January–March 1978*. Bergen, Norway, Institute of Marine Research.

IMR. 1978c. *Cruise Report No. 4 of R/V Dr Fridtjof Nansen. Joint NORAD/Mozambique/FAO Project to Investigate the Fish Resources off the Coast of Mozambique, April–June 1978*. Bergen, Norway, Institute of Marine Research.

IMR. 1978d. *Survey results of R/V Dr Fridtjof Nansen. Joint NORAD/Seychelles Project to Investigate the Fish Resources in Seychelles waters, July 1978*. Bergen, Norway, Institute of Marine Research.

IMR. 1990a. *Cruise Report No. 1 of R/V Dr Fridtjof Nansen. Joint NORAD/Mozambique/FAO Project to Survey of the Fish Resources of Mozambique, April–May 1990*. Bergen, Norway, Institute of Marine Research.

IMR. 1990b. *Cruise Report No. 3 of R/V Dr Fridtjof Nansen. Joint NORAD/Mozambique/FAO Project to Survey of the Fish Resources of Mozambique, November–December 1990*. Bergen, Norway, Institute of Marine Research.

Iversen, S.A. 1984. *Kenyan marine fish resources in water deeper than 10 m investigated by R/V Dr Fridtjof Nansen. Report presented at a joint Kenyan/Norwegian seminar, Mombasa, Kenya, 13–15 March 1984*. Bergen, Norway, Institute of Marine Research.

Iversen, S.A., Myklevoll, S., Lwiza, K. & Yonazi, J. 1984. *Tanzanian marine fish resources in the depth region 10–500 m investigated by R/V Dr Fridtjof Nansen*. S.A. Iversen, ed. pp. 45–83. The proceedings of the NORAD/Tanzania seminar to review the marine fish stocks and fisheries in Tanzania, 6–8 March 1984, Mbegani, Tanzania. Bergen, Norway, Institute of Marine Research.

Johnsen, E., Krakstad, J., Ostrowski, M., Serigstad, B., Strømme, T., Alvheim, O., Olsen, M., Zaera, D., André, E., Dias, N., Sousa, L., Sousa, B., Malauene, B. & Abdula, S. 2007. *Surveys of the living marine resources of Mozambique: Ecosystem Survey and Special Studies. 27 September–21 December 2007*. Report No. 8/2007–2007409. Bergen, Norway, Institute of Marine Research.

Kaehler, S., Gammelsrød, T., Hill, J., Ternon, J.-F., Cotel, P., Potier, M., Huggett, J., Miggel, A., Pillay, K., Dyer, B., Backeberg, B., Langa, A., Malaune, B., Benivary, D., Morris, T., O'Reilly, B. & Olsen, M. 2008. *2008 ASCLME Survey No 4. Preliminary cruise report No 8/2008. 28 November–17 December 2008*. Report No. EAF-N2008/7. Bergen, Norway, Institute of Marine Research.

Kesteven, G.L., Nakken, O. & Strømme , T. 1981. *The small-pelagic and demersal fish resources of the north-west Arabian Sea. Further analysis of the results of the R/V Dr Fridtjof Nansen Survey, 1975–1976.* Bergen, Norway, Institute of Marine Research.

Krakstad, J.-O., Mehl, S., Roman, R., Escobar-Porras, J., Stapley, J., Flynn, B., Olsen, M. & Beck, I. 2008. *Cruise Report Dr Fridtjof Nansen. East Madagascar Current Ecosystem Survey ASCLME / FAO 2008 Cruise 1, 24 August–1 October 2008*. Bergen, Norway, Institute of Marine Research.

Krakstad, J.-O., Zaera, D., Aasen, A. & Soondron, V. 2010. *Survey of the demersal resources on the western slopes of St. Brandon and Nazareth Bank, Mauritius. 16–25 September 2010*. Report No. EAF-N2010/7. Bergen, Norway, Institute of Marine Research.

Krakstad, J.-O., Krafft, B., Alvheim, O., Kvalsund, M., Bernardes, I., Chacate, O., Mutombene, R., Filipe, O., Hajy, B., Zacarias, L., Zivane, F., M, P. & Varela, D. 2015. *Cruise report Dr Fridtjof Nansen. Marine Ecosystem Survey of Mozambique, 11 November–02 December 2014*. Report No. GCP/INT/003/NOR. Bergen, Norway, Institute of Marine Research.

Lutjeharms, J. & da Silva, A. 1988. The Delagoa bight eddy. *Deep Sea Research Part A. Oceanographic Research Papers*, 35(4): 619–634.

Machu, E., Lutjeharms, J.R.E., Webb, A.M. & Van Aken, H.M. 2002. First hydrographic evidence of the southeast Madagascar upwelling cell. *Geophysical Research Letters*, 29(21): doi:10.1029/2002GL015381.

Malauene, B.S., Shillington, F.A., Roberts, M.J. & Moloney, C.L. 2014. Cool, elevated chlorophyll-a waters off northern Mozambique. *Deep Sea Research Part II: Topical Studies in Oceanography*, 100: 68–78.

Malauene, B.S. 2015. *Environmental influences on banana shrimps of the Sofala Bank, Mozambique Channel.* Cape Town, South Africa, University of Cape Town (PhD thesis).

Nehama, F.P.J. 2012. *Modelling the Zambezi River plume using the Regional Oceanic Modelling System.* Cape Town, South Africa, University of Cape Town (PhD thesis).

New, A.L., Alderson, S.G., Smeed, D.A. & Stansfield, K.L. 2007. On the circulation of water masses across the Mascarene Plateau in the South Indian Ocean. *Deep Sea Research Part I: Oceanographic Research Papers*, 54(1): 42–74.

Olsen, E., Padera, M., Funke, M., Pires, P., Wenneck, T. & Zacarias, L. 2009. *Survey of the living marine resources of North Mozambique, 6–20 August 2009. SWIOFP/ASCLME 2009 Cruise 1*. Report No. EAF-N/2009/7. Bergen, Norway, Institute of Marine Research.

Parson, L.M. & Evans, A.J. 2005. Seafloor topography and tectonic elements of the Western Indian Ocean. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 363(1826): 15–24.

Pous, S., Lazure, P., André, G., Dumas, F., Halo, I. & Penven, P. 2014. Circulation around La Réunion and Mauritius islands in the south-western Indian Ocean: A modeling perspective. *Journal of Geophysical Research: Oceans*, 119(3): 1957–1976.

Quartly, G.D., Buck, J.J.H., Srokosz, M.A. & Coward, A.C. 2006. Eddies around Madagascar – the retroflection reconsidered. *Journal of Marine Systems*, 63(3): 115–129.

Ridderinkhof, W., Le Bars, D., Heydt, A.S. & de Ruijter, W.P.M. 2013. Dipoles of the South East Madagascar Current. *Geophysical Research Letters*, 40(3): 558–562.

Sætersdal, G., Bianchi, G., Strømme , T. & Venema, S. 1999. *The Dr. Fridtjof Nansen programme: 1975–1993. Investigations of fishery resources in developing regions. History of the programme and review of results*. FAO Fisheries Technical Paper No. 391. Food and Agriculture Organization of the United Nations.

Sætre, R. & da Silva, A.J. 1984. The circulation of the Mozambique Channel. *Deep Sea Research Part A. Oceanographic Research Papers,* 31(5): 485–508.

Sandven, S. 1979. *Coastal oceanography of the Arabian Sea. Data processing and interpretation.* Bergen, Norway, University of Bergen.

Schott, F. 1983. Monsoon response of the Somali Current and associated upwelling. *Progress in Oceanography*, 12(3): 357–381.

Schouten, M.W., de Ruijter, W.P.M., Van Leeuwen, P.J. & Ridderinkhof, H. 2003. Eddies and variability in the Mozambique Channel. *Deep Sea Research Part II: Topical Studies in Oceanography*, 50(12): 1987–2003.

Spencer, T., Laughton, A. & Flemming, N. 2005. Variability, interaction and change in the atmosphere–ocean–ecology system of the Western Indian Ocean. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 363(1826): 3–13.

Stramma, L. & Lutjeharms, J.R.E. 1997. The flow field of the subtropical gyre of the South Indian Ocean. *Journal of Geophysical Research: Oceans*, 102(C3): 5513–5530.

Strømme, T., Ansorge, I., Bornman, T., Kaehler, S., Ostrowski, M., Tweddle, D. & Alvheim, O. 2009. *2008 ASCLME Survey No 3 Cruise report No 7/2008. 8 October–27 November 2008*. Report No. EAF-N2008/7. Bergen, Norway, Institute of Marine Research.

Strømme, T., Groeneveld, J., Alvheim, O., Fossheim, O. & Svoren, T. 2010. *Mauritius and Southern Mascarene: Pelagic Ecosystem Survey SWIOFP/FAO 2010 Cruise 1 2010. 6–21 December 2010. Final report*. Report No. EAF-N2008/7. Bergen, Norway, Institute of Marine Research.

Tomczak, M. & Godfrey, J.S. 2003. *Regional Oceanography: an Introduction 2nd edn.* Delhi, India, Daya Publishing House.

Venema, S.C. 1984. Fishery resources in the North Arabian Sea and adjacent waters. *Deep Sea Research Part A. Oceanographic Research Papers,* 31(6–8): 1001–1018.

Vianello, P. 2015. *A qualitative and physical analysis of processes around Mascarene Plateau.* Cape Town, South Africa, University of Cape Town (PhD thesis).

Voldsund, A. 2011. *The dynamics of the East Madagascar Current System and its influence on the biological production associated to the shelf - an observational study.* Bergen, Norway, University of Bergen (MSc thesis).

Weijer, W. 2008. Normal modes of the Mascarene Basin. *Deep Sea Research Part I: Oceanographic Research Papers,* 55(1): 128–136.