Summer Surface Circulation on the Gascoyne Continental Shelf

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Abstract- As part of a multidisciplinary investigative effort to establish an understanding of the relatively unstudied coastal waters off the Gascoyne region, 11 cross-isobath transects, spanning latitudes of 21^0S -28^0S off the West Australian coast were made during 13-27 Nov 2000. This paper examines CTD and ADCP data that were gathered aboard the RV Franklin, along with concurrent satellite SST imagery, to provide a description of the summer surface circulation on the Gascoyne continental shelf. The Leeuwin Current has generally been depicted as an eastern boundary current carrying warm, low salinity water poleward along the West Australian continental shelf break. This study reveals details of the Leeuwin Current ageing from its warm (24.85^0C), relatively fresh (34.92psu) nature, to a cooler (21.21^0C), more saline (35.44psu) condition, as it journeyed along its meandering path southward, encountering I) the Ningaloo Current and an anticyclonic recirculation pattern south of Point Cloates, II) hypersaline outflow from Shark Bay, III) the Capes Current, IV) offshore eddies, and V) drastically varying shelf widths. Evidence was also seen of persistent 'common shelf water' south of Shark Bay, with a very distinct 35.2psu salinity signature.

I. INTRODUCTION

A. Study Area

Along the central coastline of Western Australia is the Gascoyne (Fig. 1) – a region encompassing protected marine parks, nurseries and aquaculture farms. It is important that the dynamics of the ocean in this region be fully understood, as this knowledge would aid better management of the area. However, due to complexity of the summer ocean dynamics and to lack of data, the understanding of oceanic processes in the region remains extremely vague. This project is an attempt to rectify this lack of knowledge.

During 13-27 November 2000, our team aboard the RV *Franklin* collected data as part of a multidisciplinary effort to study the marine processes occurring off the Gascoyne. In this paper, we use meteorological data, satellite images and ship-based data to examine the structure of the surface current system between Shark Bay and North-west Cape in summer. Hydrographic data for deeper waters shall be discussed in a companion paper.

B. General Surface Circulation

On the eastern boundary of the Indian Ocean, flowing poleward along the Western Australian coastline, is the Leeuwin Current. Observational and modelling studies undertaken over the past decade have shown the Leeuwin Current to be produced by a meridional pressure gradient that overwhelms the opposing equatorward wind stress [1-6]. The Leeuwin Current has been reported to carry warm, low salinity, tropical water from a source on the Northwest Shelf. It flows broad (400km) and shallow (50m) at North West Cape, gradually narrowing (~100m) and deepening (~300m) as it accelerates (to 1-1.5m/s) poleward along the shelf break, whilst being augmented by geostrophic inflow from the west [7,8]. The current has been observed transporting 7 Sv of water in midwinter [8], and 1.4 Sv in summer [9]. This seasonal change in intensity has been attributed to regional wind stress variability, i.e. the current flows weakly against maximum southerly (opposing) winds in October-March, and strongly against weaker southerly winds in April-March [3]. The current is also often associated with coastal downwelling.

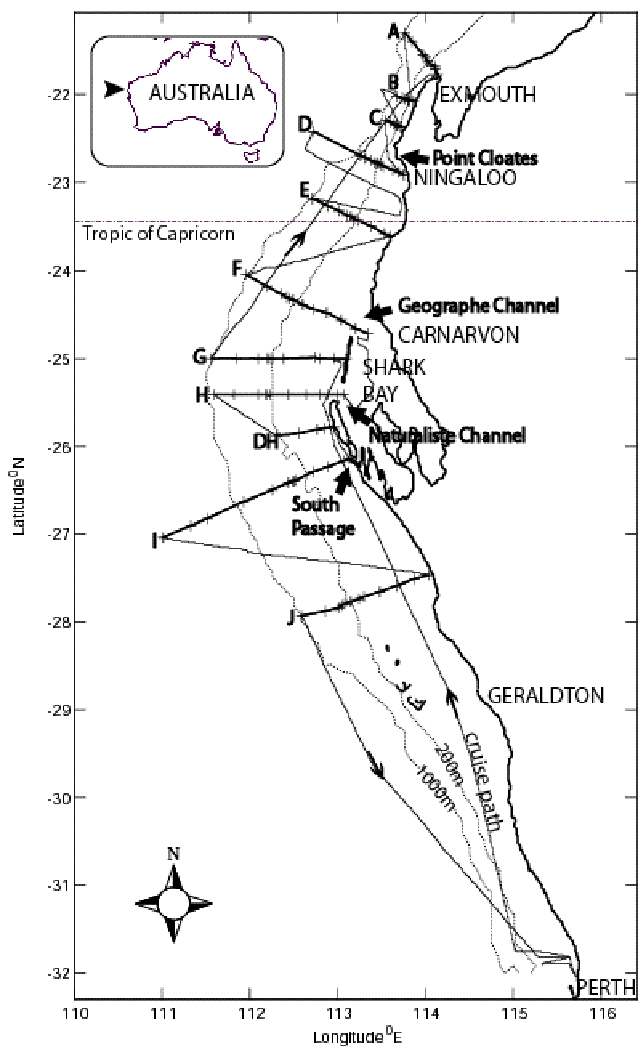

Fig. 1. Location map of FR10/2000 cruise track through the Gascoyne research area.

Inshore of the Leeuwin Current, evidence of high-salinity, wind-driven currents have been recorded along various locations on the Western Australian coastline [8, 9, 10-13]. Generally, the northward coastal current is strongest in summer when the wind pattern is predominantly southerly. Of particular interest to the project discussed here has been a northward coastal current indicated at Ningaloo during summer, i.e. the Ningaloo Current [14]. The Ningaloo Current is thought to be driven by southerly winds [14], much like the more southern coastal currents are. Considering records of cold water anomalies at Ningaloo coast [15], Taylor & Pearce (1999) postulated that coastal upwelling might occur at Ningaloo. However, convincing evidence for this had yet to be found.

A recurring feature of interest, revealed by satellite imagery, has been an anti-cyclonic circulation pattern located immediately south of Point Cloates. Although the actual dynamics of this feature is still poorly understood, a Platform Transmitter Terminal (PTT) (which accidentally detached from a whale shark and became a current drogue) has indicated it to be a region of some degree of cross-shelf exchange/re-circulation (Taylor & Pearce, 1999). Taylor & Pearce (1999) speculated that the presence of the Ningaloo Current and the circulatory movement of water could have major implications for the regional ecosystem. However, no hydrological evidence had been found from historical cruise data to describe the recirculation.

II. DATA SET

The fieldwork for this study was performed over a 2-week period at the onset of the austral summer of 2000, aboard the RV *Franklin*, a 55m Australian National Research Facility vessel. Instrumentation used on board included a Neil-Brown Conductivity-Temperature-Depth (CTD) recorder with 24x 5L-bottle Niskin rosette for calibration and water sampling, a 150-kHz RDI Acoustic Doppler Current Profiler (ADCP) served by the Global Positioning System (GPS), meteorological sensors and a Thermosalinograph.

The RV *Franklin* undertook the cruise path illustrated on Fig. 1. Eleven standard lines were conducted along the continental shelf between 21^0S and 28^0S. For each transect, 5-13 CTD stations were occupied depending on the shelf width. The transects generally extended from the coast (30m-isobath) to the 1000m contour, with stations positioned over the isobaths of 30m, 100m, 150m, 200m, 250m, 300m, 500m, 750m, 1000m, and at intermediate intervals between isobaths if they were widely spaced. Surface salinity, temperature and water depth were continuously monitored.

Wind data during the voyage was logged by the underway meteorological station onboard. Also, half-hourly wind data were taken from land-based meteorological stations at Learmonth, Shark Bay and the Abrolhos (North) Island.

During the cruise, concurrent satellite Sea Surface Temperature (SST) data were made available for this project through a collaborative arrangement with Alan Pearce of the CSIRO Division of Marine Research and Assoc./Prof. Merv Lynch of Curtin University of Technology.

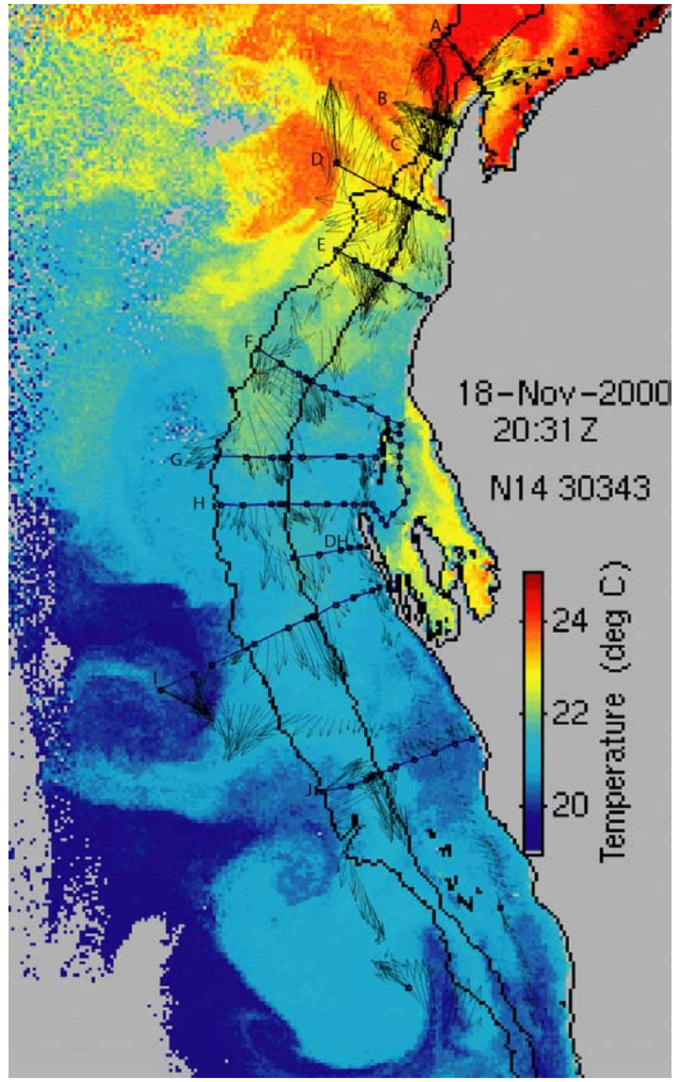

Fig. 2. Satellite SST image with ADCP overlay showing surface water directions as observed along the cruise track.

III. RESULTS AND DISCUSSIONS

Throughout the past two decades, extensive observational and modelling studies have established the eastern boundary current found off the coast of Western Australia to be the Leeuwin Current. During the time of our fieldwork, this current was clearly observed passing along the Gascoyne coast. Concurrent satellite SST imagery showed a large raft of warm water residing in the north (Fig. 2), serving as the northern source from which the Leeuwin Current flowed, relatively warm and fresh, poleward along the shelf-break. From surface ADCP velocities taken along our cruise-path, it may be seen that the strongest poleward flow followed the 200m isobath (Fig. 2).

A more detailed view of the cross-sectional structure of the Leeuwin Current was seen in ADCP and CTD cross-sections, where the Leeuwin Current was generally identified as a distinct core of relatively fresh, warm water, pushing strongly poleward along the shelf-break. Isopleths beneath the Leeuwin Current appeared depressed, indicating downwelling.

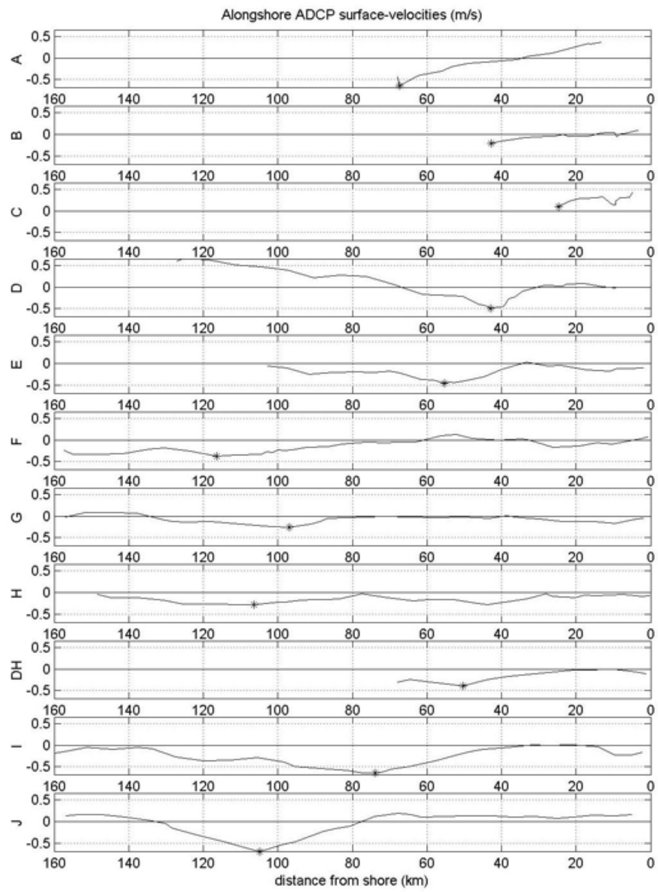

Fig. 3. Alongshore ADCP measurements across the surface of 11 transects. Asterisks show closest recorded positions for strongest poleward flow.

Flowing poleward along the Gascoyne, the Leeuwin passed over regions where the width of the continental shelf varied markedly: from an extremely narrow cliff-like structure in the north, to a very wide and gradual table extending from Shark Bay, and then to a shelf which narrowed again towards the south (Fig. 1). Consequently, the structure and strength of the Leeuwin Current also altered. Examining alongshore surface flows in ADCP records taken across 11 transects (Fig. 3), the Leeuwin Current was detected narrow and strong in the north (transect D), broadening and slowing as it rounded the broadest section of the shelf (between transects F and DH) and then rapidly narrowing and speeding up again, away from Shark Bay, along a steepening shelf (transects I through J). Thus, at its narrowest, its surface width measured only 37km, while at its broadest, its width was in excess of 100km. Meanwhile, the alongshore flow varied from as weak as 0.26m/s, to as strong as 0.68m/s poleward.

Analysing CTD data collected at each transect, on the station closest to the strongest poleward flow, a pseudo-transect line was constructed, slicing through the length of the Leeuwin Current core (Fig. 4). The pattern that ensued revealed that the current core turned cooler and more saline southward. Indeed, while scrutinizing CTD data taken from successive transect lines, it had been impossible to define the current's presence merely by tracking water of a fixed TS-signature, because in effect, the TS-signature itself continuously transformed with the Leeuwin Current's passage along the coast. The signature, beginning at the top left corner of the TS-diagram, gradually slid towards the bottom right corner of the chart (Fig. 5). Hence, in the course of its journey through the study area, the core temperature and salinity of the Leeuwin Current fell some 3^0C, and increased 0.5psu respectively. Evaporation and atmospheric cooling were contributors to the aforementioned changes in water properties. Besides these, another significant cause for the Leeuwin Current's 'ageing' was its mixing with surrounding waters along the way. It was found from calculations of geostrophic flow across the 1000m and 500m (Fig. 4) isobaths, that there existed an influx of offshore water towards the shelf, carrying 4Sv and 2Sv respectively, across the top 300m layer. This water incorporated cooler, more saline properties into the poleward flow, as inferred from the fact that such water was found offshore, at the end of the furthest-reaching transect I. This agrees with the description by Church *et al.* (1989) of an inflow of high salinity water from the West Australian Current [16].

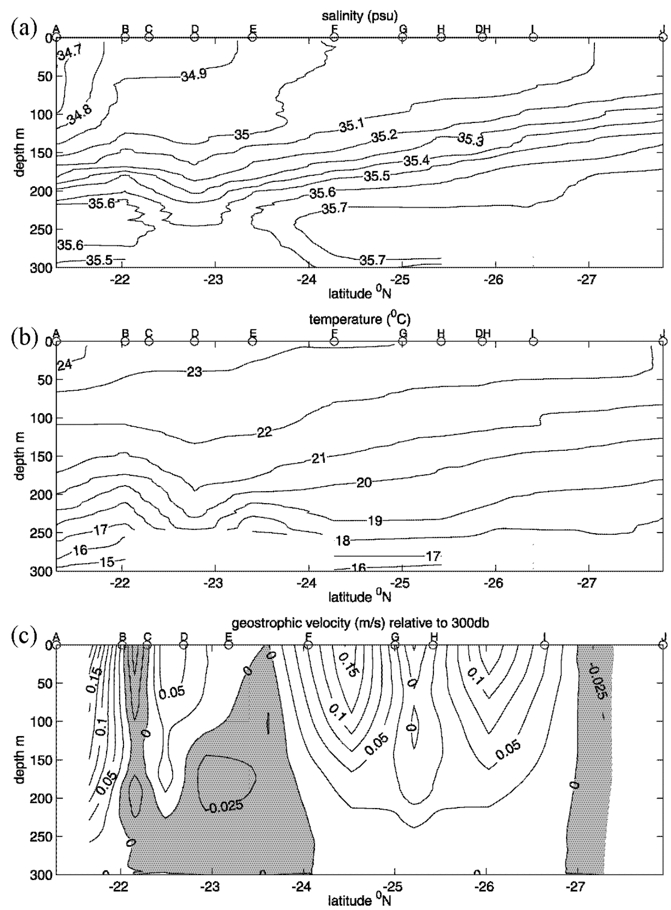

Fig. 4. (a) Salinity and (b) temperature properties along the length of the Leeuwin Current, and (c) geostrophic flow relative to 300db across the 1000m isobath. Shaded areas indicate flow away from the Leeuwin Current.

Another element which interfered with the Leeuwin Current flow on its seaward side was the presence of offshore eddies which swept the current into deviating directions. During this study, three transects reflected the effect of offshore eddies. At transect D, a large anti-cyclonic eddy was observed flowing quite rapidly, causing water at the deep end of the transect to flow equatorward at speeds of up to 0.65m/s. As a result, the seaward edge of the Leeuwin Current was also swept into a reversed direction. The eddy brought warmer, fresher water, similar to the 'younger' Leeuwin Current water found further north. It was likely that water in both the eddy and the Leeuwin Current had come from the same source in the north, except, having moved south more quickly, the eddy's water had 'aged' less than its counterpart at the shelf break. Eddies were also observed at the ends of transects I and J, spinning clockwise and anti-clockwise respectively. In addition to pulling the Leeuwin Current into the direction of their flow (seaward and coastward, respectively), these eddies also introduced cooler, more saline surface waters with average measurements of 20.94^{0}C, 35.44psu from an offshore source. Such interactions between the offshore eddies and the Leeuwin Current would conceivably contribute to exchanges of substances or biological species between the Leeuwin Current and the offshore environment.

On the landward side of the Leeuwin Current, coastal processes exerted their effect. Along various other locations on the Western Australian coastline, evidence of cooler, high-salinity, wind-driven currents have often been recorded flowing inshore of the Leeuwin Current, and the situation along the Gascoyne coastline in summer is no different. During this study, two such coastal currents were recorded.

At southernmost end of the research area, a cool coastal current was identified in satellite SST images as a cool (blue) strip running between 30.5^{0}S and 27^{0}S (Fig. 2). Properties of the coastal current were measured at stations of transect J. Inshore of the Leeuwin Current, CTD and ADCP measurements clearly showed a coastal current carrying cool (21.21^{0}C), saline (35.44psu) water equatorward at a maximum alongshore velocity of 0.15m/s. Upwelling was not evident in the records. However, as local winds were also persistently southerly, this coastal current was likely to have been wind-driven, coming from an upwelling region south of the study area, i.e. being the northern continuation of the Capes Current [10, 11].

The other coastal current, the Ningaloo Current [14], was observed at the northernmost region of the study area, between 21^{0}S and 24.5^{0}S. As is typical of coastal currents found elsewhere along the coastline, the Ningaloo Current at transect A was also confined to the coast (within 35km from land), inshore of the Leeuwin Current (Fig. 3). CTD and ADCP records showed the coastal flow to comprise cooler (22.95^{0}C), higher salinity (34.92psu) water, moving northward with the prevailing wind at a maximum alongshore velocity of 0.35m/s. Additionally, upward-sloping isohalines and isotherms beneath the Ningaloo Current were indicative of associated coastal upwelling.

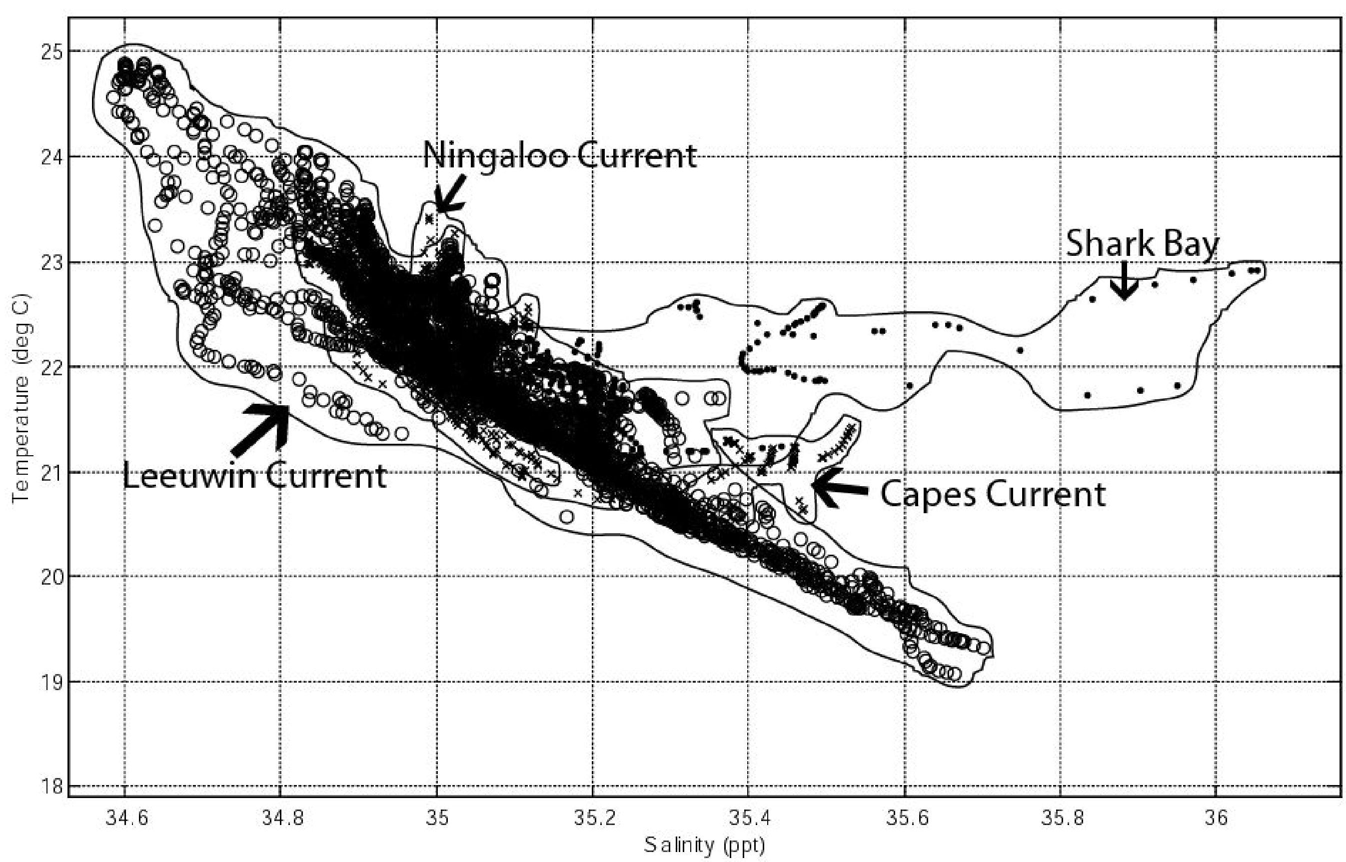

Fig. 5. TS-diagram for 150m surface layer of water across all 11 transects.

Elsewhere in the Ningaloo Current system, complications to the flow were observed, most notably as a result of interactions with a peninsular and its associated changes in bathymetry, as well as with the Leeuwin Current, which flowed very closely to the coastline along the peninsular.

The seaward extension of the peninsular effectively blocked off the broad, gradual southern shelf, leaving only a narrow, extremely steep shelf to its north (Fig. 1). Satellite SST imagery and ADCP measurements showed that south of Point Cloates, the Ningaloo Current flowed northward up along the coast. On arrival at the blockade at Point Cloates, it turned with the curve of the promontory, westward across the shelf and out across to the shelf-break. This resulted in relatively cool, high salinity (mean values: 22.71^{0}C, 35.00psu) Ningaloo Current water being witnessed over the entire shelf across transect D. On reaching the seaward margin of the promontory, part of the Ningaloo Current turned to continue north towards North West Cape, while the rest of the current swept around to flow poleward along with the Leeuwin Current.

In satellite SST imagery, the arm of the Ningaloo Current proceeding equatorward along the edge of the peninsular was seen as a very narrow strip of cool water along the coast (Fig. 2). This flow, which was further evidenced in CTD data, was found to carry water different from the local Leeuwin Current flowing there. Yet interestingly enough, its TS-signature bore close resemblance to that of the 'older' Leeuwin Current found back at Point Cloates. This indicated some extent of re-circulation of the 'older' Leeuwin Current equatorward, in the Ningaloo Current.

Whilst moving northward along the constricted shelf off the peninsular, the Ningaloo Current abutted the Leeuwin Current (which travelled in the opposite direction at the shelf-break very close to the coast here) and went off in coastal offshoots seen at transects B and C (Fig. 2). As a result, the surface waters became well mixed.

The arm of the Ningaloo Current that did not carry on along the peninsular, was swept poleward along with the Leeuwin Current against the wind. This produced a southward Ningaloo Current observed in transect E. Here, although all of the coastal water went poleward, TS analysis clearly revealed that apart from Leeuwin Current water, there was the cooler, more saline Ningaloo Current water present at the coast. Notably, the Ningaloo Current water detected both here and at the previous transect (i.e. at transects D & E) bore close resemblance to the 'aged' Leeuwin Current water found in the next transect south (transect F). So it was likely that the water from the Leeuwin Current at transect F had been re-circulated up the coast as the Ningaloo Current. This postulation received some support from the finding that the surface water at the coastal border of the Leeuwin Current was seen turning back coastward and northward on this transect. No northward coastal current had been seen at Transect E, however. It was a possibility that it had in fact travelled undetected to Transect D, as a narrow coastal current beyond the coastal extent of the transect.

The re-circulative patterns at Ningaloo would imply that coastal substances swept away by the Leeuwin Current, could be re-circulated and returned up the coast in the Ningaloo Current, hence affecting the retention and recycling of nutrients in the Ningaloo ecosystem, and the distribution of marine life in the region.

Between 24.5^{0}S and 27^{0}S, a different set of coastal processes were observed. Here, the dominant geographical feature was Shark Bay, a 14 000km^2 hypersaline embayment whose coastline was broken at three places: 1) Geographe Channel, 2) Naturaliste Channel, and 3) South Passage. (Fig. 1).

Transect F, which extended from Geographe Channel, saw the introduction of Shark Bay water into the coastal system. Hypersaline water (>35.3psu) was seen to flow from Geographe Channel out onto the shelf, with the most intensely saline water (36psu) moving along the bottom on the shelf-bed. Due to Coriolis forces, the water turned poleward on exiting the mouth. Transect H, which extended through Naturaliste Channel, also recorded Shark Bay outflow. A hypersaline slug (35.4psu) was detected at the coastal stations, spanning 30km along the seabed out to sea.

From the surface velocity chart (Fig. 2) it can be seen that at Transect G, whilst the Leeuwin Current continued to flow poleward at the shelf-break, another current had begun also flowing poleward at the coast. CTD measurements show this coastal current to carry water of a very distinctive 35.2psu salinity signature, well mixed in the vertical water column at the coastal CTD stations landward of the 100m-isobath. This well mixed 35.2psu was subsequently detected on the coastal side of the Leeuwin Current through all the more southern transects of the research area, hence existing as some sort of 'common shelf water'. The water did not come about from mixing between the Capes Current and Leeuwin Current, since its position at 25^{0}S could not be explained because the Capes Current did not extend far enough north, and the 'common shelf water' was poleward-moving. The idea that the coastal water resulted from local upwelling was also improbable, as poleward currents here do not encourage upwelling.

The most plausible explanation emerged from meteorological data logged onboard, which showed the wind streaming eastward on the shelf at transect G, and then poleward on approaching the land. Moreover, meteorological logs from the land-based stations at both Shark Bay and the Abrolhos (North) Island showed the northerly wind to persist for 2 consecutive days. This wind pattern would have been conducive to the development of a wind-driven poleward coastal current which in turn may have promoted mixing between the Shark Bay outflow and the coastal edge of the Leeuwin Current, forming the 35.2psu water on the shelf. Transect H was performed a week after Transect G was done. In the time that elapsed in-between, the winds had swung back around to a southerly direction, and it could be seen from salinity profiles that the vertically mixed structure of the coastal water column had begun to collapse. Here, although the 35.2psu water was still present on the shelf at the 6 coastal stations (furthest station being at 135m-isobath), apart from the well mixed water column at the nearest station, the upper 40m of the other 5 coastal stations now clearly exhibited more influence by Leeuwin water.

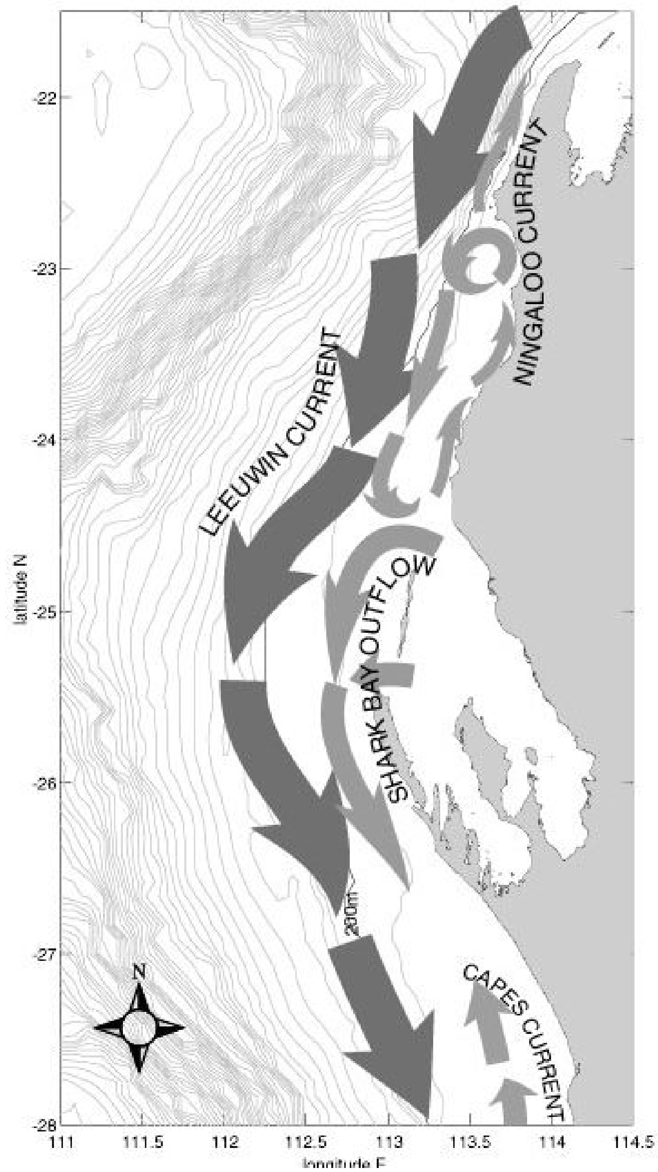

Fig. 6. Generalised circulation pattern of the major surface currents in the Gascoyne coastal waters.

Transect I extended seaward from South Passage, the southernmost and smallest opening out of Shark Bay. Here, inshore of the Leeuwin Current, evidence of the 'common shelf water' was also seen at the coast. However, salinity of the water here was 0.02psu higher than in the previous transects, due to the proximity to the hypersaline bay water through South Passage.

At transect J, at the southern extent of the research area, the 'common shelf water' was still present, albeit not immediately beside the coast, since that was now where the Capes Current flowed. The 35.2psu water was detected at the stations in the coastal edge of the Leeuwin Current. It is likely that the coastal water had been swept along in the Leeuwin Current, and taken offshore with it. It should be noted however, that because sustained northerly winds are generally not a regular occurrence at the Gascoyne in summer, the 35.2psu 'common shelf water' is not expected to be a frequent phenomenon.

To illustrate the relative positions of signatures of each major surface water-mass, a TS-diagram is charted from CTD data taken from the 150m surface layer across all 11 transects (Fig. 5). Notably, signatures of both Shark Bay and Capes Current waters are conspicuously separate from that of the Leeuwin Current. On the other hand, the Ningaloo Current in part comprises re-circulated Leeuwin water, so its signature and that for the Leeuwin Current overlaps. The signature for the Leeuwin Current itself appears elongated due to its 'ageing' as it progressed along the coast; its signature occupying a position progressively from the top left corner to the bottom right. Finally, a generalised view of a likely flow regime, as outlined throughout this section, is shown in Fig. 6.

IV. CONCLUSION

The coastal circulation in the Gascoyne region comprises a complicated system of currents and their interactions with offshore eddies, wind patterns, varying shelf-widths, a coastal promontory and a hypersaline bay.

The Leeuwin Current is the major boundary current found through the Gascoyne. It carries relatively fresh, saline water and generally flows poleward along the vicinity of the 200m-deep shelf-break. However, because the current was continually 'ageing' along its journey, cooling and gaining salt along the way, it could not be traced as a 'river' of water of defined make-up. In the course of its journey through the research area, its signature was seen to have gradually transformed from a warm (24.85^{0}C), relatively fresh (34.92psu) nature at Exmouth, to a much cooler (21.21^{0}C), more saline (35.44psu) condition, as a result of evaporation, atmospheric cooling and its mixing with surrounding waters along the way. Contributing to the latter, there was a geostrophic influx of offshore water (possibly from the West Australian Current) towards the shelf which introduced cooler, more saline conditions to the poleward flow.

The Leeuwin Current also meandered. On its seaward side, offshore eddies were observed interacting with the Current, and on the landward side, coastal processes exerted an effect. Where unimpeded by seaward jets or outflows from the bay, the Leeuwin Current flowed strongly at 0.6–0.75m/s. Otherwise, it slowed to about 0.2–0.4m/s. Downwelling events were persistently associated with the Leeuwin Current.

The Ningaloo Current flowed on the shelf along the northernmost coast of the Gascoyne. Although upwelling was detected, its water properties were also clearly suggestive of recirculation of Leeuwin Current water from more southern locations. A recurring anticlockwise flow pattern, detected south of the promontory of Point Cloates, would have caused such a re-circulation. Some indication of possible re-circulation was also observed just north of Shark Bay at Transect F. The impact of such a system on the coastal ecosystem may be found to be significant, as it would imply that coastal substances swept away by the Leeuwin Current could be re-circulated and returned up the coast in the Ningaloo Current.

Shark Bay influenced the coastal system mainly through Geographe and Naturaliste Channels. While the most hypersaline water was found on the seabed within 30km seaward of the Channels, the surface water mixed with the Leeuwin Current, forming a distinctive 'common shelf water' with a vertical salinity profile of 35.2psu. This mixing was likely encouraged by persistent northerly winds at the onstart of the voyage. The 35.2psu coastal water was then swept poleward and out seaward along with the Leeuwin Current. Because sustained northerly winds are generally not a regular occurrence at the Gascoyne in summer, it is unlikely that the 35.2psu coastal water be a recurring phenomenon.

The southernmost end of the research area saw the flow of cool, relatively saline water up the coast. This was possibly the northern continuation of the Capes Current, a wind-driven current originating from further south.

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