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Summer sea surface temperature fronts and elevated chlorophyll-a in the entrance to Spencer Gulf, South Australia

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ABSTRACT

Historical and recent oceanographic cruise data, MODIS chlorophyll-a satellite data, and an analytical model are used to examine SST fronts in the entrance to Spencer Gulf, South Australia. The fronts (2–3 °C) due to the contrast between warm Spencer Gulf waters and cooler waters of the continental shelf are readily observable on satellite imagery. Three water masses: cool, fresh upwelled shelf water; warm, salty Great Australian Bight water; and very warm and salty Spencer Gulf bottom water occupy the area. In consequence a summer density minimum is formed at the entrance to Spencer Gulf. The analytical model predicts that this thermohaline structure sets up an ageostrophic circulation, which favours upwelling in the central portion of the entrance. This is confirmed by the satellite data which show an increased chlorophyll-a concentration in the vicinity of the upwelling.

1. Introduction

Spencer Gulf (SG), South Australia (Fig. 1), is classed as an inverse estuary (in which seawater is concentrated by the removal of freshwater). It penetrates into the arid zone of Australia to about 32° 30′S with an average net evaporation rate of about 1.2 m/year (Nunez Vaz et al., 1990). Throughout the year there is little freshwater input from rivers or precipitation. In the summer at the head of SG the salinities exceed 48 (Nunes and Lennon, 1986) due to excessive evaporation.

During austral winter a bottom-residing high density outflow occurs along the eastern side of SG (Lennon et al., 1986). A similar outflow of high density waters occurs in the Great Australian Bight (GAB) eastward of the head of the GAB (Petrusevics et al., 2009). In both cases, the discharge occurs as a result of their acting as inverse estuaries, which expel high density bottom waters formed by cooling of high salinity waters in the winter. Both discharges from the GAB and SG eventually cascade over the continental shelf south-west of Kangaroo Island.

During summer the high density discharges in both SG and the GAB cease, and sea surface temperature (SST) fronts occur at the entrance to SG (Nunez Vaz et al., 1990; Petrusevics, 1993), which is the focus of this paper.

Such fronts exist in many shelf seas, (Simpson and Hunter, 1974; Simpson and Bowers, 1981; Yanagi and Yoshikawa, 1987), and they were first documented in SG in the mid-1960s in CSIRO oceanographic cruise reports (Anon, 1965, 1968a, b, 1969) of the tuna fishing grounds, and the Flinders University of South Australia cruises in the late 1980s (Petrusevics, 1993).

The SST fronts form about December, intensify in March and collapse in April, and are the result of warmer surface waters of the relatively shallow SG abutting cooler surface shelf waters at the entrance to SG. These surface features have been observed on satellite imagery since the mid-1980s using NOAA Advanced Very High Resolution Radiometer imagery (Petrusevics, 1993) and more recently using Moderate Resolution Imaging Spectradiometer (MODIS) satellite data (Petrusevics and Bye, 2008) and are described using climatological data in Middleton and Bye (2007).

Temperature fronts are often reported to be associated with increased biological activity represented by increased chlorophyll-a levels at the surface, for example in the Celtic and Irish Seas (Savidge and Foster, 1978). Worm et al. (2005) examined worldwide patterns of tuna and billfish diversity over the past 50 years and concluded that diversity was positively correlated with

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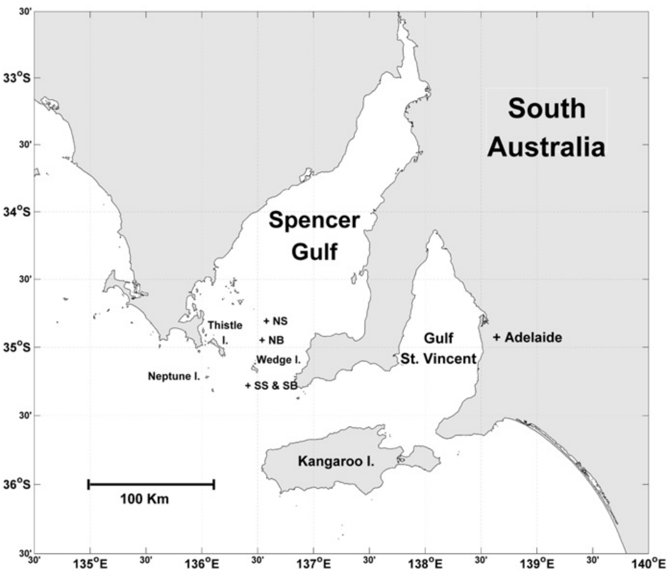

Fig. 1. Study region showing current meter locations during MV *Boobook* cruise March 1988. NS and NB north surface and bottom moorings, and SS and SB south surface and bottom mooring.

thermal fronts and dissolved oxygen, which appeared to hold generally for other predators and zooplankton.

In the local context Bruce and Short (1990) reported a discontinuity in larval distribution and an increase in larval diversity within the SG temperature frontal zone, and since 2002 MODIS satellite observations have revealed co-located seasonally persistent regions of elevated chlorophyll-a levels.

This paper examines in detail the interaction between the SST fronts and increased biological activity represented by increasing seasonal concentrations of chlorophyll-a levels in SG. In Section 2, the origin of the density minimum in the entrance to SG in the context of the regional oceanography is discussed, and Section 3 presents the results from two historic summer cruises (1988 and 1989), which describe the fine structure of the density minimum, and have not been previously reported.

In Section 4, MODIS satellite observations of the monthly averaged SST and chlorophyll-a structure over an annual cycle (July 2002–June 2003) along a longitudinal section through the entrance to SG are presented, which show the seasonal onset, persistence and decay of chlorophyll-a in the frontal zone, and in Section 5 the results of a recent summer cruise (2009) in the entrance to SG are discussed, in which for the first time, coincident MODIS data, and also shipborne observations of fluorescence were available.

Finally in Section 6, a simple analytical model of the density minimum in the entrance to SG is derived, which predicts the uplift of nutrient rich waters to the surface that give rise to the elevated concentrations of chlorophyll-a, and Section 7 is a brief conclusion.

2. The regional oceanographic origin of the summer density minimum in the entrance to Spencer Gulf

The SST fronts are formed by the warmer surface waters of the relatively shallow SG abutting cooler surface shelf waters at the entrance to SG. The regional and seasonal picture is shown in the CARS surface climatology (Ridgway et al., 2002) for the austral summer (Middleton and Bye, 2007, Fig. 20), which shows that in the western and central GAB, warm high salinity water occurs inshore along the southern coast of Australia, with cold low salinity water in the Southern Ocean, which mix together laterally to form a region of lower density water. The density minimum appears to be due to the summer heating, which reduces the surface density of the oceanic water as it approaches the coast, until it is sufficiently inshore for the increase in salinity to become dominant, and cause the surface density to rise. In the eastern GAB the density minimum extends south-eastward in an arm of the anti-cyclonic gyre centred on the wide continental shelf (Herzfeld and Tomczak, 1999). This warm saline stream, which flows between the cooler upwelled water along the west coast of Eyre Peninsula and the cooler Southern Ocean water to the south, has been called the Great Australian Bight Plume (GABP) (Herzfeld and Tomczak, 1999; Richardson et al., 2009).

To the south of SG the progress of the GABP is interrupted by a corridor of higher density water, which is due to an onshore arm of the mesoscale structure of the Flinders Current (Bye, 1983, Middleton and Bye, 2007), brought about by the coastal wind structure, as is evident in the fields at 50 and 40 m (Fig. 2), obtained by CSIRO during February 1965 (Anon, 1965).

At 50 m depth (Fig. 2a–c) the GAB water extends as a warm saline low density intrusion at the surface south of Eyre Peninsula. This intrusion is also evident in the CARS climatological atlas. The temperature (Fig. 2b) and salinity (Fig. 2c) charts show that the intrusion meets a region of cooler fresher shelf water to the west of Kangaroo Island, which is due to the Kangaroo Island pool of water upwelled from over the shelf break (Middleton and Bye, 2007). At the 40 m level, the density minimum propagates into the entrance to SG (Fig. 2d), with warmer saltier waters on the eastern side and cooler fresher waters on the western side (Fig. 2e–f), until it meets a density front formed by the saline high temperature gulf waters.

These three interacting water masses (shelf water, gulf water, and GAB water) were first identified by Hahn (1986). The TS properties described above are also discussed in Petrusevics (1993) in which the three water masses are identified in a TS diagram.

3. The structure of the density minimum in entrance to Spencer Gulf

3.1. The MV Boobook survey (summer 1988)

The first, and most detailed, survey of the structure of the density minimum in the entrance to SG was undertaken during March 1988. The purpose of the investigation was to relate SST fronts, readily observed on satellite imagery (Petrusevics, 1993) to underlying water properties.

The commercial vessel, MV *Boobook*, was used to conduct the survey (Fig. 3) in water depths ranging from about 60 m on the shelf to about 40 m in SG (*Boobook 03/88*). A Seabird CTD logger with 0.5 s sampling rate and a descent rate of 1 m s^{-1} was used. SST was measured with a standard mercury-in-glass thermometer and water samples (top and bottom) were analysed with an autolab inductive salinometer. A horizontal section at 10 m depth shows a region of lower density (Fig. 4a) in the centre of the entrance to SG and almost zonal temperature and salinity fronts (Fig. 4b and c) at about 34°55′S. A similar structure was observed at 40 m.

The wind rose for the summer season (December 1987–February 1988) at Neptune Island (35°20′S, 136°7′E) which lies about 40 km to the south-west of Wedge Island (Fig. 1), indicated that during the study period, the winds were mainly south south-easterly with speeds of 5–10 m s^{-1}, indicating that the components of mean wind stress were similar to the climatological mean values of -0.029 and 0.058 N m^{-2}.