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The Hillarys Transect (1): Seasonal and cross-shelf variability of physical and chemical water properties off Perth, Western Australia, 1996-98

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Abstract

A 27-month study of the water properties across the continental shelf off Perth, Western Australia (the "Hillarys Transect") has provided the first systematic inter-disciplinary climatology of the physical, chemical, optical and biological cycles across the shelf. This paper describes the main features of the seasonal and cross-shelf variability of the physical oceanography and chemistry, while companion papers discuss some of the links between the biology and physics of the region.

The oceanography is dominated by the seasonally-varying Leeuwin Current flowing southwards along the shelf break and outer shelf, and the northwards inshore Capes Current which is driven by the net southerly wind stress between about October and March (the austral summer). As a result of the poleward boundary current, there is no large-scale upwelling comparable with the Humboldt and Benguela Current systems. Water temperature and salinity in the shallow coastal waters are largely influenced by air-sea heat flux processes, while advection plays a more important role along the outer shelf; as a consequence, seasonal variations in the inshore temperature and salinity are much larger than those offshore. Cross-shelf exchange of water and plankton is effected by (1) large-scale meandering of the Leeuwin Current, (2) horizontal mixing as tongues of Leeuwin Current water penetrate across the shelf, (3) cascading of high-density coastal water offshore along the seabed, and (4) sporadic summer upwelling onto the outer shelf (including the wake effect north of Rottnest Island).

Nutrient and chlorophyll concentrations are low in comparison with other typical west coast situations. While there is some indication of a seasonal cycle, the relatively short sampling period and high patchiness have precluded definitive patterns being described and longer-term sampling may be required to resolve this.

The effects of smaller-scale temperature and chlorophyll variability on satellite remote sensing measurements (both "within-pixel" and "between pixel") in these coastal waters have been quantified using the underway (horizontal) and profile (vertical) data from the surveys. The

project has demonstrated the great potential of using remote sensing information for regular monitoring of the Western Australian continental shelf waters provided that adequate in situ validation measurements are also undertaken.

Keywords: hydrography, remote sensing, chlorophyll

1. Introduction

Australia possesses an extensive coastline and Exclusive Economic Zone (EEZ) that covers over 30° of latitude and encompasses tropical, subtropical and temperate realms, giving rise to a great diversity in bioregions. The Australian National Oceans Policy (Environment Australia, 1998) provides the motivation to understand these bioregions as a precursor to developing management strategies for conservation and utilisation for public and commercial benefit. The latter include fishing, tourism, recreation, resources development, and maintenance of cultural and heritage values. An integrated, ecosystem-based approach to planning and management of marine and coastal environments is required and there is significant support for the adoption of a bioregional marine planning approach as the most appropriate strategy.

The Interim Marine and Coastal Regionalisation for Australia (IMCRA) provides the first major attempt at such bioregionalisation at a national level. Briefly, regions were defined at three spatial scales and based on the available physical and biological data. Sixty diverse meso-scale regions covering the entire coastline and continental shelf were defined and described (IMCRA, 1998), with the metropolitan waters of Perth falling on the boundary between the Central West Coast (CWC 33) and Leeuwin-Naturaliste (LNE 34) regions. The Hillarys Transect is on the southern limit of the CWC region. However, the available data in most of the remote regions were sparse and varied, indicating that much more data collection and research were required in order to understand the regional variability in the physical oceanography and the basic biogeochemical processes. The establishment of baseline conditions in a bioregion and the identification of the natural variability under seasonal and interannual climatic forcing are essential elements in the description and understanding of a bioregion.

It is important therefore to develop and evaluate methods for a systematic study of selected coastal bioregions to support their classification, monitoring and management. Since satellite remote sensing can play a crucial role in such bioregion monitoring, a number of standard and evolving remotely sensed ocean products should be evaluated to determine their accuracy and utility in support of bioregion management.

This provides the motivation for the present research in Perth's coastal waters, which have some unique features. Instead of a cool northwards boundary current (as found off the west coasts of southern Africa and South America), the dominant current off Western Australia is the warm *south*-flowing Leeuwin Current (Godfrey and Ridgway, 1985). The lack of large-scale upwelling (which occurs in the Benguela and Humboldt Current regions) results in a generally nutrient- and chlorophyll-poor ocean environment (Rochford, 1980; Pearce *et al.*, 2000; Lourey et al., 2006), with the commercial fisheries being dominated by benthic invertebrate species rather than pelagic fish (Lenanton et al., 1991; Caputi et al., 1996). The major sources of nutrients along the Western Australian continental shelf are river run-off and local inshore recycling, with only a small contribution from sporadic localised upwelling (Gersbach et al., 1999; Hanson 2005a).

Because of the large expanse of the Western Australian coastline, satellite remote sensing provides the only feasible means of monitoring the near-surface water properties along the continental shelf on a regular basis. Sea-surface temperature (SST) data can show current circulation patterns provided the thermal gradients are sufficiently distinctive, and water temperature is also an important factor in marine ecology and fisheries. Estimates of the chlorophyll content of the water (and hence phytoplankton abundance and distribution) can be obtained from ocean colour satellite imagery, although there are potential problems of interpretation near the coast because of non-phytoplanktonic components in the water (so-called “Case 2” waters), bottom reflection effects and the proximity of land. It is important, therefore,

to validate the remotely-sensed data using *in situ* measurements of temperature and chlorophyll to ensure that the satellite-derived estimates can be applied with confidence in coastal waters.

As part of a national program for validation of both SST (NOAA-AVHRR) and ocean colour (SeaWiFS) satellite imagery, monthly surveys were undertaken on a transect across the continental shelf off Perth in southwestern Australia (Figure 1) between 1996 and 1998. The surveys were termed the "Hillarys Transects" as they extended due westward from Hillarys Marina (31°50'S). The inshore stations were in the nominally pristine waters of the Marmion Marine Park (CALM, 1992) while the offshore stations were along the outer continental shelf and hence likely to be influenced by the Leeuwin Current.

To improve our knowledge of the physical and biological processes on the continental shelf off Perth, the opportunity was also taken to monitor a much wider range of physical, optical and biological quantities than those required simply for satellite validation. With rapid growth in the population of metropolitan Perth (the capital city of Western Australia) and the resulting pressures on the coastal marine environment, it is increasingly important that the water properties on the continental shelf are well understood. While some major studies have been undertaken in this region over the years, mainly for effluent dispersal purposes, there have been no systematic surveys examining the physical, biological and optical water properties across the continental shelf. This project was therefore the first consistent interdisciplinary study of the water across the continental shelf of southwestern Australia.

The objectives of the Hillarys Transect surveys were:

1) To characterise the physical, chemical, optical and biological properties of the continental shelf waters off Hillarys (IMCRA region CWC 34) in terms of seasonal and cross-shelf variability;

2) To examine relationships between biological distributions and the oceanographic climatology;

3) To use the *in situ* near-surface observations to validate satellite measurements of water temperature and ocean colour.

4) To assess whether relatively simple in situ measurements complemented by satellite observations can provide adequate information for defining the dominant characteristics of coastal bioregions.

This paper introduces the transect and measuring techniques, provides some relevant background meteorological and oceanographic information, and presents the results of the oceanographic measurements (temperature, salinity, nutrients, chlorophyll). It has a dual focus on seasonal relationships across the continental shelf and on the quality of surface measurements for local validation of remotely sensed data. As such, it also serves as an introduction to the companion papers on bio-optical properties and phytoplankton (Fearns et al., submitted), zooplankton (Gaughan et al., submitted) and SST (McAtee et al., this volume), and provides an overview and integration of the salient results from those papers.

The Hillarys Transect surveys complement and extend earlier work on the Perth continental shelf including the Southern Metropolitan Coastal Waters Study (1991 to 1994; Department of Environmental Protection, 1996) and the Perth Coastal Waters Study (PCWS, also 1991 to 1994; Lord and Hillman, 1995) which examined the assimilative capacity of the metropolitan coastal waters for increased effluent loadings from submarine outlets. The two outlets nearest to Hillarys are the Ocean Reef and Swanbourne outlets, situated some 7 km north and 15 km south of Hillarys, respectively (Figure 1).

During the PCWS, detailed measurements were made of the ocean currents, water properties and nutrients (inter alia) near the existing Ocean Reef outlet between December 1992 and January 1994, and the results were then integrated into a hydrodynamic/ecological model to represent the main features of nutrient cycling in the area. The primary focus of the study was the inner continental shelf, although a series of inshore surveys were undertaken across the shelf some distance north of Hillarys (Pattiaratchi et al., 1995; Zaker et al., submitted). The intensive fieldwork component of the PCWS has given way to an ongoing monitoring project ("Perth Long-term Ocean Outlet Monitoring" = PLOOM) which has subsequently sampled the water

quality in the vicinity of the coastal outlets in the Perth area on a regular basis (e.g. Institute for Environmental Science, 2002).

2. Climatological and oceanographic background

2.1. Winds and rainfall

The climate and seasonal variability of the mesoscale wind field of the southwestern coast of Australia are dominated by the meridional shift in the position of the subtropical high-pressure belt. During the southern summer, this belt is at its southernmost limit of about 40°S (thereby lying south of the Australian landmass; Gentilli, 1971) resulting in a net southerly wind system (Figure 2). Strong coastal sea-breezes (particularly during summer afternoons: Masselink and Pattiaratchi, 2001) are caused by large land-sea temperature contrasts and result in a switch between south-easterlies in the morning and south-westerlies in the afternoon. The afternoon southerlies continue to dominate into autumn and spring (Figure 2). In winter, on the other hand, the high pressure belt migrates northwards to about 30°S, allowing the eastward passage of travelling cyclones and storm fronts along the southern and southwestern coasts and resulting in a much more variable wind system with little sea-breeze pattern.

Steedman and Craig (1983) classified the wind systems into 6 main categories with the following speed ranges: land/sea breezes 0 to 15 m/s (spring-to-autumn months), winter high-pressure systems about 5 m/s (autumn/winter), low-pressure systems 5 to 20 m/s (throughout the year), summer high-low pressure systems about 5 m/s, dissipating tropical cyclones (which occasionally extend southwards to the latitude of Perth in summer) 10 to 20 m/s, and calms defined as less than 1.5 m/s. Clearly, the coastal winds are highly variable on a range of temporal and spatial scales as a result of the combination of the geostrophic wind, the land/sea-breeze cycle, storm events and a residual of shorter-term fluctuations (Breckling, 1989).

The only river of note in the Perth metropolitan area is the Swan River some 25 km to the south of the transect. Rainfall in this area is highly seasonal with some 80% of precipitation occurring between May and October. The monthly median rainfall on the mainland peaks at

about 160 mm between June and August (130 mm at Rottnest Island in July), while during the summer months it falls to < 10 mm (unpublished data, Bureau of Meteorology: http://www.bom.gov.au/climate/averages/tables). The response of the Swan River lags by a month or so, with the highest monthly median discharge of about 60,000 Mlitres in August (unpublished data, courtesy of the Department of Environment); the monthly discharge drops rapidly after September and is less than about 1000 Mlitres between December and April. The coastal currents tend to flow southwards in winter, and it is only after the seasonal current switch in September/October (Steedman and Associates, 1981) that riverine outflow could perhaps be carried northwards along the coast by the developing Capes Current.

Evaporation greatly exceeds precipitation between September and April (Bureau of Meteorology, 1966).

2.2. The Leeuwin Current

The Leeuwin Current is a southward flow of relatively low salinity tropical water along the Western Australian coast, the only significant poleward eastern boundary current in the world and as such is completely different from the equatorward Benguela and Humboldt Currents occurring off the west coasts of southern Africa and South America. It is forced by an anomalously large meridional pressure gradient resulting from the throughflow of low-density equatorial Pacific Ocean water through the Indonesian Archipelago into the tropical eastern Indian Ocean (Godfrey and Ridgway, 1985). The Leeuwin Current flows most strongly during the autumn and winter months when the alongshore pressure gradient is strongest and the opposing (equatorward) wind stress is weakest (Godfrey and Ridgway, 1985; Smith et al., 1991; Feng et al., 2003).

The presence of the Leeuwin Current is responsible for the occurrence of corals and a variety of tropical marine organisms and birds much further south than would otherwise be the case (Hutchins, 1991; Hutchins and Pearce, 1994; Dunlop and Wooller, 1990; Maxwell and Cresswell, 1981; Hatcher, 1991). It is relatively shallow (<300 m) and narrow (50 to 100 km),

and tends to flow southwards along the edge of the continental shelf. Periodically, however, large meanders carry the warm water over 200 km from the shelf (Cresswell, 1980; Pearce and Griffiths, 1991; Department of Environmental Protection, 1996). Woo et al. (2006) suggest that these meanders may entrain relatively high-chlorophyll shelf waters and transport them into offshore eddies thus effectively exporting chlorophyll from the shelf, while Mills et al. (1996) found that some shelf-break upwelling can also result from the meandering process.

The strongest surface temperature gradients visible in thermal satellite images generally occur along the offshore (western) boundary of the Current; the gradients along the inshore boundary of the Current are weaker, which can create some difficulty in unambiguously distinguishing between Leeuwin Current and shelf water regimes (see later). As shown by Cresswell (1996), however, while the strongest currents approaching 1 m/s are generally within the Current as visible in the satellite images, relatively strong southward currents can still occur beyond the offshore Current "boundary" SST front, raising some questions perhaps of how the Leeuwin Current is actually defined.

As no current measurements were made during the period of the Hillarys Transects, the historical PCWS current data (Lord and Hillman, 1995; Pattiaratchi et al., 1995) have been re-analysed to summarise the shelf and coastal current regimes. During the PCWS, currents were measured at two "deep-water" sites near the shelf-break and three "shallow-water" sites along the inner shelf north of the Hillarys Transect between December 1992 and January 1994. The outer shelf current meters were initially deployed for 4 months (until March 1993) at a site in about 200 m water depth, and the mooring was then moved inshore to a depth of 110 m for the next 10 months -- for convenience, these two deployments have been simply merged to describe the outer shelf flow over the full year. The monthly mean alongshore current components at about mid-depth (Figure 3a) illustrate the relatively strong southward currents for most of the year. The strongest currents were in March 1992 where the southward component averaged over 40 cm/s, while individual current speeds in this month were up to 80 cm/s. The relative

proportions of the alongshore flow in 90° sectors northward and southward (Figure 3b) confirm that there was a persistent southwards tendency throughout the year although there were also appreciable periods of northwards flow along the shelf-break for the second half of the measuring period. More detail of the current measurements can be found in Pattiaratchi et al. (1995), who pointed out that the Leeuwin Current was relatively weak during the PCWS period.

2.3. Shelf currents and the Capes Current

The PCWS current measurements on the inner continental shelf showed that the nearshore waters are largely wind-driven, particularly during the summer months when there is a persistent northwards wind stress (Lord and Hillman, 1995).

As the southerly (northward) wind stress strengthens during the late spring months, the Leeuwin Current tends to weaken and move slightly offshore. A seasonal wind-driven inshore countercurrent (the Capes Current -- Pearce and Pattiaratchi, 1999; Gersbach et al., 1999; Cresswell and Griffin, 2004) forms near or south of Cape Leeuwin some 250 km south of Perth, associated with localised upwelling between Cape Leeuwin and Cape Naturaliste and forming the main source of the Current (Gersbach et al., 1999; Hanson et al., 2005a). The Capes Current transports relatively cool water northward past Rottnest Island between October and March, and Woo et al. (2006) found evidence of Capes Current water as far north as Shark Bay (26°S). During the remainder of the year, the mid-shelf currents tend to flow southwards but with many weather-related reversals (Steedman and Associates, 1981; Cresswell et al., 1989; Pattiaratchi et al., 1995).

A re-analysis of the PCWS current measurements was undertaken for the mooring site SW2 (water depth 27 m about 8 km offshore), and showed a far more distinct seasonal pattern than at the shelf break. The northwards Capes Current was the dominant flow during the summer months of October to February, illustrated by both the mean alongshore component (Figure 3c) and the relative frequency of the northwards currents over that period (Figure 3d). In winter when the Capes Current had ceased, there was a small net southwards tendency but the current

directional frequencies nevertheless showed a good proportion of northward flow as well. Peak near-surface current speeds sometimes exceeded 50 cm/s but were more commonly about 30 cm/s. These results effectively matched some earlier measurements made in 20 m water depth 4 km west of Point Peron just south of Perth (Steedman and Associates, 1981) which showed a very distinct switch between northwards currents from October to April and a net southwards flow between May and September.

Subsequent oceanographic surveys around Rottnest Island in 1995 combined with satellite imagery revealed that a cool plume extending northwards in the wake of Rottnest Island during the summer months resulted from a secondary circulation induced by curvature of the Capes Current past the offshore tip of the Island (Alaee, 1998; Alaee et al.,1998). The cooler water was drawn up from the outer shelf just west (offshore) of the Island creating a dome of upwelled water on the mid-shelf north of the Island. (As will be shown below, this has an important effect on the water structure along the Hillarys Transect).

Despite the dominance of the wind stress in forcing the nearshore flow, Zaker et al. (submitted) found that, on occasion, meanders of the Leeuwin Current onto the shelf had a direct influence on the currents nearer the coast. Similarly, Mills et al. (1996) observed that a northwesterly wind in winter 1991 led to an onshore surface migration of warm Leeuwin Current water accompanied by downwelling and an active flushing of the inner shelf by offshore transport near the seabed. Under weaker wind conditions, a mesoscale anti-cyclonic meander of the Leeuwin Current forced a northward flow along the shelf and some upwelling.

The tidal regime along the southwestern coast is predominantly diurnal, and because of the small tidal range (up to 0.6 m), tidal currents in the area are negligible.

3. Data and Methods

3.1. The Transect

The transect consisted of 9 stations H0 to H40 (Figure 1, Table 1) extending to 40 km offshore (the numerical suffix denoting the station distance from the coast in km). The latitude

was selected to ensure safe passage through a gap in the nearshore reef system some 4 km offshore. From the reef, the seabed slopes down to station H5 beyond which lies a gentle plain some 30 to 45 m deep before the seabed finally drops away suddenly at an escarpment some 37 km offshore (Figure 4). Station H0 was in the nearshore lagoon, and all the stations except for H40 were in water less than 50 m deep. The only bathymetric feature likely to influence the shelf circulation was the nearshore reef system which could tend to channel the alongshore flow at the innermost station. Station positions were fixed by the vessel's GPS.

A total of 27 monthly transects were undertaken between October 1996 and December 1998. However, methods were still being developed and equipment evaluated during the first 3 surveys, so some of the results are presented for only part of the 27 month period.

On the outward (westward) leg of each transect, both surface and profile measurements were taken at each station; the homeward leg was a continuous run, except for (from March 1997) a repeat stop at H5 for a comparison of the morning and afternoon conditions. Throughout each trip, surface temperature, conductivity and fluorescence were recorded continuously. The round trip typically took about 5 hours, departing the quayside at 0900 WAST (Western Australian Standard Time). The arrival of the seabreeze around midday usually raised sea conditions at the outer Transect stations, with winds frequently exceeding 10 m/s (Masselink & Pattiaratchi, 2001), but such conditions were in fact beneficial for the SST validation work by ensuring vertical mixing down the upper water column.

The schedule covered the pass of the SeaWiFS satellite, while the afternoon NOAA-14 pass was generally within a couple of hours of the end of the transect. While attempts were made to run the surveys on days when the sea was reasonably calm and the skies clear (for the satellite validation), personnel and boat commitments necessitated occasional trips in adverse or cloudy conditions. On only one occasion (August 1998) did weather conditions prevent the complete transect to H40 being completed.

3.2. Meteorology

Some simple wind measurements were made using a hand-held anemometer from the bow of the boat at each station to provide an indication of "on-station" winds. Although hourly meteorological data were available from a weather station in Hillarys Marina operated by the National Tidal Centre, the measurements are considered unrepresentative of the coastal waters because of the low height of the anemometer and some "sheltering" from adjacent buildings. Accordingly, wind data were obtained from an Automatic Weather Station (AWS) operated by the Australian Bureau of Meteorology at Rottnest Island (Figure 1); the base of the AWS is 43 m above mean sea level, and the anemometer is 10 m above ground level. (The Rottnest wind speeds were more than double those from the Hillarys anemometer).

Wet- and dry-bulb air temperatures were measured on station using a hand-held sling psychrometer.

3.3. Underway measurements

"Surface" temperature was logged continuously from a through-flow system drawing water from a depth of about 50 cm, together with time and GPS position; the specified accuracy of the temperature sensor was ± 0.1 °C. Fluorescence was measured simultaneously during the 1998 surveys using a Wetstar fluorometer, calibrated against chlorophyll concentration using water samples drawn at regular intervals from the flow system. The temperature and fluorescence were recorded on a laptop computer initially at 5-second intervals, representing an along-track sample about every 40 m at the cruising boat speed of 16 knots or 8 m/s, and later at 2-second intervals. We estimate that the time for the water to flow through to the sensors was about 5 seconds, during which time the vessel would have moved through about 40 m which is unimportant for our purposes.

3.4. On-station measurements

At each station, vertical temperature/conductivity profiles were obtained using a Yeokal Model 606 Submersible Data Logger (SDL; rated temperature accuracy ± 0.1°C, resolution 0.01 °C) sampling at 1 second intervals. Unfortunately, the conductivity sensor on the SDL proved

unreliable and so the subsurface salinities are not discussed in any detail in this paper. The instrument was lowered into the water from the bow of the vessel and held within the top 50 cm for about a minute to stabilise the sensors and provide good "surface" data. It was then lowered by hand at a speed of about 1 m/s to touch the seabed at all stations (except H40 where the depth was too great), and raised again to the surface, where it was held at the surface for another minute before being brought back on board. During the first two transects, profiles were only taken at stations H0, H10, H20, H30 and H40. The SDL failed in February, July, August and September 1998. 1-m depth-averages were computed for each down- and up-cast.

As an independent near-surface temperature measurement, "bucket" samples were taken using a 15-litre plastic bucket scooping water from the top 30 cm or so, some distance away from the engine cooling-water outlets. The bucket was brought on deck into the shade and the temperature noted immediately using a mercury thermometer graduated to 0.1 °C. The mercury thermometers were calibrated in a laboratory tank against reference thermometers reading to 0.01 °C; the estimated accuracy of the bucket temperatures was ± 0.1 °C, with perhaps a similar "error" resulting from possible temperature changes within the bucket between taking the sample and reading the temperatures. This accuracy was adequate for our purposes, and there was a good correlation (0.99) between the surface temperatures measured using the bucket, the SDL and the underway sensor. A salinity sample was also taken from the bucket and later analysed in the shore laboratory using an Autolab salinometer, with a rated accuracy of ± 0.003 psu.

For the satellite SST validation, some extra measurements were made of the temperature within a few cm of the water surface using a floating thermister while the "skin" temperature was measured with a TASCO radiometer (see McAtee *et al.*, this volume).

3.5. Nutrient and chlorophyll samples

On each station, vertically-integrated water samples were obtained by pumping water through a hose which was lowered from the surface to a depth of 18 m (or near the bottom in shallower water) and back to the surface. Chlorophyll samples were collected by filtering 5 litre

volumes through Whatman GF/C filters (47mm diameter), which were stored in the dark in plastic centrifuge tubes on ice. Back at the laboratory, the filter was placed in a 10 ml test-tube and 8 ml of a 90:10 (vol:vol) acetone:water solution were added. The sample was then sonicated for 10 minutes in an ultrasonic bath to break down the cells, and stored at 4°C overnight. The sample was filtered again through a GF/C filter into a clean 10 ml test-tube.

These samples were analysed using both a Varian DMS-90 UV/VIS spectrophotometer and a Turner fluorometer. A 90:10 acetone:water solution was initially used in both the reference and sample cuvettes on the spectrophotometer; the absorbance was read and the machine zeroed at each wavelength (480, 510, 630, 647, 664 and 750 nm). Each chlorophyll sample was then inserted into the sample cuvette in the spectrophotometer and the absorbance read at each wavelength. Periodically (after 10 to 15 samples), the acetone sample was again placed in the sample cuvette and the "blank" reading noted. After the spectrophotometer analyses, the test-tube samples were also analysed for fluorescence using a Turner Fluorometer following the acidification technique of Parsons et al. (1989).

Replicate nutrient samples were taken at each station; these were frozen and stored for subsequent analysis in the shore laboratory for nitrate, silicate and phosphate concentrations using standard analytical methods (Cowley et al., 1999). As the nutrient samples prior to September 1997 were unfortunately lost due to handling/contamination errors, only the results after this date are presented here.

3.6. Optical measurements

As part of the validation of ocean colour from SeaWiFS, optical measurements were taken on each station. Simple Secchi depths were derived by observing the depths at which the disc was just no longer visible (down-cast) and when it first became visible again on the up-cast; there was some subjectivity in this measurement depending on the skill and experience of the operators and on factors such as sun-glint, shading by the vessel and surface roughness. Subsurface light profiles were obtained using a 4-PI Li-cor LI-250 Lightmeter, giving an

estimate of the reduction of Photosynthetic Available Radiation (PAR) with depth. This part of the study is dealt with by Fearns et al. (submitted).

3.7. Satellite images

Advanced Very High Resolution Radiometer (AVHRR) satellite imagery has been received in Perth since 1981, and NOAA-14 images for each Hillarys transect date were obtained from the Western Australian Satellite Technology and Applications Consortium (WASTAC). Full-resolution (1.1 km) images for the region 30° to 35°S were processed to show thermal structures associated with the Leeuwin Current and coastal waters in the vicinity of the transect, and hence aid interpretation of the transect data. On 6 of the 27 transect days, cloud covered the transect area so imagery on adjacent days was used if they were cloud-free.

Surface temperatures were derived from the brightness temperatures in AVHRR bands 4 and 5 using the McMillin and Crosby (1984) algorithm and also the MultiChannel SST (MCSST) algorithm, the coefficients for which were obtained from the NOAA website http://www.osdpd.noaa.gov/EBB/pubs/SST/noaa14sst.asc. The two algorithms are compared against the surface radiometer temperatures in the companion paper by McAtee *et al.* (this volume). Digital SST transects extending much further offshore than the Hillarys stations were extracted from the AVHRR data to complement the transect temperature measurements by providing a larger-scale perspective on the surface thermal structure and position of the Leeuwin Current in relation to the shelf waters and the transect stations.

SeaWiFS chlorophyll images were obtained from WASTAC after the satellite was launched in December 1997. Chlorophyll concentrations were derived using SeaDAS software supplied by NASA; relationships between the *in situ* chlorophyll measurements and the satellite data are dealt with in the companion paper by Fearns et al. (submitted).

4. Results and Discussion

In this section, we present the main oceanographic results from the Hillarys Transects, focusing on the seasonality and cross-shelf variability of temperature, salinity, chlorophyll and

nutrients. In addition, some estimates are made of uncertainties in the validation of satellite-derived SSTs and chlorophylls as a result of the observed small-scale horizontal and vertical gradients.

4.1 Meteorology

The meteorological measurements from Rottnest Island during the period covering the Hillarys Transects effectively match the seasonal wind roses of Figure 2. The wind vectors show that the winds were dominantly from the southerly sectors between about October to March (Figure 5), but were much more variable in winter and had a net north-westerly tendency. The wind stability, which is defined as the ratio of the vector wind speed to the scalar wind speed (Neumann, 1968) and is an indication of the persistence of the wind in any particular sector, showed a corresponding strong seasonality with values of over 70% during the persistently southerly winds in summer and as low as 10% in winter (Figure 5).

Monthly mean scalar wind speeds (derived as the simple averages of the hourly wind speeds) varied between 6 and 9 m/s, but the hourly speeds often exceeded 20 m/s and peak individual gusts during the late autumn/winter months approached 30 m/s (almost 60 knots).

4.2 Satellite imagery and the Leeuwin Current

An overall perspective on the dominant seasonal circulation patterns across the shelf and further offshore can be gained from the satellite thermal images and digital transects. In general, the Leeuwin Current tended to flow along the shelfbreak or further offshore (Smith et al., 1991), sometimes in the form of a large anticyclonic meander (Pearce and Griffiths, 1991). While its full strength (associated with the warmest water and the strongest SST gradient) generally occurred beyond the shelfbreak, the Current was also observed to spread onto the outer shelf and indeed at times appeared to be fully contained on the shelf (as in Cresswell, 1996) -- on such occasions, it was encountered towards the offshore end of the Transect.

The winter situation may be typified by the SST image in July 1997 (lower panel in Figure 6), showing the warm Leeuwin Current flowing southwards as a narrow, well-defined

stream slightly overlapping the Transect on the outer continental shelf, with some offshore re-circulation in the form of a cyclonic eddy. Just to the north was the zonal southern boundary of a strong anticyclonic meander, the shorewards flow evident in the small cyclonic shear eddies along the Current boundary. The corresponding digital SST transect (Figure 7, lower curve) clearly showed the southflowing current and the warm northward eddy flow (separated by the cool eddy core) and beyond this the temperature dropped by over 3°C in a series of steps to the open-ocean water west of 114°E. The nearshore water was 2°C cooler than the Leeuwin Current, and the Transect SDL stations closely matched the cross-Transect gradient in the AVHRR profile.

In January 1997, by contrast, the Leeuwin Current was further offshore and well beyond Transect station H40 (upper curve in Figure 7); the cooler Capes Current was flowing northwards along the mid- and outer shelf regions, and a band of warmer summer-heated water hugged the coast. This nearshore band was now 2 °C warmer than the Capes Current, again well matched by the satellite profile, and the thermal relief across the Leeuwin Current was about 1 °C. Figures 6 and 7 well demonstrate the value of using satellite imagery to provide a larger-scale perspective to localised surveys.

In many of the satellite images (particularly in the winter/early spring months when the thermal contrast between the coastal and offshore waters was greatest), cross-shelf advective/mixing events were evident as tongues of Leeuwin Current water penetrating onto and across the continental shelf (Pearce and Griffiths, 1991). They could be broad (of order shelf width) and weakly-defined areas of warm water spreading right across the shelf apparently to the coast, but at other times they were much narrower (and presumably stronger) jet-like flows, representing an exchange of heat/salt between nearshore and offshore waters and thus providing an active mechanism for the exchange of planktonic larvae across the shelf. As an example, in July 1997 the Leeuwin Current “wrapped-round” the southern coast of Rottnest Island (Figure 6, lower panel); this form of intrusion helps explain the presence of reef-building corals and the

annual settlement of larval tropical fish along the south coast of the Island (Hutchins and Pearce, 1994; Hutchins, 1999).

On the other hand, in October of both 1997 and 1998 (the latter shown in the lower panel of Figure 8), an intrusion was curving in towards Rottnest Island from the north -- a remarkably similar pattern was observed using Landsat imagery in August 1991 (Wyllie et al., 1992; Department of Environmental Protection, 1996; Mills et al., 1996) and showed the interaction between the Leeuwin Current and a plume of discoloured water from the Peel-Harvey estuary well south of Perth.

These cross-shelf mixing events have been observed elsewhere along the Western Australian coast (see satellite images in Legeckis and Cresswell, 1981; Pearce and Griffiths, 1991; Pearce, 1997). A re-analysis of historical current meter records near the Houtman Abrolhos Islands (29°S; Cresswell et al., 1989) by Pearce and Phillips (1994) showed that cross-shelf current speeds were typically up to 10 cm/s and could persist for a few days. Since 1 cm/s ~~ 1 km/day, planktonic larvae can be passively transported cross the 40 km wide shelf (either towards or away from the coast) within a week, while actively-swimming animals such as the puerulus stage of the western rock lobster would be greatly assisted (or hindered) by cross-shelf currents (Pearce and Phillips, 1994; Griffin et al., 2001). The re-analysis of PCWS current measurements mentioned earlier showed that there was little seasonality in the cross-shelf flow; currents at the 27m site were either onshore or offshore (with no preference) for between 10 and 25% of the time in any month of the year. (Onshore currents were defined as being in the sectors between NE and SE, and offshore flow was between NW and SW).

The satellite images also frequently showed an upwelling plume north of Rottnest Island during the summer months (as in January 1998, Figure 8 upper panel), associated with a secondary circulation due to the curvature of the flow around the western tip of the Island when the Capes Current was flowing (Alaee, 1998; Alaee et al., 1998). While the northward extent of

the plume in the satellite images was usually restricted to 2 or 3 island widths (but still crossed the Hillarys Transect), on at least one occasion it seemed to extend far beyond that.

4.3. Surface temperature and salinity

The surface temperatures at the Transect stations showed a marked seasonal reversal of gradient across the continental shelf (Figure 9a), resulting in a change of both amplitude and phase in the annual temperature cycle between the inshore and offshore waters. At station H0 close inshore, water temperatures peaked at 22 to 23°C in January and dropped to 16° in June 1998 (July/August in 1997), giving an annual temperature range of 7°C near the coast. In the deeper offshore waters, on the other hand, where the influence of the Leeuwin Current was more apparent, the temperature rose from 21°C in January to 23°C in April/May 1998 before falling gradually to a trough of 20°C in September -- an annual range of only 3°C. The cross-shelf temperature differential accordingly reversed from -1°C in January to +6°C in June; February/March and December were transition months when the cross-shelf gradients were minimal. The warmest water (24.1°C) was observed at H0 in January 1997 and the coolest (15.9°C) again at H0 in June 1998. Summer temperatures near the coast were higher in 1997 than in 1998, while those at the shelf break were higher in 1998 than in the previous year; however, no realistic interannual pattern can be deduced from just these two years.

The salinity transects (Figure 9b) presented a similar picture albeit less clearly defined, with most of the variability again occurring near the coast. Inshore surface salinities were well above 36 psu in summer (exceeding 36.6 psu in February 1997) as a result of evaporation (Zaker et al., submitted); monthly evaporation at Perth exceeds 250 mm in mid-summer (Bureau of Meteorology, 1966), and this high-salinity water extended as far offshore as station H20 in 1997 and H15 in 1998. The salinity then fell rapidly as the winter rainfall commenced in May and low-salinity Leeuwin Current water mixed onto the shelf. By mid-year, the salinity was fairly uniform at about 35.5 psu across the shelf and there were pulses of <35.4 psu water close inshore

in late winter. At the offshore station H40, summer and winter salinities were respectively about 36 and 35.5 psu giving a seasonal variation of only 0.5 psu compared with 1.1 psu close inshore.

The lowest surface salinities recorded during the surveys were 35.0 psu at the nearshore station H0 in September 1997, 35.24 psu at the same station in November 1998, and 35.26 psu at H5 (not H0) in September 1998 (Figure 9b). In the September 1997 survey, the low salinity water at H0 extended down to the seabed (water depth of only 6 m); the surface and bottom salinities at H5 were about 35.4 and 35.6 psu respectively with a very strong halocline at mid-depth while the salinities from H10 outwards were all above 35.65 psu, suggesting a local inshore source of the fresh water which then extended offshore as a surface lens over more saline water at H5. The wind speed was only about 2 m/s at the inshore stations.

Monthly mean temperatures and salinities have been derived from the full 27-month period for stations H0 and H5 (representing inshore waters) and H35-H40 (outer shelf) to summarise the annual surface temperature and salinity cycles (Figure 10) across the shelf. Effectively, the shallow inshore waters are largely influenced by air-sea heat fluxes and by rainfall/runoff and evaporative processes while the Leeuwin Current plays the dominant role along the outer shelf.

Approximate limits can be assigned to the water properties for the inner and outer shelf using the surface T/S characteristics (Figure 11) for the two innermost and two outermost stations:

	Inner shelf (H0/H5)	Outer shelf (H35/H40)
Summer	T > 21°C / S > 36.0 psu	21° < T < 23°C / 35.7 < S < 36.0 psu
Winter	T < 18°C / S < 35.6 psu	19° < T < 21°C / 35.4 < S < 35.6 psu

As is shown below, vertical mixing generally ensures that the deeper shelf water properties are little different from those at the surface.

Although there are no river outflows in the immediate vicinity of the Hillarys Marina (and no freshwater discharges into the Marina), effluent plumes from the Swan River some 25

km to the south (Figure 1) could perhaps extend northwards along the inner- to midshelf when the coastal currents reverse to northgoing in September (Steedman and Associates, 1981; Zaker et al., submitted). As mentioned in Section 2.1**,** the peak monthly river discharge occurs in August and there is still a substantial outflow in September after which the flow is generally an order of magnitude lower. Sampling by Gaughan and Potter (1994) just inside the river mouth showed that surface salinities can be as low as 12 psu in August.

There appear to be no published salinity measurements along the shelf north of the Swan River of sufficient spatial and temporal resolution to show any freshwater influence from the river, but Mills et al. (1996) presented a Landsat image revealing a plume of coloured water from the river mouth extending northward well past the Hillarys region in August 1991.

Assuming salinity to be a conservative property, we have used two (unpublished) surveys of the salinity between the river mouth and Hillarys to examine in more detail the northwards extent of Swan River outflow. The alongshore distribution of salinity at 6 stations between the Swan River mouth and Scarborough (just north of the Swanbourne ocean outlet -- Figure 1) was measured during 31 surveys between 1985 and 1989 (CSIRO unpublished data: Figure 12). The lowest salinities recorded just outside the river mouth (station A) were 24 to 26 psu in August (with nitrate concentrations of 8 μM), and depressed salinities (< 35 psu) were occasionally observed during the winter months within about 5 km of the river mouth at stations V and W (Figure 12). However, these extremes reverted to near-normal coastal values north of this location (i.e. from station U northwards): monthly mean salinities in winter/spring at stations S, T and U (Figure 1) varied between 35.15 and 35.48 psu and the minimum salinities measured at those stations were down to 35.0 psu -- very similar to the Hillarys Transect (inshore) means and minima in Figure 10b.

Salinity measurements were also made during the PLOOM monitoring study near the Swanbourne ocean outlet (Figure 1) between 2000 and 2005 (unpublished data, Water Corporation), with 4 routine sampling stations numbered SB1 (4 km south of the outlet) to SB4

(8 km north of the outlet). The sampling programme found that the wastewater plume from the outlet was generally undetectable more than about 4 km from the discharge point (Institute for Environmental Science, 2002). We have analysed the salinity data from the southernmost and northernmost stations SB1 and SB4 as least likely to be affected by the freshwater discharge from the outlet. The monthly mean salinities varied between 35.00 and 35.45 psu during the winter/early spring months while the monthly minima were just below 35 psu -- although these measurements were from close inshore, they were similar to the Hillarys Transect values for H0/H5.

From both studies, it appears that from Swanbourne northwards the winter/spring salinities are generally not very different from those measured on the Hillarys Transect and it is therefore debatable whether Swan River discharge on a regular basis penetrates as far as Hillarys without substantial dilution. It is nevertheless possible that on occasion (such as after exceptionally heavy rainfall and strong northwards currents) the river plume could be evident north of Hillarys (as observed in the published satellite image).

Another potential source of freshwater is submarine groundwater discharge (SGD) which contributes high-nutrient low-salinity water into the nearshore region of Marmion Lagoon (Johannes, 1980; Johannes and Hearn, 1985). Zaker et al. (submitted) have also suggested that SGD can play an important role in nearshore salinity variability especially during winter. Johannes and Hearn (1985) measured nitrate concentrations of 400 µM in the freshest parts of the discharge immediately off the beach, and found that reduced salinities (and correspondingly enhance nitrate concentrations) could extend out to 1.5 km from the shore under very calm conditions although more generally the affected area was less than 300 m offshore. Station H0 was within about 100 m of the Marina breakwater, and it is therefore likely that SGD was responsible for the reduced salinities at that station.

4.4. Water masses

As shown by Cresswell and Peterson (1993), the Leeuwin Current is a mixture of low-salinity tropical water (brought down from the north) and more saline subtropical water (in the geostrophic inflow from the west), the latter dominating during the summer months when the net equatorward wind stress reduces the south-flowing tropical component. The Capes Current and its associated upwelling in the Capes region are also effectively derived from the Leeuwin Current (Gersbach et al., 1999).

High-salinity South Indian Central Water (Rochford, 1969; Cresswell, 1991), which may perhaps be linked with the geostrophic inflow, has previously been identified (by its salinity of >35.8 psu) intruding from the west along the upper slope near Cape Leeuwin (34.5°S; Cresswell and Griffin, 2004), off Perth (Greig, 1986; Cresswell and Griffin, 2004) and at Geraldton (29°S; Pearce et al., 1992). Between October and April, the Hillarys outer station H40 frequently encountered subsurface intrusions of more saline water near the seabed with T/S properties of 19° to 22°C and >35.8 psu, indicating the presence of this water mass but it was not observed to penetrate any further onto the shelf. While it is likely that sporadic localised upwelling onto the outer shelf (as found off the Capes area by Gersbach et al., 1999) is of Central Water origin, the elevated nearshore salinities of 36 to 36.5 psu observed during the summer months are much higher than those in the Central Water mass and must therefore be a result of evaporation in the shallow water.

As no other "new" water comes into the system, the water on the southwest Australian continental shelf must ultimately be derived from the Leeuwin Current, albeit modified by air-sea heat and moisture flux and mixing as it moves onto and across the shelf, possibly with some subsurface inclusion of more saline Central Water along the outer shelf and in localised upwelling on occasion.

To assist interpretation of the physical, nutrient and optical properties as well as the plankton distributions over the 27-month period, the satellite images have been used in conjunction with the temperature/salinity data to classify the water regime at each station

position (Table 2). Coastal Water (CW) was by definition the water regime at stations H0 and H5 within the coastal boundary layer described earlier but at times seemed to extend out to H20 or even H25. Where the Leeuwin Current could be reasonably identified by its thermal signature the station was classified as LC, but on many occasions the water seemed to be derived from (but not implicitly part of) the Leeuwin Current and so was labelled Leeuwin Current Water (LCW). Capes Current water (CC) was clearly in the cool band of midshelf water apparently moving northwards (an exclusively summer phenomenon) and was sometimes evident out to station H40, perhaps more as an absence of the Leeuwin Current rather than a very clear Capes Current itself. Although the upwelled plume of cooler water north of Rottnest Island is closely linked with the Capes Current, the water in the plume was classified as UW where it could be unambiguously identified as such. While these distributions are somewhat subjective, the seasonal and cross-shelf patterns were reasonably clear.

These results effectively confirm Zaker et al.'s (submitted) suggestion of a coastal boundary layer of order 10 km wide, although the satellite imagery suggests that this "coastal water" on occasion extended beyond station H10 (Table 2). The horizontal gradients of temperature, salinity and nutrients between each pair of stations over the 27 months clearly indicate that most of the hydrographic variability was contained within the coastal band out to station H15 (and the largest gradients were within 5 km of the coast). The nearshore shallow reef system is an obvious explanation for the changes between H0 and H5, but there are no prominent bathymetric features beyond that as the seabed is a relatively flat plain out to almost H40 (Figure 4). While the Leeuwin Current was identified along the outer shelf on 7 occasions out of 25 cloud-free images (with a further 2 possible occurrences, all between March and September -- Table 2), water derived from the Current and mixing onto/across the shelf could be present at any time of year. It penetrated across the shelf on occasion as close inshore as H20 and (rarely) H15 (Table 2).

In summary, the external water masses influencing our continental shelf are the tropical and subtropical waters of the Leeuwin Current and a summer subsurface intrusion of more saline South Indian Central Water which may on occasion upwell onto the outer continental shelf. These are then modified by mixing and by air-sea exchange processes as they cross the shelf to form the nearshore waters.

4.5. Vertical structure

Apart from the horizontal temperature and salinity variability described above, there were also changes in the water column structure which illustrate some of the dynamics and are also important for satellite SST validation.

As the conductivity profiles from the SDL proved somewhat unreliable, they are used here only to help explain some of the features of the vertical structure (the salinity changes were generally small in comparison with those of temperature). Because the SDL was lowered right down to touch the seabed at each station, it was able to sample the bottom mixed layer which would be unwise with more expensive CTD equipment.

The basic temperature structure across the shelf was vertically well-mixed but with the seasonally-reversing horizontal structure described above. However, vertical stratification was observed irregularly at different stations and in different months through the year, either induced by surface heating or by the upwelling-like process in the lee of Rottnest Island (described earlier) -- these were both largely summer phenomena.

Particularly in summer, virtually isothermal conditions could prevail right across the continental shelf (e.g. December 1996, Figure 13a), with a narrow band of warmer water within 5 km of the coast and only marginal surface heating. In December 1998 (Figure 13b), by contrast, surface heating resulted in a temperature differential of over 1.5 °C between the surface and 20 m depth. The strongest stratification was observed at the mid-shelf stations resulting from the Rottnest Island wake upwelling (as in January 1998, Figure 13c) described earlier. The central plume of the upwelling generally tended to lie near stations H20 to H25 due north of the

Island leading to the "doming" evident in Figure 13c. The depth of the dome was typically below 20 m, and as our depth-integrated nutrient sampling extended down to only 18 m depth it was unable to show any nutrient enrichment in the upwelled water mass (Alaee et al. (1998) did not report on salinity or nutrient measurements in the upwelled plume).

The water column was also typically well-mixed during the winter months, but there was almost invariably a pronounced cross-shelf temperature gradient sometimes intensifying into discrete frontal zones as in June 1998 (Figure 13d). Starting from the coast, there was a rapid rise in water temperature as a result of heat loss to the atmosphere from the shallow water (Pattiaratchi et al., 1995; Zaker et al., submitted), then a strong mid-shelf front of more than 1.5 °C. The sloping front was fairly common in autumn and winter, probably associated with the downwelling process described by Mills et al. (1996); Symonds and Gardiner-Garden (1994) have shown that transient downwelling events and weak cross-shelf currents can result from convective cooling of nearshore waters during the winter.

A similar situation was observed during the summer/autumn months when high-salinity nearshore water was denser than the offshore waters despite the coastal warming. In March 1997 for example (not shown here), the temperature, salinity and density of the water at the coastal station H0 were greater than the near-surface waters further offshore but effectively matched the properties of the near-bottom shelf water.

It appears that an intermittent "slumping" or cascading of high-density coastal water down and across the shelf may occur at any time of year, this downwelling process representing an active mechanism for cross-shelf water and larval exchange (Symonds and Gardiner-Garden, 1994; Wells and Sherman, 2001; Shapiro et al., 2003).

The surface mixed layer depth (SMLD) is usually defined either by a specified temperature (or density) difference from the surface value or by a change in the temperature (or density) gradient. Different temperature departures from the surface value have been used by various authors: Colborn (1975; 1°C), Longhurst (1995; 0.5°C), Hamilton (1986; 0.2°C),

Rochford et al. (2000; 0.1°C), Feng et al. (2003; 0.5°C) and Lourey et al. (2006; 0.4°C from the 10 m temperature), while different thermocline gradients have been defined by other authors: 0.05°C/m (Watts and Owens, 1999; Qu, 2001) or 0.5°C/m (Gray and Kingsford, 2003).

We prefer the gradient definition for our shallow water work because use of any specified temperature difference will give a SMLD even if the temperature simply decreases uniformly with depth and no abrupt change of gradient is actually present. For our purposes, the 1-m depth-averaged temperature profiles were smoothed by a simple 5-point running mean, starting at a depth of 5 m below the surface to avoid the highly variable near-surface layer. By examining the temperature profiles over the 2-year period, a thermocline was defined as a region in which the vertical temperature gradient exceeded 0.02 °C/m over at least 5 m depth interval (i.e. > 0.1 °C over the 5 m). Smaller regions (< 5 m) of higher gradients within a mixed layer were thus effectively ignored as being (for practical purposes) inconsequential. The SMLD was then derived as the water column down to the first thermocline, and the bottom mixed layer depth (BMLD) correspondingly as the water column from the seabed up to the base of the deepest thermocline.

Using these criteria, the surface mixed layer depth (SMLD) extended throughout the water column to the seabed on 42% of stations, with a weak seasonality. As would be expected, the shallowest stations were most frequently isothermal, and only at H40 was it a rare occurrence (because of the greater water depth) but even there conditions were effectively isothermal on 4 days out of 22. The SMLD right across the shelf tended to be least during the summer months when the thermocline was up to the water surface. In deeper off-shelf waters, Hamilton (1986) and Feng et al. (2003) also concluded that the deepest mixed layers occurred during the winter months.

When it existed, the thermocline was typically thin and relatively weak with temperature differences of less than 1 °C across 5 m or more. On only 1 day (January 1998 -- Figure 13c) did the temperature differential across the thermocline exceed 2 °C. Below the thermocline there was

usually a well-defined BML, particularly in the mid-shelf region where the upwelling was occurring.

Near-surface temperature gradients are important for validation studies for satellite-derived temperatures. Conventionally, validation of satellite SSTs is undertaken using “bulk” temperature measurements from sensors in the upper 1 m or so of the water column whereas the upwelling radiance sensed by the satellite is actually from a very thin surface “skin” (less than a millimetre in thickness). The temperature difference between the surface skin and the subsurface layer is typically of order 0.3°C (Robinson et al. 1984) and so very accurate measurements of both are required. The bulk temperature measurements in this study were made using the surface bucket and the SDL profiler while the “skin” temperature was measured using a radiometer (see McAtee et al., this volume). Neither of these have provided temperatures of sufficient resolution to address the skin-bulk temperature question, so the SDL profiles (which have a resolution of 0.01 °C) are used here to examine the bulk near-surface gradients.

Because of the rolling motion of the vessel while on station, the SDL was moving vertically up and down through the uppermost 1 m or so of the water for the first part of the cast prior to being lowered through the water column (see Methods). During that time, it was in some sense "profiling" that near-surface layer, and we have taken the highest temperature sampled as representing the water immediately below the surface skin. Over the 27-month period, the differential between the highest SDL temperature and the 1-m average was less than 0.1°C for 89% of the time and less than 0.2°C for 94%; the maximum value was 0.56°C. This effectively gives an indication of the uncertainty of conventional bulk temperature measurements for comparison with satellite-derived quantities, ignoring the surface skin effect. Those differentials of more than 0.1°C were at on-station wind speeds of less than about 4 m/s (Figure 14 -- using the hand-held anemometer 5 m above the sea surface).

Because bulk SSTs from merchant or research vessels will be drawn from deeper below the water surface, the temperature differential between the near-surface (highest SDL

temperature) and the 3 m temperatures were also analysed (T0-T3; Figure 15). About 68% of the temperature differences were less than 0.1°C and 83% were <0.3°C; the 8% of observations that exceeded 0.5°C were all (with one exception) in November and December, before the strong land- and sea-breezes of summer had set in.

Extending the analysis down to 18 m (the layer from which the depth-integrated chlorophyll and nutrient samples were drawn), almost half the temperature differentials between 3 m and 18 m depth were <0.1°C and 75% were <0.3°C (Figure 15); 14% exceeded 0.5°C, occurring mainly between December and January.

4.6 Depth-integrated chlorophyll and nutrients

The correlation between the spectrophotometric and fluorometric methods of measuring the chlorophyll concentration was 0.92 (Figure 16), with higher values generally obtained from the fluorometer. The fluorometric technique is 5 to 10 times more sensitive than the spectrophotometric technique (Parsons et al., 1989), an important consideration given the relatively low-chlorophyll waters off Western Australia (Pearce et al., 2000). The fluorometer results will therefore be used in this paper.

By global standards, chlorophyll a levels were generally low (< 1 mg m^{-3}; Figure 17) and within the range of other chlorophyll data for Western Australian coastal waters (Department of Environmental Protection, 1996; Pearce et al., 2000; Institute for Environmental Science, 2002). The chlorophyll concentration was almost invariably higher within the coastal boundary layer (stations H0 and H5) than further offshore; beyond station H10 the chlorophyll level rarely exceeded 0.6 mg m^{-3} and indeed was often ≤ 0.3 mg m^{-3} (Figure 17). However, there was a high degree of patchiness (Lord and Hillman, 1995), with little apparent seasonal pattern across the two years; PLOOM sampling of chlorophyll a by Hale et al. (2001) has shown that chlorophyll concentrations can vary an order of magnitude over a 24 hr period and by more than 0.1 ug/L within 200 m distance. There were elevated chlorophyll levels right across the shelf in June 1998; the highest value measured during the entire project (2.3 mg m^{-3}) was at H0. Yet in the

autumn/winter of the previous year (May and July 1997 -- there were no samples in June), chlorophyll concentrations were uniformly low across the shelf, so any seasonality is perhaps questionable from our results.

Chlorophyll measurements in the south-eastern Indian Ocean covering 5 degree latitude/longitude squares (including adjacent to the Western Australian continental margin) showed a clear winter peak (Humphrey, 1966), while Lourey et al. (2006) found summer concentrations of about 0.25 mg m^{-3} rising to 1 mg m^{-3} in winter inshore of the Leeuwin Current, attributing this seasonal increase either to terrestrial sources or through re-suspension of sandy sediments in the shallow coastal waters during winter storms . A similar seasonal pattern was evident in summer/winter sampling in Perth coastal waters in 1991/92 (Department of Environmental Protection, 1996; Pearce et al., 2000). Satellite data from the Coastal Zone Color Scanner (CZCS, which operated between 1979 and 1986 with some large data gaps off southwestern Australia) also indicated that both the open-shelf and offshore chlorophyll concentrations were higher between May and August than at other times of the year (Pearce et al., 2000). However, there was a less distinct seasonal variation in a more recent study near the Ocean Reef outlet (Figure 1; Thompson and Waite, 2003) where there were small chlorophyll peaks in autumn and spring. We have re-examined the chlorophyll data from the 'control site' south of the outlet and found that concentrations ranged from 0.01 to 2.68 mg chl a m^{-3} but without a clear seasonality.

The summer and winter SeaWiFS satellite chlorophyll images in Fearns et al. (submitted) largely support the surface measurements, in particular the contrast between the low concentrations in January 1998 and the elevated levels across the shelf in June 1998, as well as the high level of fine-scale variability.

The nutrient dataset was limited to 16 months; all parameters (nitrate, phosphate and silicate) showed considerable differences between the corresponding months for which data were available. Nitrate and phosphate levels were usually highest within the coastal boundary layer

although there were a couple of pronounced mid-shelf peaks in nitrate in late 1997 (Figure 18a,b).

Because of the short time-series as well as the high level of variability, distinct seasonal patterns were not evident. Both nitrate and phosphate were relatively high in late winter and spring (September to December) of 1997; in mid-shelf and offshore regions, depth-integrated nitrate ranged between 1.0 and 1.8 µM in a somewhat patchy distribution (Figure 18a). Concurrently, phosphate reached a peak concentration of 0.29 µM in inshore waters, although was elevated (0.20 – 0.25 µM) right across the shelf (Figure 18b). This contrasted with the same period in 1998 when nitrate was almost uniformly < 0.2 µM (Figure 18a) and phosphate was generally < 0.15 µM (Figure 18b), with the exception of the inshore waters. Overall, the 1998 nitrate results matched the seasonal pattern found earlier in the same coastal waters by Johannes et al. (1994) who found monthly means of about 0.5 µM in summer rising to 1.5 µM in June/July.

At the PLOOM site off Ocean Reef sampled between 1996 and 2001, nitrate sampling (away from the immediate outlets) showed a broad winter peak concentration of about 2.5 µM underlying a high degree of variability (Thompson and Waite, 2003), whereas longer-term sampling further offshore (west of Rottnest Island, Figure 1) showed monthly mean nitrate concentrations varying between 0.3 and 0.5 µM with no clear seasonal pattern (Pearce et al., 1985). On the even broader scale of offshore waters, Lourey et al. (2006) found a small seasonal signal with summer values of about 0.2 to 0.3 µM rising to 0.5 µM in winter but expressed caution in interpreting seasonal patterns from parameters which fluctuate widely both spatially and temporally.

Maximum silicate concentrations (≥ 2.5 µM) were primarily associated with offshore waters and the autumn/winter period (Figure 18c). Mid-shelf and inshore waters showed evidence of silicate depletion, especially during the summer of 1998 when there was a large mid-shelf diatom bloom (Fearns et al., submitted) and silicate levels were drawn down below 1.5 µM

(Figure 18c). Diatom growth rates are thought to be limited at silicate concentrations below approximately 2.0 µM (Dortch and Whitledge, 1992), especially heavily silicified species such as *Chaetoceros* (Trull et al., 2001). Silicate re-supply of shelf waters appears to come from offshore, possibly via the Leeuwin Current which, based on recent analyses of nutrient climatology for the region, may be a source of silicate (***Lourey et al., 2006***). High nitrate levels in nearshore (2.1 µM) and mid-shelf (0.8 – 1.0 µM) waters during June 1998 coinciding with replenished silicate concentrations from April and May 1998 may have been responsible for the large cross-shelf diatom bloom evident both in cell counts (Fearns et al., submitted) and the elevated cross-shelf chlorophyll mentioned above.

Local sewage outlets are known to contribute dissolved nutrients to the coastal waters, increasing both water column productivity and chlorophyll concentrations (Thompson and Waite, 2003). The nearest outlets to the Hillarys Transect are the Ocean Reef pipeline some 7 km north of the Transect and Swanbourne 15 km to the south (Figure 1). During the PLOOM monitoring program at the Ocean Reef outlet, nitrate levels were below 3 µM at the control site 4 km south of the outlet but peak individual values immediately above the outlet occasionally exceeded 20 µM (Thompson and Waite, 2003). Those authors also found that there were slightly elevated chlorophyll concentrations in spring and autumn. Since the highly elevated nutrient concentrations were localised around the outlet site and did not extend more than about 4 km from the outlets (Institute for Environmental Science, 2002), they would be unlikely to have contributed to the nutrient spikes along the Hillarys Transect.

Although no regular measurements were made of chlorophyll and nutrient levels within Hillarys Marina (Figure 1), occasional chlorophyll samples were taken for calibration purposes within the Marina at the start of some Transects and tended to show elevated concentrations (see for example the extreme point in Figure 16). An unpublished study of chlorophyll and nutrient levels in the Marina between December 1999 and March 2000 showed highly variable concentrations (Bowman Bishaw Gorham, 2001): chlorophyll a concentrations in the Marina

828 varied from 0.4 to 6.8 mg m^{-3} while at a station immediately outside the Marina entrance the range was 0.5 to 2.5 mg m^{-3}. Corresponding ranges of nitrate were 0.14 to 2.93 µM (in the
830 Marina) and 0.14 to 1.43 µM (entrance). Although this was only a brief summer study, it showed that tidal outflow of high-chlorophyll Marina waters could contribute pulses of chlorophyll and
832 nutrients into the nearshore waters off Hillarys -- station H0 was only about 100 m outside the Marina entrance.

834 Another source of nearshore nutrients is submarine groundwater discharge (SGD, mentioned above) which is extremely high in nitrate levels (Johannes, 1980; Johannes and
836 Hearn, 1985) and may well be an important seasonal source of nutrients in Perth coastal waters, although Lourey et al. (2006) suggest the effect may be rather localised in extent.

838 Although we sampled only the vertically-integrated water column (to a maximum of 18 m depth), vertical fluorescence profiles were measured by Fearns et al. (submitted) on some
840 transects using a profiling fluorometer. In most cases, there was some "noise" in the upper 10 m or so of the water column but typically thereafter the fluorescence was reasonably constant or
842 increased only slightly down to near the seabed. These profiles confirmed that the depth-integrated sampling generally gave a good representation of the concentrations in the upper 18 m
844 layer. Historical data from a 3-year study of the water properties at stations in 10 and 22 m water depth a few kilometres north of Hillarys (Pearce et al., 1985) showed that there was rarely any
846 consistent difference between surface and near-bottom nutrient samples. Similarly, Thompson and Waite (2003) found no significant differences between surface and depth-integrated samples
848 at the PLOOM sites, and Hanson et al. (2005a) have shown that nitrate is often uniform down the water column off the Capes (except when upwelling was occurring). Because of generally good
850 vertical mixing in this area and the relative shallowness of the water on the shelf, we believe that the depth-integrated nutrients would be typical of the whole water column on most occasions,
852 especially at the shallower stations.

In summary, the high degree of nutrient and chlorophyll patchiness and the relatively short time-series have tended to obscure any seasonal pattern in our results, but other studies have (generally but not universally) indicated winter peaks in both nitrate & chlorophyll concentrations.

4.7. Horizontal small-scale surface variability

Some of the uncertainties in validating satellite temperatures or chlorophyll concentrations against surface in situ values are a result of the different kinds of measurement. These include spot (i.e. single-point CTD sample) versus areal (satellite pixel) measurements ("within pixel" uncertainties), and navigation errors in the satellite or boat geolocation leading to uncertainty in the pixel location ("between pixel" uncertainty). These can be examined using the boat underway data at 1 km scales, the nominal pixel size for AVHRR and SeaWiFS products. The underway measurements also revealed smaller-scale variability embedded within the larger-scale cross-shelf temperature and chlorophyll structure discussed earlier.

The 1-km statistics (mean, standard deviation, maximum and minimum) were derived from the underway SST and chlorophyll measurements (sampled at nominally 20 to 40 m distance intervals) for both the outward and homeward runs in 1997 (SST only) and 1998. Because there were sometimes "spikes" in SST or chlorophyll when the vessel stopped on station and re-started, we have excluded the on-station positions from the analysis.

The highest variability was predictably within the coastal boundary layer inshore of station H10 (Figure 19), encompassing the nearshore reef system where the water was shallowest and the bathymetry most complex. However, weaker thermal and chlorophyll fronts were also encountered further offshore with no clustering at any preferred sites.

Finer-scale frontal zones of order 0.5 to 1 °C were embedded within the gross cross-shelf structure in both summer and autumn/winter (Figure 19). These fronts did not appear to group at specific locations (except perhaps at the nearshore reef system), and so were presumably

associated more with the dynamics of the flow (such as the Leeuwin Current and the cross-shelf tongues of water described earlier) than with any bathymetric features.

Chlorophyll patchiness was also evident. In December 1998 for example (Figure 19b), there were two patches of relatively high chlorophyll water, one near the coast and the other mid-shelf (this matched a small rise in the SST). Similar isolated patches of relatively high chlorophyll water extending across 2 or 3 stations (5 to 15 km) were observed between April and July 1998 at various positions on the shelf. Some (but certainly not all) of these were associated with thermal fronts but their source is not immediately clear. Such surface chlorophyll peaks may be associated with the filamentous cyanobacteria *Trichodesmium*, which is known to form large surface slicks in Perth coastal waters (Institute for Environmental Science, 2002) and was noted to be abundant at the Hillarys mid-shelf stations during December 1998 (Fearns et al., submitted).

The differences between the 1 km averages and the individual minima or maxima within each 1 km segment enable an estimate to be made of the "within-pixel" variability when comparing satellite SSTs and chlorophyll concentrations against spot in situ measurements. From the 1997 and 1998 underway SST transects, 64% of the within-pixel differences were less than 0.1°C and 93% less than 0.2°C (Figure 20a); very few differences exceeded 0.5°C. The chlorophyll concentrations were more variable, but 85% of the differences were less than 0.05 mg m^{-3} (Figure 20b). Almost all the differences exceeding 0.1 mg m^{-3} were inshore of station H5 where the small-scale patchiness is greatest -- however, these shallow waters are unlikely to be useful for satellite chlorophyll validation anyway because of bottom reflectance effects.

In a similar manner, uncertainties in SST or chlorophyll validation resulting from errors in satellite geolocation can be assessed by examining the differences between adjacent 1-km segments. For a positional error of 1 pixel, the SST differences between adjacent pixels were less than 0.1°C for 68% of the observations and 87% were less than 0.2°C (Figure 21a); again, most of the higher variability was close inshore. 57% of the chlorophyll differences were less than

0.02 mg m^{-3} and 86% within 0.05 mg m^{-3} (Figure 21b), but near the coast individual differences sometimes exceeded 0.1 mg m^{-3}.

These results provide an indication of the potential "error-bars" associated with natural within-pixel variability when single point in situ validation measurements are compared with the 1 km pixel averages sensed by the satellite and with geolocation errors of one pixel; larger geolocation uncertainties may have larger differences but are in fact unlikely for modern remotely-sensed products. In summary, then, the uncertainties in validation of satellite SST due to within-pixel and between-pixel variability combined is of order 0.4 °C while the uncertainties for chlorophyll validation are of order 0.1 mg m^{-3}.

4.8 Short-term temporal variability

There will be differences between the satellite and *in situ* temperatures associated with the time interval between the surface measurements and the satellite overpass, as a result of both air-sea heat flux (diurnal warming) and advection (see McAtee et al., this volume). The NOAA-14 satellite was generally overhead in the early afternoon shortly after the Transect work had been completed. Stratification in these shallow waters is very transient, breaking down over a period of hours under sea-breeze conditions; Zaker et al. (2002) found that wind speeds of 6 m/s were sufficient to vertically mix any diurnal stratification that develops. Nevertheless, the shallow coastal waters would tend to warm more rapidly than the deeper water and so both horizontal and vertical temperature differences can develop.

Some indication of typical warming trends during the day can be assessed using the change in surface temperature at position H5 between the morning station (about 0930) and the repeat station during the return leg some 4 hours later. The rise in bucket temperature was always less than 1°C except for an isolated maximum of 1.3°C in March 1998, and a temperature *decrease* of about 0.3°C in March and December 1997.

Because of the small number of station observations, a better estimate of the diurnal heating may be obtained from the temperature sensor on the PCWS current meter 5 m below the

surface (discussed earlier). This showed that, on average, the daily lowest temperatures occurred between 6 and 10 am, while the peak temperatures were from 3 to 8 pm; the mean diurnal temperature range varied from 0.11°C in June to 0.39°C in February. Taking 10 am as the approximate average time of the Transect stations and 2 pm as the time of the NOAA-14 overpasses, the differences between the bucket and satellite temperatures were less than 0.3°C on 89% of the days during the year, but about 1% of these differences were just over 0.5 °C.

4.9. Interannual perspective

There is a clear El Nino/Southern Oscillation (ENSO) signal along the Western Australian coast (Pearce and Phillips, 1988, 1994), so a plot of the monthly Southern Oscillation Index (SOI), the anomaly of Fremantle sea level and the Reynolds satellite-derived sea-surface temperature (Reynolds and Smith, 1994) places the 27-month Hillarys Transect surveys in the broader perspective.

The monthly or annual mean sea level at Fremantle has been used as a simple index of the "strength" of the Leeuwin Current (originally proposed by Pearce and Phillips, 1988, and subsequently confirmed and quantified by Feng et al., 2003): the higher the coastal sea level, the greater is the cross-shelf slope and accordingly the stronger is the southward flow. The close link between ENSO events and the Leeuwin Current is evident in Figure 22. During the prolonged ENSO period in the early part of the decade, small negative values of the SOI were associated with relatively low coastal sea levels and relatively low sea temperatures, implying a weak Leeuwin Current between 1990 and 1995. The strong *La Nina* of 1996 (with higher sea levels, a stronger Leeuwin Current and warmer water) was followed by the massive ENSO event of 1997, succeeded in turn by the return to strong *La Nina* conditions towards the end of 1998.

Brief as the survey period was, the 1996-98 Hillarys Transects thus experienced a complete cycle of a waning *La Nina*, a strong ENSO and a growing *La Nina*. While there were some changes in the temperatures and salinities between the 2 years (Figure 9), these did not affect the basic seasonality of the annual cycles. However, there were substantial differences in

the nutrient concentrations between the spring seasons of 1997 and 1998, and a much longer monitoring programme will be required to establish any real interannual nutrient pattern that may exist.

5. Summary of all results from the Hillarys Transect study

The field surveys off Hillarys between 1996 and 1998 have provided the first systematic, multidisciplinary climatology of the physical, chemical and bio-optical properties across the continental shelf in Southwestern Australia, as well as providing (near-) surface data for remote sensing validation of sea-surface temperature and ocean colour. The study has also shown the efficacy of using relatively simple methods to define the dominant oceanographic characteristics of IMCRA coastal bioregions.

The major findings of the project, including the companion papers of McAtee et al. (this volume), Fearns et al. (submitted) and Gaughan et al. (submitted) are:

5.1 Shelf water properties and cross-shelf exchange

* Seasonally-reversing temperature and salinity gradients across the continental shelf result from both advective (Leeuwin Current, Capes Current) and air-sea flux processes. During the austral spring and summer months of October to March, coastal heating and evaporation result in a band of warmer and more saline water in a coastal boundary layer extending some 10 km offshore. In winter by contrast, the warm, low salinity Leeuwin Current flows strongly southwards along the shelfbreak, and the nearshore waters are much cooler (heat loss to the atmosphere) and less saline (precipitation and freshwater input).

* The cross-shelf exchange (which has important implications for the exchange of plankton and fish larvae between the Leeuwin Current and the coastal waters) is effected by 4 dominant mechanisms: mesoscale meanders of the Leeuwin Current, smaller-scale tongues of Leeuwin Current water penetrating across the continental shelf, high density nearshore waters episodically cascading offshore down the seabed, and upwelling in the lee of Rottnest Island during the summer months.

5.2 Small-scale variability in relation to satellite measurements

* Some of the uncertainties in comparing satellite and conventional surface temperatures in local waters have been quantified using vertical temperature profiles and underway horizontal SST sampling. The near-surface waters were usually well-mixed: for about 94% of the time there was less than 0.2°C temperature difference in the uppermost metre of the water column (ignoring surface "skin" effects).

* Differences between satellite-derived SSTs and in situ measurements can result from horizontal small-scale ("within-pixel") patchiness. The underway measurements show that 93% of the differences between individual samples and 1-km averages (representing an AVHRR pixel) were less than 0.2°C -- this is effectively the potential "error" between the 1 km satellite pixels and single-point in situ SST measurements.

* "Between-pixel" variability (such as from satellite geolocation errors) is shown by the differences between adjacent 1-km block averages: SST differences between adjacent pixels were less than 0.2°C for 87% of the observations offshore of the coastal boundary layer.

* Similarly, the underway fluorescence sampling (converted to chlorophyll by a regression relationship) indicates that about 85% of within-pixel differences were less than 0.05 mg m^{-3} (again, outside the coastal boundary layer), and 86% of the "between-pixel" differences were less than 0.05 mg m^{-3}. The variability was much higher closer inshore.

* Comparisons between radiometer ("skin") temperatures and the satellite SSTs have shown generally good agreement (especially at wind speeds exceeding 4 m/s), and match the cross-shelf and seasonal variability of the temperature field sampled by direct surface measurements (McAtee et al., this volume). After correcting for time-of-day differences, the radiometer-satellite bias derived from individual monthly surveys varied between -1.5° and 0.2°C, with rms differences between 0.4° and 1.7°C -- the higher values were all in late summer/early spring. The radiometer programme has emphasised the importance of careful instrument calibration and accurate viewing angle for direct measurement of the skin SST.

1008 *5.3 Chlorophyll and nutrients*

* There was a high degree of both spatial and temporal "patchiness" in depth-integrated

1010 chlorophyll concentrations throughout the year, especially in the coastal boundary layer. Beyond this nearshore band, the chlorophyll level rarely exceeded 0.6 mg m^{-3} and indeed was often < 0.3

1012 mg m^{-3}. Despite the patchiness and large interannual differences, there was a strong peak in concentration right across the shelf in mid-winter 1998, but the seasonal cycle was less clearly

1014 defined close inshore than offshore.

* Chlorophyll concentrations derived from the SeaWiFS satellite (Fearns et al., submitted)

1016 largely supported the surface measurements along the Transect. The satellite estimates of surface chlorophyll were generally within the 35% uncertainty specifications of the sensor in

1018 phytoplankton-dominated "Case 1" waters deeper than about 30 m, although the satellite values may tend to under-estimate the true water column concentrations because of the deep chlorophyll

1020 maximum (DCM) at depths of 50 to 100 m (Hanson et al., 2005b).

* The SeaWiFS chlorophylls showed a winter peak matching that from the surface

1022 measurements. SeaWiFS estimates of the attenuation coefficient K490 were in good agreement with KPAR values derived from the light profiles at mid-shelf and offshore stations, and peaked

1024 in the winter months (Fearns et al., submitted).

* Depth-integrated nitrate, phosphate and silicate concentrations showed considerable temporal

1026 and spatial variability, with the large differences between the corresponding months of the two years sampled obscuring any clear seasonality. Nitrate and phosphate levels peaked between

1028 September and December 1997 in mid-shelf and offshore regions, but were almost uniformly low in 1998 with the exception of inshore waters. Potential sources of nitrate include local

1030 submarine groundwater discharge (SGD), river effluent, local sewage outlets and the Marina itself.

* Maximum silicate concentrations were largely associated with offshore waters in autumn/winter, while mid-shelf and inshore waters showed evidence of silicate depletion, especially during the summer months.

5.4 Phyto- and zooplankton

* Although only limited phytoplankton sampling was undertaken and despite a high level of temporal and spatial patchiness (Fearns et al., submitted), diatoms were found to be the most abundant group by far at all stations and throughout the year, followed by dinoflagellates and cyanobacteria. Diatom density was highest in the mid-shelf region and tended to peak mid-year. The dinoflagellate and cyanobacteria distributions were less distinct, peaking in different seasons and different positions along the mid-shelf region.

* Macrozooplankton (Gaughan et al., submitted) were also patchy with a large variation between the two years. The macrozooplankton community was characterised by a mixture of tropical and subtropical species (reflecting advection in the Leeuwin and Capes Current systems) but overall densities were much lower than in the Benguela Current upwelling system.

* Of the taxa processed, chaetognaths were dominant and were generally found inshore. The numbers of chaetognath and siphonophore species and their abundances peaked in autumn/winter, while the distribution of pilchard eggs shows distinct spawning periods in both summer and winter, concentrated in the mid-shelf region.

* The source of an exceptionally high abundance of most taxa close inshore in May 1998 was not evident, but the event clearly showed the high variability that can exist.

5.5 General comments

Despite the simplicity of the methods used, this project has yielded some significant advances in our knowledge of the water properties and the plankton regime across the continental shelf off Perth, and provides a good foundation for further work in this area. Inexpensive surveys of this type are adequate for defining the climatology of a coastal bioregion, classifying its main characteristics and subsequently monitoring the water quality, but longer

time-series (3 to 5 years -- see for example Pearce et al., 1985 and Thompson and Waite, 2003) may be required to more adequately define the seasonal nutrient and chlorophyll cycles because of the high level of small-scale variability.

Because of the general sparcity of information along the Western Australian continental shelf, there is significant benefit in the utilisation of satellite-derived products for defining baseline conditions, assessing natural variability and prescribing indicators of non-natural pertubations of the system due to such causes as climatic extremes or anthropogenic forcing. This project has demonstrated that Chl-a concentration and diffuse attenuation coefficient, products often used as indicators of water quality and clarity, are able to be provided by remote sensing methods, especially in open oceanic (case 1) waters where phytoplankton may be considered the dominant optically active constituent. Nearer the coast, when other constituents are present in the water column, the assumptions on which the algorithms are based may be invalid so care must be taken in their utilisation.

For confidence in the remotely-sensed products right across the shelf into shallow coastal (Case 2) waters, robust measurements of water column properties are essential. These are currently being undertaken through a new initiative (the Strategic Research Fund for the Marine Environment, or SRFME) which is investigating relationships between the oceanic environment, primary productivity and zooplankton across the Western Australian continental shelf and out into deeper open-ocean water. While the dominant features of the seasonal and cross-shelf distribution of the physical and optical water properties have been elucidated in the Hillarys Transects, more sophisticated sampling techniques and the greater geographic coverage in SRFME will provide better in situ validation data especially in the nearshore (Case 2) waters.

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Figure Captions

Figure 1: The continental shelf region of southwestern Australia, showing the location of the Hillarys Transect (filled circles, stations H0 to H40), Hillarys Marina with a weather station (HM) and the mouth of the Swan River (SR). The Swanbourne and Ocean Reef waste outlets are SW and OC respectively, and the CSIRO "Rottnest station" is ROT. The alongshore transect stations A to S (filled squares) are described in the text. The arrows depict a representation of the Leeuwin (warm water, solid arrows) and Capes (cooler water, dashed arrows) Currents. The bathymetry has been simplified from the National Bathymetric Survey 1:250,000 Series chart "Yanchep".

Figure 2: Seasonal wind roses for the Rottnest Island AWS, covering the period late 1987 to early 2006, courtesy of John Cramb, Bureau of Meteorology, Perth. The seasons are defined as December-January-February (southern hemisphere summer) etc, and the 9 am and 3 pm roses are presented separately because of the dominant sea-breeze pattern in the summer months. Directions are in the traditional meteorological sense, i.e. direction from which the wind is blowing. The wind speed and frequency scales are indicated in the attached box.

Figure 3: Monthly mean alongshore current components at mid-depth at (a) the PCWS joined deep water mooring sites DW1 + DW2 (in 220 m and 110 m water depths respectively; the change occurred in March 1993) and (c) the shallow water mooring SW2 (in 27 m water); northward flow is positive. Figures (b) and (d) show the relative frequencies of northwards (solid bars) and southwards (pale bars) currents, defined by the sectors NW to NE and SW to SE respectively, at the deep and shallow water sites. Data courtesy of DA Lord and Associates (now Oceanica Consulting), the Centre for

Water Research (University of Western Australia) and Steedman Science and Engineering (now Metocean Engineers).

Figure 4: Bathymetric profile along the Hillarys Transect derived from an echo-sounding run (out to H40) and thereafter from the National Bathymetric Survey 1:250,000 Series chart "Yanchep". The dropped lines show the station positions H0 to H40.

Figure 5: Monthly mean wind vectors and wind components over the 3-year period 1996 to 1998 from the Rottnest Island weather station operated by the Australian Bureau of Meteorology. Both the wind vectors and the components are in the direction towards which the wind is blowing. The stability is defined in the text.

Figure 6: NOAA-AVHRR satellite images of sea-surface temperature off Perth in January 1997 (upper panel, representing summer conditions) and July 1997 (lower panel, winter). The warmest water is depicted as red, cooling through yellow and green to the coolest water in blue; the images have been individually colour-enhanced to show greatest detail of the thermal structure so the colours do not match between the two images. The temperatures are the brightness temperatures in AVHRR band 4, and have not been corrected for atmospheric effects. The black contour marks the position of the 200 m isobath, approximately delineating the edge of the continental shelf, and the Hillarys Transect is the solid line partly crossing the shelf.

Figure 7: Digital AVHRR SST transects from 113°E to the coast in January 1997 (upper curve -- summer) and July 1997 (lower curve -- winter), matching the images in Figure 6. The Hillarys Transect is shown by the H40-H0 bar at the top of the Figure, and the squares and triangles represent the SDL temperatures at the Transect stations. The vertical line marks the approximate position of the 200 m isobath ("shelf-break").

The southward-flowing Leeuwin Current is visible in each season (circles with dots) while the cool Capes Current and the warm eddy (derived from the Leeuwin Current) are northward currents (circles with crosses).

Figure 8: NOAA-AVHRR satellite images of sea-surface temperature off Perth in January 1998 (upper panel) and October 1998 (lower panel). Details as in Figure 6.

Figure 9: Time-distance contour diagrams of (a) surface temperature and (b) surface salinity along the Hillarys Transect between October 1996 and December 1998. The dots show the station positions.

Figure 10: Monthly mean (a) surface temperature and (b) salinity near the coast (stations H0 and H5 -- filled circles) and offshore (stations H35 and H40 -- open circles) derived from the 27 monthly transects. The minima and maxima measured in each calendar month are also indicated.

Figure 11: Temperature/salinity (T/S) diagram for surface temperatures and salinities at all stations between 1996 and 1998. The blocked areas depict the approximate characteristics of the seasonal water properties defined in the text.

Figure 12: Surface salinities sampled at stations A to S (Figure 1) between 1985 and 1989 (CSIRO unpublished data), collapsed into a single year. Salinities below 32 psu have been omitted to show more detail of the finer-scale differences above 35 psu.

Figure 13: (a) to (d) Examples of the vertical temperature structure across the continental shelf derived from the SDL profiles. See text for explanation.

Figure 14: Relationship between the near-surface temperature differential (between the highest SDL temperature SDLmax and the average temperature T1 in the top 1 m of the water column) and the on-station wind speed measured with the hand-held anemometer.

Figure 15: Histogram of SDL profile temperature differences between the surface and 3 m depth (solid bars) and 3 m to 18 m depth layer (clear bars), derived from the SDL 1-m depth-interval temperature profiles.

Figure 16: Scatterplot of the chlorophyll-a concentration derived using the spectrophotometric method (horizontal axis) and the fluorometric technique (vertical axis).

Figure 17: Time-distance contour diagrams of depth-integrated chlorophyll-a concentrations along the transect between October 1996 and December 1998, measured by the fluorometer. The dots show the station positions; there were no samples in June 1997, and the August 1998 transect was truncated due to poor weather.

Figure 18: Time-distance contour diagrams of depth-integrated concentrations of (a) nitrate, (b) silicate and (c) phosphate across the transect between September 1997 and December 1998. The dots show the station positions; the August 1998 transect was truncated due to poor weather. Some of the nitrate concentrations were below the 0.03 μM analytical threshold and so are classified as zeros.

Figure 19: Along-transect 1-km averaged surface temperature (filled circles) and fluorescence/chlorophyll (open circles) in (a) May and (b) December 1998 from the underway measurements. The envelopes mark the ±standard deviation limits in each case.

Figure 20: Histograms of the along-transect 1-km (within-pixel) variability showing the mean - minimum/maximum differences for (a) SST and (b) chlorophyll derived from from the underway measurements. The SSTs are for the full period 1996 to 1998, while the chlorophylls are for 1998 only.

Figure 21: Histograms of the along-transect between-pixel variability showing the differences between adjacent 1 km segments for (a) SST and (b) chlorophyll derived from from the underway measurements. The SSTs are for the full period 1996 to 1998, while the chlorophylls are for 1998 only.

Figure 22: Monthly values of the Southern Oscillation Index (SOI -- small dots), Fremantle sea level anomaly (FMSL -- filled circles) and the Reynolds SST anomaly for the 1-degree square 31°-32°S and 115°E to the coast (SST -- open circles) between 1990 and 1998. The anomalies have been derived by subtracting each individual monthly value from the long-term mean for that month, and smoothed by a simple 5-month moving average to reduce smaller-scale variability. The Hillarys Transects covered the last 27 months.