Pelagic Regionalisation

National Marine Bioregionalisation Integration Project

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Summary

The three-dimensional nature of the marine environment and its temporal variability have posed difficult challenges in understanding and managing the pelagic (water column) component of the oceans. Other than in satellite-based plankton images, biological information lacks spatial and temporal coverage to adequately regionalise this environment, or to determine surrogate relations between geophysical properties and ecological structures and processes. Management needs and potential uses of pelagic regionalisation information are consequently also unclear because there are no synergies with terrestrially based studies or with regionalisations of benthic marine systems based on distributions of biota and the geophysical properties of the seafloor.

We describe a hierarchical framework for regionalising the pelagic marine system that relies primarily on physical properties and satellite plankton images. Three levels of the framework (Levels 1–3) are described by application to Australia's Marine Jurisdiction. The first level (Level 0) describes the structure at the scale of the oceans. The second level (Level 1) describes ocean zones that appear as latitudinal bands at the surface (Level 1a) but also have an underlying three-dimensional structure (Level 1b). The third level (Level 2) describes the different circulation regimes arising from mixing and transport of water properties. The fourth level (Level 3) describes the energetics and variability of water masses; we present only the surface characterisation at this level. Although finer-scale levels (Levels 4a and 4b) are presented in the regionalisation framework, we only present analyses down to Level 3. The finer-scale levels are dynamic features whose description is left as a subject for future research.

Key conclusions of this project are summarised below:

1. Substantial progress has been made in classifying the pelagic environment through an integrated analysis of the whole water column. A hierarchically nested classification appears possible from the scale of oceans (Level 0) down to at least Level 2 (Circulation Regimes). However, the complications due to seasonal and longer timescale variability are yet to be examined in a systematic way.

2. Biological information is required to guide and inform the analyses; this is currently the main major shortcoming of the regionalisation.

3. This is one of the most comprehensive studies undertaken for a pelagic regionalisation. A valuable collection of data for future extensions of this study now exists in a well documented state (Hayes et al. 2005).

4. A workable pelagic framework has been constructed down to the scale of features (Level 4a) and substructure of features (Level 4b).

5. Beyond Level 2, energetics in the ocean system as characterised by fields of homogeneity and heterogeneity in water masses provide useful qualifiers for Level 2 classes. The rich variety of oceanographic processes that can be identified with such an analysis may have implications for biological productivity and hence for marine resource management. Deciding how best to use the available information at the various Levels and what future information will help refine the analyses and descriptions will require careful consideration.

6. The complexity and richness of the pelagic regionalisation demands innovative methods of visualisation and a dedicated program of education and information dissemination for managers, researchers and stakeholders, including the general public and students.

At this stage, the pelagic regionalisation of Australia is being used mainly to illustrate the complexity of the structure of the marine water column. It is at an earlier stage of development than the benthic regionalisation. However, as with the benthic regionalisation, the key aim

ultimately in using the pelagic regionalisation is to determine linkages between biological and geophysical attributes, which we expect to be much stronger in pelagic than benthic systems. Our work also suggests that the coupling between pelagic and topographic structures is much tighter than we expected, and that a unified treatment of pelagic and benthic regionalisations should be possible. A corollary conclusion is that benthic structures may be influenced by the pelagic environment and that past benthic regionalisations should be reviewed to take account of this project’s findings.

1 Introduction

1.1 Project background

According to Australia's Oceans Policy:

… the Australian Government is committed to an ecosystem-based approach to oceans management. This approach requires planning and management to be based on ecosystem characteristics. Bioregionalisation is one way of defining ecosystems as it defines regions based on physical and biological properties.

Ecosystems-based management has been implemented through Regional Marine Planning. At a broad scale, regional marine plans have been based on the Large Marine Domains (Lyne et al. 1998) while smaller scale plans have been based on the Interim Marine and Coastal Regionalisation for Australia (IMCRA) (IMCRA Technical Group, 1998).

The current National Marine Bioregionalisation (NMB) project, coordinated by the National Oceans Office, consists of both pelagic (water column) and benthic (seafloor) components. Its intended outcome is a set of bioregions for Australia's Exclusive Economic Zone that will underpin a spatial framework to support planning and management of Australia's oceans. This technical report outlines the work on the pelagic regionalisation.

The Pelagic Integration project aims to map and describe the pelagic bioregions of the Australian Exclusive Economic Zone, with a particular focus on regions offshore of the continental shelf. It complements the existing pelagic bioregions on the continental shelf described in the IMCRA. In the process of the current regionalisation, we have produced datasets and analyses that may help update the IMCRA pelagic bioregions and their descriptions in the future. The results of this project should not be extrapolated to the continental shelf.

CSIRO Marine Research has responsibility for the Pelagic Integration project as part of its contribution to a consortium effort (along with the National Oceans Office and Geoscience Australia (GA)) in the NMB projects.

To facilitate discussions in the rest of the report, Figure 1-1 shows a schematic illustration of the major current systems and fronts in the oceans surrounding Australia (from Condie et al. 2003).

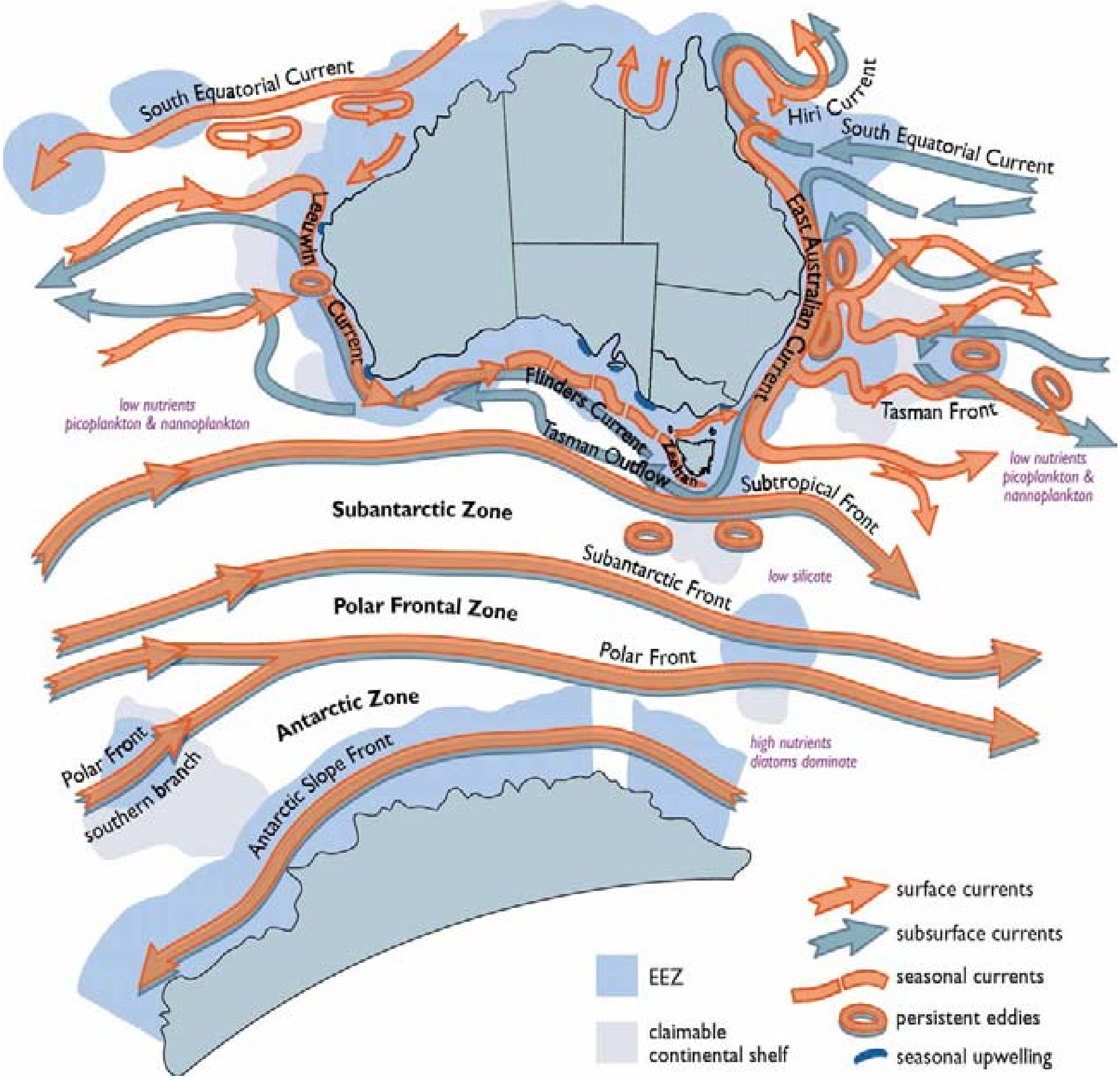

Figure 1-1 Schematic illustration of the larger-scale oceanographic features across the region encompassing the Australian Marine Jurisdiction.
Surface currents are indicated by orange arrows and subsurface currents by green arrows. Dashed arrows indicate that currents are present only on a seasonal basis and blue shading indicates regions of significant seasonal upwelling into near-surface waters.

1.2 Bioregionalisation background

The growing global interest in ecosystem-based management combined with the spatially complex and time-variable nature of the marine environment has increased the need for a systematic analysis of ecological structures and linkages in the pelagic environment. One component in this endeavour is the development of regionalisation and classification schemes capable of describing and mapping pelagic habitat structures.

Until recently, there were no global datasets necessary to undertake large-scale pelagic bioregionalisations, and to date there are still very limited biological data available. Over recent decades, scientists have had access to satellite-derived datasets for ocean colour and temperature. This has allowed attempts to be made at surface and near-surface regionalisation and classifications (Longhurst 1995b, 1998, Harding 1997, Snelder et al. 2004). Nonetheless, globally, there have been few attempts at pelagic regionalisations and none that we are aware of that involved the entire water column from the seafloor to the surface, as described in this work.

While a comprehensive review and critique of regionalisations/classifications of pelagic systems around the world is not possible within the scope and limitations of this project, it is instructive to review a few of what we consider to be the major efforts in this field. Ideally, what is needed is an approach that is *systematic*, *structured and integrative*, and capable of being tailored to meet a variety of needs at various scales and ecological levels of interest. *Systematic* implies that there is an underlying conceptual framework that relates spatial structures to environmental and ecological processes at various scales. *Structured* implies that spatial and temporal scales of variability and ecological levels (for example communities, species, genes) are structurally linked – including the three-dimensional nature of the pelagic environment. *Integrative* implies that the full suite of available information can be assimilated to provide the best possible description and that future updates to information can be used to update the analyses.

It is also important to distinguish between a conceptual framework and the pragmatic considerations involved in applying that framework. Methods used in regionalisations/classifications range from Delphic approaches using experts (for example CONCOM 1985) to so-called “objective” statistical classifications or clusterings of finely resolved multivariate data (for example Snelder et al. 2004). What matters in the end are not the precise details of the method used but rather whether the chosen structural arrangement of units is justifiable (from the available information) and whether it is representative of the underlying ecological elements and structures that are relevant to management concerns. Delphic approaches by their very nature are highly dependent on the knowledge of the experts involved. While the results may be just as good as, if not superior to, statistical approaches, their lack of reproducibility and inadequate documentation of complex decisions may be unacceptable in this age of accountability. In so-called “objective analyses”, subtle but far-reaching subjective decisions may be implicitly embedded in the choice of variables, normalisation, combination, gridding, interpolation, extrapolation, distance metric, and so on. It is our experience that the methods of analysis are not as important as the way in which the information is selected (including controls for quality), processed and presented for analysis (be it Delphic or objective). In fact we would go so far as to say that, in our experience, it is more important to consider how the information is selected, simplified and preconditioned than to obtain the best resolution data.

We have not found any existing analyses, limited as our search may have been, that adhere closely to all of the above considerations. The Canadian approach as detailed by Harding (1997) comes close, in that the authors developed a hierarchical framework, wrote detailed descriptions of each level of the hierarchy and used an integrative approach to apply the framework. The classification system consisted of the following levels:

Classification Level	**Criteria**
1. Ecozones	Ocean basins and coastal zone

2. Ecoprovinces	Major oceanic surface-current systems and continental margins.
3. Ecoregions	Marginal seas
4. Ecodistricts	Mixing processes/stratification/smaller-scale currents

A largely Delphic approach was used in applying the framework, but close consultation was maintained with users and managers. The product is intended to be used to monitor and report on marine ecosystems, with a secondary aim of helping to plan, conserve and protect Canada's marine ecosystems.

The New Zealand experience, as described by Snelder et al. (2004), used physical variables to classify New Zealand's Exclusive Economic Zone. Multivariate hierarchical clustering was conducted for spatially explicit physical data layers that included depth, sediment type, long-term annual mean surface radiation, sea-surface temperature, mean and maximum wave height, and tidal currents. The New Zealand analysis produced a two-dimensional classification for various numbers of classes. For the 20 class case, when 14 out of the 20 classes were tested with available biological datasets, these classes were found to be biologically distinct. The approach highlights the need for physically based classifications to be tested against biological information. But while biological data may be found that support a particular physical class, there is no guarantee of the ecological (surrogate) relevance of a set of physical classes.

Both the Canadian and New Zealand attempts are a mixture of pelagic and benthic regionalisations/classifications, restricted to regional scales. The few studies that provide classifications comparable to the present study are described below.

Longhurst (1995b, 1998) identified bioregions over the global ocean principally from the seasonal cycles of mixed-layer productivity. The initial analysis used monthly averaged fields of mixed-layer depth (NOAA-NODC compilation), stratification, deformation radius, and CZCS (Coastal Zone Colour Scanner) data on a 1.0º grid (Longhurst 1995a). Four primary ecological domains (polar, westerly wind, trade wind and coastal boundary domains) were identified on the basis of exchange rates between the photic layer and nutrient-rich deeper water. Subsequent work showed that the regions were statistically distinct (Longhurst 1998). These realms were further subdivided into more than 50 provinces on the basis of prevailing currents and fronts, topography and persistent ocean-colour features. Figure 1-2 shows Longhurst's provinces for the region described in our study.

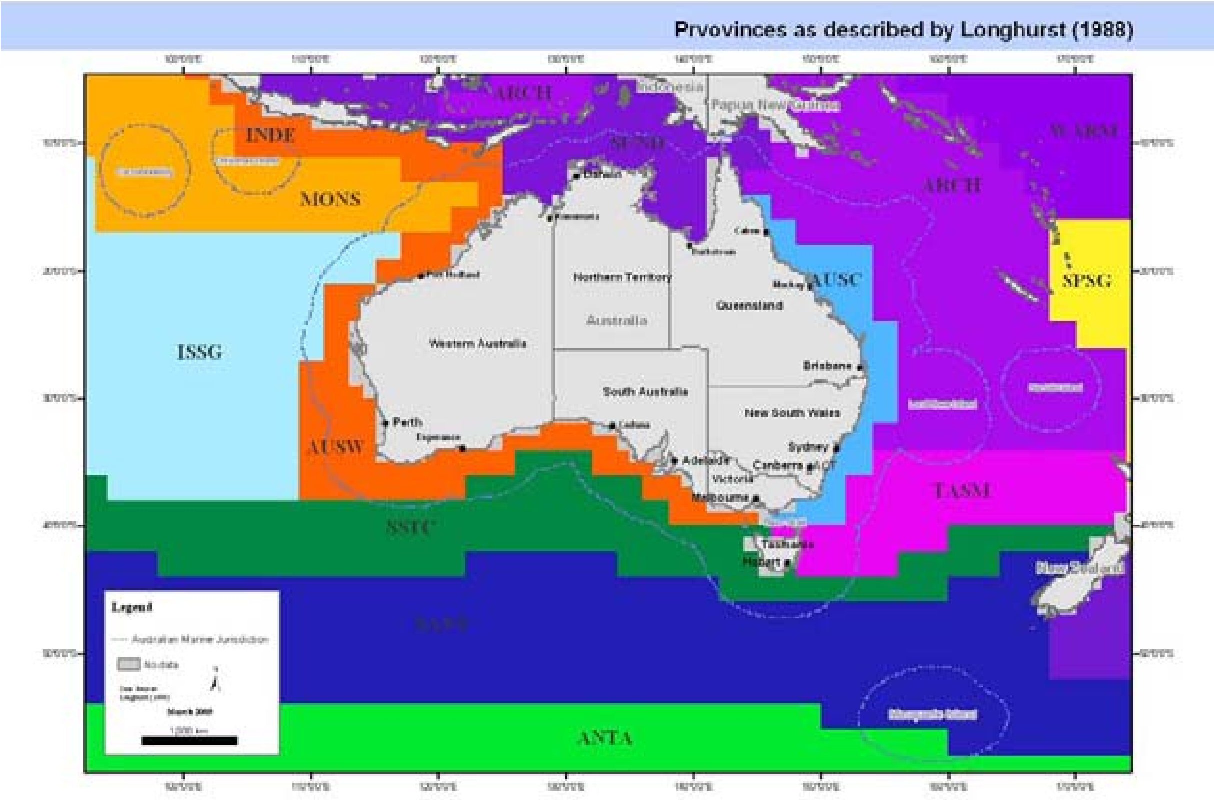

Figure 1-2 Provinces as proposed by Longhurst (1998) for the region examined in this study. Acronym descriptions are as follows: ISSG Indian South Subtropical Gyre Province; INDE Eastern Indian Coastal Province; MONS Indian Monsoon Gyres Province; ISSG Indian South Subtropical Gyre Province; SUND Sunda-Arafura Shelves Province; ARCH Archipelagic Deep Basin Province; WARM Western Pacific Warm Pool Province; SPSG South Pacific Subtropical Gyre Province; TASM Tasman Sea Province; AUSW East Australian Coastal Province; AUSC East Australian Coastal Province; SSTC South Subtropical Convergence Province; SANT Subantarctic Water Ring Province; ANTA Antarctic Province.

Other large-scale biogeographic analyses have been developed using biological data. For example, Jeffrey and Hallegraeff (1990) identified four regions around the Australian continent on the basis of distribution of phytoplankton communities (Figure 1-3). One region corresponded to Australia's northern tropical shelf seas (Arafura Sea, Timor Sea and the Kimberly portion of the North West Shelf); it contained species of diatoms, dinoflagellates, cyanobacteria (Trichodesmium) and a high proportion of nanoplankton. A second region in the west (Pilbara half of the North West Shelf and the Southeast Indian Ocean, excluding the eastern Great Australian Bight) contained diatoms, cyanobacteria and a great diversity of dinoflagellates. A third region off eastern Australia (Great Barrier Reef, Coral Sea and northern Tasman Sea) supports a similar community, but at lower cell concentrations. A fourth region was characterised by a wide variety of diatoms and dinoflagellates, with nanoplankton contributing most of the chlorophyll except during diatom blooms. As part of the oceanographic dataset collation project (in Hayes et al. 2005), Hallegraeff updated the phytoplankton distribution map (Figure 5-7) to show phytoplankton distribution at a range of regionalisation scales.

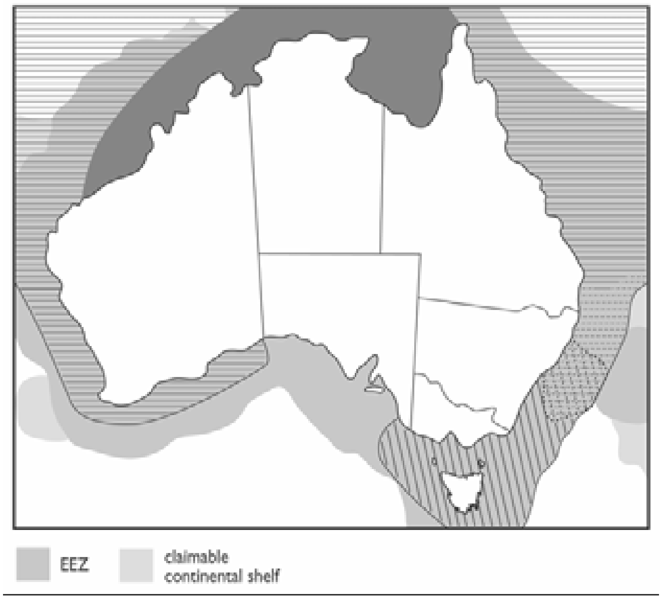

Figure 1-3 Biogeographic description based on phytoplankton communities identified by Jeffrey and Hallegraeff (1990).

Biogeographic analyses based on water-column properties have been undertaken at a range of scales. For example, Muller-Karger et al. (1991) examined two regions (each 200 x 200 km^2) in the Gulf of Mexico, using monthly averaged Coastal Zone Color Scanner (CZCS) data and mixed-layer depths estimated from mean monthly climatological profiles of temperature, salinity and density (NOAA-NODC). Condie and Dunn (in prep.) produced a biogeographic description based on CSIRO Atlas of Regional Seas (CARS) and estimates of chlorophyll from SeaWIFS ocean-colour data (see Figure 1-4). Their regions correspond fairly well with Longhurst's provinces (Longhurst 1998) but include additional smaller regions off northern Australia and within the Indian Archipelago province.

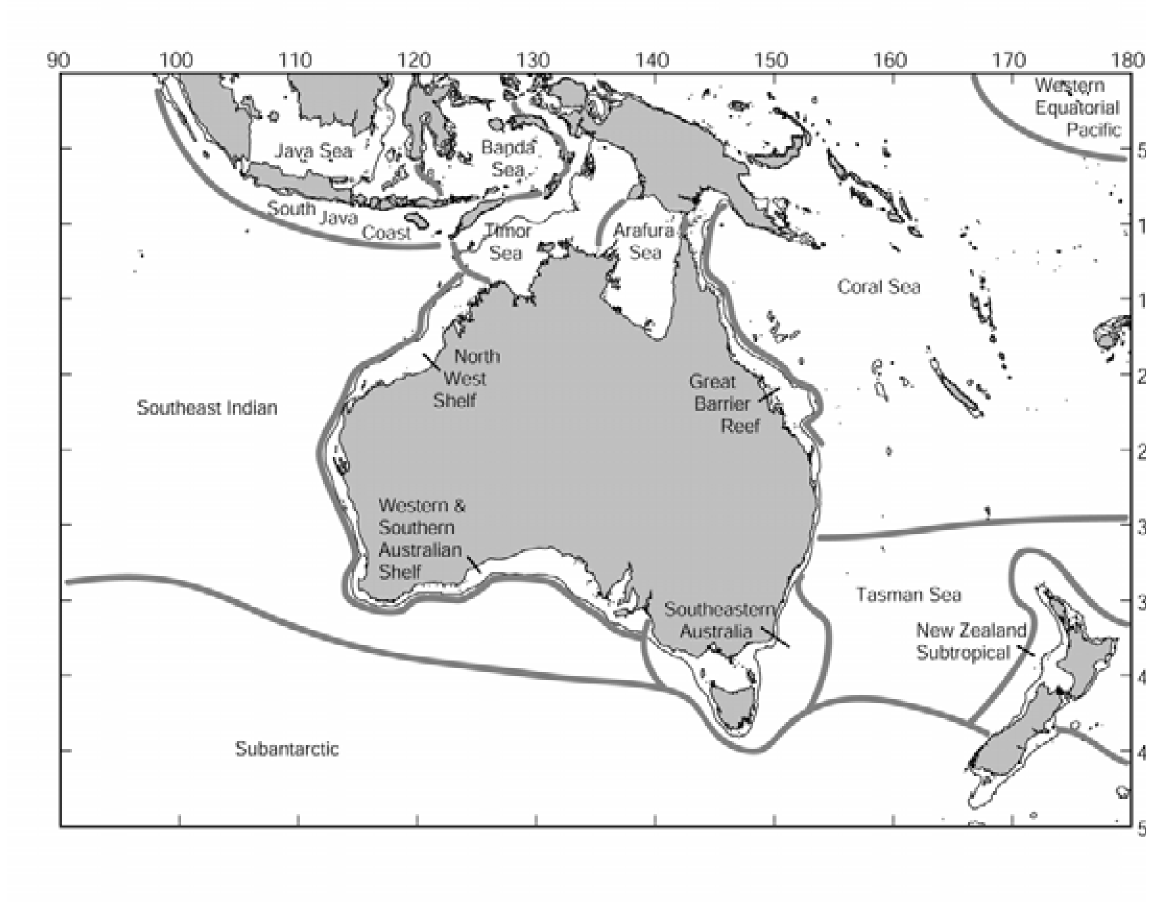

Figure 1-4 Major biogeographic regions suggested by Condie and Dunn (in prep.).

Pelagic and demersal regionalisations were done for the Australian marine region by the Interim Marine and Coastal Regionalisation for Australia Technical Group (IMCRA 1998). Pelagic bioregions on the continental shelf were characterised by extensive range distributions of fish that reflected their dispersal transport pathways and evolutionary adaptations. Two core provinces and two zootones[1] were identified on the continental shelf (Figure 1-5). A physical oceanographic regionalisation was also produced by CSIRO (1996) for the IMCRA regionalisations, for waters beyond the shelf break for three different depth layers (Figure 1-6). The surface and 150 m regionalisations had 20 classes while the 800–1000 m regionalisation had 10 classes. These classifications were preliminary assessments of water-mass types based on such properties as temperature, salinity and a variety of nutrients. The IMCRA Group had intended to develop a more structured and rigorous regionalisation of offshore pelagic waters in the future. The current project was conducted with that intention in mind, but tempered by the limited time and resources available to do so. Nonetheless, the IMCRA regionalisations do provide a preliminary indication of the spatial structuring of offshore water masses and variations by depth.

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[1] ***Zootones*** are areas where species from disparate provincial core regions undergo mixing (which may also be the endpoint for a provincial core region).

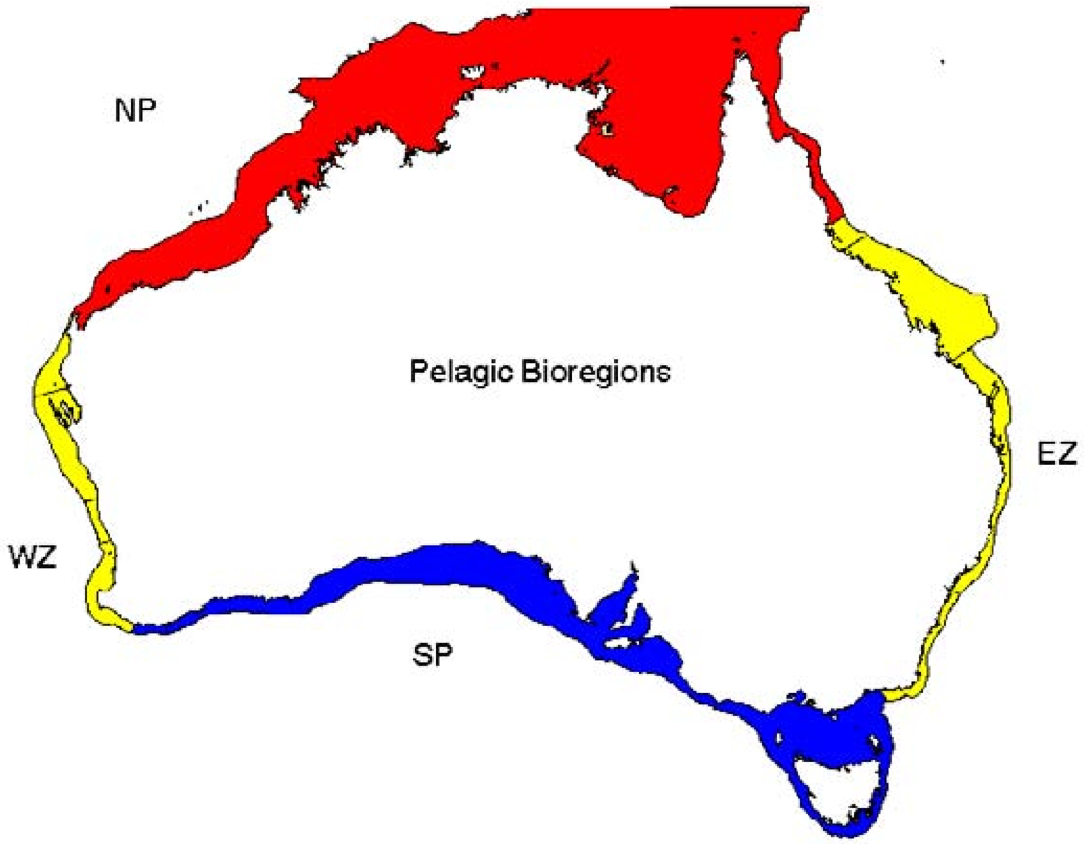


Figure 1-5 Pelagic bioregions as defined by IMCRA (1998).
SP Southern Pelagic Province, WZ Western Pelagic Zootone, EZ Eastern Pelagic Zootone, NP Northern Pelagic Province.

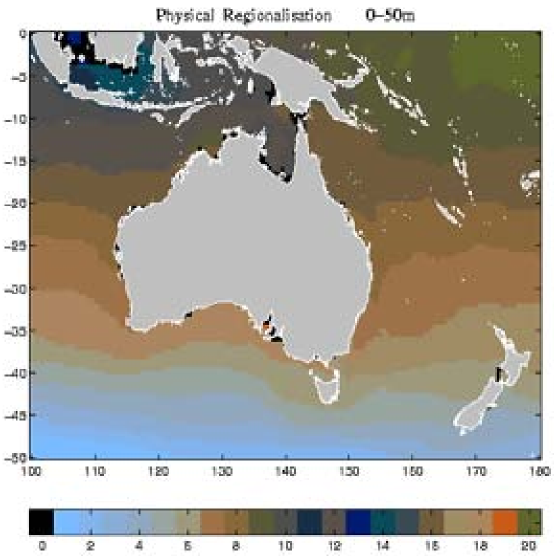
The IMCRA offshore surface regionalisation (Figure 1-6a) shows stronger gradient groups in the west and semi-continuous southern groups that dip slightly southward in the east. The Indonesian Archipelago stands out as a unique environment in keeping with the patterns evident from the attributes (see CSIRO, 1996). Similarly, the southward dip of isolines on the western and eastern coasts, associated with the boundary currents there, is also evident. Lower Spencer Gulf in South Australia stands out as a distinct class, reflecting the unique high temperature and high salinity environment of that region.

The 150 m physical oceanographic regionalisation (Figure 1-6b) provided the strongest reflection of the east-west gradient disparity. The north-western region stands out as a distinct pattern. The boundary current regions also appear to be more strongly differentiated in the 150 m pattern. The 800–1000 m regionalisation map (Figure 1-6c) shows a distinct change in the east–west water masses across the north. Sharp changes can be seen in a band running westward and slightly northward off central Western Australia, with less variability south of this band.

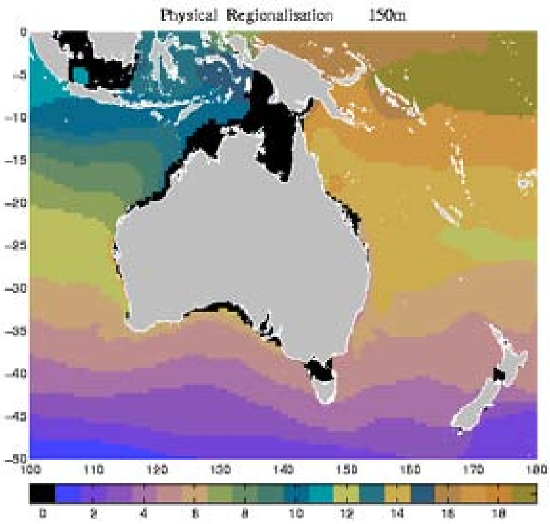
For comparison purposes, it is inappropriate to compare the shelf IMCRA provinces with those in the offshore region because of substantial differences in oceanographic and biological processes. The shelf IMCRA provinces therefore complement the offshore pelagic regionalisation conducted here at Level 1a (which is the equivalent provincial scale classification in the offshore region). Our regionalisation also updates the IMCRA offshore pelagic classes because we used updated oceanographic datasets and structured analyses guided by an underlying framework. The offshore classifications produced here therefore supersede the IMCRA offshore classes.

In summary, while a more detailed review of existing pelagic regionalisations/classifications is needed, the main studies to date suggest a need for a systematic, structured and integrative approach, and for international collaboration to advance this field. This study provides the strategic framework and guidance on tactical applications for such endeavours.

a.



b.



c.

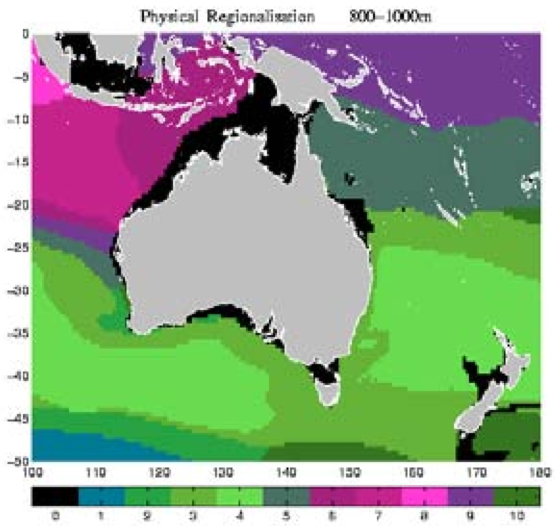


Figure 1-6 Physical oceanographic regionalisation for depth ranges (a) 0–50 m (b) 150 m and (c) 800–1000 mm.
The difference in colour between the total properties of those groups indicates the degree of difference between the total properties of those groups. For example, in the 0–50 m analysis, there are shades of blue in the cold south and the hot north-west. However, in both these regions salinity tends to be low and nitrate tends to be high and very seasonal. There is no significance in the group numbers – they are for identification (CSIRO Division of Fisheries and CSIRO Division of Oceanography 1996).

2 Project Scope and Objectives

The National Oceans Office specification for this project required integrated products to be delivered by December 2004. Given this constraint, CSIRO Marine Research's original 18-month work plan was scaled back to what was achievable within the tight budget and the timeframe of a few months. This limited both the information incorporated in the regionalisation as well as the analyses used in deriving the regions. The tight delivery deadline required the work to focus on available datasets and analyses, and many of the biological data that were intended to have been used (primarily Myctophids) had to be excluded. The longer-term goals of producing new and updated datasets for future revisions of the bioregionalisation and of developing methods for using bioregionalisations in a marine planning context were thus put on hold.

CSIRO Marine Research's contributions to the overall NMB work plan were thus restricted to:

- *contributing to the Consortium work plan to deliver a set of integrated bioregionalisation products by the December 2004 deadline.*

The specific, contracted deliverables of the project were:

- *static maps ('snapshots') of the pelagic realms of Australia's Marine Jurisdiction, which portray information on spatial structure and, to a certain extent, temporal variability*

- *a short technical report that describes the methods used to derive the bioregions.*

The basis for CSIRO's participation in the project was defined in a workshop held at the CSIRO Marine Laboratories in Hobart from 7 to 9 June 2004.

3 Pelagic Regionalisation Framework

Ever since the early draft pelagic regionalisation reported in IMCRA (1998), there has been much interest at a national level in developing a framework for an improved regionalisation. In recent years at least two major informal workshops involving international participants have been funded by the National Oceans Office and the Fisheries Research and Development Corporation to progress this field. In the following sections, we discuss the background to the main issues which have been debated over the years and we propose a framework within which the current regionalisation is conducted.

3.1 Introduction

Ideally, ecosystem-based management should be based on a comprehensive and integrated understanding of coastal and marine ecological systems, but this is unlikely to be achievable. Regionalisation provides a framework within which issues can be examined at different scales. Furthermore, since spatial scales and species diversity are intimately related (for example in the commonly used species–area relationships), the purpose of regionalisation helps simplify the complex relationship between the environment and species' distributions. At the broadest scale, we recognise that species that primarily inhabit the water column of the oceans (pelagic species) have evolved separately to those that inhabit the seafloor (benthic or demersal species). However, this separation is not distinct: environmental, chemical and biological interactions occur between the pelagic and benthic systems at virtually all spatial scales. Nonetheless, separate consideration of pelagic and benthic systems at the broadest scales provides a useful first cut at understanding the spatial structures.

A common misconception of regionalisation is that each region within the regionalisation is a self-contained structure within which is encapsulated a largely self-sustaining association between species and their environment. This is not so. A regionalisation should be viewed as no more than providing a structural metric within which ecological associations, processes and functions can be examined more carefully and with due regard to the influence of scale.

A key difference between the pelagic and benthic environments is the continual movement of water that influences pelagic flora, fauna, water properties and dynamics. Evolutionary processes in pelagic systems are thus more influenced by ecological adjustments to changes in water properties and circulatory regimes than by paleo-biogeography (that is to say, by processes such as continental drift that are associated with benthic systems – and may appear to be correlated). The frame of reference in pelagic systems is thus relative to water properties and circulatory systems, and pelagic bioregions are more likely to be defined by these factors. However, the precise definition of these bioregions must still rely upon knowing how biological elements and processes of relevance at a particular scale utilise their environment. So, while we may be able to delineate the boundaries from physical considerations, precisely which are of relevance ecologically requires analyses of biological distributions and associations. This is in contrast to the benthic provincial and biomic regions (Last *et al.* 2005), where physical and geological variables are used as corroborating factors, rather than primary drivers, of the bioregions.

Depth structuring in pelagic and benthic systems is also different in the sense that the depth structures in benthic systems are less dynamic. In the pelagic realm, three-dimensionality and temporal variability at a variety of scales add considerable complexity when delineating spatial bioregions. Water properties and circulatory regimes are highly depth-structured, as is temporal variability, so that pelagic bioregion definitions, and analyses, must consider these factors.

3.2 A Pelagic Classification

We propose in this section a classification scheme that takes account of the issues discussed in the previous section.

At global scales, a natural inclination is to assume that the broadest classification of the pelagic realm will be that associated with ocean basins – following the approach used for benthic systems. However, attempts to apply such an approach will fail because, unless ocean basins are tightly enclosed or semi-enclosed, broad mixing and transitional zones will blur the definition of boundaries at the open ends of the basin and so will three-dimensionality. In the absence of continental land masses, intrinsic scales of variability are set by those arising from hydrodynamic and atmospheric waves and instabilities, along with external forcing due to radiative input. These will primarily be oriented with latitude and include three-dimensional (re)circulatory systems. Continental masses disrupt these structures and create circulatory systems arising from both hydrodynamic flow around the continental obstructions, and intrinsic “closed” circulatory responses and boundary currents (for example, North Atlantic circulation and Gulf Stream) – all of which interact in a complex way with each other. A summary of the spatial framework and description of the hierarchical levels is provided in Table 3-1 and further details are provided in Section 3.3.

For the purposes of this project we only apply the framework down to Level 3 but note that features of the lower order levels are described in the accompanying report by Hayes *et al.* (2005).

Table 3-1 Pelagic classification framework.
The framework is presented as a hierarchy of levels with names, definitions, example units at each level and explanations of how these units are defined for this project. Note that temporal variability, combined with transitional adjustments between and within levels, results in overlaps between levels and units so that, in application, the framework is not strictly hierarchical.

Level	Name	Definition	Examples	Defined by CMR[2] using
0	Oceans	In a global context, partitioning at this level recognises the distinction between fauna (collective ecosystems) of the Indian, Pacific and Southern oceans. Regionalisation at this level needs to be at global scales (since the distinctions are global in context). For this project, a descriptive narrative is used to distinguish the differences and transitions between the Indian, Pacific and Southern oceans.	Pacific, Indian and Southern oceans.	Literature
1a	Oceanic zones	Winds, solar forcing and geostrophy dynamically combine to drive a series of largely circumferential and latitudinally oriented water masses within oceans, each of which can be characterised by its water properties, circulation and assemblages of biota. Transitional zones between some water masses are generally characterised by higher plankton production, which influences trophic structure and interactions. For this project, the classifications based on physical properties are guided and corroborated by the distribution of phytoplankton and pelagic fish on the continental shelf.	The dominant water masses surrounding Australia are the South West Pacific Central Water, Indonesian Throughflow Water (Australasian Mediterranean Water) and Indian Central Water.	CARS[3], but for zones that extend across ocean basins, datasets that are global, or at the very least basin-wide, should ideally be used.
1b	Oceanic Substructure – Water Masses	Within the Oceanic Zones, substructure is characterised by largely latitudinal bands of water masses extending through the water column. These bands represent segments of circulatory systems that may span ocean basins.	Antarctic Intermediate Water, Subtropical Lower Water, Tropical Surface Water.	CARS, full suite of variables.

[2] CSIRO Marine Research

[3] CSIRO Atlas of Regional Seas

Level	Name	Definition	Examples	Defined by CMR[2] using
2	Seas: Circulation Regimes	Within latitudinal bands, different ocean circulations and air/sea moisture exchanges result in different retention, mixing and transport of water properties and biological organisms. Such regions respond differently to seasonal and inter-annual climate variations. Consequently temporal changes may occur in the location, extent and strength of circulation regimes and their biota. Transitional zones characterise the temporal changes and adjustments between the different circulation regimes – and again may be characterised by higher productivity.	Sea between Tasmania and New Zealand. Circulation associated with the East Australia Current (EAC). Arafura Sea off NW Australia. Great Australia Bight offshore circulation. Circulation associated with Leeuwin Current.	CARS: nested analysis of temperature, salinity and oxygen within the level above.
3	Fields of Features	Within Circulation Regimes, structure can be characterised by regions of differing energetics; for example, mixing due to eddy activity, frontal oscillations and boundary currents. Transition regions represent changes in the energetics at the boundary of the field and seasonal movements, and variations in strength.	Fields of eddies: eddies of the EAC. The seasonal movements of the eddy fields of the EAC.	Sea-surface temperature (SST) data, geostrophic currents.
4a	Features	Description of structure and dynamics of individual features.	Individual eddies: Eddy J of the EAC.	
4b	Feature Structure	Internal structure and dynamics of individual features.	The semi-permanent eddies of the EAC.	

3.3 Levels in the pelagic classification framework

Following the proposed framework, we provide qualitative descriptions of the expected regionalisations at each of the levels in the hierarchy. This will set the stage for the analyses which are to follow.

3.3.1 Oceans

Our proposal for the broadest scale of pelagic structuring is **Oceans** (see Figure 3-1) defined loosely, in a global context, by the presence of a unique set of three-dimensional ecological systems whose discriminating characteristics are due to water properties and circulatory systems influenced by continental landmasses and ocean basins (as traditionally defined). We expect the boundaries at this level to be defined at the open ends of oceans from analyses of water properties and circulatory dynamics at global and basin scales. For the purposes of this project, qualitative descriptions only are provided for this level.

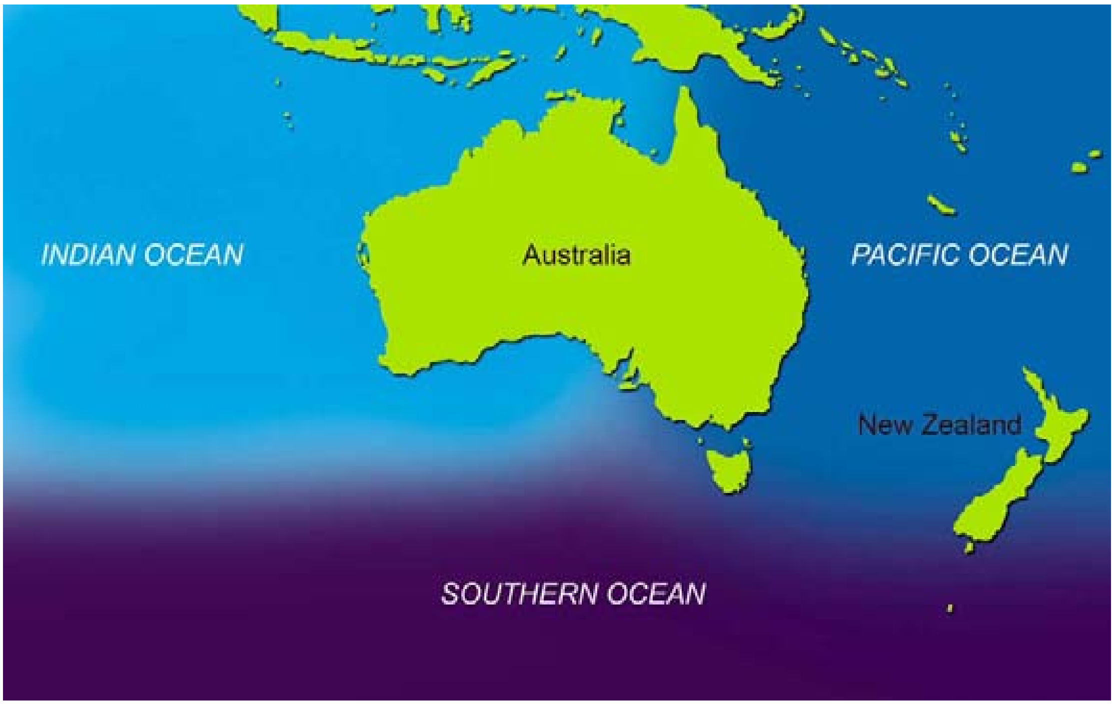


Figure 3-1 The Australian Marine Jurisdiction.
It spans three oceans: the Pacific, Indian and Southern oceans.

3.3.2 Level 1 Oceanic Zones and Water Masses

Within Oceans, regional substructure is determined by primarily latitudinal processes occurring within the oceans. At these scales, winds, solar forcing, air/sea moisture exchange and geostrophy combine dynamically to drive a series of latitudinal circulatory processes that result in banded water-mass structures referred to as **Oceanic Zones (Level 1a).** Near the surface, these bands are dominated by the so-called “thermocline” water masses, which are defined as having formed on the surface before being subducted into the interior of the ocean. To the east of Australia the main thermocline water mass is the South Pacific Central Water, which is formed and subducted in the Subtropical Convergence. To the west of Australia the thermocline water masses are the Indian Central Water, which is formed and subducted in the Indian Ocean Sector of the Subtropical Convergence, and the

Indonesian Throughflow Water. Water properties, circulation and assemblages of biota vary with depth and span similar scales to ocean basins. Transitional adjustments in water properties that occur between some bands are generally characterised by higher plankton production, which influences trophic structure and interactions (see Figure 3-2a). At the October 2004 Bioregionalisation Working Group meeting, the group decided that these zones were too large to be of use to management. We therefore consider this level only in a qualitative sense.

The substructure, including the depth structure, of the Oceanic Zones is made up of bands of water types comprising a series of latitudinal core water masses and transitional water masses and fronts; they are referred to in this report as **Water Masses (Level 1b)** (see Figure 3-2b). As an example, these water masses may be segments of basin-scale circulatory systems (northern segment, central core, southern segment, etc.).

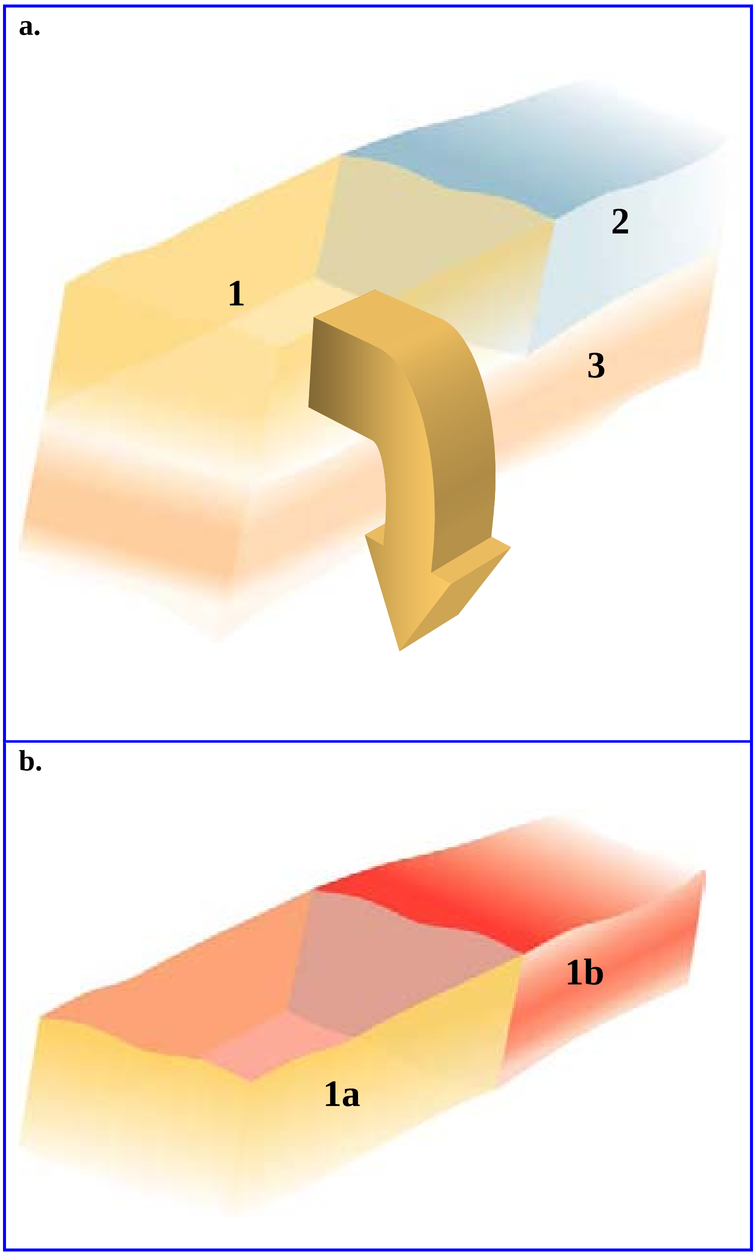


Figure 3-2 Ocean Zones and levels.
The top image (a) represents three different Ocean Zones (Level 1a). In the second image (b) nested within the Ocean Zones are Level 1b water masses, which include depth structuring.

3.3.3 Seas: Circulation Regimes

Within latitudinal bands at Level 1b, different ocean circulations result in different retention, mixing and transport of water properties and biological organisms. The resulting regions at this level (Level 2) respond differently to seasonal and inter-annual changes. Consequently temporal changes also may occur in the location, extent and strength of these regions and their biota. Transitional zones, between the different circulation regimes, may be characterised by higher productivity.

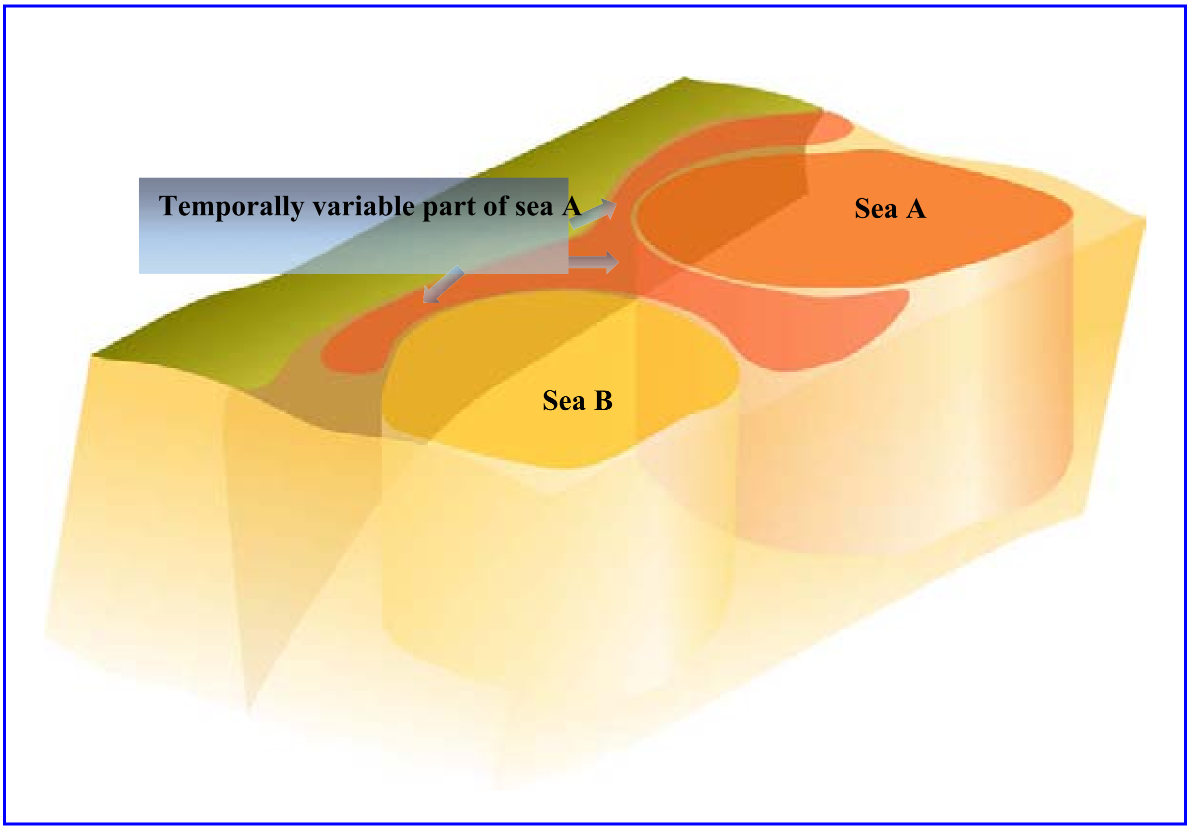


Figure 3-3 Seas and circulation regimes.

3.3.4 Fields of Features

Within Circulation Regimes, structure can be characterised by regions of differing energetics (Figure 3-4), such as eddy activity, frontal oscillations and boundary currents. Transition regions represent changes in energetics at the boundary of the field and seasonal movements, and variations in strength. In this classification, fields of features at the sea surface are defined by variability in sea-surface temperature.

Figure 3-4 Fields of Features.
(Compare with Figure 4.1, which depicts an SST image of similar fields of features.)

3.3.5 Features

Level 4a describes the structure and dynamics of individual features; for example, an individual eddy in a field of eddies (Figure 3-5a). Eddies are interesting features that form and separate from a body of water. Water properties and biota are often carried long distances from the parent water body (see "The dynamics of the East Australian Current" in Hayes *et al.* 2005). Note that at this level and below, features may be dynamic and hence may not be identified in a static map – for example, the location of an eddy at any point in time.

3.3.6 Feature Structure

Level 4b was based on structural elements of an individual feature. For example, Figure 3-5b illustrates the internal structure and dynamics of an eddy in winter when convection has modified the mixed-layer depth.

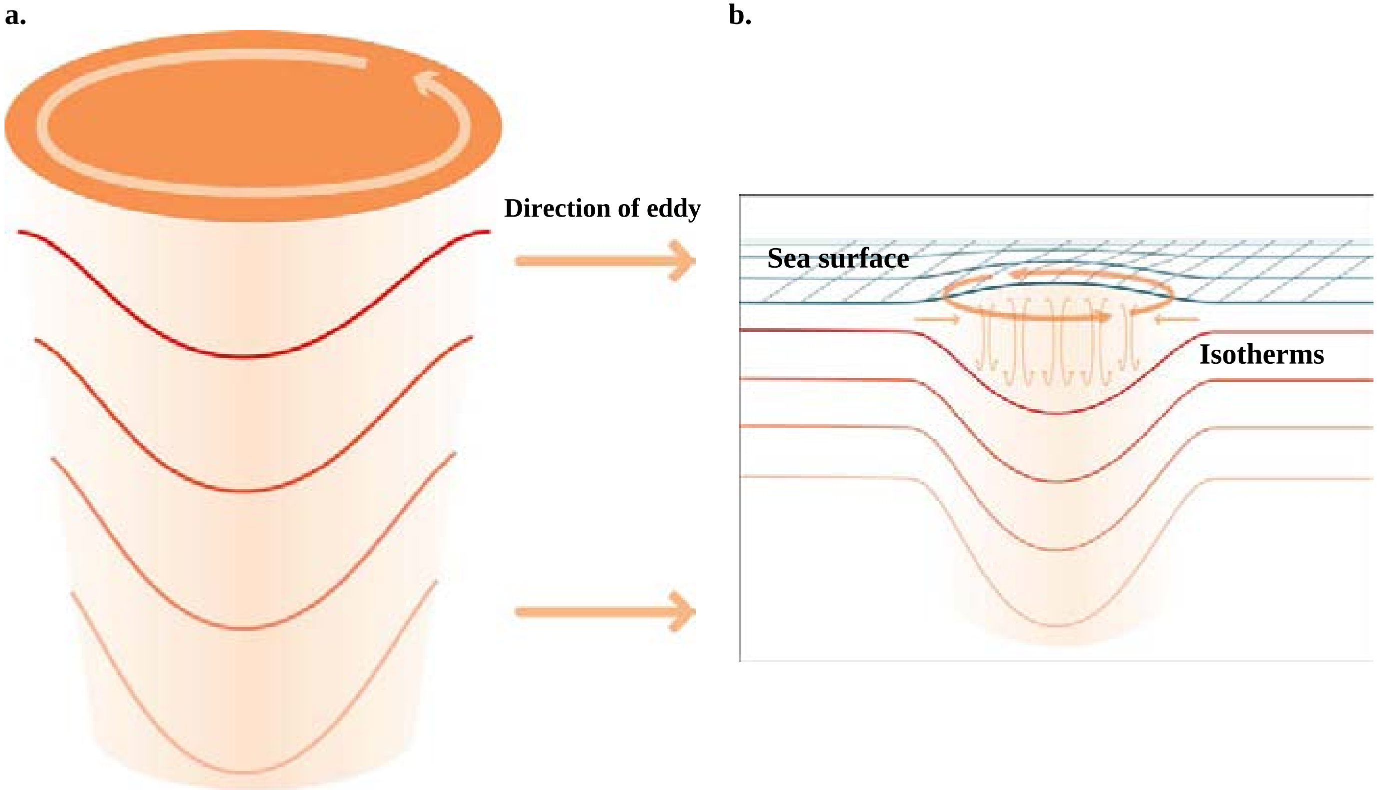


Figure 3-5 Structural elements of a feature.
(a) An individual feature and (b) internal structure of the feature showing winter mixing in the mixed layer.

4 Regionalisation methods

As outlined in Table 3-1, descriptive and analytical approaches were used to define the various levels of the pelagic regionalisation framework. In many cases, the descriptions and analyses were still experimental and tentative, but they serve to illustrate the approaches and patterns of relevance. The analytical techniques used in this project are therefore preliminary and require further testing and trial applications.

4.1 Input Data

The selection of appropriate combinations of datasets and data processing methods is critical to the proper delineation of regions at various levels in the pelagic regionalisation framework. The key attributes of datasets required at each level are:

- **Scale:** Information inherent in the dataset is at the appropriate scale for the level.
- **Structure:** Dataset displays definitive effects of processes that influence the structure of the bioregions at that level.
- **Dominance:** Smaller-scale variability in the data, due perhaps to sampling or other process variations, does not overpower the patterns at that level.
- **Process Pattern:** Recognising that for each variable, while distributional properties may be governed by sources, sinks and dynamic exchange due to transport and mixing, what matters for regionalisation is that the pattern is set by the processes of interest at that level. For example, at Level 1, temperature and nutrients will have different sources and sinks, but their patterns reflect basin-wide circulatory dynamics.
- **Pattern Resolution:** Where more than one process has substantive influence on the pattern of a variable, the patterns may be resolved by a structured or iterative approach.

In practice, all of these requirements may not be met. To be pragmatic, one must do what is best with the available data, time and resources. Nonetheless, it is worth bearing in mind these guidelines when assessing and analysing datasets. In this section we include a discussion about the datasets we used to produce the regionalisation. A fuller discussion of these datasets and their corroboration is included in the report “Collation and Analysis of Oceanographic Datasets for National Marine Bioregionalisation” (Hayes *et al.* 2005).

4.1.1 CARS: Temperature, Salinity, Nutrients and Silicate

The CSIRO Atlas of Regional Seas (CARS and CARS2000) is a set of seasonal maps of temperature, salinity, dissolved oxygen, nitrate, phosphate and silicate, generated by a weighted least squares (Loess) mapping from all available hydrographic data in the region. It covers the region 100^o–200^oE, 0^o–50^oS, on a 0.5^o grid, at 56 standard depth levels. Higher-resolution versions are available for the Australian continental shelf. The data were obtained from the World Ocean Atlas 98 (WOA98), CSIRO Marine Research and the National Institute of Water and Atmospheric Research Ltd (NIWA) archives. We used interpolated versions of the data at a 0.1-degree resolution to match other datasets; this is the standard grid size to which data were interpolated before analysis. Annual mean maps of these properties at 0, 150, 500, 1000 and 2000 m are presented in Appendices A through to F.

4.1.2 Sea-surface temperature

Sea-surface temperature (SST) data collected by the U.S. National Oceanographic and Atmospheric Administration (NOAA) satellites were received and processed at the remote-sensing facility at CSIRO Marine Research at Hobart. These data provide high-resolution spatial and temporal information at the sea surface, as can be seen in the image of the East Australian Current and associated eddies shown in Figure 4-1. SST data, which have a resolution of about 1 km, contain a rich set of features in addition to the broad patterns of latitudinal variability seen in the CARS data. The enhanced temporal and spatial resolution offers better discrimination of the units at Level 3 and finer, as evident in Figure 4-1.

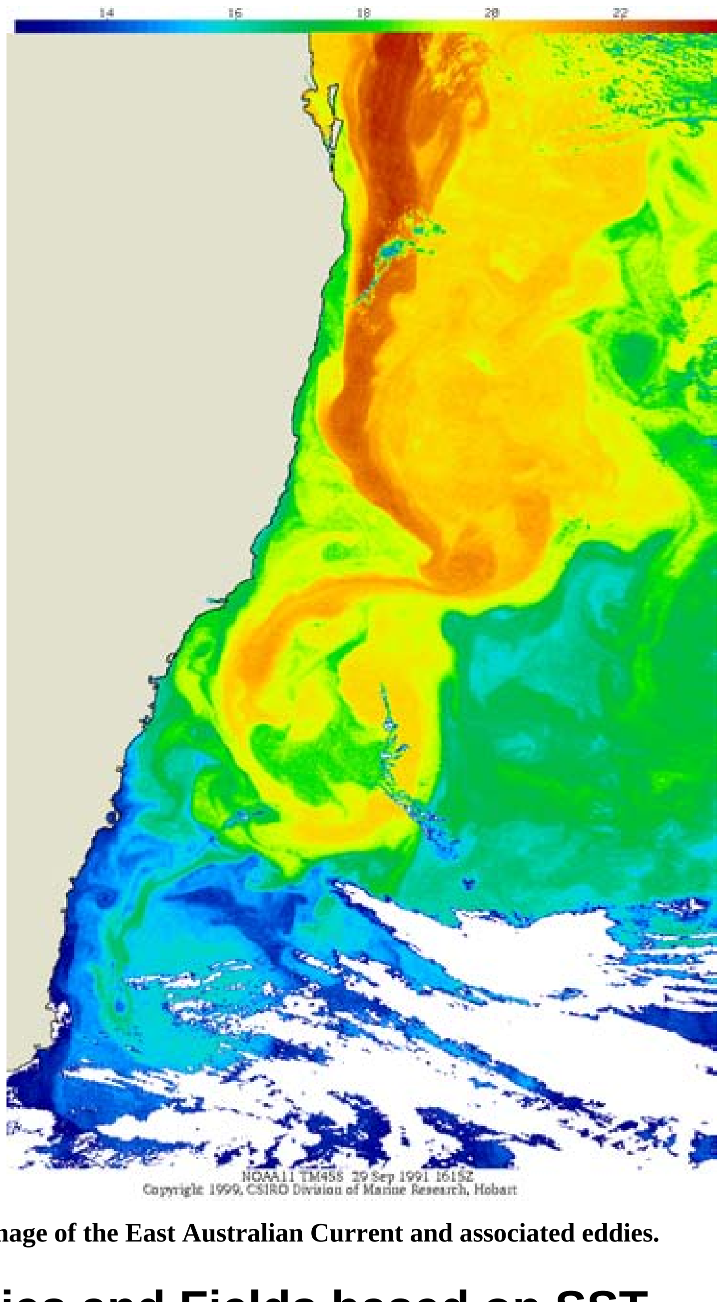


Figure 4-1 An SST image of the East Australian Current and associated eddies.

4.1.3 Eddies and Fields based on SST

Feature classes determined from SST were used as input to the (Fields of Features) “Level 3” pelagic regionalisation, which quantified variability/homogeneity fields in the SST.

The strategy in computing the classes was to classify the observed shape/form of the histogram of SST spatial gradients so that the classified fields were a function of the frequency (in space) with which different types of spatial gradients occurred. The procedures used in deriving the classes were as follows:

1. Individual SST images were median-filtered with a 13 pixel by 13 pixel spatial filter to reduce the noise inherent in the images. The filter size, which was determined by exploratory analyses, was a compromise chosen to reduce noise and to minimise the loss of the gradient information used in the classifications. Pixel values in the SST images range between 0 and 255, so the median was applied only to pixels with values greater than 0 and less than 250; values outside these limits were due to land or cloud effects.

2. Standard deviations were computed at each location of the median–filtered image, using a spatial window of 25 by 25 pixels. An overall median of the standard deviation for the whole image, denoted Std^m, was also computed.

3. The key classes were identified as follows:

CLASS	FEATURE	DESCRIPTION	STD RANGE
0	Land, cloud	Almost completely homogeneous (land or cloud), not discussed further.	Std < 0 and Std > 20
1	Core water masses	Low heterogeneity.	Std > 0 and Std < 0.55*Std^m
2	Mixed water masses	Medium heterogeneity (as in eddy cores).	Std ≥ 0.55*Std^m and Std < 1.55* Std^m
3	Frontal water masses	High heterogeneity (as in fronts and eddy edges).	Std ≥ 0.55*Std^m and Std < 20
4	High gradient fronts	Same as Class 3, but with high gradients (not a useful class).	Std ≥ 0.55*Std^m and Std < 20 and high gradient

Note: "Std" denotes the standard deviation at a location determined from procedure (2) described above. Class 4 was computed to capture very high gradient regions, but this class was not used in the analyses and is not discussed further.

4. The available archive of SST time-series images (see Hayes *et al.* 2005 for details and Appendix H for example images) were processed to calculate average occurrences of the classes for each month. These were then averaged over the year to produce an overall image (for each class). Alternative treatments of the temporal variability are possible but were outside the scope of the project.

Interpretation:

Class 1: This identifies fields of relatively homogenous and stable temperature characteristic of "core" water masses. The main regional distributions of this class occur off the north-west coast of Australia, the Great Australian Bight and a companion offshore area to the south-west, Bass Strait, the Gulf of Carpentaria, offshore of the Great Barrier Reef, and the extensive area offshore of the northern portion of eastern Australia.

Class 2: To a large extent, this field complements the Class 1 field but appears more pervasive. This is to be expected, as the Class 2 field characterises the peak in the histogram distribution of SST standard deviation. The textured nature of the field reflects the occurrence of numerous fronts embedded within it.

Class 3: This field characterises the high gradient/variability region that typically occurs between the Class 1 and 2 fields. The Class 3 field is most extensive in the Southern Ocean region due to the highly energetic nature of mixing in the major Southern Ocean frontal systems and to the underlying influence of bottom topography. Two other major areas occur: one off south-eastern Australia and the other off south-western Australia. The East Australia Current eddy field is responsible for the former, while the latter is associated with the Leeuwin Current and its instabilities. The Leeuwin Current itself is clearly demarcated as a thin jet in the south-west of Australia which disappears just west of the Great Australia Bight, although elements of this current reappear to the east of the Bight and off western Tasmania (as the Zeehan Current). The shelf-break region of eastern Australia is also characterised as highly variable which also may reflect the interaction of the East Australia Current and its eddies with the shelf/slope.

4.1.4 Geostrophic Currents

- ***Surface Currents***

  This field was computed from sea-surface dynamic height, so in essence the patterns reflect those of sea-surface height while highlighting such features as fronts, boundary currents and eddy fields (see Hayes *et al.* 2005 and Appendix G). These data were used in the preliminary Level 1a and 1b analyses, and in the updated Level 1b analyses.

- ***Subsurface Currents***

  This field, computed from sea-surface dynamic height, highlights subsurface fronts, currents and eddies (see Hayes *et al.* 2005). These data were used in the preliminary Level 1a and 1b analyses.

4.1.5 IMCRA Pelagic Fish Provinces

The IMCRA provinces on the shelf, derived from distributions of fish, were used to complement the offshore regionalisations at Level 1a produced in this project.

4.1.6 Phytoplankton

Dr Gustaaf Hallegraeff's updated 1990 phytoplankton distribution map (Figure 5-7) was used to corroborate the boundaries of water masses at the sea surface (see discussions in sections 1 and 5).

4.2 Data Analyses

The analyses were conducted in two stages:

1. A rapid analysis stage, where the objective was to obtain feedback from the National Bioregionalisation Working Group on outputs of most use to management.

2. An updated, but still rapid, analysis phase, focused on producing the outputs identified in stage 1.

Analyses in stage 1 for Levels 0 and 1 were based on descriptive approaches combined with statistical analyses carried out by Rick Smith using the *isocluster* divisive hierarchical clustering package in the ArcInfo Geographic Information System. These analyses were based on the CARS data, which were the main data available at that time. Rapid preliminary results derived for Level 0 and Level 1 were presented to the Bioregionalisation Working Group for discussion at their October 2004 meeting in Canberra. Preliminary results of a Level 3 classification, carried out by Vincent Lyne, using the satellite sea-surface temperature archive, were also presented to the Working Group.

In stage 2, analyses were updated to take account of the recommendations and discussions from the Bioregionalisation Working Group. These analyses were carried out by Vincent Lyne using updated data and the classification routines available in the statistical package "R".

Descriptive approaches, as used for Level 0 and to a limited extent Level 1a, were based upon literature searches and reviews, our assessments from atlases and discussions with experts in the field. “Descriptive Oceanography” is an old science and one that appears sadly out of favour in modern research, which is increasingly relying on remote sensing and modelling approaches. The information was compiled to map the location of water masses and fronts and to describe their properties. These maps were used to qualitatively assess the location and extent of major oceanic fronts at the boundary between water masses at this scale.

In the following section we describe these two analysis stages.

4.2.1 Preliminary Analyses

The first objective of the preliminary analyses was to statistically assess the broadest scale (Level 0: Ocean Realms) of discrimination possible for water masses surrounding Australia and to determine the next level substructure (Level 1: Ocean Zones). The second objective was to develop approaches for determining the Level 3 structure. Due to the limited time and resources available, it was more important to try and analyse the difficult Level 3 regionalisation rather than Level 2, which was seen as an extension of the techniques applicable to Level 0 and 1.

For Level 0 and 1, standard statistical classification approaches that normalise variables by scaling with the range of the variable or by subtracting the mean and dividing by the standard deviation, did not perform well. The key problem was that as more classes were added, these were allocated preferentially to transition zones where water mass composition varies rapidly. In retrospect, this is an obvious outcome of linear scaling techniques, which take no account of the intrinsic spatial clustering in the data. One alternative approach is to scale the variable by some measure of its local spatial gradient. Under ideal circumstances this approach should work; however, in practice, gradient measures are in essence high-pass local filters that amplify noise and errors which get magnified yet again as denominators in “normalising” the variable. There is also the non-trivial problem of division by zero, or a very small number, in areas of relative homogeneity in the variable.

An alternative approach suggested by Dr Mark Bravington is to use “histogram scaling”. This involves sorting the variable in ascending or descending order and then assigning an index that ranges from zero at one end of the sorted variable to one at the other end. In between, index values are determined by position along the sorted axis. It is not obvious why such an approach should work, except to note that there is an intrinsic relationship between the value of a variable, such as temperature, and the location of fronts in the ocean. In essence, the value of a variable embodies some spatial connotation so that histogram scaling, or ranking of the variable, intrinsically also sorts the variable spatially (in a broad sense; for example, warm water is more likely to be found in the tropics than in the south). Thus, with histogram scaling, frontal regions where variables vary rapidly get lumped into a narrow range, which de-emphasises their importance in the classification. Our scaling of variables is one of the main differences between the work reported here and other attempts at classifying oceanographic properties.

Other concerns which we assessed included:

- the influence of depth averaging of variables over the surface layers
- using the value of the variable at the base of the mixed-layer depth
- the influence of different combinations of variables
- the need to spatially filter the data, via median filtering, to enhance broad patterns.

We found high correlations between many of the variables and in the end used temperature and salinity for the Level 1 definition. We also found that using the value of the variables at the base of the mixed-layer depth provided better discrimination of the classes.

Level 2 classes were hierarchically nested in Level 1 by conducting clusterings of variables within each Level 1 class. Overall there were three Level 1 classes and two to three Level 2 classes within each Level 1 class. All of the CAR variables were used to define the Level 2 clusters which were averages over the top 500 m layer. The choice of 500 m was a trial-and-error choice that approximately matched the known empirical distribution of fronts and water masses determined from literature and textbook references.

4.2.2 Updated Analyses

At the October 2004 meeting, the Bioregionalisation Working Group decided that Level 0 was too broad scale and ill-defined, in terms of biological significance and relevance, to be of use to management. At that level, it was agreed there was a need for qualitative recognition of the ecological distinction between the Indian, Pacific and Southern oceans and that the boundaries between these regions were difficult to define. Therefore no further analyses were made at this level.

The Level 1 regionalisation was suggested as being at the appropriate scale for management along with the depth structuring in each of the classes. It was also recognised that depth structure derived from analyses of physical and chemical properties might not be entirely relevant to biological processes and to organisms that rely upon surface light and the decay of light with depth. Dr John Paxton of the Australian Museum pointed out that, almost globally, depth structuring of organisms was due to their response and adaptation to surface and deepwater light fields. It was, however, also recognised that water properties did influence depth structuring of organisms (through, for example, physiological constraints) and that an analysis of depth structures based on water properties was necessary but was not by itself sufficient to define the ecological depth structures.

With these considerations in mind, updated analyses were planned. It soon became apparent that the intimate link between surface and deeper waters, through such processes as subduction and deepwater formation, would result in disjunct depth structures if these were determined individually for each Level 1 class. An integrated analysis was required to seamlessly define the surface and depth structures. The main problem with such an analysis was the sheer volume of data (in three dimensions, approximately 25 million points per variable) that had to be analysed. Compromises were made in selecting the variables and subsampling the data so that it could be analysed by the available computational resources and statistical software.

4.3 Exploratory Analyses – Level 1b

With limited time and resources available, analyses were focused at Level 1b, which appeared to be of most use for regional management purposes. In the following sections, we detail the factors that influenced the selection of data and analyses used in deriving the Level 1b classification.

Temperature and salinity are two key variables that have traditionally been used to define global and regional water masses, and these were retained for analysis. Phosphate, nitrate and oxygen were found to be highly correlated but the data were of variable quality. Nitrate and phosphate were less well sampled and contained artefacts of sampling variability (seasonal and spatial). They were therefore excluded in favour of oxygen, which is now almost a standard measurement made with modern conductivity, temperature and depth (CTD) loggers, unlike the nutrients. Silicate displayed strong localised patterns that were tied to ocean currents that impinged onto continental and island landmasses. As such effects would have biased the analyses, silicate was excluded at this level (but it may be more appropriate at another level). Thus, temperature, salinity and oxygen were used. Details of these and other datasets used in the analyses are extensively detailed in Hayes *et al.* (2005).

The 56 depth levels available for analysis were (in metres):

0 10 20 30 40 50 60 70 75 80 90 100 110 125 150 175 200 225 250 275 300 350 400 450 500 550 600 650 700 750 800 850 900 950 1000 1100 1200 1300 1400 1500 1600 1750 2000 2250 2500 2750 3000 3250 3500 3750 4000 4250 4500 4750 5000 5500

With each variable in each depth layer comprising over half a million points, subsampling was clearly necessary. Ideally, subsamples should be taken as uniformly as possible from the expected classes. Since the classes are unknown to begin with, *a priori* stratification and selection were necessary to begin the analysis. For the first iteration, the following depth levels were chosen heuristically, with a bias towards the surface levels, which were considered to be more relevant to current management concerns:

0
100
250
500
1000
2000
3000
4000

Even with such a drastic cutback in the number of depth levels, there were still too many data points to be analysed; furthermore the number of data points does not necessarily equate to information content. In fact, an adequate number of well-chosen data points, preferably uniformly distributed in the inherent classes, is all that is required. Thus the number of appropriate points should scale with the number of classes to be derived. So, for example, using 10 data points per class to discriminate 25 classes requires only 250 "well-chosen" points. Assuming that the classes will be uniformly distributed across the data range (including depth), a random but uniform selection of data points (across space, including depth) was used to subset the data. All data were first combined into a list from which random points were chosen – hence there is no **explicit** depth discrimination beyond this stage. Of course, the depth attribute is still inherent in the data but depth per se is not explicitly treated.

We input the data into the R statistical analysis package and used the clustering routine *clara* (**C**lustering **LA**rge **A**rray), which is specifically designed to deal with large datasets. Histogram scaling (see Section 4.2.1) was used on all the variables and the normal standardisation routine used in *clara* was disabled. Euclidean distance measures were then used to discriminate the classes. Silhouette plots, which show the level of discrimination between classes and also the overlap between classes, were used to determine that the "best" groupings occurred with 5 and 25 classes. We excluded the 5-classes case as being of broader extent than expected for Level 1b. Thus we concentrated on determining the 25-classes case. The routine *knn* (for k nearest neighbours based on Euclidian distance) was used to interpolate/extrapolate the classes across the entire dataset. The use of such interpolation schemes requires data to be normalised before analysis.

4.3.1 Seas: Circulation Regime – Level 2

Recalling that Level 2 defines seas/circulation regimes, input data chosen to reflect this definition comprised:

- surface currents
- subsurface geostrophic currents
- MODIS primary productivity
- Sea surface height (satellite-derived)

We refer the reader to Hayes *et al.* (2005) for details on these datasets.

In addition, the standard deviation fields were available for all the above data. All variables were highly skewed and a double square-root transformation was necessary to more nearly normalise the variables. Some degree of normalisation is necessary because the dominant information in these data (i.e. the most frequently occurring value) is usually not the one of interest. For example, low chlorophyll values dominate the tropical waters of eastern Australia and values are elevated primarily in the rarer fronts and upwellings. Part of the role of the data transformation is to increase the relevance of the rare information in the classification. The other role, mentioned previously, is to facilitate interpolations, across the entire dataset, if data are subsampled before analysis.

Visually, the spatial patterns in the standard deviation fields lacked coherence, with the exception of the MODIS productivity data, which was the only standard deviation field to be included in the analysis. A double square-root transformation was also applied to this field. For each Level 1b class, *clara* analyses were run for a number of classes ranging from 2 to 12. We then examined the average silhouette widths as an indication of the distinctiveness of the class separations; large silhouette widths indicate distinct class separations (a width with a value of 1 corresponds to perfect separation) while the lower the value the greater the overlap in classes. Analyses of silhouette widths produced the following results (Table 4-1):

Table 4-1 Results of exploratory *clara* analyses to determine the average silhouette width as a function of the number of classes. For each Level 1b class, the maximum silhouette width and the corresponding number of classes are listed. The larger the silhouette width, the more distinct the classes.

Level 1b Class	Max Silhouette Width	Number of Classes
1	0.9	2
7	0.48	4
9	0.59	2
10	0.33	2
11	0.4	3
12	0.34	5
13	0.24	5
17	0.41	2
18	–	2
20	0.33	2

For class 18, there were not enough points in the class to run an analysis, so we arbitrarily chose the number of classes as 2. The Level 2 analysis was made using the number of classes listed in Table 4-1. Note the low value of silhouette width for class 13, which is the Central Pacific class that contains the East Australia Current region, and the high value for class 1, which is the southernmost class.

4.3.2 Fields of oceanographic features – Level 3

The primary variable available for the Level 3 analysis was the homogeneity/heterogeneity classification based on sea-surface temperature. Recall that Level 3 is meant to depict "Fields of Features" and regions with different energetics. In the sense of energetics, one view of Level 3 is that it is a qualifier for units at Level 2. For example, in the East Australia Current region, areas of different energetics may consist of the core of the current, the offshore mixing boundary of the current or the downstream region where eddies shed off and mix with surrounding waters. Water-mass properties may also vary in response to changes in energetics because the dynamics of currents will, to a large extent, depend on geostrophy, due to relative changes in water density between adjacent water masses. With these considerations in mind, one option for Level 3 is to use the homogeneity/heterogeneity field as an “energetics” qualifier for the Level 2 classes. Thus, descriptions for the Level 3 classes would be preceded by the Level 2 descriptor.

For the overlay approach to work some indication of the degree of energetics is required. One strategy to take account of the inherent energetics parameterisation in each of the energetics fields is to combine them by scaling and addition as follows:

$$csum = c1 + c2*2 + c3*4$$

where csum is the overall energetics field and c1, c2 and c3 refer to classes 1, 2 and 3 respectively.

The reasoning behind this formulation is that classes 1, 2 and 3 represent increasing energy fields. The scaling factors (1, 2, and 4) were chosen to reflect this. Other scaling factors could be chosen, based on any particular aspects of the energetics fields that need to be emphasised. Unfortunately, we did not have time to explore the effects of different combinations of scaling factors; this is left as a task for future updates.

5 Results and Discussion

The results for each of the Levels analysed as described in the Data Analyses section are presented and discussed here.

5.1 Level 0: Oceans

At this broad level, three oceans are recognised within the Australian Maritime Jurisdiction: the Indian, Pacific and Southern oceans. Because their boundaries are not constrained by landmasses, they are difficult to define. Biologically and ecologically it is known (Peter Last, pers. comm.) that they are distinct. Precisely what this distinction is and whether it is related to contemporary physical or chemical properties and processes are yet to be determined. This analysis is not part of the current project and remains a key gap for future investigations.

Indian Ocean

The Indian Ocean is bounded by the landmasses of Africa in the west, Asia in the north, and Australia in the east. The Indian Ocean is arbitrarily separated from the Atlantic Ocean by a line along the meridian 20^{o} East, connecting Cape Agulhas at the southern end of Africa with Antarctica. The boundary between the Indian Ocean and the Pacific Ocean to the south and north of the Australian continent is undefined at this stage.

Pacific Ocean

The Pacific Ocean is bounded by the landmasses of North and South America in the east, the Bering Strait in the north, and Asia in the west. It is arbitrarily divided from the Atlantic Ocean in the south by the Drake Passage along longitude 68^{o} West.

Southern Ocean

The Southern Ocean is bounded by Antarctica in the south and qualitatively by the Subtropical Convergence in the north.

5.2 Level 1a Oceanic Zones: Thermocline Water Masses

Oceanic zones, which are defined by a combination of winds, solar forcing and geostrophy, are a series of largely circumferential and latitudinally oriented water masses. Each can be characterised by its unique water properties, circulation and assemblages of biota that vary with depth. Transitional adjustments in water properties between some zones are generally characterised by higher plankton production, which in turn influences trophic structure and interactions. Greater departures from zonal orientation are noted in response to influences on circulatory processes by land masses and subsurface topography

The preliminary analysis (Figure 5-1) broadly defined three oceanic zones or thermocline water masses surrounding Australia: the Indian Central water, Indonesian Throughflow Water and the South Pacific Central Water. Weak influences of basin scale processes are seen in the divergence of the class boundaries from zonal lines (lines oriented by latitude) as for example the divergence in the north-east section offshore of Australia, and the steering of water properties south of Australia/Tasmania by sub-Antarctic currents (which in turn are being influenced by subsurface topographic steering).

The predominant zonal nature of the boundaries implies that climatic forcing (with a zonal signature) dominates the pattern along with oceanographic processes which are also zonally oriented. Exceptions to this occur near the corners of the ocean basins (for example, north-east Australia) and the topographic steering in the Southern Ocean which is influenced by land mass extensions such as Tasmania and New Zealand, and by the presence of subsurface topographic ridge systems..

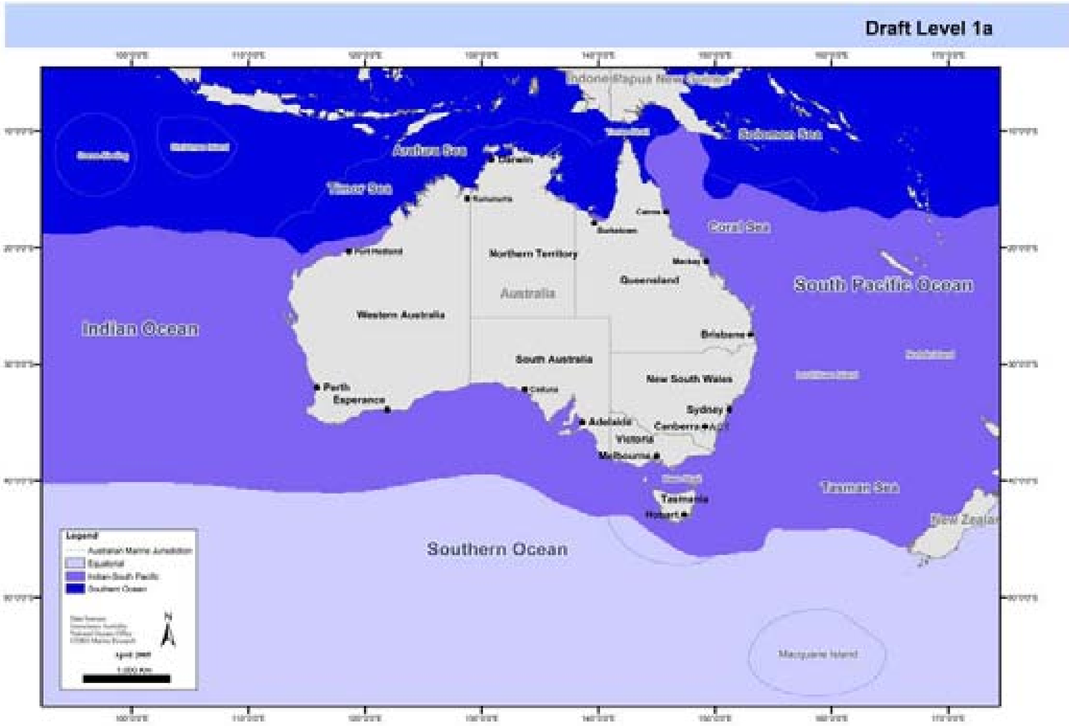


Figure 5-1 Preliminary analysis results of Level 1a regionalisation based on temperature and salinity at the base of the mixed layer.
Three classes are apparent: Indonesian Throughflow Water in the north, Indian Central Water in the west, and South Pacific Central Water in the east.

5.3 Level 1b: Oceanic Substructure – Water Masses

Water masses are defined by latitudinally oriented oceanographic processes, with exceptions in the equatorial and tropical areas and the previously noted topographic steering effects in the Southern Ocean. Water masses with a common formation history are present as core water masses with adjacent transition regions. For example, the transition between sub-Antarctic surface water and Central Water is marked by the Subtropical Convergence.

Preliminary results based on averages of water properties in the top 500 m of the water column are shown in Figure 5-2. While six classes are shown, it must be borne in mind that the analysis did not take into account the distinction between the oceans as would have been defined by a full analysis (one that includes biology and biogeographic considerations) of the Level 0 regions. In other words, similar water masses in the Indian Ocean and Pacific Ocean would, with a full analysis, be deemed to be different from biological or ecological perspectives.

The results of the updated classification (see Data Analyses section 4.2) using data from the whole water column are presented in Appendix I with a selected range of depths in Figure 5-3. Summary statistics for level 1b are in Appendix J.

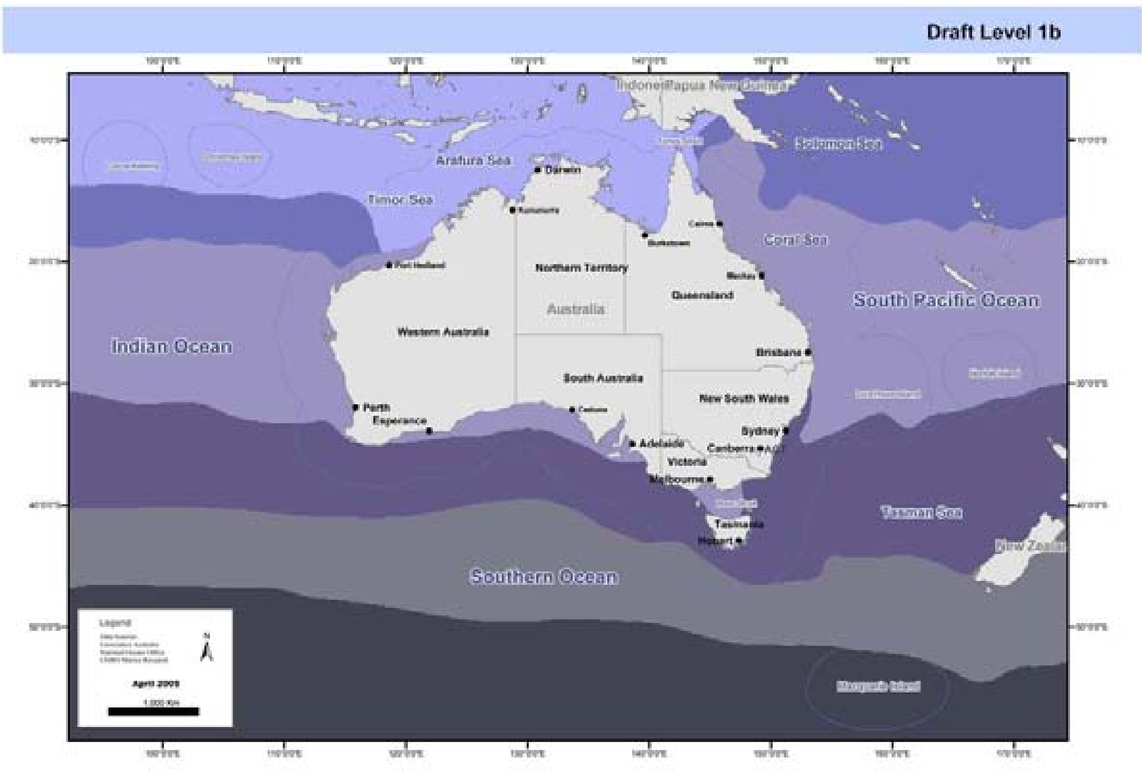
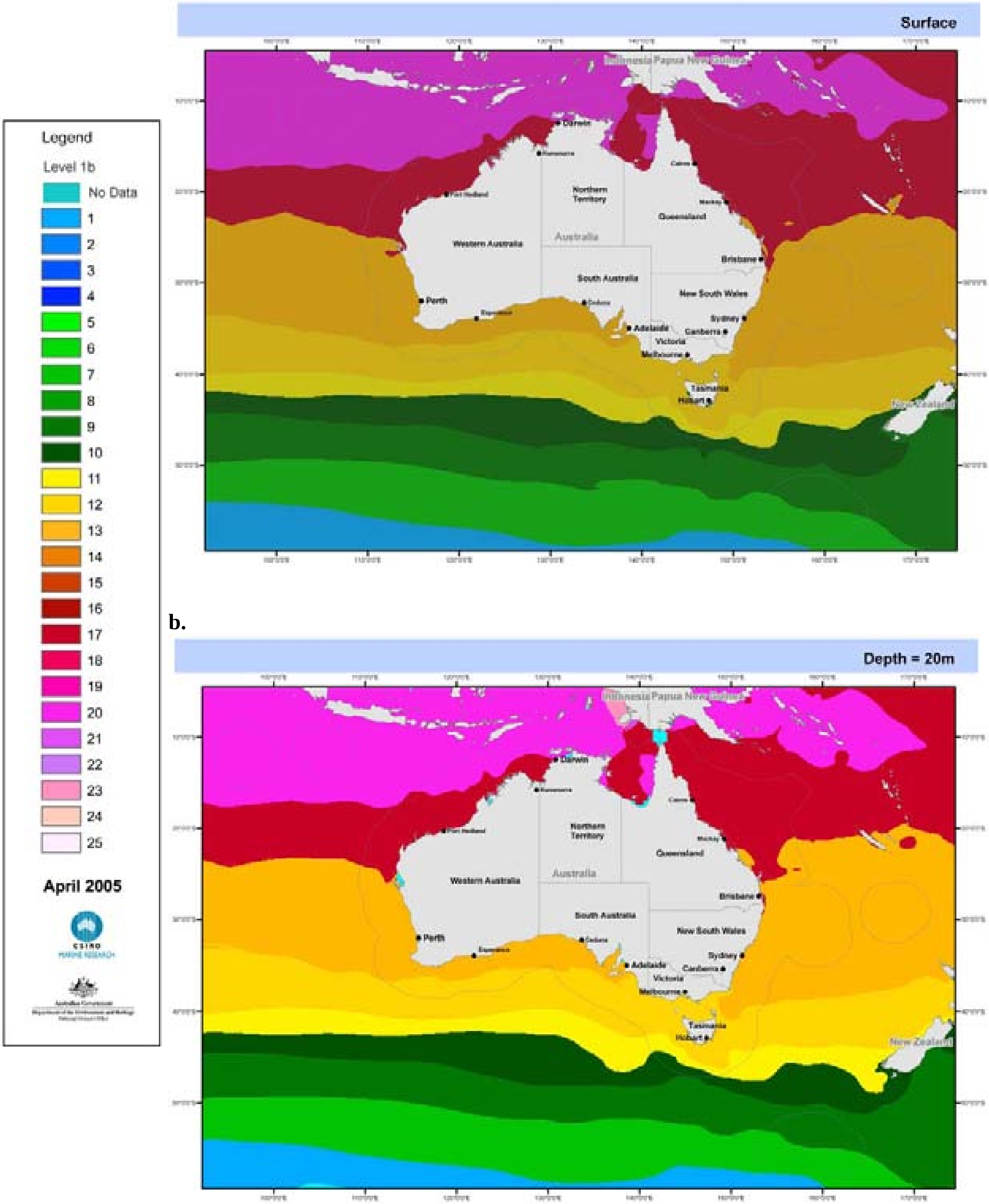
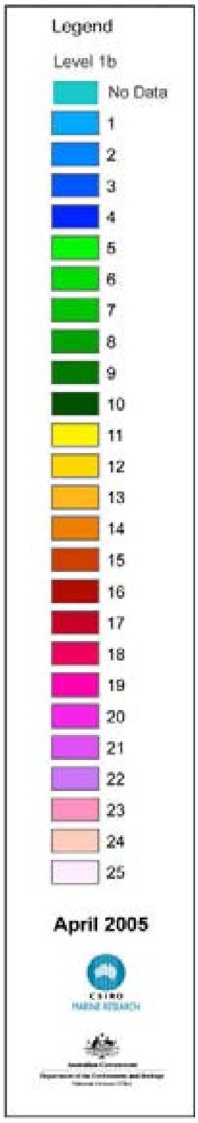


Figure 5-2 Preliminary analysis results of Level 1b regionalisation based on all CARS water properties averaged over the top 500 m of the ocean.
See Hayes *et al.* (2005) for a description of the CARS data.

Figure 5-3 Example Level 1b classification for selected layers.
(a) the surface, (b) 20 m, (c) 150 m, (d) 250 m, (e) 500 m, (f) 1000 m, (g) 2000 m and (h) 5500 m layers based on classifying the whole water column.

a.




Legend
Level 1b
No Data
1
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3
4
5
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17
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22
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24
25
April 2005
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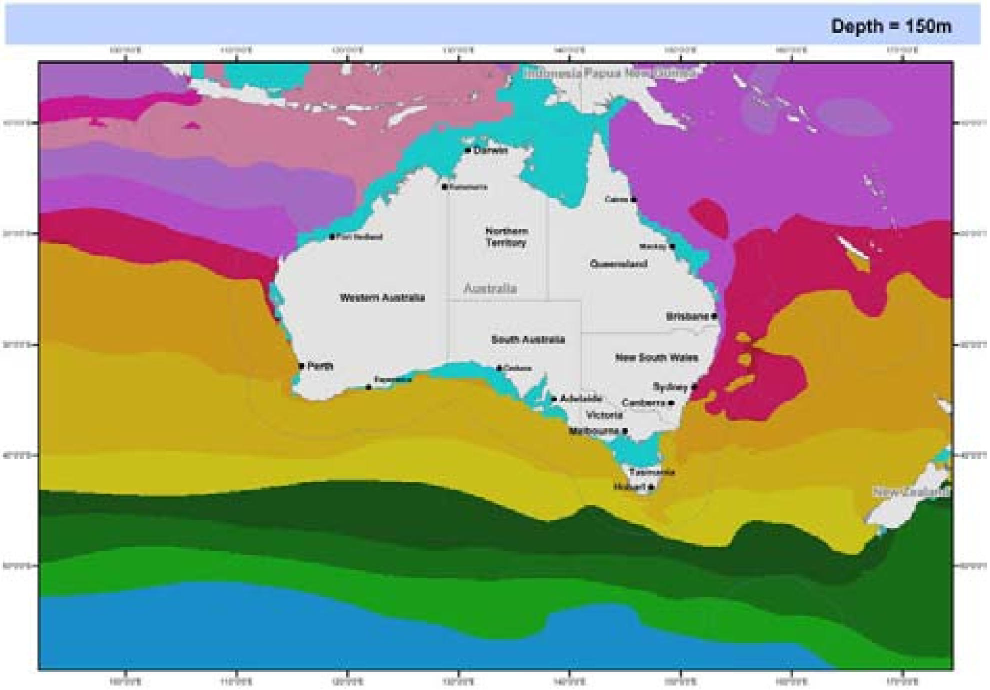
c.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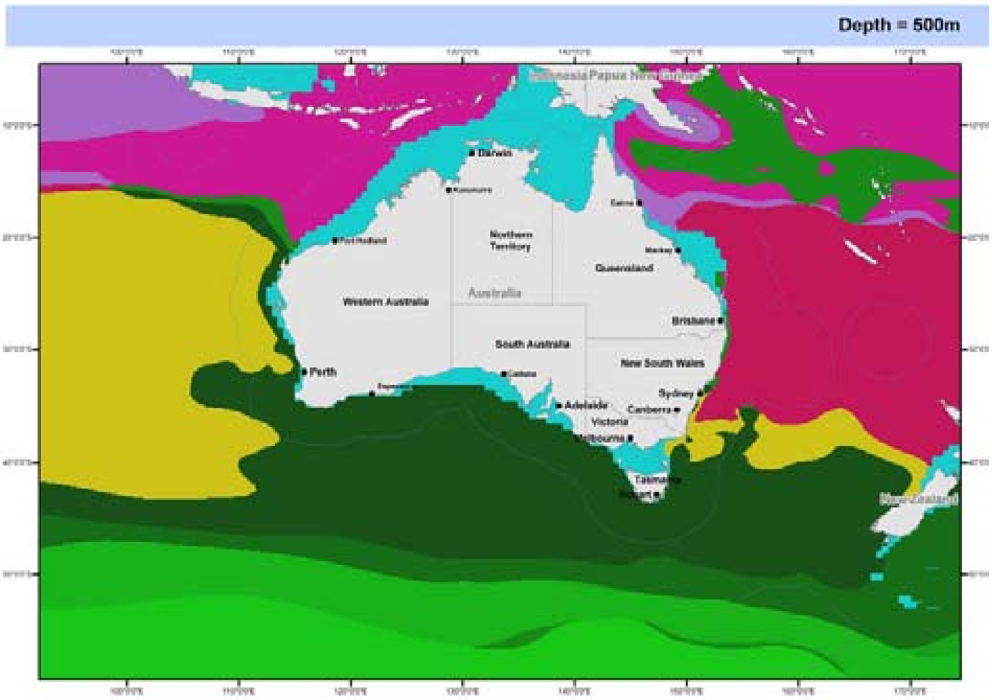
Darwin
Port Hedland
Northern Territory
Queensland
Western Australia
Australia
Brisbane
South Australia
New South Wales
Perth
Sydney
Adelaide
Canberra
Victoria
Melbourne
Tasmania
Hobart
New Zealand

d.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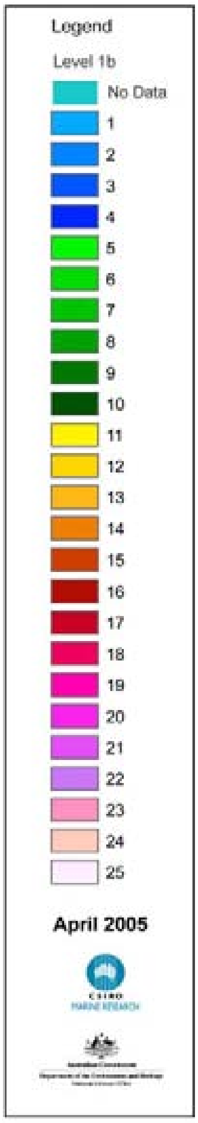
Port Hedland
Northern Territory
Queensland
Western Australia
Australia
Brisbane
South Australia
New South Wales
Perth
Sydney
Adelaide
Canberra
Victoria
Melbourne
New Zealand



Legend
Level 1b
No Data
1
2
3
4
5
6
7
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9
10
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13
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16
17
18
19
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22
23
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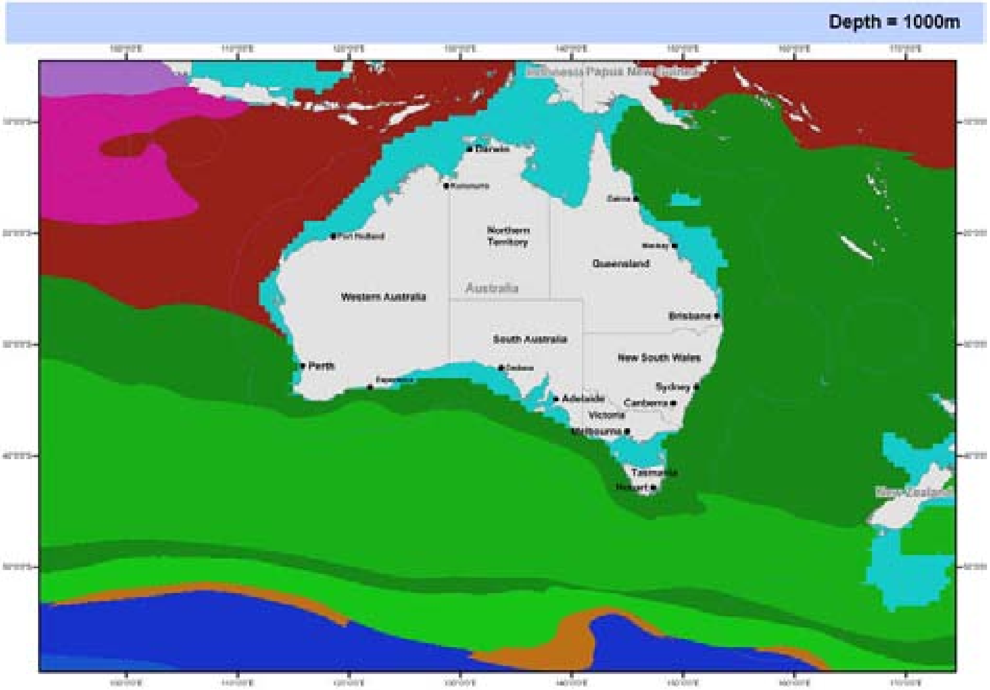
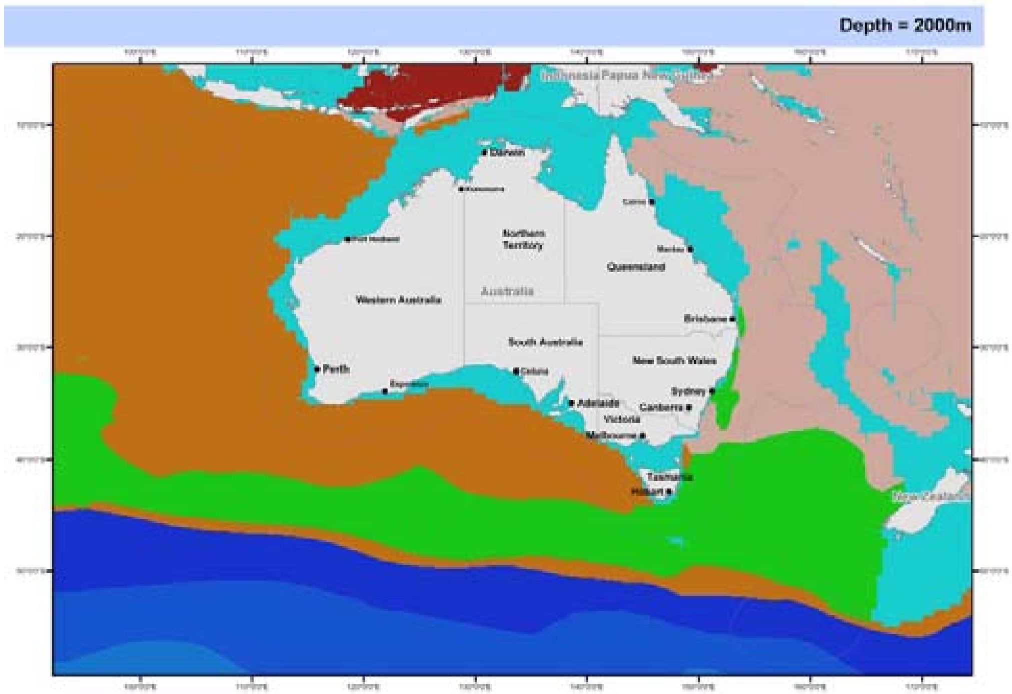
25
April 2005

e.



Depth = 1000m
Darwin
Northern Territory
Queensland
Western Australia
Australia
Brisbane
South Australia
Perth
New South Wales
Sydney
Adelaide
Canberra
Victoria
Melbourne
Tasmania
Hobart

f.



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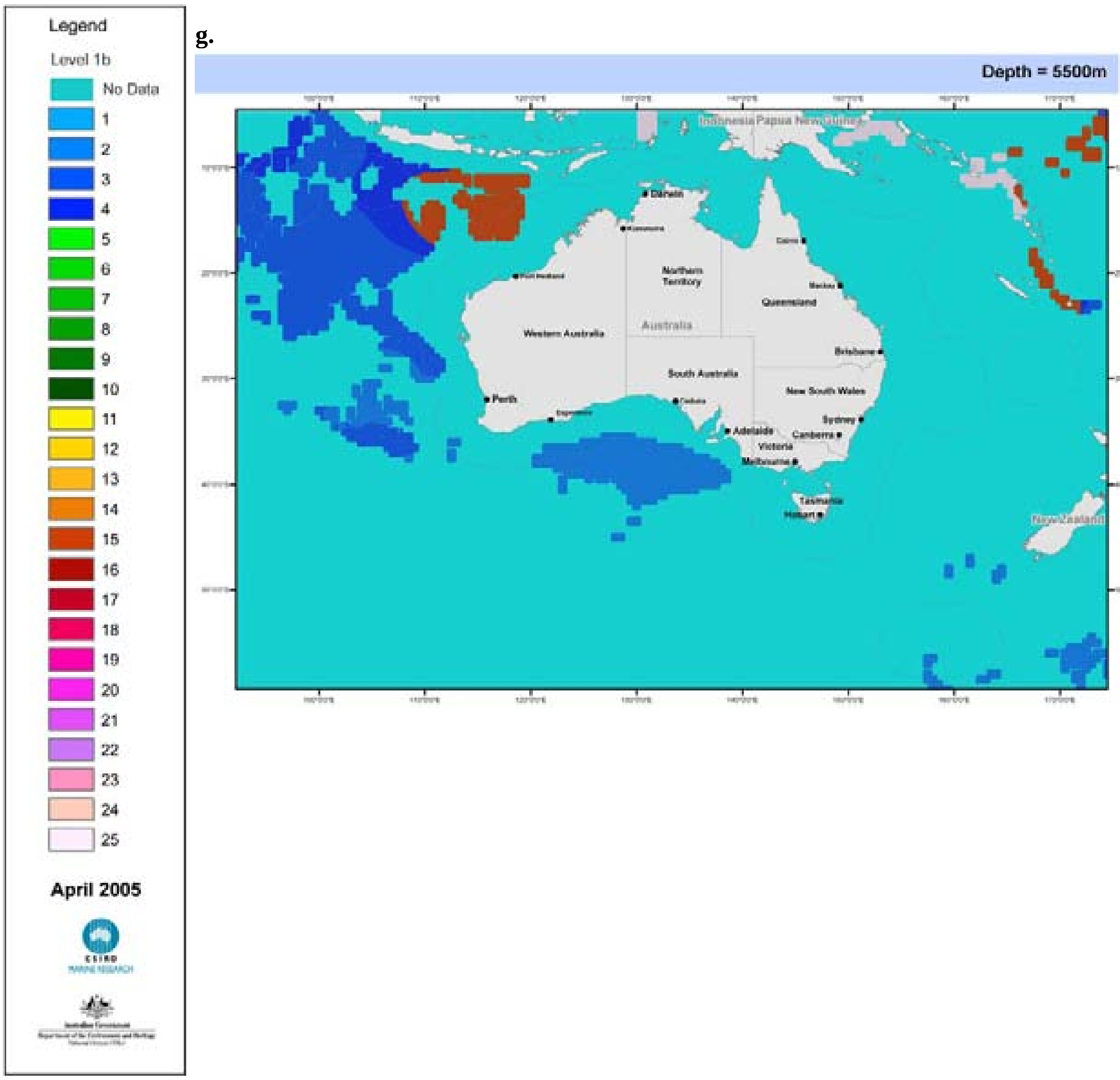
Darwin
Northern Territory
Queensland
Western Australia
Australia
Brisbane
South Australia
Perth
New South Wales
Sydney
Adelaide
Canberra
Victoria
Melbourne
Tasmania
Hobart
New Zealand


Legend
Level 1b
No Data
1
2
3
4
5
6
7
8
9
10
11
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13
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16
17
18
19
20
21
22
23
24
25
April 2005
g.
Depth = 5500m
Darwin
Northern Territory
Queensland
Western Australia
Australia
South Australia
Brisbane
New South Wales
Perth
Sydney
Adelaide
Canberra
Victoria
Melbourne
Tasmania
Hobart
New Zealand

5.4 Seas: Circulation Regimes – Level 2

After data analysis (see Section 4.2), classes for Level 2, derived for each Level 1b class of the surface layer, are shown in Figure 5-4 where they are colour-coded as shades of the Level 1b classes.

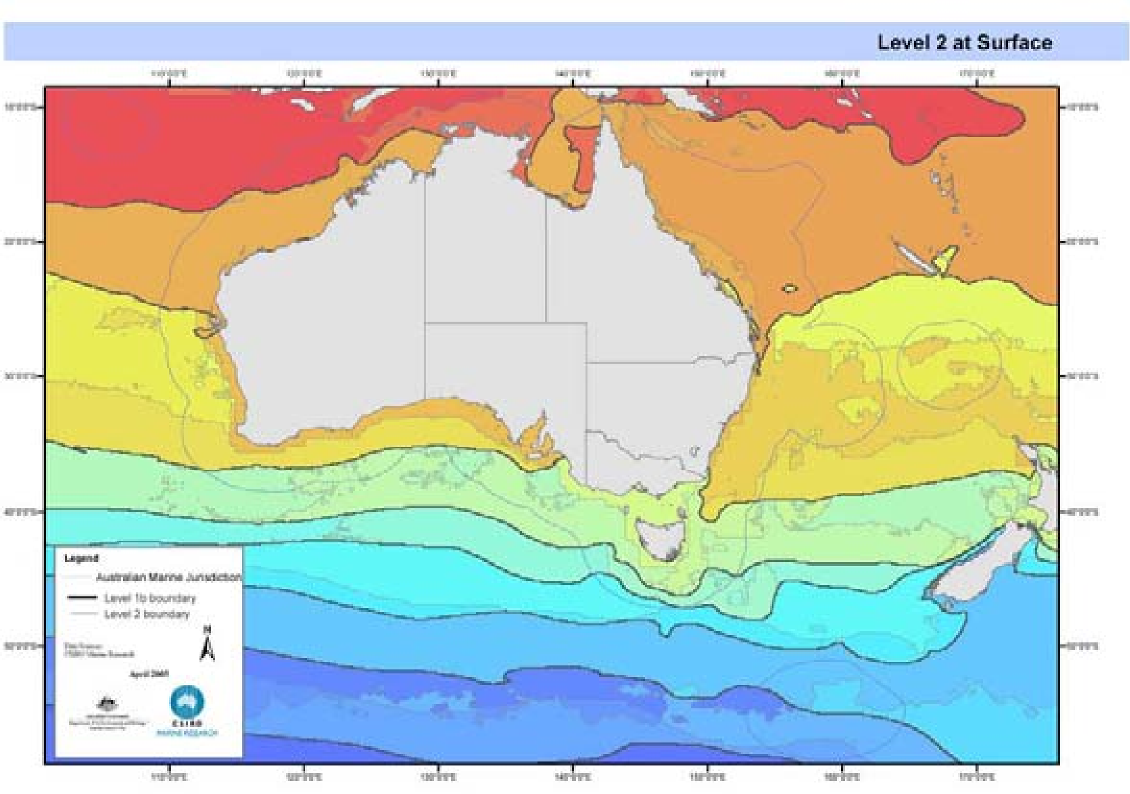


Figure 5-4 Level 2 classification produced by nesting substructure within the Level 1b classes.

One observation is that the sub-structuring of water masses is greater near energetic circulatory fields such as the East Australia Current, the Tasman Sea and to the south and east of landmass extensions or corners; for example, the south-west of Western Australia, Tasmania and its associated subsurface shelf extensions (South Tasman Rise, Cascade Plateau), New Zealand and its surrounding subsurface plateaus (for example, Campbell Plateau). One conclusion from such observations is that the effects of bottom topography are much more important than we had expected. This implies that benthic–pelagic interactions are much more pervasive and closely linked. It also suggests that, in light of this finding, previous regionalisations of the benthic environment should be re-examined for evidence of pelagic influences.

The discrimination of classes in such regions is also less distinct, which in turn reflects the intense mixing processes. For example, the least distinct set of Level 2 classes is embedded within the East Australia Current Level 1b_13 (as also seen in the silhouette widths in **Table 4-1** for), yet those (Level 2) classes do demarcate substructure, such as the core waters of the East Australia Current and various other mixing regions that extend south and eastward to the north-eastern extremity of New Zealand.

Level 2 water masses also encompass narrower (and lower level) features such as the Leeuwin Current, which is noticeable as a band of water extending from about Shark Bay in Western Australia around to the gulfs of South Australia.

5.5 Fields of Oceanographic Features – Level 3

As described in the Data Analyses section (4.3), this level uses energetics derived from analyses of homogeneity/heterogeneity fields (Figure 5-5) to qualify the distribution of classes derived at Level 2. To visualise this, in Figure 5-6 we overlay the energetics field as a “brightness” attribute for the Level 2 classes.

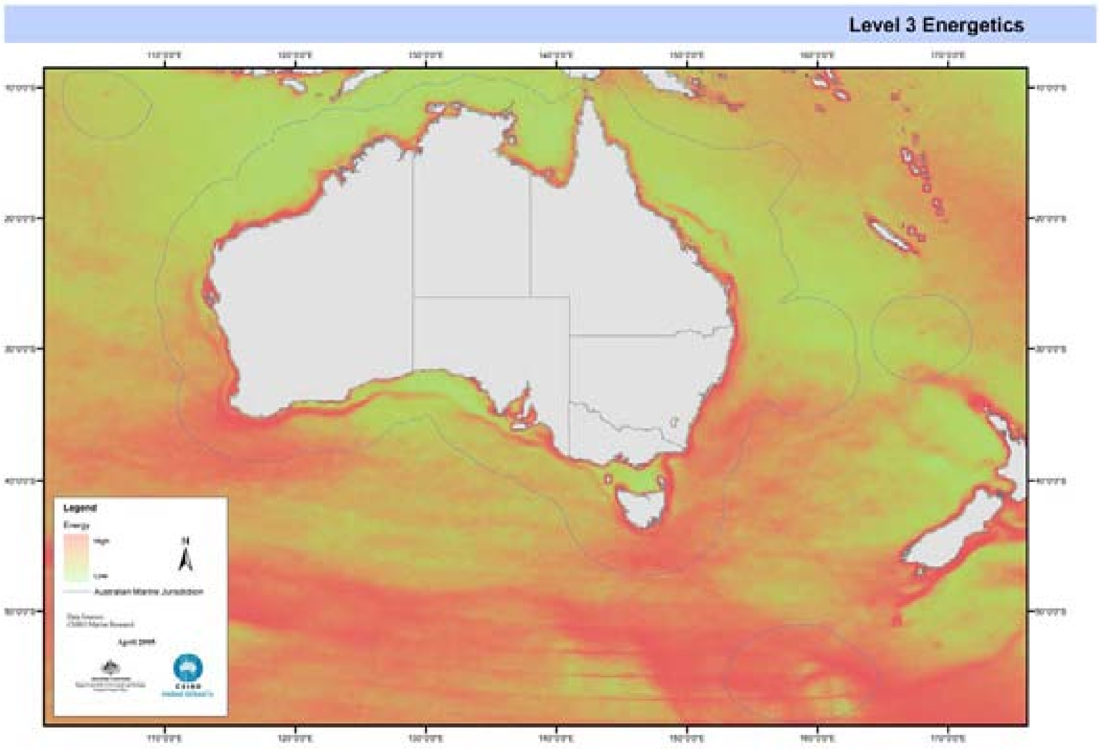


Figure 5-5 Energetics field derived from analyses of homogeneity/heterogeneity.
The redder regions correspond to greater energetics and heterogeneity.

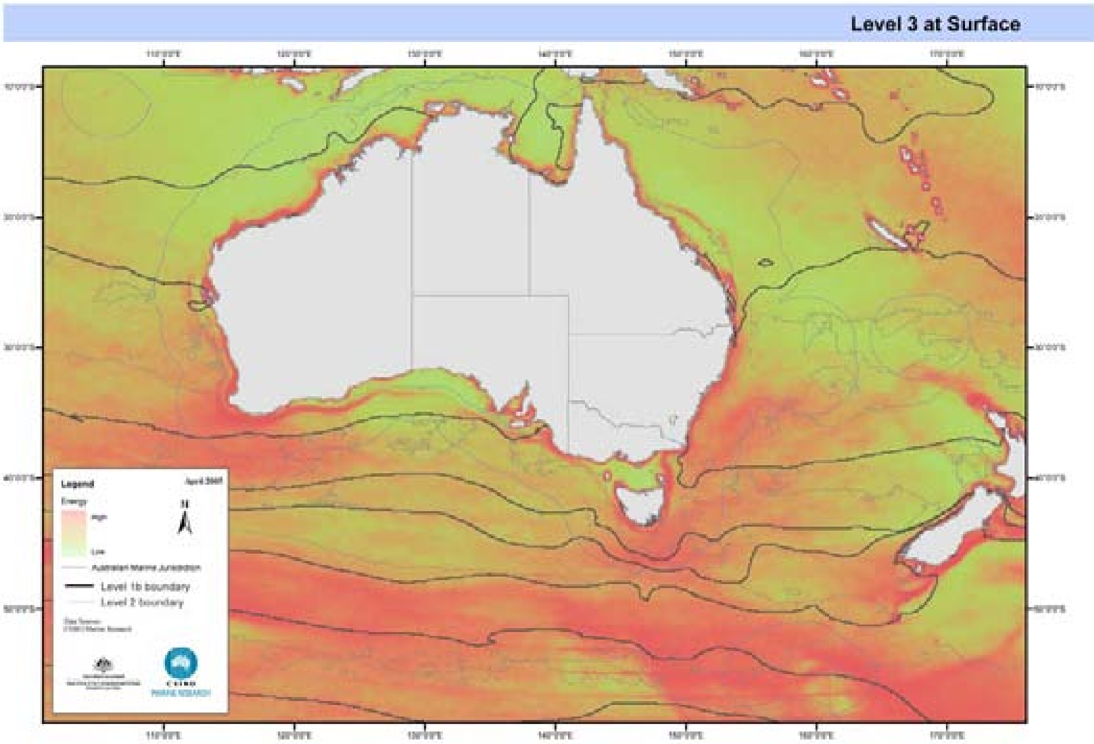


Figure 5-6 Level 3 qualification, via brightness variations, of Level 2 classes (defined by colour classes).

The energetics field shows a range of features, from the narrow elongated features, such as the Leeuwin Current off south-west Western Australia and mixing regimes associated with the East Australia Current system, to broad scale features, such as those in the tropics. In a strict hierarchical sense there is mixing of scales and features that may belong to different levels in the framework (for example, the Leeuwin Current could be interpreted to be a feature rather than a “field of features”). However, in the context of an energetics qualifier, it does make pragmatic sense. Within a given water-mass type, regions of higher energetics can be expected to be more productive and hence able to support a greater biomass of flora and fauna. The energetics field also identifies energetic locations that appear not to have been previously described. For example, the south-west corner of Western Australia is known to be energetic, but the high-energy region off the shelf that is associated with a subsurface ridge system appears not to have been previously described. Also, some locations in the East Australia Current Level 2 class are identified as being more energetic; it would be useful to investigate any association of such regions with catches of commercial fish or findings from research voyages.

5.6 Region Descriptions

The following section provides descriptions, including statistics, of the Level 1b classes. Circulation regimes and oceanographic features nested within oceanic regions are described only for upper water masses. ***Upper water masses*** are generally considered to include the mixed surface-layer (region of uniform hydrographic properties) and the upper part of the permanent thermocline. The thicknesses of these upper water masses depend on local processes. We describe and discuss the Level 1b surface classes first, and then the Level 1b subsurface classes.

Note that in a strictly hierarchical classification a single class could not extend over both the Pacific and Indian oceans, which are already in separate classes at the level above (Level 0). For convenience we have split the classes that fall into both the Pacific and Indian Oceans, i.e. Level 1b_13, Level 1b_17 and Level 1b_20. These classes are identified by the prefix P for Pacific or I for Indian (for example, Level 1b_P13 and Level 1b_I13). Level 1b_12 could have been similarly divided; however, as the location of the division between the Pacific and Indian Oceans is not clear, we decided to describe it as one region, while noting this division.

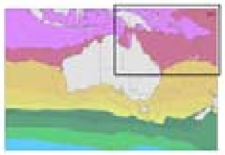
Some of the classes of Level 1b correspond to known water masses. These are named in Table 5-1.

Table 5-1 Descriptive names of the Level 1b surface classes.

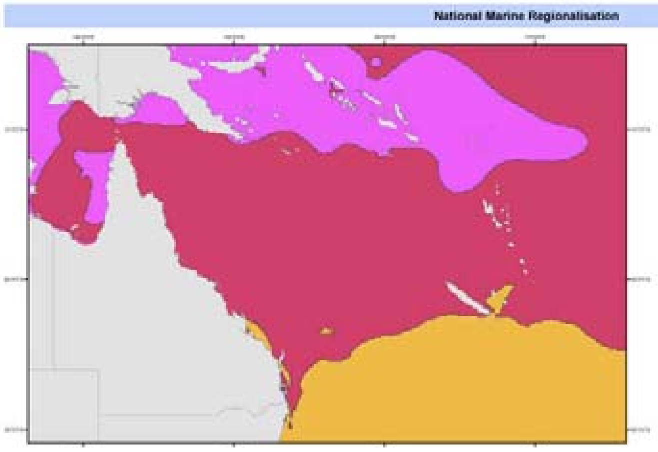
Level 1b	Name
1	Southern sub-Antarctic
9	Sub-Antarctic Front
10	Southern Subtropical Convergence
11	Central Subtropical Convergence
12	Northern Subtropical Convergence
P13	Coral Sea Circulation
I13	Indian Central
P17	Coral Sea
I17	Indian Transition
I20	Indonesian Throughflow Region

5.6.1 Descriptions of Level 1b surface water masses

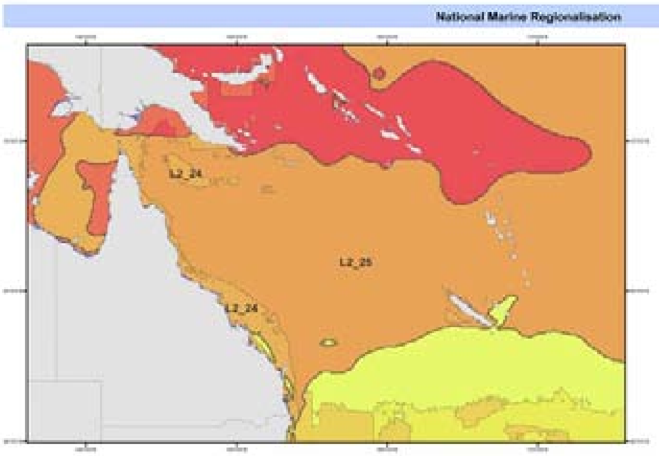
Level 1b_P17
Coral Sea:
Pacific North-West Tropical Warm Pool



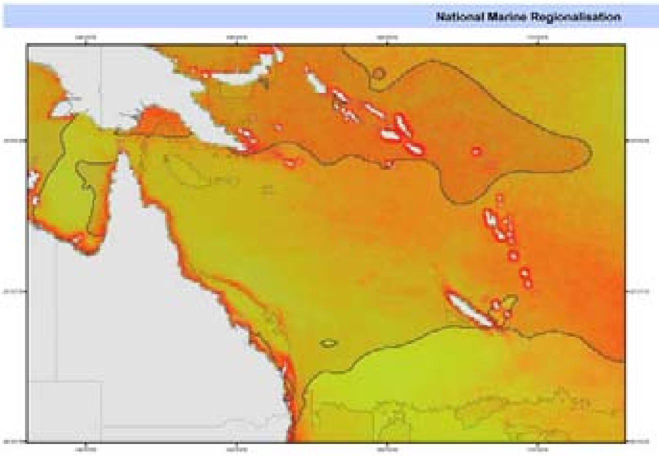
Description: Level 1b_P17 is a near-surface layer representing the core of the Coral Sea region in the tropical band of the north-west Pacific to the south of Papua New Guinea. The water here is warmer and more saline than water south of the Tasman Front. The higher salinity is due to convective evaporation when water is transported into the region by way of the Equatorial Current, which splits at the Australian coast. The northward arm feeds into the Solomon Sea and the southern arm becomes the East Australian Current, the western boundary current of the South Pacific Subtropical gyre. Increased energetics in this layer (Level 3 map) occur to the east of the island chain that extends from New Caledonia to Papua New Guinea. An energetic shelf-edge strip occurs offshore of the Great Barrier Reef, presumably associated with the splitting of the Equatorial Current system.



Level 1b



Level 2

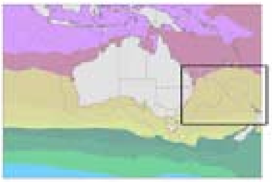


Level 3

Level 1b_P17	Mean	Min.	Max.	Std Dev.
Temperature (^oC)	25.62	10.67	29.41	3.43
Salinity	35.12	34.66	36.04	0.25
Oxygen (mm/l)	4.62	4.07	5.35	0.13
Nitrate (mg/l)	0.92	0.00	17.38	2.08
Silicate (mg/l)	2.56	0.25	16.21	1.69

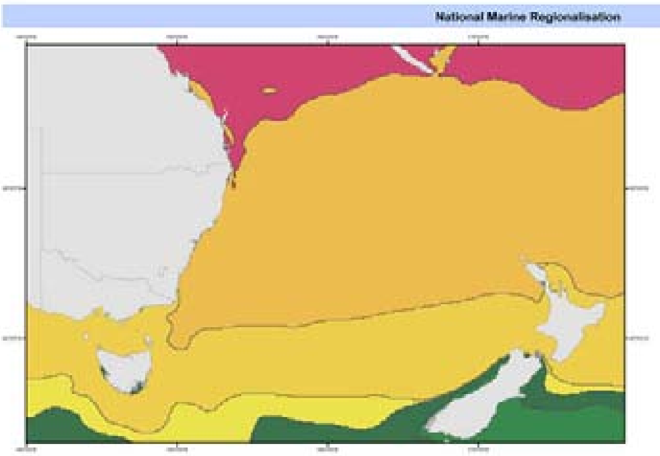
Mean Depth (m)	Latitude (^oS)	Longitude (^oE)	Volume ($km^3/10^6$)
50	-16.5	157.8	1.00

Level 1b_P13
Coral Sea Circulation:
Pacific Central-South Subtropical Water Mass



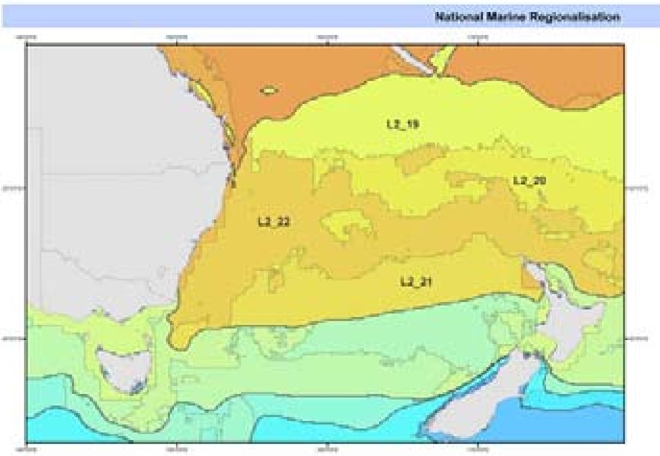
Description: The Coral Sea Circulation region contains the East Australian Current waters and associated eddy fields. This current which is the western boundary current in the South Pacific Ocean, leaves the Australian coast at about 34°S to flow around the northern end of New Zealand and down its east coast (East Auckland Current). The path of the current between Australia and New Zealand is known as the Tasman Front. This front separates the cooler, fresher waters of the Tasman Sea region (L2_21) from the warmer and more saline waters of the Coral Sea region (L2_19).

The presence of these fields can be seen in the Level 2 map adjacent (L2_22). These fields can be further refined by the Level 3 energetics map. The path of the East Australian current down the coast and across the Tasman sea (Tasman Front) can be seen clearly. The lighter shades of red to the south of the Tasman Front represent disturbances that move westward with Rossby speed.



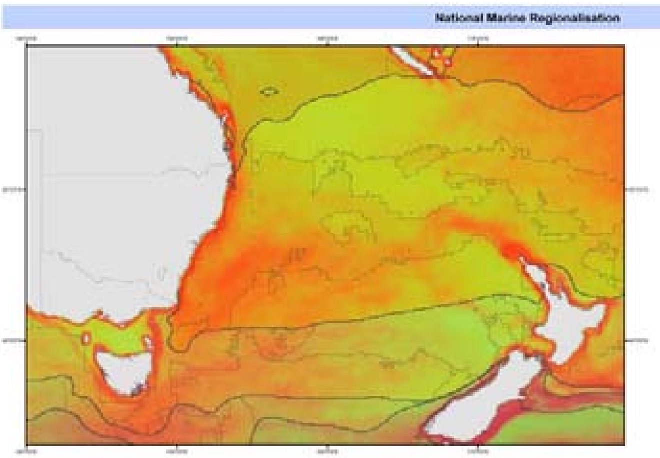
Level 1b

When these reach the Australian coast, they separate from the main current and form eddies, which move southwards. Generally, the meander of the Rossby wave extends southward at the Australian coast, trapping the warmer Coral Sea water. The East Australian Current generally spawns only warm-core eddies (anticyclonic eddies; see Figure 5-4). The eddy field can be seen in the Level 2 map as the southward projection of L2_22 along the east coast of Australia.



Level 2

Examination of the Level 3 energy maps shows that the eddy fields have higher "energetics" than the East Australian Current – an indication that the core jet of that current is relatively stable (as regards temperature variations), while mixing associated with the current occurs at its offshore edge. Note also that the current interacts strongly with the slope/shelf extending south to Tasmania.

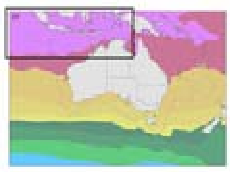


Level 3

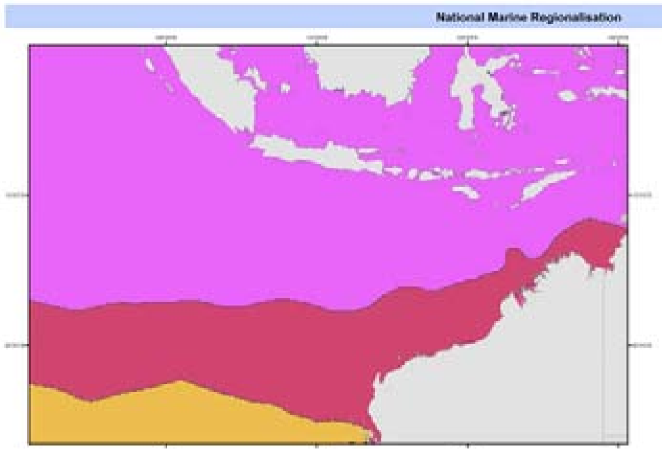
Level 1b_P13	**Mean**	**Min.**	**Max.**	**Std Dev.**
Temperature (^{o}C)	19.15	12.89	26.25	2.50
Salinity	35.64	35.13	37.56	0.14
Oxygen (mm/l)	5.09	4.61	5.95	0.23
Nitrate (mg/l)	1.36	0.00	13.09	1.57
Silicate (mg/l)	2.55	0.31	16.21	1.58

Mean Depth (m)	**Latitude (^{o}S)**	**Longitude (^{o}E)**	**Volume (km^3/10^6)**
70	-29.1	153.4	1.58

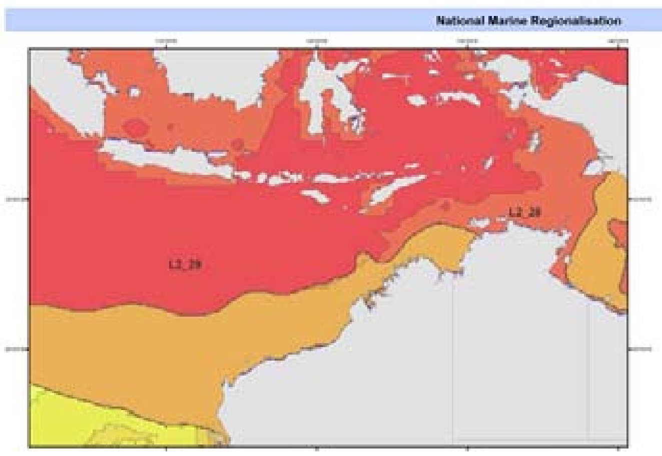
Level 1b_I20
Indonesian Throughflow:
Indian North-East Equatorial Water Mass



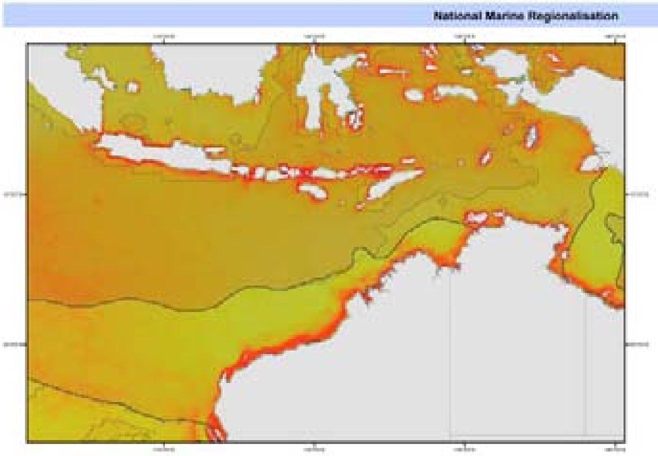
Description: Indonesian Throughflow Water derives from Pacific Ocean Central Water and is formed during transit through the Indonesian archipelago, where the high precipitation rates reduce salinity levels (Water masses 20 and 23). The water enters the Indian Ocean between Timor and the North West Shelf and through the various passages between the islands east of Bali. It spreads across the central Indian Ocean as a latitudinal tongue of high-temperature, low-nutrient, and low-salinity water. This outflow occurs throughout the upper 1000 m of the water column (but at depth is classed as Level 1b_23) and has a major influence on the climate of the entire ocean basin and the Western Australian region in particular. Substructure at Level 2 appears to be related to regional influences of freshwater runoff affecting salinity levels. Energy levels are elevated around the numerous islands and coastline irregularities, and there is a general increase to the west, presumably associated with the westward tongue of the outflow waters.



Level 1b



Level 2



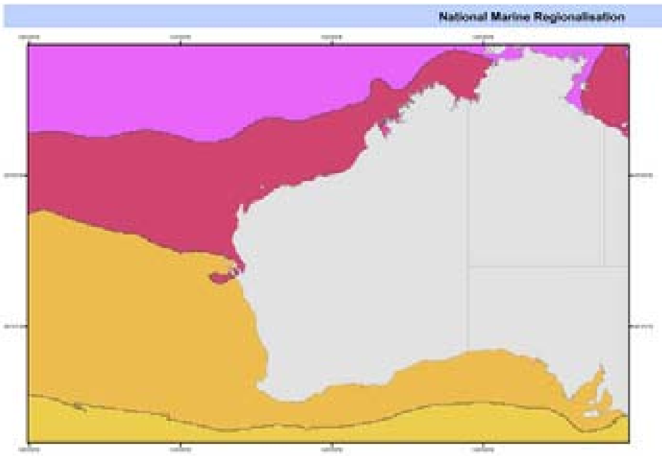
Level 3

Level 1b_20	**Mean**	**Min.**	**Max.**	**Std Dev.**
Temperature (^{o}C)	27.69	21.61	30.34	1.16
Salinity	34.21	29.32	34.72	0.50
Oxygen (mm/l)	4.42	3.63	5.33	0.17
Nitrate (mg/l)	0.66	0.00	10.65	0.78
Silicate (mg/l)	3.76	0.00	56.33	2.25

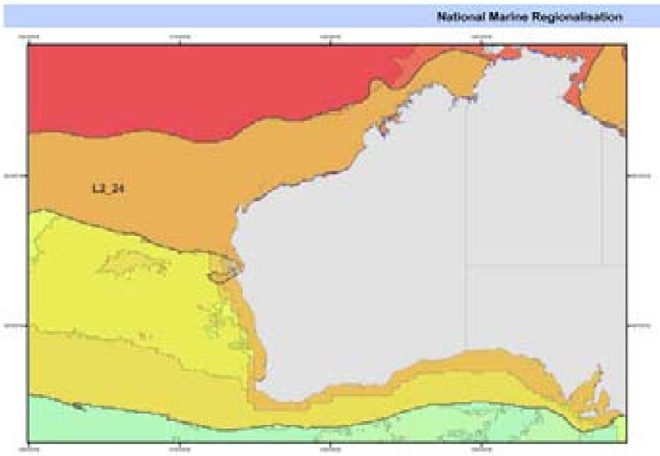
Mean Depth (m)	**Latitude (^{o}S)**	**Longitude (^{o}E)**	**Volume (km^3/10^6)**
20	-8.3	116.4	0.62

Level 1b_I17
Indian Transition:
Indian Central Tropical Transition Water Mass

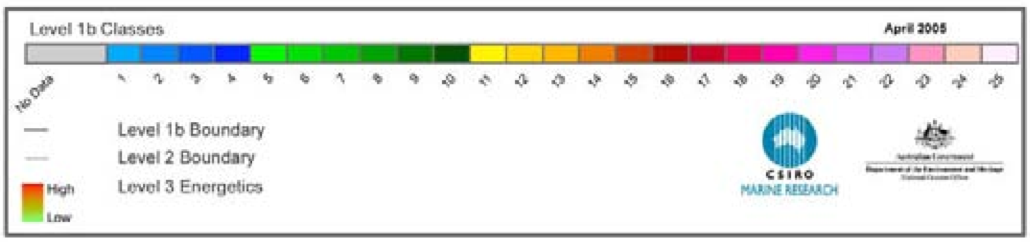
Description: Level 1b_I17 has the same water properties as the Coral Sea Region (Level 1b_P17) but occurs as a narrow band extending out from a broad base that originates from about the offshore Kimberley region of Western Australia down to as far south as Shark Bay. The rapid narrowing of the water mass band to the west is an indication that it is entrapped as a transition zone between adjacent core regions. Energy levels increase offshore and to the south and there is an intensified band along the coast that may reflect strong tidal stirring.

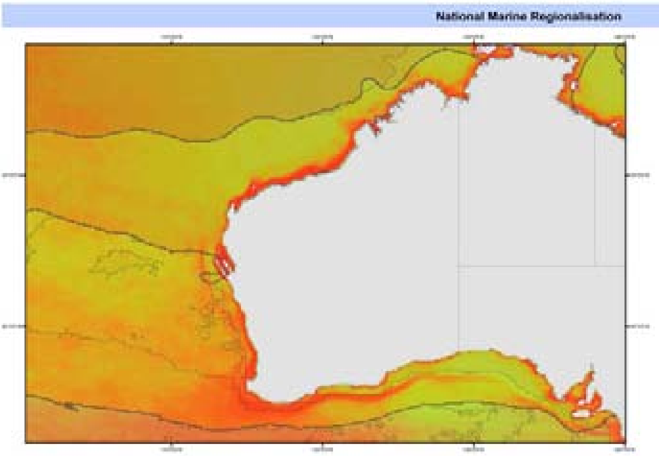


Level 1b



Level 2





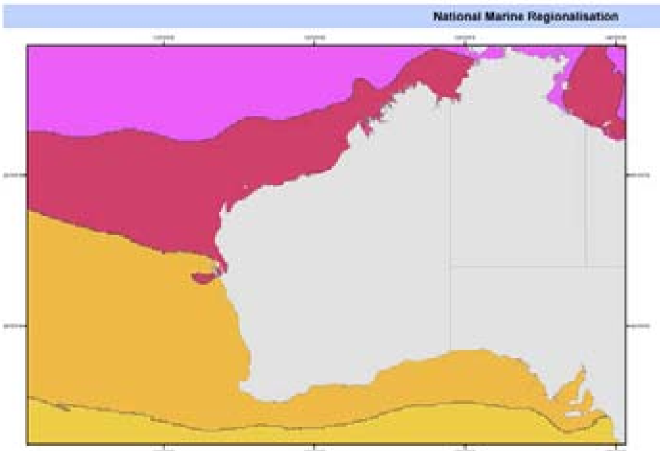
Level 3

Level 1b_I17	**Mean**	**Min.**	**Max.**	**Std Dev.**
Temperature (°C)	25.62	10.67	29.41	3.43
Salinity	35.12	34.66	36.04	0.25
Oxygen (mm/l)	4.62	4.07	5.35	0.13
Nitrate (mg/l)	0.92	0.00	17.38	2.08
Silicate (mg/l)	2.56	0.25	16.21	1.69

Mean Depth (m)	**Latitude (°S)**	**Longitude (°E)**	**Volume (km^3/10^6)**
50	-16.5	157.8	1.00

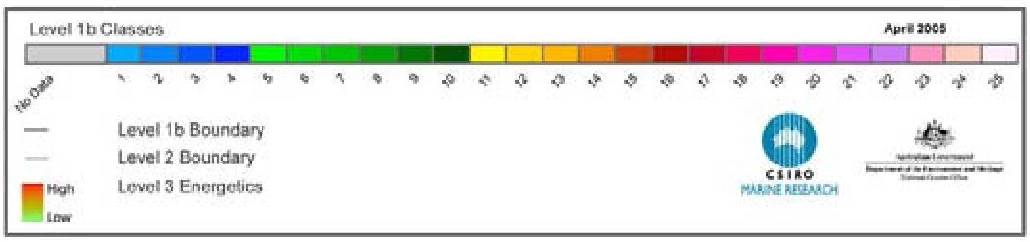
Level 1b_I13
Indian Central Region:
Indian Central Core Water Mass

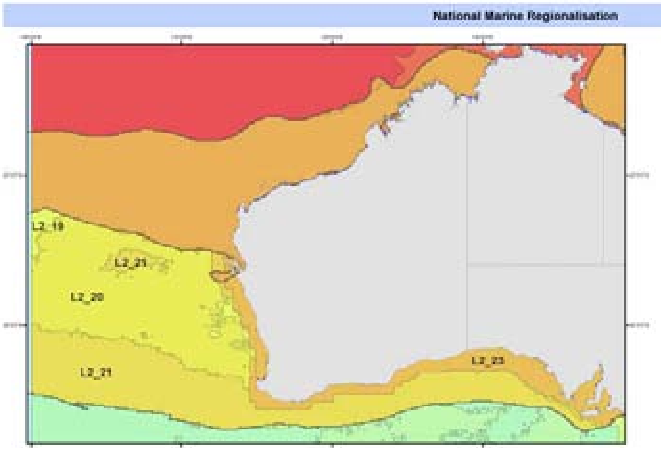
Description: A core water body in the Central Indian Ocean that shares the same water properties as the Coral Sea Circulation Region in the Pacific (P13). The seasonal Leeuwin Current, which flows down the west Australian coast from an origin around Shark Bay, suggests there will be seasonal changes in the circulation of this water mass. The bulk of the seasonal eastward drift feeding the Leeuwin Current continues around Cape Leeuwin and floods over the shelf of the Great Australia Bight, ending just to the east of Kangaroo Island in south Australia. The change in direction of the current around Cape Leeuwin coincides with increased eddy activity in the south-west shelf and offshore region of western Australia. This is indicated in the Level 3 energetics map, which also clearly demarcates the offshore edge of this current system.



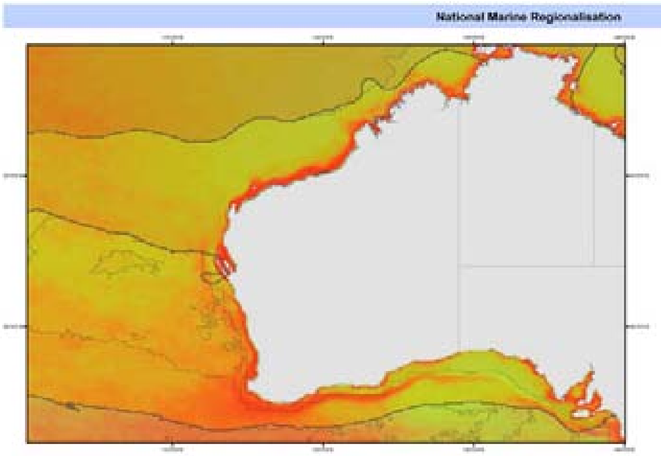
Level 1b

Near the central Great Australia Bight, the Leeuwin Current appears to dissipate and at the same time a core homogeneous water mass appears at the head of the bight. The extension of the Leeuwin Current reappears to the east of this region.





Level 2



Level 3

Level 1b_I13	**Mean**	**Min.**	**Max.**	**Std Dev.**
Temperature (^{o}C)	19.15	12.89	26.25	2.50
Salinity	35.64	35.13	37.56	0.14
Oxygen (mm/l)	5.09	4.61	5.95	0.23
Nitrate (mg/l)	1.36	0.00	13.09	1.57
Silicate (mg/l)	2.55	0.31	16.21	1.58

Mean Depth (m)	**Latitude (^{o}S)**	**Longitude (^{o}E)**	**Volume ($km^3/10^6$)**
70	-29.1	153.4	1.58

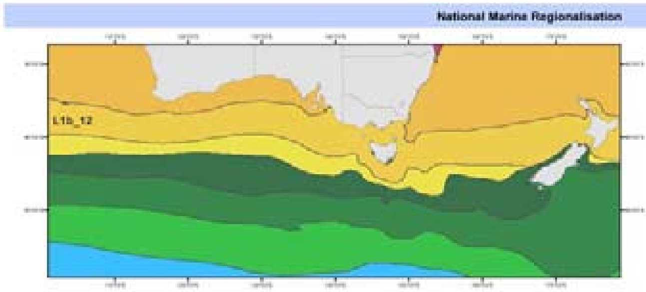
Level 1b_I12
Northern Sub-Tropical Convergence

Description:
Level 1b_12 between Tasmania and New Zealand is part of the Tasman Sea region; it is probably the core of the Tasman Sea. This water is formed and subducted in the Subtropical Convergence and is cooler and fresher than the water north of the Tasman Front. The north-eastward orientation of this water mass in the Tasman Sea suggests that its alignment is under the control of large-scale circulatory processes that deflect the water mass northward, under topographic steering forces, as it approaches New Zealand.

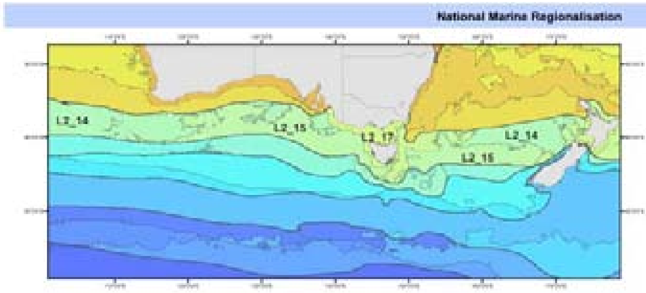
Indian Region and Central Region of Level 1b_12: The broad structure of this band of water mass is characterised by meanders that, by and large, appear to be influenced by the topography of southern Australia and Tasmania. A narrowing of the band as it approaches Cape Leeuwin is accompanied by increased enegetics (see Level 3 map).

Likewise, as the water mass circulates around Tasmania, energetics increase to the south and east.

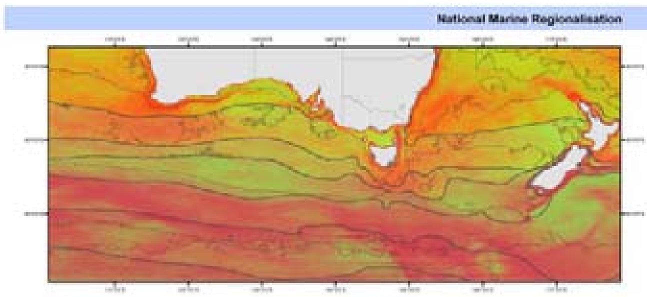
The Level 2 substructure consists of a southern band terminating in the mixed region surrounding Tasmania. Part of it continues into the Tasman Sea.



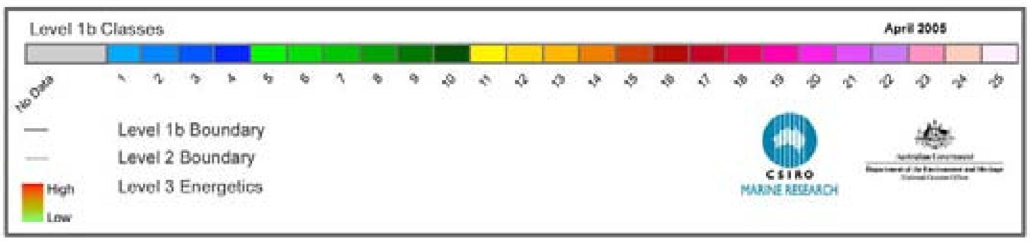
Level 1b



Level 2



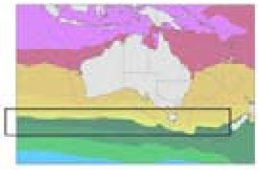
Level 3



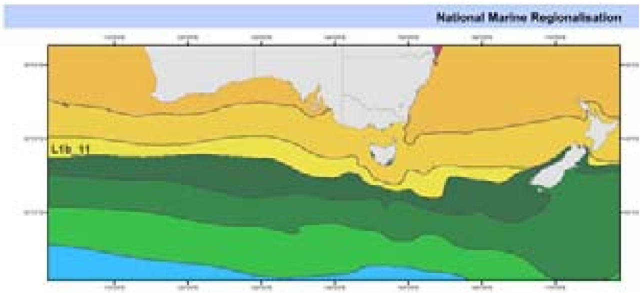
Level 1b_12	Mean	Min.	Max.	Std Dev.
Temperature (^oC)	13.59	10.06	19.67	1.44
Salinity	35.24	34.74	35.72	0.17
Oxygen (mm/l)	5.58	4.73	6.22	0.27
Nitrate (mg/l)	4.33	0.02	18.80	3.07
Silicate (mg/l)	2.71	0.27	14.17	1.42

Mean Depth (m)	Latitude (^oS)	Longitude (^oE)	Volume ($km^3/10^6$)
100	-37.9	127.5	1.95

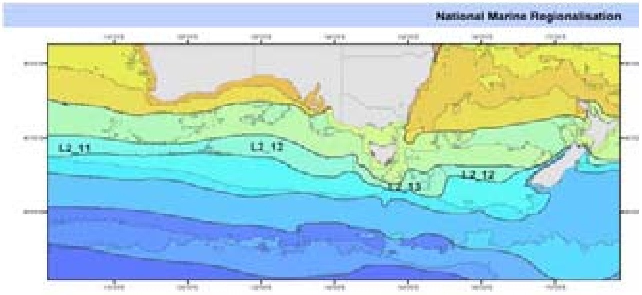
Level 1b_11
Central Sub-Tropical Convergence



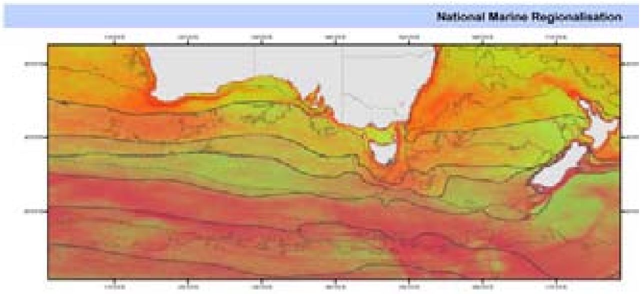
Description: While this water mass appears narrower and less extensive at the surface than Level 1b_12 just to its north, it is a larger and deeper body of water. It is one of the main bodies of waters of the Subtropical Convergence. The Subtropical Front or Subtropical Convergence (Level 1b_11) is the interface between sub-Antarctic and subtropical water masses above 400 m. This dynamically active zone has significant exchange across the boundary and large seasonal variability. It is just to the south of the topographically influenced Level 1b_12 band. Significant mixing processes occur in this band at its eastern end and to the south of Tasmania where it intersects the South Tasman Rise. Nutrient levels are generally high and subject to seasonal draw downs during phytoplankton blooms in spring and autumn.



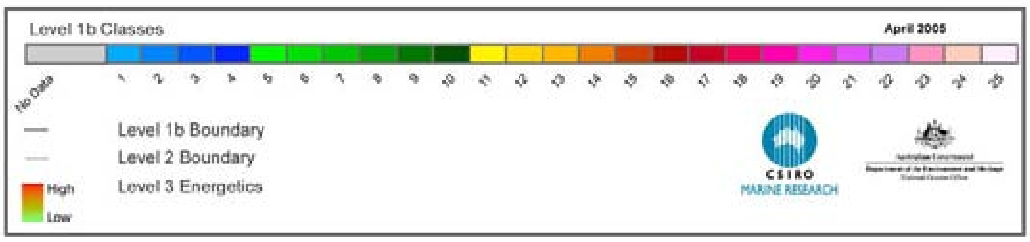
Level 1b



Level 2



Level 3

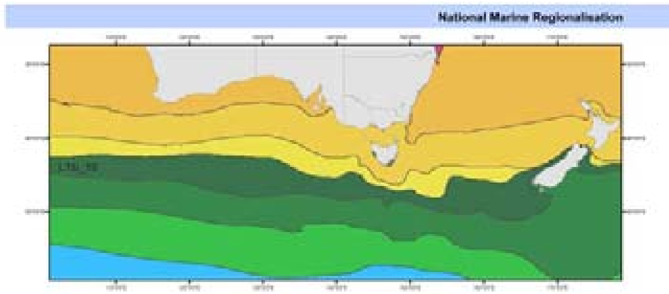


Level 1b_11	Mean	Min.	Max.	Std Dev.
Temperature (^oC)	10.64	8.60	15.47	0.90
Salinity	34.83	34.69	35.08	0.08
Oxygen (mm/l)	5.74	4.36	6.40	0.34
Nitrate (mg/l)	10.63	0.37	24.41	4.05
Silicate (mg/l)	4.27	0.74	20.09	2.00

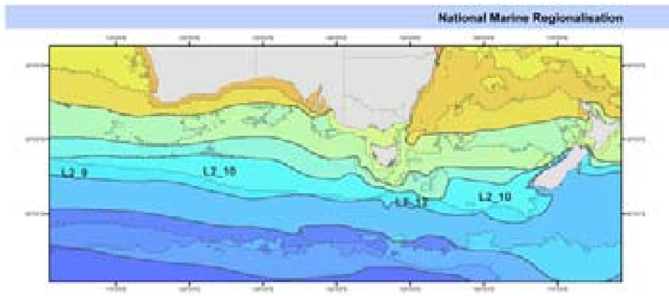
Mean Depth (m)	Latitude (^oS)	Longitude (^oE)	Volume ($km^3/10^6$)
250	-40.9	116.5	2.59

Level 1b_10
Southern Sub-Tropical Convergence

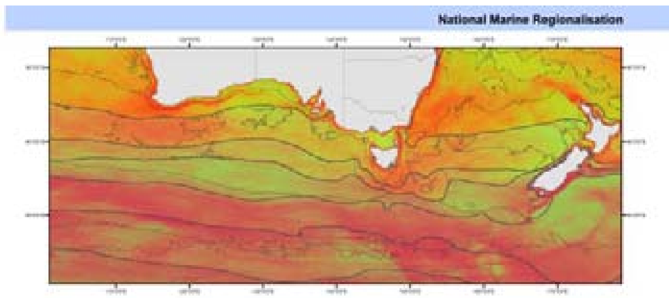
Description: This region, which is bounded to the south by the Sub-Antarctic Front (see Level 2 map adjacent), forms the southern part of the Subtropical Convergence. It is the deepest, largest part of the Subtropical Convergence and has the highest nutrient concentrations, but it otherwise has similar formation dynamics to Level 1b_11 to the north.



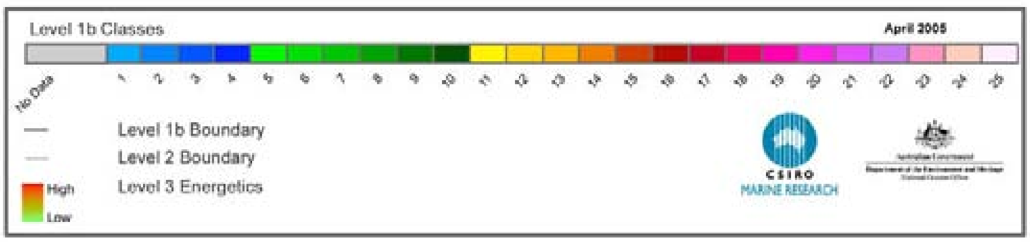
Level 1b



Level 2



Level 3

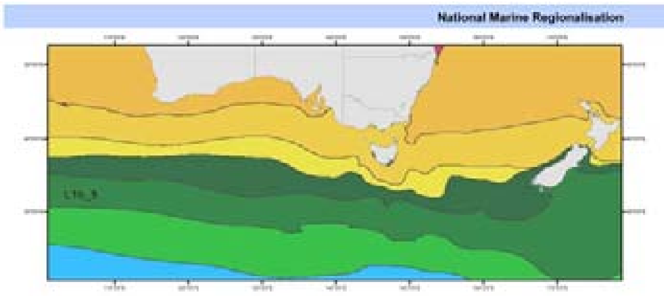


Level 1b_10	Mean	Min.	Max.	Std Dev.
Temperature (^oC)	8.93	5.30	21.99	0.98
Salinity	34.60	34.40	34.73	0.06
Oxygen (mm/l)	5.75	4.45	6.63	0.49
Nitrate (mg/l)	16.22	0.04	28.59	4.82
Silicate (mg/l)	6.90	0.94	32.41	3.81

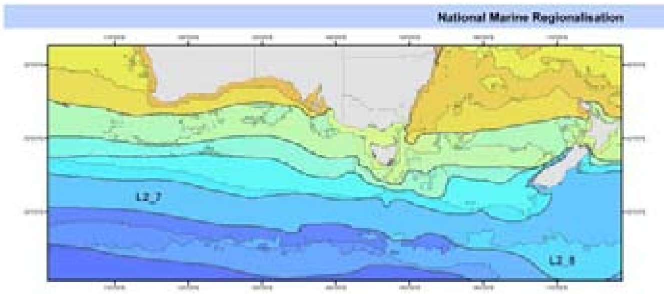
Mean Depth (m)	Latitude (^oS)	Longitude (^oE)	Volume ($km^3/10^6$)
400	-44.1	127.5	4.40

Level 1b_9
Sub-Antarctic Front

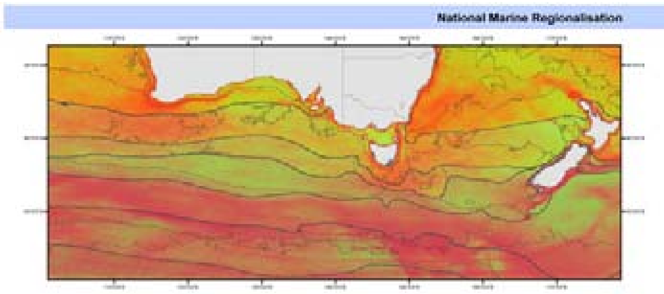
Description: This region is the Sub-Antarctic Front, which separates the Subtropical Convergence zone in the north from sub-Antarctic water masses to the south. The water mass is aligned with a current system whose magnitude and direction can be clearly visualised in Appendix G (Figure G-4) and which corresponds closely with the region of higher energy in the Level 3 map. The strong and pervasive energetics in this region reflect the mixing processes of a sub-Antarctic current interacting with the sub-Antarctic ridge system. Nutrient levels are very high and salinities are relatively low.



Level 1b

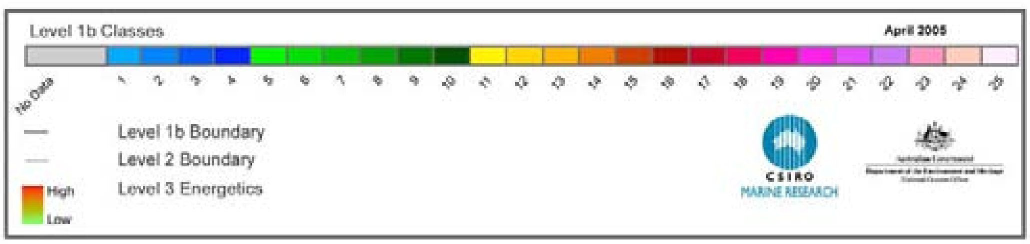


Level 2



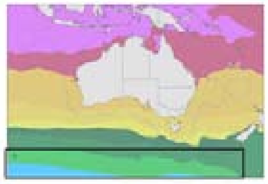
Level 3

Level 1b_9	Mean	Min.	Max.	Std Dev.
Temperature (^{o}C)	7.14	4.32	15.31	1.24
Salinity	34.28	33.79	34.53	0.14
Oxygen (mm/l)	6.38	4.90	7.24	0.48
Nitrate (mg/l)	18.59	0.56	32.96	4.47
Silicate (mg/l)	7.65	0.65	38.03	5.51

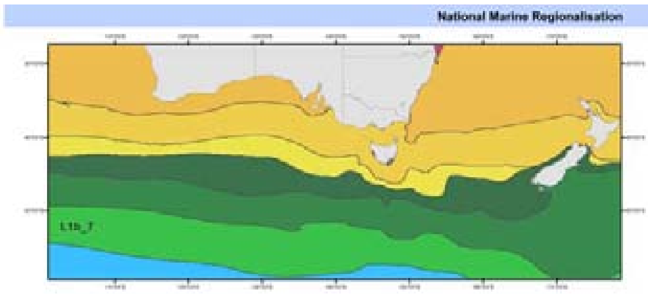


Mean Depth (m)	Latitude (^oS)	Longitude (^oE)	Volume ($km^3/10^6$)
100	-49.6	151.7	2.05

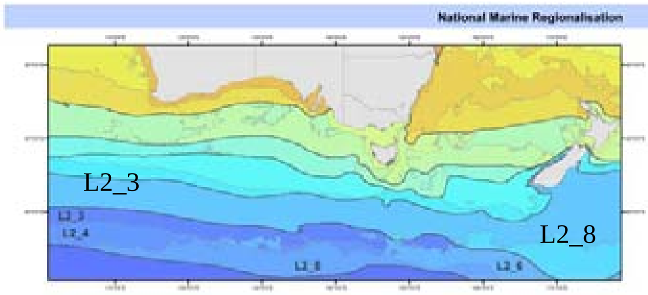
Level 1b_7



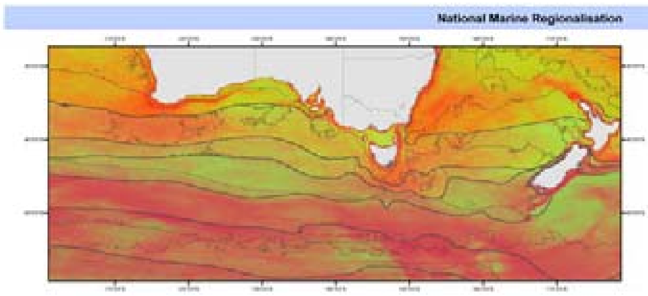
Description: this water mass lies to the south of the sub-Antarctic frontal zone. It is a region of strong energetics, very high nutrients, and low salinity and temperature.



Level 1b

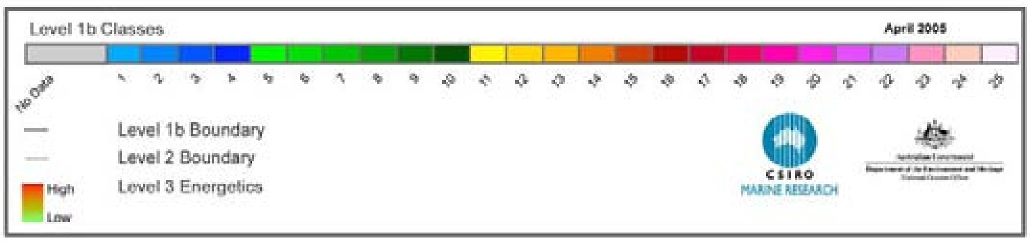


Level 2



Level 3

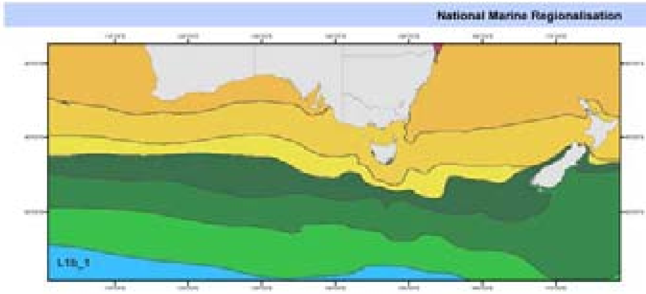
Level 1b_7	Mean	Min.	Max.	Std Dev.
Temperature (^{o}C)	3.46	1.72	5.90	0.96
Salinity	33.99	33.80	34.37	0.11
Oxygen (mm/l)	6.97	5.19	7.78	0.54
Nitrate (mg/l)	24.24	15.70	33.00	2.71
Silicate (mg/l)	14.02	0.82	54.29	8.67



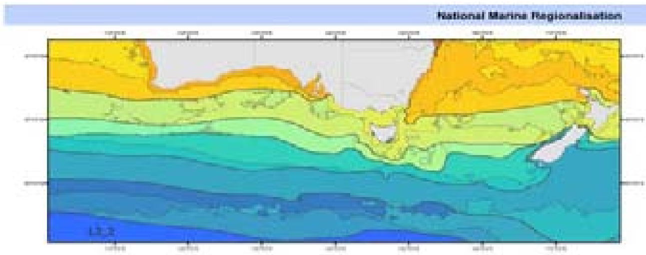
Mean Depth (m)	**Latitude (^{o}S)**	**Longitude (^{o}E)**	**Volume ($km^3/10^6$)**
80	-53.7	131	0.93

Level 1b_1
Southern Sub-Antarctic Front

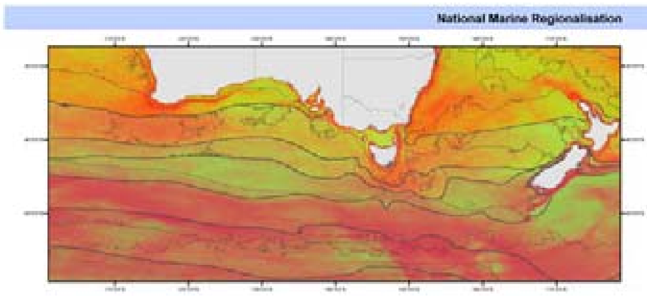
Description: Level 1b_1 lies to the south of the Sub-Antarctic Front. Energetic levels are not as intense as in the sub-Antarctic frontal zone, but nitrate and silicate levels are higher. This level is at the southern extremity of the study region, so some caution is required in our interpretations. In particular, boundary effects may prevent us from seeing the full context and extent of this water mass.



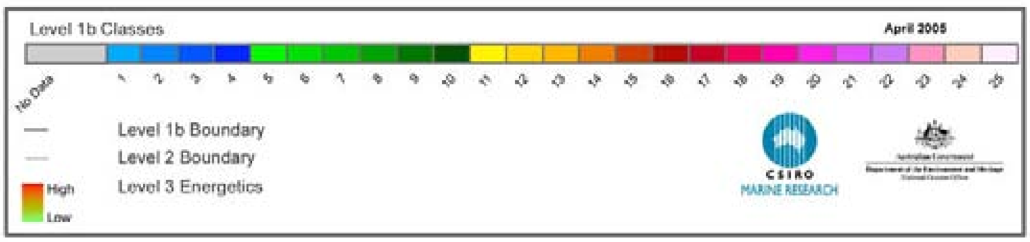
Level 1b



Level 2



Level 3



Level 1b_1	**Mean**	**Min.**	**Max.**	**Std Dev.**
Temperature (^{o}C)	1.09	land	2.21	0.53
Salinity	34.04	33.80	34.52	0.15
Oxygen (mm/l)	7.06	4.76	7.95	0.84
Nitrate (mg/l)	27.67	22.62	34.26	2.42
Silicate (mg/l)	32.82	7.60	76.22	13.41

Mean Depth (m)	**Latitude (^{o}S)**	**Longitude (^{o}E)**	**Volume (km^3/10^6)**
90	-57.4	115.2	0.57

5.6.2 Corroborating biological evidence for surface water masses

5.6.2.1 Phytoplankton species distributions

We examine in this section Hallegraeff's phytoplankton province map (Hallegraeff 1990) to determine if it provides corroborating information for the Level 1b surface layer classes. It is appropriate to compare only biological distributions with the physical oceanographic classifications in the top 100 m of the water column.

Qualitatively, there is broad agreement between the Level 1b units and the phytoplankton provinces shown in Figure 5-7. Detailed features, such as those associated with the Leeuwin Current, the region offshore of the shelf break in the western Great Australia Bight, the inshore current along the Australian east coast and associated eddy features, correspond with units in the Level 2 and 3 regionalisations. In the offshore regions, the surface classes of Level 1b are in broad agreement with the phytoplankton provinces off both western and eastern Australia and most of the boundary limits off northern Australia.

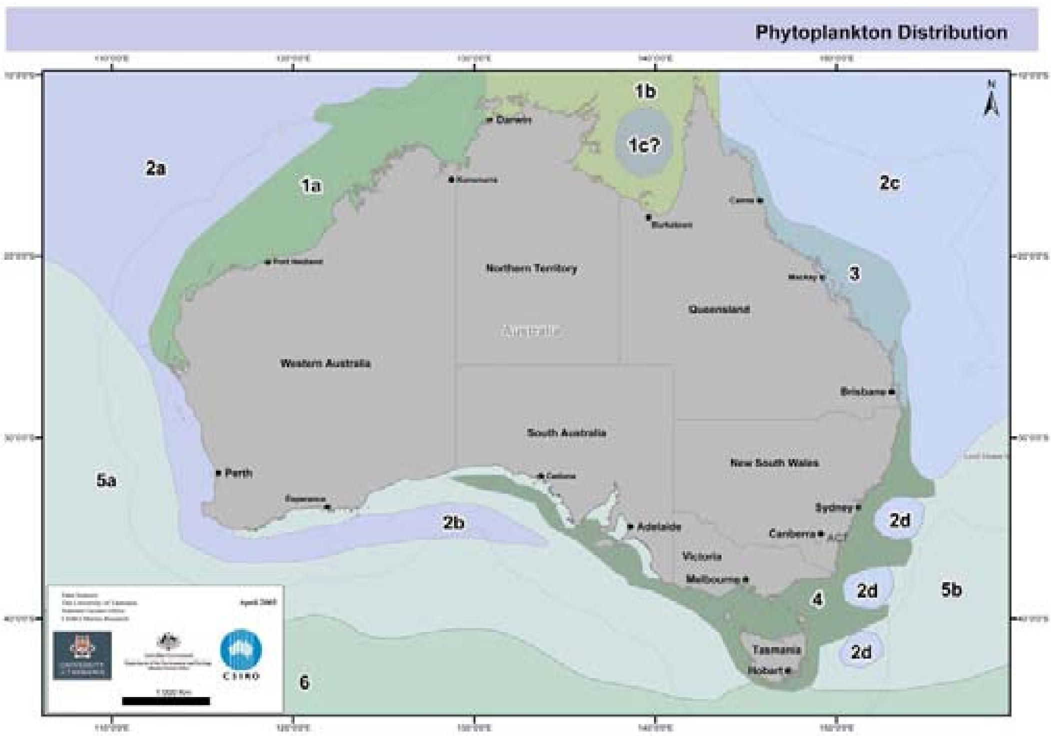


Figure 5-7 Updated Phytoplankton distribution (Hallegraeff in Hayes *et al.* 2005).
The productive phytoplankton province (1) comprising the shelf waters of North West Australia, the Gulf of Carpentaria, Arafura Sea and Timor Sea is basically a tropical diatom flora (keystone genera are *Bacteriastrum*, *Chaetoceros*, *Coscinodiscus*, *Rhizosolenia*, *Thalassionema*,*Thalassiothrix*). Subtle differences in species dominance and phytoplankton chlorophyll biomass are discriminants of the biomes 1 a, b, c, while the floristically largely distinct shallow waters of the Great Barrier Reef lagoon (3) are dominated by fast-growing nanoplankton diatoms. These tropical neritic communities are distinct from the tropical oceanic, predominantly dinoflagellate flora (*Gonyaulax birostris*, *Histioneis*, *Ornithocercus*) of the Indian Ocean (2a) and Coral Sea (2c), which are carried southwards by the Leeuwin Current (2b) and East Australian Current (2d), respectively. The productive temperate neritic province (4) comprising coastal waters of New South Wales, Tasmania, Victoria and South Australia exhibits predictable phytoplankton species succession patterns from small diatoms (*Asterionellopsis*, *Pseudo-nitzschia*, *Skeletonema*, *Thalassiosira*) to large diatoms (*Detonula*, *Ditylum*, *Eucampia*) to larger dinoflagellates (*Ceratium*, *Protoperidinium*), in response to nutrient enrichments from current-

induced upwelling phenomena. A highly variable oceanic transition zone (5), distinct from inshore phytoplankton communities (4) and embedded tropical flora (2b, 2d) is bordered to the south by a sub-Antarctic phytoplankton province (6), including the coccolithophorid *Coccolithus pelagicus* as an indicator organism.

5.6.2.2 Chlorophyll and Primary Production

There is very little ground truth data available in the Australian region that would allow a quantitative bioregionalisation of chlorophyll distribution, or primary productivity. Satellite data were used because there are too few in-water samples available to substantiate any quantitative or qualitative interpretations. We used the monthly mean (from 2001–2004) chlorophyll product from the MODIS ocean colour satellites to divide the waters around Australia into regions (Appendix K, Figures K-1 a, b, c and d) to describe the seasonal patterns detailed below.

The data in these figures are the 9 km resolution data, averaged over the calendar month in question. These satellite products from the MODIS satellites measure chlorophyll in surface waters only. The weekly images (9 km resolution) for the period 1997–2001 in the SeaWiFs movie loop included with this report give a much better indication of the dynamic nature of the patterns in chlorophyll distributions and how these move and change over annual cycles. The reader is encouraged to view the movie loop to fully understand the patterns being described in what follows. As well, we have used the patterns of primary production (Appendix K, Figures K-2 a, b, c and d), calculated with the Berhenfeld-Falkowski VGPM model and MODIS ocean colour satellite, monthly 9 km resolution, mean chlorophyll estimates (for the period 2002–2004) to allow regions of similar primary production patterns to be qualitatively grouped. These patterns are subjective, based on similarities in the weekly to annual patterns in remotely sensed chlorophyll abundance and calculated primary production. The accuracy of these measurements is on the order of ±20%.

The oceans around Australia, in our subjective assessment, may be grouped into three zones and six major regions based on the similarities in seasonal patterns of chlorophyll abundance and the ranges in primary production. Note that these regions are not independent of each other; there are clear interactions and gradations between regions. Features of the seasonal chlorophyll primary production distributions generally coincide with Level 1b_classes in the surface layers seen at Level 1b. Finer scale features such as those associated with the Leeuwin Current and East Australia Current also correspond with features seen at Level 2.

The three zones are:

1. The monsoonal tropics, encompassing the regions north of about 20^{o}S.
2. The central, Subtropical regions of the Indian and Pacific oceans.
3. The broad region south of Australia bounded on the northern edge by the Subtropical Convergence.

These zones correspond roughly to the major oceanic zones of the preliminary Level 1a regionalisation.

The six regions of similarity between chlorophyll abundance and primary productivity are:

1. The Southern Ocean, in a broad latitudinal band between about 40^{o}S and 60^{o}S and 90^{o}E to 180^{o}E.
2. The Indian Ocean sector between about 20^{o}S and 40^{o}S.
3. The Timor Sea region.
4. The Arafura Sea/Gulf of Carpentaria region to Torres Strait.
5. The Coral Sea region north of 25^{o}S.
6. The Tasman Sea sector, between about 25^{o}S and 40^{o}S (Figure 5.8).

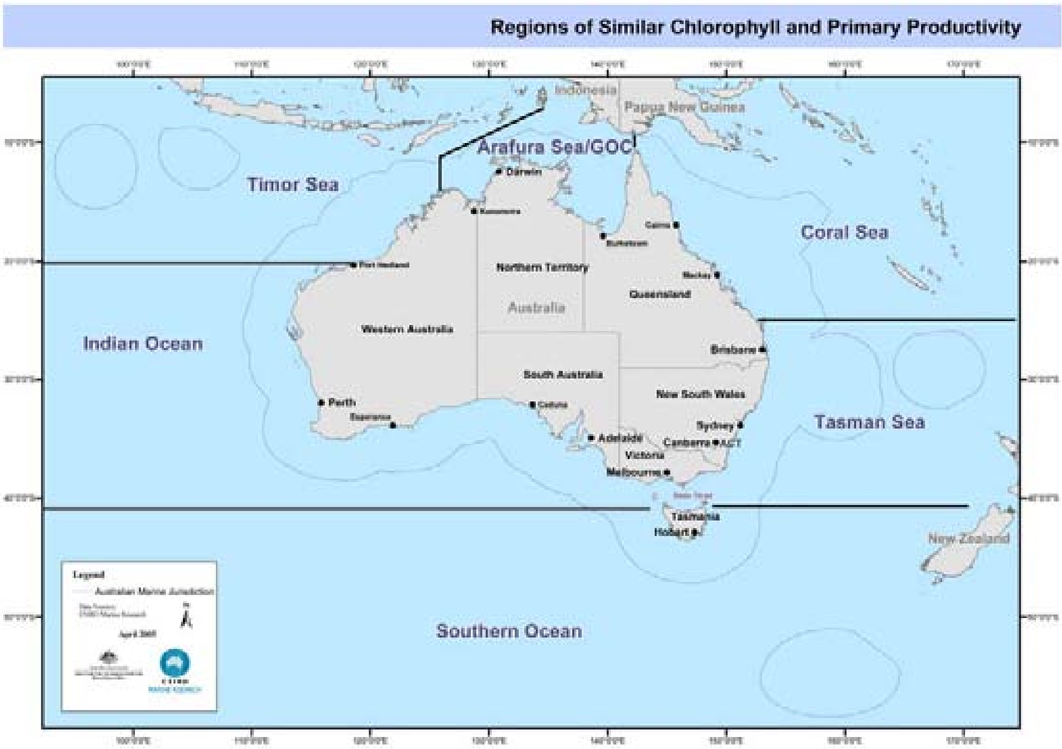
Within the monsoonal tropics, there is a division into the Timor Sea/Indian Ocean region west of about 120°E, the shallow Arafura Sea/Gulf of Carpentaria region and the Coral Sea region. These regions are characterised by having higher standing stocks and primary production in the dry season (winter) than in the wet season (summer). Phytoplankton biomass and primary production are nutrient-limited in these regions. However, phytoplankton in surface waters are typically not light-limited because of high sun angles, though there may be some limitation from suspended sediments or self-shading when phytoplankton biomasses become very high.

In the central Subtropical water masses, phytoplankton biomass and primary production are also nutrient-limited. The seasonal patterns of growth and production are slightly different, but the amount of primary production is similar. Highest production occurs in August to November, but nutrient exhaustion in the euphotic zone sets the limits on primary production during November to February. Light may become limiting to phytoplankton growth in the southern end of this region in winter.

In the broad band of water masses in and south of the Subtropical Convergence south of Australia, phytoplankton growth and primary production tend not to be nutrient-limited to the same degree as further north. There is a very large seasonal change in available photosynthetically active radiation, and growth in much of the region is light-limited in winter. In the high-nitrate, high-silicate regions, low iron concentrations may be limiting diatom growth and hence primary production.

The waters around Australia range from being very low to moderately productive, due primarily to the low supply of nutrients. Much of the primary production may be taking place deep in the water column at the nutricline, especially in tropical and subtropical waters, and actual primary production may be somewhat higher than shown on the maps in this section. This is because the satellites can only “see” chlorophyll in the upper 10 to 25 m (the depth depends on the chlorophyll concentration) in the surface waters, while nutriclines are typically at depths of between 50 and 140 m. There are insufficient data to estimate the chlorophyll or primary production in the total column from satellite estimates of surface chlorophyll. Griffiths and Matear (abstract, 2005) showed that this relationship (in chlorophyll between the surface and the total column) varies with season and between water masses in the Southern Ocean. Even if a correction to total water column chlorophyll or total water column primary production were made, the increase would not be sufficient to raise the production estimates in Australian waters above “moderately productive”.

Figure 5-8 Regions of correspondence between chlorophyll abundance and phytoplankton provinces.



The correspondence of these six regions with the surface pelagic regionalisation classes is detailed in the table below.

Table 5-2 Correspondence between phytoplankton regions and surface pelagic regionalisation classes (listed in the "Correspondence" column). In the label for the pelagic class, prefix "P" represents the Pacific Ocean component of the class and "I" is the Indian Ocean component.

Chlorophyll Region	Name	Correspondence	Comparison
1	Southern Ocean	Preliminary Level 1a Southern Ocean. Updated Level 1b: Water masses 11, 10, 9, 7, 1	Spans several Level 1b regions; low temperatures and deep mixed layers limit chlorophyll in the south during winter but the northern portion is part of the highly productive Tasman Sea. Corresponds closely to the broad preliminary Level 1a Southern Ocean unit; the Level 1b classes provide a finer classification.
2	Indian Ocean	Preliminary Level 1a Indian Ocean. Updated Level 1b: Water masses I13, I12, I17	Good correspondence with a collection of Level 1b units again suggests that chlorophyll regions approximate the same scale as the preliminary Level 1a unit.
3	Timor Sea	Preliminary Level 1a Indonesian Throughflow. Updated Level 1b_I20	Good correspondence with the Indonesian Throughflow Water.
4	Arafura Sea/Gulf of Carpentaria	Updated Level 2 of Level 1b_20	A shallower region that corresponds to Level 2 units
5	Coral Sea region	Updated Level 1b:	Good correspondence with two Level

Chlorophyll Region	Name	Correspondence	Comparison
		Water masses P17, P20	1b units
6	Tasman Sea	Updated Level 1b: Water masses P13, P12	Good correspondence with the bulk of the Coral Sea Circulation unit Level 1b_P13 and part of Level 1b_P12

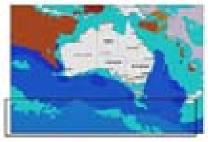
5.6.2.3 Summary of corroborative evidence from chlorophyll and primary production

To summarise the comparison, the larger offshore oceanic regions correspond well with the results of the preliminary Level 1a regionalisation, and with a collection of the updated Level 1b units, which suggests that productivity changes are broad scale. Units closer to the coast and in the energetic Tasman Sea correspond to smaller scale Level 1b and Level 2 units.

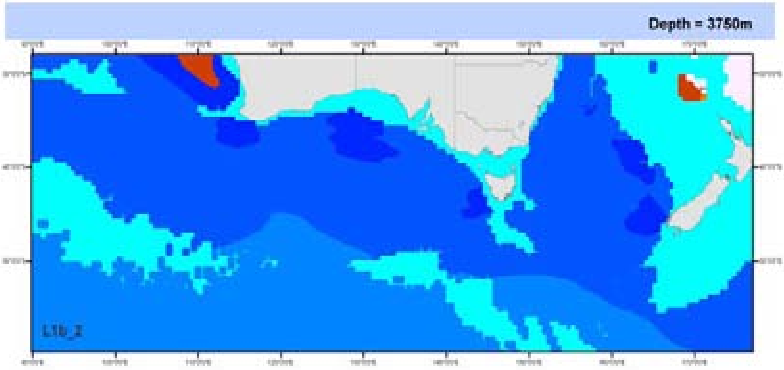
5.6.3 Subsurface Descriptions

The following descriptions refer to the subsurface water masses. The water masses are plotted at their average depth (see Table 5-1).

Level 1b_2

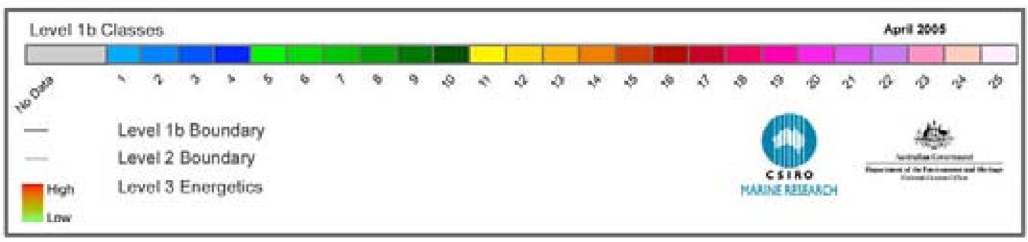


Description: A large body of deep water comprising over 12 million cubic kilometres in the study region. Antarctic deep water is restricted in its northward excursion by the sub-Antarctic ridge system, although there is some “leakage” into the South Australian Basin south of the Great Australian Bight.

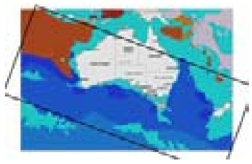


Level 1b_2	Mean	Min.	Max.	Std Dev.
Temperature (^{o}C)	0.53	land	1.67	0.35
Salinity	34.70	34.44	34.72	0.02
Oxygen (mm/l)	5.01	4.46	5.79	0.21
Nitrate (mg/l)	32.05	25.04	38.30	1.59
Silicate (mg/l)	120.59	53.15	138.63	7.09

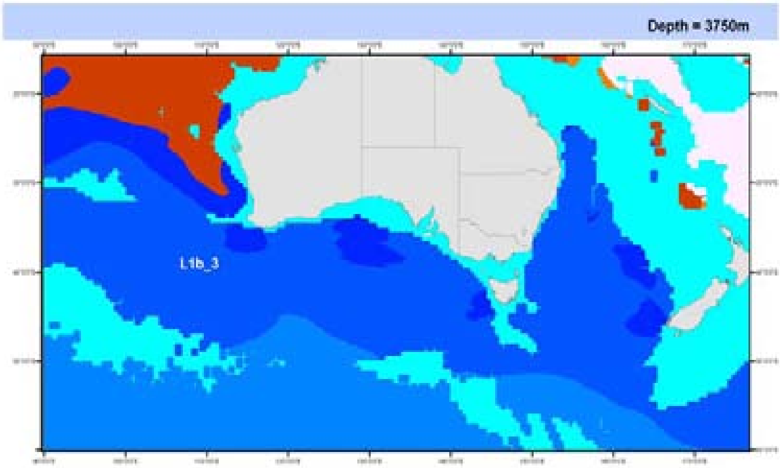
Mean Depth (m)	Latitude (^{o}S)	Longitude (^{o}E)	Volume (km^3/10^6)
3750	-55.5	123.4	12.45



Level 1b_3

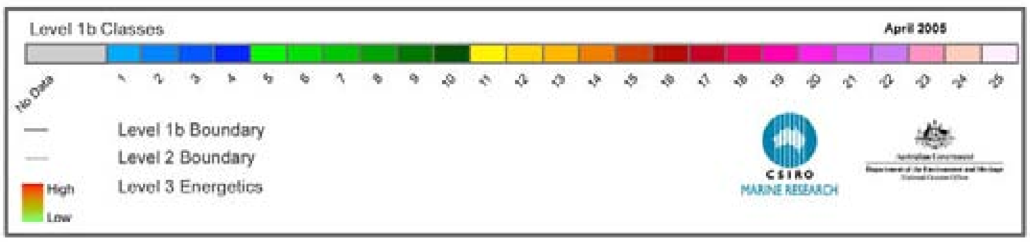


Description: This is the largest body of deep water in the study region. It is located in shallower depth to the east but gradually deepens to the north and to the west. In the Pacific, its northward excursion is limited by the confines of the Tasman Abyssal Plain, while in the Indian Ocean it infiltrates further north at depth.



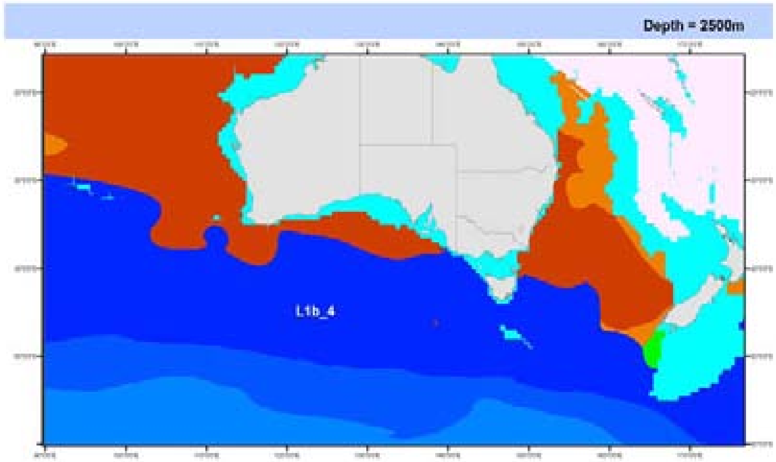
Level 1b_3	Mean	Min.	Max.	Std Dev.
Temperature (^{o}C)	1.17	0.65	1.75	0.16
Salinity	34.72	34.70	34.76	0.01
Oxygen (mm/l)	4.65	4.36	4.95	0.11
Nitrate (mg/l)	32.49	25.55	38.16	1.87
Silicate (mg/l)	114.48	83.96	141.95	10.18

Mean Depth (m)	Latitude (^{o}S)	Longitude (^{o}E)	Volume (km^{3}/10^{6})
3750	-44.4	119.6	22.71



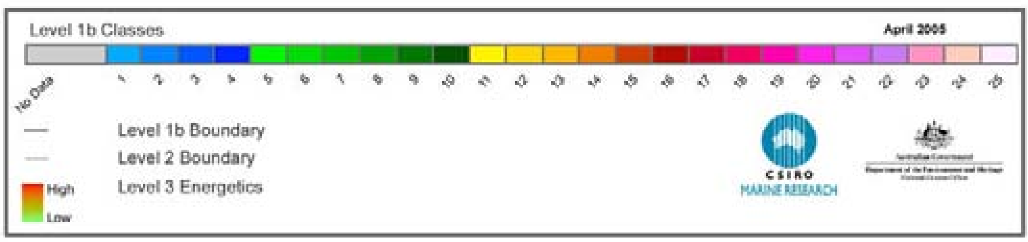
Level 1b_4

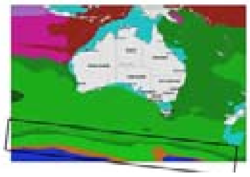
Description: A large body of deep Antarctic bottom water that appears to the north of and shallower than, the extensive Level 1b_3 unit. It has a similar distribution and limits to Level 1b_3.



Level 1b_4	Mean	Min.	Max.	Std Dev.
Temperature (°C)	1.73	0.95	2.35	0.27
Salinity	34.74	34.68	34.77	0.01
Oxygen (mm/l)	4.43	4.01	4.73	0.12
Nitrate (mg/l)	32.05	25.99	40.36	1.96
Silicate (mg/l)	96.54	70.90	144.66	13.77

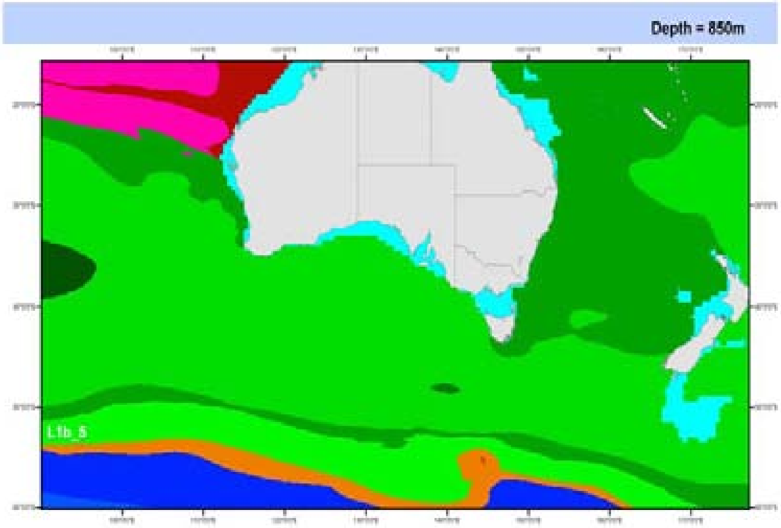
Mean Depth (m)	Latitude (°S)	Longitude (°E)	Volume ($km^3/10^6$)
2500	-48.8	121.8	18.05





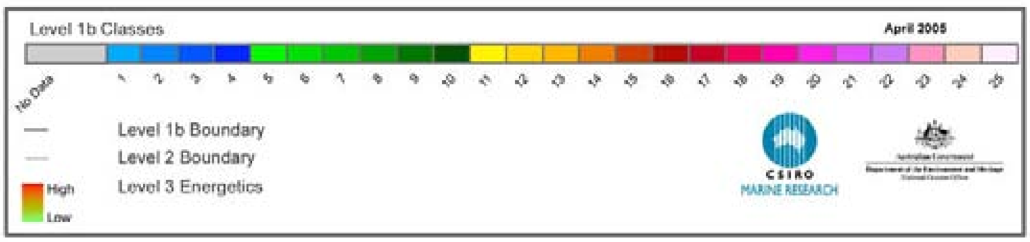
Level 1b_5

Description: This is an intermediate-depth water mass. It intrudes into the study region at a depth of about 200 m and at its maximum extent occupies the entire South Australian Basin at a depth of about 1600 m.



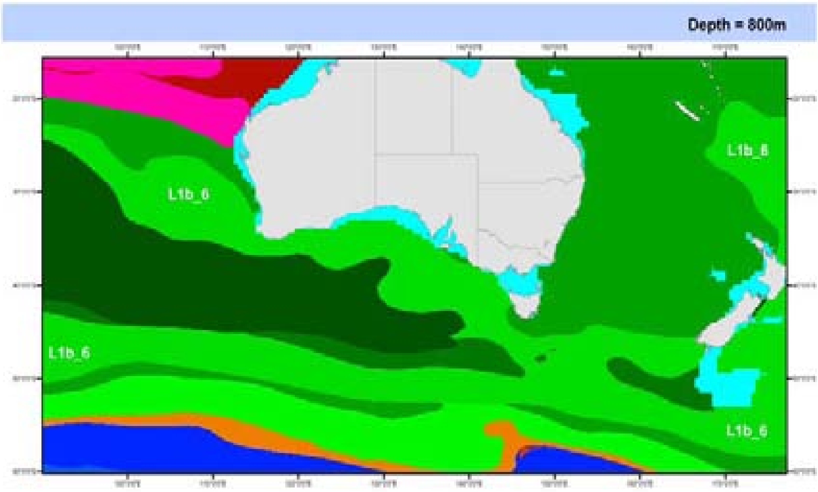
Level 1b_5	Mean	Min.	Max.	Std Dev.
Temperature (^oC)	2.24	1.15	9.78	0.65
Salinity	34.63	34.40	34.72	0.06
Oxygen (mm/l)	4.18	3.74	4.60	0.12
Nitrate (mg/l)	32.73	14.22	41.38	1.84
Silicate (mg/l)	74.81	8.59	118.90	8.18

Mean Depth (m)	Latitude (^{o}S)	Longitude (^{o}E)	Volume ($km^3/10^6$)
850	-54.5	127.8	5.81



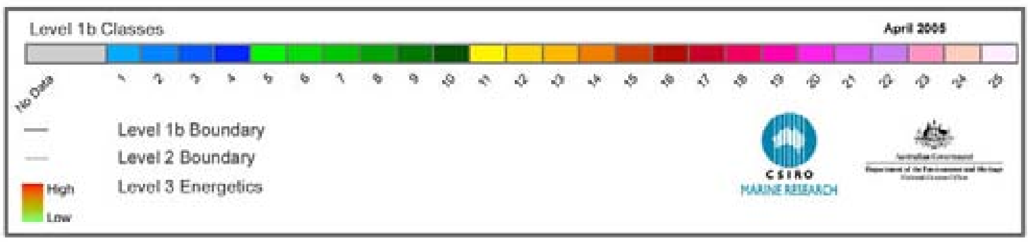
Level 1b_6

Description: Part of the Antarctic Intermediate Water that appears in the study region at about 150 m and migrates northward with depth until it fills the southern portion of the study region at about 850 m depth. Its maximum depth is about 1400 m. An apparent bifurcation of the water mass at about 600–700 m suggests that different sources or circulation pathways may be operating.



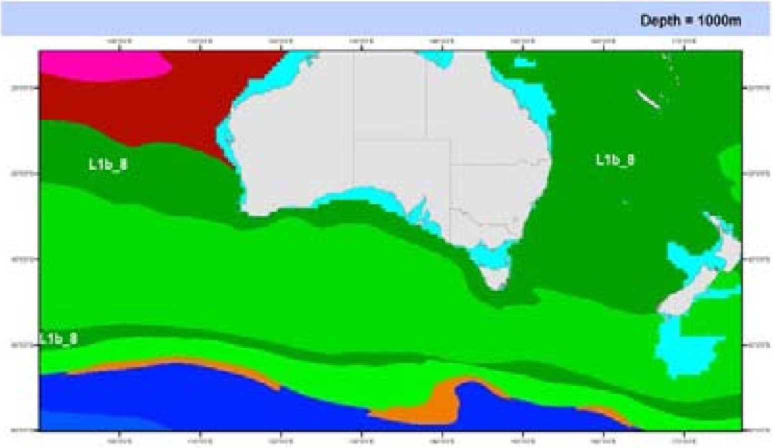
Level 1b_6	Mean	Min.	Max.	Std Dev.
Temperature (^oC)	4.47	0.83	8.70	1.72
Salinity	34.41	34.15	34.62	0.07
Oxygen (mm/l)	4.74	4.31	5.67	0.24
Nitrate (mg/l)	29.94	15.73	38.09	3.10
Silicate (mg/l)	35.77	8.97	78.54	14.66

Mean Depth (m)	Latitude (^{o}S)	Longitude (^{o}E)	Volume ($km^3/10^6$)
800	-47.2	133.2	6.60



Level 1b_8

Description: A large body of water that is part of the Antarctic Intermediate Water (located beneath Level 1b_6), with a complex distribution. It appears in the study region in the northern Pacific at about 500 m depth. With increasing depth, it expands to fill the Pacific at about 650 m, with a narrow frontal band extending off towards Africa from about North-West Cape in Western Australia. It shifts southwards with depth, contracts and then disappears at about 1600 m depth.

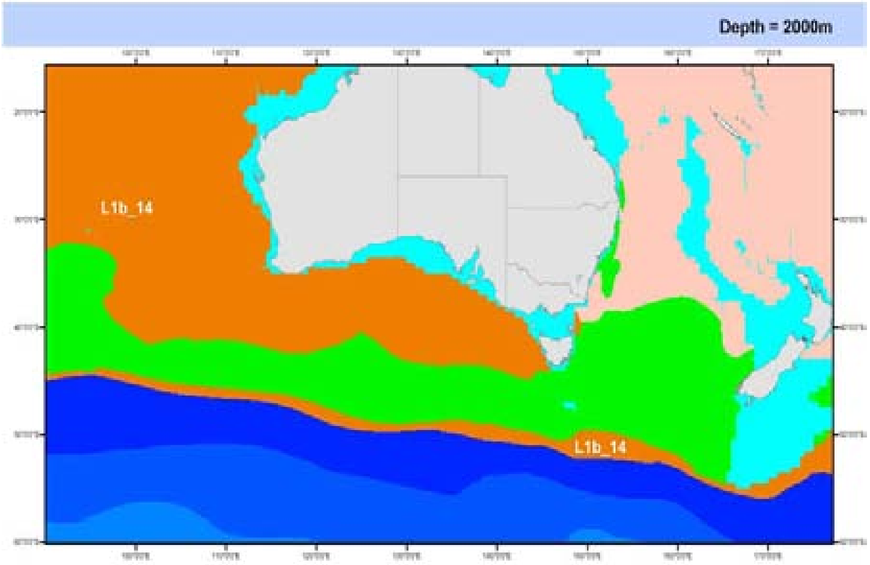


Level 1b_8	Mean	Min.	Max.	Std Dev.
Temperature (^oC)	4.72	1.93	9.94	1.77
Salinity	34.50	34.38	34.72	0.06
Oxygen (mm/l)	4.08	3.36	4.64	0.26
Nitrate (mg/l)	31.61	14.55	41.54	4.15
Silicate (mg/l)	48.16	land	100.06	20.24

Mean Depth (m)	Latitude (^oS)	Longitude (^oE)	Volume ($km^3/10^6$)
1000	-33.4	156.7	13.70

Level 1b_14

Description: A deep water mass that appears in the study region at about 1100 m depth from the north-eastern corner of the Indian Ocean. It subsequently expands with depth to fill the Indian Ocean at about 1750 m depth. At around 2000 m, it fills the Tasman Abyssal Plain basin in the Pacific and disappears in the north-west corner of the deep Pacific at about 4000 m.

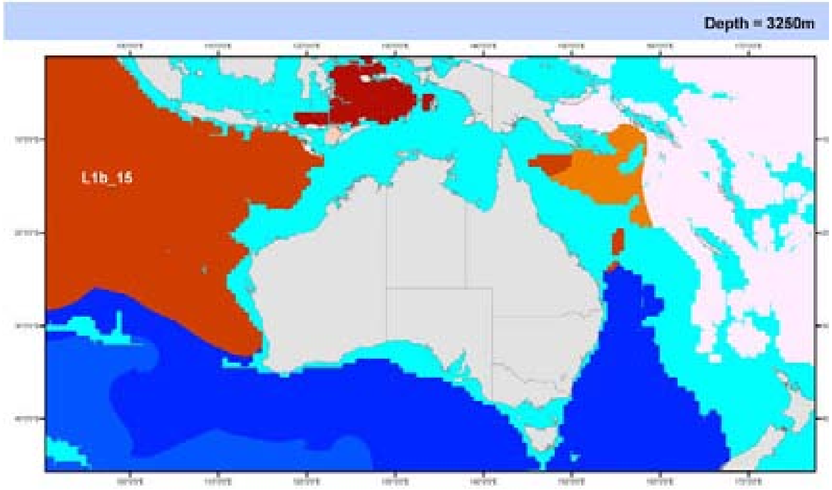


Level 1b_14	Mean	Min.	Max.	Std Dev.
Temperature (°C)	2.42	1.63	4.48	0.54
Salinity	34.72	34.67	34.85	0.03
Oxygen (mm/l)	3.65	1.96	4.45	0.63
Nitrate (mg/l)	34.03	25.34	41.21	2.05
Silicate (mg/l)	94.72	68.47	141.21	13.49

Mean Depth (m)	Latitude (°S)	Longitude (°E)	Volume ($km^3/10^6$)
2000	-31	112	9.08

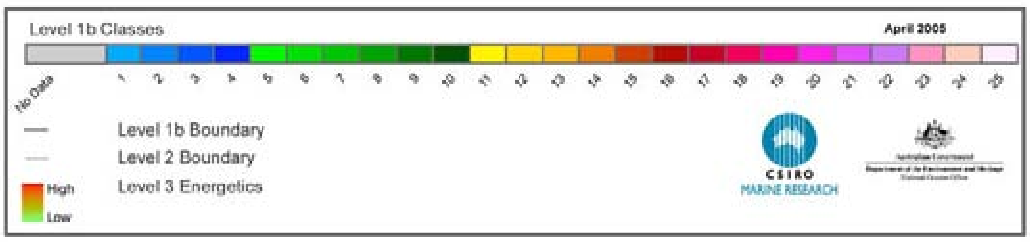
Level 1b_15

Description: A large body of deep water in the West Australian Basin. It appears in the central band of this basin at about 2000 m depth and extends no deeper than about 2250 m, at which depth it also intrudes into the northern portion of the South Australian Basin. With depth, it contracts to the north and is confined to the extreme north-east corner of the West Australian Basin at 5500 m, the deepest depth of the study area.

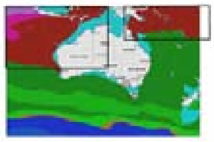


Level 1b_15	Mean	Min.	Max.	Std Dev.
Temperature (^{o}C)	1.60	1.09	2.34	0.32
Salinity	34.72	34.68	34.76	0.01
Oxygen (mm/l)	3.99	3.22	4.46	0.26
Nitrate (mg/l)	34.00	24.28	39.56	1.51
Silicate (mg/l)	117.75	71.99	147.96	13.09

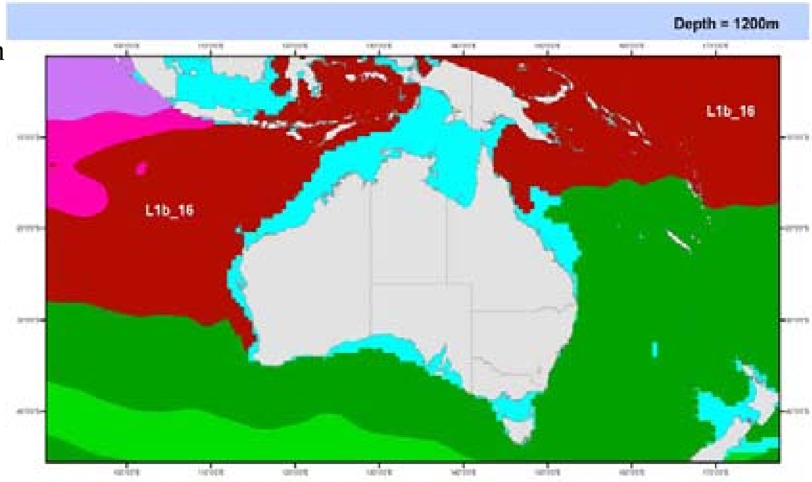
Mean Depth (m)	Latitude (^{o}S)	Longitude (^{o}E)	Volume (km^3/10^6)
3250	-15.5	105.7	18.76



Level 1b_16

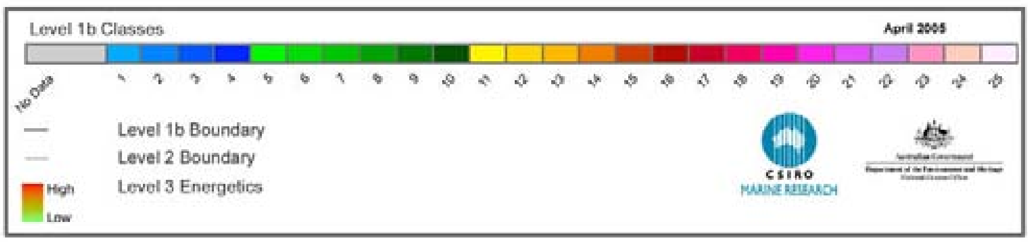


Description: A northern, deep, water mass that appears in the North Pacific and central part of the West Australian Basin at about 600 m. At greater depths, its Pacific distribution expands south. At 850 m this water occupies the eastern portion of the West Australian Basin. At about 1200 m depth, it fills the West Australian Basin except for the far north-western portion, from which it is separated by a strong front. At a depth of 1500 m the water mass is sparsely distributed in the Pacific. A remnant pool remains at the deepest depths in the South Banda Basin between the north-west Australian landmass and Sulawesi.



Level 1b_16	Mean	Min.	Max.	Std Dev.
Temperature (°C)	2.42	1.63	4.48	0.54
Salinity	34.72	34.67	34.85	0.03
Oxygen (mm/l)	3.65	1.96	4.45	0.63
Nitrate (mg/l)	34.03	25.34	41.21	2.05
Silicate (mg/l)	94.72	68.47	141.21	13.49

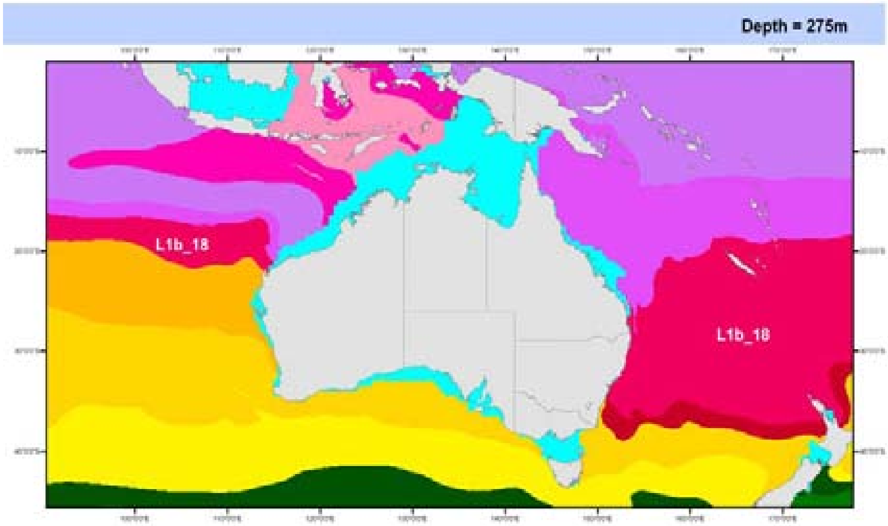
Mean Depth (m)	Latitude (°S)	Longitude (°E)	Volume ($km^3/10^6$)
1200	-8.9	145.1	14.54



Level 1b_18

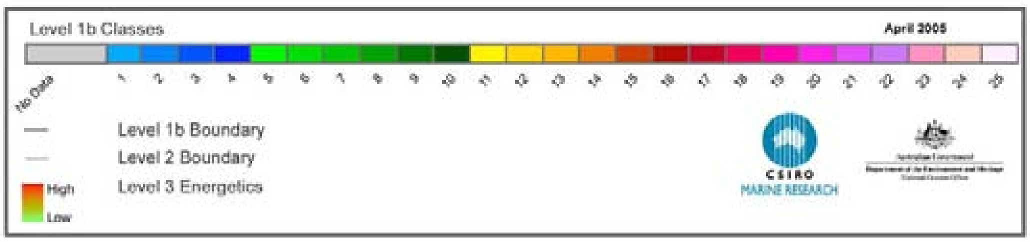
Description: This is an upper-layer frontal water mass that extends westward from the North West Cape of Western Australia into the Indian Ocean. It is first detectable at about 70 m depth, but extends to a maximum depth of about 450 m.

A water layer with similar properties occurs as an extensive band in the southern portion of the Pacific Ocean.

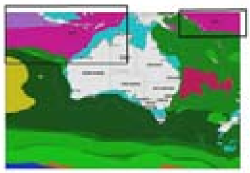


Level 1b_18	Mean	Min.	Max.	Std Dev.
Temperature (^{o}C)	3.94	2.43	6.75	0.90
Salinity	34.59	34.47	34.68	0.04
Oxygen (mm/l)	2.71	1.90	3.75	0.45
Nitrate (mg/l)	36.53	25.13	46.11	2.45
Silicate (mg/l)	91.33	37.66	148.00	21.03

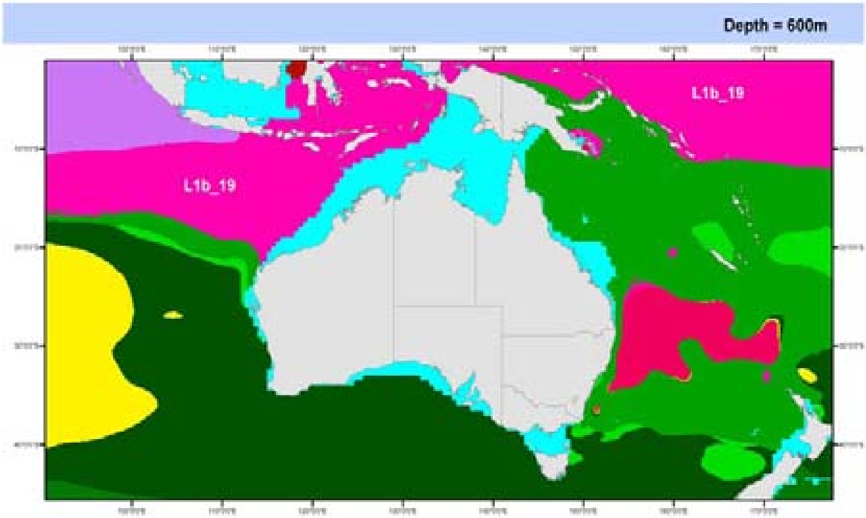
Mean Depth (m)	Latitude (^{o}S)	Longitude (^{o}E)	Volume (km^{3}/10^{6})
275	-23.9	163	2.66



Level 1b_19

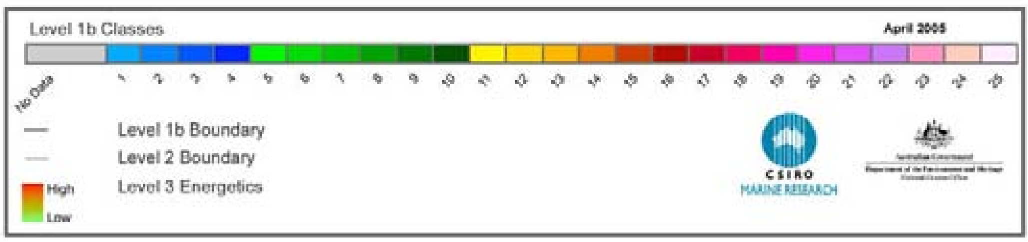


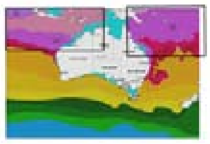
Description: An intermediate-sized water body that is associated with the Indo-Pacific Throughflow. It appears at about 125m depth in the northern Indian Ocean as a front extending out from the north-west of Western Australia. A northern front is seen off western Papua New Guinea at about 450 m depth. It is at its maximum extent between about 450 and 600 m and disappears at about 1200 m, at which depth it is part of the intermediate-depth front in the north-west portion of the West Australian Basin.



Level 1b_19	Mean	Min.	Max.	Std Dev.
Temperature (^{o}C)	7.42	3.51	19.08	2.00
Salinity	34.61	34.46	34.74	0.06
Oxygen (mm/l)	2.49	1.52	4.38	0.53
Nitrate (mg/l)	31.79	8.95	40.90	4.26
Silicate (mg/l)	52.45	7.98	116.91	20.04

Mean Depth (m)	Latitude (^{o}S)	Longitude (^{o}E)	Volume (km^3/10^6)
600	-8.9	122.9	5.44

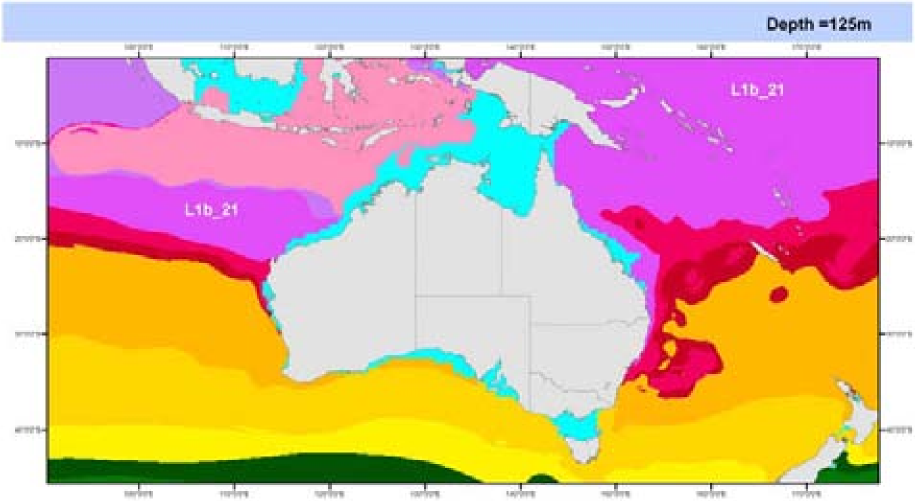




Level 1b_21

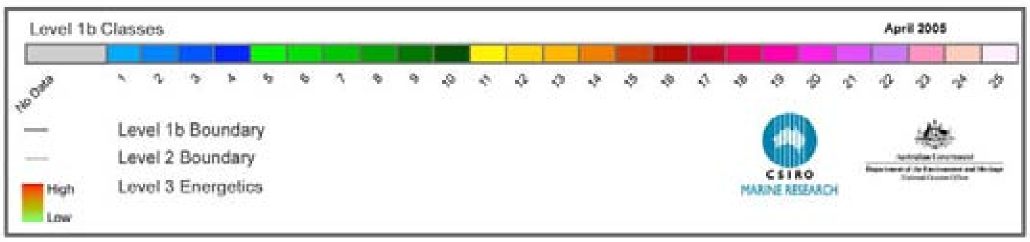
Description: The interface between the jet-like flow of Indonesian Throughflow Water and the eastward penetration of the South Indian Central Water produces a massive frontal region between 10 and 15^{o}S (water masses 1b_22, 1b_21 and 1b_18).

An extensive band with similar water properties occurs in the northern Pacific off north-eastern Australia and Papua New Guinea, with a narrow southern intrusion down the coast to New South Wales.



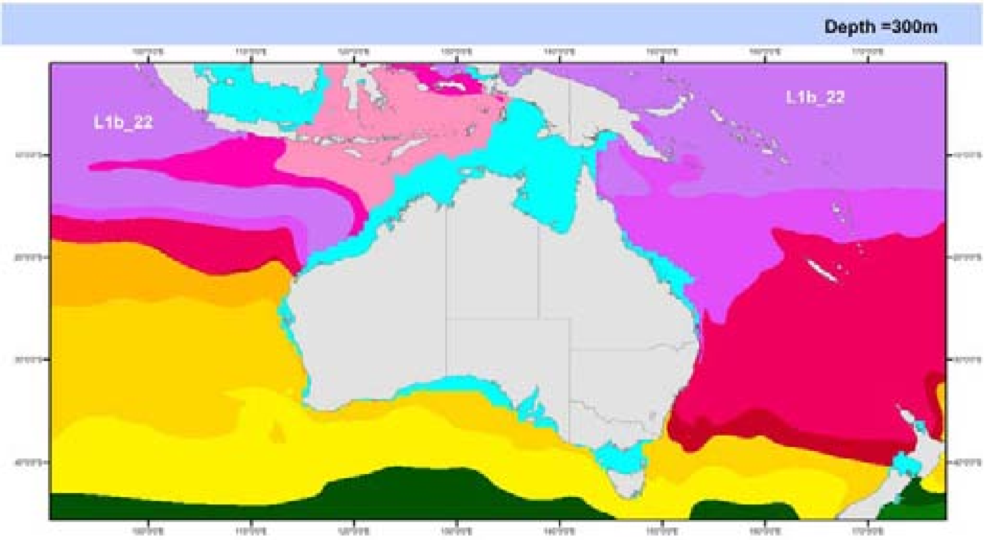
Level 1b_21	Mean	Min.	Max.	Std Dev.
Temperature (^{o}C)	22.89	12.26	29.07	3.96
Salinity	35.43	34.71	36.11	0.27
Oxygen (mm/l)	3.83	2.95	4.39	0.29
Nitrate (mg/l)	5.46	0.01	21.84	3.00
Silicate (mg/l)	3.68	0.76	20.25	2.73

Mean Depth (m)	Latitude (^{o}S)	Longitude (^{o}E)	Volume (km^{3}/10^{6})
125	-11.6	156.3	1.71



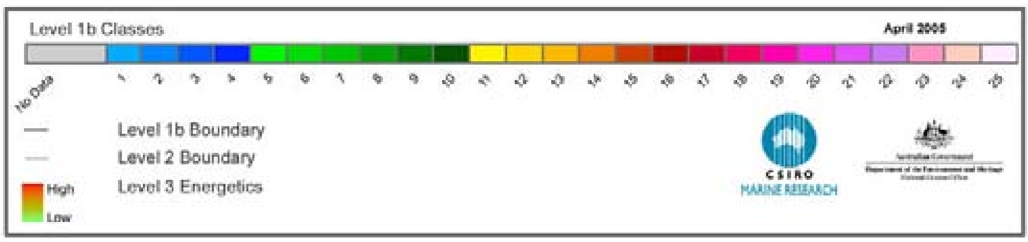
Level 1b_22

Description: This layer is, like Level 1b_21, part of the interface between the jet-like flow of Indonesian Throughflow Water and the eastward penetration of the South Indian Central Water. It also has a companion band of similar water properties in the northern Pacific off Papua New Guinea.



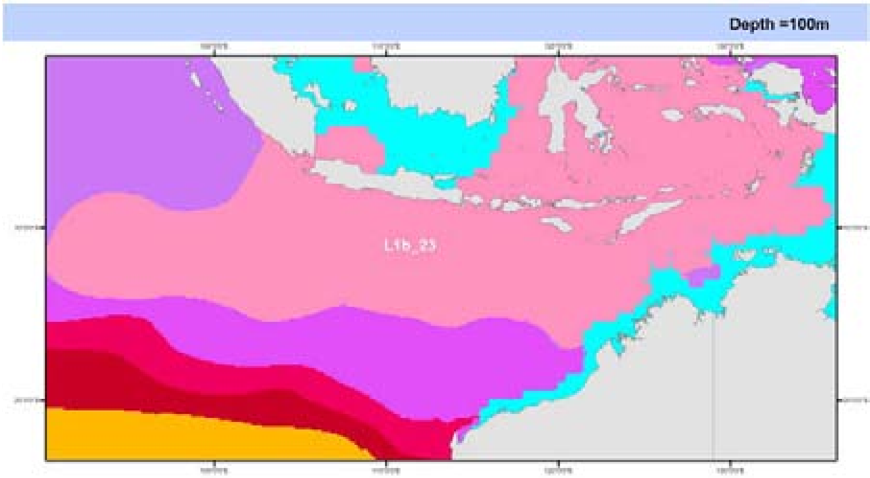
Level 1b_22	Mean	Min.	Max.	Std Dev.
Temperature (°C)	12.93	4.30	28.29	4.62
Salinity	34.96	34.69	35.84	0.22
Oxygen (mm/l)	2.53	1.23	4.38	0.78
Nitrate (mg/l)	22.69	0.54	40.25	8.97
Silicate (mg/l)	26.44	1.94	105.42	21.09

Mean Depth (m)	Latitude (°S)	Longitude (°E)	Volume ($km^3/10^6$)
300	-6.3	106.8	3.70



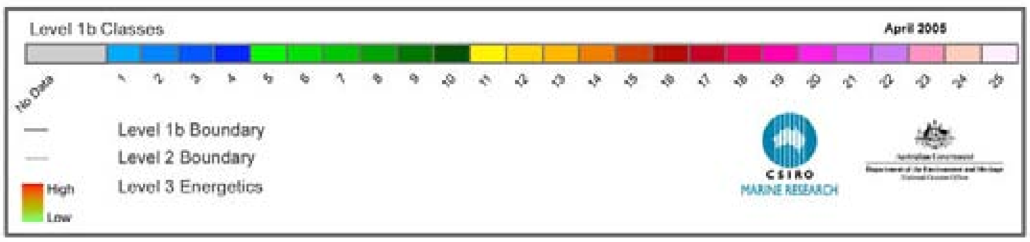
Level 1b_23

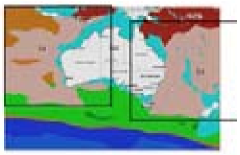
Description: This upper-surface layer starts in the northern portion of the Indo-Pacific region. By about 80 m depth it is distributed as a tongue of water penetrating westward into the Indian Ocean to a southern limit of about 20°S. It is distributed largely to the west of Papua New Guinea and descends to a depth of about 350 m.



Level 1b_23	Mean	Min.	Max.	Std Dev.
Temperature (°C)	20.99	9.22	28.84	4.94
Salinity	34.50	32.85	34.73	0.15
Oxygen (mm/l)	3.21	2.04	4.32	0.55
Nitrate (mg/l)	10.96	0.28	32.18	7.60
Silicate (mg/l)	15.00	1.54	49.80	10.17

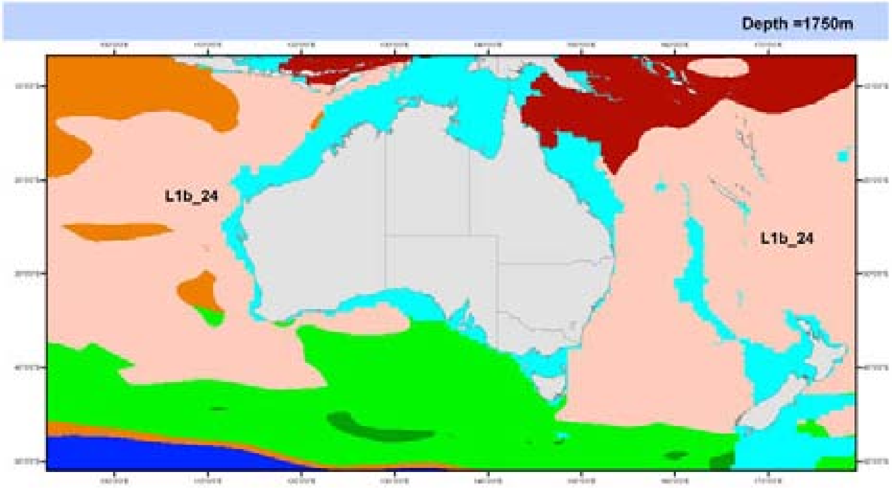
Mean Depth (m)	Latitude (°S)	Longitude (°E)	Volume ($km^3/10^6$)
100	-8.5	119.5	0.91





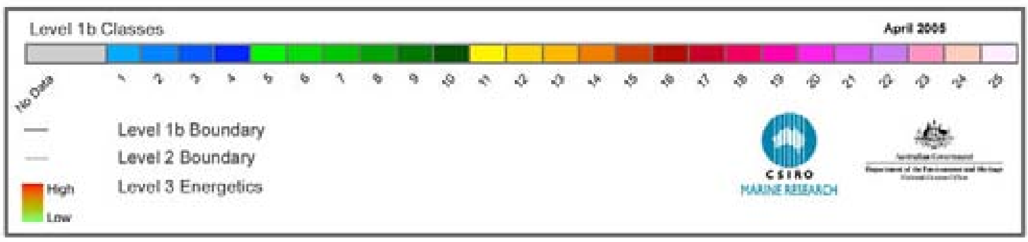
Level 1b_24

Description: A deep water mass that appears at about 1300 m depth in the central Indian Ocean. With increasing depth it expands to the east. At 1500 m it encircles Australia, but bifurcates to flow into the Indian and Pacific oceans. By 1750 m depth it is confined to the Pacific Ocean and disappears to the north. Its maximum depth is about 2250 m.

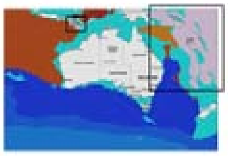


Level 1b_24	Mean	Min.	Max.	Std Dev.
Temperature (°C)	2.71	1.90	4.44	0.45
Salinity	34.64	34.56	34.72	0.03
Oxygen (mm/l)	3.30	2.05	3.98	0.40
Nitrate (mg/l)	35.99	27.46	42.37	1.86
Silicate (mg/l)	102.63	61.57	149.93	16.86

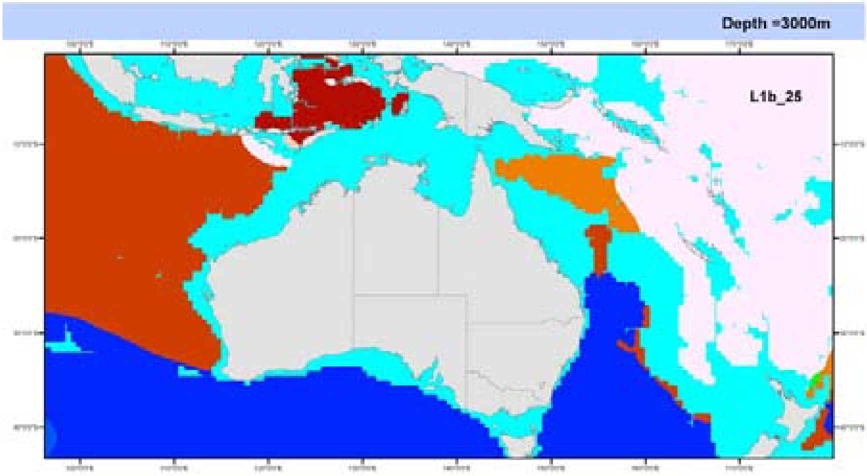
Mean Depth (m)	Latitude (°S)	Longitude (°E)	Volume ($km^3/10^6$)
1750	-22.2	154.7	11.06



Level 1b_25



Description: A deep water mass largely confined to the north-east Pacific. At its shallower depth of about 2000 m it is found in the Coral Sea Basin and the Lord Howe Trough (located to the east of the Lord Howe Rise). At about 2750 m depth, it is no longer found in the Coral Sea Basin but is restricted to the other deep basins in the north-east Pacific. It is sporadically distributed throughout that region at deeper depths.



Level 1b_25	Mean	Min.	Max.	Std Dev.
Temperature (^oC)	1.81	1.15	2.21	0.18
Salinity	34.68	34.65	34.72	0.01
Oxygen (mm/l)	3.49	2.31	4.15	0.23
Nitrate (mg/l)	36.02	27.41	42.42	1.71
Silicate (mg/l)	126.53	82.55	152.92	11.47

Mean Depth (m)	Latitude (^oS)	Longitude (^oE)	Volume ($km^3/10^6$)
3000	-13.1	167.9	14.74

6 Summary table of levels

A summary of the pelagic regionalisation in terms of the levels, the classes in each level, the datasets and analyses is presented in Table 6-1.

Table 6-1 Summary table of the results of the pelagic regionalisation.

Level	Name	Classes	Dataset	Analysis	Comment
0	Oceans	Three: Indian Ocean, Pacific Ocean, Southern Ocean.	Literature.	Preliminary: based on literature.	Transition boundaries unidentified.
1a	Oceanic zones	Three zonal regions nested within Oceans; potentially five classes overall if the two northern-most classes are split between the Indian and Pacific oceans.	CARS: temperature, salinity at the base of the mixed-layer.	Preliminary: cluster analysis using properties at base of mixed-layer.	Analyses need to be revised using updated analysis methodology.
1b	Oceanic Substructure – Water Masses	Twenty-five classes over all depths; not split across oceans. Nine classes at the surface; potentially 12 if classes are split across the oceans.	CARS: temperature, salinity and oxygen.	Updated analysis.	3-D *clara* analysis.
2	Seas: Circulation Regimes	Twenty-nine classes in the surface layer, not split across oceans.	CARS: surface currents, subsurface geostrophic currents. MODIS primary productivity. Sea surface height.	Updated: Surface layer only. Classes nested within Level 1b classes.	Small scale classes around islands and coasts; analysis needs to be refined to remove these.
3	Fields of Features	Three classes of homogeneity/heterogen-eity combined to produce continuous energetics layer.	Satellite sea-surface temperature archive.	Updated: Surface layer only. Variance analysis of individual images combined into monthly and then yearly summaries.	Energetics used as qualifier for Level 2.
4a	Features			Descriptive.	At this level and below, the classes are dynamic (as for example a moving eddy).
4b	Feature Structure			Descriptive.	As above.

7 Conclusions

The key conclusions of this project are summarised below:

1. Substantial progress has been made in classifying the pelagic environment through an integrated analysis for the whole water column. A hierarchically nested classification appears possible from the scale of oceans (Level 0) down to at least Level 2 (Circulation Regimes). However, the complications due to seasonal and longer timescale variability are yet to be examined in a systematic way.

2. Biological information is required to guide and inform the analyses; this is currently the main major shortcoming of the regionalisation.

3. This is one of the most comprehensive studies undertaken for a pelagic regionalisation. A valuable collection of data for future extensions of this study now exists in a well documented state (Hayes et al. 2005).

4. A workable pelagic framework has been constructed down to the scale of features (Level 4a) and substructure of features (Level 4b).

5. Beyond Level 2, energetics in the ocean system, as characterised by fields of homogeneity and heterogeneity in water masses, provide useful qualifiers for Level 2 classes. A rich variety of oceanographic processes can be identified with such an analysis, which may have implications for biological productivity and hence for marine resource management. Deciding how best to use the available information at the various Levels and what future information will help refine the analyses and descriptions will require careful consideration.

6. The complexity and richness of the pelagic regionalisation demands innovative methods of visualisation and a dedicated program of education and information dissemination for managers, researchers, stakeholders, including the general public and students.

8 Future Research

Framework: A workable framework for a national pelagic bioregionalisation now exists, but the findings of this project suggest that links with the benthic regionalisation framework may be much more intimate than previously assumed. Strong links are now apparent at Level 2 in the pelagic hierarchy. We also need to examine carefully how best to integrate the myriad data at the various levels within the framework, and how to deal with issues of temporal variability and sampling artefacts.

Biological Information: The limited biological data collated for this project qualitatively supports the classifications. A dedicated and sustained effort is required to provide a firm biological and ecological basis to guide the analyses and to assist in interpreting and making use of the results. We recommend:

1. Set up a concerted national and international collation of data and information on Myctophids and mid-water fishes using the current regionalisation framework to guide the collation and to identify gaps.

2. Develop strategies for analysing the data from (1) to identify Level 1 and 2 bioregions that can be compared to those from the current study.

3. Investigate the relationship between commercial fish catch data and the Level 2 classes and energetics.

Classification Methodology: Much of the work in this project was completed within a very tight schedule that allowed little time for developing, testing and refining the methods of analysis. As an example, the Level 2 classification includes many small-scale regions, particularly around islands and along the coast, which do not belong as separate classes at this Level. Substantial effort has been expended into other regionalisation projects for data collation and management. To use this valuable information well will require a commitment of time and resources to mine the information and knowledge inherent in the data and in the experience of researchers in the field. To materially assist managers and stakeholders, innovative techniques must be developed to make progress beyond the descriptive and qualitative stage.

Visualisation and Education: Innovative techniques are required to visualise the complexity of information and to convey the value of such information to end users. As an example, Figure 8-1 shows a visualisation of some of the classes in Level 1b in a 3-D framework, using the commercial software Amira. Such packages are now capable of dealing with large datasets and, with modern computers, are sufficiently fast to be useful in real-time interactive mode. They allow complex datasets to be visualised from various perspectives and enable operators to isolate components in 3-D form for detailed visualisation and analysis. We recommend that significant effort be put into researching and developing the potential of such tools along the lines suggested by the review in Hayes et al., 2005.

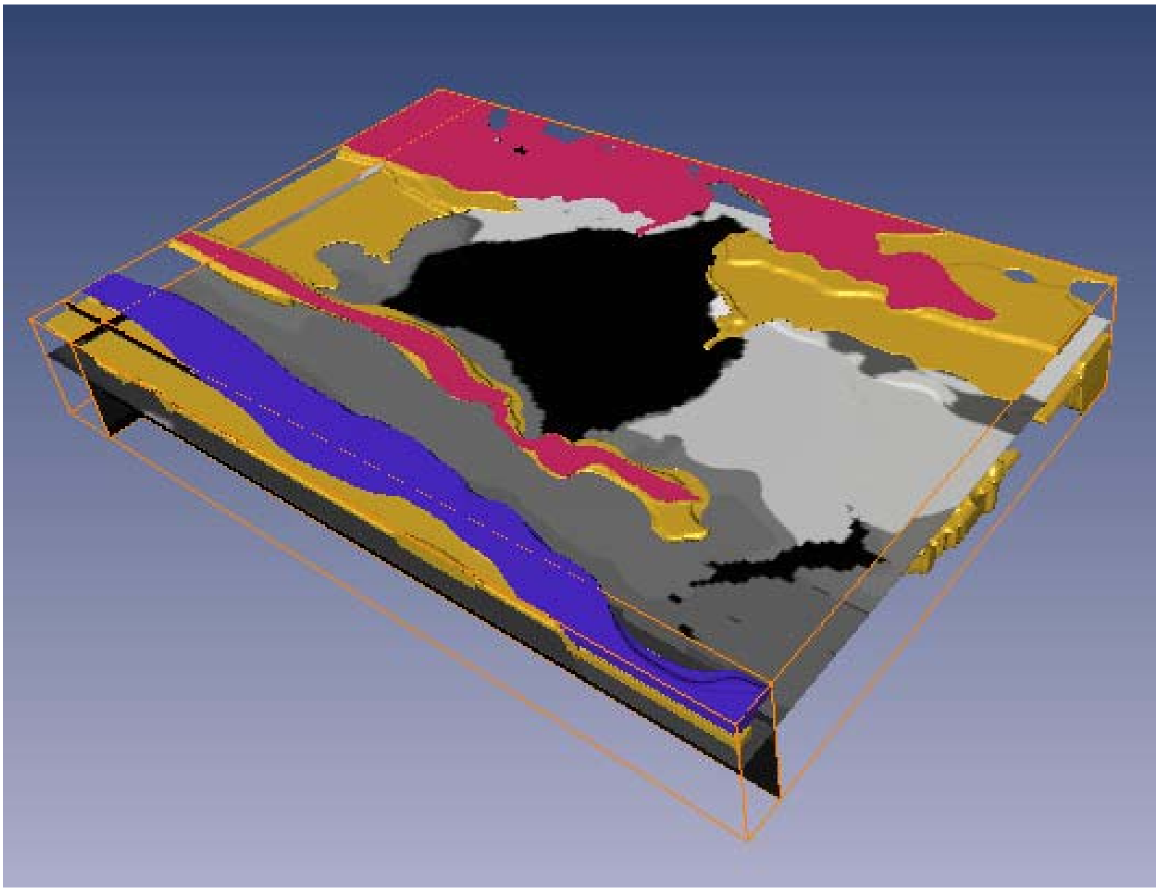


Figure 8-1 3-D visualisation of Level 1b classes, a few of which are displayed as 3-D volumes.
A commercial software package (Amira – an evaluation copy, used with kind permission from the developers) was used produce this image.

9 Acknowledgements

We thank the National Oceans Office and CSIRO Marine Research for having the vision to implement and fund this project – with particular thanks to Miranda Carver and Vicki Nelson for their management of the project. In retrospect, it was a far more ambitious endeavour than we had expected, mainly due to the shortened deadlines and demanding reporting requirements. Nonetheless, superhuman performances by project staff, notably Donna Hayes, Rick Smith and Brian Griffiths, have enabled us to achieve far more than would otherwise have been possible. Donna, in particular, despite injuries and a major operation, worked through many nights and weekends to complete an amazing amount of dedicated work to a high standard. Without her efforts this project would not have been completed; we owe her a debt of thanks. We would like to thank Dr Vivienne Mawson for her editorial comments and the developers of Amira for allowing us to use a demonstration copy of their software.

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Attached Appendices

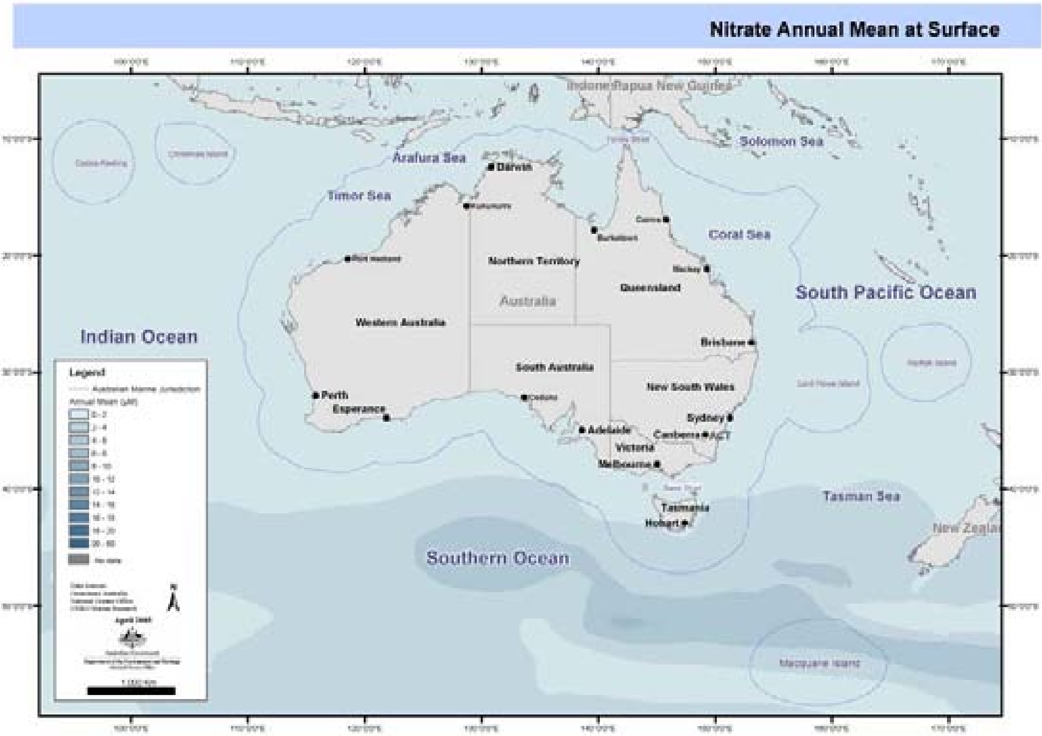
Included with this report are a set of separate appendices which are compilations of images showing various datasets and analysis results:

- Appendix A: Annual Mean Concentration of Nitrate at Different Depths
- Appendix B: Annual Mean Concentration of Oxygen at Different Depths
- Appendix C: Annual Mean Concentration of Phosphate at Different Depths
- Appendix D: Annual Mean Concentration of Salinity at Different Depths
- Appendix E: Annual Mean Concentration of Silicate at Different Depths
- Appendix F: Annual Mean Temperature at Different Depths
- Appendix G: Input Data Sets: Sea-Surface Dynamic Height, Sea-Surface Height Variability, Surface Currents
- Appendix H: Eddies and Fields Derived from Sea-Surface Temperature
- Appendix I: Pelagic Regionalisation at Level 1b for 56 Depths
- Appendix J Tables of Level 1b Class Statistics
- Appendix K Chlorophyll and Primary Production Patterns

Appendix A

Annual Mean Concentration of Nitrate at Difference Depths

a



b

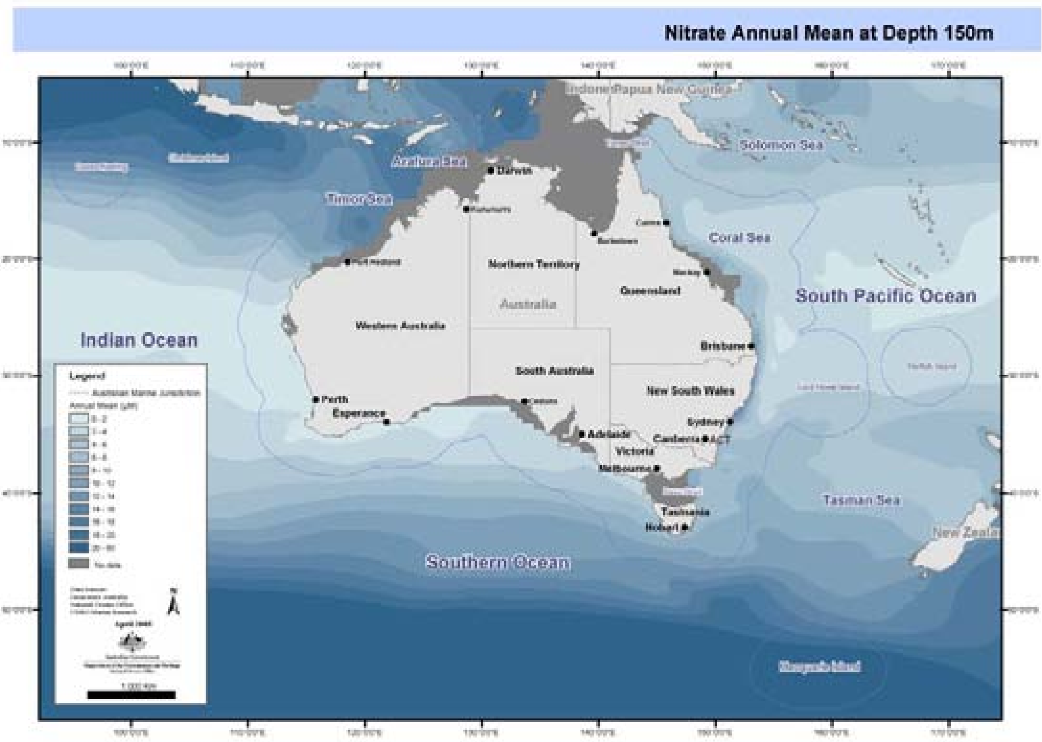
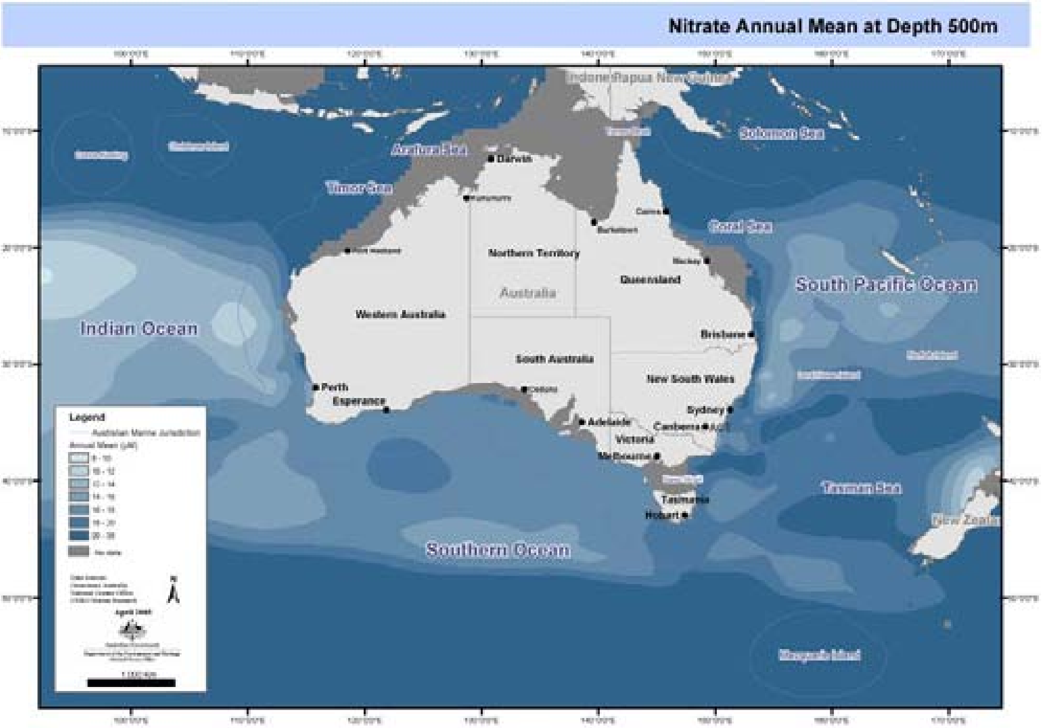


Figure A.1 Nitrate Annual Mean (years 1970-2000) at a) the surface, b) 150m, c) 500m, d) 1000m and e) 2000m. Derived from the CSIRO Atlas of Regional Seas (CARS) . For more information see Hayes

et al. (2005).

c



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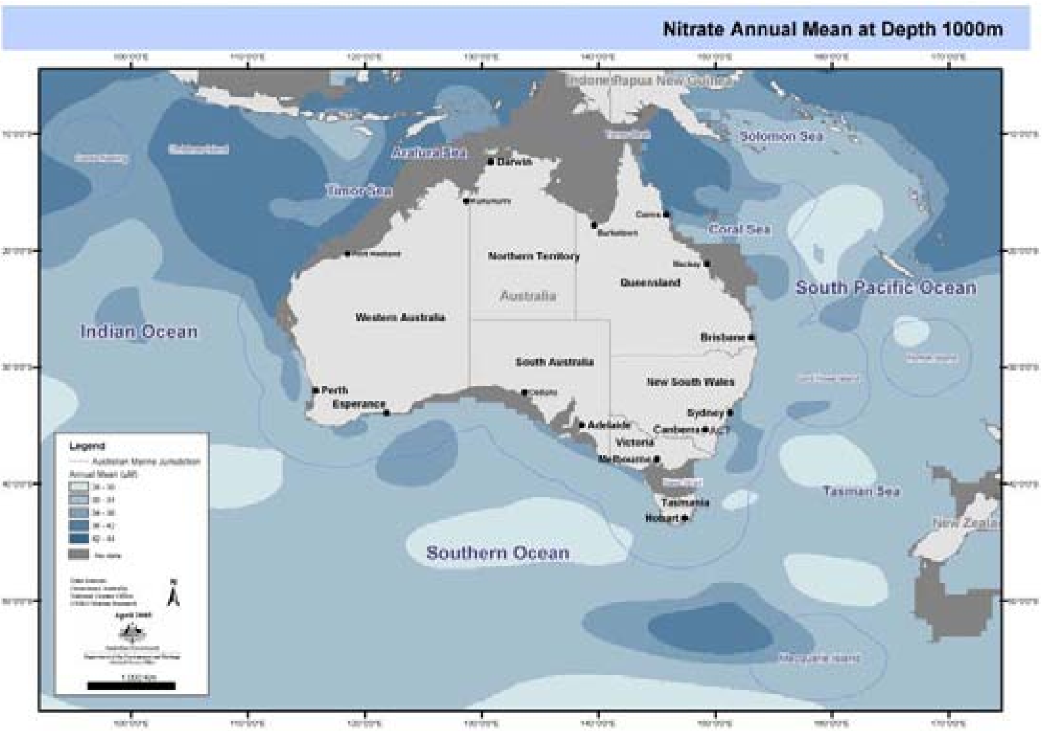


Figure A.1 (cont) Nitrate Annual Mean (years 1970-2000) at a) the surface, b) 150m, c) 500m, d) 1000m and e) 2000m. Derived from the CSIRO Atlas of Regional Seas (CARS) . For more information see Hayes et al. (2005).

e

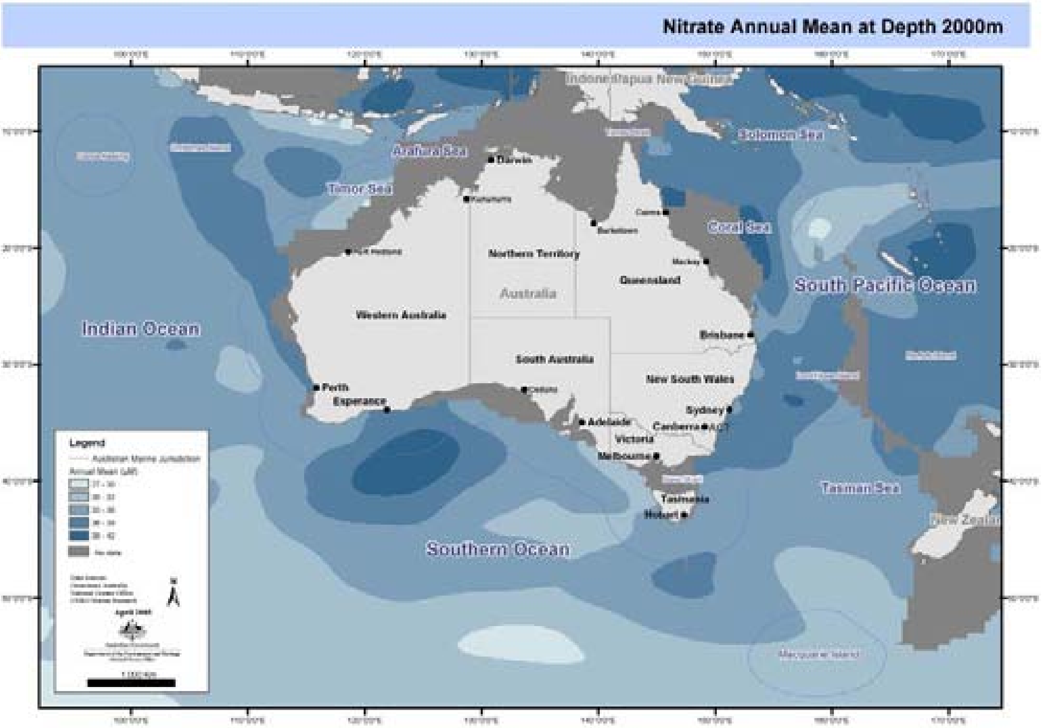
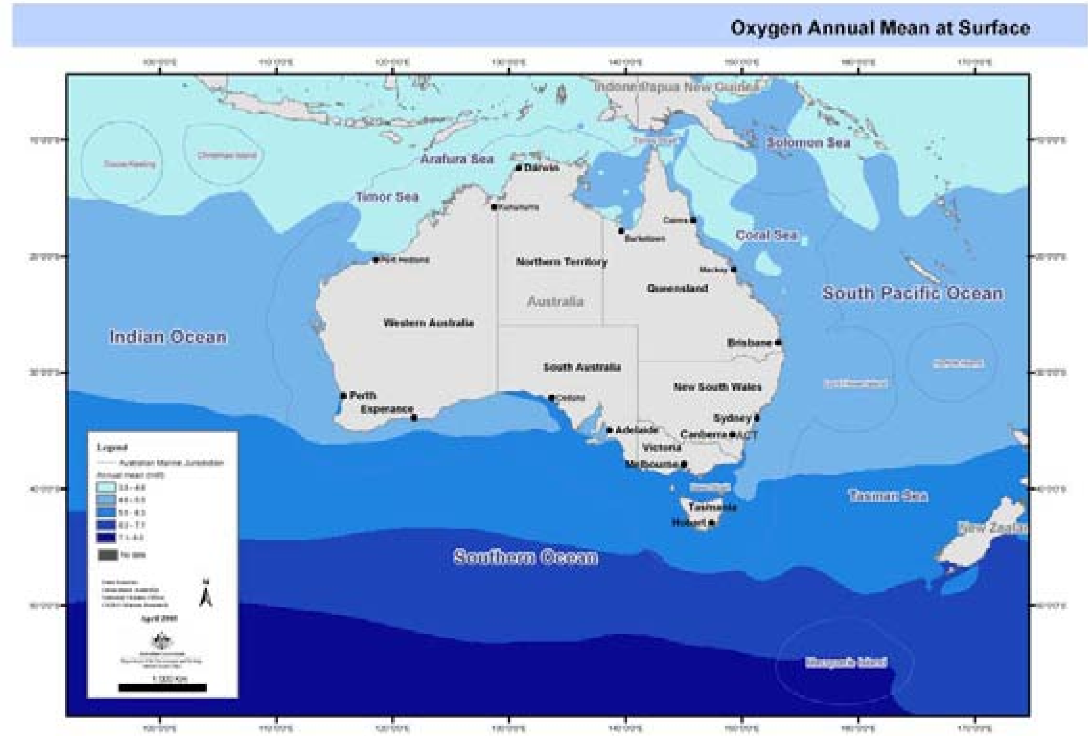


Figure A.1 (cont) Nitrate Annual Mean (years 1970-2000) at a) the surface, b) 150m, c) 500m, d) 1000m and e) 2000m. Derived from the CSIRO Atlas of Regional Seas (CARS) . For more information see Hayes et al. (2005).

Appendix B

Annual Mean Concentration of Oxygen at different Depths

a



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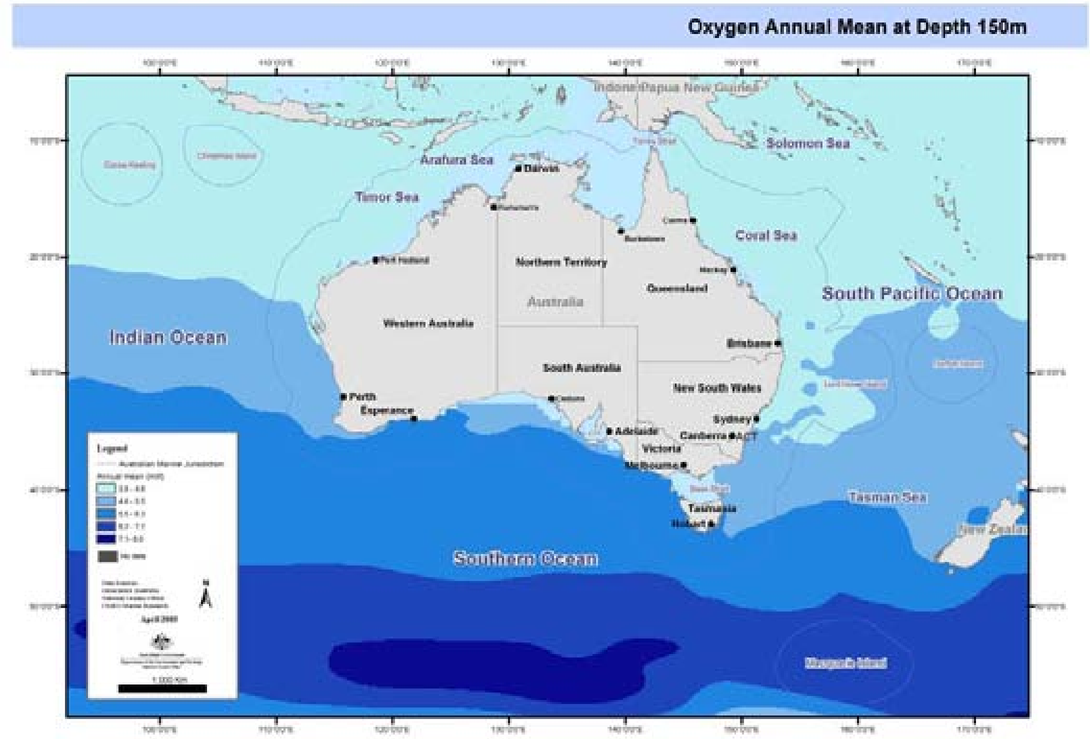
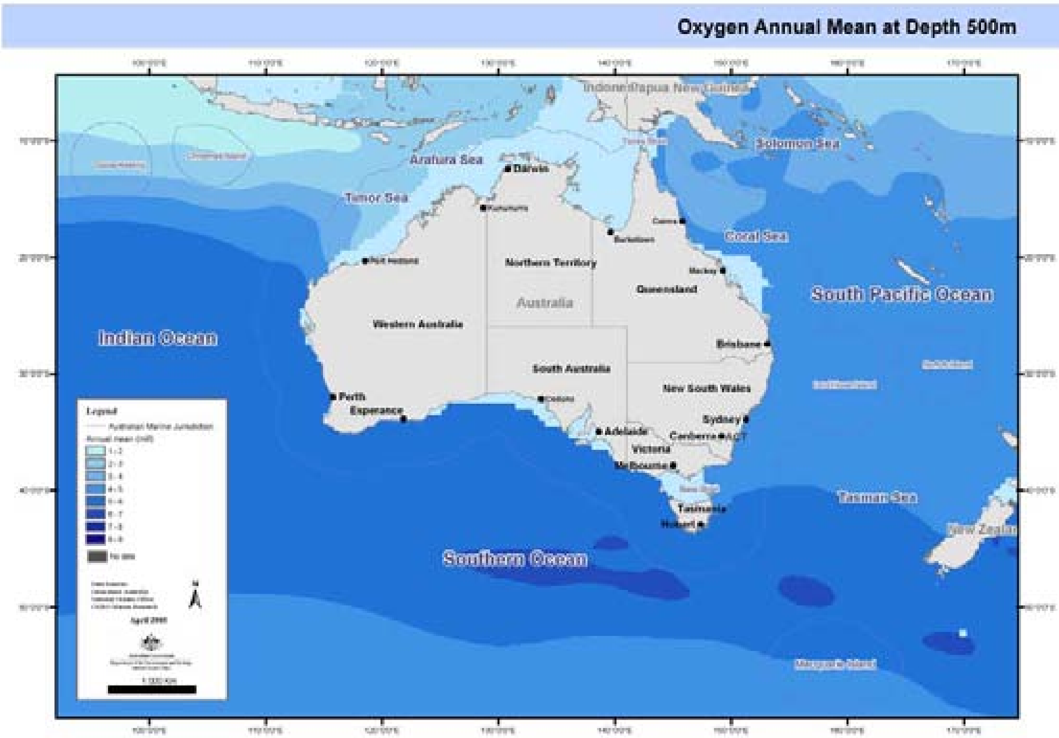


Figure B.1 Oxygen Annual Mean (years 1970-2000) at (a) the surface, (b) 150m, (c) 500m, (d) 1000m and e) 2000m. Derived from the CSIRO Atlas of Regional Seas (CARS) . For more

information see Hayes et al. (2005).

c



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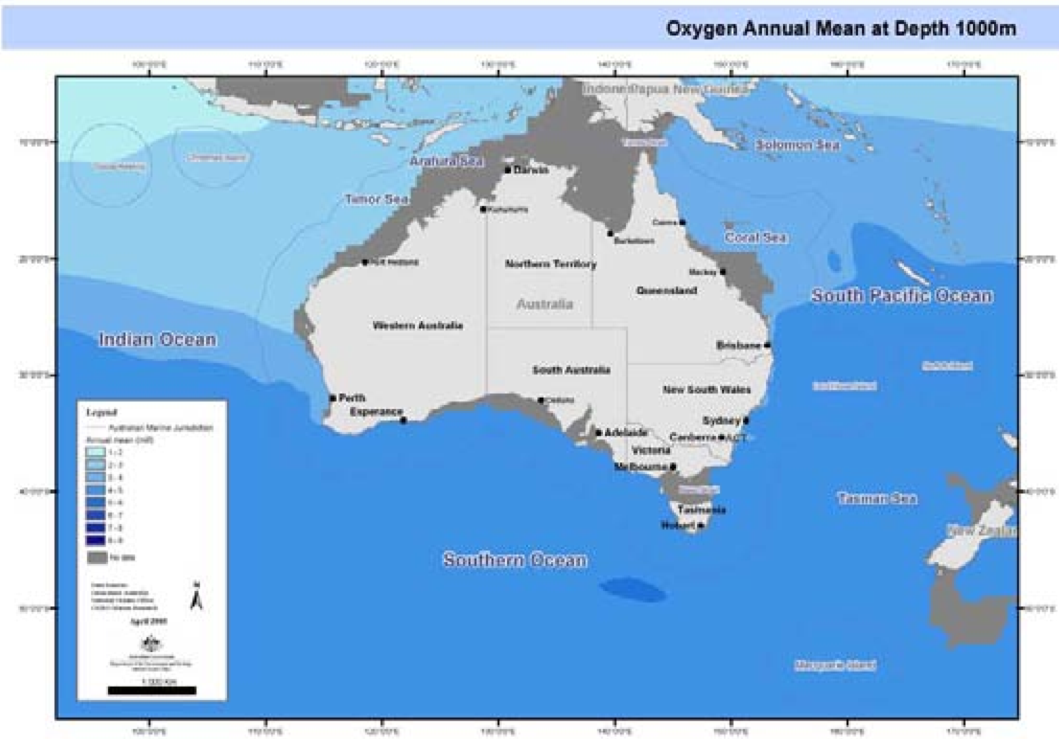


Figure B.1 (cont.) Oxygen Annual Mean (years 1970-2000) at (a) the surface, (b) 150m, (c) 500m, (d) 1000m and (e) 2000m. Derived from the CSIRO Atlas of Regional Seas (CARS) . For more information see Hayes et al. (2005).

e

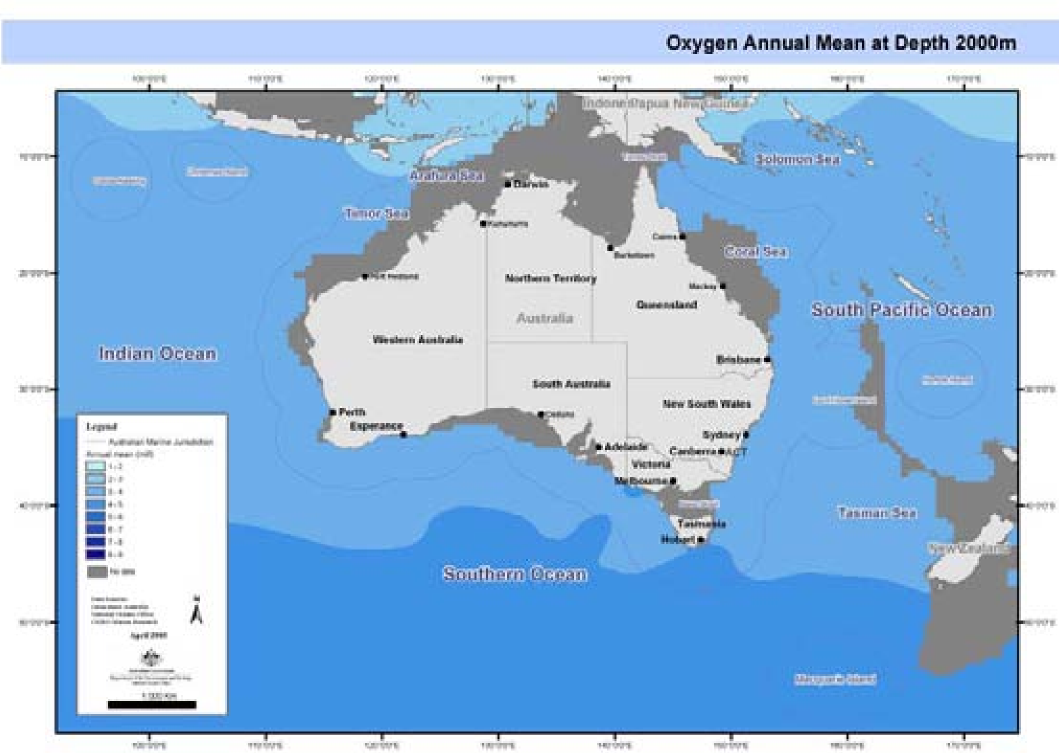
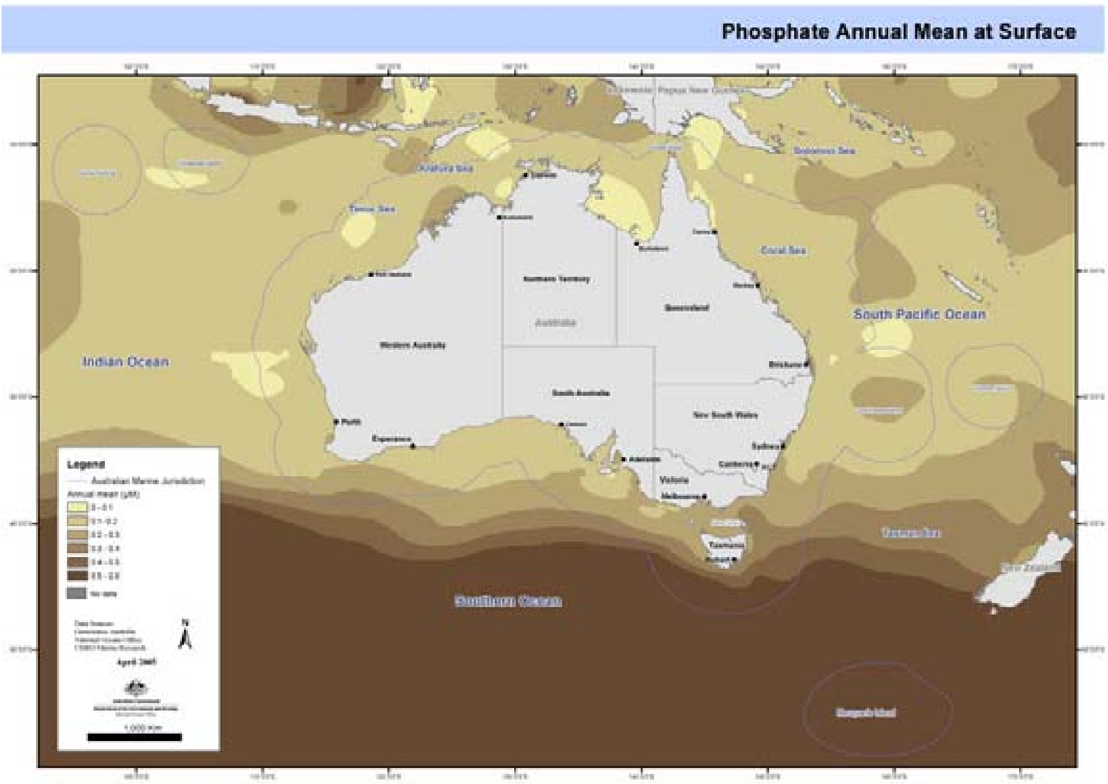


Figure B.1 (cont.) Oxygen Annual Mean (years 1970-2000) at (a) the surface, (b) 150m, (c) 500m, (d) 1000m and (e) 2000m. Derived from the CSIRO Atlas of Regional Seas (CARS) . For more information see Hayes et al. (2005).

Appendix C

Annual Mean Concentration of Phosphate at different Depths

a



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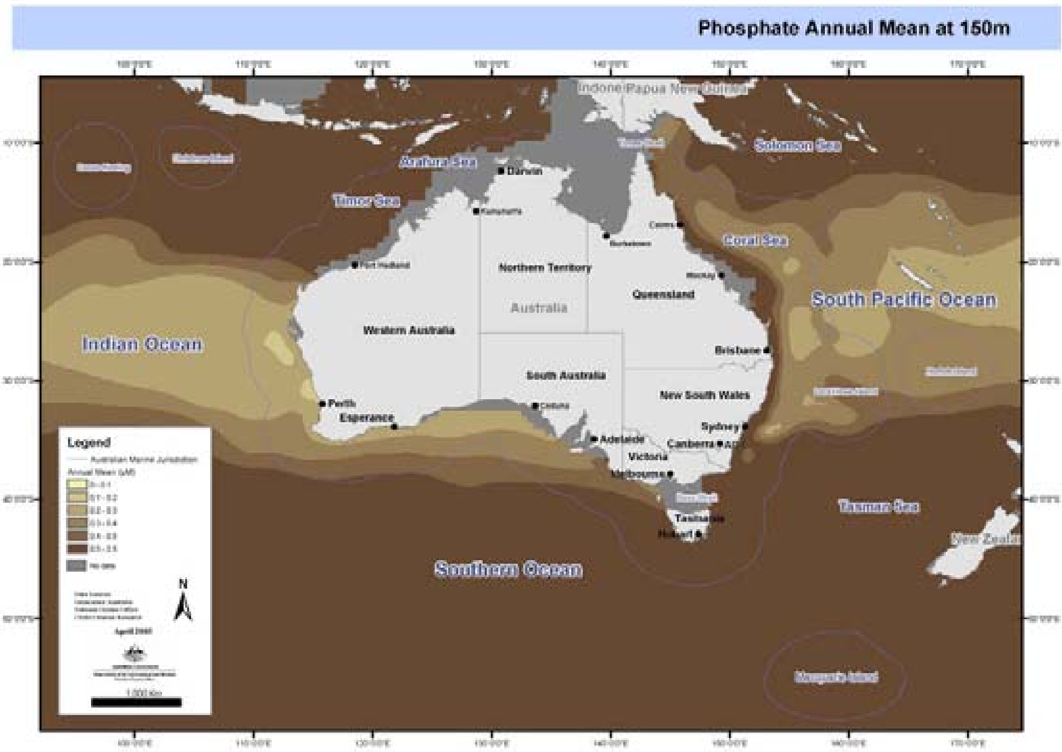
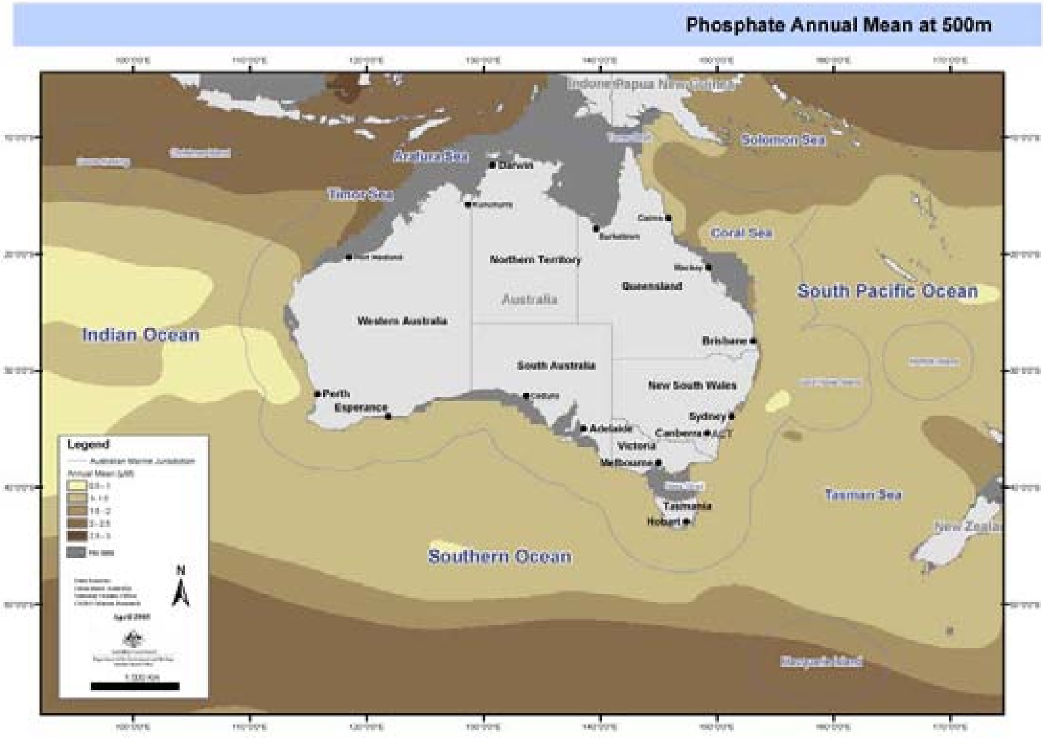


FigureC.1 Phosphate Annual Mean (years 1970-2000) at (a) the surface, (b) 150m, (c) 500m, (d) 1000m and (e) 2000m. Derived from the CSIRO Atlas of Regional Seas (CARS). For more

information see Hayes et al. (2005).

c



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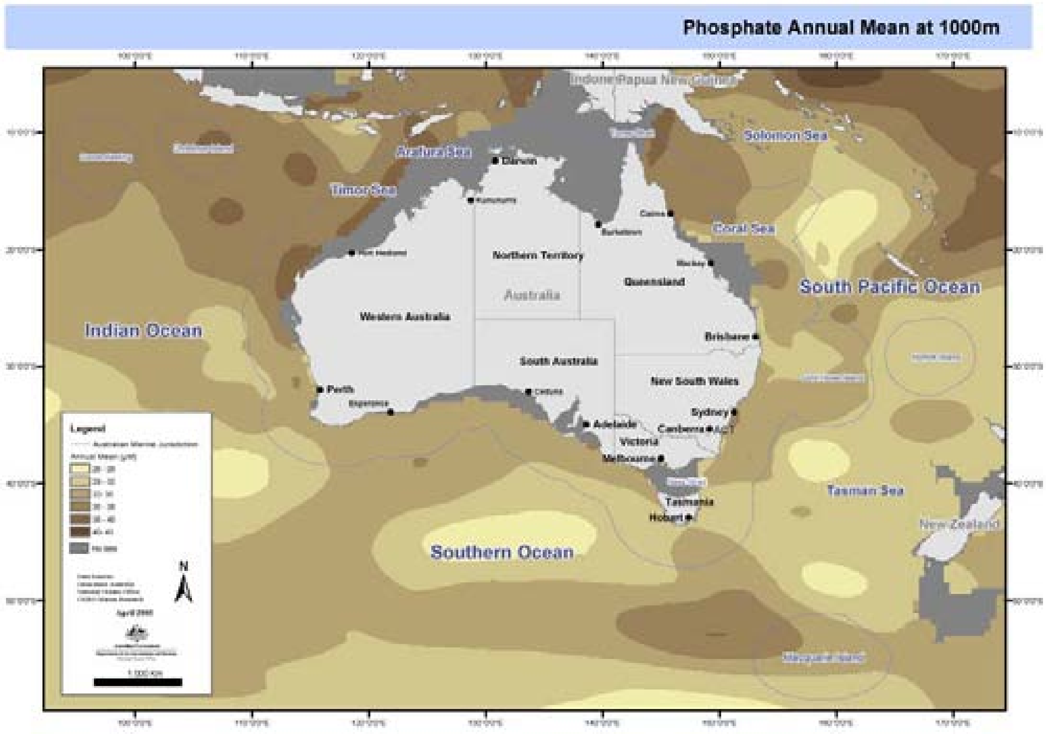

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e

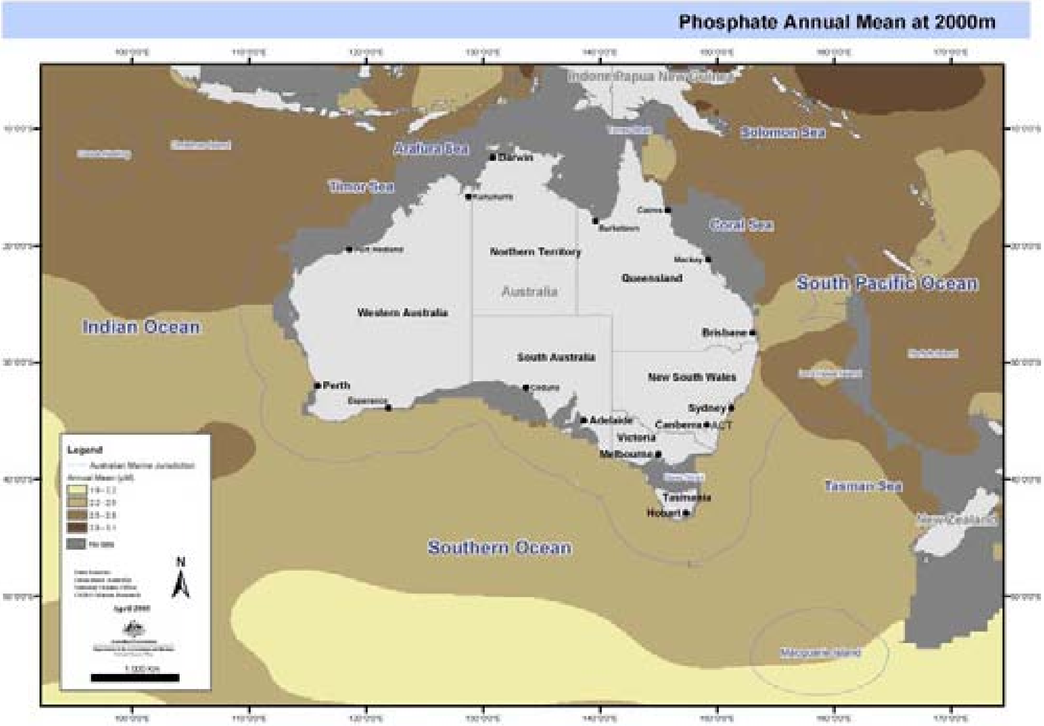
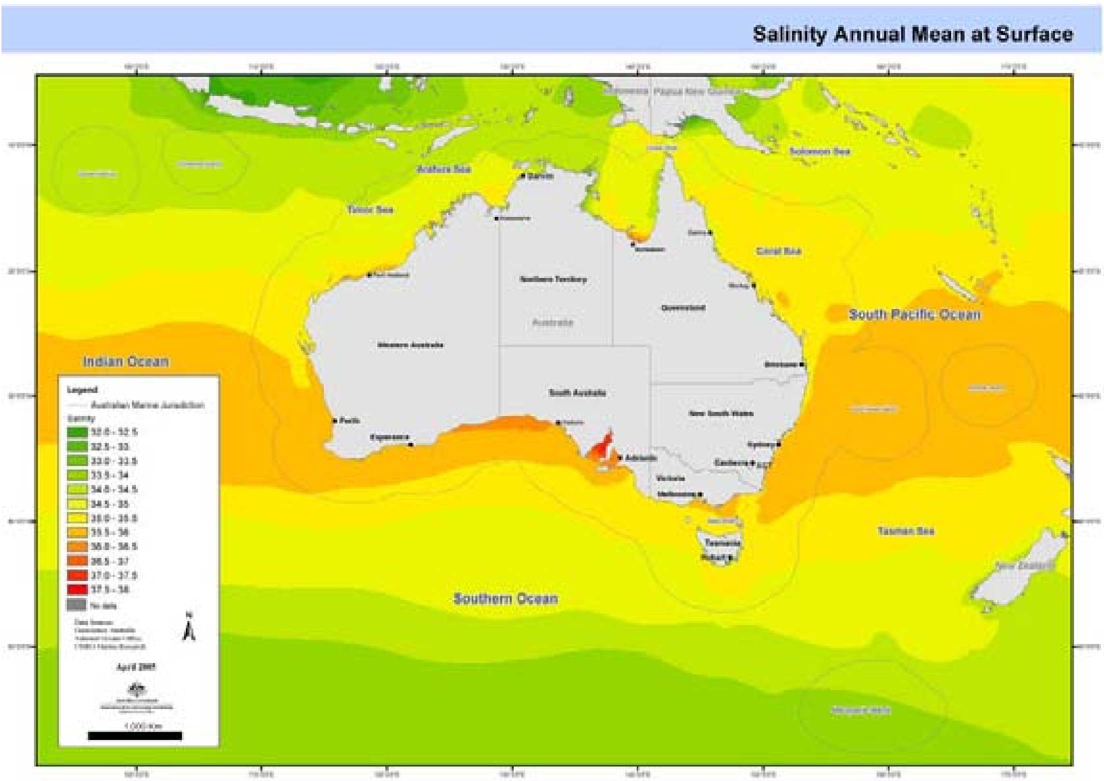


Figure C.1 (Cont.) FigureC.1 Phosphate Annual Mean (years 1970-2000) at (a) the surface, (b) 150m, (c) 500m, (d) 1000m and (e) 2000m. Derived from the CSIRO Atlas of Regional Seas (CARS). For more information see Hayes et al. (2005).

Appendix D

Annual Mean Concentration of Salinity at different Depths

a



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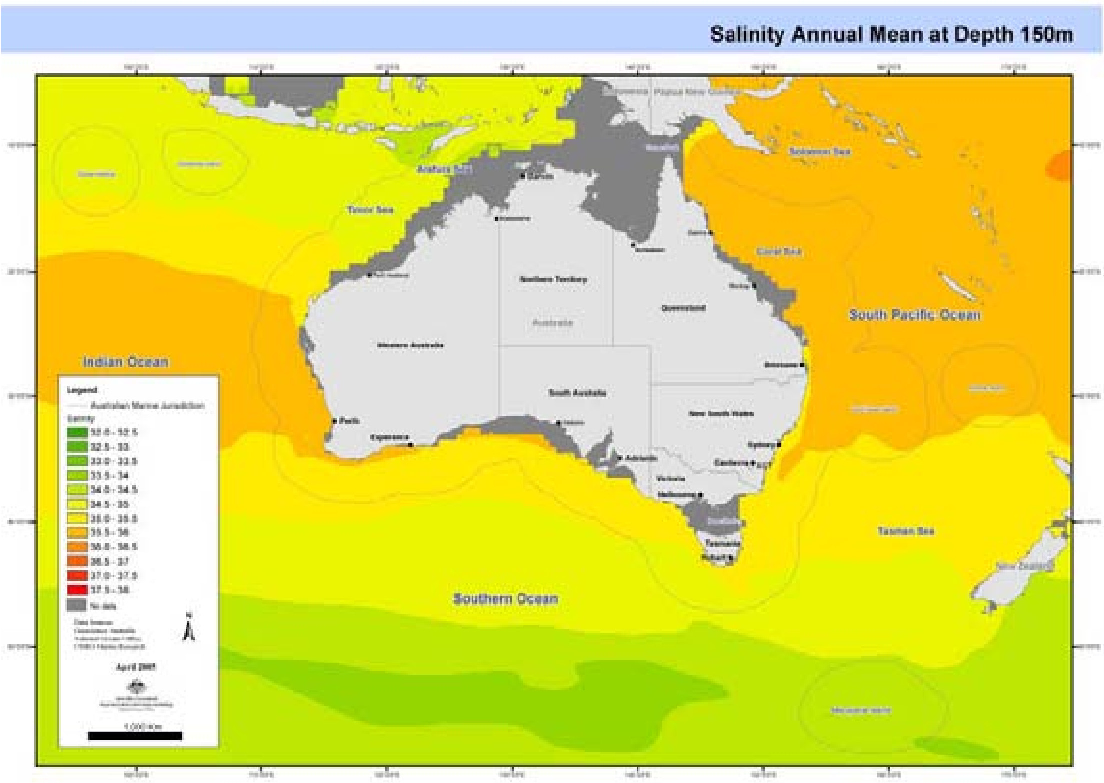
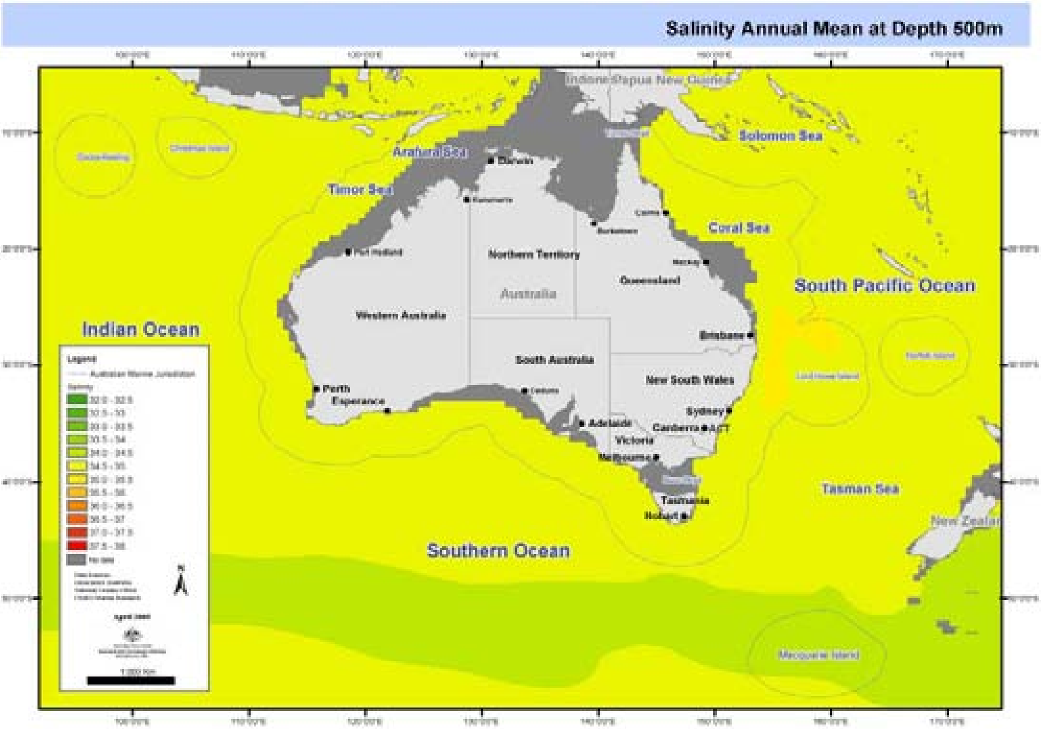


Figure D.1 Salinity Annual Mean (years 1970-2000) at (a) the surface, (b) 150m, (c) 500m, (d) 1000m

and (e) 2000m. Derived from the CSIRO Atlas of Regional Seas (CARS). For more information see Hayes et al. (2005).

c



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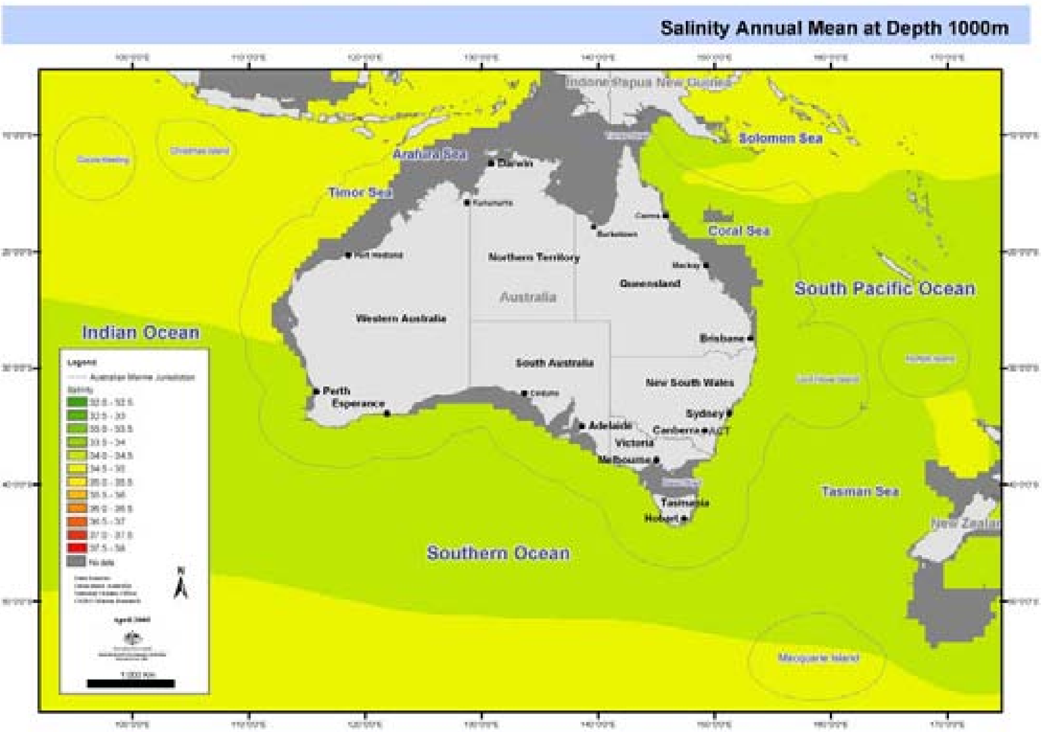


Figure D.1 (Cont.) Figure D.1 Salinity Annual Mean (years 1970-2000) at (a) the surface, (b) 150m, (c) 500m, (d) 1000m and e) 2000m. Derived from the CSIRO Atlas of Regional Seas (CARS). For more information see Hayes et al. (2005)

e

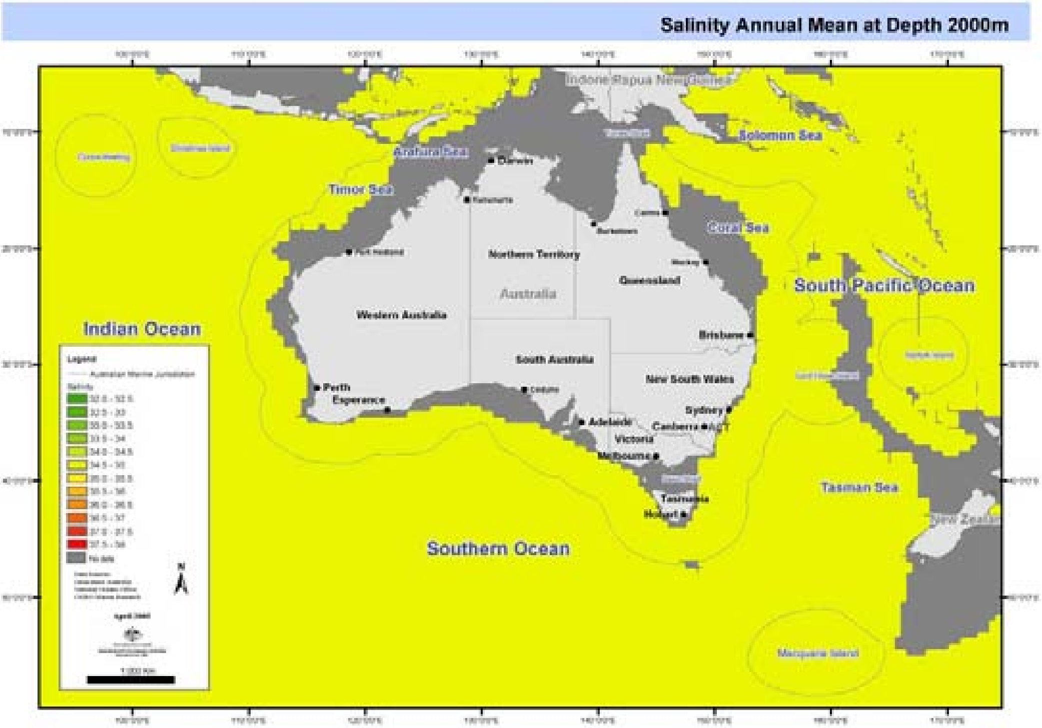
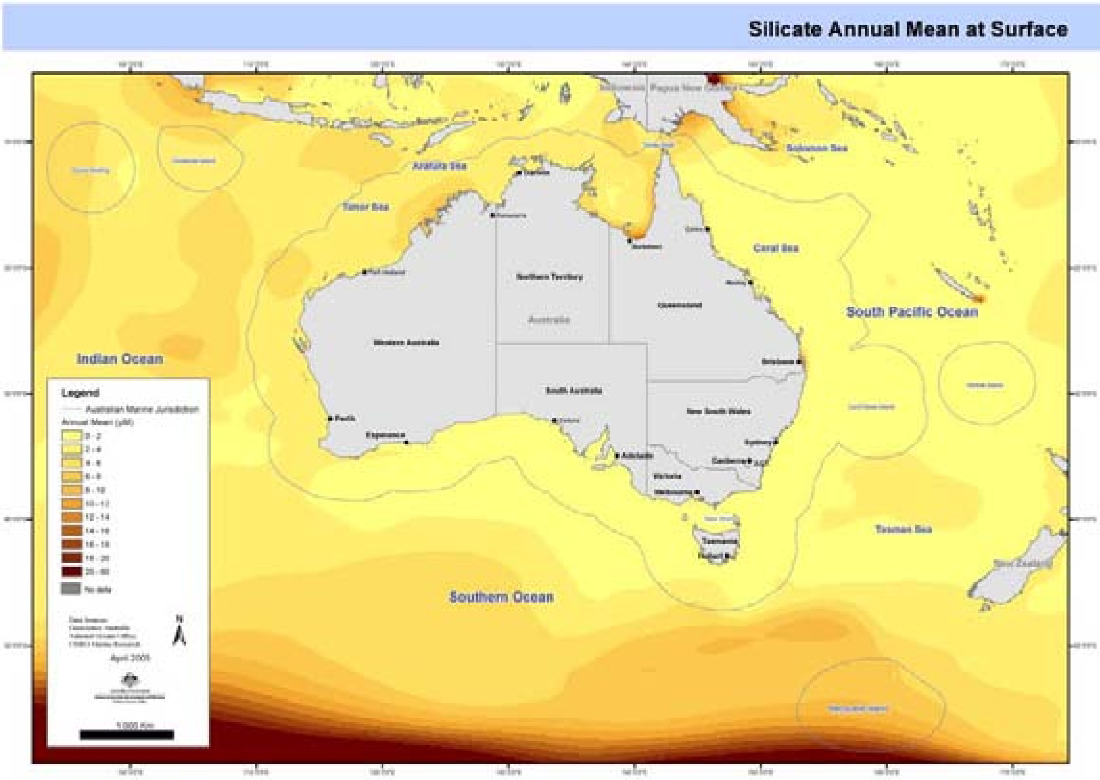


Figure D.1 (Cont.) Figure D.1 Salinity Annual Mean (years 1970-2000) at (a) the surface, (b) 150m, (c) 500m, (d) 1000m and (e) 2000m. Derived from the CSIRO Atlas of Regional Seas (CARS). For more information see Hayes et al. (2005)

Appendix E

Annual Mean Concentration of Silicate at different Depths

a



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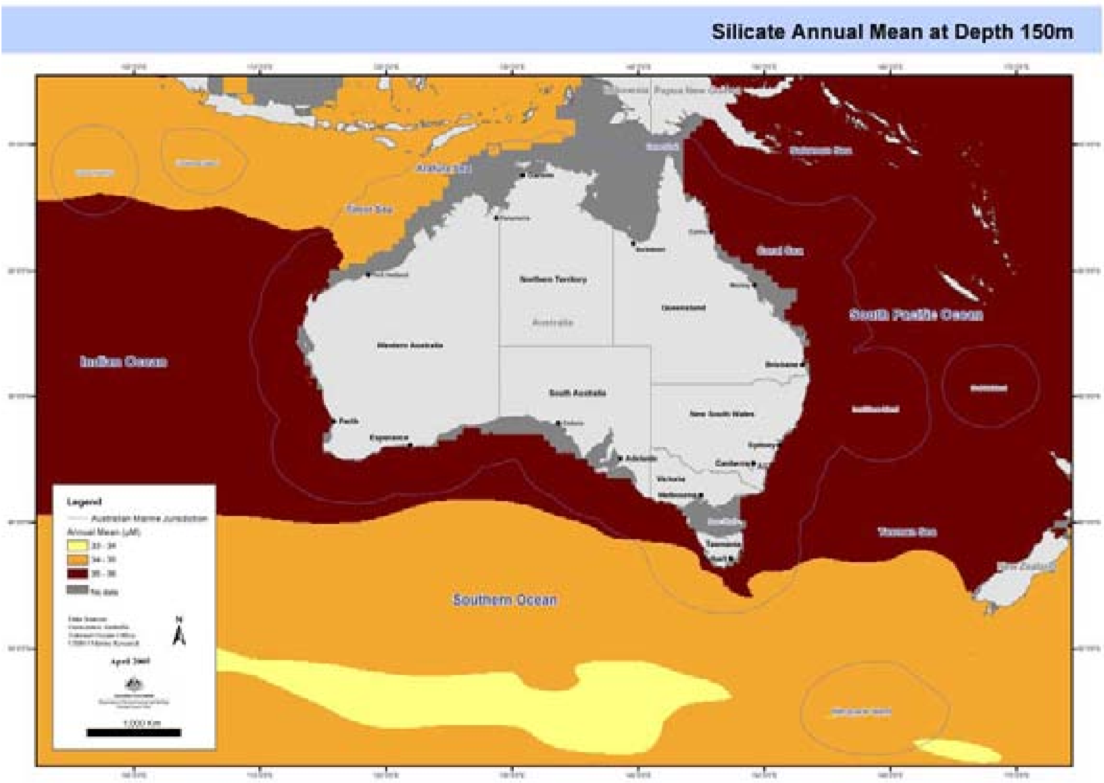

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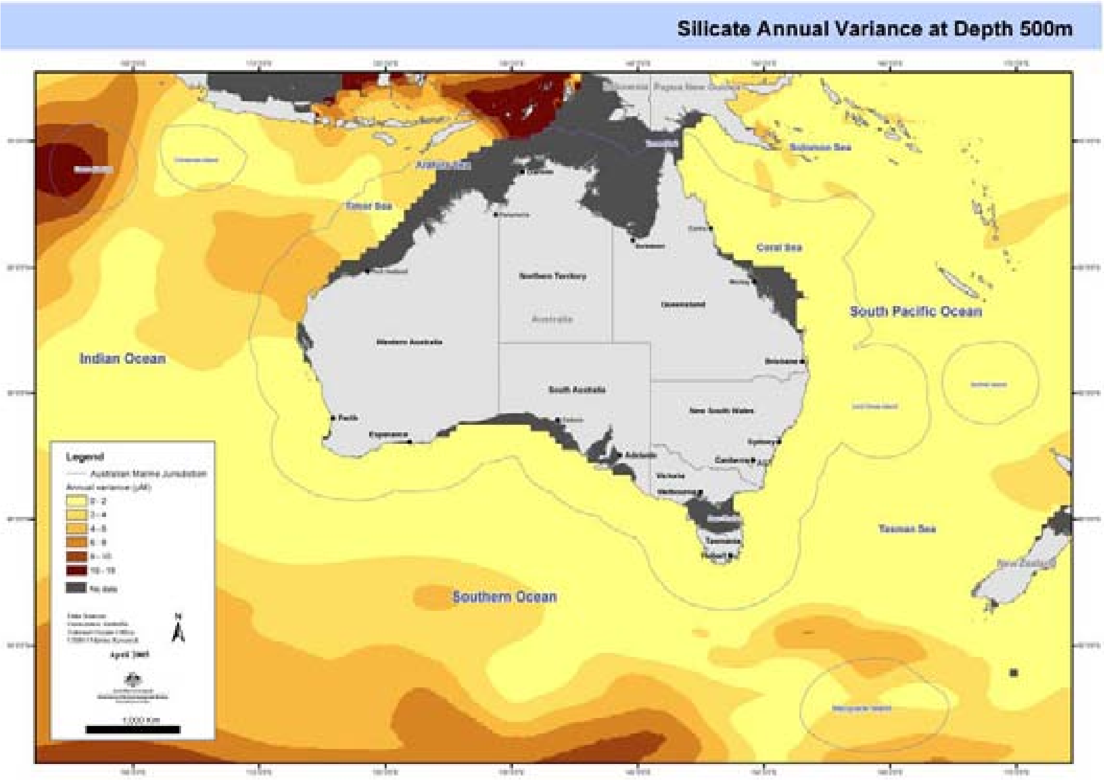
and (e) 2000m. Derived from the CSIRO Atlas of Regional Seas (CARS). For more information see Hayes et al. (2005).

c



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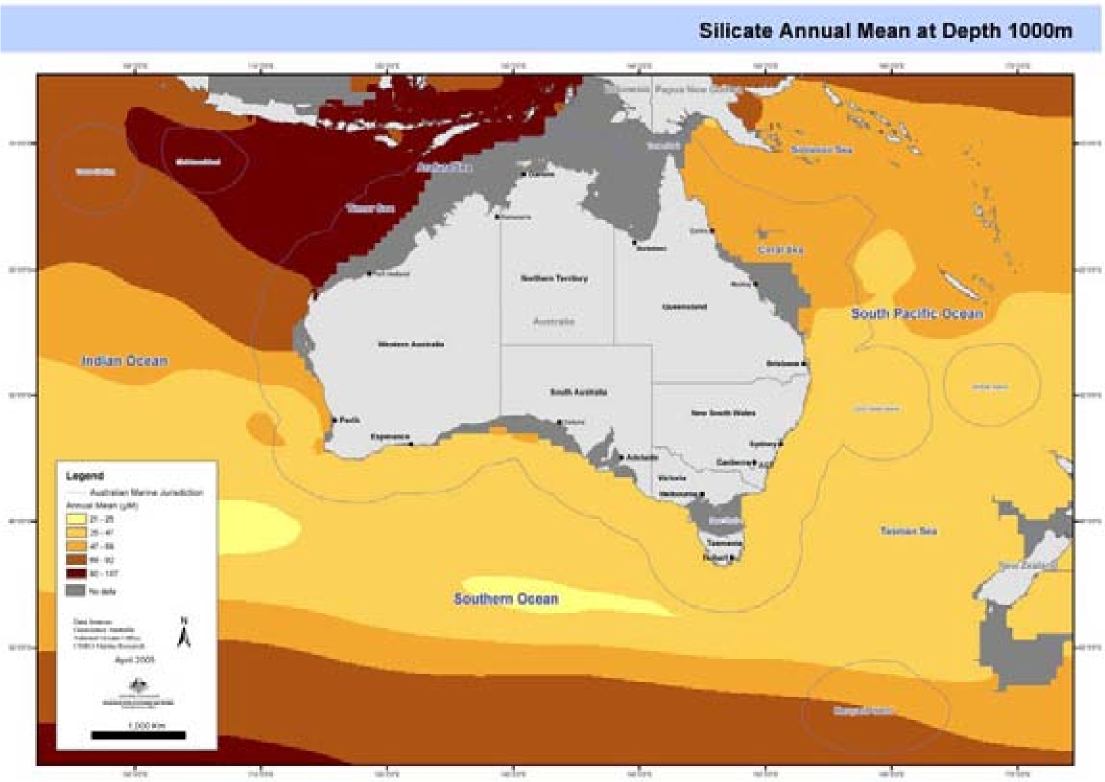
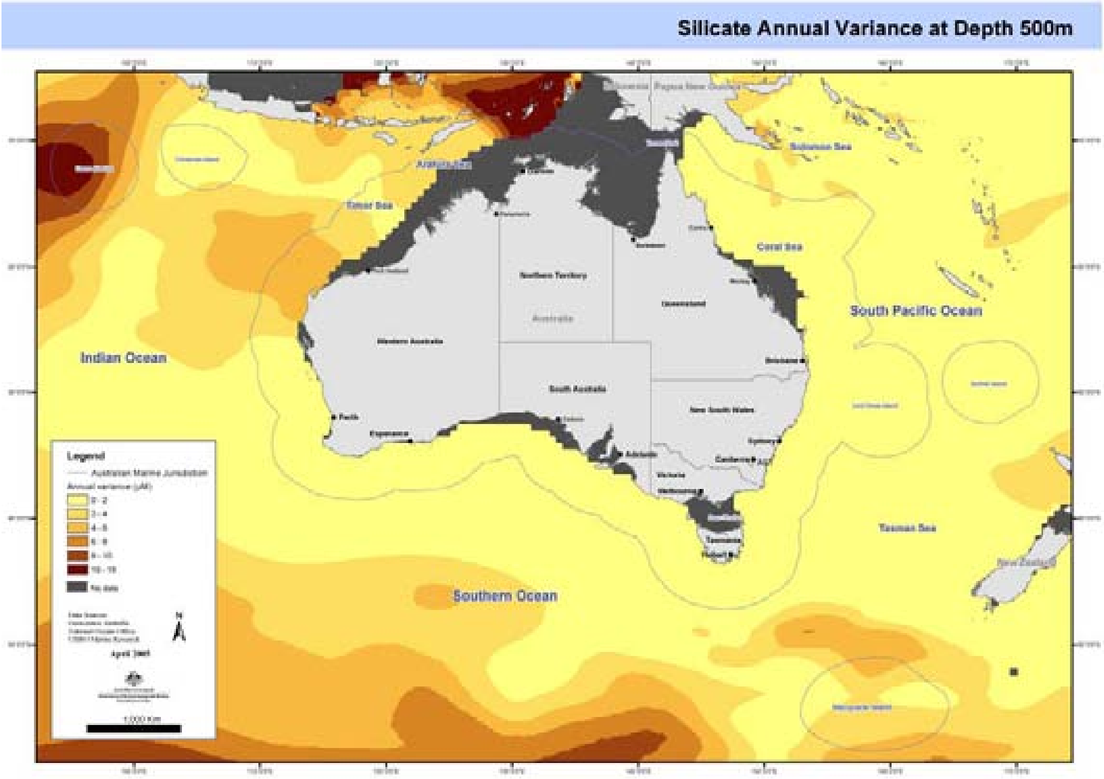


Figure E.1 (Cont.) Figure E.1 Silicate Annual Mean (years 1970-2000) at (a) the surface, (b) 150m, (c) 500m, (d) 1000m and (e) 2000m. Derived from the CSIRO Atlas of Regional Seas (CARS). For more information see Hayes et al. (2005).



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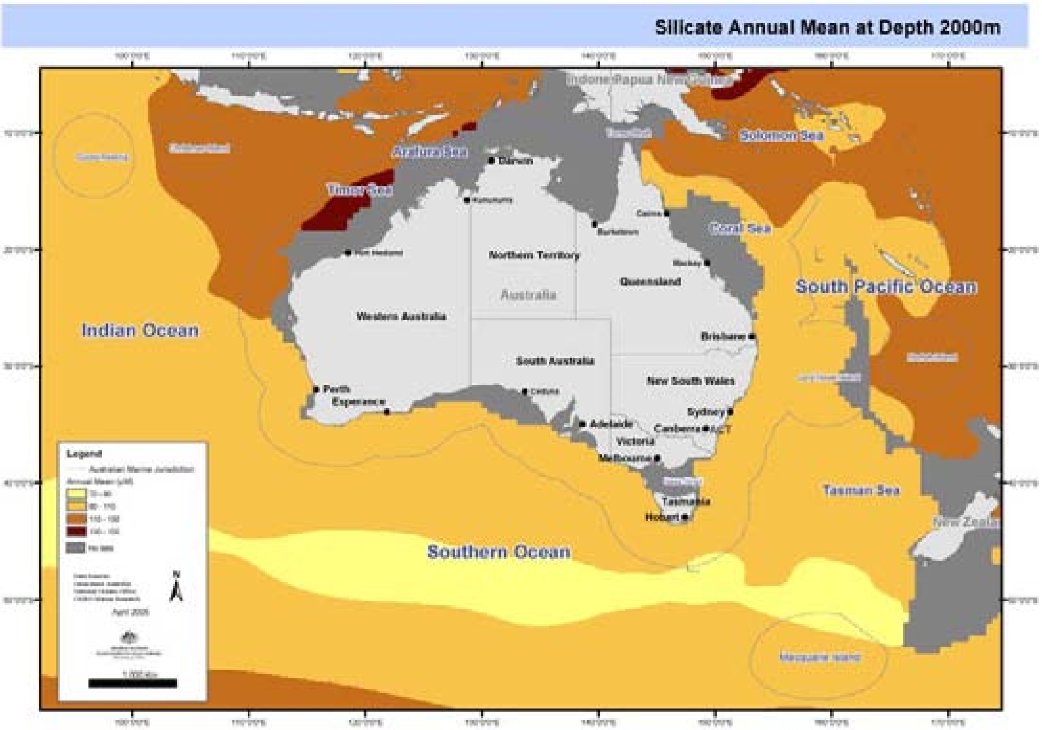
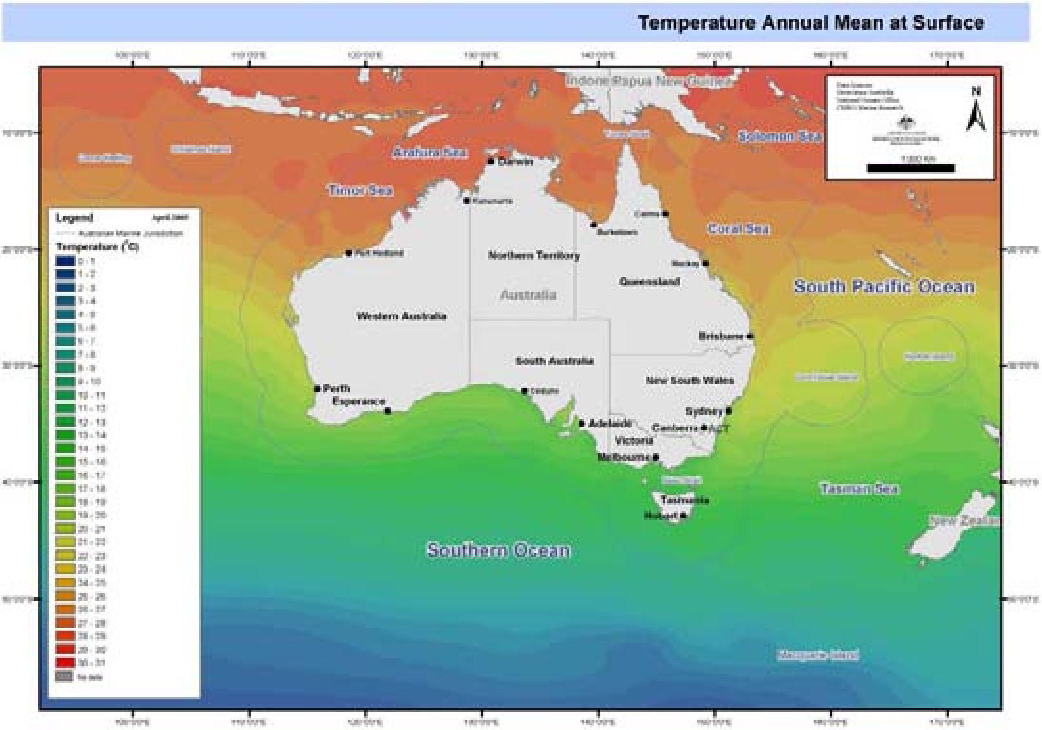


Figure E.1 (Cont.) Figure E.1 Silicate Annual Mean (years 1970-2000) at (a) the surface, (b) 150m, (c) 500m, (d) 1000m and (e) 2000m. Derived from the CSIRO Atlas of Regional Seas (CARS). For more information see Hayes et al. (2005).

Appendix F

Annual Mean Temperature at different Depths

a



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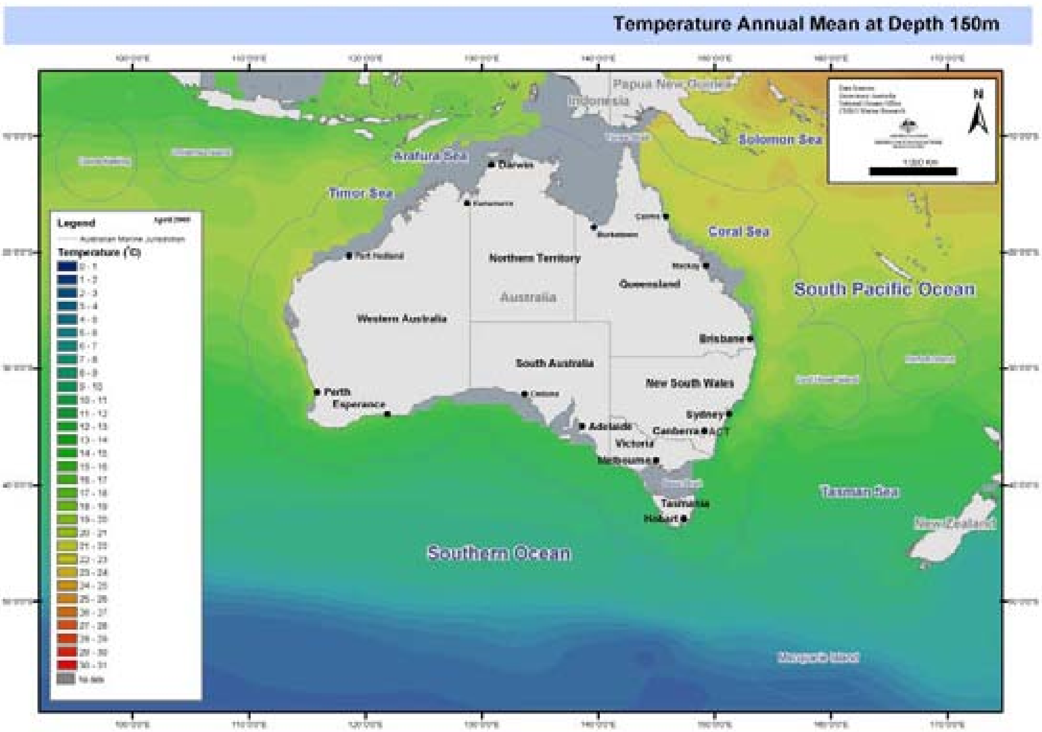
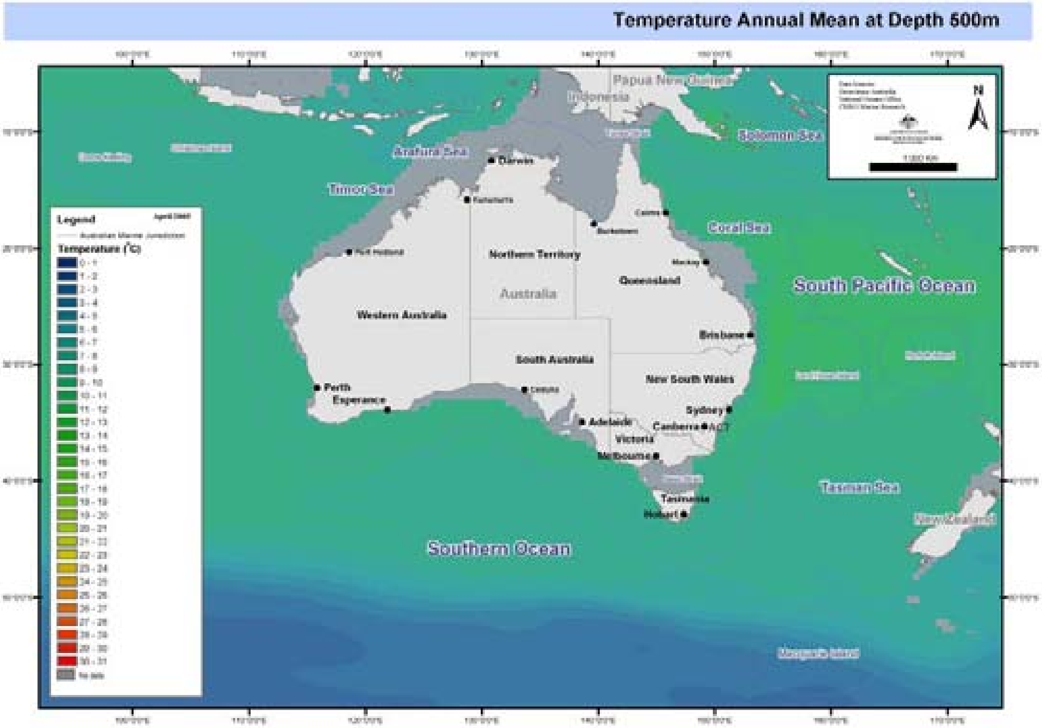


Figure F.1 Temperature Annual Mean (years 1970-2000) at (a) the surface, (b) 150m, (c) 500m, (d) 1000m and (e) 2000m. Derived from the CSIRO Atlas of Regional Seas (CARS). For more information see Hayes et al. (2005).

c



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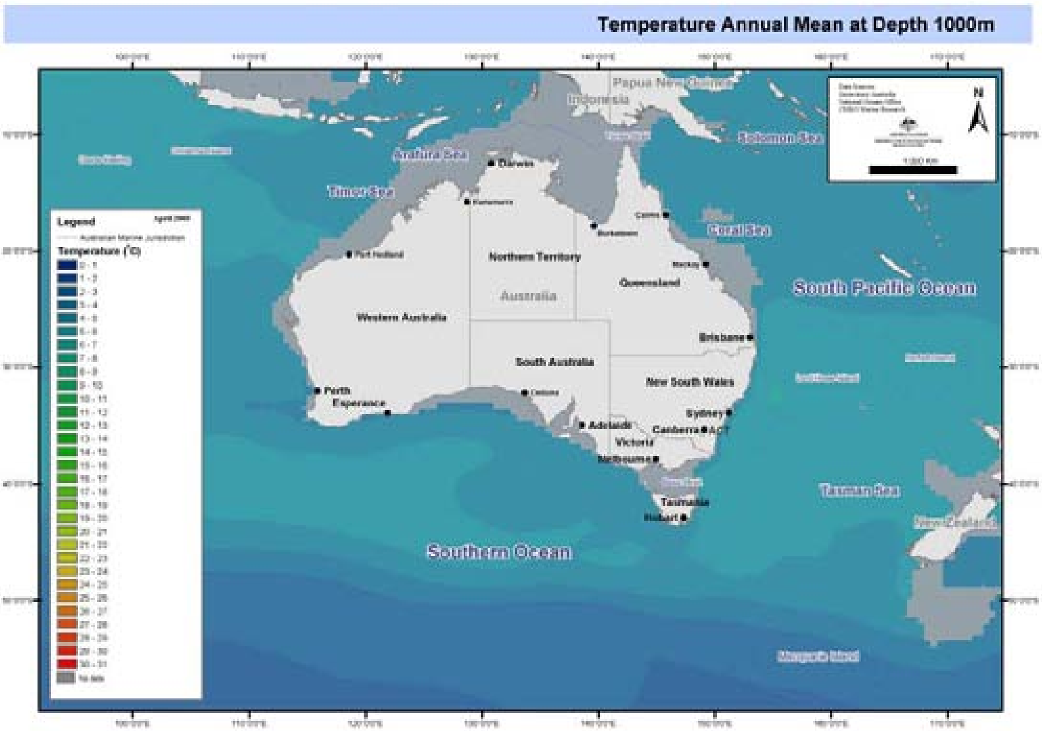

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e

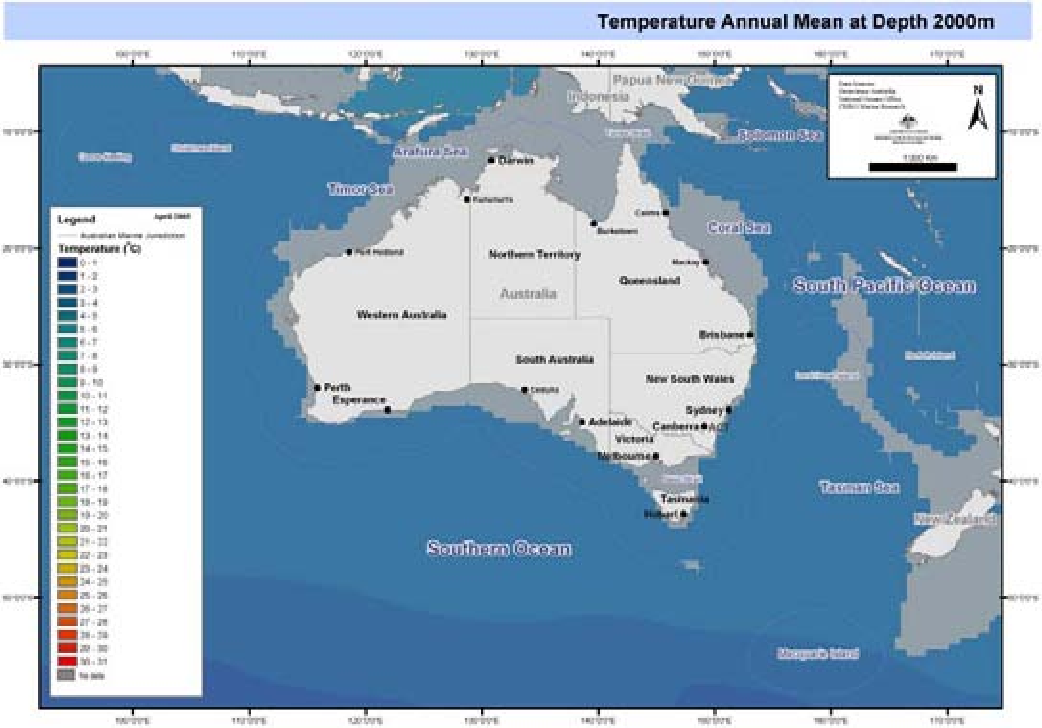
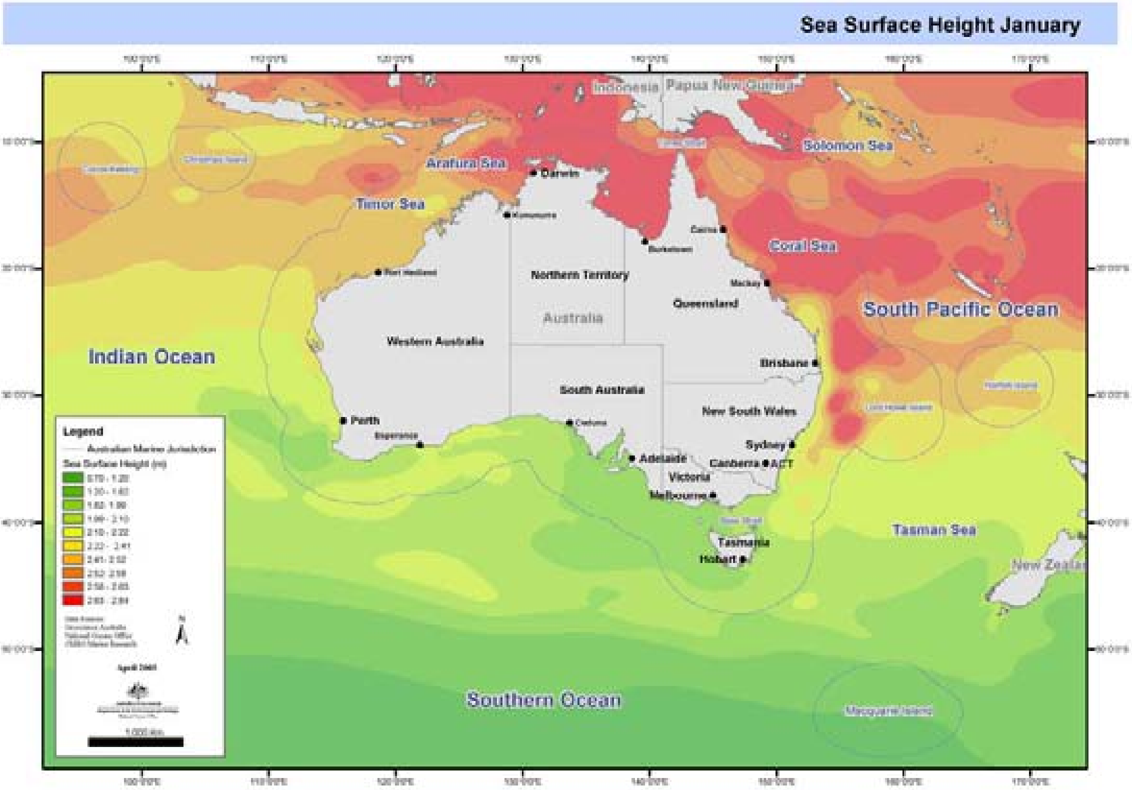


Figure F.1 (Cont.) Temperature Annual Mean (years 1970-2000) at (a) the surface, (b) 150m, (c) 500m, (d) 1000m and (e) 2000m. Derived from the CSIRO Atlas of Regional Seas (CARS). For more information see Hayes et al. (2005).

Appendix G

Input Data Sets: Sea Surface Dynamic Height, Sea Surface Height Variability, Surface Currents

a



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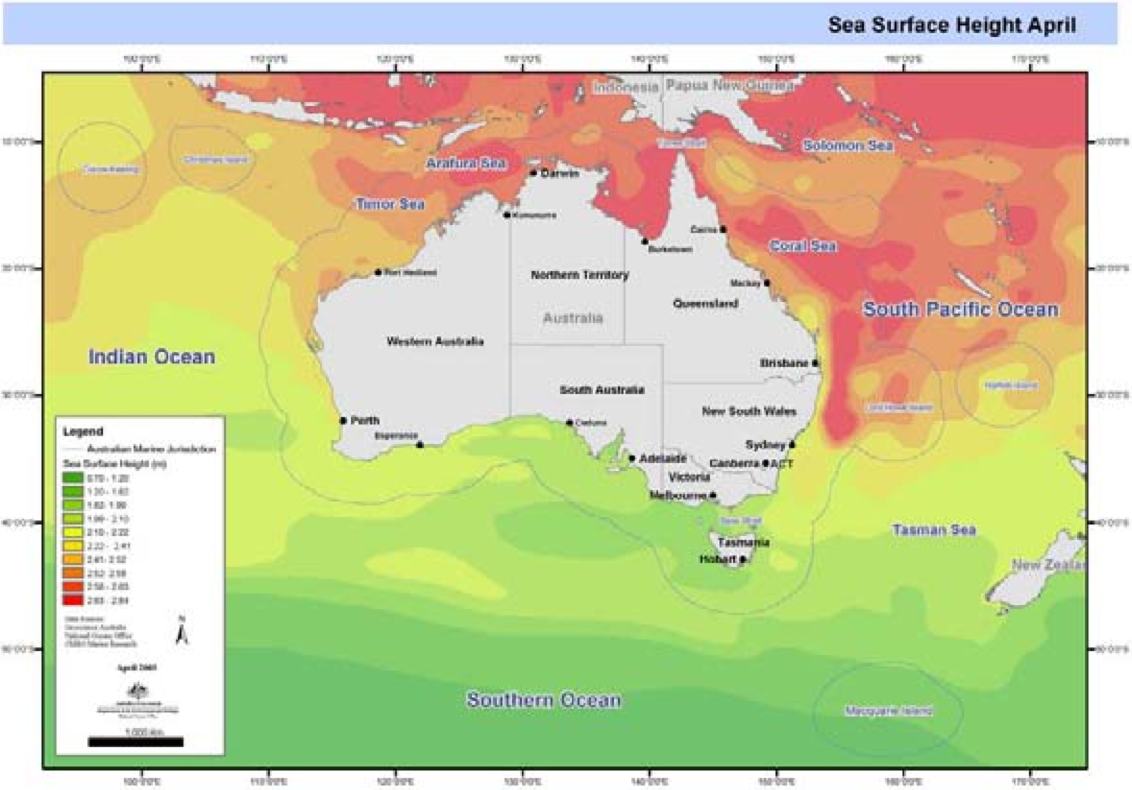
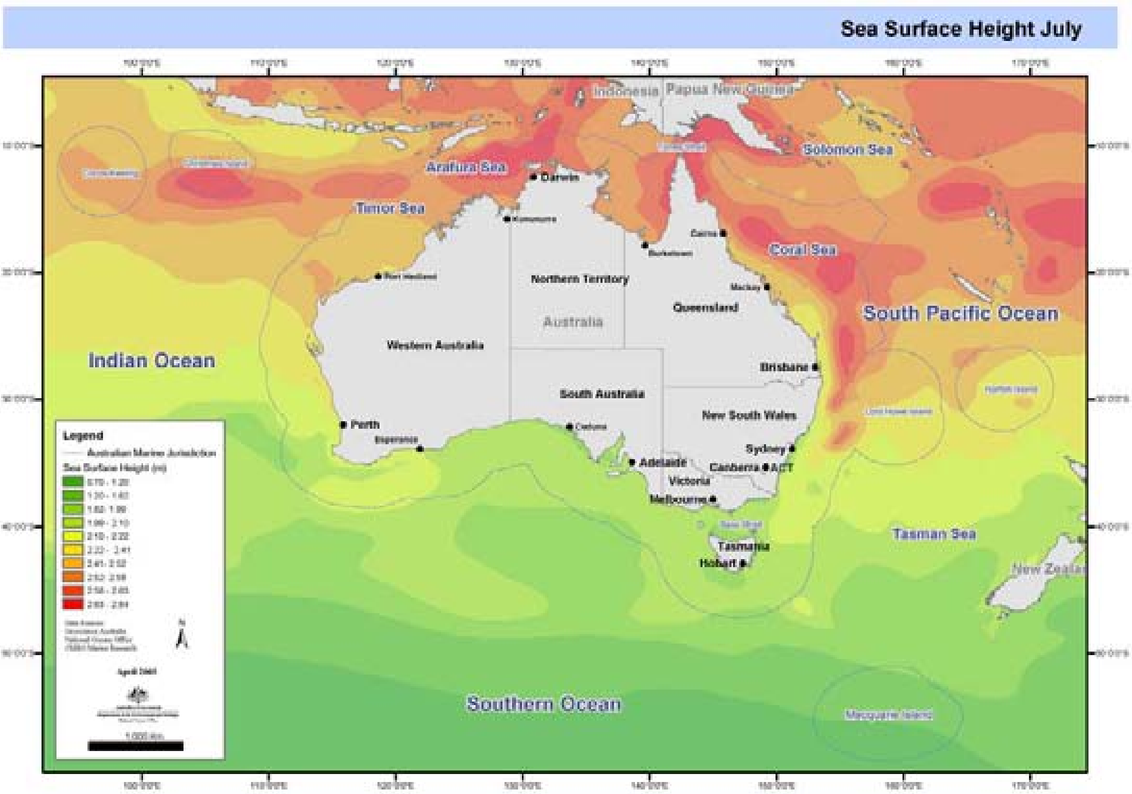


Figure G.1 Average Monthly Sea Surface Height (over years 1970 – 2000) for (a) January, (b) April, (c) July and (d) October. For further details see Hayes et al. (2005).

c



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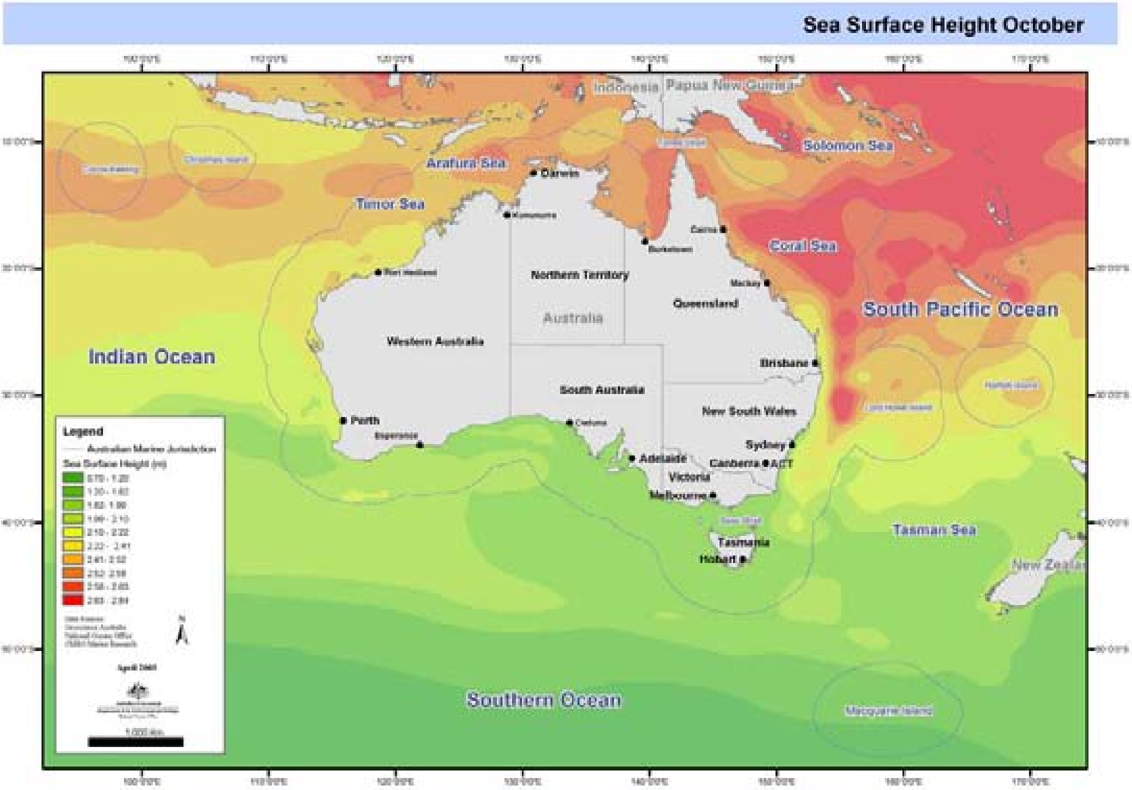
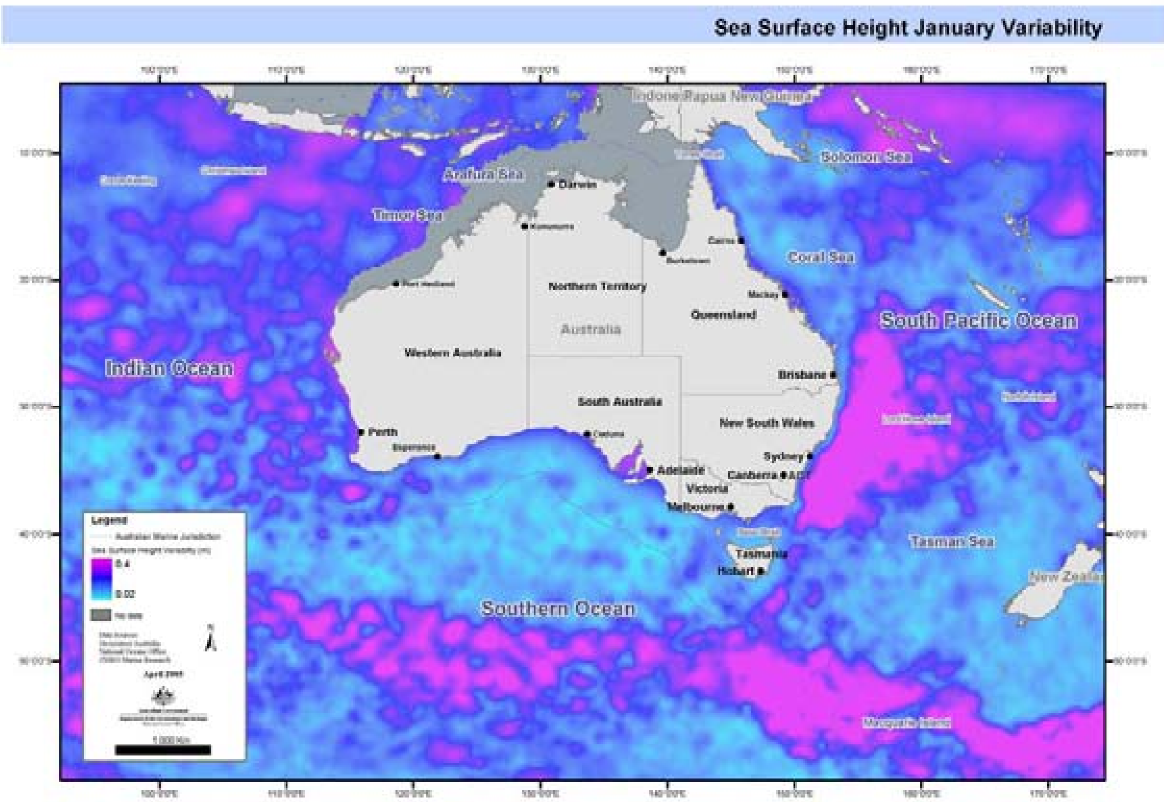


Figure G.1 (cont.) Average Monthly Sea Surface Height (over years 1970 – 2000) for (a) January, (b) April, (c) July and (d) October. For further details see Hayes et al. (2005).

a



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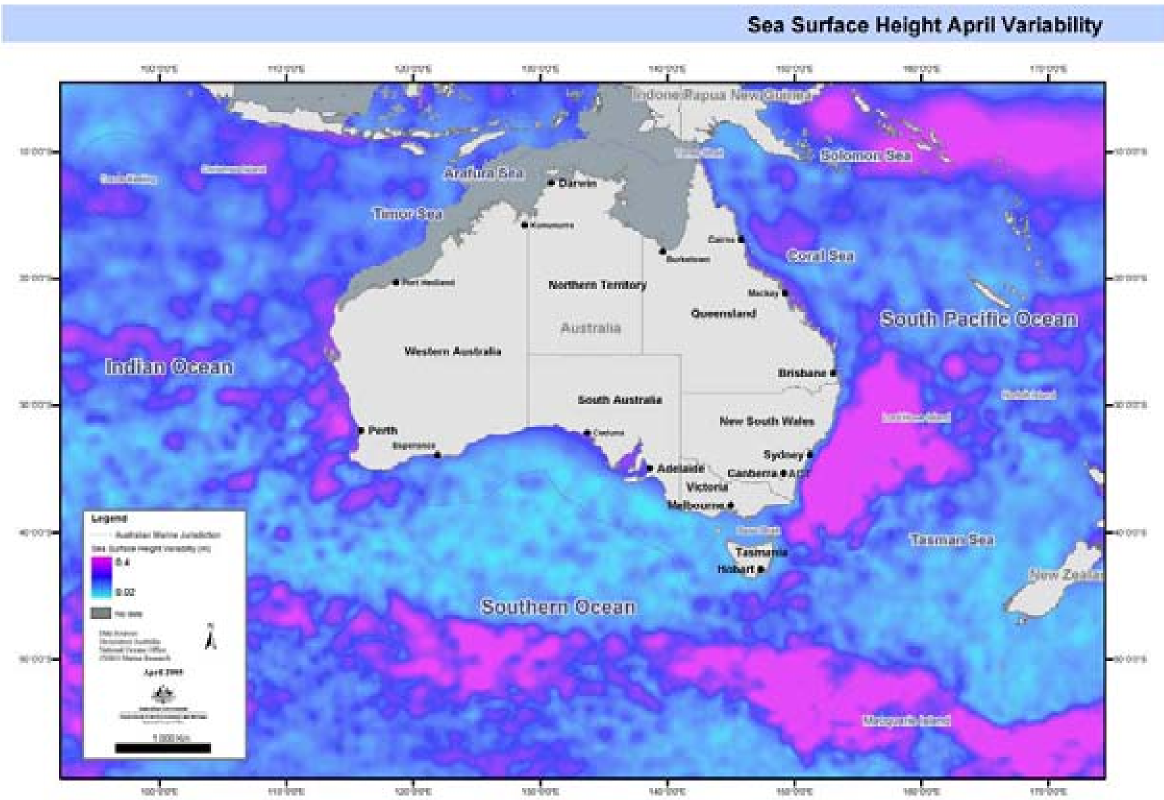
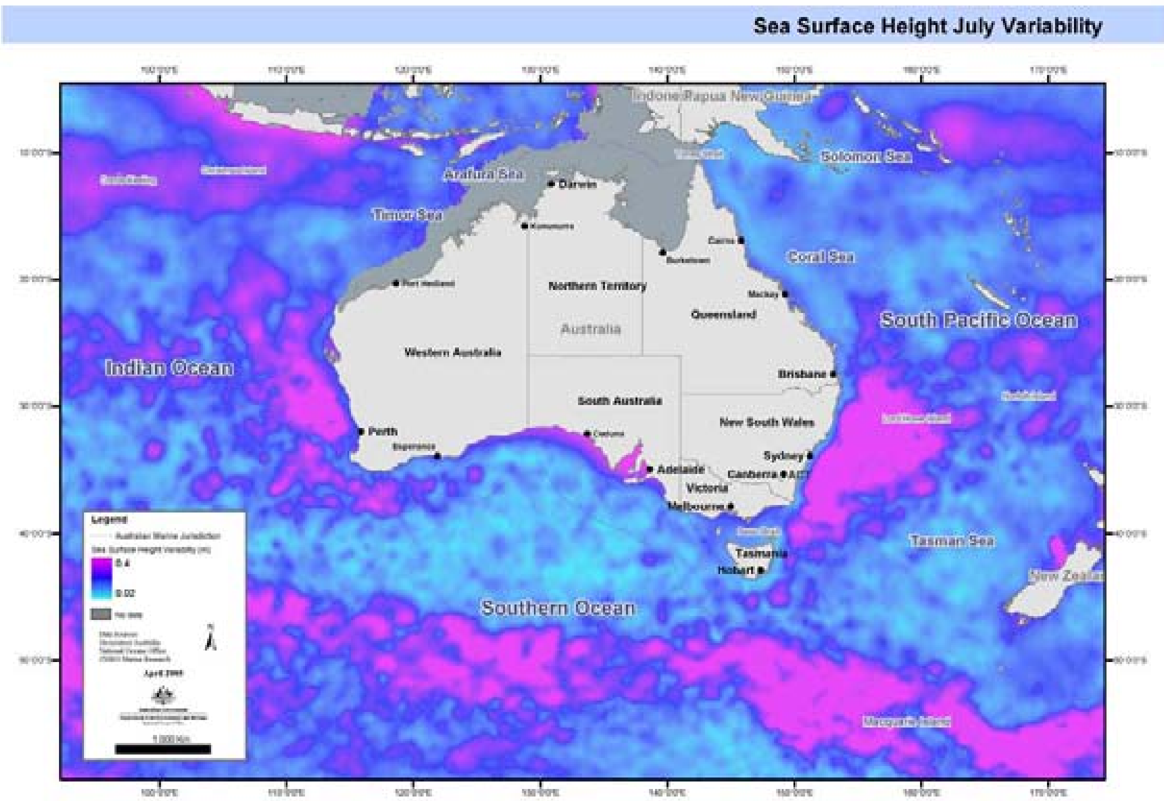


Figure G.2 Sea Surface Height Monthly Variability (over years 1993 – 2001). Calculated from altimeter data (topex/posedon, Jason-1, ERS-a and ERS-2.(a) January, (b) April, (c) July and (d) October. For full details see Hayes et al. (2005).

c



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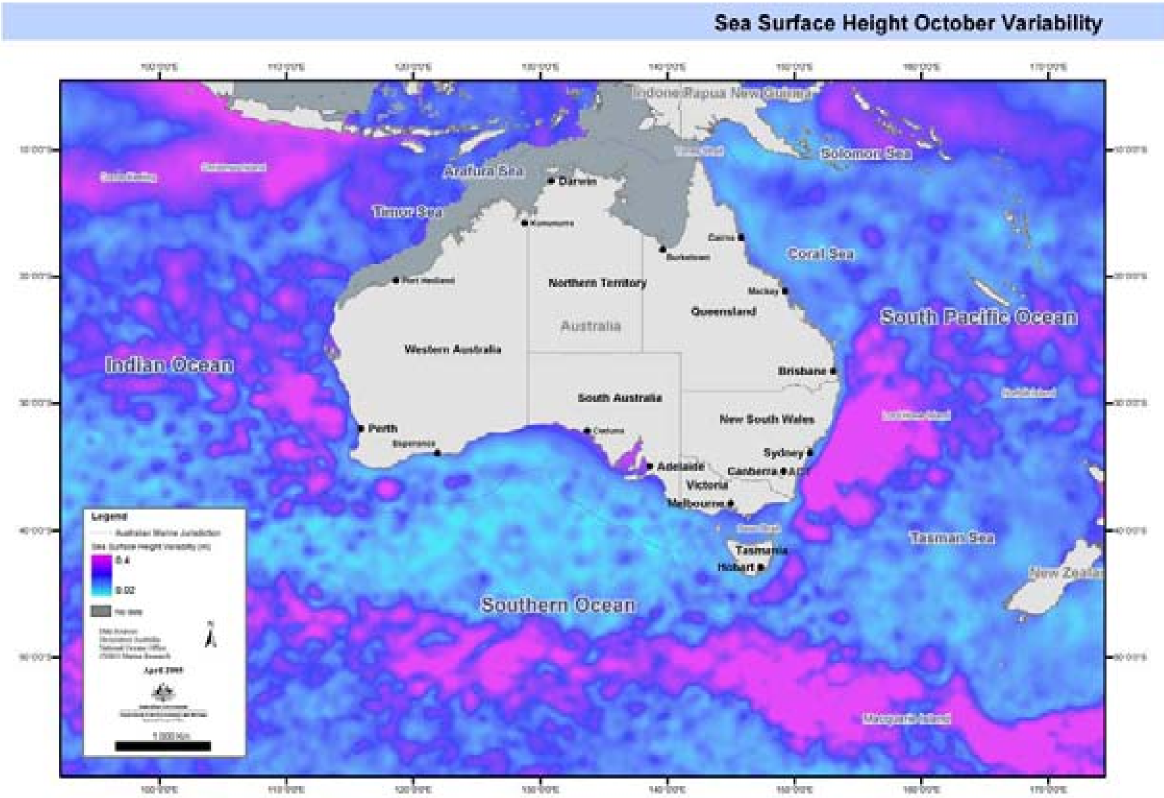


Figure G.2 (cont.) Sea Surface Height Monthly Variability (over years 1993 – 2001). Calculated from altimeter data (topex/posedon, Jason-1, ERS-a and ERS-2. (a) January, (b) April, (c) July and (d) October. For full details see Hayes et al. (2005).

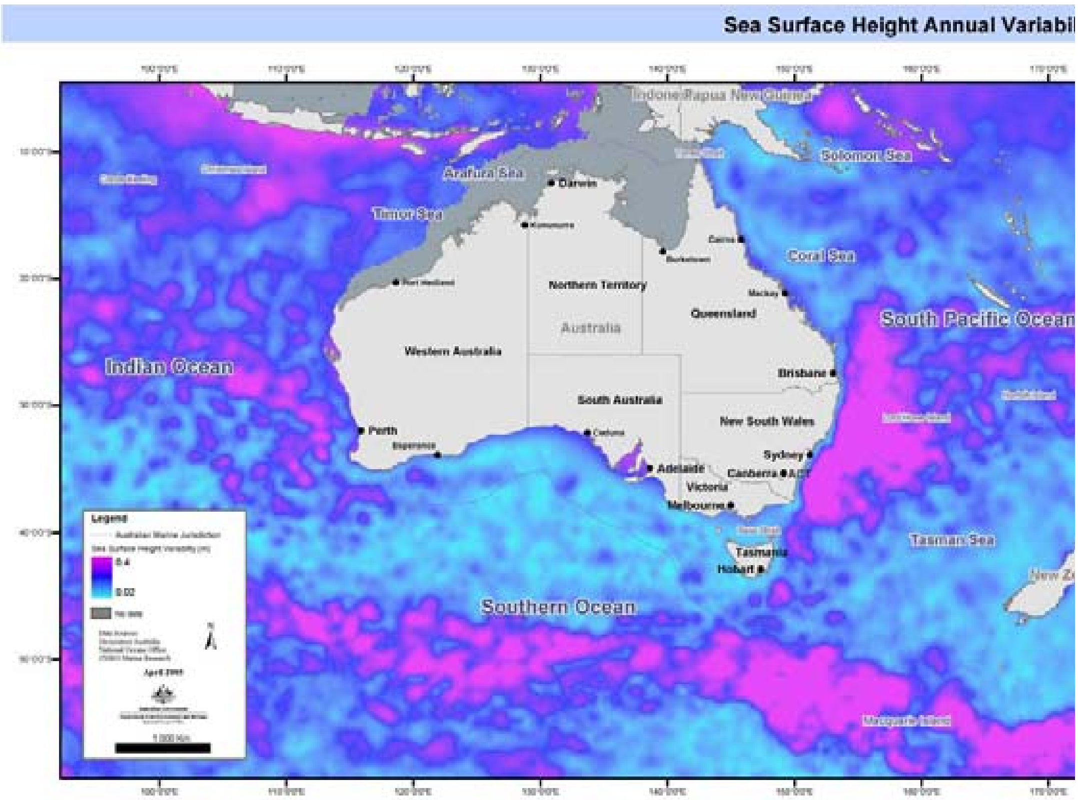
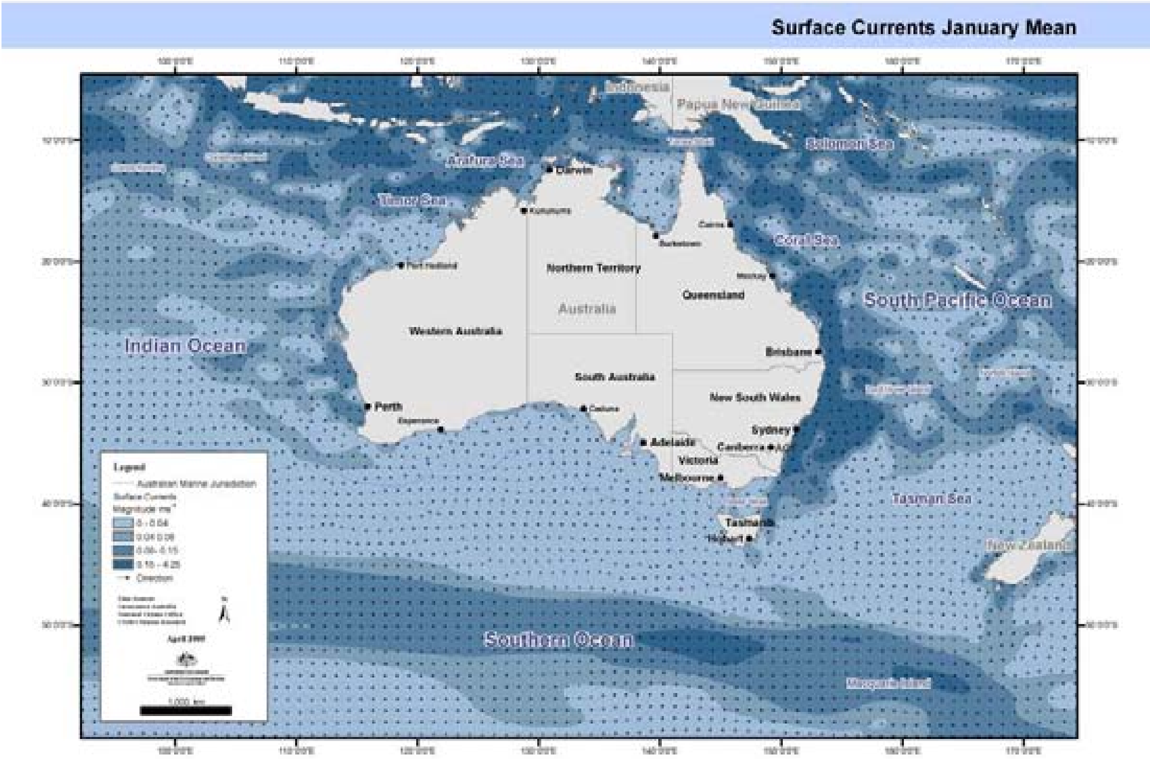


Figure G.3 Sea Surface Height Annual Variability (from years 1993 – 2001). Calculated from altimeter data (topex/posedon, Jason-1, ERS-a and ERS-2. (a) January, (b) April, (c) July and (d) October. For full details see Hayes et al. (2005).

a



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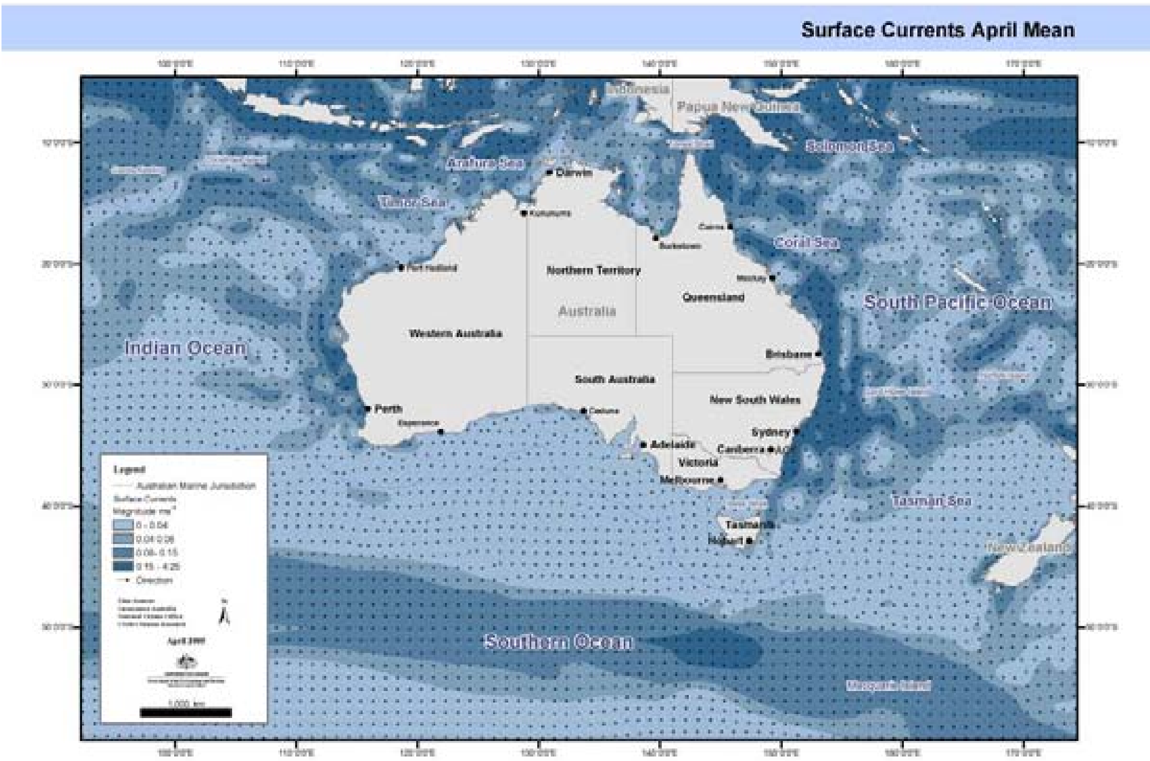
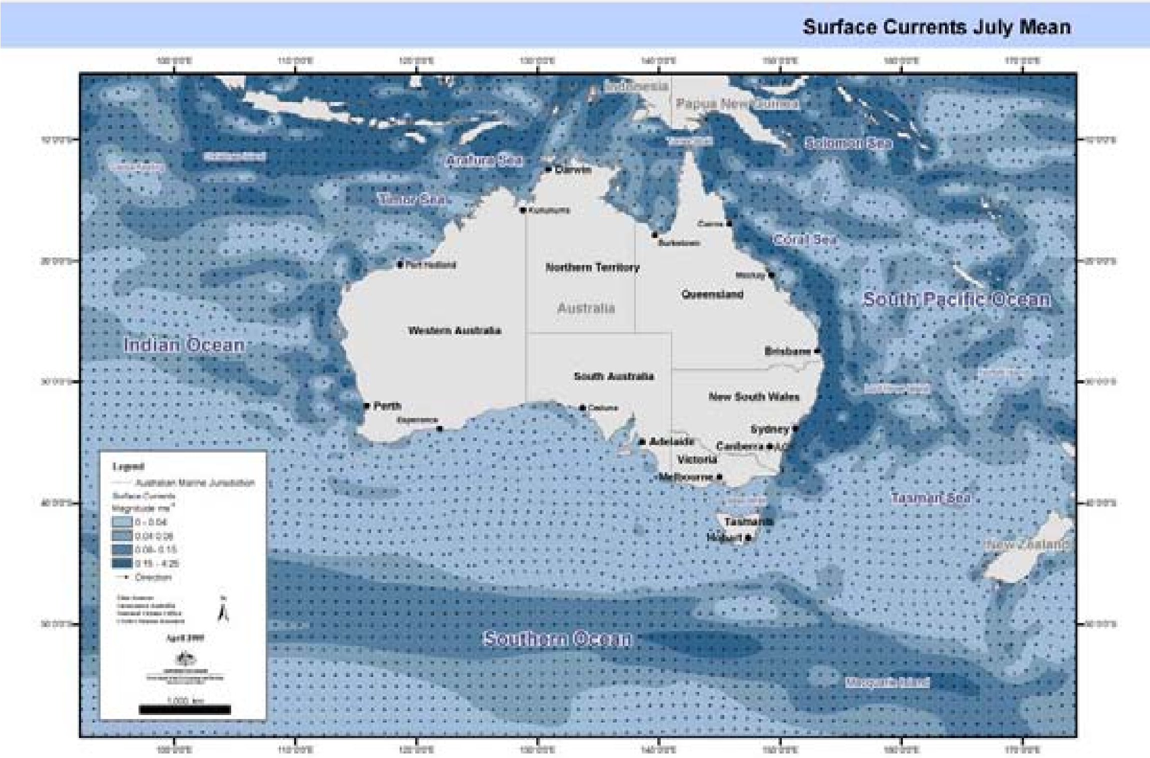


Figure G.4 Geostrophic Surface Currents calculated from Dynamic height fields derived from CSIRO Atlas of Regional Seas (monthly means calculated from years (1970 – 2000) for (a) January, (b) April, (c) July and (d) October. For full details see Hayes et al. (2005).

c



d

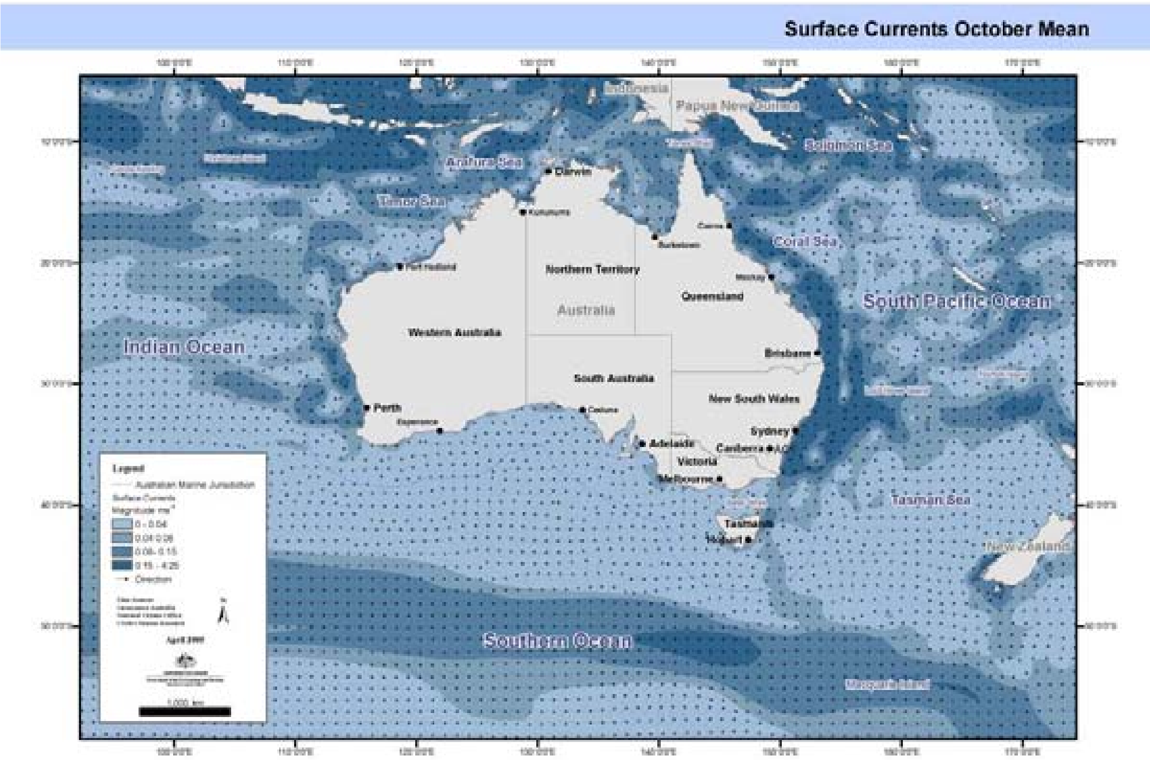


Figure G.4 9cont.) Geostrophic Surface Currents calculated from Dynamic height fields derived from CSIRO Atlas of Regional Seas (monthly means calculated from years (1970 – 2000) for (a) January, (b) April, (c) July and (d) October. For full details see Hayes et al. (2005).

Appendix H

Eddies and Field derived from Sea Surface Temperature

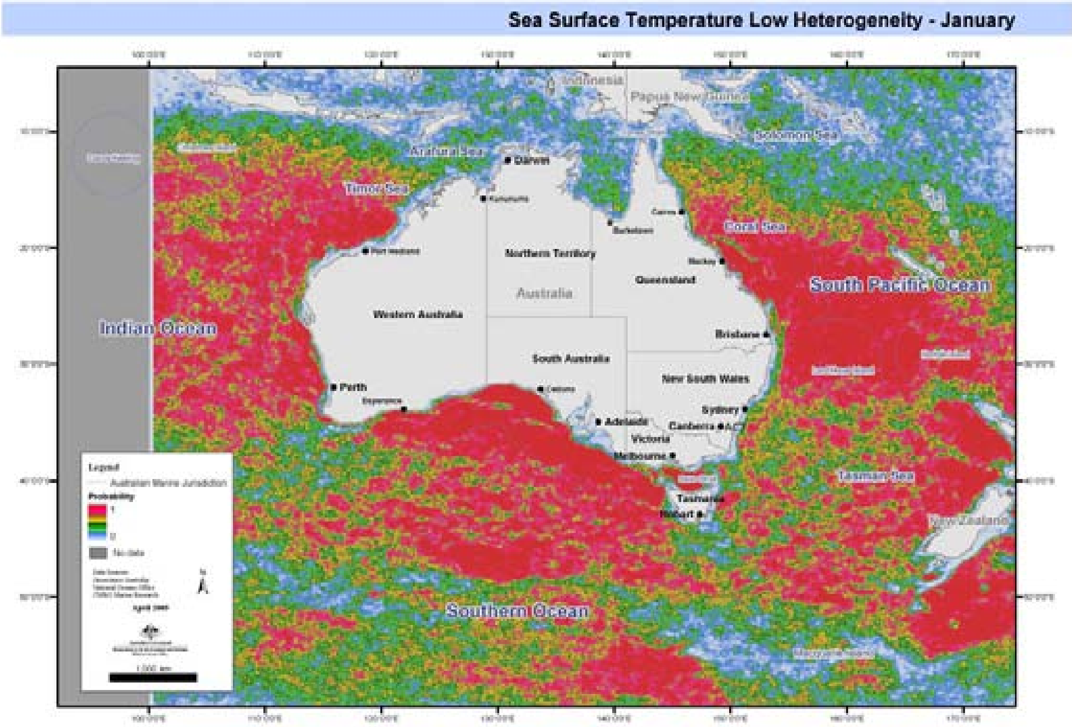
This section present results of homogeneity/heterogeneity analyses on satellite sea-surface temperature data. Three classes from those analyses are shown as follows:

Class 1: This class is meant to identify fields of relatively homogenous temperature. Thus these areas have relatively stable temperature and are characteristic of “core” water masses. The main regional distributions of this class occur off the north-west coast of Australia; the Great Australia Bight and a companion offshore area to the south west; Bass Strait; the Gulf of Carpentaria; offshore of the Great Barrier Reef and the extensive area offshore of the northern portion of eastern Australia.

Class 2: To a large extent, this field complements the Class 1 field but appears more pervasive than the Class 1 field. This is to be expected as this field characterises the peak in the histogram distribution of SST standard deviation. The textured nature of the field reflects the occurrence of numerous fronts embedded within this field.

Class 3: This field characterises the high gradient/variability region and typically occurs between the Class 1 and 2 fields. The field is most extensive in the Southern Ocean region and reflects the highly energetic nature of the mixing associated with the major Southern Ocean frontal systems and the underlying influence of bottom topography. Two other major areas occur off south eastern Australia and south west Australia. The East Australia Current eddy field is responsible for the former while the latter is associated with the Leeuwin Current and its instabilities. The Leeuwin Current itself is clearly demarcated as a thin jet in the south west of Australia which disappears just west of the Great Australia Bight – elements of this current reappear to the east and off western Tasmania (as the Zeehan Current). The shelf break region of eastern Australia is also characterised as being of high variability and again may reflect the interaction of the East Australia Current and its eddies with the shelf/slope.

a



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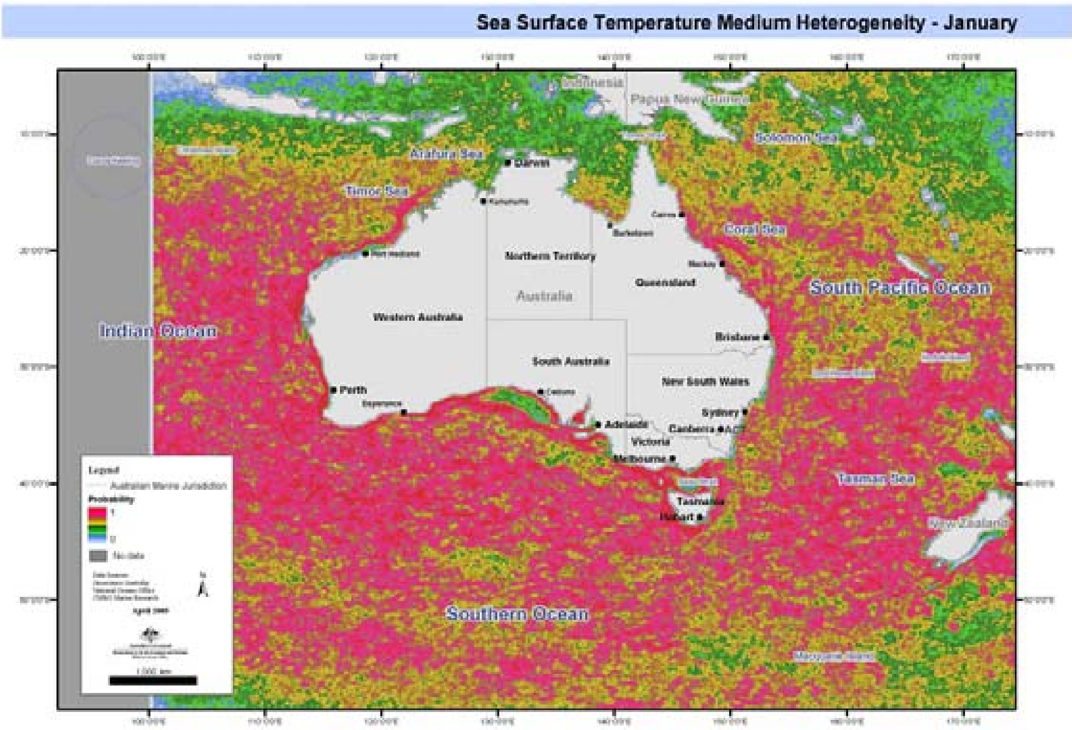
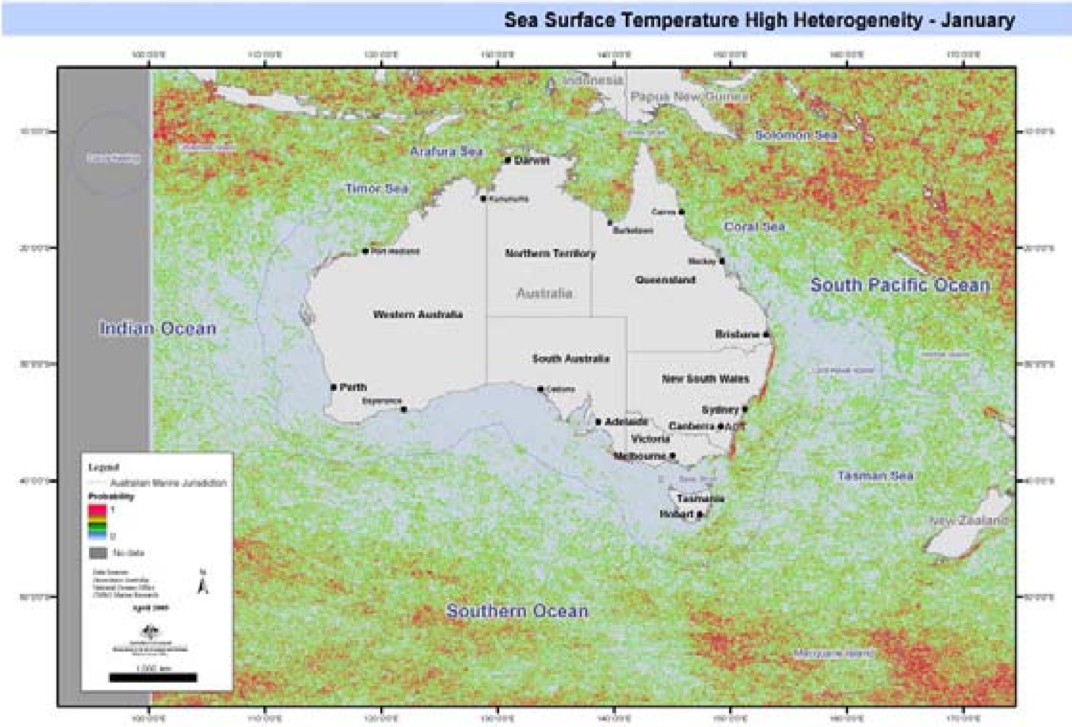


Figure H.1 Eddies and Fields based on Sea Surface Temperature January. (a) low heterogeneity, (b) medium heterogeneity, (c) high heterogeneity, (d) high heterogeneity and high gradients.

c



d

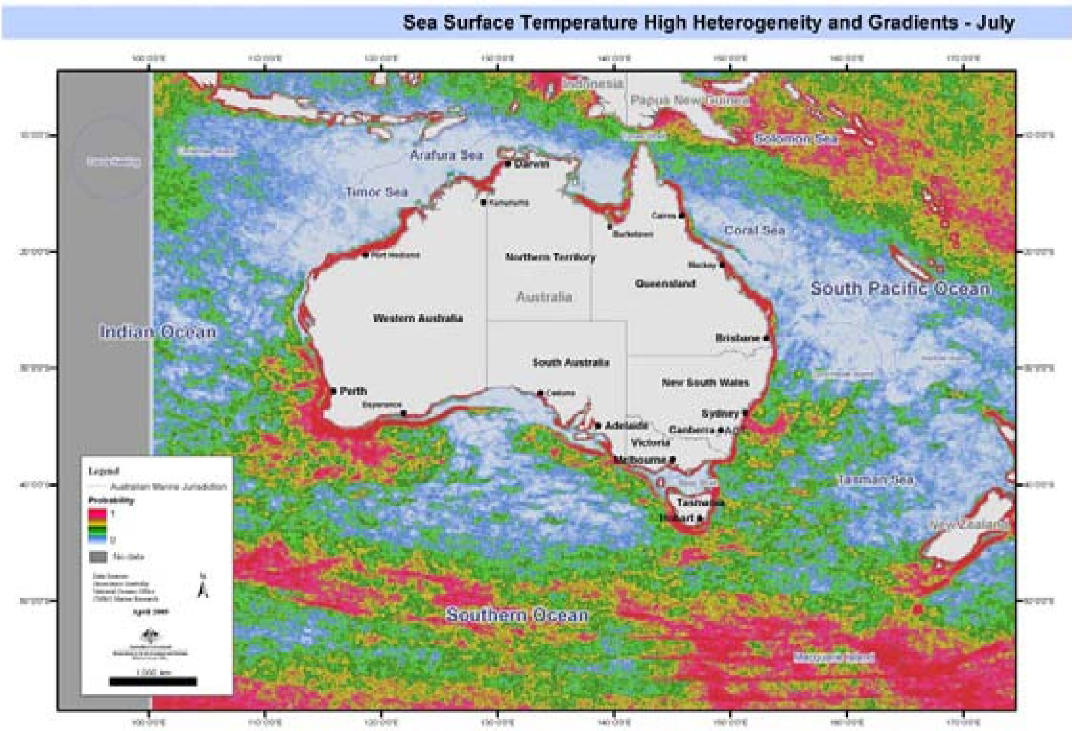
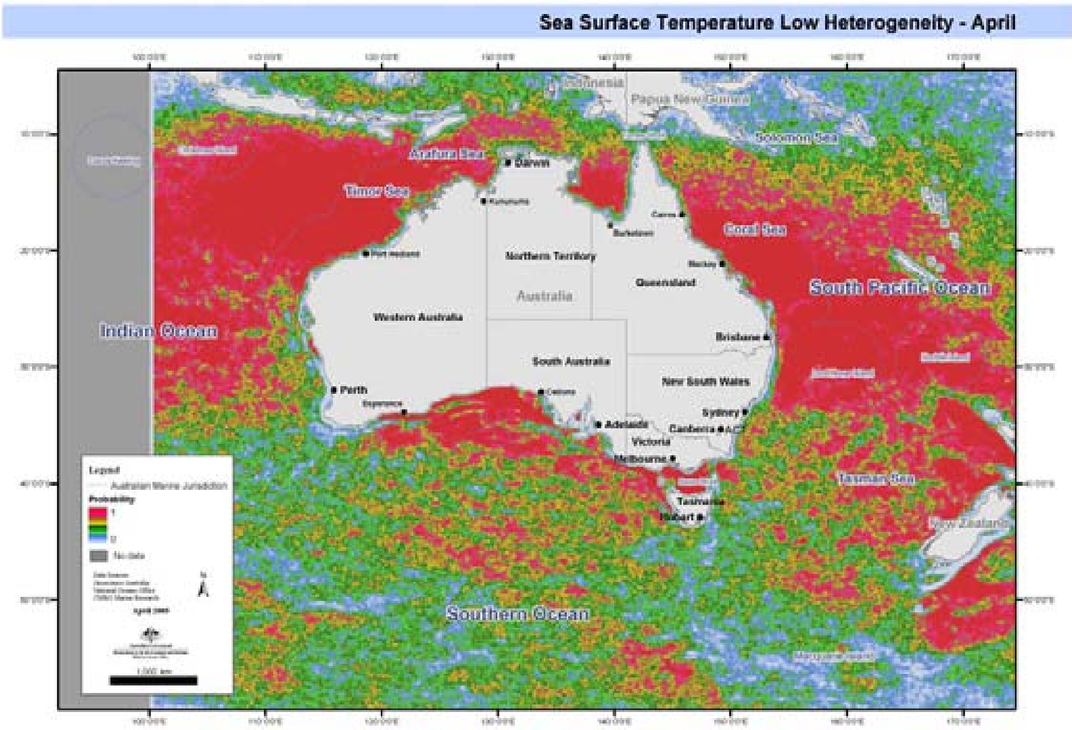


Figure H.1 (cont.) Eddies and Fields based on Sea Surface Temperature January. (a) low heterogeneity, (b) medium heterogeneity, (c) high heterogeneity, (d) high heterogeneity and high gradients.

a



b

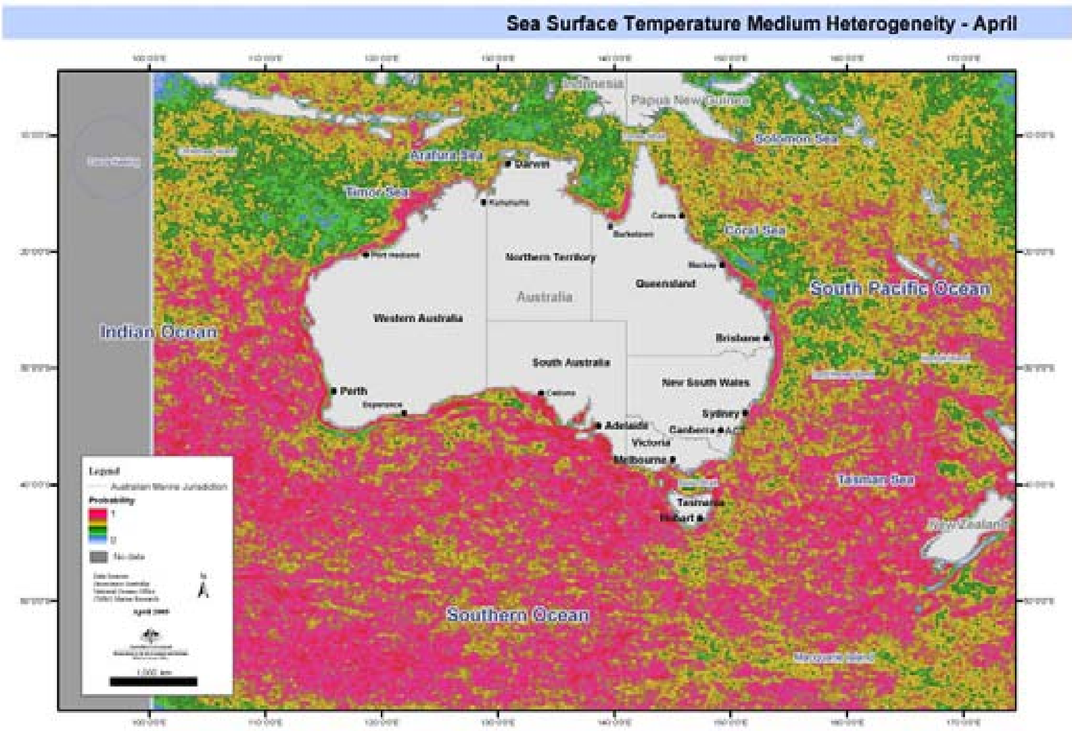
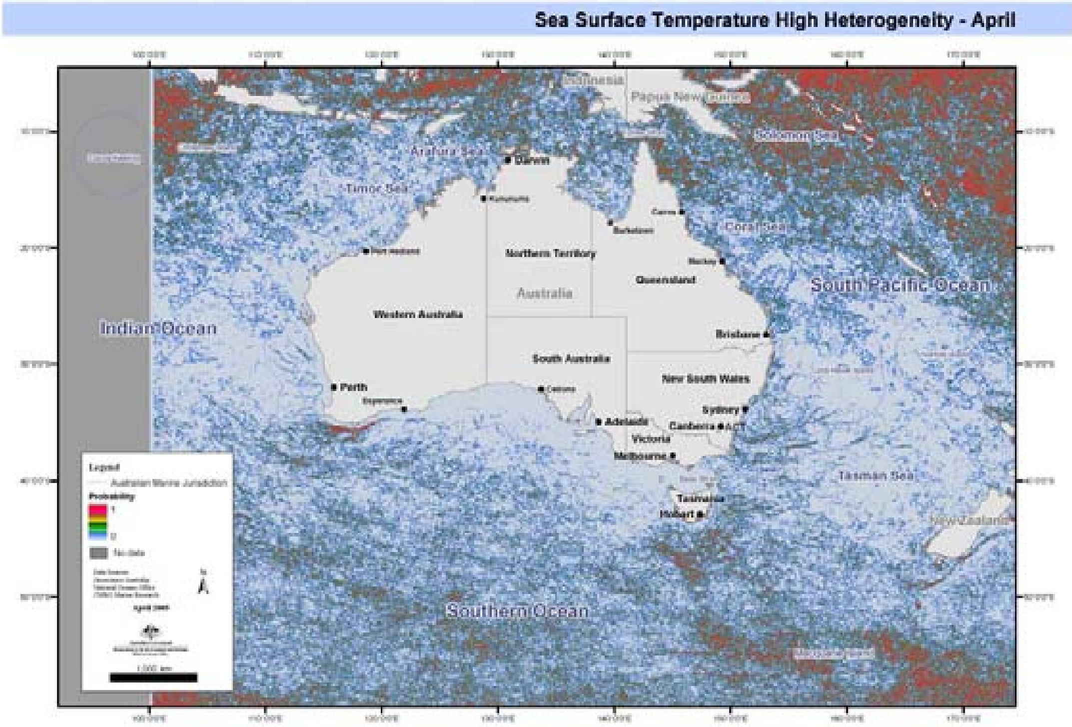


Figure H.2 Eddies and Fields based on Sea Surface Temperature April. (a) low heterogeneity, (b) medium heterogeneity, (c) high heterogeneity, (d) high heterogeneity and high gradients

c



d

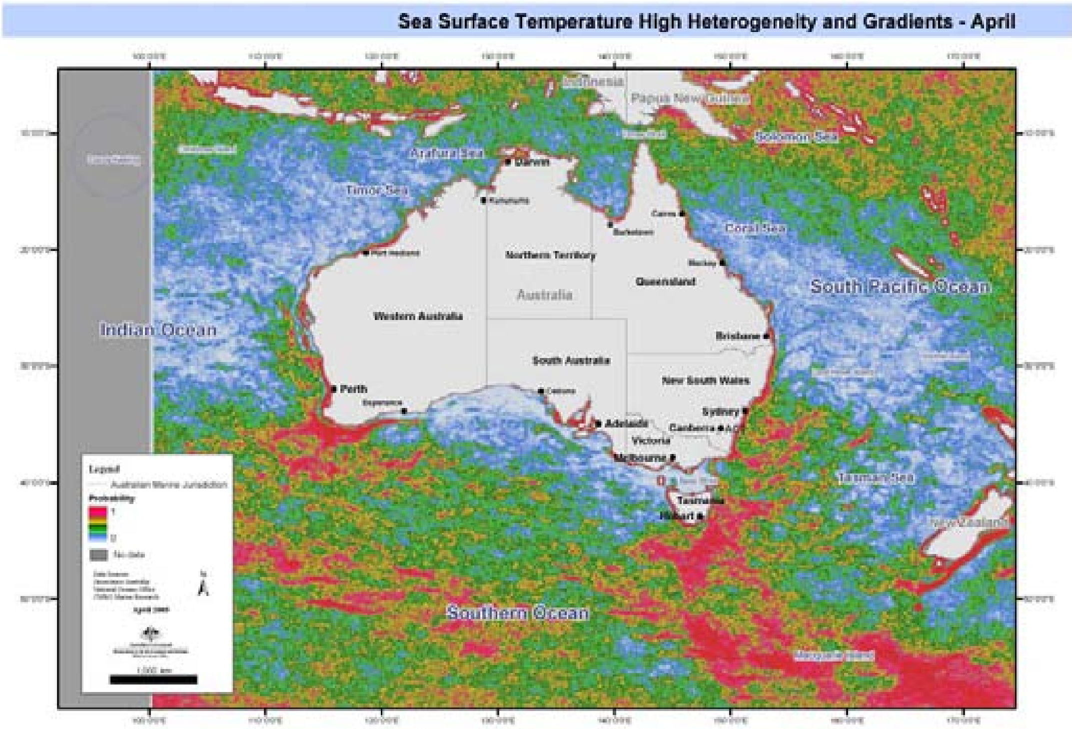
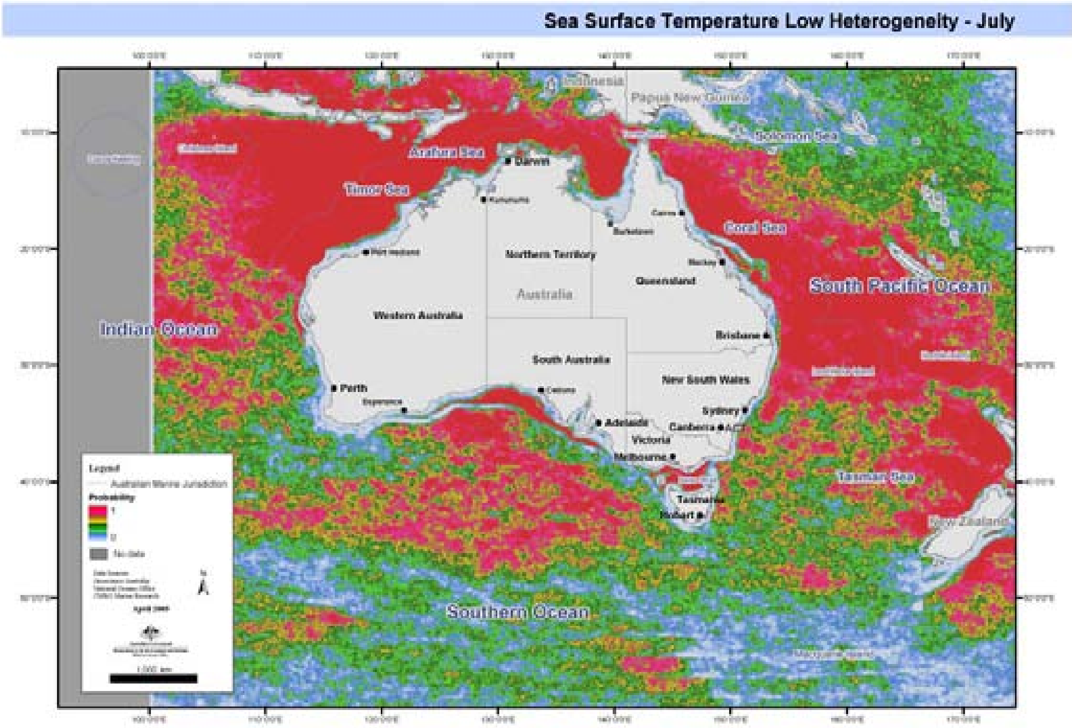


Figure H.2 (cont.) Eddies and Fields based on Sea Surface Temperature April. (a) low heterogeneity, (b) medium heterogeneity, (c) high heterogeneity, (d) high heterogeneity and high gradients.

a



b

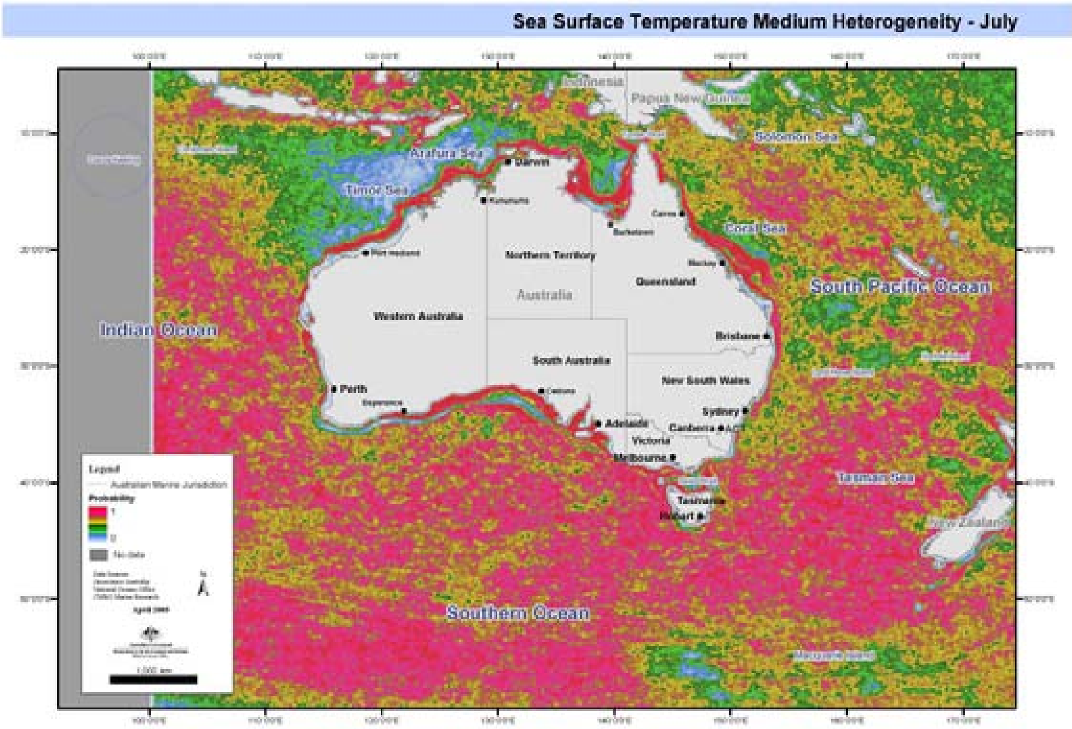
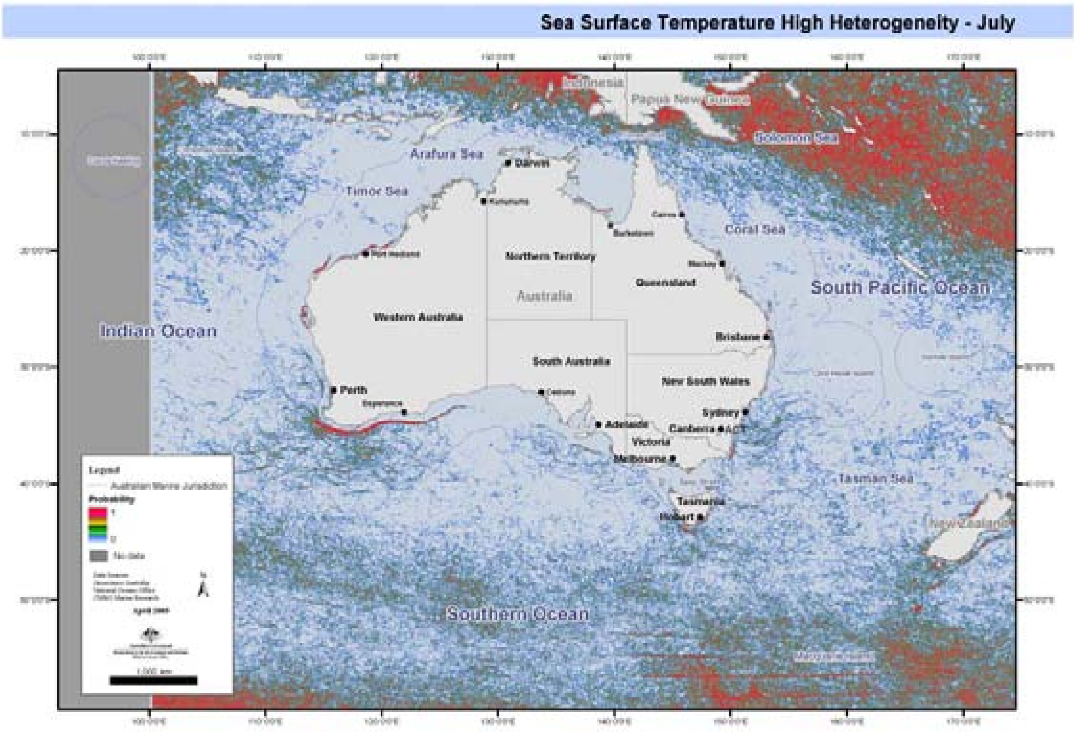


Figure H.3 Eddies and Fields based on Sea Surface Temperature July. (a) low heterogeneity, (b) medium heterogeneity, (c) high heterogeneity, (d) high heterogeneity and high gradients

c



d

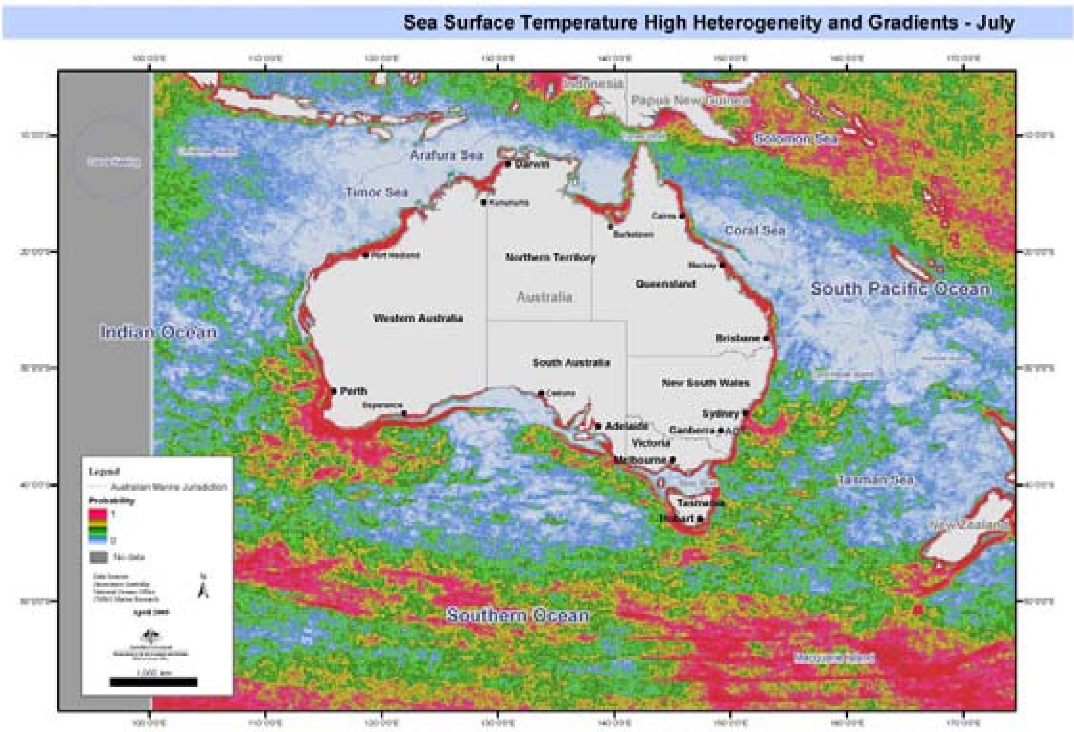
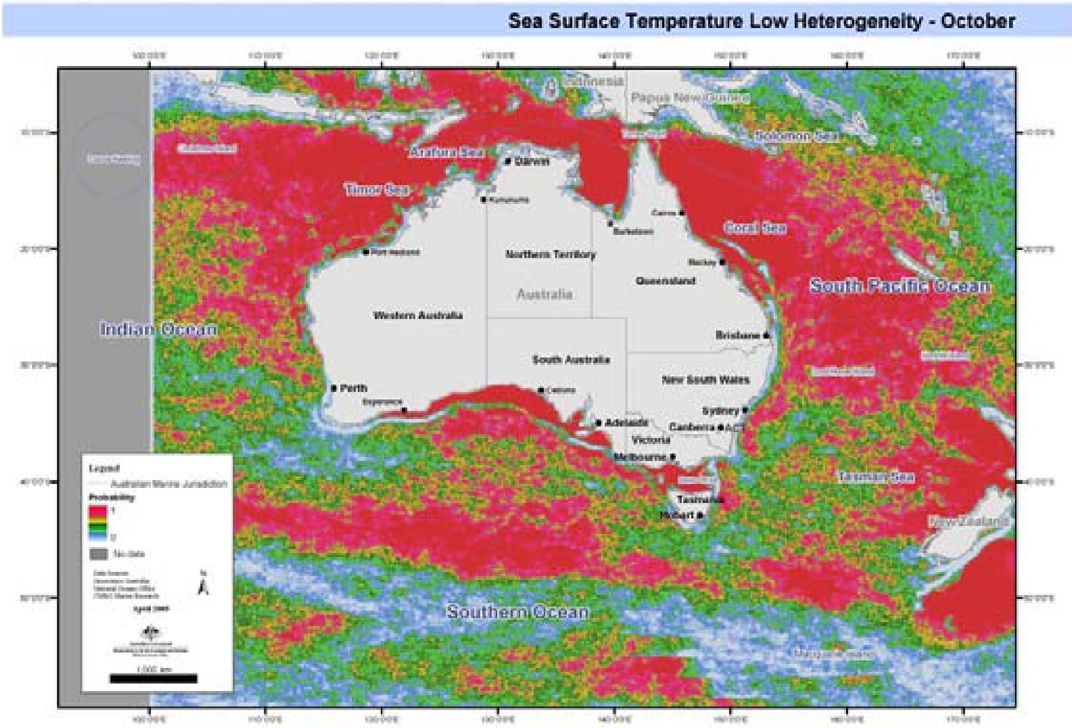


Figure H.3 (cont.) Eddies and Fields based on Sea Surface Temperature July. (a) low heterogeneity, (b) medium heterogeneity, (c) high heterogeneity, (d) high heterogeneity and high gradients.

a



b

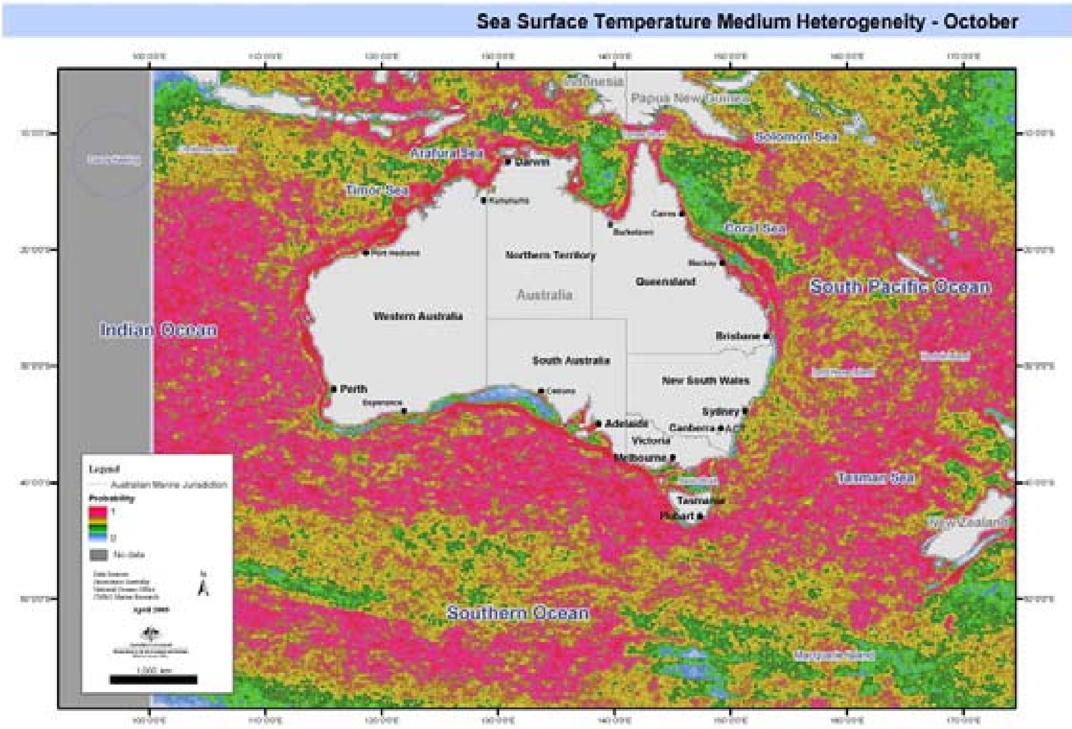
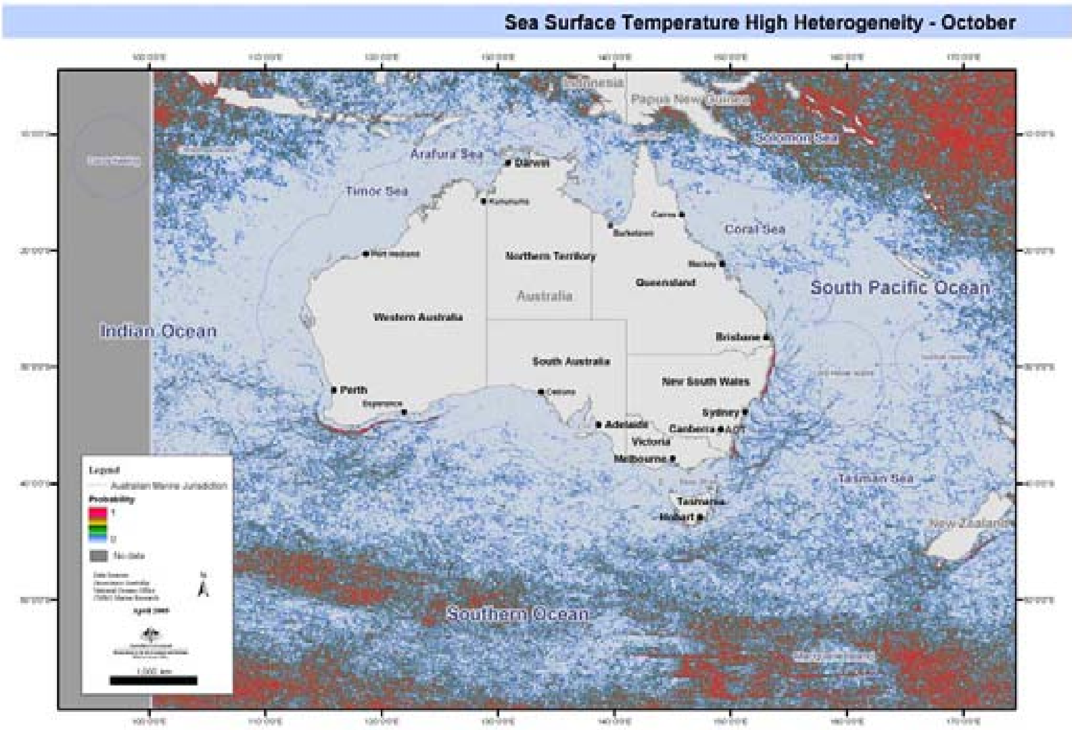


Figure H.4 Eddies and Fields based on Sea Surface Temperature October. (a) low heterogeneity, (b) medium heterogeneity, (c) high heterogeneity, (d) high heterogeneity and high gradients

c



d

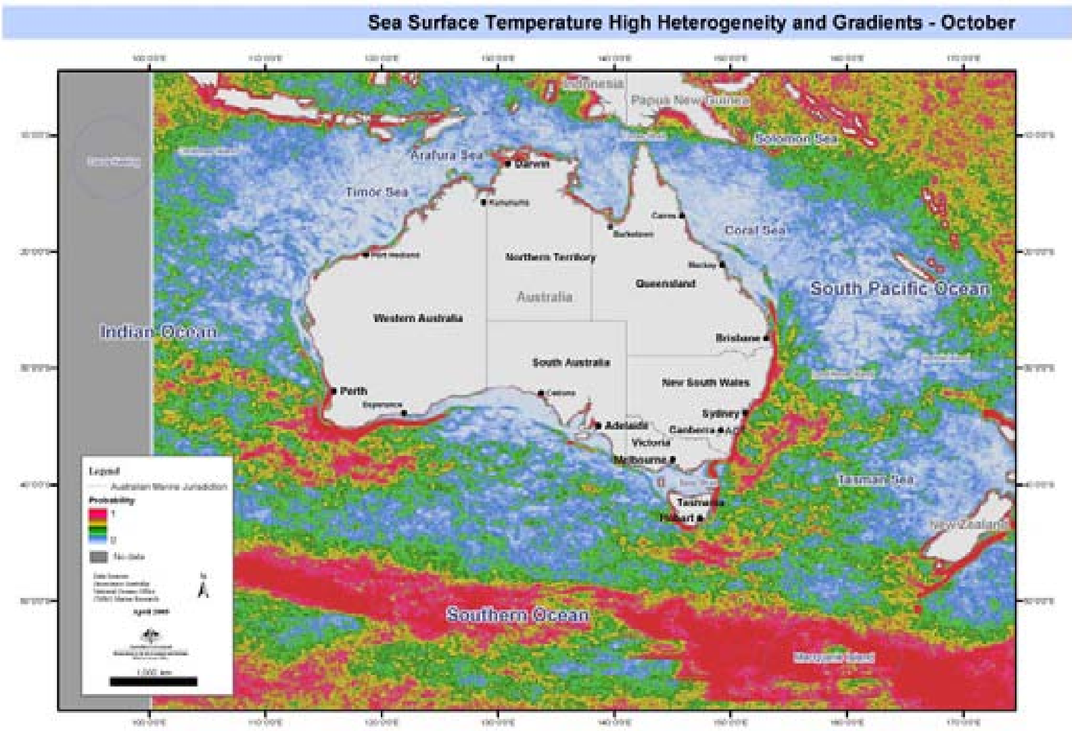
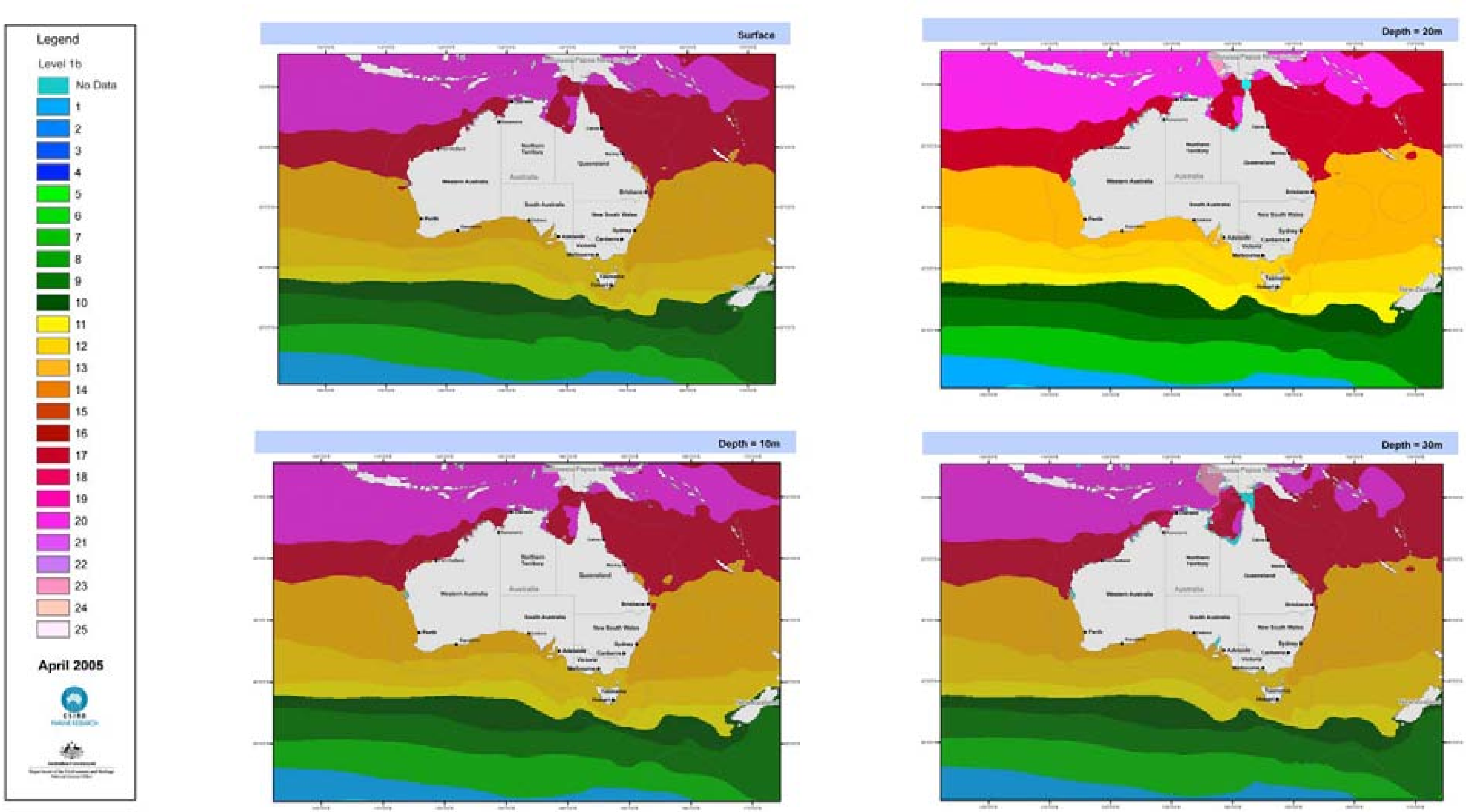


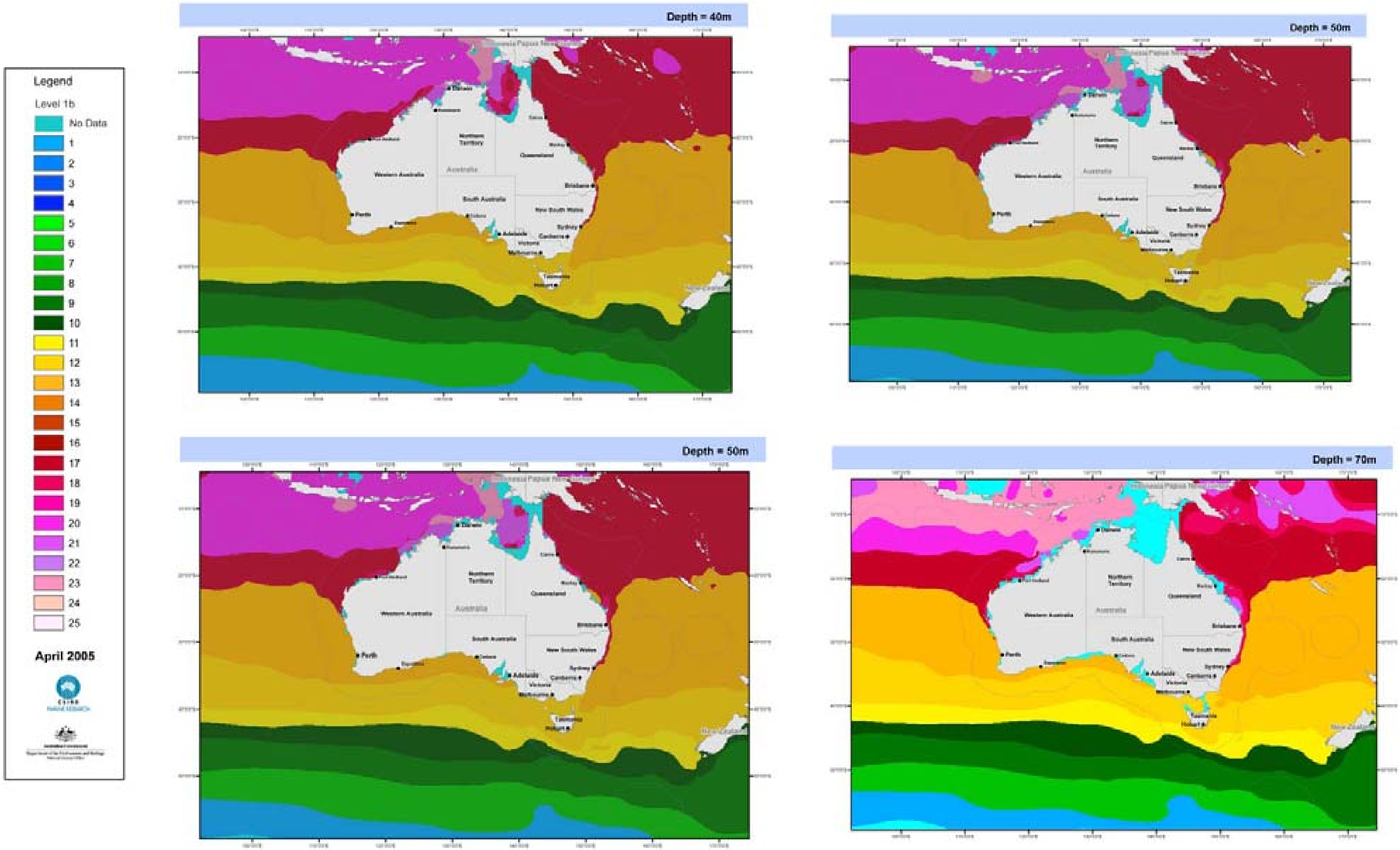
Figure H.4 (cont.) Eddies and Fields based on Sea Surface Temperature October. (a) low heterogeneity, (b) medium heterogeneity, (c) high heterogeneity, (d) high heterogeneity and high gradients.

Appendix I

Pelagic Regionalisation Level 1b for 56 Depths



I-2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Level 1b
No Data
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16
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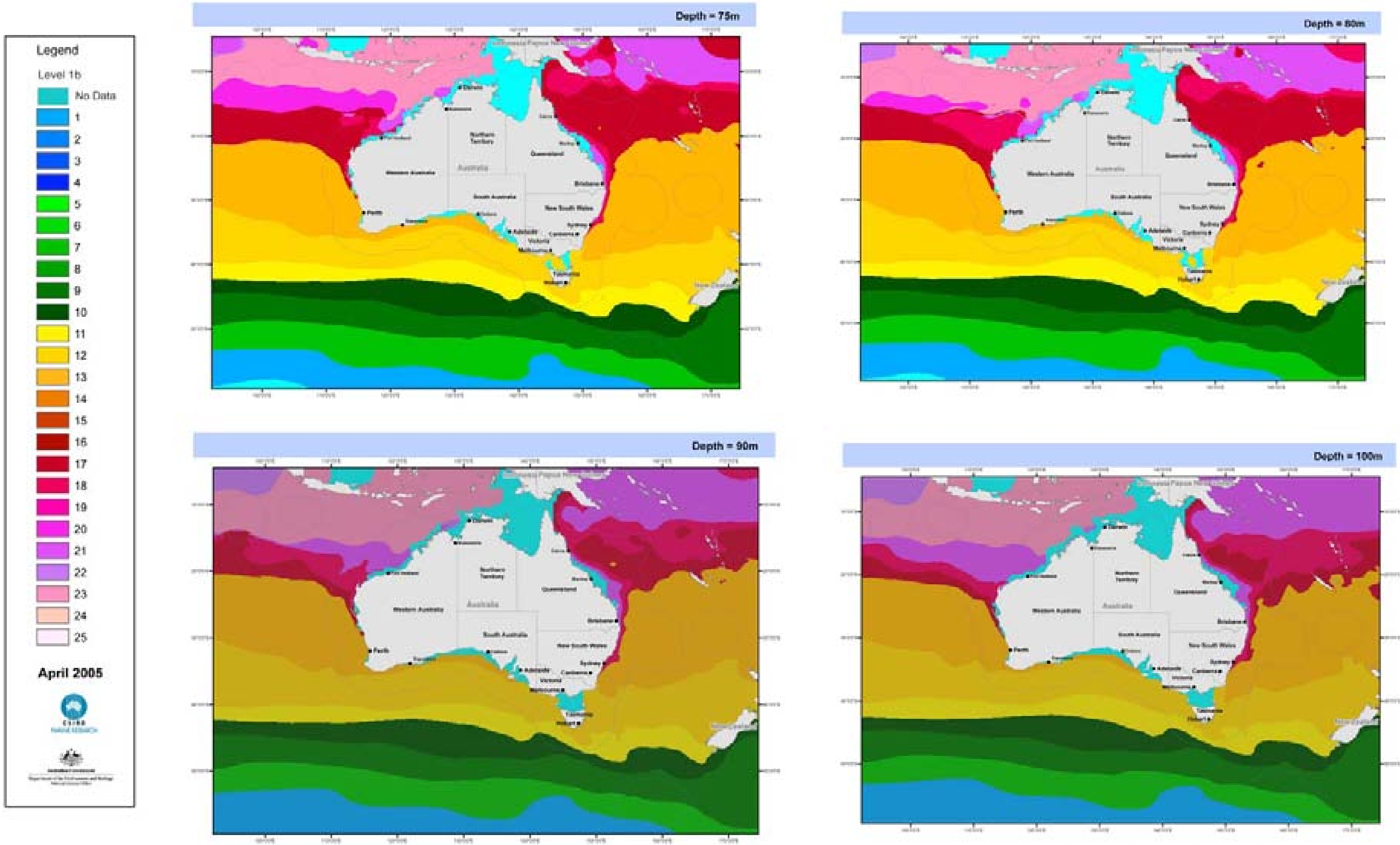
18
19
20
21
22
23
24
25
April 2005
Depth = 40m
Depth = 50m
Depth = 50m
Depth = 70m
Western Australia
Northern Territory
Queensland
South Australia
New South Wales
Victoria
Tasmania
Australia
Darwin
Perth
Adelaide
Melbourne
Canberra
Sydney
Brisbane
Hobart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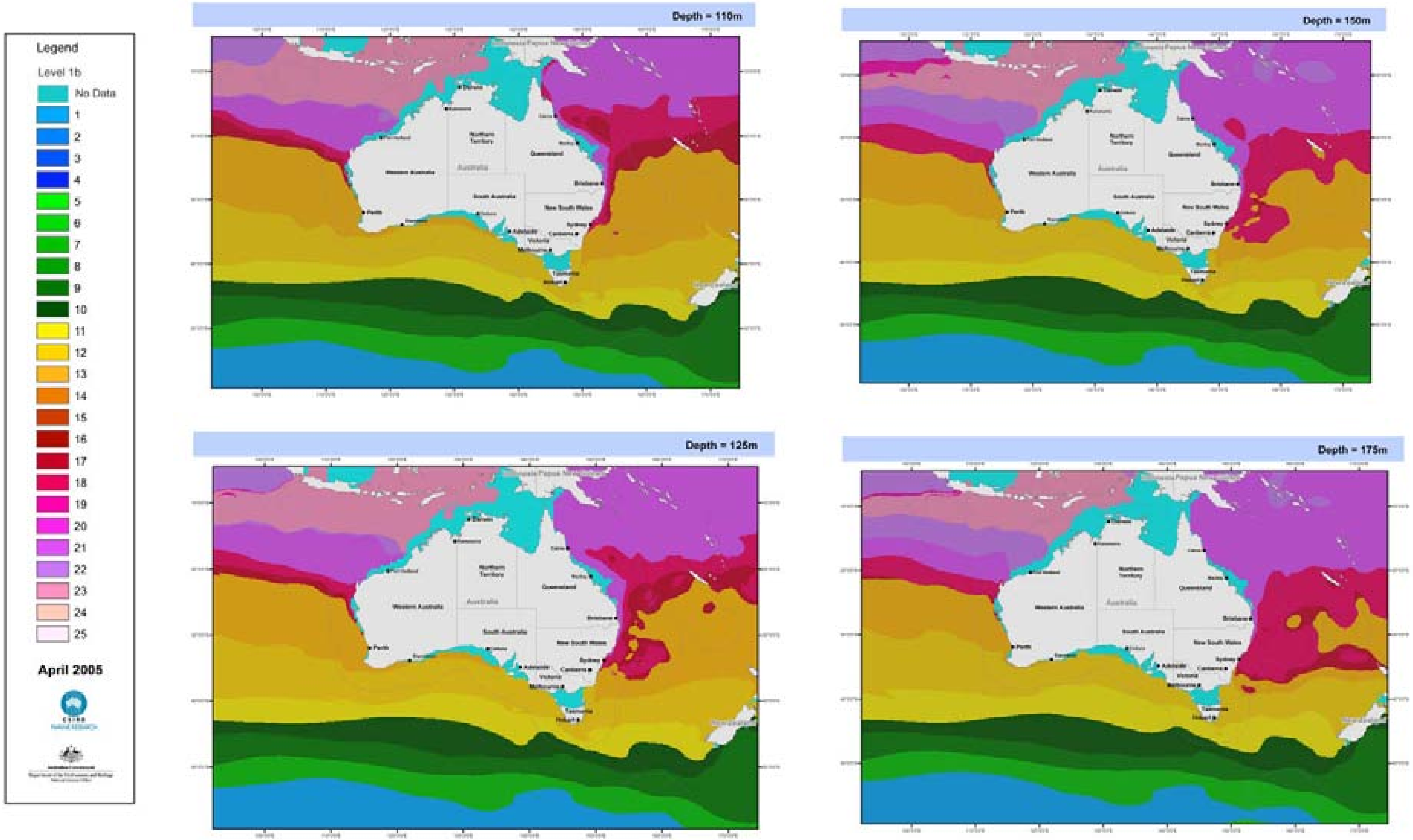
16
17
18
19
20
21
22
23
24
25
April 2005
Depth = 75m
Depth = 80m
Depth = 90m
Depth = 100m
Darwin
Northern Territory
Queensland
Western Australia
Australia
South Australia
New South Wales
Brisbane
Perth
Adelaide
Sydney
Canberra
Victoria
Melbourne
Tasmania
Hobart
New Zealand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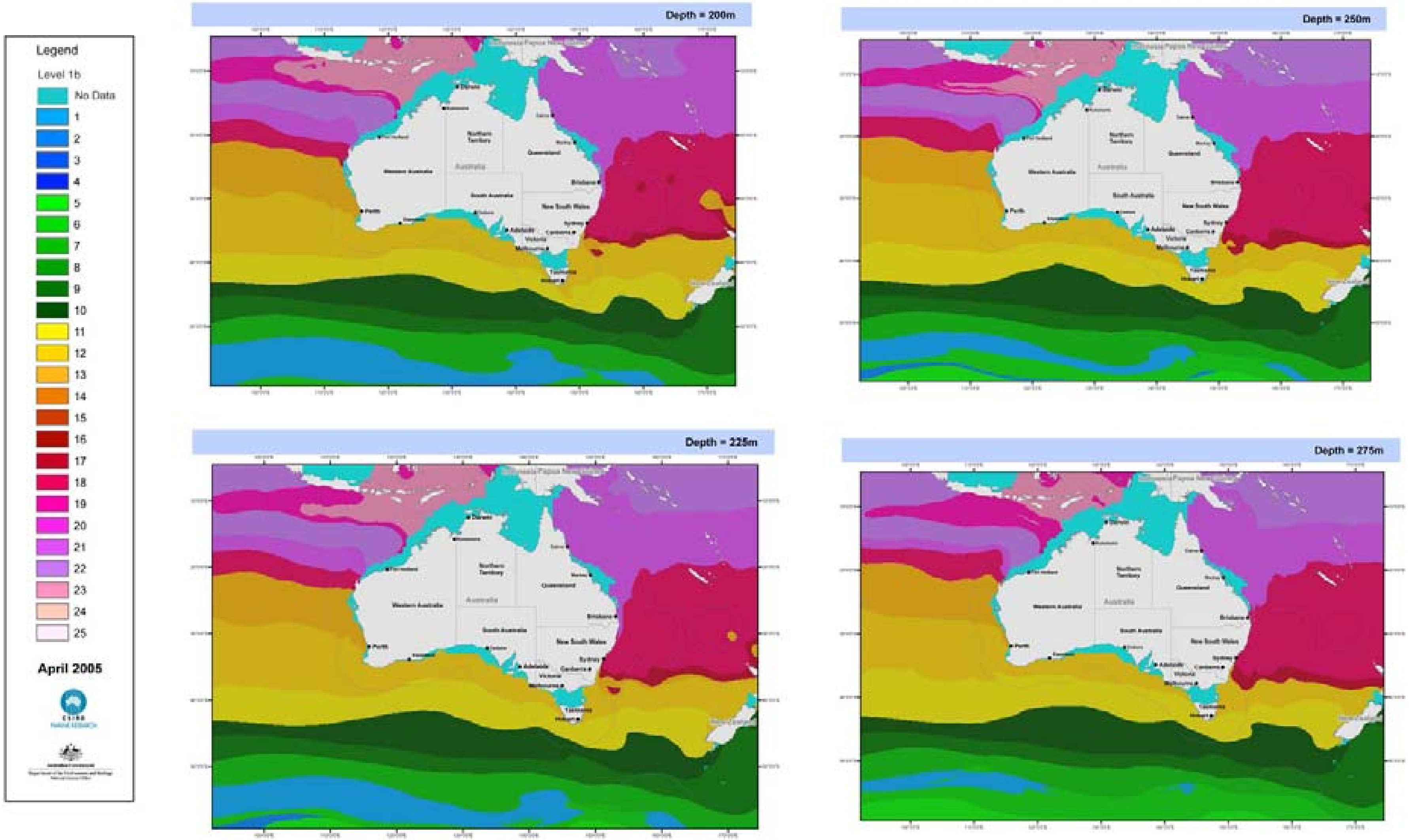
25
April 2005
Depth = 110m
Depth = 150m
Depth = 125m
Depth = 175m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Level 1b
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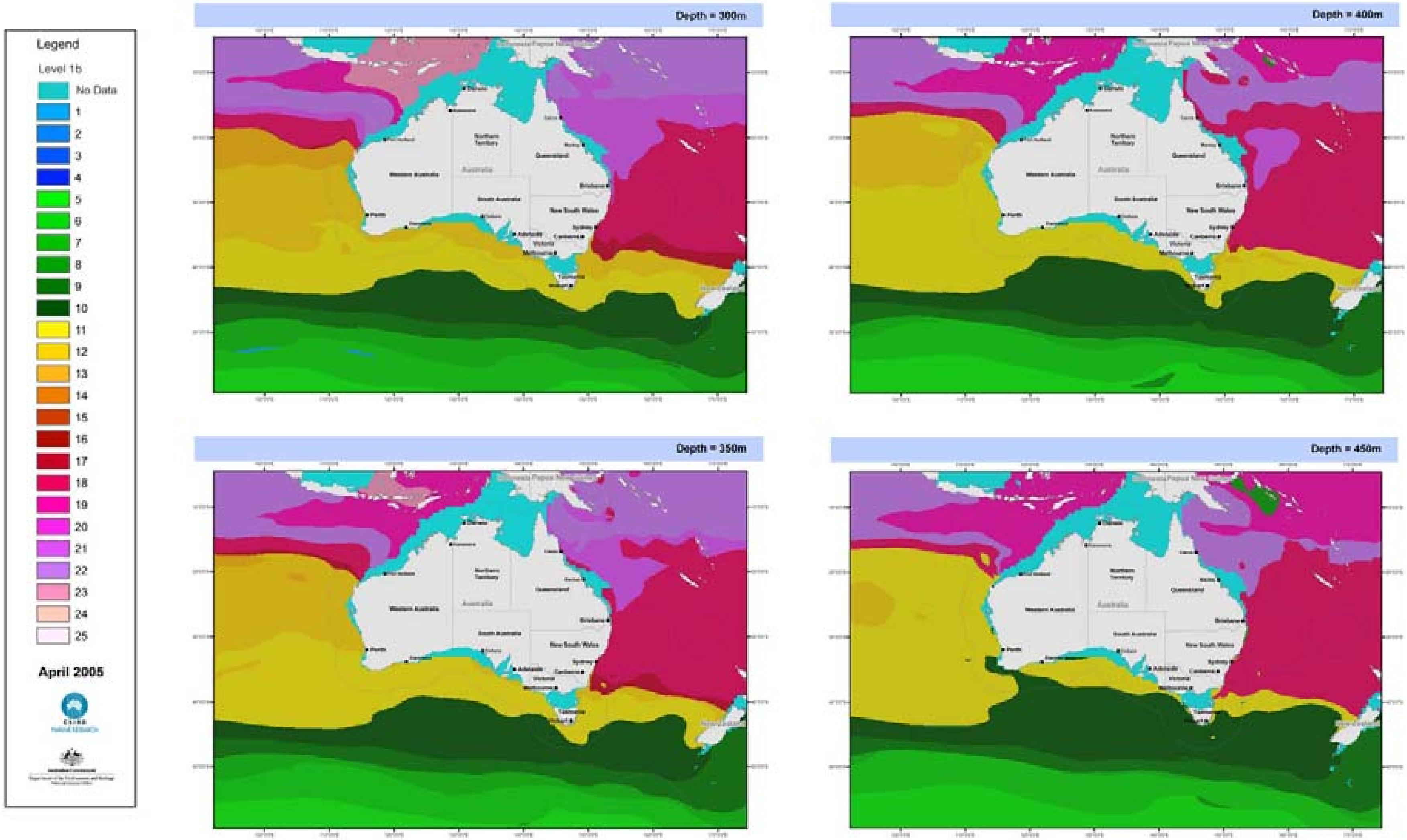
April 2005
Depth = 200m
Depth = 250m
Depth = 225m
Depth = 275m


Legend
Level 1b
No Data
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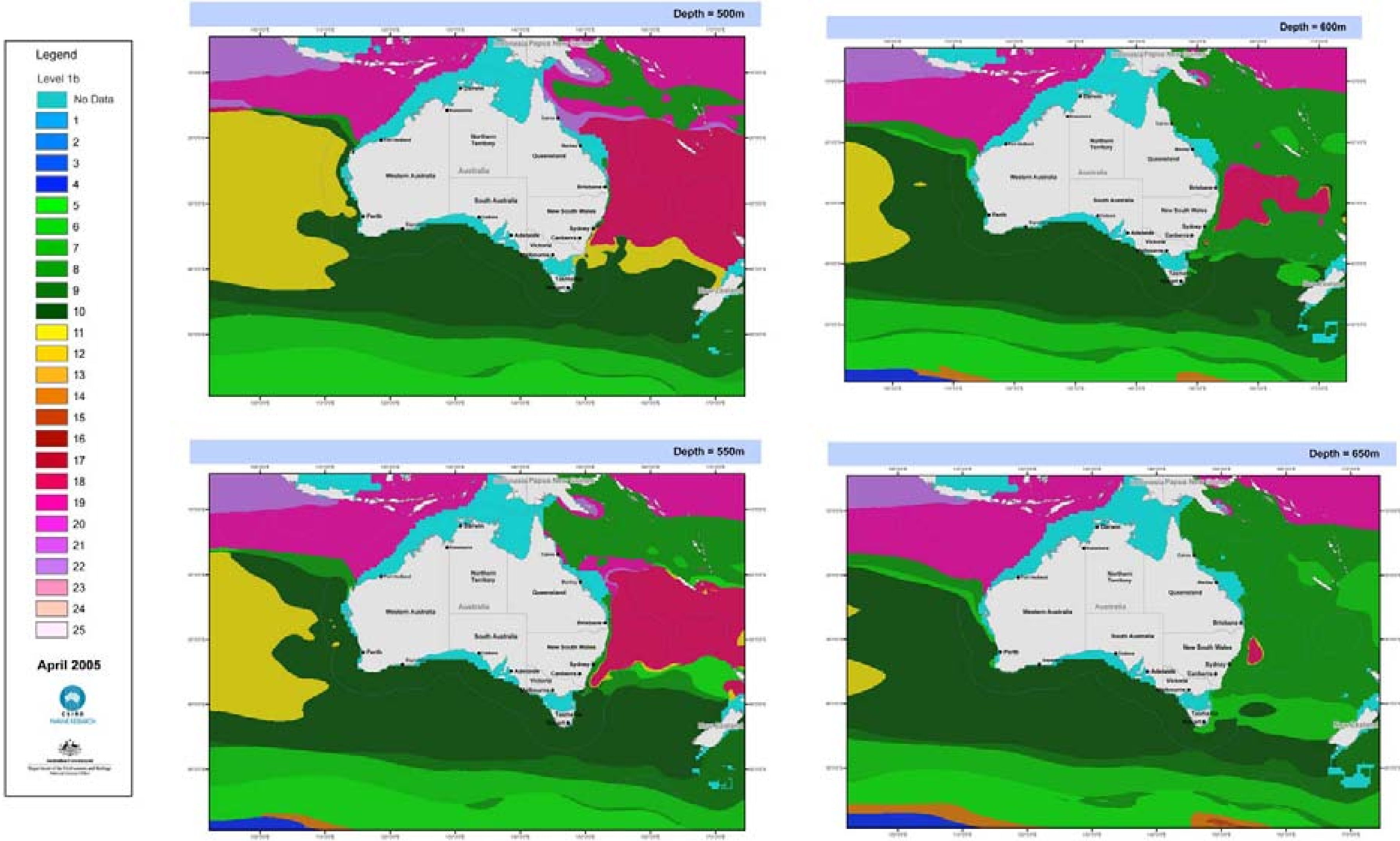
25
April 2005
Depth = 300m
Depth = 400m
Depth = 350m
Depth = 450m


Legend
Level 1b
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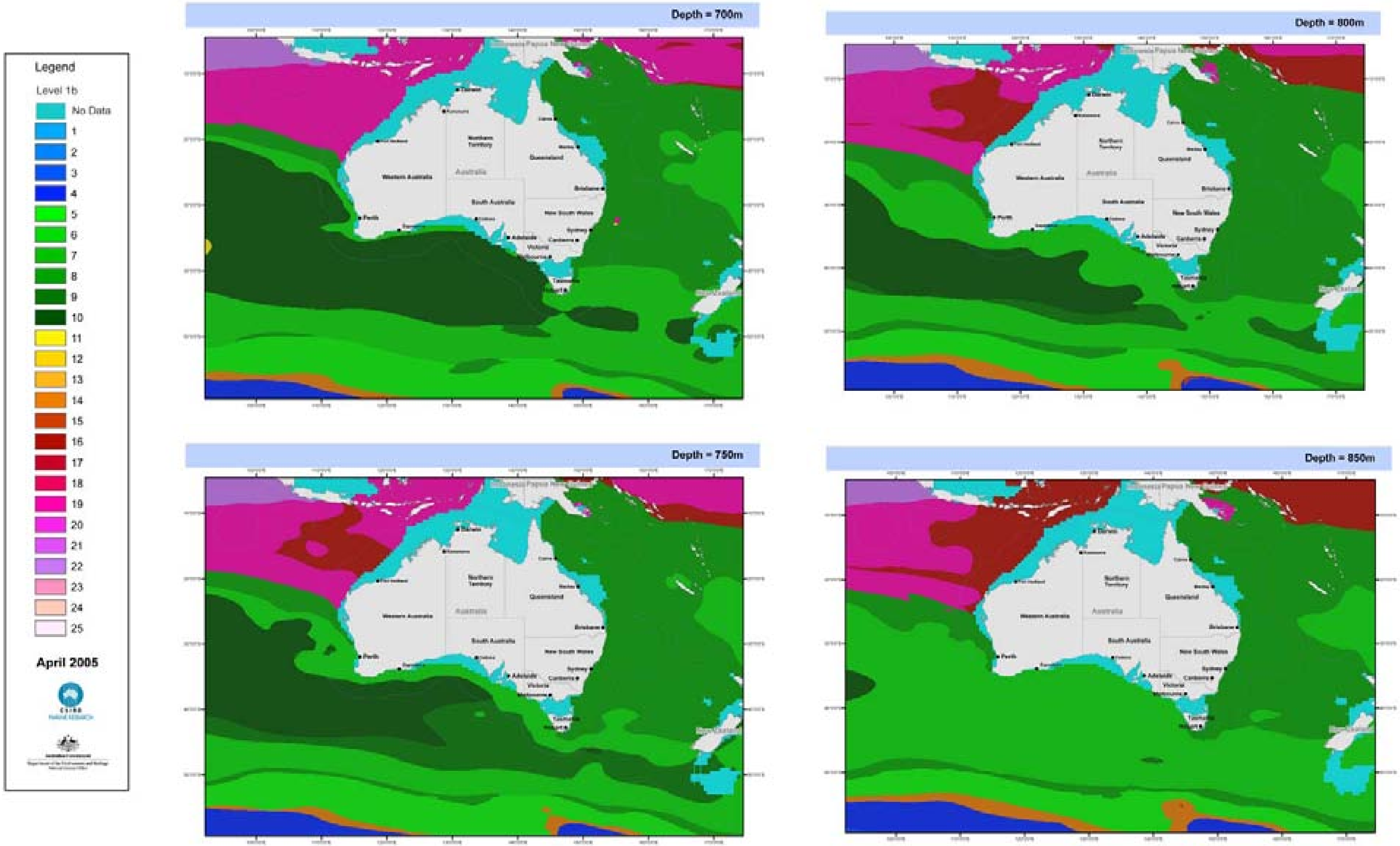
April 2005
Depth = 500m
Depth = 600m
Depth = 550m
Depth = 650m


Legend
Level 1b
No Data
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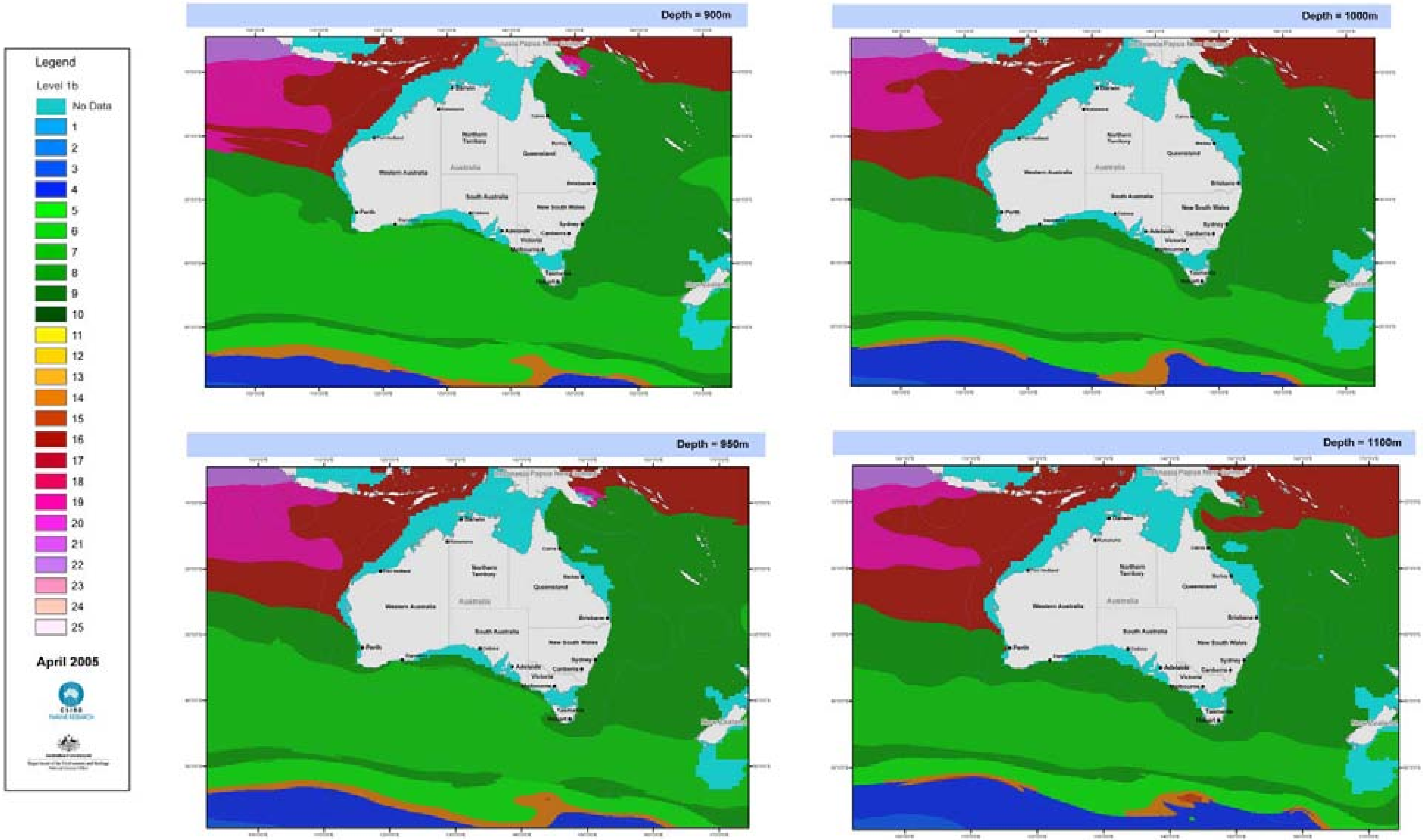
April 2005
Depth = 700m
Depth = 800m
Depth = 750m
Depth = 850m



Legend
Level 1b
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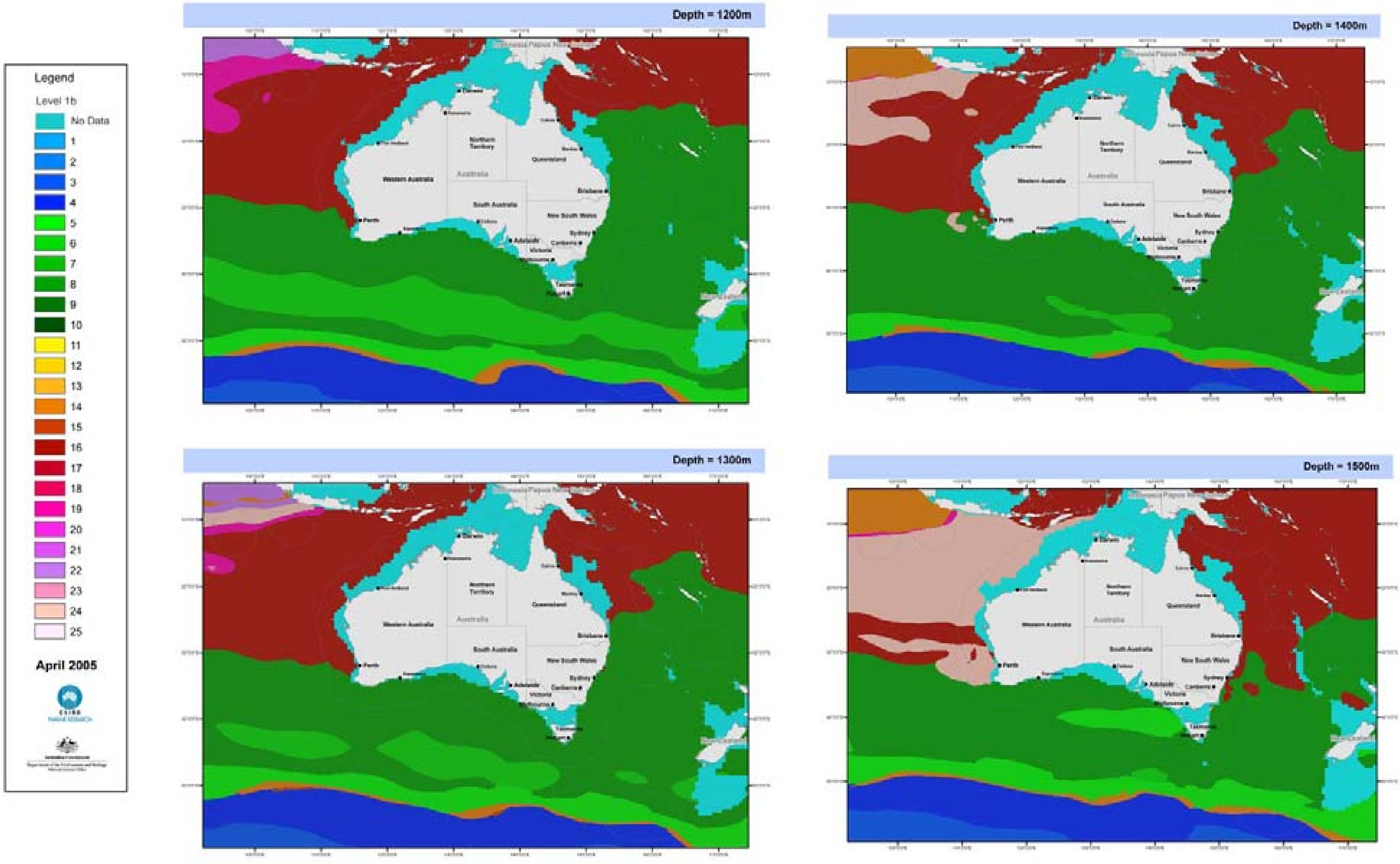
23
24
25
April 2005
Depth = 900m
Depth = 1000m
Depth = 950m
Depth = 1100m
Darwin
Northern Territory
Queensland
Western Australia
Australia
South Australia
New South Wales
Brisbane
Perth
Adelaide
Sydney
Canberra
Victoria
Melbourne
Tasmania
Hobart

I-10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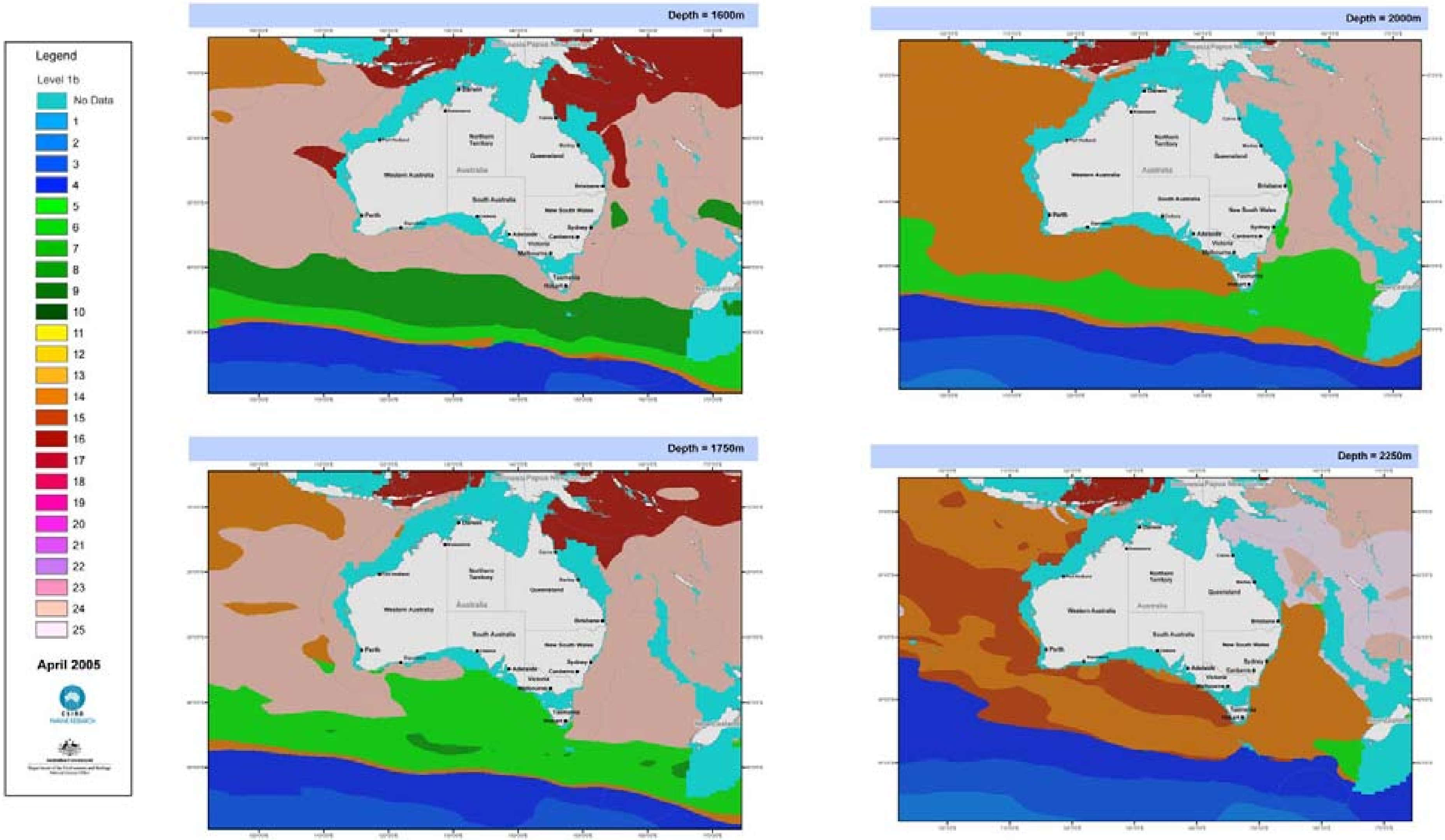
25
April 2005
Depth = 1200m
Depth = 1300m
Depth = 1400m
Depth = 1500m
Western Australia
Northern Territory
Queensland
South Australia
New South Wales
Victoria
Tasmania
Australia
Perth
Darwin
Adelaide
Brisbane
Sydney
Canberra
Melbourne
Hobart


Legend
Level 1b
No Data
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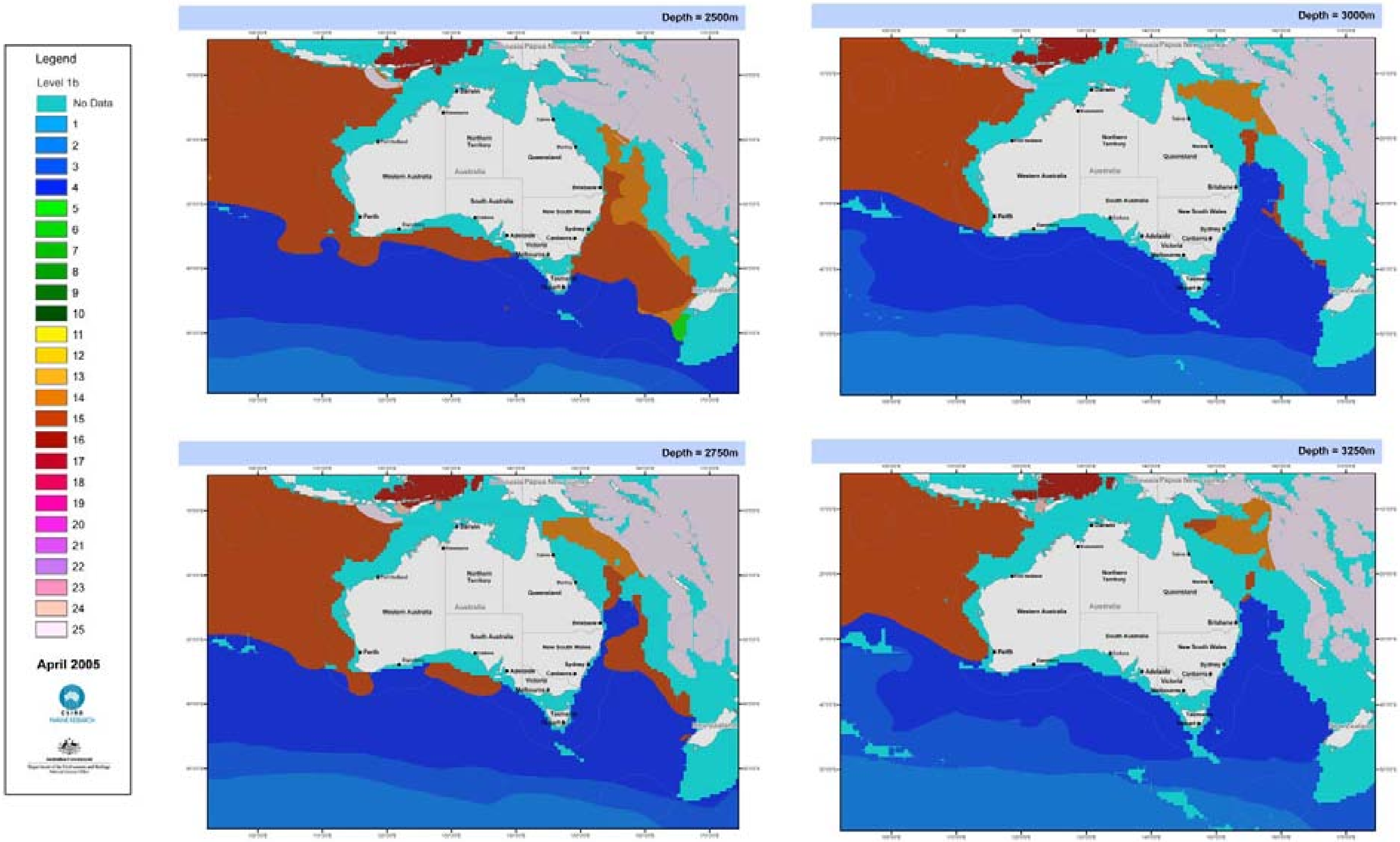
21
22
23
24
25
April 2005
Depth = 1600m
Depth = 2000m
Depth = 1750m
Depth = 2250m
Western Australia
Northern Territory
South Australia
Queensland
New South Wales
Victoria
Tasmania
Australia
Darwin
Perth
Adelaide
Melbourne
Sydney
Brisbane
Canberra
Hobart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Level 1b
No Data
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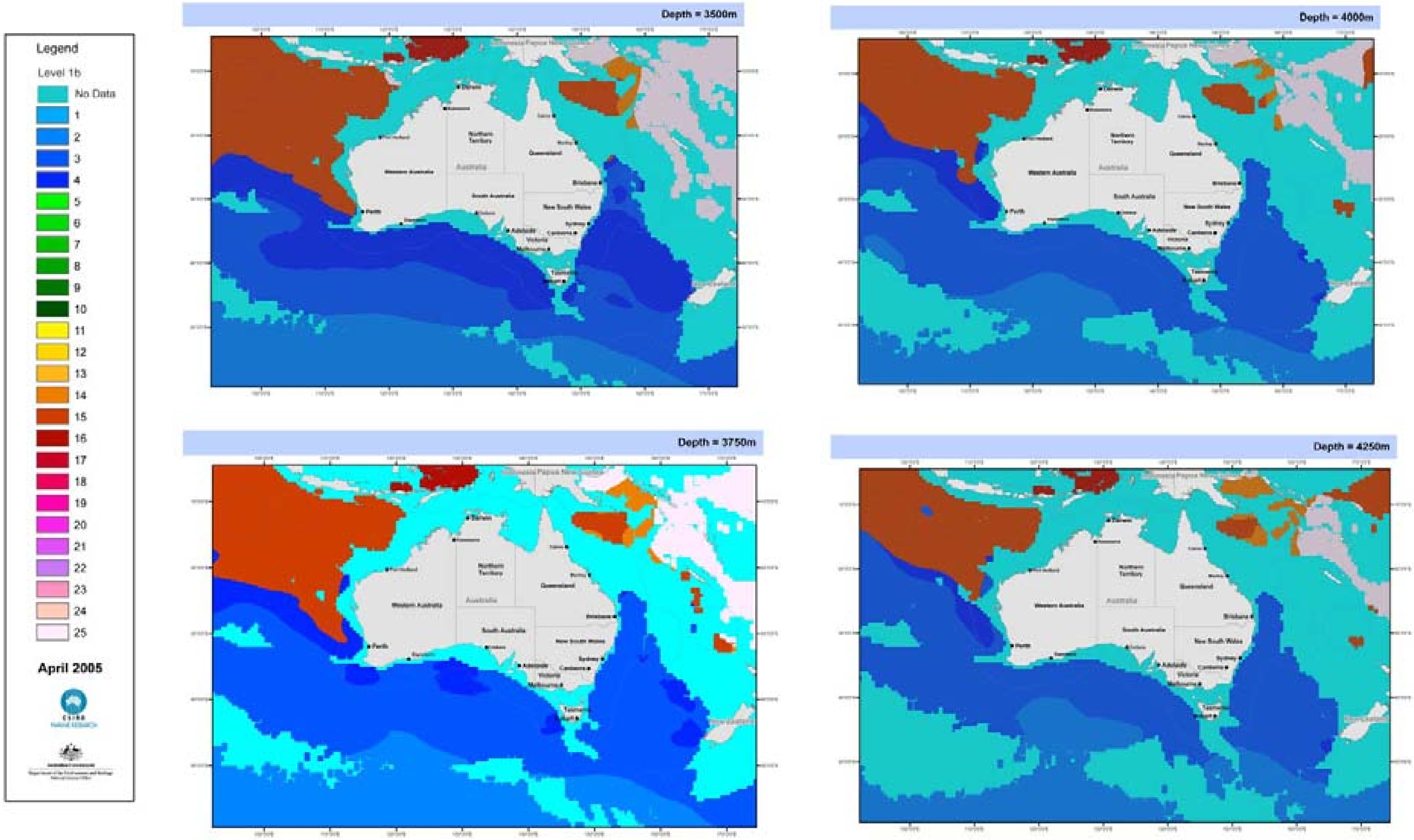
24
25
April 2005
Depth = 2500m
Depth = 3000m
Depth = 2750m
Depth = 3250m


Legend
Level 1b
No Data
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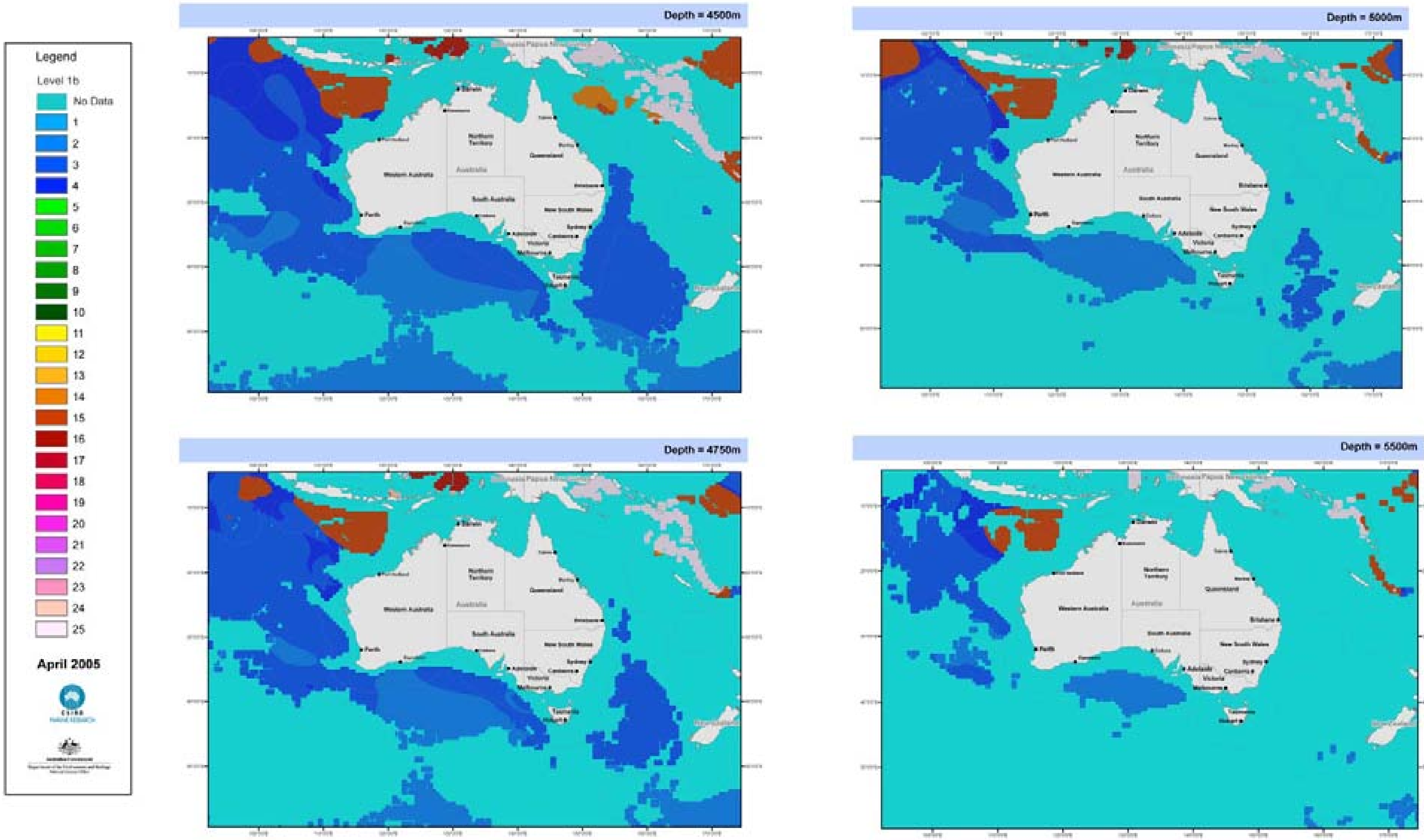
25
April 2005
Depth = 3500m
Depth = 4000m
Depth = 3750m
Depth = 4250m

I-14


Legend
Level 1b
No Data
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25
April 2005
Depth = 4500m
Depth = 5000m
Depth = 4750m
Depth = 5500m

Appendix J

Tables of Level 1b class statistics

Basic statistics for each class are tabulated in Table J-1. The classes are ordered by class number and not by location or depth. Statistics for water properties are tabulated in Table J-2.

Table J-1 Tabulation of basic statistics of the Level 1b classes in relation to depth, position and volume as millions of cubic kilometres. The largest volumes are those of deeper water masses, with a few exceptions associated with intermediate waters. See Appendix B for maps of the 56 depth levels showing the distribution of these classes.

Level 1b Class	Depth	Latitude (^{o})	Longitude (^{o}E)	Volume ($km^3/10^6$)
1	90	-57.4	115.2	0.57
2	3750	-55.5	123.4	12.45
3	3750	-44.4	119.6	22.71
4	2500	-48.8	121.8	18.05
5	850	-54.5	127.8	5.81
6	800	-47.2	133.2	6.60
7	80	-53.7	131.0	0.93
8	1000	-33.4	156.7	13.70
9	100	-49.6	151.7	2.05
10	400	-44.1	127.5	4.40
11	250	-40.9	116.5	2.59
12	100	-37.9	127.5	1.95
13	70	-29.1	153.4	1.58
14	2000	-31.0	112.0	9.08
15	3250	-15.5	105.7	18.76
16	1200	-8.9	145.1	14.54
17	50	-16.5	157.8	1.00
18	275	-23.9	163.0	2.66
19	600	-8.9	122.9	5.44
20	20	-8.3	116.4	0.62
21	125	-11.6	156.3	1.71
22	300	-6.3	106.8	3.70
23	100	-8.5	119.5	0.91
24	1750	-22.2	154.7	11.06
25	3000	-13.1	167.9	14.74

Table J-2 Basic statistics of (a) temperature, (b) salinity, (c) oxygen, (d) nitrate and (e) silicate. for each of the Level 1b classes. Note that statistics are not volume-averaged and points in each depth layer are treated equally.

(a)

	Temperature (°C)			
Class	**Mean**	**Min**	**Max**	**Std.Dev.**
1	1.09	land	2.21	0.53
2	0.53	land	1.67	0.35
3	1.17	0.65	1.75	0.16
4	1.73	0.95	2.35	0.27
5	2.24	1.15	9.78	0.65
6	4.47	0.83	8.70	1.72
7	3.46	1.72	5.90	0.96
8	4.72	1.93	9.94	1.77
9	7.14	4.32	15.31	1.24
10	8.93	5.30	21.99	0.98
11	10.64	8.60	15.47	0.90
12	13.59	10.06	19.67	1.44
13	19.15	12.89	26.25	2.50
14	2.42	1.63	4.48	0.54
15	1.60	1.09	2.34	0.32
16	3.94	2.43	6.75	0.90
17	25.62	10.67	29.41	3.43
18	16.75	8.88	29.21	5.30
19	7.42	3.51	19.08	2.00
20	27.69	21.61	30.34	1.16
21	22.89	12.26	29.07	3.96
22	12.93	4.30	28.29	4.62
23	20.99	9.22	28.84	4.94
24	2.71	1.90	4.44	0.45
25	1.81	1.15	2.21	0.18

(b)

	Salinity (psu)			
Class	**Mean**	**Min**	**Max**	**Std.Dev.**
1	34.04	33.80	34.52	0.15
2	34.70	34.44	34.72	0.02
3	34.72	34.70	34.76	0.01
4	34.74	34.68	34.77	0.01
5	34.63	34.40	34.72	0.06
6	34.41	34.15	34.62	0.07
7	33.99	33.80	34.37	0.11
8	34.50	34.38	34.72	0.06
9	34.28	33.79	34.53	0.14
10	34.60	34.40	34.73	0.06
11	34.83	34.69	35.08	0.08
12	35.24	34.74	35.72	0.17
13	35.64	35.13	37.56	0.14
14	34.72	34.67	34.85	0.03
15	34.72	34.68	34.76	0.01
16	34.59	34.47	34.68	0.04
17	35.12	34.66	36.04	0.25
18	35.27	34.72	36.97	0.29
19	34.61	34.46	34.74	0.06
20	34.21	29.32	34.72	0.50

21	35.43	34.71	36.11	0.27
22	34.96	34.69	35.84	0.22
23	34.50	32.85	34.73	0.15
24	34.64	34.56	34.72	0.03
25	34.68	34.65	34.72	0.01

(c)

Class	Mean	Oxygen (mm/l) Min	Max	Std.Dev.
1	7.06	4.76	7.95	0.84
2	5.01	4.46	5.79	0.21
3	4.65	4.36	4.95	0.11
4	4.43	4.01	4.73	0.12
5	4.18	3.74	4.60	0.12
6	4.74	4.31	5.67	0.24
7	6.97	5.19	7.78	0.54
8	4.08	3.36	4.64	0.26
9	6.38	4.90	7.24	0.48
10	5.75	4.45	6.63	0.49
11	5.74	4.36	6.40	0.34
12	5.58	4.73	6.22	0.27
13	5.09	4.61	5.95	0.23
14	3.65	1.96	4.45	0.63
15	3.99	3.22	4.46	0.26
16	2.71	1.90	3.75	0.45
17	4.62	4.07	5.35	0.13
18	4.40	3.75	4.81	0.14
19	2.49	1.52	4.38	0.53
20	4.42	3.63	5.33	0.17
21	3.83	2.95	4.39	0.29
22	2.53	1.23	4.38	0.78
23	3.21	2.04	4.32	0.55
24	3.30	2.05	3.98	0.40
25	3.49	2.31	4.15	0.23

(d)

Class	Mean	Nitrate (mg/l) Min	Max	Std.Dev.
1	27.67	22.62	34.26	2.42
2	32.05	25.04	38.30	1.59
3	32.49	25.55	38.16	1.87
4	32.05	25.99	40.36	1.96
5	32.73	14.22	41.38	1.84
6	29.94	15.73	38.09	3.10
7	24.24	15.70	33.00	2.71
8	31.61	14.55	41.54	4.15
9	18.59	0.56	32.96	4.47
10	16.22	0.04	28.59	4.82
11	10.63	0.37	24.41	4.05
12	4.33	0.02	18.80	3.07
13	1.36	0.00	13.09	1.57
14	34.03	25.34	41.21	2.05
15	34.00	24.28	39.56	1.51
16	36.53	25.13	46.11	2.45
17	0.92	0.00	17.38	2.08
18	8.60	0.03	26.56	6.25
19	31.79	8.95	40.90	4.26
20	0.66	0.00	10.65	0.78
21	5.46	0.01	21.84	3.00

22	22.69	0.54	40.25	8.97
23	10.96	0.28	32.18	7.60
24	35.99	27.46	42.37	1.86
25	36.02	27.41	42.42	1.71

(e)

Class	Silicate (mg/l) Mean	Min	Max	Std.Dev.
1	32.82	7.60	76.22	13.41
2	120.59	53.15	138.63	7.09
3	114.48	83.96	141.95	10.18
4	96.54	70.90	144.66	13.77
5	74.81	8.59	118.90	8.18
6	35.77	8.97	78.54	14.66
7	14.02	0.82	54.29	8.67
8	48.16	land	100.06	20.24
9	7.65	0.65	38.03	5.51
10	6.90	0.94	32.41	3.81
11	4.27	0.74	20.09	2.00
12	2.71	0.27	14.17	1.42
13	2.55	0.31	16.21	1.58
14	94.72	68.47	141.21	13.49
15	117.75	71.99	147.96	13.09
16	91.33	37.66	148.00	21.03
17	2.56	0.25	16.21	1.69
18	5.04	0.40	54.10	3.30
19	52.45	7.98	116.91	20.04
20	3.76	0.00	56.33	2.25
21	3.68	0.76	20.25	2.73
22	26.44	1.94	105.42	21.09
23	15.00	1.54	49.80	10.17
24	102.63	61.57	149.93	16.86
25	126.53	82.55	152.92	11.47

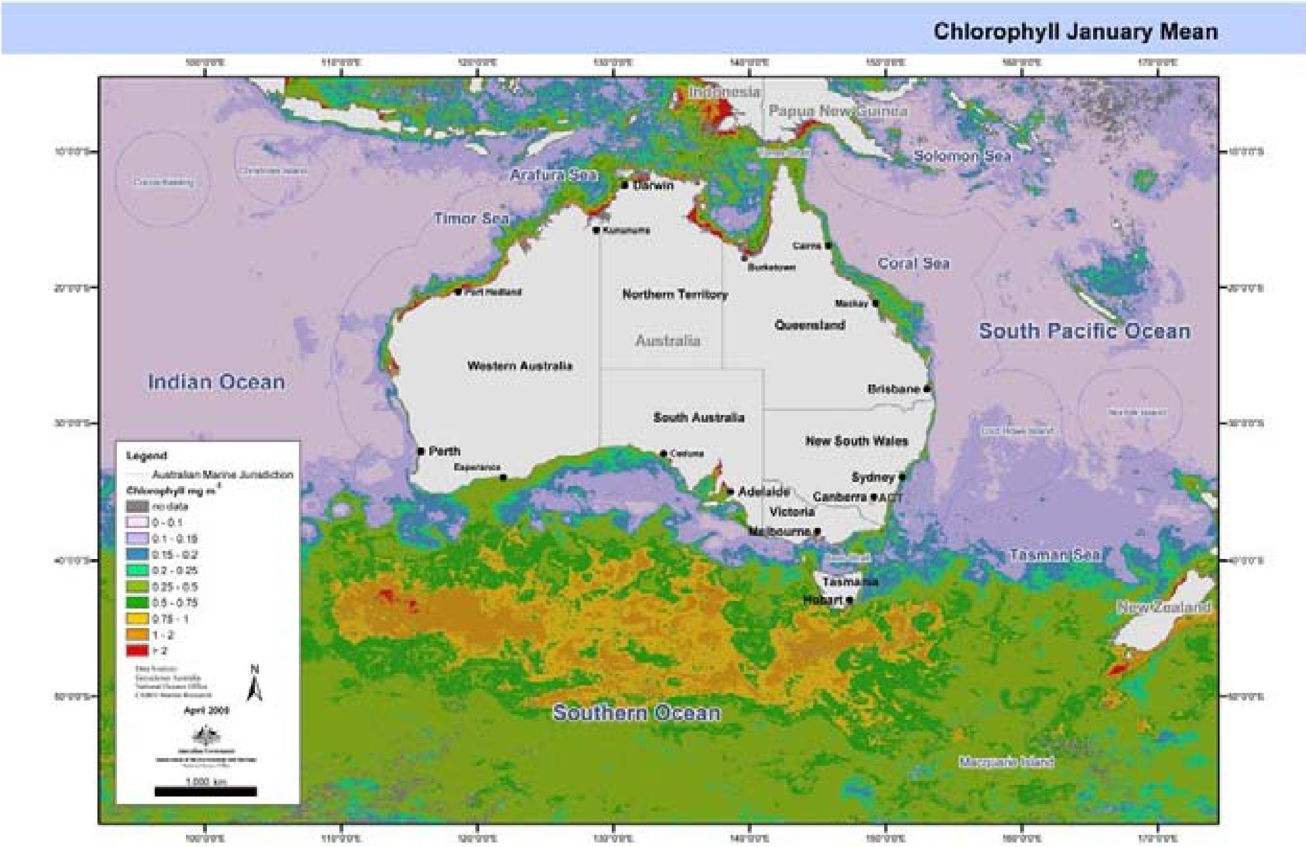
Appendix K

Chlorophyll and primary production patterns

Brian Griffiths CSIRO Marine Research

Maps and descriptions of the seasonal patterns of chlorophyll and primary production are presented in this section. These form the basis for the 6 major chlorophyll regions that are used in the main body of the report to compare with the pelagic regionalisation classes.

a.



b.

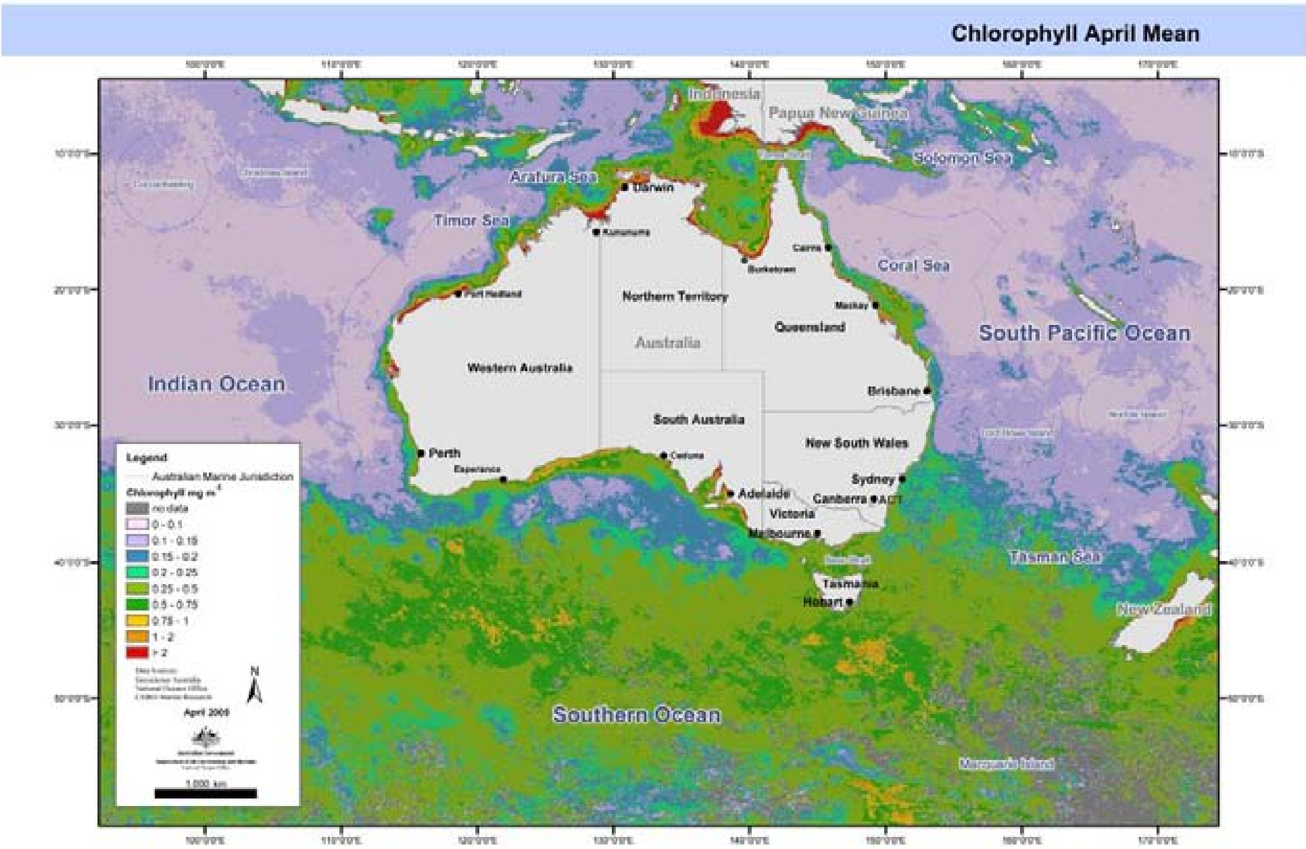
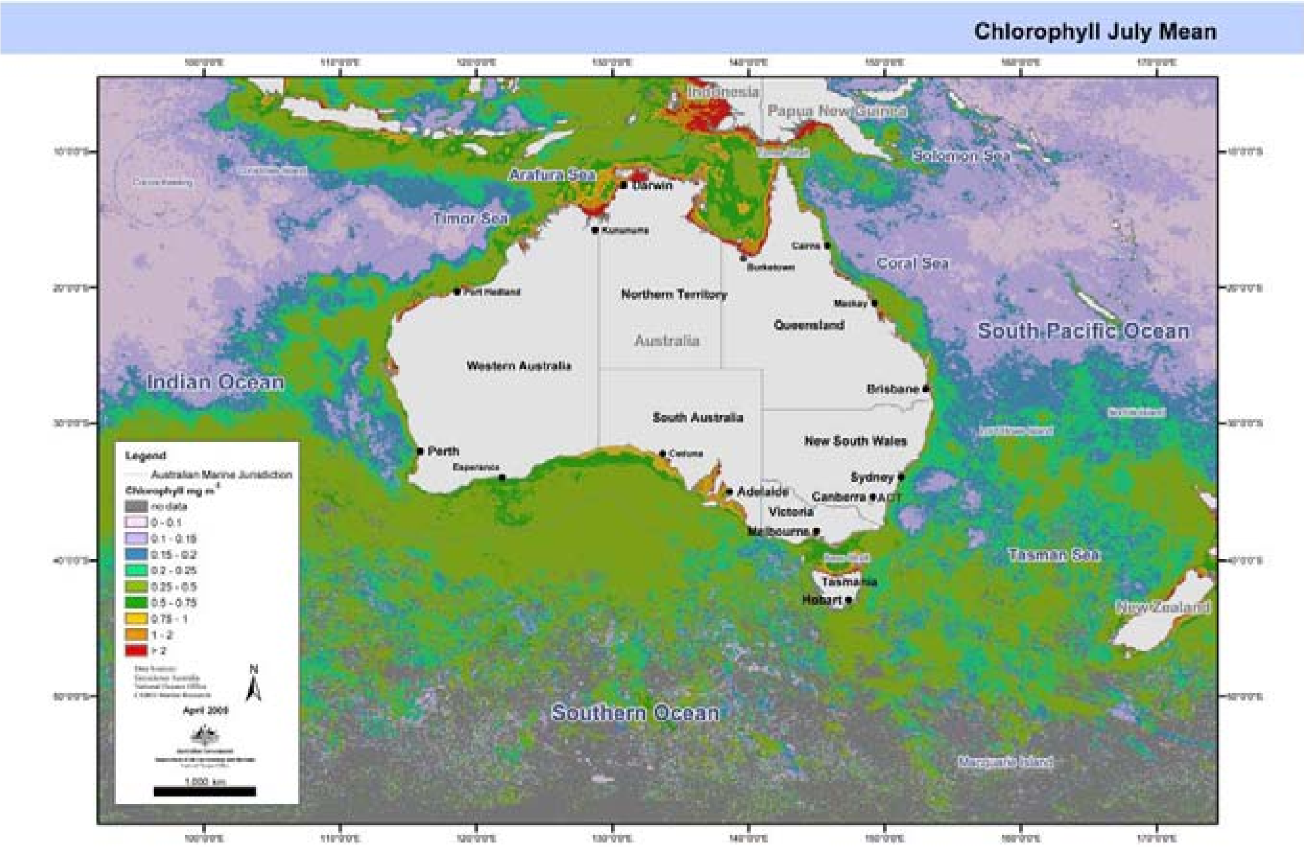


Figure K-1 Monthly means for chlorophyll for (a) January, (b) April, (c)July, (d) October (MODIS Aqua, 2002- 2004). For a full description see Hayes et al. (2005).

c.



d.

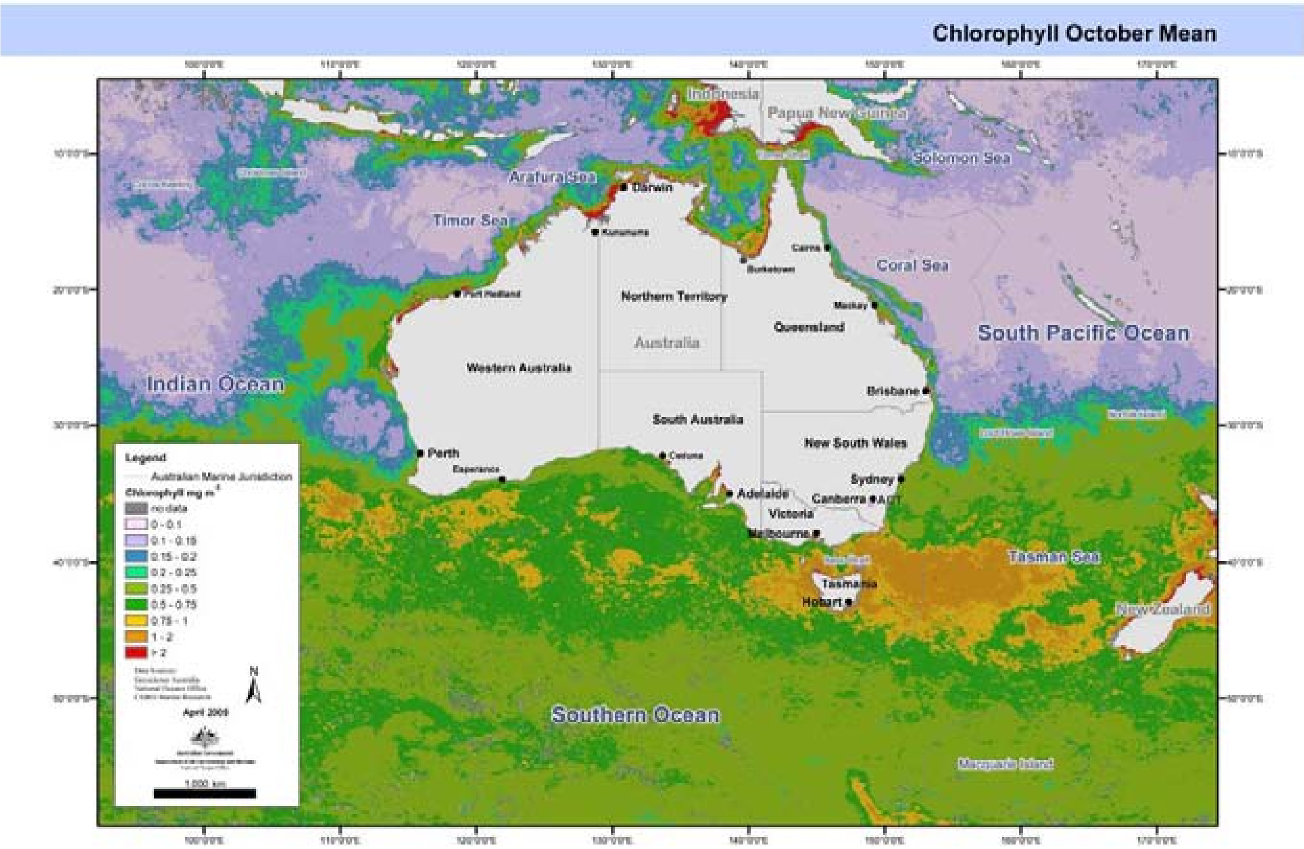
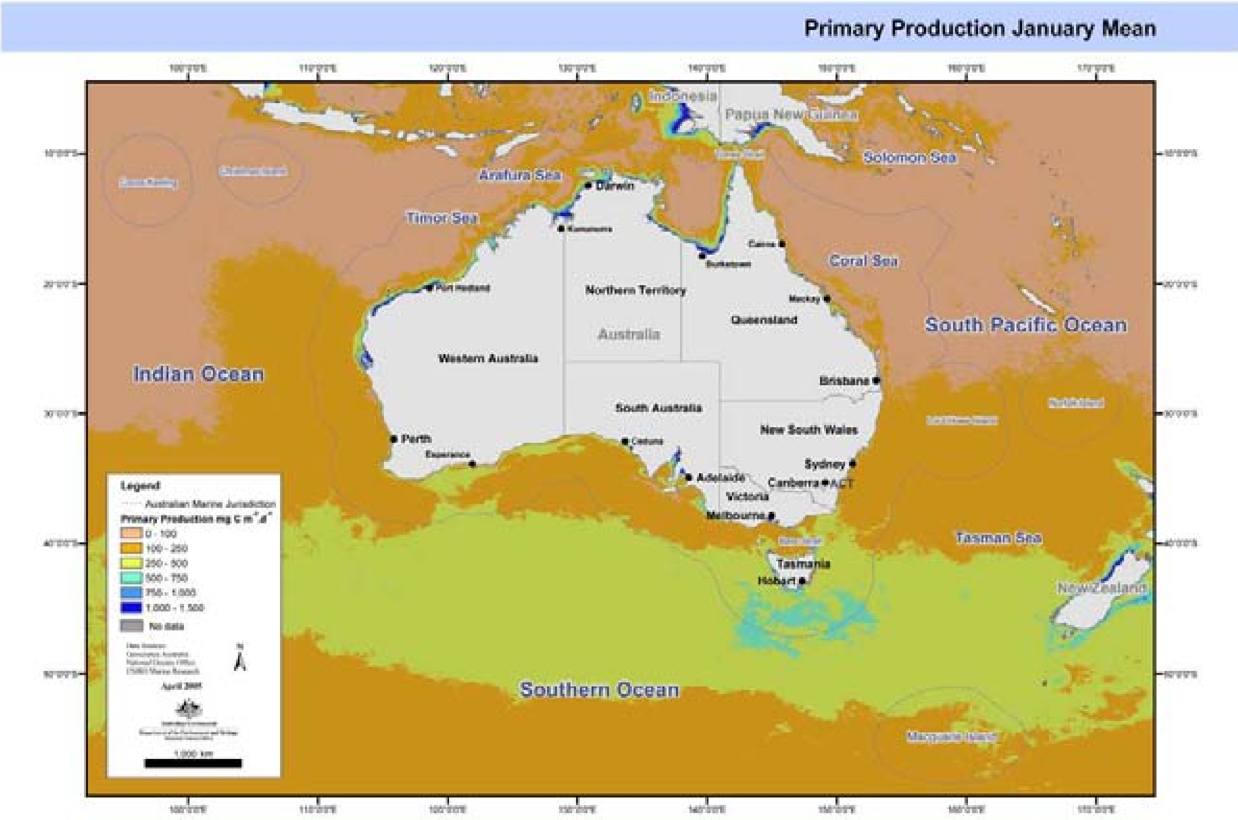


Figure K-1 (cont.) Monthly means for chlorophyll for (a) January, (b) April, (c)July, (d) October (MODIS Aqua, 2002- 2004). For a full description see Hayes et al. (2005).

a.



b.

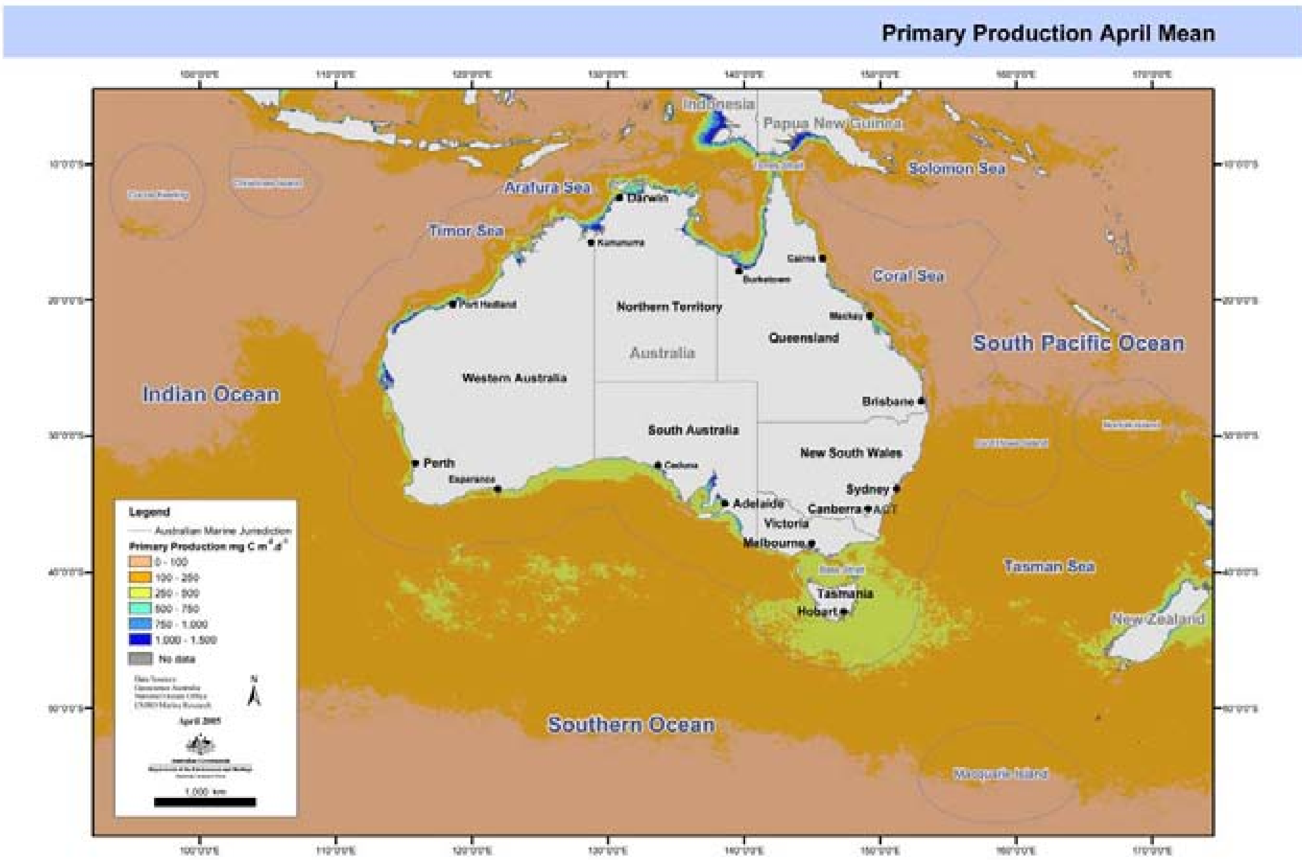
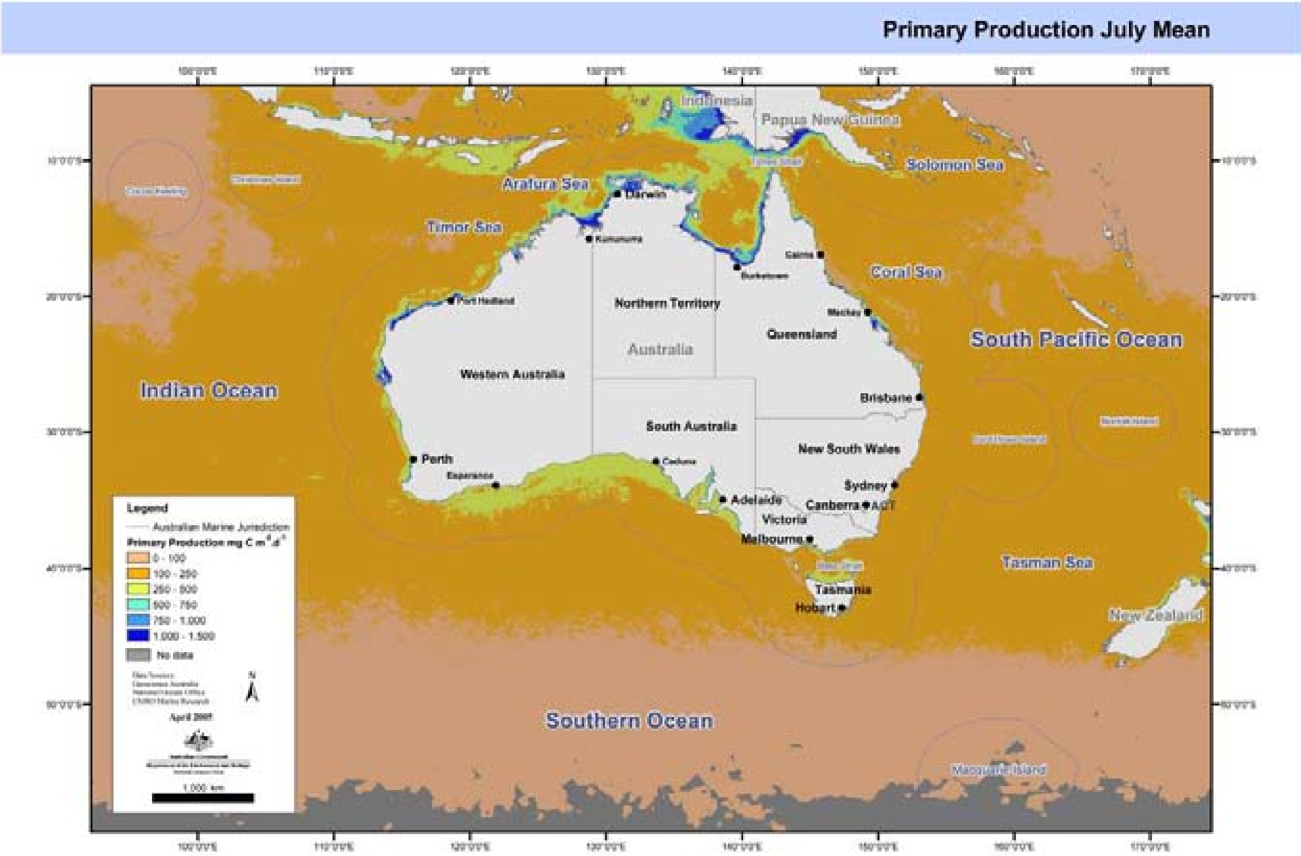


Figure K-2 Monthly means for Primary production for (a) January, (b) April, (c) July and (d) October (MODIS 1997-2004). For a full Description see Hayes et al. (2005).

c.



d.

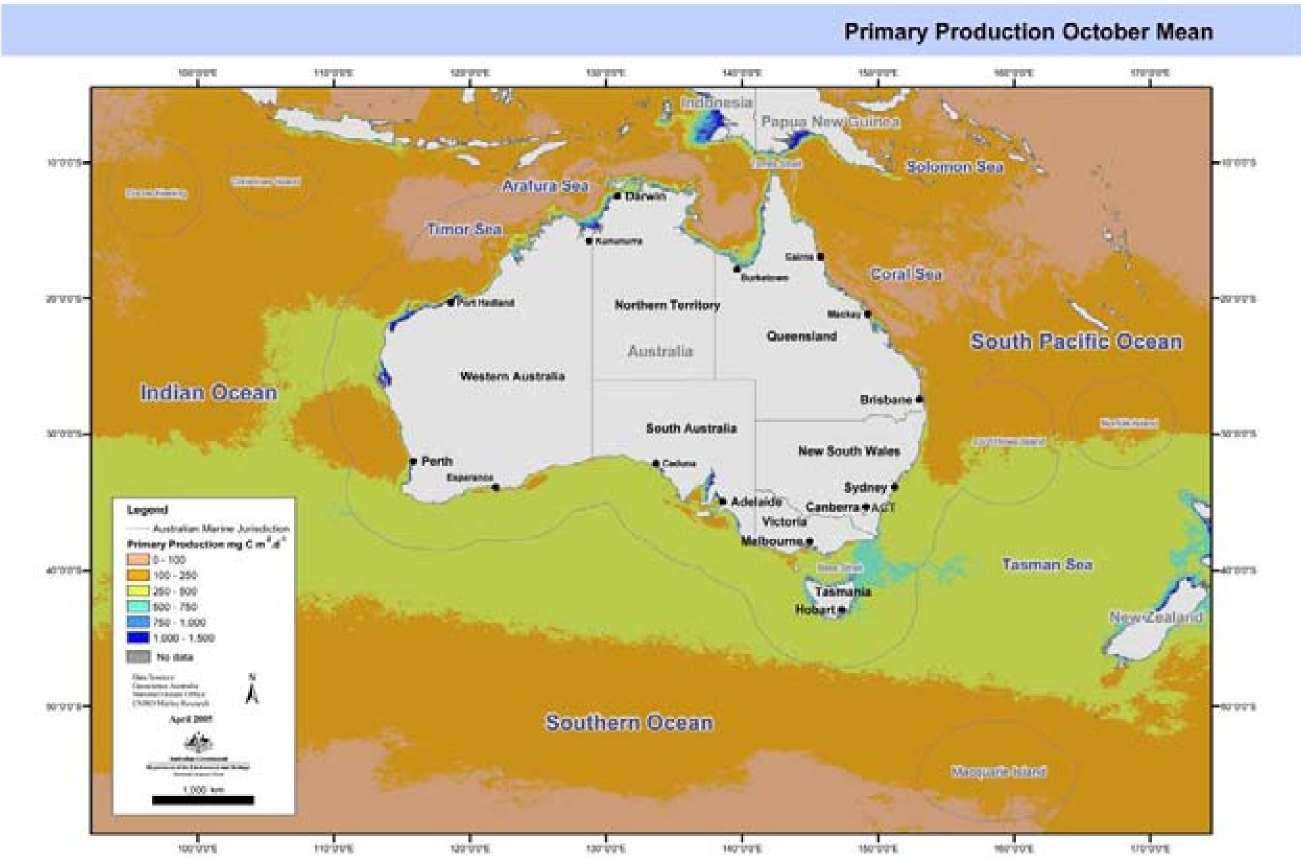


Figure K-2 (cont.) Monthly means for Primary production for (a) January, (b) April, (c) July and (d) October (MODIS 1997-2004). For a full Description see Hayes et al. (2005).

The following sections provide descriptions of the six major regions comprising:

1. The Southern Ocean, in a broad latitudinal band between about 40°S and 60°S and 90°E to 180°E.
2. The Indian Ocean sector between about 20°S and 40°S.
3. The Timor Sea region.
4. The Arafura Sea/Gulf of Carpentaria region to Torres Strait.
5. The Coral Sea region north of 25°S.
6. The Tasman Sea sector, between about 25°S and 40°S.

1. The Southern Ocean region

This region is bounded to the north by the Subtropical Convergence (STC) and in the south near 60°S, by the southern branch of the Polar Front. The water masses and fronts in this region are the Subantarctic Zone (SAZ), the Subantarctic Front, a Polar Frontal Zone, the northern branch of the Polar Front, the Polar water mass, the southern branch of the Polar Front and the Antarctic Zone south of 60°S (see Trull et al, 2001). The wind stress in this region is consistently the highest around Australia and wind stress drives much of the complex dynamics of the region. The Subtropical Convergence (STC, Level 1b_11 and 1b_12) form the northern edge of this region, separating the warm, salty, nutrient poor surface water masses from the fresher, cooler, comparatively nutrient enriched water masses to the south. Mixing of these waters occurs in the STC and this can lead to high standing stocks of chlorophyll and high productivity. Rintoul and Trull (2001) found winter mixing—a combination of seasonal cooling and wind stress—will form mixed layers extending to over 400 m in the SAZ, but somewhat shallower in the Polar waters. Nutrients from this deep mixing are brought to the surface layers and seasonal heating traps these nutrients in shallow mixed layers.

During spring and summer, there are high phytoplankton growth rates and high primary production in these layers (Figs K-2 b, d). The impact of the high-nutrient water can be seen by the extensive region of high chlorophyll in October, January and April across the Southern Ocean (Fig K-1 a, b and d) and slightly elevated levels in July (Fig k-1c). The broad band of primary production greater than 250 mg C m^{-2} d^{-1} seen in October and January, reflect increases in chlorophyll driven by the nutrient supply. Primary production (Figure K-2) declines in April, probably due to light limitation and is very low (<100 mg C m^{-2} d^{-1}) in winter due to a combination of light limitation and deep winter mixing. In the STC, nitrate, phosphate and silicate are normally limiting phytoplankton growth. In the SAZ, nitrate and phosphate remain above levels normally considered to be limiting to growth, but silicate is drawn down to levels that would limit diatom growth. South of the northern branch of the Polar Front (52°S-53°S) primary production and chlorophyll tend to be lower than in the SAZ. Macronutrients are not drawn down to limiting levels, but iron concentrations are very low and may be limiting phytoplankton growth (Sedwick et al., 1997).

2. The Indian Ocean sector between about 20°S and 40°S

The primary upper water mass in this region is the South Indian Central Water, which corresponds to water mass Level 1b_I13 at the surface and may include some of water mass 1b_I12 at 100 and 200 m depths. This South Indian Central Water is the eastern section of the Indian Ocean Subtropical Gyre, bounded in the south by the Subtropical Convergence Zone and in the north by the westward flowing Indian Ocean Current south of the South Equatorial Current. This region is reasonably isolated from the monsoon system that dominates the tropical Indian Ocean north of about 20°S. The Subtropical Gyre is driven by westerly winds in the south and the annual mean trade wind in the north. Both nitrate (typically < 2 µM) and silicate (< 3 µM) in the upper 100 m are low enough to limit phytoplankton growth and primary production most of the year. Wind stress during most of the year is very low, particularly in the west (Hayes and Lyne 2005) and there is little vertical mixing through the pycnocline to bring additional nutrients into the euphotic zone. Wind stresses are higher near the WA coast from October to April, in the period roughly corresponding to the Northeast Monsoon in the tropical Indian Ocean.

Chlorophyll concentrations in this region reach a maximum in the range 0.25 to 0.5 mg Chl-a m^{-3} in the winter-early spring period (Fig K.1 c, d) and decline quickly to very low levels by November-December (Fig K-1 a), probably due to nutrient limitation in the euphotic zone and the formation of a deep chlorophyll maximum at the nutricline near or below the 1% light depth. There is a persistent patch of low chlorophyll offshore between Cape Naturaliste and Shark Bay in the winter that may be associated with low nutrient water moving south in the Leeuwin Current and being advected offshore, thus forcing phytoplankton growth to occur deeper in the water column than can be sensed by the satellite.

Primary production in the gyral region follows the chlorophyll distribution patterns, being highest in October and then dropping to very low levels (< 100 mg C m^{-2} d^{-1}) over much of the region (Fig K-2 a, b, c, d). The higher primary production between about 105°E and the WA coast from October to April corresponds with increased wind stress seen in the region at this time. There may be some wind-mixing-induced, nutrient-replenishment across the pycnocline occurring as a result of this northerly stress. Primary production in the north-western part of the gyre is very low and almost certainly controlled by the lack of nutrients in surface waters from September through to May.

3. The Timor Sea region

This region covers a very large part of the ocean encompassing the Timor Sea out to 90°E and down to about 20°S in the Indian Equatorial water (Level 1b_I17) and including Indonesian Throughflow water (Level 1b_I20). It is a complex region with the monsoonal wind regime dominating the area. The Northeast (or northern hemisphere) winter monsoon period is between December and April, while the Southwest monsoon runs between June and October in the austral winter. November and May are the transition periods between monsoon seasons. During the winter monsoon, the South Java current flows southeast along the coast of Java and enters the Timor Sea. It circles to the west at about 15°S and joins the southern branch of the South Equatorial current flowing westwards across the Indian Ocean. In the summer monsoon period, the South Java Current reverses direction, carrying water from the Indonesian Throughflow northwest along the coast of Java and eventually forming part of the northern branch of the South Equatorial current. The reversal of the South Java Current carries low salinity, high nutrient water west along the coast of Java and other islands in the Indonesian archipelago and is probably responsible for the higher chlorophyll concentrations seen in this region during winter (Figure K-1c and d). These result in the higher primary production seen along the Indonesian archipelago in winter and the reduction seen during the summer monsoon. Once the monsoon and the current reverses and ends, chlorophyll and primary production rapidly drops back to the nutrient-limited levels seen in the rest of the region.

The increase in chlorophyll along the NW shelf in winter begins about a month earlier than the increase along the Indonesian archipelago. It coincides with the onset of the winds blowing to the north-west in April and May and continues throughout the Southwest monsoon period. The high chlorophyll water along the NW shelf moves south-east and some is carried offshore near 20°S, while the remainder turns south with the Leeuwin Current. There are few nutrient measurements in the northern part of this region, but the combination of offshore winds, strong tidal mixing and the start of the Leeuwin Current probably result in nutrients being carried by mixing into the euphotic zone, promoting phytoplankton growth and leading to the small increases in primary production seen along the NW shelf region.

The central waters of the Timor sea region, associated with water masses Level 1b_17 and 1b_20, is a low chlorophyll, low productivity region, with chlorophyll levels <0.15 mg Chl-a m^{-3} and primary production estimates below 250 mg C m^{-2} d^{-1}. The lowest chlorophyll levels occur during the North-East Monsoon period from January-April and are probably associated with shallow pycnoclines preventing nutrients from mixing up into the surface waters.

Primary production in this central area estimated from ocean colour satellites is also lowest in this period, especially in April where production is < 100 mg C m^{-2} d^{-1}. The satellite estimates agree broadly with chlorophyll and primary production measurements made by CSIRO in the 1958-1965 period.

4. The Arafura Sea/Gulf of Carpentaria region

This region, effectively a shelf region, is very different from the other areas described because much of it is < 100 m deep and the Gulf of Carpentaria has a maximum depth of about 70 m. Deep water is found only in the Timor Trough on the northern boundary of the Arafura Sea. We will treat the Arafura Sea east and west of Darwin separately because the patterns of chlorophyll abundance are different. In the western Arafura Sea, the annual cycle of chlorophyll in surface waters is similar to that of the eastern Timor Sea. Chlorophyll values are low from October through to April and especially during the Wet season in December-February. They increase from about 0.15 mg Chl-a m^{-3} to between 0.2 - 0.5 mg Chl-a m^{-3} during May to September. Primary production in this western region reaches a peak in the June-August period, but probably does not exceed 500 mg C m^{-2} d^{-1}. Primary production drops rapidly after this and by October is down to < 100 mg C m^{-2} d^{-1} and remains low. It starts to increase again in May. Surface production in the region is nutrient limited, due to very low nitrate concentrations (typically < 2 µM,) although silicate (<4 µM) and phosphate (<0.3 µM) are relatively more abundant in these waters. The raised silicate levels are probably due to resuspension of sediments. There is no deep-water pool of nutrients that can be mixed up into the euphotic zone in the shallow Arafura Sea region. The winter production increase may be due to higher-nutrient water entering via the Indonesian Throughflow.

The eastern portion of the Arafura Sea is influenced by riverine input from Irian Jaya. The satellite images (Figure K-1 a, b, c and d) show very high apparent chlorophyll in this region, but these rivers bring down substantial amounts of sediment and coloured dissolved organic matter which will interfere with the satellite chlorophyll estimates. However, the eastern areas appear to have higher surface chlorophyll compared with the western Arafura Sea all year round. The patterns show chlorophyll is highest in the April to October period and increases as soon as the Wet Season finishes. Chlorophyll concentrations can exceed 1 mg Chl-a m^{-3} in the region between Wessel Island and Cape Valsch in Iryan Jaya and in the Gulf of Carpentaria (GOC). Primary production is highest (up to 500 mg C m^{-2} d^{-1}) in the May through to August period and then quite low (< 250 mg C m^{-2} d^{-1}) for the rest of the year. Chlorophyll and primary production estimated from ocean colour satellites in the Gulf of Carpentaria follows the same patterns. The bands of apparently high chlorophyll in the very shallow waters near the edges of the GOC are more likely to be due to a combination of reflectance from the bottom and suspended sediment than chlorophyll. The production and chlorophyll values broadly agree with measurements made by Rothlisberg et al (1994) and Burford and Rothlisberg (1999).

5. The Coral Sea region north of 25^{o}S

The upper 100 m or so in this region is primarily warm, relatively fresh Tropical Surface water overlying higher salinity Subtropical Lower water (Condie et al, 2003). These correspond to water masses Level 1b_P17 and 1b_P20 respectively. The circulation patterns in this region are driven by westward flow of the South Equatorial current entering from the east and then splitting northwards as the Hiri current which follows the Great Barrier Reef edge across Torres Strait to PNG. Nutrients in surface water in this region are very low and much of the phytoplankton is concentrated in a deep chlorophyll maximum at the nutricline at depths of 60-140 m. There are raised chlorophyll levels in July (Figure K-1c) and this is part of a regular increase in chlorophyll in this region during June to August. This increase may be due to mixing of nutrients into surface water coinciding with the onset of the South-East trade winds in April reaching a maximum in July-August. There are occasional pulses of high chlorophyll entering the region through the Louisiade Archipelago south of Papua New Guinea mainly in June and July, but these pulses can occur from April to October. Primary production is highest during this period, but the satellite estimates are still not high at < 250 mg C m^{-2} d^{-1}. Surface production decreases in October, probably as a result of nutrient limitation in the near-surface waters as the Trades start to weaken. By January, primary production is very low in the whole of the region. There is some evidence of persistent, slightly increased chlorophyll and primary production along the outer edge of the Great Barrier Reef during much of the year. There is a large difference between the Coral Sea and the Timor Sea area in the timing of the peak period of primary production: in the Coral Sea production is clearly declining rapidly by October, while in the Timor Sea area it is at its maximum from July to at least October-November. These differences in timing are probably due to differences in the current and wind patterns in the two basins.

6. The Tasman Sea sector, between about 25°S and 40°S

The Coral and Tasman seas are linked but they are separated into regions north and south of 25°S because the patterns of chlorophyll abundance and primary productivity are different. The main near-surface water mass in the Tasman Sea region corresponds to water mass Level 1b_P13, which has the characteristics of being a warm, saline (>35.2 psu), low-nitrate, low-silicate water mass occupying the upper 100 m. It corresponds to the Subtropical Lower Water in Condie et al. (2003), and is cooler, fresher and higher in oxygen than the Tropical Surface Water found in the Coral Sea. Convective overturn and wind mixing in winter will recharge nutrient in surface waters, allowing phytoplankton growth rates to increase in the shallow mixed layers that form with increasing solar radiation as summer approaches. The region is bounded in the south by the Subtropical Convergence.

The dominant current system in the Tasman Sea is the East Australia Current, formed by the splitting of the South Equatorial Current as it approaches the Australian coast. The East Australia Current follows the shelf break southwards and tends to move offshore near 30°S, but sheds eddies that move further southwards. The movement of this current along and away from the shelf can upwell nutrient-rich, cool water onto the shelf which results in phytoplankton growth and increased primary production.

Offshore, the patterns of phytoplankton growth and primary production are very seasonal and operate in a latitude band about 10° wide. This is clearly seen in Figure K-1. In July, there is a region of low chlorophyll (0.15–0.2 mg Chl-a m^{-3}) between about 20°S and 30°S, with quite low chlorophyll between 30°S and 40°S. In October, the southern edge of the low-chlorophyll region is still at about 30°S, but there is a marked increase south of this. This increase progresses southward as a front and is quite dynamic. Near 40°S, in October, the spring bloom is clearly visible, with chlorophyll concentrations > 1 mg Chl-a m^{-3}. In the January image (Fig K-1a), the band of low chlorophyll has moved south, replacing the spring bloom in the October image. In April, the low-chlorophyll band moves back northwards and a slight increase in surface chlorophyll is seen in the region. From July, the seasonal increase in the intensity and duration of light causes warming of the surface layer, resulting in a shallow thermocline. Phytoplankton in the mixed layer above the thermocline are in a high-light, nutrient-rich environment and growth rates and primary production increase. As nutrients are exhausted and the seasonal thermocline deepens, both growth rates and primary production decrease. In autumn, with the onset of seasonal cooling, the mixed layer deepens again and nutrients become available for phytoplankton growth. This mechanism progresses northwards, giving the impression of a band of raised chlorophyll moving north. The dynamics of the chlorophyll cycle, as seen in a movie loop of weekly images from the satellite observations, reveal that the northern edge of the band follows the 0.2 mg Chl-a m^{-3} "contour" north and south. The same patterns can be seen on the primary production maps (Figure K-2). Production is low (100-250 mg C m^{-3} d^{-1}) over much of the region between 20°S and 40°S in July, but it doubles in October between 30°S and 40°S, with some patches of very high production near Bass Strait. By January, the high production region has moved further south, into the Subtropical Convergence and Subantarctic waters, but production in the 30°S to 40°S band has dropped back to < 250 mg C m^{-3} d^{-1}.