Climate impact on hypersalinity in an Australian coastal bay

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Abstract*
Recent work on episodes of hypersalinity in a subtropical east Australian coastal bay is reviewed. Hypersalinity is a response of coastal bays and estuaries to the local freshwater balance which fluctuates due to variable rainfall, river run-off and evaporation. Longer lasting episodes of hypersaline conditions are a likely consequence of a drying and warming climate. The response of the coastal ocean to changes in the hydrological cycle has been observed in several Australian coastal systems, including the response to persistent drought conditions resulting in increased salinity and more frequent hypersaline conditions. In addition to observing hypersaline conditions in Hervey Bay off the central Queensland coast, first modelling experiments indicate that the frequency of hypersaline conditions has increased during the last 20 years. Coastal regions are important nurseries for Australian fisheries and the likely impact of persistent below average rainfall upon marine environmental conditions is yet to be assessed. This work indicates that routine monitoring of coastal salinity is essential in order to evaluate future impacts of climate change.

1. Coastal Vulnerability to Climate Change
Climate change and variability are impacting upon natural and human coastal systems due to changes in frequency and intensity of rainfall. In particular during the last 50 years, much of coastal east, south, and south-

* Chapter originally submitted in March 2009.
west Australia has experienced significant declines in rainfall with decreases exceeding 200–250 mm (e.g. Shi et al. 2008a). These trends are likely to persist into the future and are associated with large scale changes in the ocean and atmosphere circulation. Rainfall variability has been attributed to persistent changes in phenomena such as the Southern Annular Mode, the El Niño – Southern Oscillation and the Indian Ocean Dipole which drive much of Australia’s interannual rainfall variability. It is likely that some of the changes are linked to global climate change (e.g. Cai et al. 2005; Murphy & Ribbe 2004; Shi et al. 2008a; Shi et al. 2008b; Ummenhofer et al. 2009). The Australian coastal marine systems are of immense economic value with fisheries, for example, being the fifth largest contributor to the Australian economy (e.g. ABARE 2005). Yet, our understanding of the coastal ocean’s vulnerability and response to climate change is rated as poor in a study commissioned by the Australian Government (Voice et al. 2006).

The freshwater balance composed of evaporation, rainfall and river run-off is one of the key drivers of marine environmental conditions in Australian coastal systems such as estuaries and bays and directly controls the salinity within these systems. It is likely that a change in the freshwater balance due to reduced rainfall impacts upon these environments. An indicator of possible changes in coastal systems due to reduced freshwater supplies is the occurrence of coastal hypersaline zones. These are already observed in many Australian coastal systems due to a climatological freshwater balance that is negative, meaning the evaporation is larger than the supply of freshwater. This leads to elevated coastal salinity with lower salinity in the open ocean which exchanges water with the coastal systems.

Hypersalinity has been observed in Australian coastal systems of Western Australia (Burling et al. 1999), the Northern Territory and northern Australia (Wolanski 1986), South Australia (de Silva Samarasinghe & Lennon 1987; Petrusevics et al. 2009) and Queensland (Ribbe 2006; Benfer et al. 2007). A possible response of Australian coastal systems to persistent climatic changes (i.e. shift to low rainfall regime) comes from two recent studies by Lee et al. (2007) and Gräwe et al. (2009), both studies finding from observations and modelling that drought conditions are likely to lead to more frequent and persistent hypersaline conditions.

In this chapter, recent work is reviewed that has been carried out to better understand the impact of a variable climate and changes in freshwater supplies upon the hydrography of Hervey Bay which is an east Australian bay
off the central coast of Queensland. An analysis of hydrographic observations shown in this chapter and obtained since Ribbe (2006) in combination with the historical freshwater balance indicates that continual drought conditions along eastern Australia favour the persistence and maintenance of inverse estuarine-like conditions in Hervey Bay. These are only reversed during severe flood events as observed in June 2008. During this storm event the Mary River, located in the south of Hervey Bay, discharged about three times the monthly climatology mean (~300,000 megalitres). Due to a predominantly cyclonic circulation within the Bay (Ribbe et al. 2008; Gräwe et al. 2009), freshwater is rapidly advected along the western coast and leaves the Bay. Consequently, the bay is expected to return to inverse estuarine-like conditions following events of high river run-off. Additional information from modelling studies is discussed that indicates inverse-like conditions are likely to have been enhanced during the last two decades. Salinity is not regularly and continuously monitored in Australian coastal waters, however, from this work it is projected that many Australian estuaries and confined larger bays are likely to experience increased levels of salinity due to reduced rainfall; as such operational salinity monitoring along Australia’s coastal line should be established.

2. Hervey Bay – a coastal system

Hervey Bay is located on the continental shelf of subtropical southeast Queensland, Australia. It is situated to the south of the Great Barrier Reef Marine Park and covers an area of about 4000 km² with an average depth of about 15 m (Figure 1). The main exchange of water with the open shelf and ocean occurs in the north where the shelf is about 80–90 km wide. In the east, the bay is separated from the open ocean by Fraser Island which is the world’s largest sand island. In the south, it is connected with the open ocean via a narrow, about 90 km long and shallow system (average depths of less than 2 m) of channels, the Great Sandy Strait and an eastward facing gap of about 2 km width south of Fraser Island. The Mary, Burrum, Elliott and Burnett rivers drain into the bay. The Mary and Burnett rivers are the main sources for river water discharges with the Burrum and Elliott having only a small catchment
area. The Mary River mouth is located at the northern end of the Great Sandy Strait and freshwater is drained into the southern parts of Hervey Bay and southward into the Strait itself. The mouth of the Burnett River is at the north of the study area. The Bay came into existence about 7000–8000 years ago with the flooding of the coastal regions due to global sea level rise that followed the termination of the last ice.

The climate of the Hervey Bay region is classed as subtropical, with predominantly high monsoonal summer and low winter rainfalls, and the region is characterised by significant interannual rainfall variability (e.g. Murphy & Ribbe 2004). The key climate drivers controlling the rainfall delivering weather systems into the Hervey Bay region are primarily the Australasian Monsoon circulation and the Easterly Trade Winds while interannual rainfall variability is primarily a result of the El Niño–Southern Oscillation (Murphy & Ribbe 2004). The climatological freshwater water balance (E–P–R) due to evaporation (E), precipitation (P) and total river run-off (R) is shown in Figure 2. The data is obtained as averages from three rainfall weather observation locations, i.e. Bundaberg in the north west, Sandy Cape in the north of Fraser Island, and Urangan in the south of Hervey Bay and for about the last 100 years. Monthly river flow discharges are provided by the Queensland State Government’s Department of Natural Resources. For this comparison, river run-off is converted in a virtual rainfall equivalent using a surface area for Hervey Bay of about 4000 km², i.e. river run-off is assumed to be equally distributed across the surface of the bay.

The annual freshwater balance for the bay is dominated by a net freshwater loss of about 113 mm resulting from a total annual supply of freshwater of 1425 mm due precipitation and river run-off and a total evaporative loss of about 1538 mm. In terms of seasons, the southern hemisphere summer and autumn seasons are dominated by a negative balance, i.e. freshwater supply is larger than loss, while the winter and spring seasons are dominated by a positive balance, i.e. evaporation is larger than freshwater input (Figure 2b). Recent observations indicate that the climate of
Figure 1 Map of Australia, location of Hervey Bay, and bathymetry of Hervey Bay [m].
Figure 2 a) Climatological rainfall, run-off, and evaporation for Hervey Bay in [mm/month]. The total annual gain/loss due to rainfall, river run-off and evaporation is 1146 mm, 279 mm, and 1538 mm, i.e. the annual freshwater balance is dominate by a net loss of about 113 mm due to evaporation. b) Climatological monthly freshwater balance. Data source: Clewett et al. (2003).
the region is rapidly changing and is characterised by significant downward trends in rainfall (Shi et al. 2008), an upward trend in surface air temperature (Beer et al. 2006) and shifts in ocean climate zones (Lough 2008).

Systematic research into the circulation, hydrographic characteristics of Hervey Bay, and the impact of variable climate and freshwater flows is lacking. Many previous studies of the region support the status of Hervey Bay as an important marine ecosystem and whale sanctuary, focus upon its sedimentary history, and its importance for fisheries (Preen 1995; Preen et al. 1995; Preen & Marsh 1995; Moss & Kocovski 1998; Chaloupka et al. 1999; Campbell & McKenzie 2004; Boyd et al. 2004; Ward et al. 2003). The studies report little if anything at all about physical conditions of the bay that are clearly the key determinants of marine ecological systems and interact with biological, chemical and sedimentary processes.

Some new insight into the physical characteristics of Hervey Bay comes from recent work by Ribbe (2006), Ribbe et al. (2008) and Gräwe et al. (2009). Ribbe (2006) reported the first hydrographic survey completed for the bay in September 2004. The survey identified a hypersaline zone along the western region of the bay. Ribbe (2006) linked the observed salinity distribution to freshwater supplies arguing that hypersalinity in Hervey Bay is likely to be a climatological feature during September which has not been reported or observed previously. This is clearly supported by climatological data shown in Figure 2 with evaporation exceeding freshwater supplies by at least a factor of two during September, but also by actual data during the September 2004 survey, with an almost diminished freshwater supply during that month due to persistent drought conditions.

Hervey Bay can possibly be also classed as an inverse estuary with inflowing surface water of lower salinity above a layer of outflowing sub-surface water of high salinity away from the hypersaline zone. This high salinity water is referred to as Hervey Bay Water (Ribbe 2006). It is generated within the bay, exported to the northeast of Fraser Island and possibly advected with East Australian Current (EAC) southward, a feature that has been observed by Middleton et al. (1994) within the EAC to the southeast of Fraser Island or perhaps entrained in a quasi-permanent EAC recirculation north-west along the shelf break (Griffin et al. 1987; Burrage et al. 1996).
The formation and maintenance of a hypersaline zone within Hervey Bay is aided by the water renewal process within the bay. From simple freshwater/salinity budget modelling Ribbe (2006) obtained a basin-average water renewal times scale of about 90 days. The subsequent application of a three-dimensional ocean circulation model provided insight into the spatial variation of this time scale (Ribbe et al. 2008) and was found to vary spatially from a few tens of days to more than 100 days within the interior of the bay (Ribbe et al. 2008). The region is dominated primarily by north-easterly and south-easterly trade winds which force a cyclonic or clockwise circulation within Hervey Bay. A more detailed account of the processes that drive the generation of hypersalinity and the density-driven export of saline Hervey Bay Water is provided by Gräwe et al. (2009).

Since Ribbe (2006) reporting on only one hydrographic survey, a total of four additional surveys were completed during August and December 2007 and May and June 2008. The observations from these surveys are presented and analysed in this paper and discussed in the context of the regional freshwater balance for the period from 2004 to 2008. It provides additional insight into the response of a subtropical large bay to variable freshwater supplies and provides further evidence of hypersalinity within Hervey Bay.

The hydrographic surveys reported in this chapter were carried out during a period characterised by persistent drought conditions along the central Queensland coast as well as other regions of Australia (e.g. Shi et al. 2008a). The resulting freshwater balance for the period January 2004 to June 2008 is shown in Figure 3. It is dominated by evaporative loss of water for most of the period. Climatic variability and possible change in the region lead to significant departures from the climatology mean (Figure 2), clearly affecting the supply of freshwater from river run-off and rainfall into the bay.

3. Observing hypersalinity

A total of four surveys were conducted in 2007 and 2008 complementing the only other survey for the region reported previously by Ribbe (2006). All cruises commenced and terminated in Bundaberg Port and utilised the fisheries research vessel FRV *Tom Marshall* which is managed by the
Figure 3 Monthly freshwater balance (mm/month) for the period January 2004 to June 2008 (solid line) and climatological water balance (dashed lines). The period is dominated by evaporation with only few instances where the supply of freshwater is larger than the loss due to evaporation. Data source: Clewett et al. (2003), Australian Bureau of Meteorology and Queensland Government.
Queensland Department of Primary Industries and Fisheries (DPI&F). The FRV *Tom Marshall* is a research catamaran cruising with an average speed of about 17–18 knots between sample locations which allows for a rapid quasi-synoptic survey of the bay. The distance between sample locations in all surveys reported here is about 5 nm in both longitudinal and latitudinal direction. The surveys took place during late winter (28–30 August) and early summer (4–7 December) in 2007 and during later autumn (26–27 May) and early winter (16–18 June) in 2008. This is a total of 12 observing days during which a total of 269 CTD profiles were recorded. The data was recorded using a Sea-Bird Electronics SBE 19 plus SEACAT Profiler and Falmouth Scientific Instrument CTD in August 2007. A full account of these surveys is provided by Ribbe (2008).

Depth-averaged temperature, salinity and density observations are shown in Figures 4–6 for all hydrographic surveys conducted into Hervey Bay. Included for comparison is the information from the previously referred to September 2004 survey (see Ribbe 2006 for a detailed discussion). Temperature ranges from a minimum of about 20.6°C to a maximum of about 21.2°C in September 2004 (Figure 4). For all the following surveys values are: 19.4°C to 20.8°C in August 2007, 24.4°C to 25.6°C in December 2007, 20.4°C to 23.0°C in May 2008 and 19.8°C to 21.4°C in June 2008 (Figure 4). In all cases, a southwest to northeast temperature gradient is observed with the warm water in the northeast being a signature of open ocean water entering the bay. Only during the southern hemisphere summer month of December 2007, the temperature gradient is reversed with the warmer water found within the bay. This is most likely a result of the much more rapid warming of the shallow bay region compared to that of the open ocean. In all other seasons rapid cooling overnight dominates the heat gain during the day in shallow water. In contrast, the deeper ocean’s heat capacity delays rapid cooling and establishes a temperature gradient with decreasing temperature toward the southwest. A remnant of the warming of shallow regions can also be observed during September 2004 and August 2007 where the shallow western region of the bay is found to be warmer.

In all but one of the surveys conducted, a hypersaline zone within the bay extending toward the western shore characterises Hervey Bay (Figure 5).
Maximum depths-averaged salinity within the hypersaline zone is about 36.8 psu in September 2004, 36.3 psu in August 2007, 36.2 psu in December 2007, and 35.9 psu in May 2008. In the latter case, this is just to the north of the bay. For this particular case, the survey commenced further in the north in order to chart the northern extent of the likely existing hypersaline zone outside Hervey Bay. Unfortunately, due to deteriorating weather conditions, the survey had to be terminated before Hervey Bay proper could be covered. Yet, the data shown in Figure 5 indicate elevated salinity and hypersalinity within the bay. In June 2008, no hypersaline zone within the bay is found. Depth-averaged salinity is lower throughout the bay with values smaller than 34.4 psu along the western boundary. Although these are depth-averaged salinity values, actual observed values for salinity within the hypersaline zone are of similar magnitude since the hypersaline zone, in fact the bay as a whole is vertically well mixed. The observed horizontal salinity gradients between the northeast oceanic region and the southwest within the bay are about 1 psu in September 2004, 1 psu in August 2007, 0.9 psu in December 2007, and likely to be larger than 0.7 psu in May 2008.
Figure 4 Depth-averaged temperature [°C] distribution from observations in a) September 2004, b) August 2007, c) December 2007, d) May 2008 and e) June 2008. Contour interval is 0.1°C³.
Figure 5 Depth-averaged salinity [psu] distribution from observations in a) September 2004, b) August 2007, c) December 2007, d) May 2008 and e) June 2008. Contour interval is 0.1°C³.
Figure 6 Depth-averaged density \([\text{kg m}^{-3}]\) distribution from observations in a) September 2004, b) August 2007, c) December 2007, d) May 2008 and e) June 2008. Contour interval is 0.1°C.\(^3\)
The establishment of and maintenance of a hypersaline zone within the bay is aided by bathymetry, the residual circulation within the bay, and the local freshwater balance shown in Figure 3. Simple modelling carried out by Ribbe (2008) and with a more complex model configuration by Gräwe et al. (2009) indicate that predominant north-easterly to south-easterly trade winds establish a cyclonic circulation that is associated with basin-average water renewal or flushing time scales in the order of about 89 days (Ribbe et al. 2006). The physical characteristics (bathymetry and circulation) of the bay combined with climatic conditions (freshwater balance dominated by evaporation) indicate that a mean salinity gradient of about 0.9 psu is the likely signature of a hypersaline zone within Hervey Bay during periods of persistent low freshwater supplies.

The distribution of density observed in all five surveys is characterised by a high density region that in four out of five instances is linked with zones of hypersalinity (Figure 6). In all these cases, the depth-averaged density maximum values within the hypersaline zone are about 25.8 kg m\(^{-3}\) during September 2004, 25.8 kg m\(^{-3}\) during August 2007, 24.1 kg m\(^{-3}\) during December 2007, and 25.4 kg m\(^{-3}\) during May 2008. In June 2008, depth-averaged density is largest in what could be referred to as a transition zone between lower density regions toward the west and the open ocean. Maximum depth averaged density within this transition zone is larger than about 24.8 kg m\(^{-3}\). This transition region is likely to be a remnant of a hypersaline zone found in May 2008 and seemingly to extend into the bay along the western region of the bay. This region is now dominated by low density water resulting from freshwater river run-off that is entering the bay as a result of the end of May/early June 2008 storm and following flooding event.

Although as indicated above, wind and tidal mixing are usually sufficient to homogenise the water column throughout (Gräwe et al. 2009) some indication of a vertical salinity (and density) stratification within the hypersaline zone is observed to occur (Figure 7). Examples of the vertical salinity distribution along several west to east transects across the bay are shown for the September 2004, August 2007 and December 2007 surveys. The eastern region of the bay is homogenised with only little or no stratifica-
tion at all. However, within the western zone of hypersalinity, changes in salinity between the surface and bottom layer are about 0.2–0.5 psu.

The establishment and maintenance of coastal hypersaline zones is driven by climatological/physical factors such as evaporation, precipitation, ocean circulation and is aided by the bathymetry or physical shape of the coastal system. A physical but unobservable quantity that characterises a confined coastal region such as a bay or large estuary and its communication with the open ocean is the flushing time scales. This is the time required to renew water within the bay with water derived from the open ocean. This renewal process imposes an upper limit to salinity within hypersaline coastal systems. The flushing time scale $\tau$ (days) can be assessed from a simple relationship (Wolanski 1986; de Silva Samarasinghe & Lennon 1987; Ribbe 2006):

$$\tau = \frac{H \cdot (S_2 - S_1)}{S_1 \cdot e}$$

with $H$ (m) as the mean depth of the bay (about 15 m), $S_2 - S_1$ the salinity gradient across the bay with $S_2$ being the salinity within the hypersaline zone and $S_1$ the salinity of incoming oceanic water, $e$ is the annual climatological evaporation rate (m/d). The total annual climatological loss of water due to evaporation is about 1540 mm (from data in Figure 2) which is a daily evaporation rate of about 0.42 cm/day. The observations show that an average salinity gradient of about 0.9 psu ($S_1 \sim 35.4$ psu, $S_2 \sim 36.3$ psu) characterises hypersaline conditions within Hervey Bay. This leads to a mean or climatological flushing time scale of about 91 days, or about three months. This is very similar to the 89 days estimate provided by Ribbe (2006); the difference here is that the flushing time scale is assessed on the basis of four hydrographic surveys and a mean salinity gradient of 0.9 psu characterising hypersaline conditions within Hervey Bay.
Figure 7 Vertical west to east salinity distribution in Hervey Bay during (top) September 2004 at 24° 55’ S, (middle), August 2007 at 24° 50’ S and (bottom) December 2007 at 24° 45’ S.
4. Future hypersalinity in coastal systems

There is some indication that continued climatic changes associated with a reduction in rainfall and river run-off could lead to more frequent and persistent hypersaline conditions in coastal systems. Two recent studies found some evidence that this is likely to be the case. Lee et al. (2007) examined salinity data recorded continuously from 1947 to 2006 in Port Phillip Bay, Victoria. They identified continued and increased hypersaline conditions since 1997 as a most likely response to the persistent drought conditions in eastern Australia and associated reduction in precipitation and river run-off. Lee et al. (2007) further concluded from projections based on climate change scenarios from the Intergovernmental Panel on Climate Change that hypersaline conditions within the bay will likely be more prevalent. In another study, Gräwe et al. (2009) applied an ocean general circulation model to the region of Hervey Bay and generated a hindcast of the salinity distribution within the bay for the period January 1990 to December 2007. For this period, the authors find that the salinity flux out of the bay increases by about 25%. Furthermore, hypersaline conditions are more frequent with an upward trend of about three days per year in the number of days characterised by hypersalinity. This is likely to be direct consequence of persistent drought conditions in coastal Queensland.

Salinity is a key environmental variability that impacts upon the aquatic health of marine coastal systems. There is evidence emerging from observational data and modelling studies that climatic changes leading to reduced rainfall and river run-off is impacting coastal systems which are of immense economic value to society. Routine operational salinity monitoring should be encouraged and realised in order to assess the impact of projected future climatic changes on coastal systems.

Acknowledgements

The author would like to thank the Burnett Mary Regional Group in Bundaberg, Queensland, the Hanse Institute for Advanced Study, Germany, and the University of Southern Queensland for supporting this work.
References


