The East Australian Current

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Summary: The East Australian Current (EAC) is a complex and highly energetic western boundary system in the south-western Pacific off eastern Australia. The EAC provides both the western boundary of the South Pacific Gyre and the linking element between the Pacific and Indian Ocean gyres.

The EAC is weaker than other western boundary currents and is dominated by a series of mesoscale eddies that produce highly variable patterns of current strength and direction. Seasonal, interannual and strong decadal changes are observed in the current, which tend to mask the underlying long-term trends related to greenhouse gas forcing.

Observations from a long-term coastal station show that the EAC has strengthened and extended further southward over the past 60 years. The south Tasman Sea region has become both warmer and saltier, with mean trends of 2.28°C/century and 0.34 psu/century over the 1944-2002 period, which corresponds to a poleward advance of the EAC Extension of about 350 km.

The observed intensification of the EAC flow past Tasmania is driven by a spin-up and southward shift of the Southern Hemisphere subtropical ocean circulation. Changes in the gyre strength are, in turn, linked to changes in wind stress curl over a broad region of the South Pacific. Oceanic changes are forced by an intensification of the wind stress curl arising from a poleward shift in the circumpolar westerly winds due to the trend in the Southern Annular Mode.

Observational and modelling studies indicate that these changes in the wind patterns are at least in part attributable to ozone depletion over the past decades. However, at least some of the trend is likely to be forced by increases in atmospheric CO_2. Climate models under observed CO_2 increases, also produce an upward trend of the SAM and a consequent intensification of the Southern Hemisphere gyre system.

There is strong consensus in climate model simulations that trends observed over the past 50 years will continue and accelerate over the next 100 years.

Introduction

The East Australian Current (EAC) is a complex and highly energetic western boundary system in the south-western Pacific off eastern Australia (Ridgway and Dunn 2003). Although its mean flow is relatively weak (Ridgway and Godfrey 1994) it is known to be a highly variable system with large mesoscale eddies dominating the flow (Bowen et al., 2005; Mata et al., 2007). The EAC has an important role in removing heat from the tropics and releasing it to the mid-latitude atmosphere (Roemmich et al, 2006). The Tasman/Coral Sea basin is an ocean region of importance to Australia, being adjacent to large population centres, encompassing major shipping lanes, and including regions of environmental significance. The EAC is also the dominant environmental influence on offshore pelagic fisheries in the region (Hobday and Hartmann, 2006). A central driver of key species such as southern bluefin tuna (SBT) is the seasonal changes of subsurface properties within the EAC system.
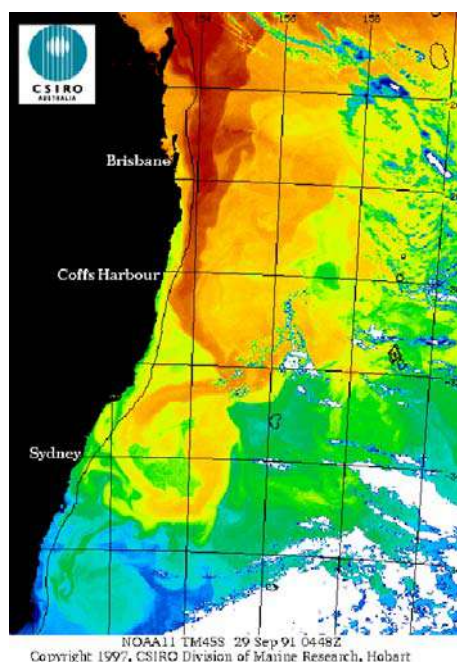

Figure 1: The warm EAC jet flows along the shelf-edge off eastern Australia.

Mean Circulation

The EAC provides both the western boundary of the South Pacific Gyre and the linking element between the Pacific and Indian Ocean gyres (Speich et al. 2002). It forms between 10° and 15°S. The current is accelerated, southward along the coastal boundary, and then separates into northeastward (Subtropical Counter Current), eastward (Tasman Front) and residual southward (EAC Extension) components at around 31°S (Figure 1, Ridgway and Dunn 2003). Between 18º to 35ºS, the southward transport ranges from 25 to 37 Sv, the latter value includes a significant recirculation feature. A portion of the Tasman Front re-attaches to the northern coast of New Zealand, forming the East Auckland Current and a sequence of semi-permanent eddies. The residue of the EAC transport continues southward along the Australian coast as far as Tasmania and then turns westward into the eastern Indian

Ocean (Tasman Outflow) with an important impact on the global ocean circulation (Speich et al. 2002).
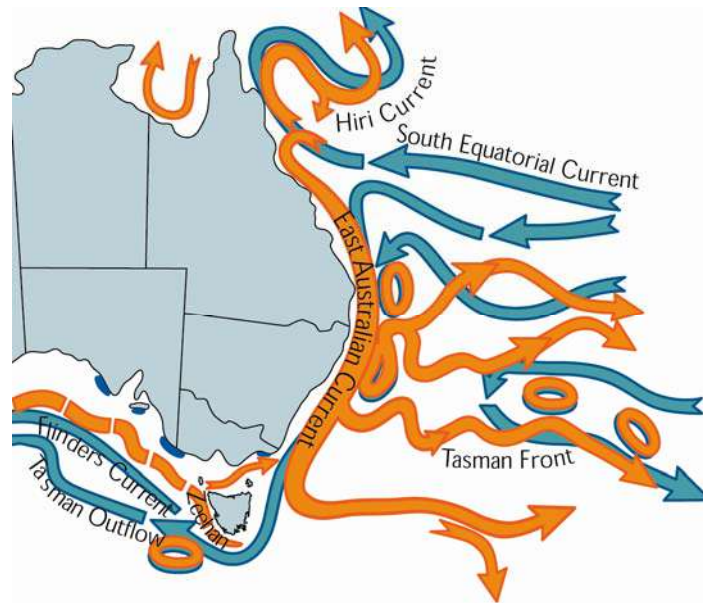

Figure 2: Schematic of the main ocean currents off eastern Australia. Surface currents are shown in orange and subsurface currents are cyan.
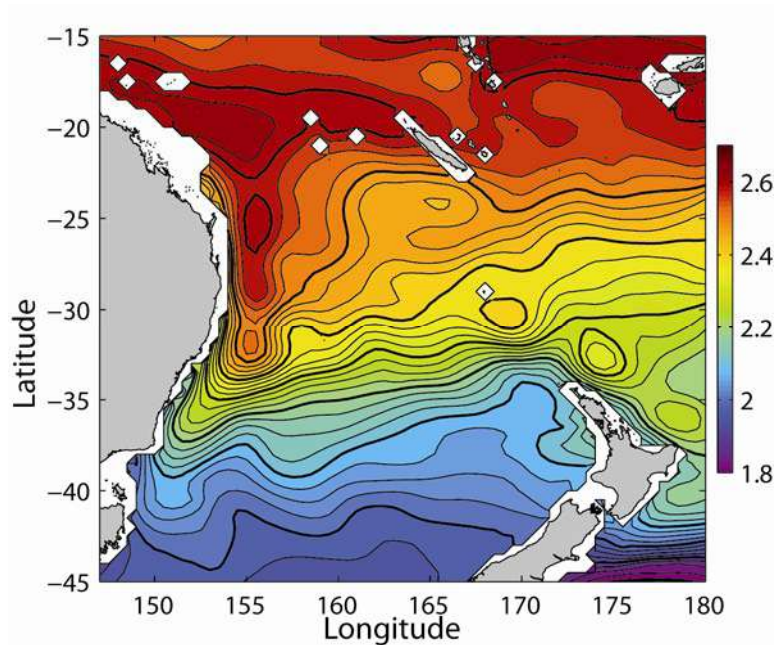
Figure 3: The mean surface height field in the southwest Pacific for the 1992-2006 period (contour interval is 0.05-m). The southward flowing EAC (shown in dark red along the Australian coast) is the dominant feature.

The variability in the EAC is large compared to the mean flow. Firstly, the EAC is weaker than its counterparts elsewhere in the world (such as the Agulhas Current and Gulf Stream), with mean southward transport estimates of 22 Sv[1] at 30°S (Mata et al. 2000) and 27 Sv at 28∘S (Ridgway and Godfrey 1994). A counter-current runs offshore of the EAC, which is about 17 Sv of northward flow. This gives a net southward transport of 9.5 Sv (Ridgway and Godfrey 1994, 1997). These transport estimates for the EAC are compared to estimates of 43 to 85 Sv for the Agulhas Current (Matano et al. 1998). It is such an eddy-rich current (Boland and Hamon 1970; Boland and Church 1981), that it is arguable whether it is a single current, as the baroclinic eddy mass transport is several times that of the mean flow.

Within the abyssal basin adjacent to the coast, the EAC is associated with a highly energetic eddy field (Figure 4). These eddies are 200-300 km in diameter and 2-3 eddies are generated annually and have lifetimes often exceeding a year (Nilsson and Cresswell 1981; Bowen et al. 2004). They follow complex southward trajectories, but are generally constrained within the deep basin.
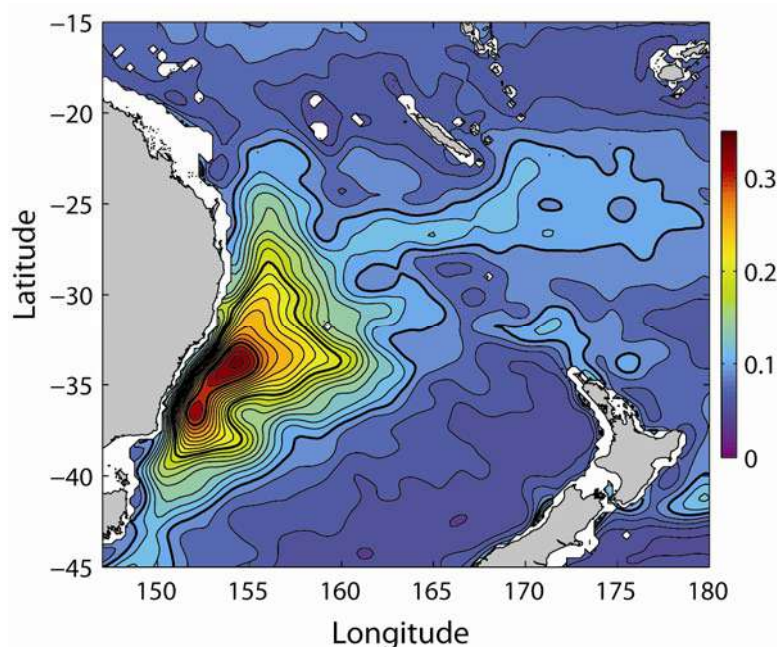
Figure 4: Variability of sea surface height (m) in the southwest Pacific for the 1992-2006 period as determined by satellite altimetry observations. The high variable region is associated with mesoscale EAC eddies.

Biological consequences

The nature of the separation of the EAC is of major importance for various fish populations. For example, the location and timing of gemfish aggregations (e.g. the gemfish run and spawning) are determined by the oscillations of the EAC. Other species such as tuna appear to favour the frontal region - either on the subtropical or subantarctic side (Hobday and Hartman 2006). Eddies themselves are important for nutrient cycling, and biological productivity. For example, the phytoplankton

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[1] Sv = Sverdrup. A unit of measure of the transport of ocean currents. 1 Sverdrup = 10^6 cubic meters per second.

productivity in eddies differs from that of the surrounding waters. Higher up the food chain, there is strong evidence of biological contrast across eddies (Tranter et al. 1980; Tranter et al. 1982).

The main biological influence of the eddies is to increase the vertical mixing within the upper ocean in the western Tasman Sea, extending the effective mixed layer depth and thus suppressing the winter phytoplankton and zooplankton populations due to light-limited conditions for phytoplankton growth. These conditions result in spring and autumn blooms of chlorophyll-a, with lower summer concentrations because of stratification and nutrient depletion. In addition, upwelling associated with eddies supplies more nutrients to the surface layer once the bloom has begun, delaying the exhaustion of nutrients and prolonging the duration of the blooms (Tilburg et al. 2004).

The EAC and its eddies frequently move onto the continental shelf and close inshore and influence the local circulation patterns. At prominent coastal features (Cape Byron, Sugarloaf Point, Port Stephens), the EAC moves away from the coast, driving upwelling, which draws nutrient-rich water from a depth of 200-m or more (Oke and Middleton, 2000, 2001). However, while the EAC may drives nutrient-rich water onto the shelf, upwelling-favourable winds (northerly) bring the water to the surface (Rochford 1984; Church and Craig 1998).

Modes and timescales of variability

While observed trends in the EAC system have attracted much attention, their impacts need to be considered in the context of variability in the system; from seasonal to decadal. The response of ecosystems to variability may also give us clues to how it might respond to long-term changes. The above description of the mean circulation of the EAC system has been developed predominantly from in situ observations collected over many decades. However, these data are irregularly distributed in both space and time and are not generally suitable for resolving changes in the EAC circulation over time periods ranging from interannnual to decadal or even long-term (Ridgway et al., 2002). After about 1990, surface observation of temperature and sea level have been collected by a diverse set of satellite platforms, enabling the seasonal, interannnual and decadal signals to be determined. Data from a long time-series off the east coast of Tasmania (Maria Island Station), and the repeated, eddy-resolving Tasman Box XBT lines, provide valuable in situ data. XBT data between Sydney and Wellington have been used with satellite altimetric observations to estimate the transport time series through this section (Ridgway et al. 2008). We use this time series to diagnose the relative importance of different temporal signals on the EAC transport (Figure 5). Within the limitations of available data, the best estimate of the state of the ocean over the last 50 years comes from ocean reanalyses, where observational data have been assimilated into global models.

Seasonal

The EAC flow varies seasonally - it is strongest in summer, and the separation location also migrates up and down the coast seasonally (Ridgway and Godfrey 1997). The seasonal amplitude is also large compared to the mean flow, with a minimum observed southward flow of 27.4 Sv in winter, and a maximum of 36.3 Sv in summer (Ridgway and Godfrey 1997). The net transport of the EAC (including the northward counter-current) is 9.5 Sv, with a seasonal amplitude of 6 Sv. Compare this to the Florida Current (Gulf Stream) at 26°S, with a background flow of 30 Sv (Schott

et al., 1988) and a seasonal amplitude of 3 Sv. In Figure 5, the seasonal amplitude of the EAC Extension is of the order of 2 Sv.
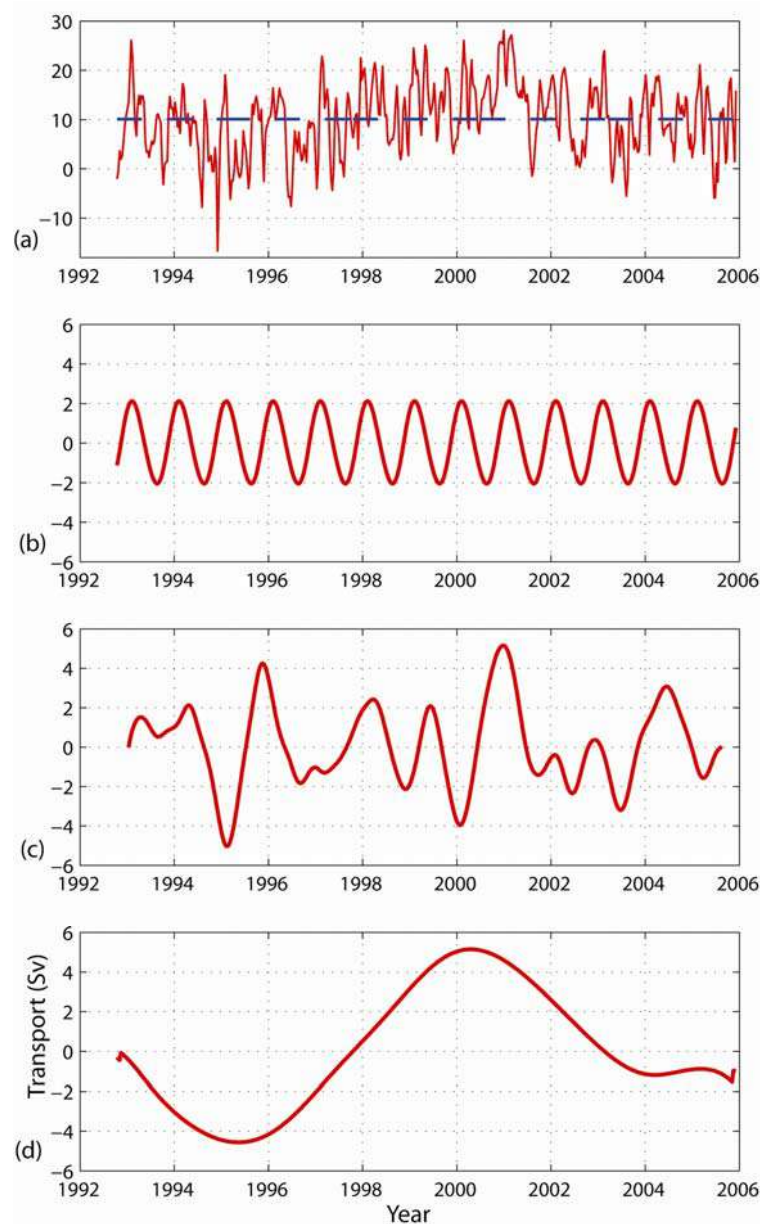
Figure 5: (a) The EAC transport (flow between Sydney and Wellington) inferred from satellite altimetry (Sv), (b) seasonal cycle, (c) interannual signal, (d) decadal change (Ridgway et al., 2008).

Interannual

The EAC undergoes changes on interannnual timescales, but only a very weak ENSO signal is evident in observations (Ridgway, 2007). In fact, the main oceanic pathway of the ENSO influence occurs through the Indonesian region and around a waveguide around the western and southern Australian coastal boundaries (Wijffels et al, 2004). This signal has almost entirely dissipated by the time it reaches the west coast of Tasmania. The pattern in Figure 5 shows that major interannnual events occur through

the period from 1992-2006. These changes have not been linked with external climate forcing signals.

Decadal

There is a strong signal of decadal variability in the temperature and salinity associated with the EAC (Sutton et al. 2005; Ridgway 2007; Ridgway et al. 2008). Results from observations and 50-year ocean reanalysis datasets show that the strength of the EAC Extension is negatively correlated with the Tasman Front on decadal timescales, which suggests that there is a gating between these two currents (Hill et al. 2009). This is due to enhanced wind stress curl in the South Pacific, which favours the EAC extension pathway over the Tasman Front, and is related to decadal ENSO variability. Decadal warming (cooling) in the tropical Pacific is associated with a weaker (stronger) South Pacific wind stress curl maximum, a weaker (stronger) EAC Extension, and a stronger (weaker) Tasman Front (Sasaki et al. 2008, Hill et al. 2009). We note that the decadal signal observed in the EAC extension is double that of the seasonal and of similar magnitude to the interannnual variability (Figure 5).

Observed Impacts (since 1944)

The long-term record from the Maria station shows that the southward penetration of the EAC has increased over the past 60 years. This station is located on the inshore edge of the warm, saline tongue of EAC water that spreads southwards along the coastal boundary (Ridgway 2007, Figure 6).
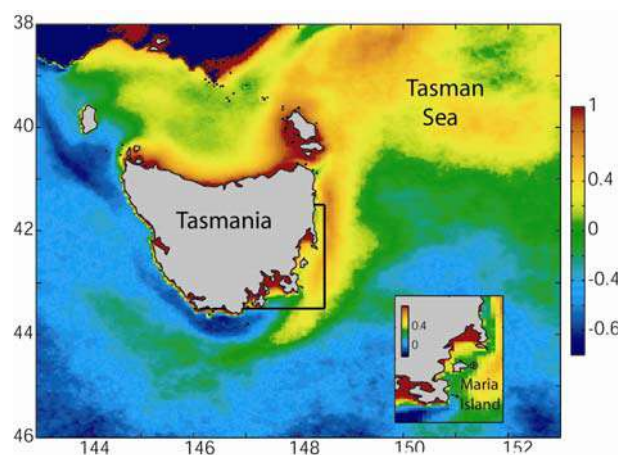
Figure 6: The mean SST for January in the waters around Tasmania. The summer penetration of the EAC Extension is seen as a tongue of warm water extending southwards past the east coast of Tasmania. The location of the long-term station off Maria Island is shown on the map.

The region has become both warmer and saltier, with mean trends of 2.28°C/century and 0.34 psu/century over the 1944-2002 period, which corresponds to a poleward advance of the EAC Extension of ~ 350 km. The intensification of the EAC is caused by strengthened winds over the South Pacific, and hence a stronger South Pacific gyre (Hill et al. 2008). Trends in summer temperature and salinity are greater than in

winter – there is an additional pulse of warm, high salinity subtropical water associated with the EAC in summer.
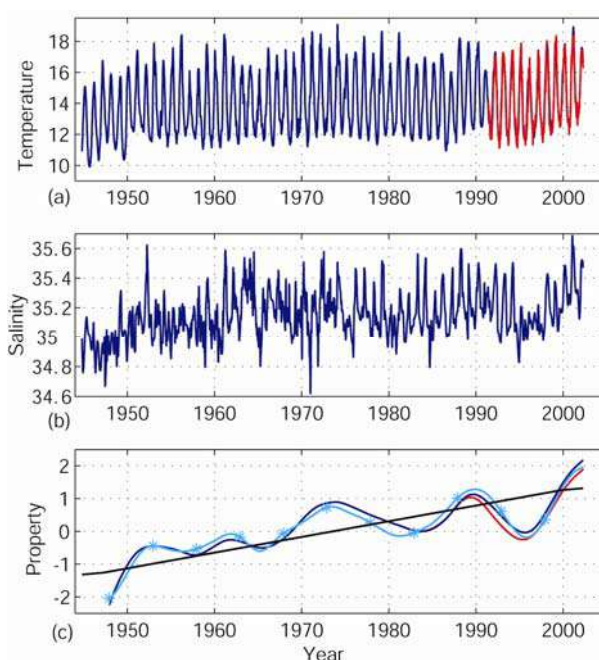

Figure 7: The (a) temperature and (b) salinity time series from the Maria Island station. In (c) each of the series has been low-pass filtered and normalized with their standard deviations. The long-term trend is also shown.

The enhanced warming in the region is confirmed by results from SST composite products (Figure 8). Other indirect evidence for EAC changes comes from biological sources. Several species previously only found in northern regions (*Centrostephanus rodgersii*, *Carcinus maenas*) have steadily ranged further southward over recent decades (Edgar et al. 1997; Thresher et al. 2003; Pittock 2003, Ling et al. 2008). These changes have been attributed to enhanced EAC flow (Edyvane 2003).

The intensification of the EAC flow past Tasmania is also seen in recent model studies describing both a spin-up and southward shift of the Southern Hemisphere subtropical ocean circulation (Oke and England 2003; Cai et al. 2005; Cai 2006). Oceanic changes are forced by an intensification of the wind stress curl arising from a poleward shift in the circumpolar westerly winds (Gillett and Thompson 2003) due to the trend in the Southern Annular Mode (SAM). Models predict that the EAC strengthens in the south while, it weakens to the north. Cai (2006) obtained an EAC increase of 9 Sv south of 30°S from 1978 to 2002.
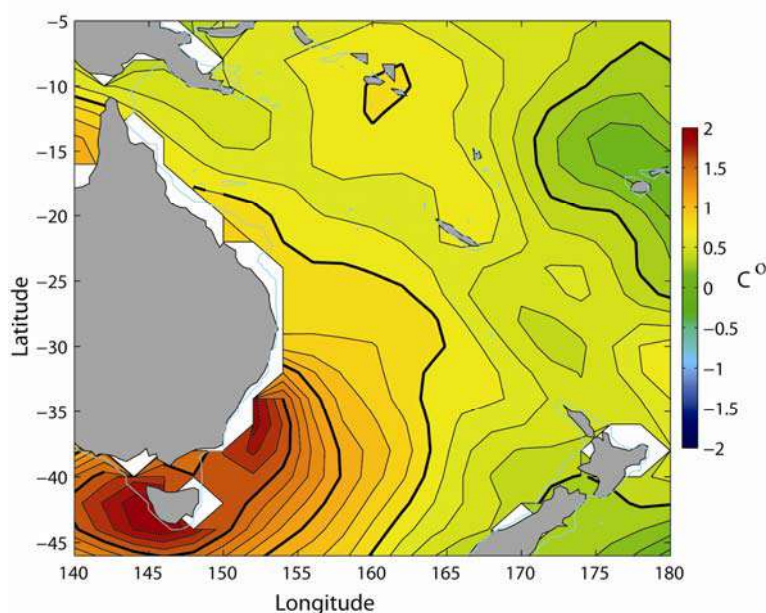
Figure 8: The trend in SST from 1944-2005 from a reconstructed data product (Smith and Reynolds, 2003).

The SAM is the dominant mode of variability of the Southern Hemisphere atmospheric circulation operating on all time scales. Over the past several decades, it has been displaying an upward trend (Thompson et al. 2000; Marshall 2003; Marshall et al. 2004), with increasing mean sea level pressure in the mid-latitudes. Observational (Thompson and Solomon 2002) and modelling studies (Gillett and Thompson 2003) indicate a significant contribution from ozone depletion forcing over the past decades (Shindell and Schmidt 2004). However, under increasing atmospheric CO_2, climate models also produce an upward trend of the SAM (Fyfe et al. 1999; Kushner et al. 2001; Cai et al. 2003).

The Maria Island time series shows that the EAC has strengthened in the southern Tasman Sea. The change in EAC surface salinity from winter to summer (0.25-0.30 psu from 1989 to 1990, Thresher et al. 2004) is of the same order as that observed over the 60-year period at Maria Island. This corresponds to a poleward extension of some 350 km in temperature and salinity. We can infer a long-term change in EAC transport of 10-15 Sv over the 60-year period, which is similar to modelling estimates (Cai 2006). In the northern EAC region, a significant thermocline cooling has been observed from 1975-1990 (Ridgway and Godfrey 1996), which matches the weakening of the EAC in this region observed in the models (Oke and England 2003; Cai et al. 2005).

Potential impacts by the 2030s and 2100s

Results from global climate models strongly suggest that changes in the EAC system will continue the observed trends of the past 50 years. These changes are primarily linked to the strengthening of the SAM. Although the overall contribution of increasing CO_2 to the observed SAM trend over the past decades is not certain, we expect a further strengthening in the SAM trend as CO_2 continues to increase into the

future. This is one of the most robust and consistent responses of the global climate system to climate change (Cai et al. 2005).

Cai et al. (2005) analyzed outputs of an ensemble of four climate change experiments with the CSIRO Mark 3 climate model forced by four different projections. The model experiments show that changes in the prevailing wind systems drive significant ocean circulation changes across the mid-latitudes of the Southern Ocean. These included a major increase in the South Pacific subtropical gyre, and an increase in the flow passing through the Tasman Sea with an associated strengthening of the recirculations in the longitudes between New Zealand and the South American coast. Overall the model shows that the connected Southern Ocean gyre system (Ridgway and Dunn 2007) strengthens and shifts southward.

Within these large-scale changes, the model predicts a 20% increase in the mean flow of the EAC passing through the southern Tasman Sea by 2070 (Cai et al., 2005). This projected increase is upon the already observed increases in EAC flow over the past 50 years (Hill et al. 2008). Associated with the EAC transport increase, is a major warming along the path of the EAC intensification, off the east Australian coast, and cooling along the path of increased northward recirculations, to the east of New Zealand. In fact the model suggests that the largest changes are found within the subsurface waters, with a clear baroclinic response. This includes weakly increased undercurrents at depth flowing in opposite directions to the surface flows, which in turn drive opposite temperature trends (cooling) at depth to that in surface layers.

The large warming shown by the model in the Tasman Sea (Figure 9) is clearly associated with a strengthening of the EAC, with a rate of warming that is the greatest in the Southern Hemisphere. Again this mirrors the results obtained from SST observations over recent decades (Figure 8). The role of the EAC change in generating the large warming in the Tasman Sea is confirmed by examining the changes of heat flux. For example, at the centre of the Tasman warming, there is a large increase in the heat loss from the ocean to the atmosphere (Cai et al. 2005). This essentially precludes the possibility of the warming being a consequence of atmospheric heating. There is a correspondence between the change pattern of wind stress curl and that of the heat flux.

These results have been obtained from coarse resolution climate models that do not capture the fine-scale structure and mesoscale eddies that are a fundamental to the dynamics of the EAC system. Observations show that there are clear seasonal, interannnual and decadal changes to the EAC eddy field. Given the importance of eddies in the EAC system, an improved representation of these features in climate models is required to reduce the uncertainty in model climate projections.
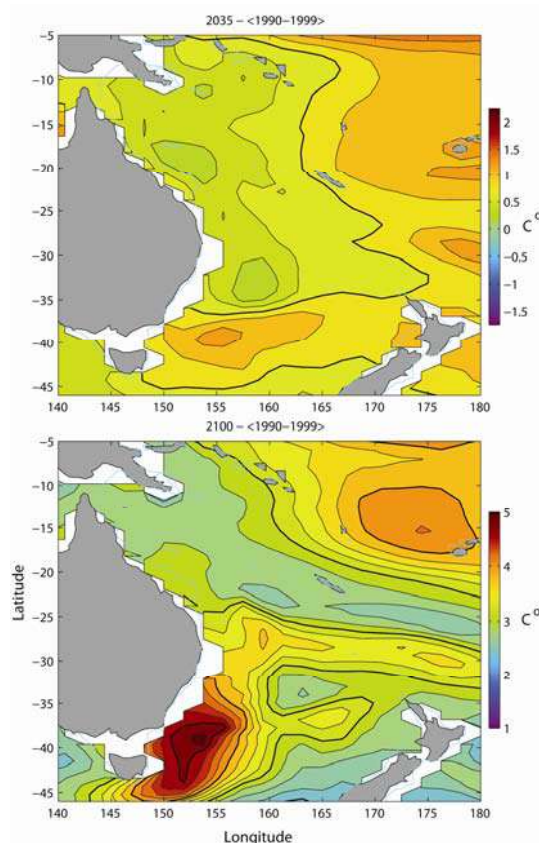
Figure 9: The projected change in SST in 2035 (upper panel) and 2100 (lower) from the CSIRO Mk 3.5 coupled model forced under the SRES A2 scenario.

Key Points

- A surface warming trend, varying in magnitude seasonally, has been observed in the East Australian Current region and on the continental shelf off the east coast of Tasmania.

- There has been an increasing trend in sea surface salinity off the east coast of Australia, which is associated with a strengthening of the East Australian Current.

- Impacts of these trends need to be explored in the context of strong interannual and decadal variability in the EAC system.

- Changes in the range of species across a number of marine species have been related to changes in the strength of the EAC. The projected strengthening of the EAC and continued warming of the south Tasman Sea is predicted to have a detrimental effect on cold temperate species in South East Australia, and will also impact on commercially important fisheries such as abalone and rock lobster.

- Oceanic changes are forced by an intensification of the wind stress curl arising from a poleward shift in the circumpolar westerly winds due to the trend in the Southern Annular Mode.

- Decadal variations are related to decadal ENSO, through an atmospheric teleconnection from the tropics impacting on the westerly winds in the South Pacific.
- Results from global climate models strongly suggest that changes in the EAC system and their underlying causes will continue the observed trends of the past 50 years.

Confidence Assessments

Observed and future impacts

Physical variables	Observed changes	Projected changes	
		2030s	2100s
Volume transport	The transport of the East Australian Current has increased over the past 60-years, by up to 10-Sv.	Further increase	Predicted increase of >20%
Coastal sea level	Fort Denison sea level: A rising trend of 1.54 mm per year over the 20th century, which is slightly less than the global trend	Sea level rises at a similar trend as global average	Sea level rises at a similar trend as global average
Sea surface temperature	Warming recorded at Maria Island station of 2.28°C/century over the 1944-2002 period;. This trend is well above the global value. The summer trend is greater than for winter.	A continued warming by 0.7-1.4°C, most pronounced in the southern Tasman Sea and around Tasmania	Rise by 2.0–3°C, most pronounced in the southern Tasman Sea and around Tasmania???
Thermocline	Intensified EAC flow since 1944 implies a deepening of thermocline offshore and uplift at the coastal boundary. Subsurface cooling on continental slope.	Continue shallowing trend of thermocline depth at boundary and increase offshore	The trend tends to persist.
Sea surface salinity	Sea surface salinity risen by 0.34 psu/century over the 1944-2002 off the east coast as recorded at Maria Island. The summer trend is greater than for winter.. Little seasonal cycle before 1960. From 1970 to the mid 1990s, the seasonal	Increase in surface salinity due to intensification of EAC transport	Further increases in surface salinity

Physical variables	Observed changes	Projected changes	
		2030s	**2100s**
	cycle intensifies		
Air-sea heat fluxes	Advection of heat into Tasman Sea leads to heat loss from ocean to atmosphere. Heat loss increases with strengthening of EAC	Within EAC warming region, there is large heat loss to the atmosphere. High correlation with changes in wind stress curl. Increase in out-going long wave radiation. Reduction in in-coming short-wave radiation.	Similar trends likely
Winds	Weakening of the westerlies off the southwest coast of Australia during austral winter since mid-1970s	Broadening and intensification of subtropical high appears to cause easterly anomalies centred at 30°S	Dominance of the subtropical high to continue to extend southeastward
Precipitation		Ocean warming enhances local convection leads to increased cloud cover and rainfall	Trends are maintained

Knowledge Gaps

- What is the relationship of the South Equatorial Current bifurcation latitude and vertical structure with the inflow and the outflow streams into the Coral Sea? What are the dynamics associated with the temporal changes in its location?

- What are the mechanisms associated with the EAC separation and reattachment, location of semi-permanent eddies, retroflection?

- How are EAC eddies generated? Are they generated by local forcing or are they entering the region from the east? How do eddies interact with the mean flow and topography?

- How are climate-change-related variations in the South Pacific gyre transport and density structure communicated through the western boundary via the EAC?

- How are changes in the EAC at seasonal interannnual, decadal and long-term timescales affecting regional marine ecosystems?

- Within the Tasman Sea, what are the relative contributions of advection and heat storage compared to the surface heat flux? How do they vary on interannual to decadal timescales? How is heat partitioned between the atmospheric fluxes and recirculated within the gyre?

- Climate models need an improved representation of the EAC and its eddy field?

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