South Eastern Australian
Climate initiative

Final report for Project 1.2.1

1.2.1 Role of the Indian Ocean. What controls sea-surface temperature warming?

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Project title
1.2.1 Role of the Indian Ocean.

Abstract

The linear trends in oceanic temperature from 1960 to 1999 are estimated using the new Indian Ocean Thermal Archive (IOTA), a compilation of historical temperature profiles. Widespread surface warming is found, as in other datasets, and reproduced in IPCC climate model simulations for the 20th century. This warming is particularly large in the subtropics, and extends down to 800 m around 40-50°S. Models suggest the deep-reaching subtropical warming is related to a 0.5° southward shift of the subtropical gyre driven by a strengthening and southward shift of the westerly winds, and associated with an upward trend in the Southern Annular Mode index. In the tropics, IOTA shows a subsurface cooling corresponding to a shoaling of the thermocline and increasing vertical stratification. Most models suggest this trend in the tropical Indian thermocline is likely associated with the observed weakening of the Pacific trade winds and transmitted to the Indian Ocean by equatorial and coastal waveguides through Indonesia. At this stage we do not know which IPCC models are best to use for estimating climate impacts over Australia. To gain some insight, the correlation between eastern Indian Ocean SST and Australian rainfall in observations was compared to the IPCC simulations.

Summary of project results against each objective

Objective 1: Identify variability and trend in time series of surface temperatures and deep temperature profiles of the Indian Ocean using historical ocean profile data to 400m.

The new Indian Ocean Thermal Archive (IOTA) is a compilation of historical temperature data above 1000m in the Indian Ocean available from an earlier project (Gronell and Wijffels, 2007). It has been meticulously quality controlled using both statistical and manual expert quality-control. In addition, all data from the Indian Ocean WOCE data assembly centre and all the available profiles from the new international Argo program were combined with IOTA. The total number of profiles is 420,000 casts (for 1960- 2005) with 85% reaching 100m, 50% reaching 400m and only 20% reaching 800m.

After considering other spatial mapping methods, a mean seasonal climatology was formed using a LOESS mapping method similar to Ridgway et al. (2002). This technique deals well varying data densities, a feature of this sparsely sampled ocean. To prevent the climatology from being biased regionally to years when data were many, a quadratic time change over 50 years was also included in the parametric model used for mapping. The use of LOESS method also prevented any remaining outliers from biasing the fits. Preparing the seasonal climatology was a necessary step but analysis is not part of this project. We focused here on the trends in the Indian Ocean surface and subsurface variability and their spatial variability. The long-term trends were computed only from 1960 due to the low density of observations before.

We generated horizontal maps and vertical transects of the observed temperature trends (Figure 1). As the SST estimated from IOTA corresponds in fact to the first level of the temperature profiles, it may be biased compared to dedicated SST measurements. It has thus been compared to two more comprehensive datasets of SST, which are reconstructions based on combined satellite and in situ observations. Despite some differences in the spatial pattern, all three SST datasets showed a general SST warming in the Indian Ocean over the 1960-1999 period, which is particularly large (around 2°C) in the subtropics along the subtropical and subantarctic fronts (40°S-50°S). The zonally-averaged latitude-depth plot of the IOTA trends showed that the subtropical warming extends from the surface down to 800 m around 45°S. It also extends down to 250 m at 25°S and north of 10°N. In the tropics from 5°N to 15°S, the surface warming is trapped above the thermocline, roughly delimited by the 20°C isotherm, while below we find a subsurface cooling around depths of 100-200 m. This pattern corresponds to a shoaling of the thermocline and an increase of vertical stratification at the base of the mixed layer.

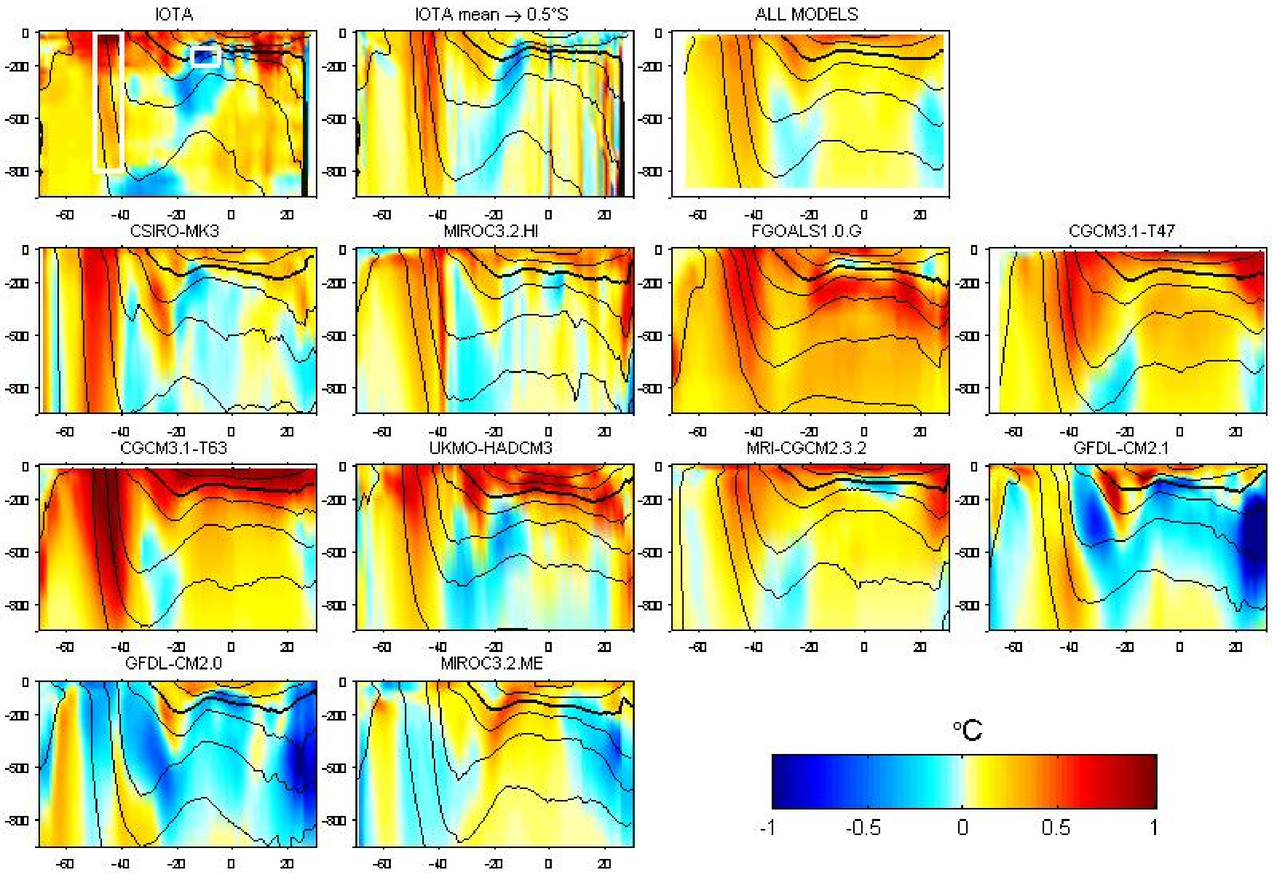

Figure 1. Zonally-averaged linear trends in subsurface temperature over 1960-1999 (colours, in °C), and mean subsurface temperature (contours every 4°C, 20°C isotherm in bold). Panel 2 shows the trends expected from a 0.5° southward shift of the observed mean temperature structure.

Objective 2: Compare the 15 IPCC AR4 model runs that simulate the behaviour of the Indian Ocean during the 20th century and validate them against the datasets described above.

We first reviewed 15 models from the Intergovernmental Panel for Climate Change (IPCC) fourth assessment report for which the surface and subsurface temperature from the 20th century climate experiments driven by greenhouse gas and aerosol forcing (natural and anthropogenic) were available. We further reduced this set to the 10 models for which the barotropic streamfunction and surface wind variables were also available, to be able to interpret the temperature trends in term of changes in ocean circulation and forcing.

We generated surface and latitude-depth maps of the modelled temperature trends and compared them to the observed maps (Figure 1). Most models reproduced the observed general SST warming. A robust feature in the modelled subsurface trend patterns, consistent with observations, is the deep-reaching strong warming along 40°S-50°S, found in 8 out of 10 models. The warming down to 250 m at 25°S is generally reproduced too. The tropical cooling in the thermocline, however, is only reproduced by half of the models.

As we qualitatively described these trends in the first version of our paper now published in *Geophysical Research Letters*, a reviewer questioned their significance. On his suggestion, we then compared the trends with the range of natural variability, estimated from the model control simulations without greenhouse forcing. The results of these rigorous statistical tests strongly suggest that the subtropical warming and tropical subsurface cooling are related to climate change. That is to say, the trends are not due to a natural mode of variation.

To interpret these trends in term of changes in ocean processes, we looked for changes in the modelled barotropic streamfunction, which represents the vertically-integrated circulation predominant in the subtropics. The amplitude of the deep-reaching warming trend was found related to a southward shift of the subtropical gyre circulation, by 0.5° on average in the models, driven by a strengthening of the subtropical westerly winds. The southward shift of the subtropical gyre circulation is an expected response to global warming (Cai et al., 2005a). It also implies a southward shift of the gyre's thermal structure, which explains why changes in circulation generate temperature trends. This link was reinforced by differencing the mean IOTA field from itself shifted by 0.5° southward, a simple test which proved able to reproduce much of the observed temperature change in the subtropics over 1960-1999 (Figure 1).

The observed subsurface cooling in the tropics is located in the latitude range that corresponds to the Indonesian Throughflow (ITF) which connects the Indian and Pacific oceans. At interannual timescales, thermocline depth anomalies associated with ENSO in the Pacific can be transmitted through the Indonesian region to the Indian Ocean though an oceanic wave path (Cai et al., 2005b). We thought that, by the same process, the shoaling of the western Pacific thermocline associated with a weakening trend in the equatorial Pacific trade winds observed over the last century (Vecchi et al., 2006) may be transmitted to the Indian Ocean. To test this hypothesis, we compared the trend in the equatorial Pacific winds with the trend in subsurface temperature in the tropical Indian Ocean in models and observations. We found that both trends are linearly related, which suggest the proposed oceanic teleconnection could operate on the 40 year timescale.

Objective 3: Interpret results in terms of Ocean's impact on the behaviour of the atmosphere.

It is worth noting here that the strengthening of westerly winds has been noted in numerous observational and modelling studies, in particular those by Wenju Cai as part of the IOCI and SEACI programs. The wind pattern is also associated with southward shift of the barometric pressure (i.e. a change in the so called Southern Annular Mode) and a southward shift in cyclo-genesis and storm tracks. These changes in the atmosphere are associated with the declining rainfall in southern Australia. Clearly, the ocean has responded to these changes in the atmosphere. At this point, we do not know if the ocean plays a positive feedback role in generating changes in the atmosphere.

The feedback of east-equatorial Indian Ocean SST on winter rainfall in south-east Australia through north-west cloud bands has already been established in observations (Ansell et al., 2000). To check the existence of such a relationship in the models, we plotted the correlation maps of winter Australian rainfall (July-October) with SST in the south-east equatorial Indian Ocean (10°S-EQ, 90°E-110°E), after removing ENSO influence by a multiple regression analysis (Figure 2). Most models indeed show, like observations, relatively high correlation values in South-East Australia, which appear to propagate across the continent along a north-west/south-east direction. This statistical test is a first step towards future model studies dedicated to understand how the tropical Indian Ocean SST warming impacts on Australian rainfall and how well the relationship is simulated in IPCC climate models.

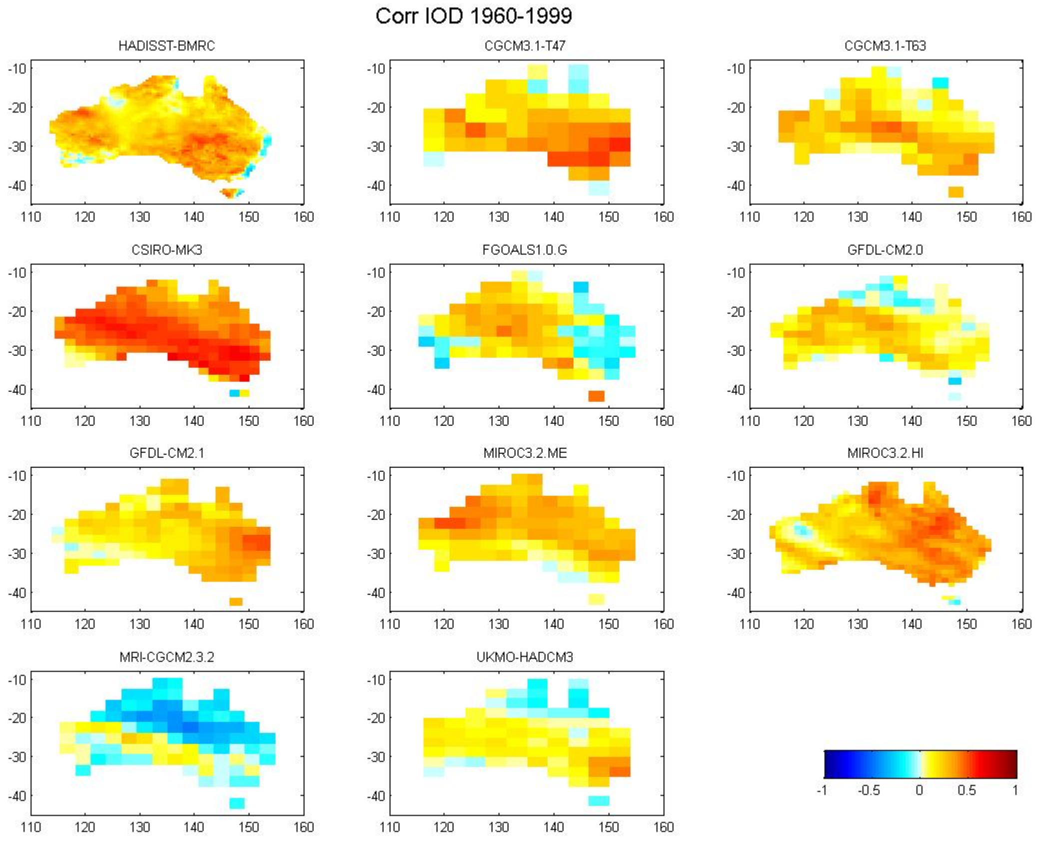

Figure 2. Correlation maps of Australian rainfall with SST in the southeast Indian Ocean (10°S-EQ, 90°E-110°E), after removing ENSO influence (SST in 5°S-5°N, 170°W-120°W), for observations (first panel) and models.

As a part of Project 1.2.1, an observational study of the relationship of between ENSO and the so called Indian Ocean Dipole (IOD) was completed with SEACI support, although most of the work was done under an earlier project. The impact of positive IOD in the absence of El Niño on Australian rainfall from this study is shown in Figure 3e. This pattern can be compared to the results from IPCC models in Figure 2. Clearly the impact of IOD is distinct from the impact of El Nino (Figure 3a) in the absence of positive IOD; and the impact of El Nino and positive IOD (Figure 3b) occurring together is yet different again. This study highlights the need to test the representation of both ENSO and Indian Ocean SST patterns in climate change models before using the models for climate change projections. In collaboration with Peter McIntosh, farming production in south eastern Australia was assessed for each of the seven rainfall patterns shown in Figure 3. The Indian Ocean was shown to have the largest impact.

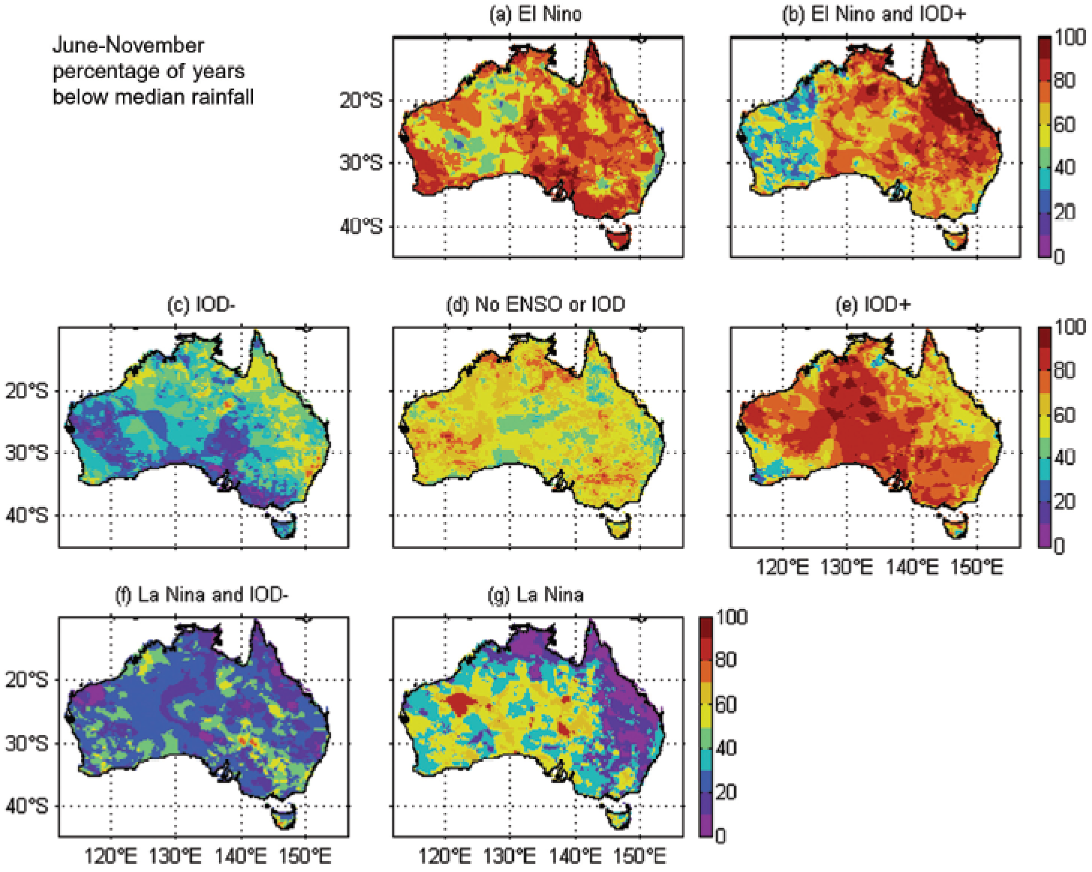

Figure 3 Probability of below median rainfall

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Ridgway, K. R., J. R. Dunn, and J. L. Wilkin (2002), Ocean interpolation by four-dimensional weighted least squares - application to the waters around Australasia, J. Atmos. Ocean. Tech., 19(9), 1357-1375.

Vecchi, G. A., B. J. Soden, A. T. Wittenberg, I. M. Held, A. Leetmaa, and M. J. Harrison (2006), Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing, Nature, 441, 73-76, doi:10.1038/nature04744.

Publications issued from this project

Alory, G., S. Wijffels and G. Meyers (2007). Observed temperature trends in the Indian Ocean over 1960–1999 and associated mechanisms, Geophys. Res. Lett., 34, L02606, doi:10.1029/2006GL028044.

Meyers, G., P. McIntosh, Pigot, L. and M. Pook 2006: The years of El Nino, La Nina and interactions with the tropical Indian Ocean. *J. Climate* (in press).

Acknowledgement

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As part of this project, the referees' comments on a paper submitted to the *Journal of Climate* were addressed and the final version of the paper submitted for publication. The paper is entitled, "The years of El Nino and La Nina and interactions with the tropical Indian Ocean" and is due to appear before mid-year. Subsequently, several enhancements of the results were prepared in collaboration with Peter McIntosh, showing that the impact of the eastern-equatorial Indian Ocean is the strongest control on rainfall and wheat production in the southern Murray Darling Basin. Additional analyses aimed at understanding the physical mechanisms that link the Indian and Pacific Oceans documented the patterns of atmospheric parameters associated with the El Nino-Southern Oscillation—Indian Ocean relationship. The enhancements are not yet mature enough for publication.

Project Milestone Reporting Table

To be completed prior to commencing the project				Completed at each Milestone date	
Milestone description[1] (brief) (up to 33% of project activity)	Performance indicators[2] (1- 3 dot points)	Completion date[3] xx/xx/xxxx	Budget[4] for Milestone ($) (SEACI contribution)	Progress[5] (1- 3 dot points)	Recommended changes to workplan[6] (1- 3 dot points)
1. Assemble XBT data and IPCC model results	Quality controlled data available	01/04/06	25K	--Temperature profile data are assembled and QC'd. --Model data are downloaded and on-site. --Visualisation software and templates are developed.	--Careful approach to the scarcity of observational data
2. Map surface and subsurface temperature trends for model and obs.	Mapped products available	01/07/06	25K	--After trying a few methods, a reliable way estimate subsurface temperature trends from sparse data was developed. --Maps and vertical sections of trend in temperature and current (barotropic stream function) are available	--No changes necessary. A quick look at mapped products reveals a rich structure of changes in the Indian Ocean. Understanding the processes that control the changes will be a challenge.

3. Interpretation What controls SST warming?	Draft scientific papers	01/10/06	25K	--Discovery and documentation of surface and subsurface signals --Results of attempts to understand the surface and subsurface structure --First submission of paper	--New approach to identifying significant trends in data and models.
4. Integration with other work. What is impact on southern region?	Project final report. One or more papers submitted to scientific journals	31/12/06	25K	--Paper on temperature changes accepted in GRL --Most IPCC climate models capture the impact of equatorial Indian Ocean on SE Australia, but differ considerably in intensity and detail.	
5. Synthesis: Assess the accuracy of IPCC climate change simulations by validating sub-surface Indian Ocean temperature modulating global warming.	--Quality of observed temperature profiles and analysis --Presentation of Indian Ocean model results --Interpretation of mechanisms of SST warming	31/12/06	As above	--Showing how the models represent the relationship of rainfall to SST in the region of warming --The results of this study have been integrated with other studies of climate change in the region, in particular those related to southward shift of cyclogenesis.	