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Tendências recentes das propriedades termohalinas na camada superior do Oceano Austral

JÔNATAS FILIPE AIRES MIRANDA

Dissertação apresentada ao Programa de Pós-Graduação em Oceanografia Física, Química e Geológica, como parte dos requisitos para a obtenção do Título de Mestre.

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Rio Grande, RS, Brasil

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por

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Tendências recentes das propriedades termohalinas na camada superior do Oceano Austral

[ATA DE DEFESA]

*“O Senhor é a minha força e o meu escudo; nEle o meu coração confia, e dEle
recebo ajuda.”
Salmo 28:7a*

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Resumo

Atualmente, a Terra passa por mudanças climáticas que são responsáveis pelo aumento de temperatura atmosférica e oceânica. O hemisfério sul do planeta concentra a maior parte das alterações percebidas no oceano e cerca de 80% do aquecimento do hemisfério sul acontece no Oceano Austral, na faixa circumpolar ao sul de 30°S. Neste cenário, o presente trabalho investigou como as alterações nas camadas superficiais do Oceano Austral se propagam para o interior da coluna da água, especificamente através das alterações em suas características termohalinas médias, utilizando dois produtos de Reanálises Oceânicas (UR025.4 e GLORYS2V3), que abrangem o período de 1993 a 2014, e uma climatologia derivada de dados do sistema Argo, no período de 2004 a 2015. O Oceano Austral está, em sua maior parte, aquecendo, porém uma região ao sul de 50°S mostra uma tendência de resfriamento de menor magnitude do que o aquecimento. Tanto o aquecimento quanto o resfriamento podem ser consequência da tendência positiva do Modo Anular do Sul, que intensifica e desloca o cinturão de ventos oeste para sul, aumentando o transporte de Ekman para norte. Isto, por sua vez, traz águas mais frias de latitudes mais altas, o que causa o resfriamento ao sul de 50°S. À medida que esta água é transportada para norte, absorve calor e em torno de 45°S sofre subducção, levando esse calor para o interior da coluna de água. Em relação à salinidade, os resultados mostraram que regiões mais salinas estão tendo a salinidade aumentada e regiões menos salinas estão passando por um processo de dessalinização. Isto sugere uma intensificação do ciclo hidrológico, i.e., aumento nas taxas de evaporação e precipitação. Também há a atuação do gelo marinho, que com o Transporte de Ekman intensificado para norte, está transportando uma maior quantidade de gelo marinho. O eventual derretimento deste gelo contribui para uma diminuição da salinidade no Oceano Austral.

Palavras-Chave: temperatura potencial, salinidade, Oceano Austral.

Abstract

Currently, the Earth goes through climate changes that are responsible for the increase of atmospheric and oceanic temperature. The southern hemisphere of the planet concentrates most of the perceived changes in the ocean and about 80% of the warming of the southern hemisphere occurs in the Southern Ocean, in the circumpolar range south of 30°S. In this scenario, the present work investigated how the changes in the Southern Ocean surface layers propagate to the interior of the water column, specifically through the changes in their average thermohaline characteristics. It were used two products of Ocean Reanalysis (UR025.4 and GLORYS2V3) that cover the period from 1993 to 2014 and a climatology derived from the Argo system from 2004 to 2015. The Southern Ocean is heating in most of its area, but a region south of 50°S shows a cooling trend of lesser magnitude than the heating. Both heating and cooling may be a consequence of the positive trend of the Southern Annular Mode, which intensifies and shifts the westerlies wind belt polewards, increasing Ekman transport to the north. This brings in colder waters from higher latitudes, which causes the cooling south of 50°S. As this water is advected northwards, it absorbs heat and subducts around 45°S, heating the interior of the water column. Regarding salinity, the results showed that the salinity of regions that are more saline is increasing and regions that are less saline are freshening. This suggests an intensification of the hydrological cycle, i.e., an increase in rates of precipitation and evaporation. There is also the action of the sea ice, which with the Ekman Transport intensified to the north, is carrying a greater amount of sea ice. The eventual melting of this ice contributes to a decrease in salinity in the Southern Ocean.

Keywords: potential temperature, salinity, Southern Ocean.

Estrutura da Dissertação

Como requisito para a obtenção do título de Mestre em Oceanografia Física, Química e Geológica na Universidade Federal do Rio Grande (FURG), é necessário a produção de uma dissertação e de um artigo científico como primeiro autor em um periódico indexado. Sendo assim, esta dissertação é dividida em 4 capítulos seguidos das referências. No capítulo 1 é feita uma introdução ao tema principal da pesquisa, apresentando também os objetivos do estudo. O capítulo 2 contém a metodologia utilizada na pesquisa, bem como uma descrição sucinta da área de estudo e dos produtos de Reanálises Oceânicas utilizadas neste estudo. O capítulo 3 é composto do artigo submetido para publicação no formato exigido pela revista. No capítulo 4 são feitas as conclusões e o sumário do estudo contendo os principais resultados. Finalmente, a seção de referências completa desta dissertação, contendo todas as fontes utilizadas neste trabalho.

Capítulo I: Introdução

I.1 - Introdução

As complexas interações entre o oceano e a atmosfera têm sido alvo de diversos estudos pela comunidade científica nas últimas décadas, visto que o seu entendimento é fundamental para compreendermos o clima do planeta. O oceano, devido à alta capacidade calorífica da água, absorve e retém cerca de 90% do excesso de energia presente no sistema climático do planeta [e. g. Levitus *et al.*, 2012]. Gille [2008] estimou que cerca de 80% do aquecimento observado no hemisfério sul está localizado no Oceano Austral, em latitudes ao sul de 30°S, o que indica que este ambiente é sensível às mudanças climáticas atuais.

No oceano, evidências a partir da análise de dados hidrográficos históricos e perfis de temperatura recentes indicam que há uma tendência de aumento de temperatura ao longo de várias faixas de profundidade, alcançando áreas bem abaixo da superfície [e.g. Böning *et al.*, 2008; Gille, 2008]. De acordo com o estudo recente de Gille [2014], o aquecimento do Oceano Austral está concentrado na faixa circumpolar correspondente à Corrente Circumpolar Antártica (CCA).

O Oceano Austral é agente importante no clima global, já que conecta os oceanos Pacífico, Atlântico e Índico, principalmente através da CCA, servindo como um canal de transmissão de sinais climáticos entre esses oceanos [Rintoul & Sokolov, 2001] (Fig. 1). Trani *et al* [2014] corroboram esta ideia afirmando que tanto a estrutura da CCA quanto a dinâmica de mesoescala associada a ela são importantes para a circulação de massas de água e para a ventilação do oceano profundo em altas latitudes austrais. O Oceano Austral também possui características regionais que lhe conferem um papel de destaque no entendimento das questões relativas às mudanças climáticas globais [Gille, 2008], atuando na ventilação das camadas de fundo de grande parte dos oceanos globais, sendo então responsável por uma parcela expressiva do transporte global de calor [Orsi *et al.*, 1999].

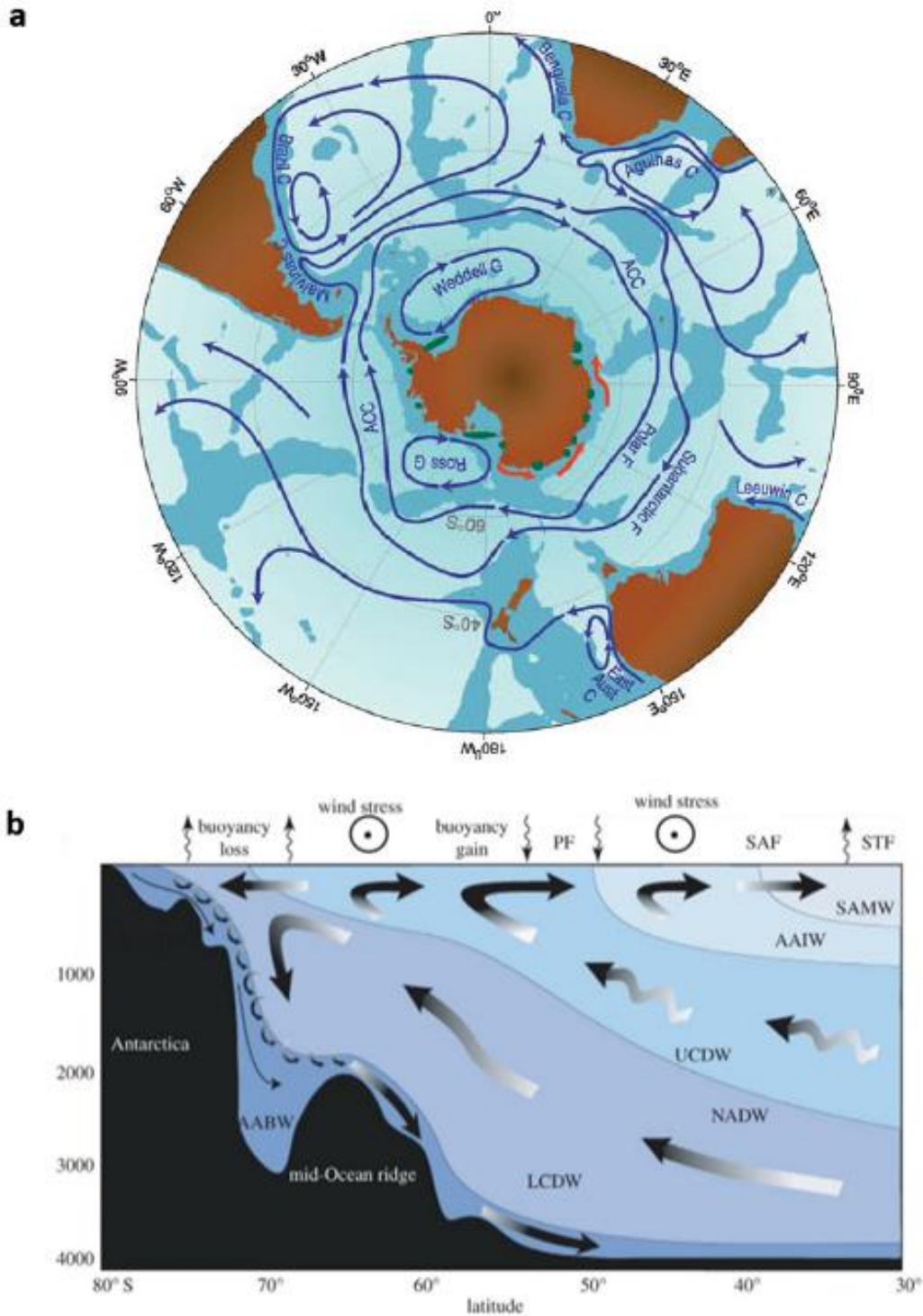


Figura 1: (a) Oceano Austral. As setas brancas mostram as principais correntes. A CCA é uma feição circumpolar que conecta as bacias oceânicas do Atlântico, Pacífico e Índico. Fonte: National Research Council [2011]. (b) Esquema da circulação de revolvimento meridional no Oceano Austral, com a posição das frentes e massas d'água. As siglas das massas d'água constam na lista de abreviaturas usadas neste trabalho. AABW: Água de Fundo Antártica; LCDW: Água Profunda Circumpolar Inferior; UCDW: Água Profunda Circumpolar Superior; NADW: Água Profunda do Atlântico Norte; AAIW: Água Intermediária Antártica; SAMW: Água Modal Subantártica. PF: Frente Polar; SAF: Frente Subantártica; STF: Frente Subtropical. Fonte [Naveira Garabato, 2012].

O hemisfério sul contém alguns modos (i. e. padrões) de variabilidade climáticas, destacando-se a importância do Modo Anular do Sul (SAM, de *Southern Annular Mode*), também conhecido como Modo de Alta Latitude ou Oscilação Antártica. Segundo Mayewski *et al.* [2009], este fenômeno é o principal modo de variabilidade na circulação atmosférica na região extratropical e de altas latitudes do hemisfério sul. O SAM tem uma estrutura anular zonalmente simétrica, com anomalias síncronas de sinais opostos em altas e médias latitudes. Este pode ser identificado em vários parâmetros mensurados em altas latitudes, como pressão superficial e temperatura, altura geopotencial e componente zonal do vento (Fig. 2). Os autores também afirmam que estudos observacionais e de modelagem já demonstraram que o SAM contribui com cerca de 35% da variabilidade climática do hemisfério sul em escalas temporais que vão de diárias até decadais. É provável que o SAM seja a principal forçante da variabilidade da circulação de larga escala do Oceano Austral.

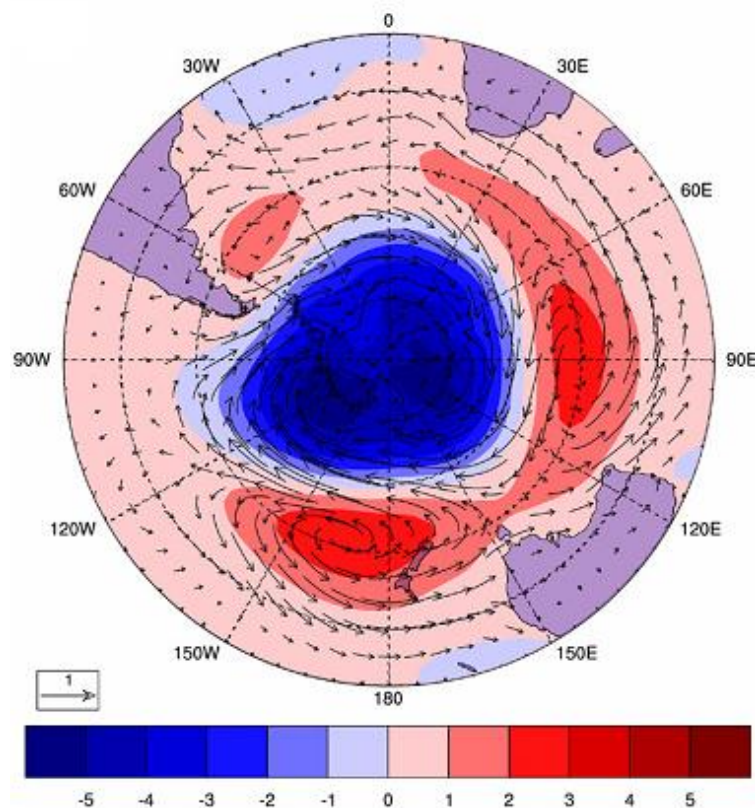


Figura 2: SAM representado na Reanálise Atmosférica ECMWF ERA-40, a partir da tendência linear calculada de 1979 a 2002. As setas representam a intensidade dos ventos em superfície (a seta padrão representa 1m/s) e a escala de cores indica a anomalia de pressão ao nível do mar (hpa) baseados no índice do SAM. Fonte: retirado de Sen Gupta & England [2006].

O SAM consiste basicamente, em sua fase positiva, na diminuição (aumento) da pressão ao nível do mar em altas (médias) latitudes; e em sua fase negativa ocorre o oposto [Mayewski *et al.*, 2009]. Com o SAM em fase positiva, os ventos de oeste são intensificados e deslocados em direção a maiores latitudes, aproximando-os do continente Antártico, intensificando o fluxo da CCA e o seu campo de variabilidade de mesoescala (na sua fase negativa ocorre o contrário) [Meredith & Hogg, 2006; Mayewski *et al.*, 2009]. Thompson & Solomon [2002] verificaram mudanças no SAM desde metade dos anos 1970, o que foi atribuído posteriormente à depleção da camada de ozônio [Thompson *et al.*, 2011]. Marshall [2003] calculou o Índice SAM utilizando estações com medições *in situ* da pressão atmosférica ao nível do mar, entre altas e baixas latitudes desde 1958 até 2000 e seus resultados confirmaram o aumento já observado no SAM entre 1960 e 2000, com maior tendência a partir de 1970 (Fig. 3).

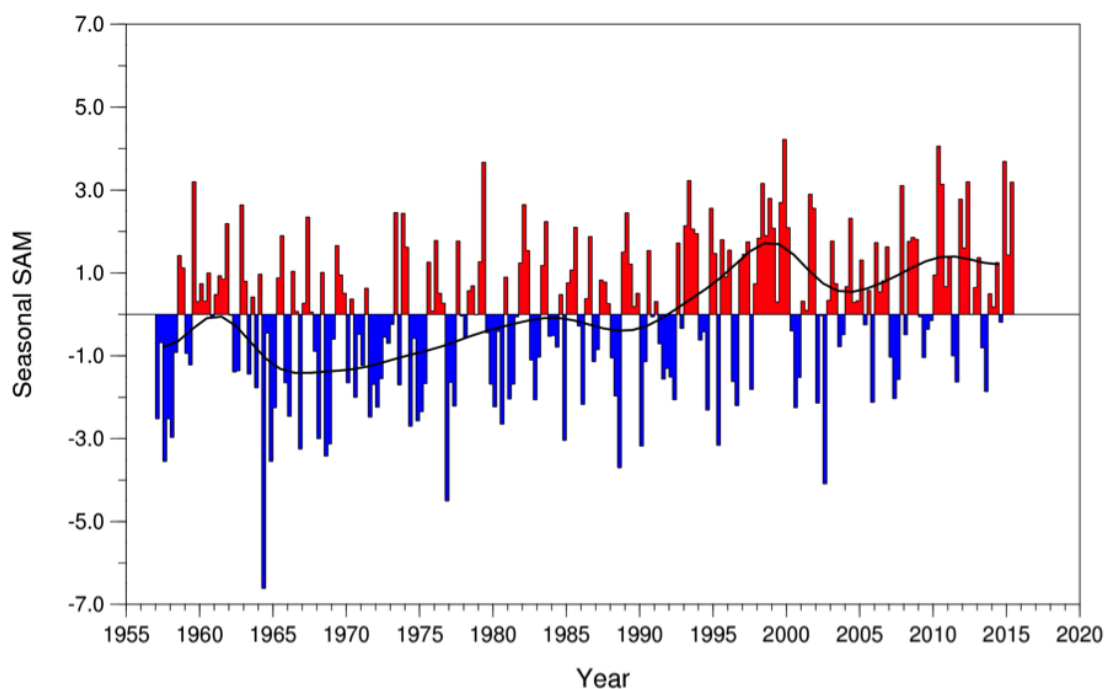


Figura 3: Valores sazonais do Índice SAM, como proposto por Marshall [2003]. Barras vermelhas (azuis) representam episódios SAM com índice positivo (negativo). A linha preta representa a tendência. Note a tendência positiva desde a década de 1960. Fonte: Marshall, Gareth & National Center for Atmospheric Research Staff (Eds). The Climate Data Guide: Marshall Southern Annular Mode (SAM) Index (Station-based). Atualizado em 2016.

Os efeitos do SAM na intensidade e posição dos ventos causam variações na intensidade e nas características da circulação termohalina, sendo peças fundamentais para a evolução do clima do planeta, tanto no passado quanto no futuro, e constituem uma importante conexão entre a atmosfera regional e criosfera com o oceano profundo [Mayewski *et al.*, 2009].

Como já foi dito, o SAM vem mostrando uma tendência positiva desde a década de 1960 [Thompson & Solomon, 2002]. A influência da intensificação dos ventos de oeste e seu deslocamento em direção ao polo pode ser detectada através do Transporte de Ekman (movimento horizontal de água causado pelo vento aliado ao efeito de Coriolis), que mostra uma alteração ao longo do tempo nas taxas de ressurgência e subsidência (Bombeamento de Ekman, i.e., movimento vertical da água) na região, formando regiões de ressurgência em torno de 60°S e de subsidência em 45°S [Hall & Visbeck, 2002] (Fig. 4). A intensidade desses fenômenos também é alterada, sendo que a ressurgência é aumentada em 40% próximo ao continente Antártico e diminuída em cerca de 15% na região próxima a 45°S [Hall & Visbeck, 2002].

Ferreira *et al.* [2015] e Parise *et al.* [2015] abordam o efeito do Bombeamento de Ekman no contexto das alterações de temperatura da superfície do mar (TSM) no Oceano Austral. Ferreira *et al.* [2015] estudaram o efeito da depleção da camada de ozônio sobre o continente Antártico e detectaram um aumento dos ventos catabáticos que promovem um maior transporte de Ekman em direção ao norte no entorno do continente. Parise *et al.* [2015], por sua vez, pesquisaram efeitos resultantes do aumento do gelo marinho no entorno da Antártica e constataram que durante o período em que o gelo marinho está presente, este isola as trocas de calor entre a água superficial e a atmosfera, diminuindo a TSM. Outro efeito dessa cobertura de gelo é promover condições semelhantes ao SAM em sua fase positiva (e.g., aumento dos ventos de oeste na região). Isto, inicialmente, também contribui para a diminuição na TSM da região, porém a ressurgência que se segue após alguns anos (Ferreira *et al.* [2015] menciona 20 anos e Parise *et al.* [2015] fala em cerca de 9 anos) gera um sinal de aquecimento na superfície devido às águas subsuperficiais terem uma temperatura maior.

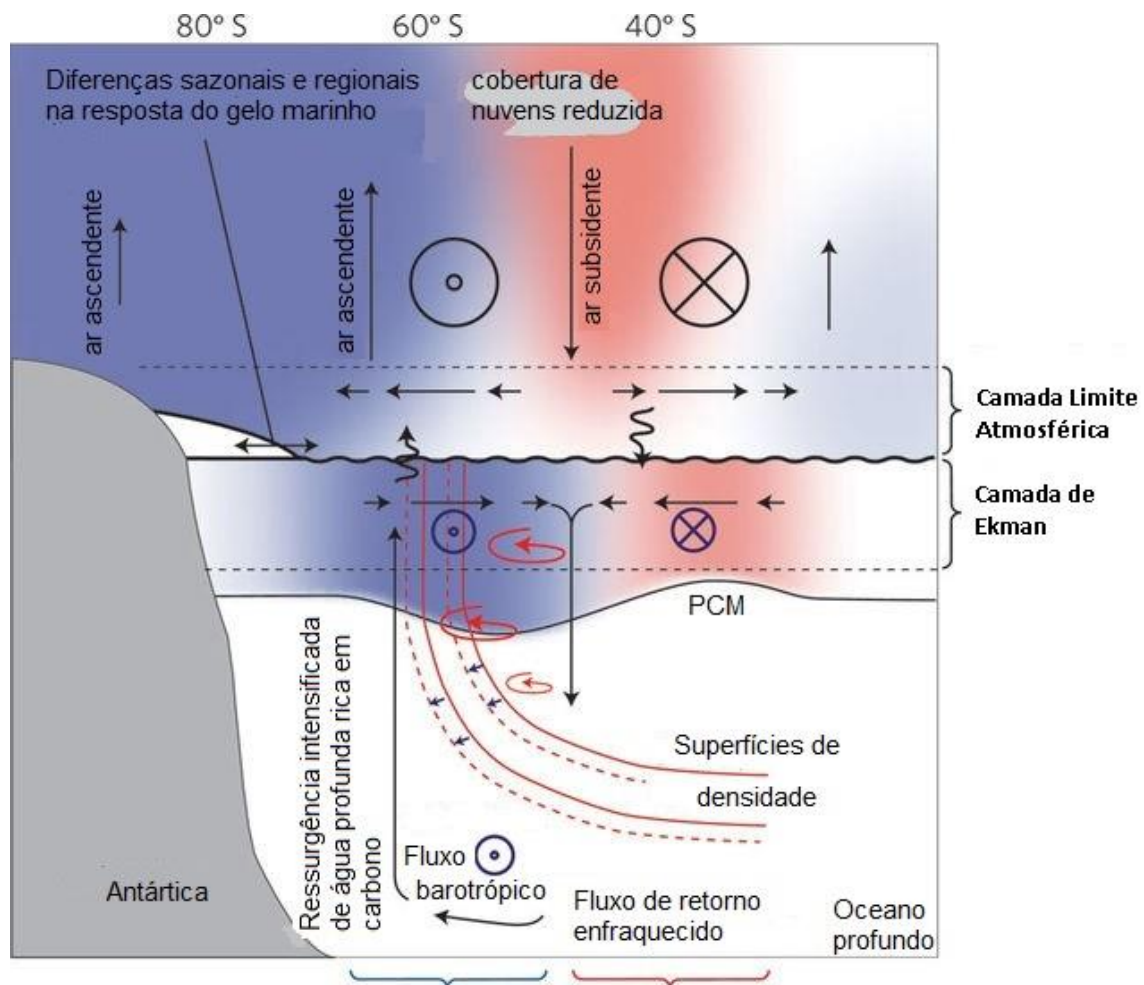
Outros efeitos da intensificação do cinturão de ventos oeste na região é um aquecimento na superfície e subsuperfície das águas no limite norte da CCA

e um resfriamento superficial ao sul desta [Sen Gupta & England, 2006; Fyfe *et al.*, 2007; Gille, 2008; Screen *et al.*, 2008; Spence *et al.*, 2010; Armour *et al.*, 2016].

[Meredith & Hogg, 2006; Fyfe *et al.*, 2007; Böning *et al.*, 2008; Hogg *et al.*, 2008; Screen *et al.*, 2008] mencionam um mecanismo pelo qual a região ao sul da CCA possivelmente se aqueça. Com a intensificação dos ventos de oeste, a atividade de mesoescala (vórtices) na CCA aumentaria e com isso mais calor seria transportado em direção sul. Este aquecimento eventualmente poderia compensar e ultrapassar o resfriamento inicial. Outro mecanismo de aquecimento proposto consiste na ressurgência de águas subsuperficiais mais aquecidas no limite sul da CCA. [Ferreira *et al.*, 2015; Parise *et al.*, 2015; Kostov *et al.*, 2017].

Assim como a temperatura, a salinidade também sofre consequências das mudanças climáticas. Atualmente, considera-se que o ciclo hidrológico tem sido intensificado, i.e., evaporação e precipitação intensificados, como resultado do aumento de temperatura global e indiretamente isso tem afetado a salinidade dos oceanos fazendo, de maneira genérica, com que regiões mais salinas fiquem com a salinidade ainda maior e vice versa [Helm *et al.*, 2010; Durack *et al.*, 2012; Aretxabaleta *et al.*, 2015]. Há, também, outro mecanismo que contribui para a diminuição da salinidade no limite sul da CCA: com a intensificação dos ventos de oeste, o transporte de gelo marinho em direção ao norte aumenta, o que acaba transportando uma quantidade maior de água doce e que após o derretimento do gelo diminui a salinidade da região [Haumann *et al.*, 2016]. Recentemente tem sido registrado um aumento sistemático na cobertura de gelo marinho no entorno da Antártica e isto também possivelmente contribui para a diminuição de salinidade no Oceano Austral (Parise *et al.*, 2015).

Isto sugere que há uma maior ressurgência de água ao sul do eixo da CCA, o que, potencialmente, traria efeitos nas propriedades físicas da água na região e influenciaria a circulação termohalina [Hall & Visbeck, 2002; Sen Gupta & England, 2006]. Porém, alguns estudos sugerem que este Transporte de Ekman intensificado (para norte) é balanceado por processos de mesoescala que o estariam compensando, i.e. levando calor para águas a sul do eixo da corrente [Fyfe *et al.*, 2007; Böning *et al.*, 2008; Screen *et al.*, 2008].



Fluxos superficiais, Transporte de Ekman e mudanças na PCM agem causando alterações na TSM. Fluxos de calor gerados pela mesoescala agem no sentido oposto.

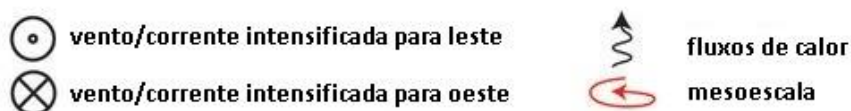


Figura 4: Esquema mostrando o efeito da intensificação dos ventos de oeste no Oceano Austral. Há regiões de ressurgência mais próximas ao continente e regiões de subsidência mais afastadas deste, além da atividade de mesoescala em subsuperfície. Esses fenômenos são intensificados com eventos positivos do SAM. *PCM: profundidade da camada de mistura; TSM: temperatura da superfície do mar. Fonte: adaptado de Thompson *et al.* [2011].

A importância de se investigar este tema está no fato de que a variabilidade registrada no Transporte e Bombeamento de Ekman na região, especialmente no entorno da CCA, e nos valores observados de temperatura e salinidade podem estar influenciando na circulação oceânica regional, e também em maiores escalas, ao propagar essas alterações para o interior do oceano.

Böning *et al.* [2008] analisaram dados da climatologia oceânica denominada CARS2006 (CARS, *CSIRO Atlas of Regional Seas - 2006*; contendo dados da década de 1960 a 1990) e perfiladores Argo lançados de 2002 a 2006 para investigar a resposta da CCA às mudanças climáticas a partir de tendências nas mudanças de densidade da coluna da água. A metodologia deste estudo consistiu basicamente em um cálculo de tendências lineares de aquecimento/resfriamento e salinização/dessalinização ao longo do período coberto pelo CARS2006 e Argo (i.e., 1960 a 2006). A área estudada foi o Oceano Austral de 30-60°S e foi feita uma média zonal de toda a área, gerando um perfil de latitude × profundidade.

No estudo de Böning *et al.* [2008] foi constatado um aquecimento na superfície próxima ao continente Antártico e ao longo do eixo da CCA sem diferenças significativas entre as bacias dos oceanos Pacífico, Atlântico e Índico. Além disso, o aquecimento das camadas mais superficiais do Oceano Austral foi maior na região adjacente ao limite sul da CCA. Em relação à salinidade, Böning *et al.* [2008] encontraram uma tendência de diminuição da salinidade ao longo de toda a faixa latitudinal da CCA (Fig. 5), sendo mais expressivo na camada superficial. Os autores atribuíram o aquecimento aos fluxos de mesoescala levados em direção ao sul por conta da intensificação dos ventos e a diminuição de salinidade foi atribuída ao aumento na precipitação na região decorrente do deslocamento do cinturão de chuvas de latitudes médias.

Historicamente, a amostragem do Oceano Austral tem sido uma tarefa difícil devido às características inerentes a esse ambiente. O Oceano Austral é uma parte esparsamente amostrada dos oceanos globais e os dados de temperatura coletados pelos navios de pesquisa nas últimas décadas contêm inúmeras lacunas a serem preenchidas, que impedem a avaliação das mudanças e tendências de temperatura do Oceano Austral [Gille, 2008; Roemmich & Gilson, 2009; Riser *et al.*, 2016].

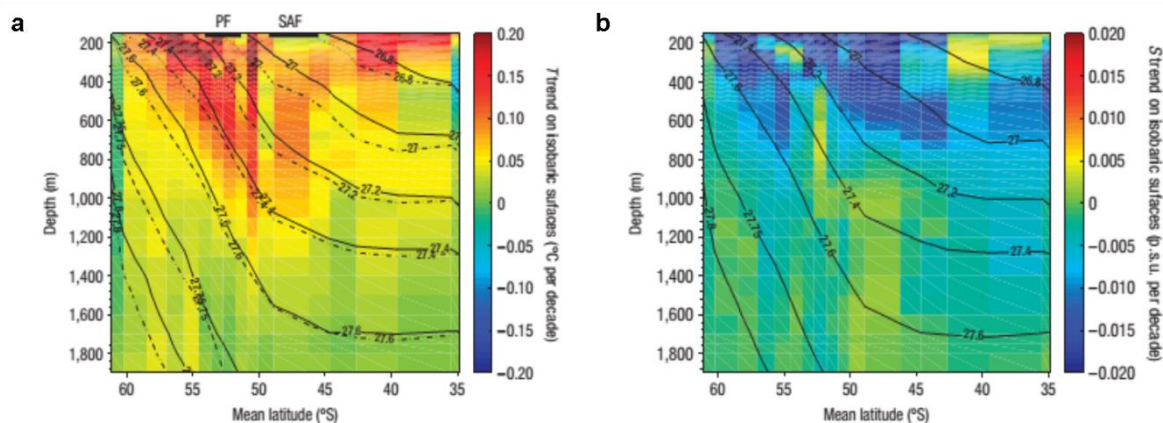


Figura 5: Variabilidade da temperatura e salinidade ao longo da CCA. Tendência média decadal de temperatura potencial (a) e salinidade (b), plotadas em superfícies isobáricas. Extraído de Böning *et al.* [2008].

Além disso, os dados de salinidade são historicamente escassos, com uma cobertura muito esparsa e conjuntos de dados históricos contendo fortes vieses regionais e sazonais devido à dificuldade de coletar dados em todo o oceano simultaneamente [Roemmich & Gilson, 2009]. Neste contexto, o sistema Argo surge como uma poderosa ferramenta para fornecer informações da camada superior dos oceanos, entre 0 e 2000 m de profundidade. Começando no final da década de 1990, o Argo alcançou uma cobertura global (ainda esparsa) em 2004, sua população chegou a 3.000 flutuadores em 2007 e, atualmente, está em 3.900 perfiladores em operação. A quantidade de dados coletados no Oceano Austral pelo Argo em um ano, no inverno do hemisfério sul, supera o total de dados observados nos últimos 100 anos por todas as outras plataformas observacionais. Desta forma, atualmente, a maioria dos dados de temperatura e salinidade do Oceano Austral são oriundos do sistema Argo [e.g. Riser *et al.*, 2016].

Diante desta temática, o presente trabalho visa investigar as tendências nas propriedades físicas das águas do Oceano Austral (i. e. temperatura potencial e salinidade) ao longo dos primeiros 2000 m da coluna de água. Será revisitada a abordagem de Böning *et al.* [2008] utilizando-se duas Reanálises Oceânicas de vanguarda (UR025.4, que cobre o período de 1993 a 2010 e GLORYS2V3, que cobre de 1994 a 2014) e uma climatologia derivada de dados Argo (Climatologia Roemmich-Gilson, abrangendo o período de 2004 a 2015; Roemmich & Gilson, [2009]). Além de investigar as tendências, procura-se

avaliar se as Reanálises Oceânicas estão representando bem os campos de temperatura e salinidade no Oceano Austral.

I.2 - Objetivos

Geral:

Esta dissertação tem como objetivo principal investigar as alterações espaço-temporais da temperatura potencial e salinidade nos primeiros 2000m do Oceano Austral nas últimas duas décadas.

Específicos:

- Avaliar se as Reanálises Oceânicas consideradas estão representando bem os campos de temperatura e salinidade no Oceano Austral, sua variabilidade e tendências;
- Revisitar a abordagem de Böning *et al.* (2008) com as tendências de temperatura potencial e salinidade no Oceano Austral, da superfície até 2000 m.

I.3 - Área de estudo

Há mais de uma definição para delimitar o Oceano Austral. A definição que foi adotada para este trabalho consiste na mais ampla, que considera todos os fenômenos ao sul da Frente Subpolar (30°S) [Talley *et al.*, 2011]. O limite sul adotado foi 65°S, devido a disponibilidade de dados. O Oceano Austral é caracterizado por possuir a maior corrente oceânica do mundo, a CCA, que transporta em média ~130Sv [Sloyan & Rintoul, 2001]. Esta é fortemente impulsionada pelos ventos de oeste [e.g. Böning *et al.*, 2008; Sallée *et al.*, 2008], fluindo no sentido leste ao redor do continente Antártico por milhares de quilômetros sem nenhuma barreira física, nas latitudes do Estreito de Drake. Deste modo, o Oceano Austral mantém contato com os três maiores oceanos da Terra – Pacífico, Atlântico e Índico – e é peça fundamental na circulação oceânica global.

O padrão de circulação atmosférica sobre o Oceano Austral consiste em uma região de alta pressão em torno de 30°S, referente aos ramos de ar subsidente das células de Hadley e Ferrel; nesta região é onde se localiza o cinturão de ventos oeste. Na latitude de 60°S há uma região de baixa pressão, devido aos ramos de ar ascendente das células de Ferrel e Polar. Sobre o continente Antártico há uma área de alta pressão formada pela subsidência do ar polar com temperaturas muito baixas e seco (Fig. 6).

O Oceano Austral possui regiões de frentes, i. e., regiões de gradientes horizontais de propriedades físicas que variam espacial e temporalmente (Fig. 7). A CCA contém três regiões de frentes: a Frente Subantártica e a Frente Polar, que são nitidamente identificadas em toda a extensão circumpolar do Oceano Austral, e a Frente Sul CCA, localizada a sul da Frente Polar, sendo a última frente que marca o limite sul do núcleo da CCA [Orsi *et al.*, 1995]. Ao longo destas três frentes, o fluxo geostrófico de água é mais intenso [Tomczak & Godfrey, 1994; Orsi *et al.*, 1995].

Para este estudo, a área é limitada entre 30°S a 65°S e profundidades da superfície até 2000m. Dividimos a análise espacial em duas partes: uma com todo o Oceano Austral zonalmente promediado (o que resultou em um perfil de latitude $\times$ profundidade); depois seccionamos a área em 5 setores horizontais: Mar de Weddell (60°W-20°E), Índico (20°E-90°E), Pacífico Oeste (90°E-160°E), Mar de Ross (160°E-140°W) e Mares de Bellingshausen & Amundsen (140°W-60°W), como descrito em Zwally *et al.* [2002] e aplicada por vários autores (por exemplo, Kerr *et al.*, [2012] e Azaneu *et al.*, [2014]), novamente calculando a média das longitudes em cada setor para gerar perfis de latitude $\times$ profundidade (Fig. 8).

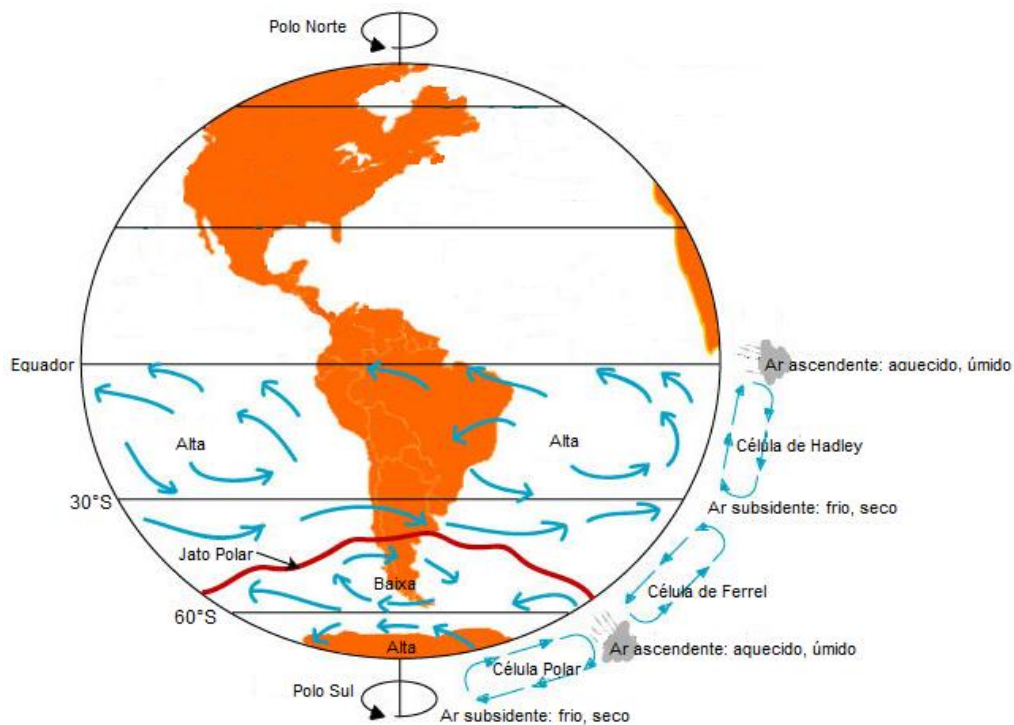


Figura 6: Padrão de circulação atmosférica do hemisfério sul, mostrando o sentido dos ventos e as regiões de subsidência e ascendência de ar (altas e baixas pressões, respectivamente). Abaixo da linha de 30°S está o cinturão de ventos oeste que atua sobre a CCA e sofre influência do SAM. Fonte: figura adaptada. Disponível em: <<https://www.learner.org/courses/envsci/unit/text.php?unit=2&secNum=6>>

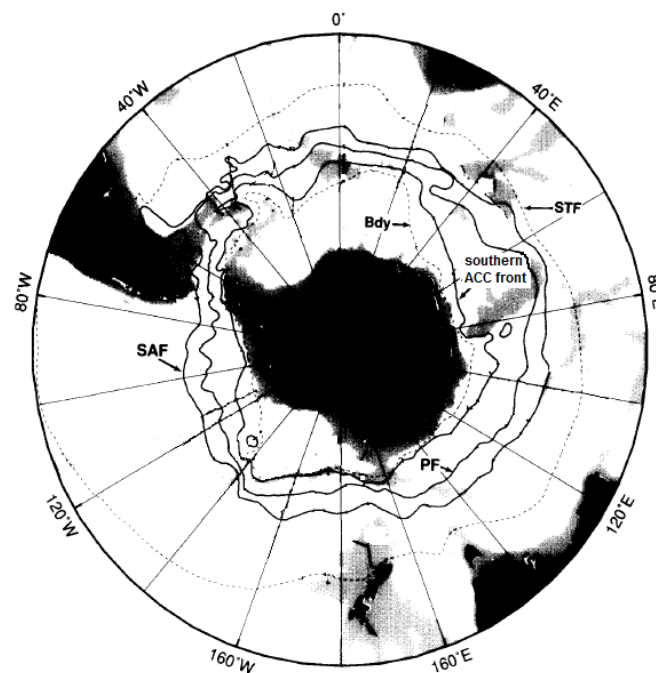


Figura 7: Mapa do Oceano Austral mostrando a posição das frentes. De norte para sul: STF: Frente Subtropical; SAF: Frente Subantártica; PF: Frente Polar; Southern ACC front: Frente Sul da Corrente Circumpolar Antártica; bdy: limite sul do alcance da Água Profunda Circumpolar Superior. Fonte: adaptado de Orsi *et al.* [1995].

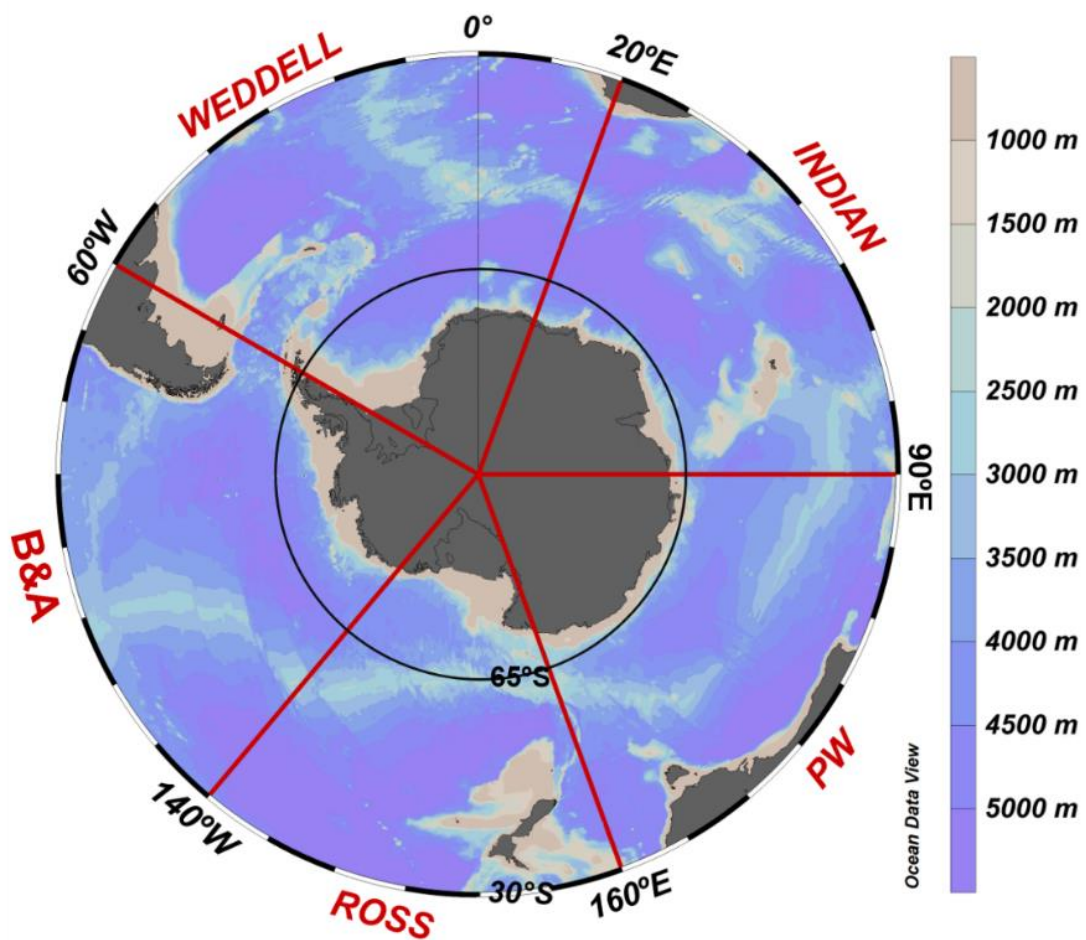


Figura 8: Área de estudo: Oceano Austral em latitudes ao sul de 30°S com a divisão horizontal dos 5 setores. Weddell: setor do Mar de Weddell; Indian: setor do Índico; PW: setor do Pacífico Oeste; Ross: setor do Mar de Ross; B&A: setor dos Mares de Bellingshausen & Amundsen).

Capítulo II: Dados e métodos

II.1 - Dados

Produtos de reanálise oceânica têm sido amplamente utilizados em estudos de larga escala visando suprir a falta de dados observacionais disponíveis nesta escala uma vez que são gerados a partir da assimilação de dados obtidos por observações diretas e modelagem numérica. Para a mesma área deste estudo, Swart *et al.* [2015] concluíram que a reanálise atmosférica ERA-Interim representa bem o campo de ventos superficiais no Oceano Austral. Dotto *et al.* [2014], em seu trabalho sobre massas de água no Mar de Weddell, concluíram que a reanálise *My Ocean University of Reading – version 025.4* (UR025.4 - NEMOv3.2) apresenta resultados consistentes e é a mais indicada dentre as analisadas para representar características hidrográficas como temperatura e salinidade. Adicionalmente, Aguiar *et al.* [2017], em seu estudo comparando três reanálises na formação de Água de Fundo Antártica, no Oceano Austral, constataram que a UR025.4 foi a que melhor representou a formação da massa d'água, sendo dinamicamente mais acurada.

Para este trabalho, analisou-se os campos de distribuição da temperatura potencial e da salinidade de duas reanálises oceânicas recentes e uma climatologia gerada a partir de dados do sistema Argo. As reanálises escolhidas para o nosso estudo foram duas *MyOcean Global Reanalysis* (<http://marine.copernicus.eu/>), uma da *Mercator Océan* (GLORYS2V3) e uma da *University of Reading* (UR025.4). Estas foram escolhidas principalmente por sua forçante atmosférica, que é a reanálise atmosférica ERA-Interim [Simmons *et al.*, 2007], considerada a melhor reanálise disponível para representar o SO [Swart *et al.*, 2015], e também pelo período que elas cobrem. A reanálise *MyOcean University of Reading* (UR025.4) abrange o período de 1993 a 2010, e a *MyOcean Mercator Océan* (GLORYS2V3) possui dados de 1994 a 2014.

A reanálise GLORYS2V3 utiliza o modelo de circulação oceânico baseado em NEMO v3.1 e a grade horizontal é a grade irregular tri-polar padrão ORCA025, fornecendo uma resolução de 1/4° no equador que aumenta irregularmente em direção aos polos [Madec, 2008]. A resolução vertical compreende 75 níveis. A resolução diminui da superfície até a camada mais profunda, sendo de 1m na superfície e 200m nas últimas camadas. A forçante superficial é derivada da reanálise atmosférica ERA-Interim, com correções nos

fluxos radiativos e de precipitação. Além dos fluxos de chuvas fornecidos pela ERA-Interim, é incluído o fluxo fluvial mensal de Dai & Trenberth [2002] na reanálise. O sistema de assimilação é o chamado *Système d'Assimilation Mercator* versão 2 (SAM2) [Pham *et al.*, 1998]. O GLORYS2V3 assimila dados de temperatura *in situ* e satélite da superfície do mar e perfis de salinidade do banco de dados CORAv3.3, fornecido pelo *MyOcean Coriolis Data Center*, que contém dados do Argo, e perfis verticais de temperatura e salinidade do banco de dados do projeto de mamíferos marinhos (Tabela 1).

A reanálise UR025.4 é um produto bastante semelhante ao GLORYS2V3, baseado em uma versão mais nova do NEMO (v. 3.2), tendo a mesma configuração de grade do ORCA025, exibindo assim a mesma resolução horizontal e mesma resolução vertical, e também a mesma forçante atmosférica (ERA-Interim) e fluxos de água doce. A principal diferença entre as reanálises é o método de assimilação utilizado. O UR025.4 usa um método de assimilação baseado no sistema de previsão operacional do Reino Unido *FOAM-NEMO* [Storkey *et al.*, 2010]. Os dados assimilados provêm de produtos de satélites e *in situ*, sendo que os perfis *in situ* de temperatura e salinidade são assimilados do conjunto de dados ENACT/ENSEMBLES [Ingleby & Huddleston, 2007], que contém dados do *World Ocean Database* 2005 (WOD2005), o Programa Global de Perfis de Temperatura e Salinidade (do inglês *Global Temperature and Salinity Profile Program* - GTSP) e Argo. A tabela 1 contém as informações das reanálises sumarizadas. Para uma descrição completa, informações mais detalhadas sobre as duas reanálises e dados de validação, o Manual do Usuário é disponibilizado pelo *Copernicus Marine Environment Monitoring Service* [CMEMS, 2015].

Para servir como referência de dados *in situ* no sentido de avaliar a performance das reanálises para a região deste estudo, utilizou-se o produto *Roemmich-Gilson Argo Climatology* [Roemmich & Gilson, 2009] (RG Climatology), que foi produzido inicialmente com os dados do sistema Argo de 2004-2008 e disponibilizado pelo *Argo Global Data Assembly Center* (GDAC, <<http://www.usgodae.org/argo/argo.html>>). Atualmente, a climatologia compreende dados de 2004 a 2016. A resolução horizontal é de 1° e a dimensão vertical possui 58 níveis (superfície até 2000m), com resolução de 10m na superfície e aumentando gradualmente até 100m nas camadas mais profundas.

Os dados do Argo são submetidos a dois controles de qualidade antes de serem disponibilizados, sendo um automatizado para os dados em tempo real e um realizado sob supervisão. Além disso, Roemmich & Gilson [2009] realizaram um teste adicional aos dados automatizados. Os dados que passaram nos testes de controle de qualidade foram interpolados verticalmente para formar a grade de 58 níveis mencionada acima. A interpolação horizontal foi feita calculando um campo médio de 5 anos para cada mês usando um ajuste ponderado de mínimos quadrados para dados próximos. Então, as anomalias desta estimativa foram calculadas usando um método de análise objetiva. Em nosso estudo, utilizamos temperatura e salinidade médias mensais de 2004 a 2015. Informações mais detalhadas podem ser encontradas em Roemmich & Gilson [2009].

II.2 - Comparação entre Argo e Reanálises e cálculo de tendências

A fim de comparar os resultados das reanálises com os dados de referência (Argo), calculamos o coeficiente de correlação entre eles, que mostra o quanto as reanálises concordam com Argo; e a diferença centralizada quadrática média (RMSD), que representa a precisão dos conjuntos de dados. Como uma ferramenta para mostrar esses parâmetros, usaremos um Diagrama de Taylor normalizado, que os resume (mais o desvio padrão) de maneira visual para facilitar as comparações [Taylor, 2001]. Também realizamos testes-*t* pareados com relação à média zonal do Oceano Austral e a cada setor para ver se os conjuntos de dados apresentavam diferenças significativas no nível de confiança de 95%. Além disso, aplicamos o teste-*t* entre os setores e a média do Oceano Austral e nos setores entre si.

O período investigado abrange de 2004 a 2010, que nossos três conjuntos de dados cobrem concomitantemente. Como descrevemos anteriormente, as resoluções horizontal e vertical de nossos conjuntos de dados diferem e, para fazer as comparações, tivemos que realizar alguns ajustes. Redimensionamos horizontalmente a grade das reanálises para corresponder ao tamanho da grade do Argo. Além disso, redimensionamos os três conjuntos de dados verticalmente para uma resolução vertical padrão com 50 níveis de profundidade, usando, em ambos os casos, interpolação linear.

Para os cálculos das tendências de temperatura potencial e salinidade, utilizamos as duas reanálises e os dados Argo em sua configuração original, como descrita na seção II.1. Calculamos primeiro os valores médios anuais da temperatura potencial e salinidade e procedemos ao cálculo das tendências lineares para as séries temporais. Finalmente, nossa análise foca nos padrões espaciais para identificar regiões de aquecimento/resfriamento e salinização/dessalinização no Oceano Austral, a norte e sul da CCA, a partir dos perfis de latitude × profundidade.

Tabela 1: nome e características das reanálises utilizadas. As informações foram obtidas no manual dos produtos [CMEMS, 2015].

REANÁLISE – MODELO	FORÇANTE ATMOSFÉRICA	MÉTODO DE ASSIMILAÇÃO	RESOLUÇÃO	ASSIMILAÇÃO	PERÍODO
My Ocean - UR025.4 - NEMOV3.2	ERA-Interim	FOAM NEMO <i>System</i>	1/4° horizontal 55 Níveis até 2000m (1m na superfície; ~150m a 2000m)	WOD2005 GTSP Argo	1993 - 2010
My Ocean - GLORYS2V3 - NEMOV3.1	ERA-Interim	SEEK/3D-VAR	1/4° horizontal 55 Níveis até 2000m (1m na superfície; ~150m a 2000m)	CORAV3.3 database (Coriolis data centre) SEaOS Argo	1994- 2014

Capítulo III: Artigo Científico

Para a obtenção do título de Mestre pelo Programa de Pós-Graduação em Oceanografia Física, Química e Geológica, é requerido que o discente realize a submissão de pelo menos um artigo científico como primeiro autor em periódico com corpo indexado. Desse modo, os resultados da pesquisa desenvolvida durante o período de mestrado e a discussão serão apresentados em forma de artigo neste Capítulo. O manuscrito, de autoria de Jônatas Filipe Aires Miranda e Mauricio M. Mata, é intitulado “**Recent thermohaline trends in the upper Southern Ocean from Argo and Reanalysis products**” e foi submetido para publicação no periódico “*Brazilian Journal of Geophysics*”.

INTRODUCTION

The Southern Ocean (SO) is an important agent of the global climate, as it connects the Pacific, Atlantic and Indian oceans, propagating climate signals between them through the Antarctic Circumpolar Current (ACC) system (e.g., Rintoul & Sokolov, 2001). Furthermore, the SO is characterized by tilted isopycnals, which act as a channel to transport heat from the surface to mid depths, thus acting as an important agent of global heat transport (Gille, 2008). Since the 1950s, there has been a systematic warming of the global oceans which does not seem to be associated with natural variability and phenomena (Levitus et al., 2012), with the southern hemisphere oceans accounting for 67 to 98% of the global heat gain (Roemmich et al., 2015). Furthermore, Gille (2008) estimated that 80% of the warming in the southern hemisphere oceans is located south of 30°S.

The Southern Annular Mode (SAM) dominates climate variability at the high-latitude Southern Hemisphere (SH). SAM is a large-scale natural pattern of variability characterized by fluctuations in the strength of the circumpolar vortex, reflecting in the intensity and location of the westerlies, and hence influencing the temperature and latitudinal rainfall from the subtropics to the Antarctic (e.g. Thompson & Solomon, 2002; Abram et al., 2014).

Thompson & Solomon (2002) observed changes in the SAM since the 1970s, which were later attributed to the depletion of the ozone layer (Thompson et al., 2011). Marshall (2003) calculated the SAM Index using stations with in situ measurements of atmospheric pressure at sea level, between high and low latitudes from 1958 to 2000, and their results confirmed the increase observed in the SAM between 1960 and 2000, that currently reached the highest mean index in the past 1000 years (Abram et al., 2014). Whenever in the positive phase, SAM drives changes in the westerly winds pattern, strengthening and shifting them polewards, causing a zonal geostrophic wind positive anomaly south of 45°S and a dynamic response of the ocean through changes in meridional Ekman transport (Hall & Visbeck, 2002; Sen Gupta & England, 2006). Other effect of the strengthening of westerly winds in the SO is a warming of the surface to middepth waters along the northern edge of the ACC and cooling in the surface waters in the south of it (Sen Gupta & England, 2006; Fyfe et al., 2007; Gille, 2008; Screen et al., 2008; Spence et al., 2010; Armour et al., 2016).

Böning et al. (2008) analyzed data from the CARS2006 climatology (from 1960's to 1990's) and Argo profilers launched from 2002-2006 to investigate the Antarctic Circumpolar Current (ACC) response to changes in the westerly wind field looking at trends and changes in water column density. The trends showed a warming along the

ACC axis through all the circumpolar extension of the SO, showing no significant difference between the Atlantic, Pacific and Indian sectors. Furthermore, they found that in the upper portion of the water column, the strongest warming signals were concentrated near the southern edge of the ACC. Nevertheless, warming also was present in several depth layers near the ACC. Regarding salinity, a decrease was detected along the entire latitudinal range up to the southern edge of the ACC, being stronger in the upper layers of the water column. The authors attributed the warming to the mesoscale eddies carried southwards due to the intensification of the winds, which compensate and eventually surpass the Ekman transport generated. At the same time, the decrease in salinity was attributed to the increase in precipitation in that region.

Enhanced mesoscale activity as a mechanism of warming the SO is a concept accepted as the most likely process that occurs following strengthening of the westerlies (Meredith & Hogg, 2006; Fyfe et al., 2007; Böning et al., 2008; Hogg et al., 2008; Screen et al., 2008). The salinity too responds to these changes in regional climate which also affect the evaporation-precipitation patterns, and thus lead to changes in the hydrological cycle. Currently, it is thought that the water cycle has been enhancing, with salty (fresher) areas becoming even saltier (fresher) (Helm et al., 2010; Durack et al., 2012; Aretxabaleta et al., 2015).

Historically, the sampling of the SO was a difficult task due to inherent characteristics of that environment. The SO is a sparsely sampled section of the global oceans and temperature data collected by research vessels over the past few decades contain numerous gaps, which prevent assessment of Southern Ocean temperature changes and trends (Gille, 2008; Roemmich & Gilson, 2009; Riser et al., 2016). That is even more critical in term of salinity, which presents a very sparse coverage in the historical datasets having strong regional and seasonal biases due to the difficulty of collecting data over the whole ocean simultaneously (Roemmich & Gilson, 2009). In this context, the Argo system arise as a powerful tool to provide information about the upper layer of the oceans. Beginning in the late 1990's, Argo achieved sparse global coverage in 2004, its population has reached 3000 floats in 2007 and currently is in 3.900. The amount of data collected by Argo in one year, during winter, surpasses the past 100 years of data from all other databases for the SO. Nowadays, the majority of temperature and salinity data in the SO comes from Argo system (Riser et al., 2016).

In this study, we unveil the recent state of the temperature and salinity fields in the SO, revisiting the trends of these parameters in the last 23 years (1993-2015), using the Argo-only climatology by Roemmich-Gilson (Roemmich & Gilson, 2009) and two State-of-Art Ocean reanalysis. Moreover, we assessed if the reanalysis are representing well the temperature and salinity fields in SO, as they also assimilate Argo data. In the

Data and Methods section, we describe the datasets and the analysis used here; the section of the results is divided in the mean potential temperature and salinity fields, the statistics and the linear trends. Then we bring our discussion, followed by the final section containing the summary of our findings and main conclusions.

DATA AND METHODS

Simulations and datasets

We analyzed the potential temperature and salinity of two state-of-art ocean reanalysis and one product generated from Argo-only data. The reanalysis chosen for our study were two MyOcean Global Reanalysis (<http://marine.copernicus.eu/>), one from Mercator Océan (GLORYS2V3) and one from University of Reading (UR025.4). They were chosen mainly because of the atmospheric forcing that they use, which is the atmospheric reanalysis ERA-Interim (Simmons et al., 2007), considered the best available reanalysis to represent the SO surface winds and sea level pressure (Swart et al., 2015), and for the period they cover. The MyOcean University of Reading reanalysis (hereafter, UR025.4), covers the period from 1993 to 2010, and the MyOcean Mercator Océan reanalysis (hereafter, GLORYS2V3) covers from 1994 to 2014.

GLORYS2V3 utilizes the ocean model based on NEMO v3.1 and the horizontal grid is the standard ORCA025 tri-polar irregular grid, providing a resolution of 1/4 degree in the equator that increases toward the poles (Madec, 2008). The vertical resolution comprises a grid of 75 levels. The resolution decreases from surface to bottom, with 1 meter in the surface and 200 meters in the deepest layers. The surface forcing is provided by ERA-Interim, with corrections in the radiative and the rainfall fluxes. Aside of the rainfall fluxes provided by ERA-Interim, the other freshwater flux included is the monthly climatology river runoff from Dai & Trenberth (2002). The assimilation system used is the Système d'Assimilation Mercator version 2 (SAM2), that uses a reduced order Kalman filter based on the SEEK formulation (Pham et al., 1998). The bias correction method is the 3D-VAR, applied with an Incremental Analysis Update (IAU), which is a low pass filter. GLORYS2V3 assimilates *in situ* and satellite sea surface temperature data, satellite sea level data, in situ temperature and salinity profiles from the database CORAv3.3, provided by MyOcean Coriolis Data Centre, which contains Argo data, and the temperature and salinity vertical profiles from marine mammals database. In this study, we used monthly temperature and salinity data from 1994 to 2014. For more details, see Pham et al. (1998) and Madec (2008).

The UR025.4 reanalysis is a product fairly similar to GLORYS2V3, based on a newer version of NEMO (v. 3.2), having the same grid configuration of ORCA025,

therefore displaying the same horizontal resolution and same vertical resolution, and also the same atmospheric forcing (ERA-Interim) and freshwater fluxes. UR025.4 uses an assimilation method based in the UK Met Office operational FOAM-NEMO system (Storkey et al., 2010). The data assimilated comes from satellite and in situ products and the in situ profiles of temperature and salinity are assimilated from the ENACT/ENSEMBLES dataset (Ingleby & Huddleston, 2007), which contains data from the World Ocean Database 2005 (WOD2005), the Global Temperature and Salinity Profile Program (GTSP) and Argo. We used the monthly averaged temperature and salinity data from 1993 to 2010. More information about UR025.4 can be found in Madec (2008) and Storkey et al. (2010). For more detailed information about the two reanalysis and validation data, see the Product User Manual provided by the Copernicus Marine Environment Monitoring Service (CMEMS, 2015).

For the in situ and reference data, we used the Roemmich-Gilson Argo-only Climatology product (Roemmich & Gilson, 2009), which was first produced with the data from 2004-2008 and made available by the Argo Global Data Assembly Centre (GDAC, <<http://www.usgodae.org/argo/argo.html>>). Currently, the climatology comprises data from 2004 to 2016. The horizontal resolution is 1 degree and the vertical grid has 58 levels, from surface to 2000 meters, with resolutions of 10 meters in the surface, increasing to 100 meters in the deeper layers. Argo data is subjected to two quality controls before becoming available, being one automatized for the real time data, and one performed under supervision, which consist in a more rigorous method and take some time to become available. In addition, Roemmich & Gilson (2009) performed an additional test to the automatized data. The data which passed the quality control tests were interpolated vertically to form the 58 levels grid aforementioned. The horizontal interpolation was made calculating a 5-year mean field for each month using a weighted least-squares fit to nearby data. Then, the anomalies from this estimate were calculated using objective analysis. In our study, we used the monthly mean temperature and salinity from 2004 to 2015. For further information, see Roemmich & Gilson (2009).

Regional sectorization

Our area is limited from 30°S to 65°S and depths from the surface to 2000 meters. To proceed with the analysis, we split our approach into two parts in a spatial sense. In the first one we considered the entire SO zonally averaged, which resulted in a profile of latitude x depth. In the second procedure, we sectioned the area into 5 horizontal sectors, namely, Weddell Sea (60°W-20°E), Indian (20°E-90°E), Pacific West (90°E-160°E), Ross Sea (160°E-140°W) and Bellingshausen and Amundsen Seas (140°W-60°W) as described in Zwally et al. (2002) and applied by several authors (e.g., Kerr et

al., 2012; Azaneu et al., 2013), again averaging the longitudes in each sector to generate 5 profiles of latitude x depth (Fig. 1).

Datasets comparison and trends calculation

In order to compare the reanalysis outputs with our reference dataset (Argo), we computed the correlation coefficient between them, which shows how much the reanalysis agree with Argo; and the normalized centered root-mean-square difference (RMSD), which represents the accuracy of the dataset. As a tool to show these parameters, we will use a normalized Taylor Diagram, which summarizes them (plus standard deviation) in a visual manner to facilitate comparisons (Taylor, 2001). We also performed paired *t*-tests concerning the zonally averaged SO and each sector to see if the datasets presented significant differences at the 95% confidence level. Moreover, we tested each regional sector against one another and the zonally averaged SO for each of the datasets.

The period used for comparisons spans from 2004 to 2010, which our three datasets cover concomitantly. As we described earlier, the horizontal and vertical resolutions of our datasets differ, and to make the comparisons we had to perform some adjustments. We regridded the reanalysis dataset horizontally to match the grid size of Argo and regridded the three datasets vertically to a standard vertical resolution with 50 depth layers, using in both cases, linear interpolation.

For the potential temperature and salinity trends, we used the complete time span of each dataset (i.e., UR025.4: 1993-2010; GLORYS2V3: 1994-2014; and Argo: 2004-2015). We first calculated the annual mean values of the potential temperature and salinity, given the fact that the data was originally monthly means. Then, we proceeded to calculate the linear trends for the entire time series of each dataset. Finally, we focused in the spatial patterns to identify regions of warming/cooling and salinization/freshening in the SO, north and south of the ACC, from the latitude x depth profiles.

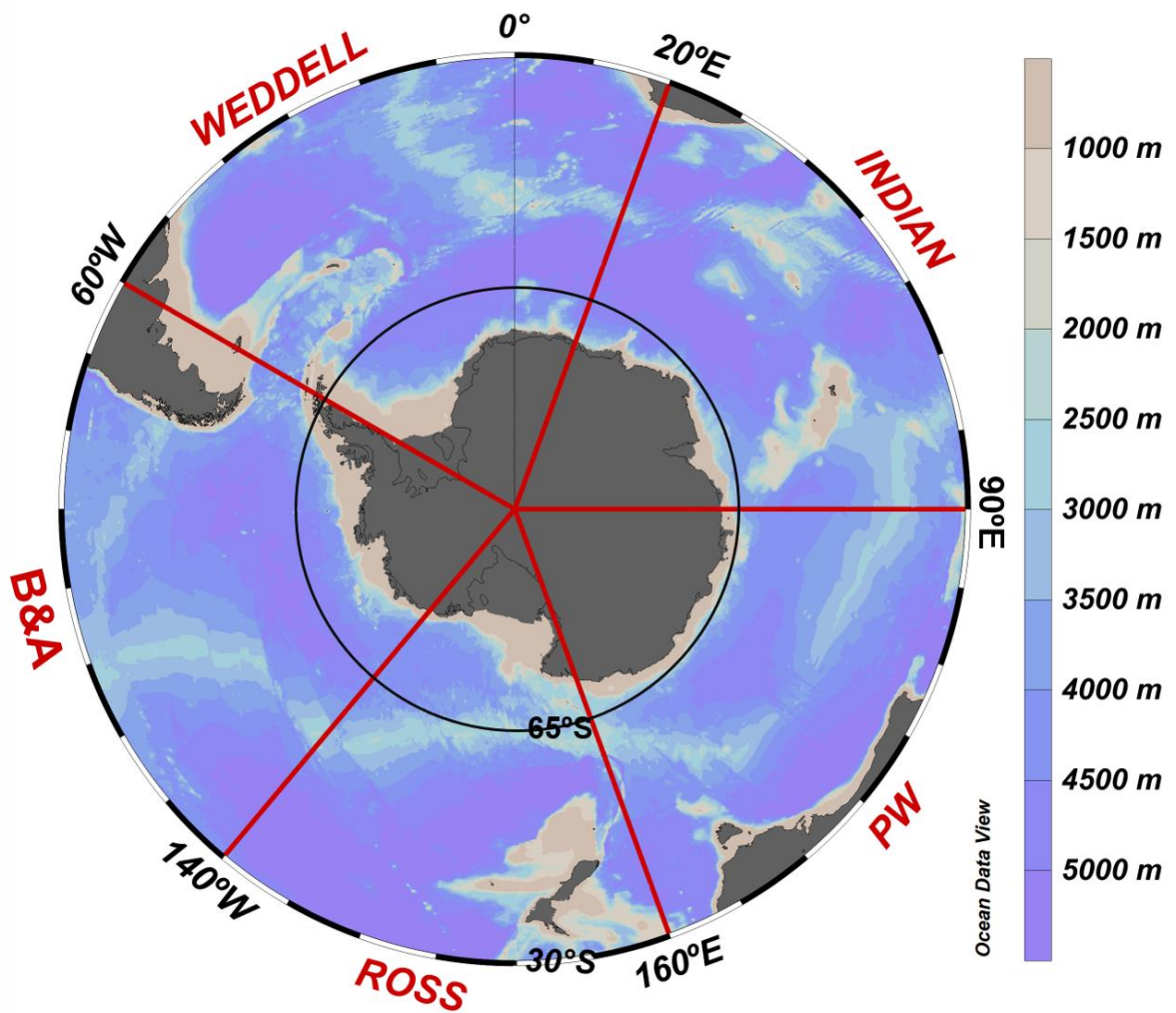


Figure 1: Map of the study area with the division of the five sectors: Weddell Sea (Weddell), Indian (Indian), Pacific West (PW), Ross Sea (Ross) and Bellingshausen and Amundsen Seas (B&A). Shades indicate depth and the units are in meters.

RESULTS

Mean fields

Before we show the results of the mean fields, we present the profile count of Argo data used in the Roemmich-Gilson climatology to show the sampling spatial distribution in the SO (Fig. 2). As expected, the higher latitudes regions are less sampled. The PW sector is the most well sampled whilst the Weddell and Indian sectors are the two regions with less measurements probably due to the sea ice coverage (Fig. 2). In Figure 3, we present the amount of measurements per year to demonstrate the increase of Argo data through time; the measurements clearly increase in the first five years and stabilize. This shows the initial effort to provide a good global coverage and that currently the Argo array reached a satisfactory number of floats.

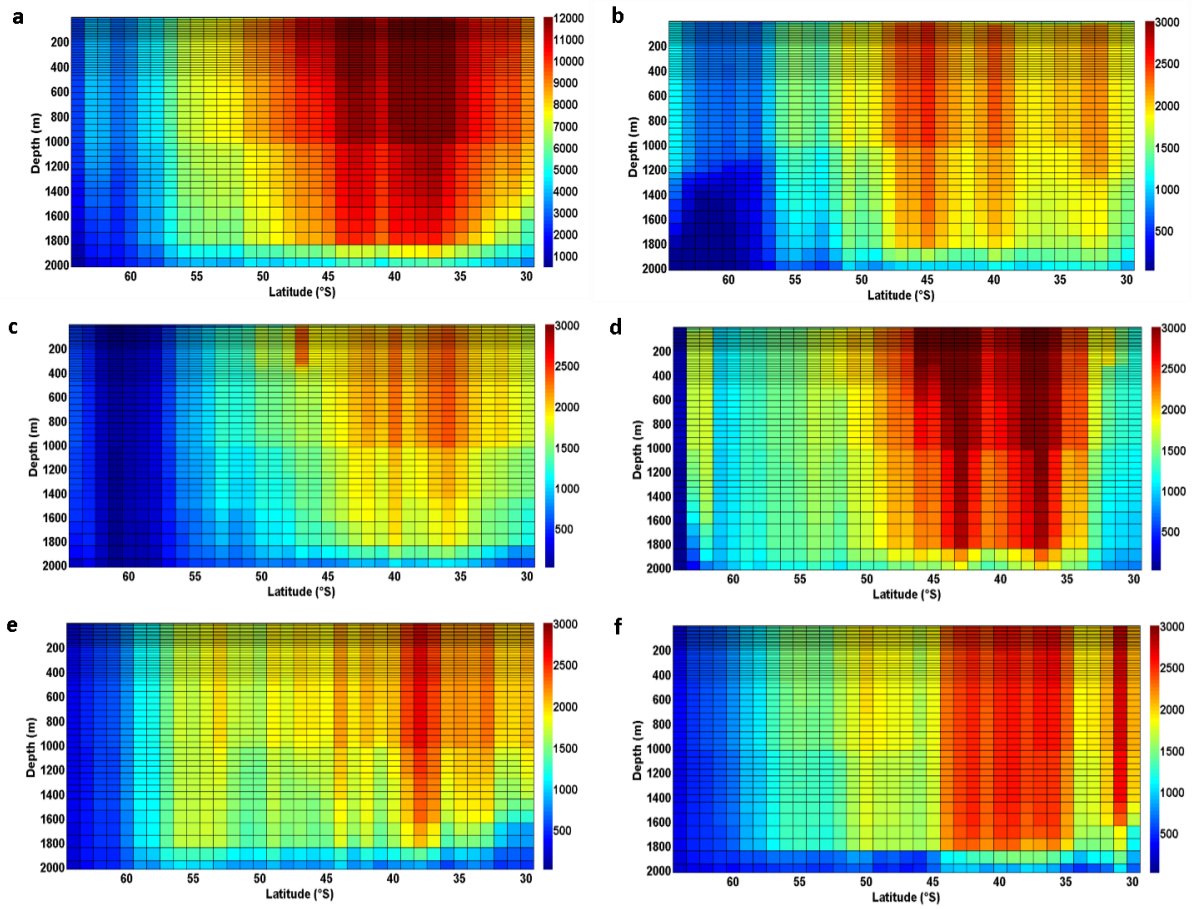


Figure 2: Total measurement count of Argo climatology summed during the period of 2004-2015. a: zonally averaged SO; b: Weddell; c: Indian; d: PW; e: Ross; f: B&A. The color scale ranges from 500 to 12.000 measurements in the zonally averaged SO and from 30 to 3.000 in the sectors. For each latitude x depth, we summed up the measurements of all the longitudes.

To evaluate the performance of the reanalysis in the Southern Ocean, we show below the mean potential temperature and salinity fields of the zonally averaged SO south of 30°S (Fig. 4) and the associated standard deviations (Fig. 5) for the entire periods of each dataset (from 1993 to 2010 for UR025.4, 1994 to 2014 for GLORYS2V3 and from 2004 to 2010 for Argo).

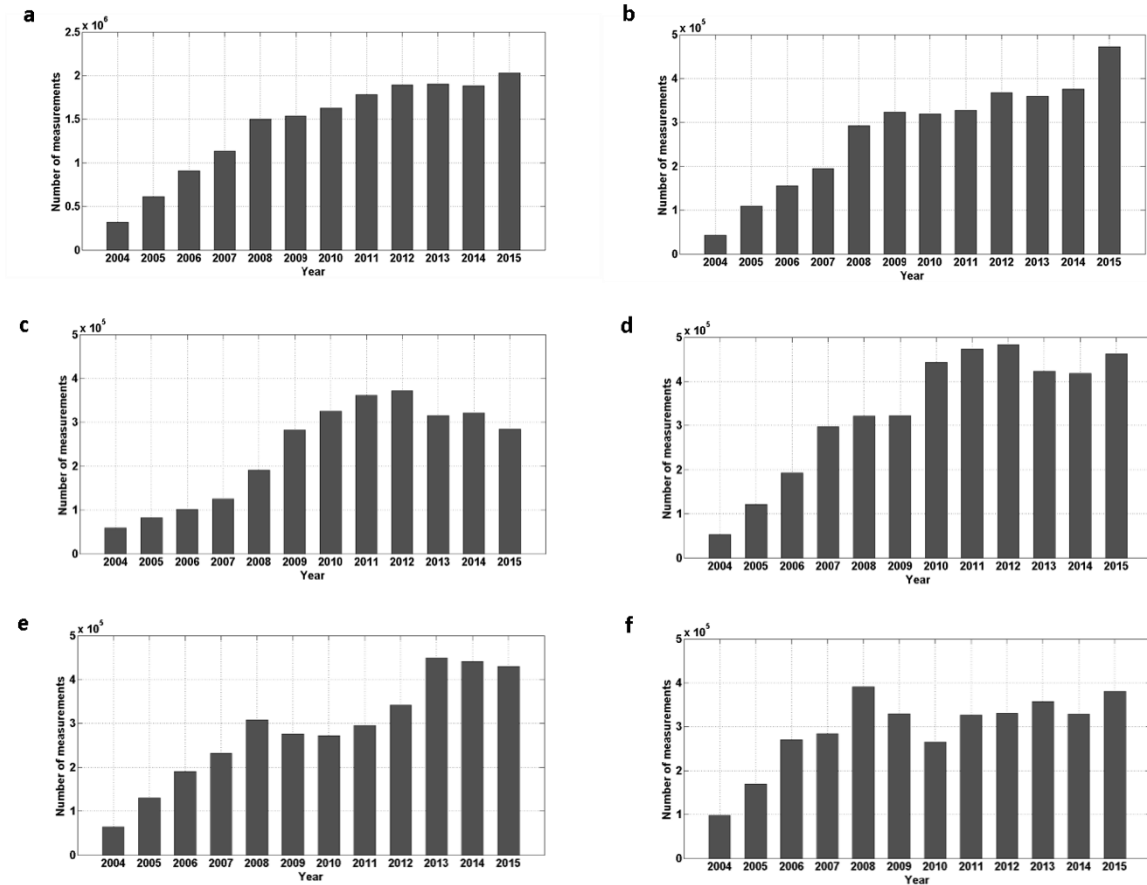


Figure 3: Total number of Argo measurements per year. a: zonally averaged SO; b: Weddell; c: Indian; d: PW; e: Ross; f: B&A. The scale ranges from 0 to 2.500.000 measurements in the zonally averaged SO and from 0 to 500.000 in the regional sectors. The bars comprise the total sum of measurements (in all the latitudes, longitudes and depth layers) taken in a given year.

In the potential temperature field, we note that the three datasets are very similar, what is an evidence that the two reanalysis assimilate and reproduce well the Argo data, with the expected features present like the meridional temperature gradient in the surface. It is visible also, south of 60°S, that the waters at about 200m are warmer than at the surface; this is seen clearer in the Argo fields, but the reanalysis represented it as well. Regarding salinity, we can also see the resemblance between the three datasets. However, GLORYS2V3 shows marked fresher water near the surface at higher latitudes when compared to the other fields, fact that became clearer in the results further below.

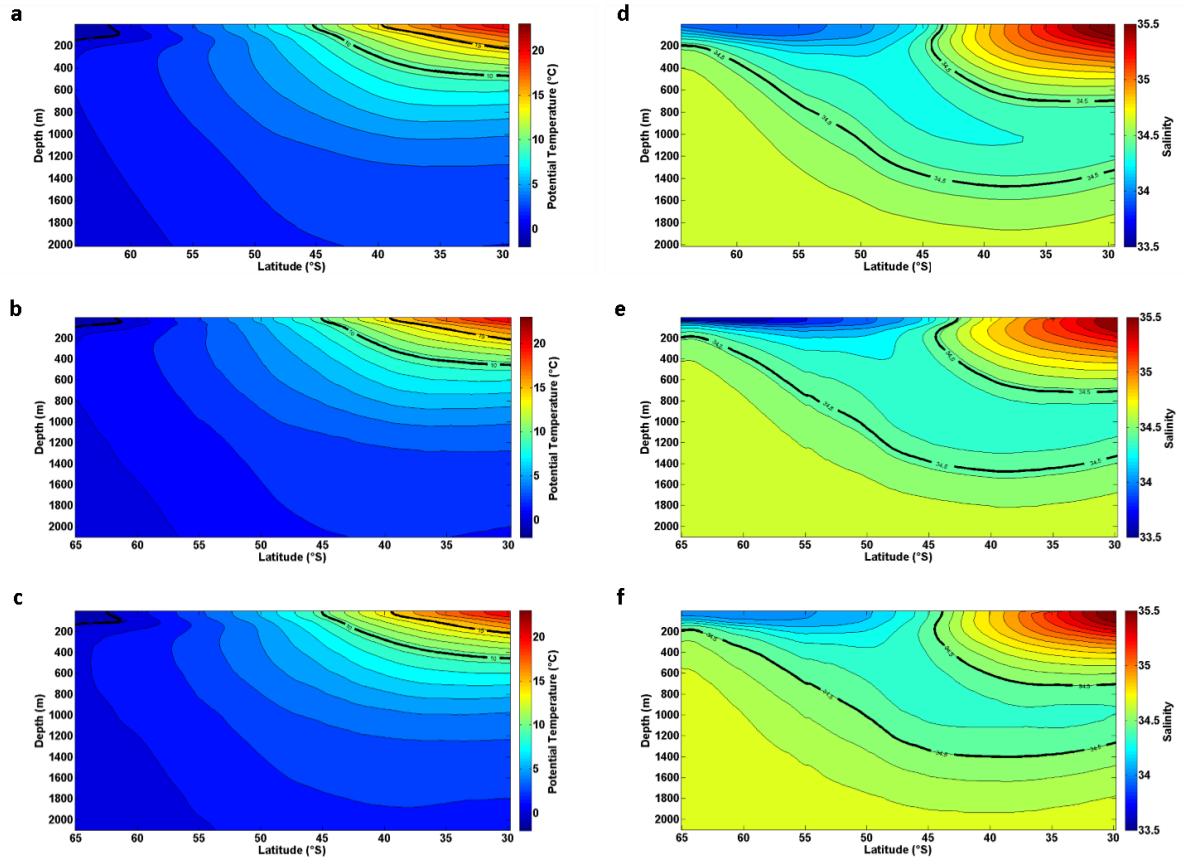


Figure 4: Zonally averaged fields of potential temperature (left panels) and salinity (right panels) comprising the entire period of each product as described in section 2.1 – Potential Temperature: a-Argo, b-GLORYS2V3, c-UR025.4; Salinity: d-Argo, e-GLORYS2V3, f-UR025.4. Thick contour lines in left panels represent the potential temperature isolines of 0, 10 and 15°C and in the right panels represent the salinity isoline of 34.5.

The three datasets captured the characteristic feature of the Antarctic Intermediate Water (AAIW) subduction wedge, with the fresher water present near the surface at higher latitudes sinking to mid depths and spreading equatorward. The highest values of standard deviations are concentrated in the upper layers. It is evident that the temperature of GLORYS2V3 and UR025.4 were the datasets that displayed the largest fluctuations. GLORYS2V3 had relatively high standard deviations (in comparison with Argo and UR025.4) in most of the upper layers, and in lower latitudes of the domain, the high variability values reached depths of 1000 m. This did not seem to affect the mean values though. Regarding salinity, the variability was much less expressive, with most values being lower than 0.1.

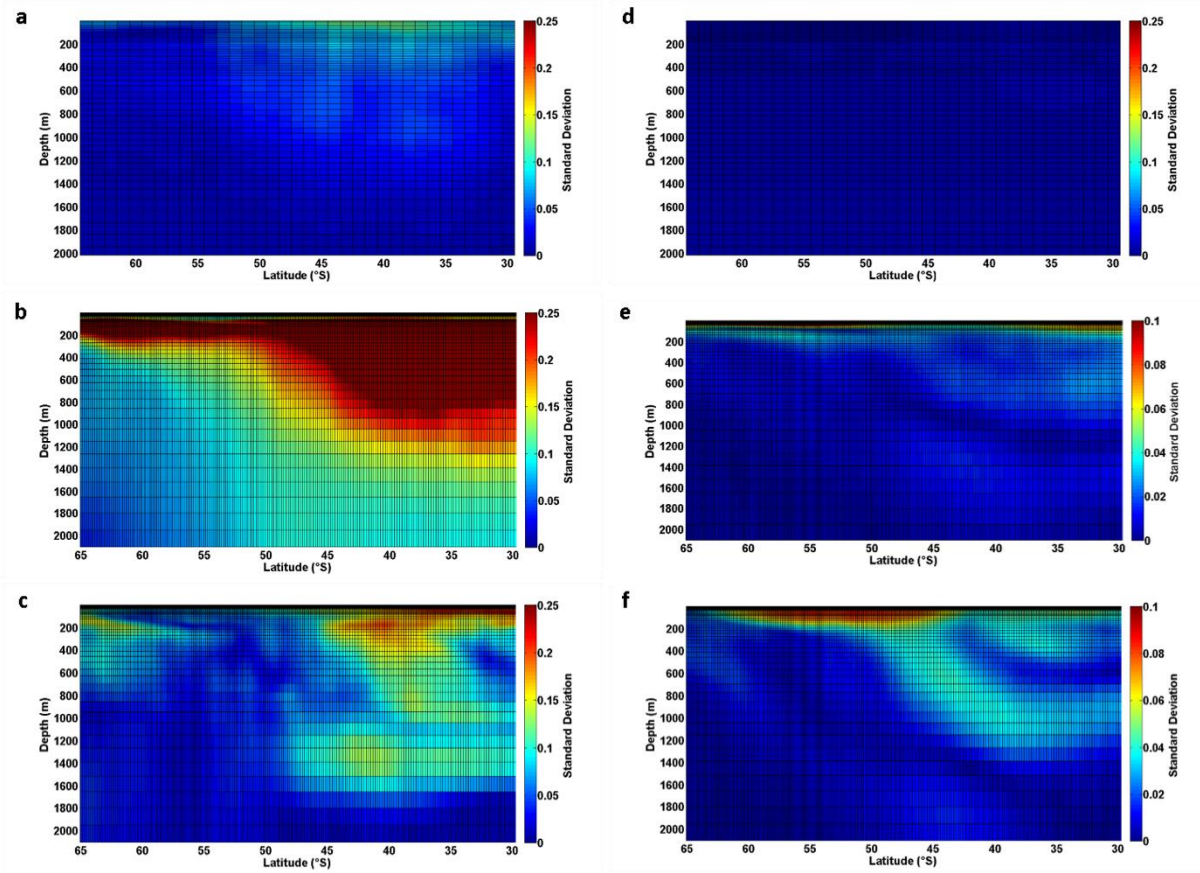


Figure 5: Standard deviations of potential temperature and salinity calculated from the zonally averaged annual means – Potential Temperature: a-Argo, b-GLORYS2V3, c-UR025.4; Salinity: d-Argo, e-GLORYS2V3, f-UR025.4. Given the different values of the potential temperature and salinity standard deviations, we plot them with different color scales ranges to facilitate viewing: the potential temperature goes from 0 to 0.25 and the salinity goes from 0 to 0.1. Only the potential temperature of GLORYS2V3 showed values above 0.25, reaching the maximum value of 0.7355.

We now present the difference fields between Argo and the reanalysis (Figure 6). Concerning the temperature field, Argo showed higher values in the northern part of the domain, when compared with both products. In the salinity field, Argo was saltier than GLORYS2V3 in the surface, but fresher in almost all the deeper layers. As the spatial pattern of the differences between Argo and UR025.4 resembles the mean field, that indicates that UR025.4 reproduces saltier (fresher) values in the fresher (saltier) areas in the SO, when compared to Argo.

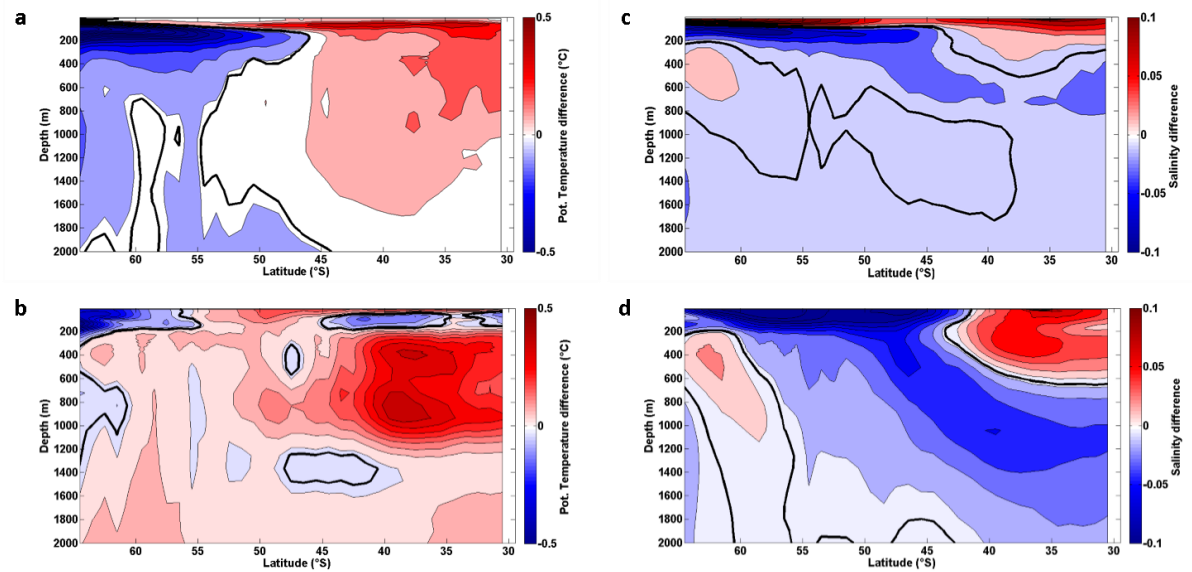


Figure 6: Difference of the potential temperature and salinity fields between the datasets. Potential Temperature - a: Argo – GLORYS2V3; b: Argo – UR025.4. Salinity - c: Argo – GLORYS2V3; d: Argo – UR025.4. The difference was calculated from the mean fields of each product after an adjustment to the size of the grids (same as described in section 2). Thick contour lines represent the 0 isoline.

The TS diagrams for the zonally averaged SO as well as for the five regional sectors are shown in Figure 7. The diagrams show that in the surface layer, there is great variability among the datasets, with Argo showing higher values for both temperature and salinity in comparison with the reanalysis. GLORYS2V3 shows a notable oscillation in salinity values that stands out from UR025.4 and Argo. The data from about 400m to 2000m depth exhibited a fairly good agreement, probably because of the relatively low amount of observations in these layers, which leads Argo to dominate the assimilated dataset for the reanalysis. Furthermore, in the surface layers there is seasonality, which may account for most of the variability.

The only sector that did not behave that way was the B&A. There, the salinity exhibited a steady behavior from the surface to about 700m and then started to increase in Argo and UR025.4, whilst in GLORYS2V3 it showed an increase from the surface to 2000m (overall, the salinity in GLORYS2V3 showed the strongest variability among the three datasets). The temperature values in the upper layers showed a difference of about 2°C between Argo and the reanalysis; the warmest sectors are the Ross and B&A, with surface mean temperatures above 10°C in Argo and about 9°C in GLORYS2V3 and UR025.4.

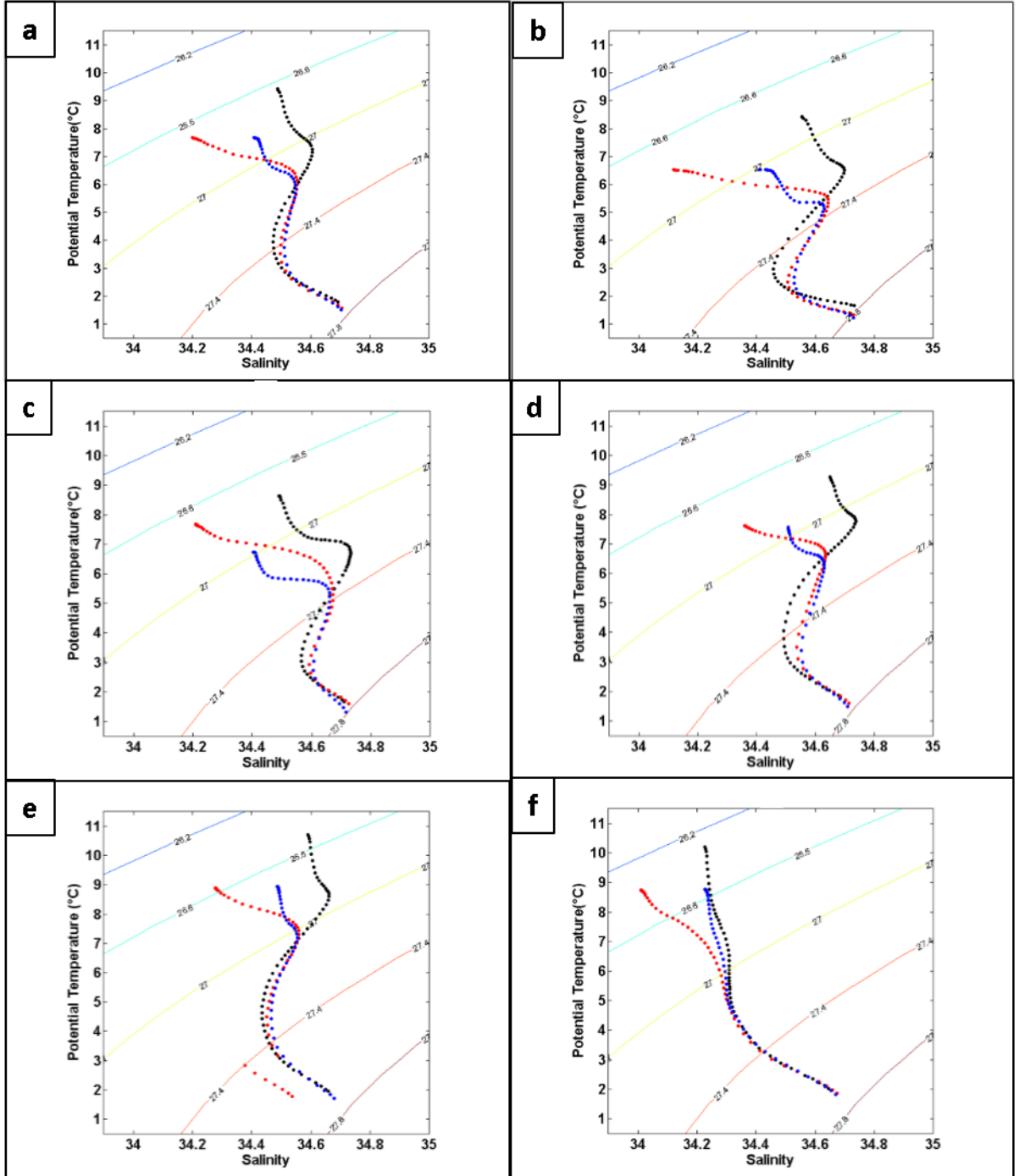


Figure 7: TS diagrams for: a-zonally averaged SO; b-Weddell sector; c-Indian sector; d-PW sector; e-Ross sector; f-B&A sector. Black-Argo, Red-GLORYS2V3, Blue-UR025.4. The diagrams were generated using the original configuration of each product and is an average of the entire period of each (UR025.4: 1993-2010; GLORYS2V3: 1994-2014; and Argo: 2004-2015).

Comparison of the datasets

In order to assess the accuracy and how the reanalysis match with Argo, we calculated the RMSD and the correlation coefficients of the two reanalysis with Argo using the latter as reference. We emphasize that some adjustments were made in order

to construct the diagram and the period compared was from 2004-2010, which is the common period to the three datasets. The results for both the potential temperature and salinity were good, with high correlation and low RMSD between the reanalysis and Argo in the zonally averaged SO and in the sectors as well. Regarding the t -tests, the p values were in general very small, with a few exceptions. The results are summarized in Table 1 and in the Taylor Diagrams (Fig. 8). Despite the fact that UR025.4 showed higher correlation with Argo in the majority of the cases, the salinity of the zonally averaged SO between Argo and UR025.4 showed significant differences. Nevertheless, the correlation was very high and the mean fields of the two products are similar. Regarding the tests between sectors, once more they showed no significant difference at the 95% confidence interval, with just two exceptions, namely, the case of Pacific West/Indian sectors, regarding salinity in GLORYS2V3 and UR025.4.

The correlations for salinity were slightly lower than the temperature's, suggesting that the reanalysis represent better the temperature fields. Overall, the correlation values were very high, reaching values of over 0.999, indicating that the two reanalysis were capable of assimilate and reproducing the Argo data well in the Southern Ocean.

Table 1: statistical parameters for the zonally averaged SO and the sectors. The results are referred to the comparisons of the reanalysis versus Argo. The p values were obtained from paired t-tests.

Sector	Zonally Av. SO						Weddell					
	Temp.			Sal.			Temp.			Sal.		
	Corr.	RMSD	p	Corr.	RMSD	p	Corr.	RMSD	p	Corr.	RMSD	p
GLORYS2V3	0.9995	0.0322	$1.5e^{-72}$	0.9950	0.1022	$1.5e^{-11}$	0.9995	0.0310	$5.0e^{-91}$	0.9916	0.1306	$6.3e^{-06}$
UR025.4	0.9998	0.0225	$1.7e^{-39}$	0.9995	0.0388	0.1649	0.9997	0.0248	$2.9e^{-82}$	0.9987	0.0599	0.0018

Sector	Indian						PW					
	Temp.			Sal.			Temp.			Sal.		
	Corr.	RMSD	p	Corr.	RMSD	p	Corr.	RMSD	p	Corr.	RMSD	p
GLORYS2V3	0.9741	0.2591	$9.7e^{-13}$	0.9964	0.0850	$8.7e^{-20}$	0.9995	0.0321	$2.2e^{-51}$	0.9898	0.1433	$6.7e^{-48}$
UR025.4	0.9995	0.0305	$4.7e^{-21}$	0.9992	0.0469	$1.7e^{-04}$	0.9997	0.0239	$5.8e^{-22}$	0.9884	0.1551	$9.0e^{-31}$

Sector	Ross						B&A					
	Temp.			Sal.			Temp.			Sal.		
	Corr.	RMSD	p	Corr.	RMSD	p	Corr.	RMSD	p	Corr.	RMSD	p
GLORYS2V3	0.9987	0.0544	$7.9e^{-19}$	0.9890	0.1481	$2.6e^{-85}$	0.9977	0.0735	$1.0e^{-11}$	0.9855	0.1754	$1.5e^{-130}$
UR025.4	0.9992	0.0430	$9.6e^{-78}$	0.9966	0.0963	$7.8e^{-153}$	0.9986	0.0563	$8.1e^{-36}$	0.9872	0.1651	$9.8e^{-41}$

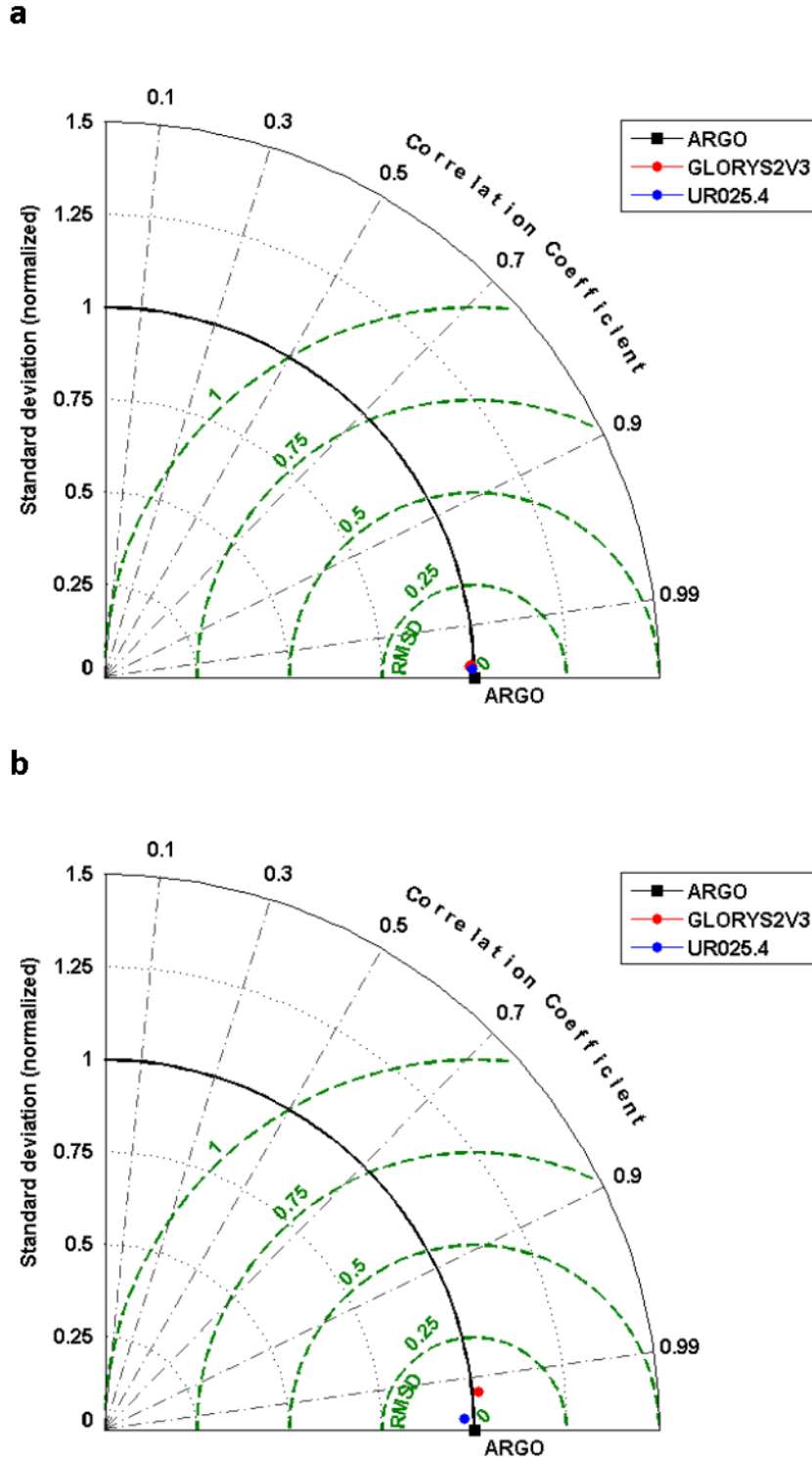


Figure 8: Taylor Diagrams of the zonally averaged SO. a: potential temperature; and b: salinity. Argo (reference): black squares, GLORYS2V3: red circles and UR025.4: blue circles.

Potential Temperature trends

Concerning the zonally averaged SO, our results show a robust signal of warming in nearly the entire domain north of 55°S (Fig. 9). This signal is more pronounced in the surface and appears to decrease with depth. Argo and GLORYS2V3 showed similar features in this regard, with GLORYS2V3 showing the strongest warming, with values surpassing $0.05^{\circ}\text{C.yr}^{-1}$. UR025.4, on the other hand, displayed a more variable scenery, with some areas even showing cooling trends and the warming being concentrated in the surface and in a portion from 200-1000 meters deep. Overall, in the spatial pattern of these trends, it is apparent that GLORYS2V3 is more similar to Argo, although its correlation with Argo was slightly lower than UR025.4's. However, this is not incoherent, as the statistics were performed with only the concomitantly period of the three products (7 years, from 2004 to 2010) and the trends were calculated from the entire period of each, in which GLORYS2V3 shares a longer period with Argo (11 years, from 2004 to 2014).

Apart from the warming region aforementioned, there is a cooling region present predominantly south of 55°S mostly in the upper layer. Argo displayed this signal restricted to the first two hundred meters, while in GLORYS2V3, this feature occupies a larger portion of the water column, reaching depths of about 400 meters and with greater magnitude as well. UR025.4 displayed a more discrete cooling signal at the surface, being smaller and with lower magnitude in comparison with the other datasets.

To further assess the longer term trends, we show the temporal evolution of potential temperature north and south of ACC in two depth layers: 0-200m and 200-1000m. In the surface to 200 m waters north of ACC Argo show lower temperatures than the reanalysis, but with a warming trend as well (Fig. 10). South of ACC (55°S-65°S) in this same depth layer, GLORYS2V3 displays a notable rise on temperature in years 2001-2003 followed by a decline, behaving as a peak, showing a cooling trend at the end of the series (Fig. 10).

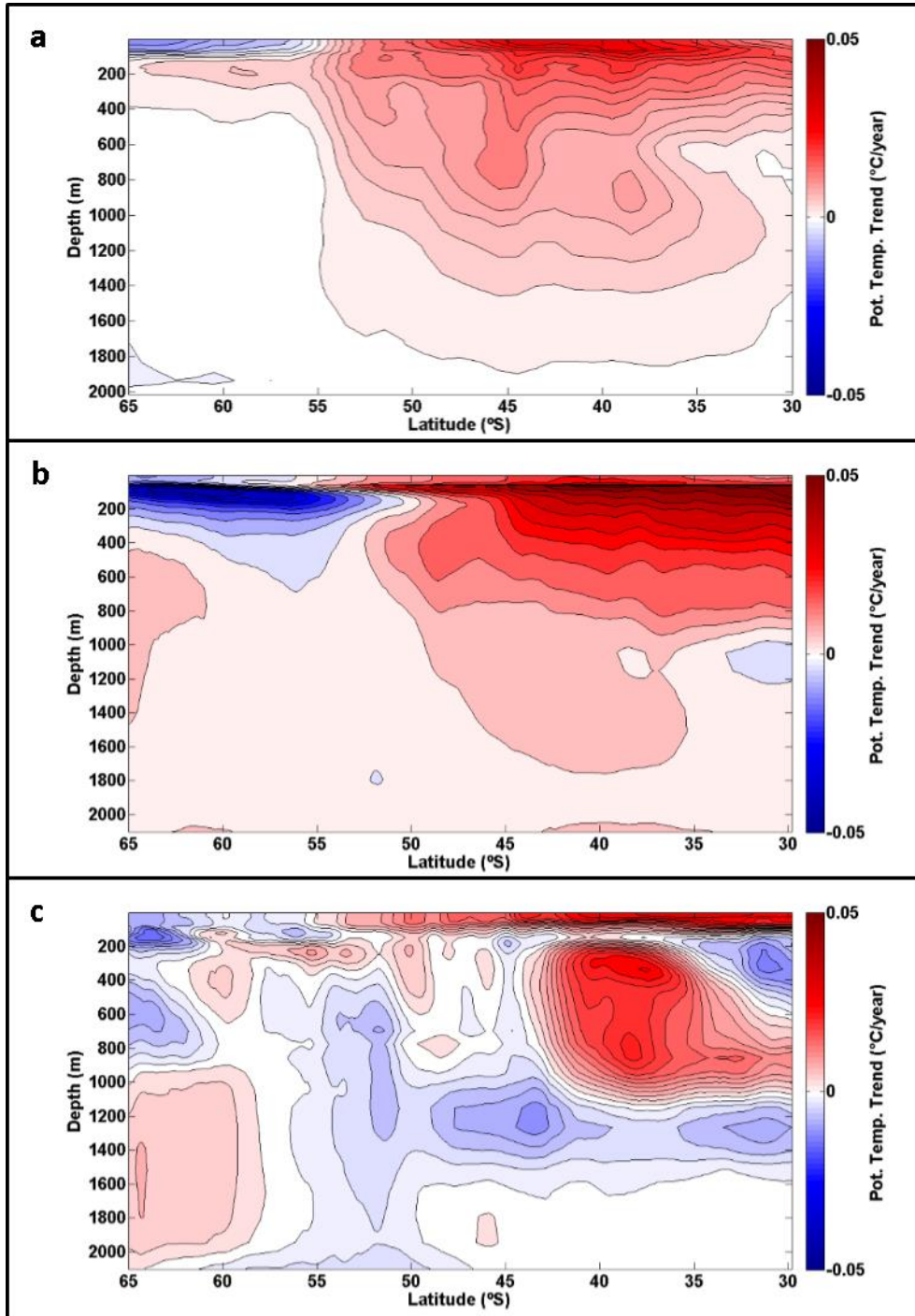


Figure 9: Zonally averaged potential temperature linear trends in the SO calculated from the entire period of the datasets. a: Argo (2004-2015); b: GLORYS2V3 (1994-2014); c: UR025.4 (1993-2010). Units are $^{\circ}\text{C}/\text{year}$.

It is interesting to note that the reanalysis show greater oscillation before the Argo onset, especially in the southern region. In depths of 200 to 1000 meters, north of the ACC (30°S - 45°S), there are two peaks in temperature in GLORYS2V3, one in 1998 and one in 2004 that persist until 2006, followed by a decline in temperature that lasts until 2010 (Fig. 11). UR025.4 also exhibits two peaks, however, the first is in 1999 and the

second in 2003. In addition to this, the temperature decline is only until 2007. Argo series begins in 2004 with a smooth cooling until 2007, resembling the end of the peak exhibited in the reanalysis, then experiencing a uniform warming until 2011. Finally, in 2012 the temperature rose again until 2014 in a faster pace, suggesting the beginning of another peak. Our dataset ends in 2015, so we did not see how this new potential peak would evolve. In this depth layer, GLORYS2V3 shows a single long peak through the entire series south of ACC, whilst Argo and UR025.4 display smaller oscillation.

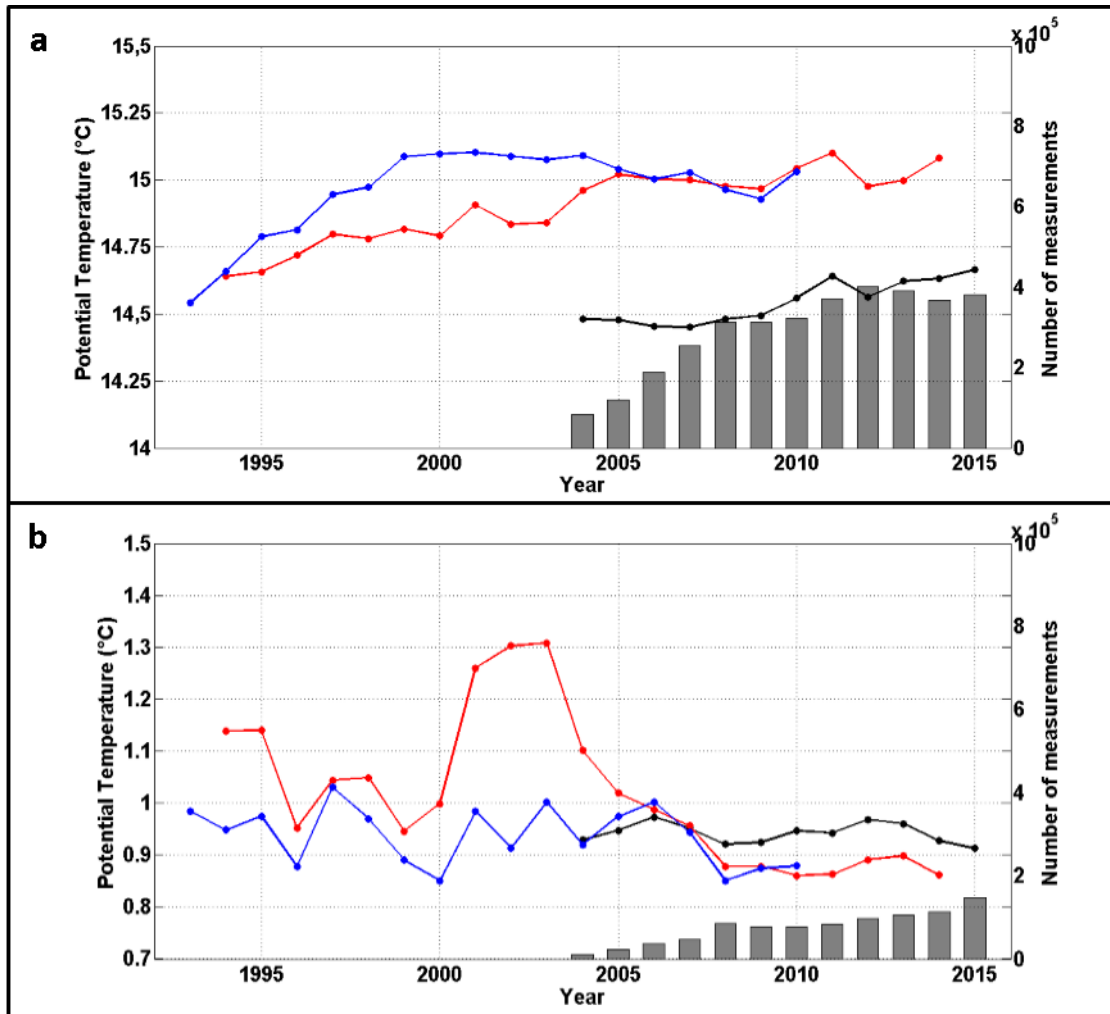


Figure 10: Temporal evolution of potential temperature in north and south of the ACC, averaged in a: 30°S-45°S, 0-200m; and b: 55°S-65°S, 0-200m. Lines: Black - Argo; Red - GLORYS2V3; Blue - UR025.4. Gray bars represent the total of Argo measurements per year in the region averaged.

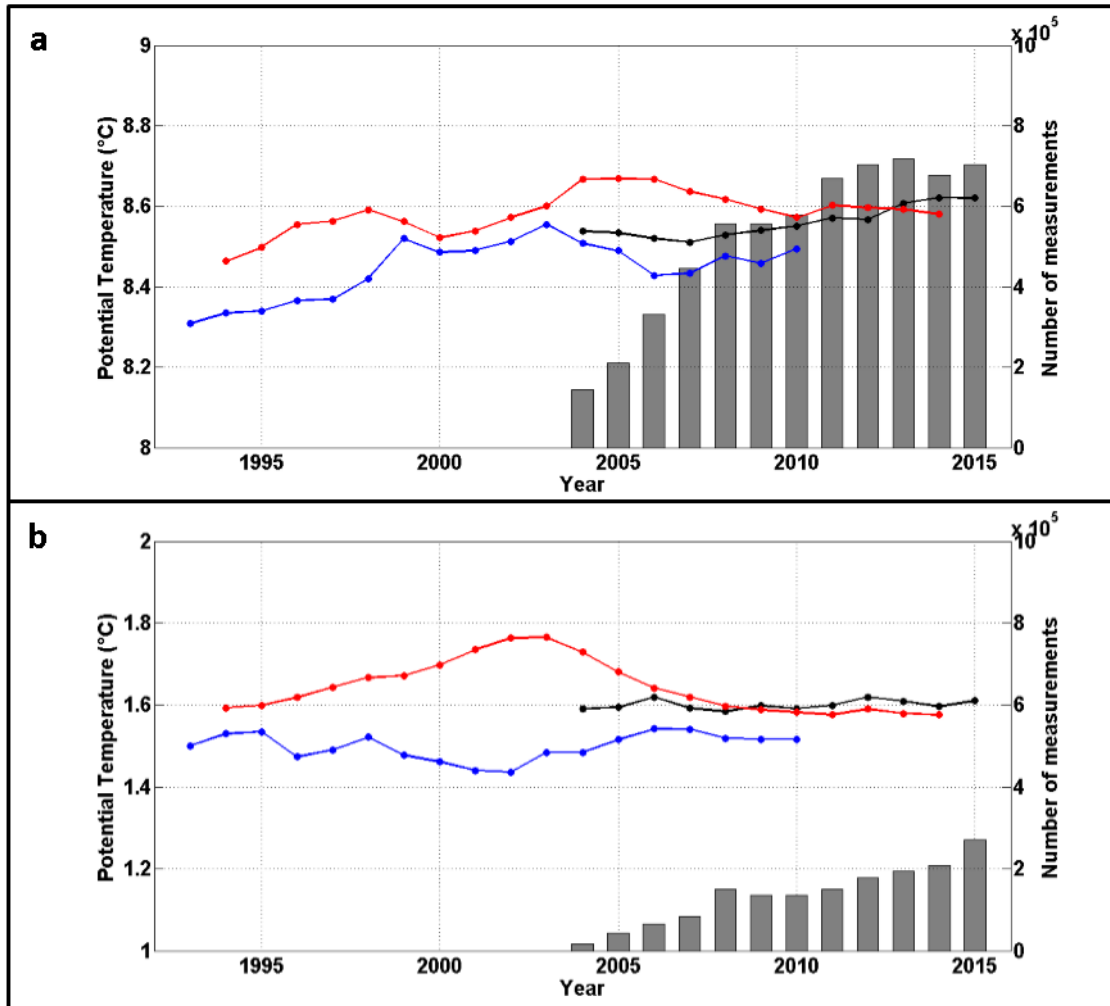


Figure 11: Same as Figure 10, but averaged in a: 30°S-45°S, 200-1000m; and b: 55°S-65°S, 200-1000m. Lines: Black - Argo; Red - GLORYS2V3; Blue - UR025.4.

Sectors

When analyzing the linear trends for the horizontal sectors of the SO, we can see that the zonally averaged pattern is not homogeneous in a circumpolar sense despite the fact that the sectors did not show significant differences in the zonally averaged SO. Figure 12 depicts some interesting and distinct features in the considered sectors, especially in the southern areas of the domain (which is historically less sampled). The warming in surface and subsurface north of the ACC can be seen in all the sectors in Argo, with the exception of a small area in the Weddell sector from about 150m to 400m in the northern part of the domain. Moreover, the warming showed by Argo extends through all the water column, while in the reanalysis that feature often reaches about 1000 m then reverting to cooling. Concerning the surface cooling south of the ACC, only the Indian sector does not show this feature, revealing a warming trend for the entire

meridional domain. The Weddell, Indian and PW sectors exhibited a less expressive cooling south of 55°S in comparison with the Ross and B&A sectors.

GLORYS2V3 also exhibit this warming signal in all but the Weddell sector, instead, showing a wedge of subsurface cooling water in this sector. However, the cooling region south of ACC is exaggerated in all sectors when compared to Argo, with the cooling signal reaching depths of over 1000m and values lower than $-0.08^{\circ}\text{C.yr}^{-1}$, with exception of the PW, which showed a pattern similar to the zonally averaged trend in this reanalysis. UR025.4, in turn, did not show a consistent pattern between sectors, with lots of areas exhibiting a cooling trend, especially in the B&A sector. The Indian and PW sectors are the only ones that showed some resemblance of the zonally averaged SO.

Salinity trends

Figure 13 shows the results of the linear trends calculated for the zonally averaged SO in the three data sets. The year 2011 of GLORYS2V3 was excluded from the analysis due to inconsistencies in the salinities of various depth ranges (i.e., from 1200 meters to the deepest layer, salinity values were as low as 31, when all the other years and in the other datasets, the values always oscillated from 33.5 to about 35.5, and this was causing the linear trend to show a strong freshening signal in these layers, so we decided to omit this year).

The Argo spatial pattern showed a region of increased salinity concentrated in the first 200m from 30°S to 50°S with magnitudes of over 0.005 yr^{-1} and the majority of the remaining domain being dominated by a freshening signal with lower magnitude. The UR025.4 reanalysis also showed a region of increased salinity in the near surface equatorward of 40°S and a wedge of freshening water resembling the structure of AAIW with values lower than -0.005 yr^{-1} , which are magnitudes greater than Argo. GLORYS2V3 showed a structure formed by three well-defined layers, being one of increased salinity in the surface of nearly the entire range of latitude of our study area, reaching magnitudes of over 0.01sal.yr^{-1} ; the second, a layer of intense freshening beneath the first reaching depths of over 1000m and values lower than -0.005sal.yr^{-1} ; and a third layer, on the bottom, of increased salinity, but with smaller magnitudes than the surface layer ($<0.002\text{sal.yr}^{-1}$).

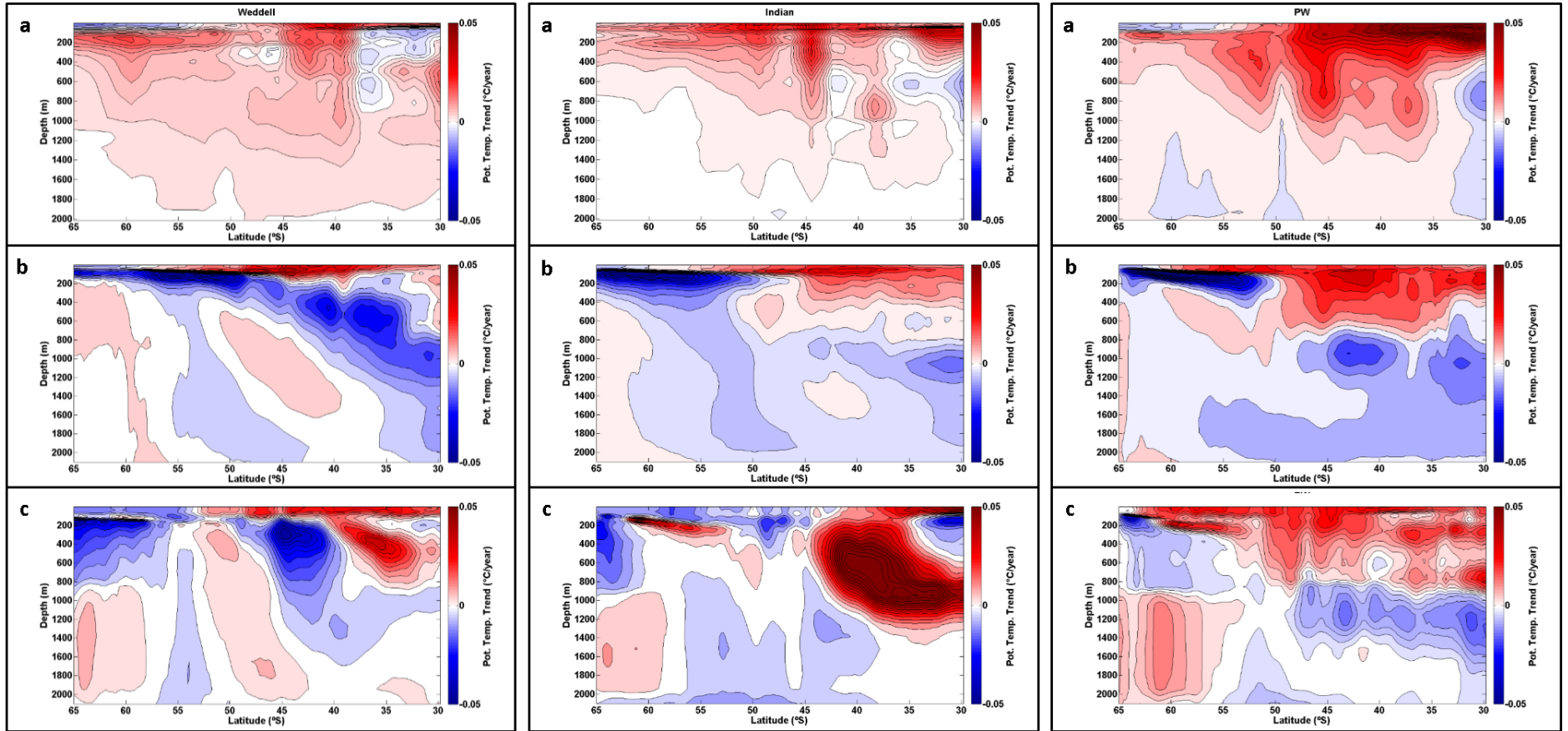


Figure 12.1: Potential temperature linear trends calculated for the entire period of each dataset for sectors Weddell Sea, Indian and Pacific West (PW); a: Argo (2004-2015); b: GLORYS2V3 (1994-2014); c: UR025.4 (1993-2010). Units are $^{\circ}\text{C}/\text{year}$.

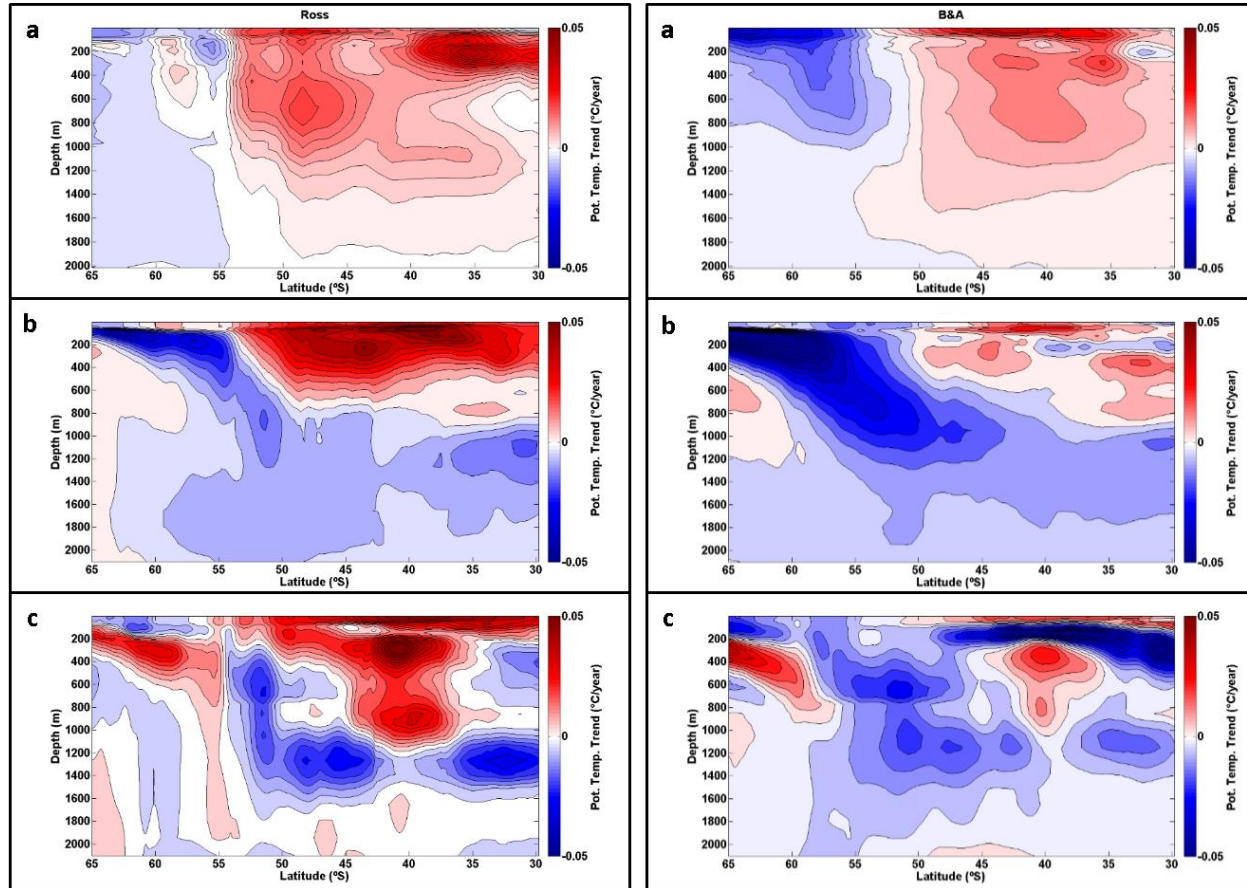


Figure 12.2: Same as Figure 12.1 for sectors Ross Sea and Bellingshausen and Amundsen Seas (B&A); a: Argo (2004-2015); b: GLORYS2V3 (1994-2014); c: UR025.4 (1993-2010). Units are °C/year.

The high values in the salinization trend in the south of ACC in GLORYS2V3 result from a depression-like feature, with a freshening trend from the beginning of the series until 2002, and then, a sudden rise in the values, inverting the trend at the end of the period; this behavior was mirrored by UR025.4, but in opposite signs (Fig. 14). Note that, as in the temperature, the values were oscillating significantly before the onset of Argo, indicating that the measures were sparse.

Sectors

Figure 15 shows the linear trends calculated for each sector. Argo exhibited a solid pattern in all sectors of salinization in lower latitudes in the surface; however, an interesting feature was present in the PW and Ross sectors, a region of freshening in the range of 30°S-35°S, from surface to about 400m. We can see in the temporal evolution of this section (Fig. 16) that in the PW sector, the salinity decreased from 2006 until 2009, stabilizing, and increasing from 2013 on. Hence, that notable decrease is probably what caused the trend to be negative at the end of our relatively short period. In the Ross sector, the oscillation is smaller, but there is a decrease in the salinity from 2007-2009 and a subsequent slight positive trend.

Nevertheless, the signal of salinization in the surface north of ACC is present in every sector, resembling the zonally averaged pattern. GLORYS2V3 showed this trend of salinization in the surface waters north of ACC in all the sectors, including the PW sector, where Argo showed a freshening signal which was previously mentioned. Argo also showed a small portion of freshening and the salinization in that region was less intense than the adjacent area. Also, in GLORYS2V3 we see a salinity decrease from 1995 to 2000. UR025.4 exhibit the same behavior. However, its trend was characterized by two peaks in salinity values, one in 1995 and other in 2006, which surpassed the first peak. The trend for this region was positive in UR025.4, in contrast with Argo and GLORYS2V3. In Ross sector, GLORYS2V3 displayed the greatest oscillation of all datasets and stabilized from 2004 on, while UR025.4 showed less oscillation, but higher salinities than both Argo and GLORYS2V3.

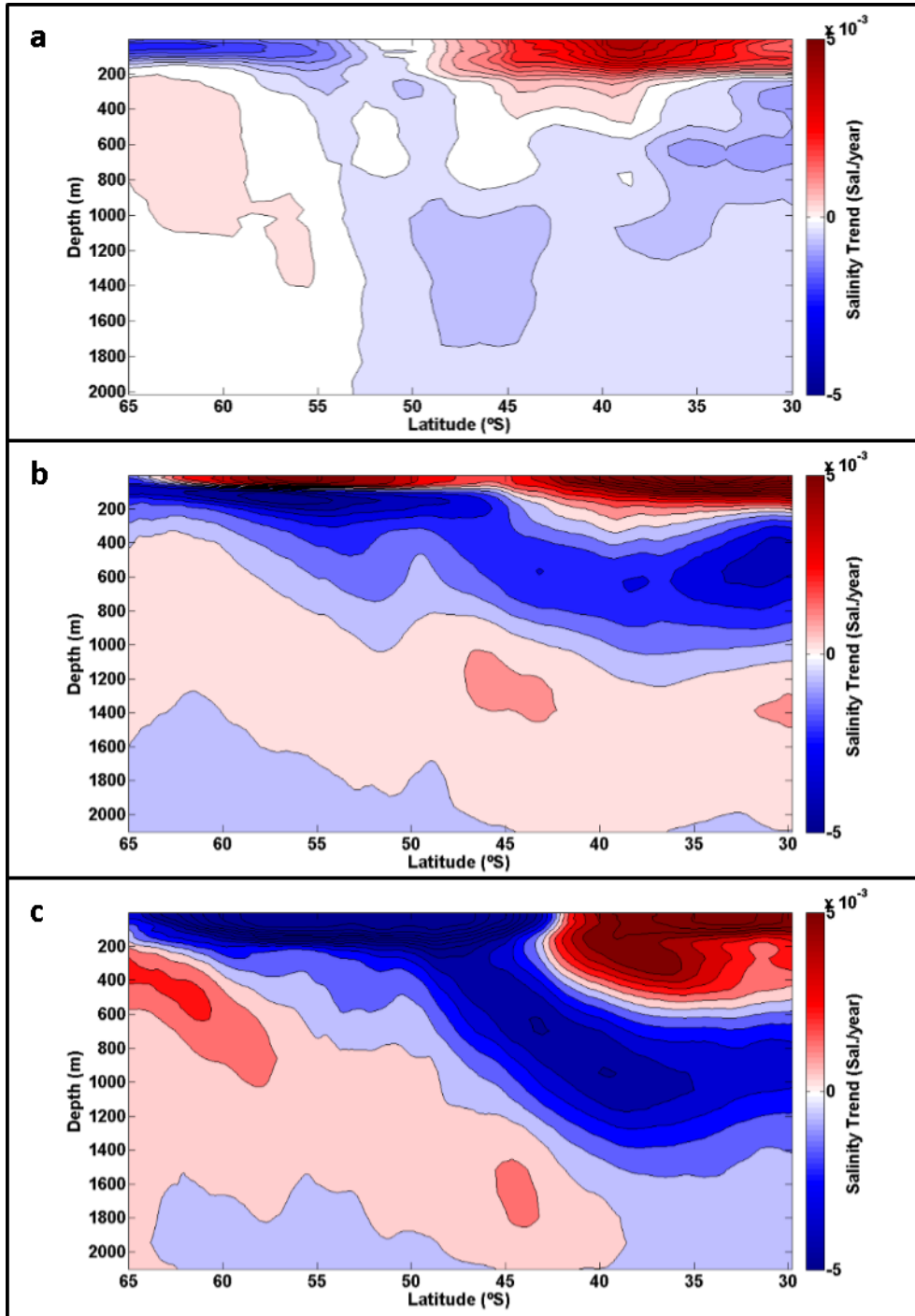


Figure 13: Salinity linear trends in the zonally averaged SO calculated from the entire period of the datasets. a: Argo (2004-2015); b: GLORYS2V3 (1994-2014); c: UR025.4 (1993-2010). Units: Salinity units/year.

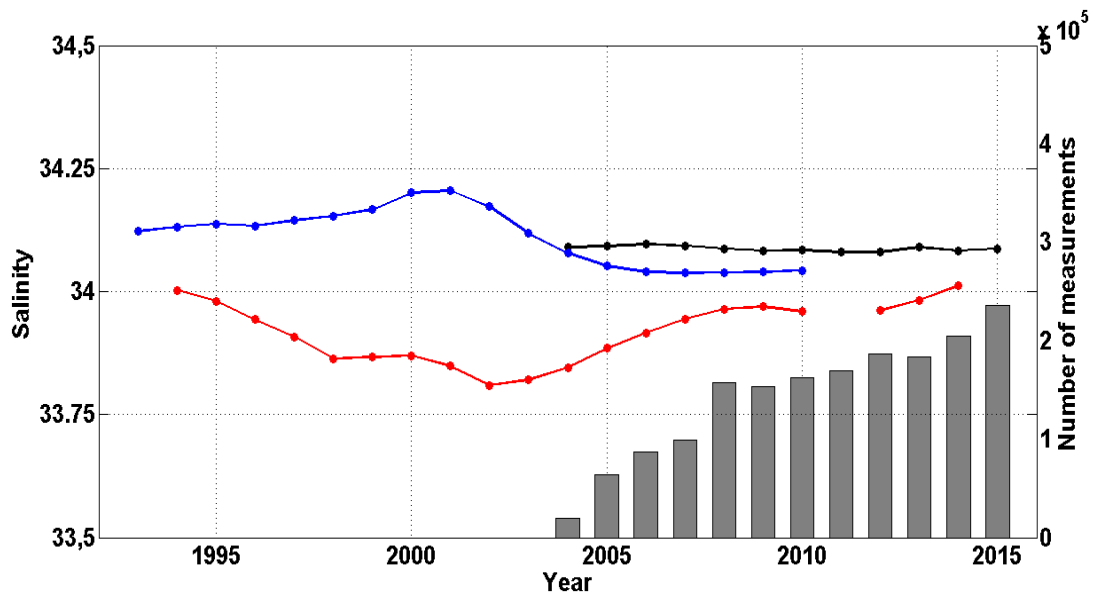


Figure 14: Temporal evolution of salinity for the zonally averaged SO in the section 50°S-65°S, 0-200m. Black line: Argo; Red line: GLORS2V3 and Blue line: UR025.4. Gray bars represent the total of Argo measurements per year in the region averaged. Note the opposite behavior of GLORYS2V3 and UR025.4 before 2005.

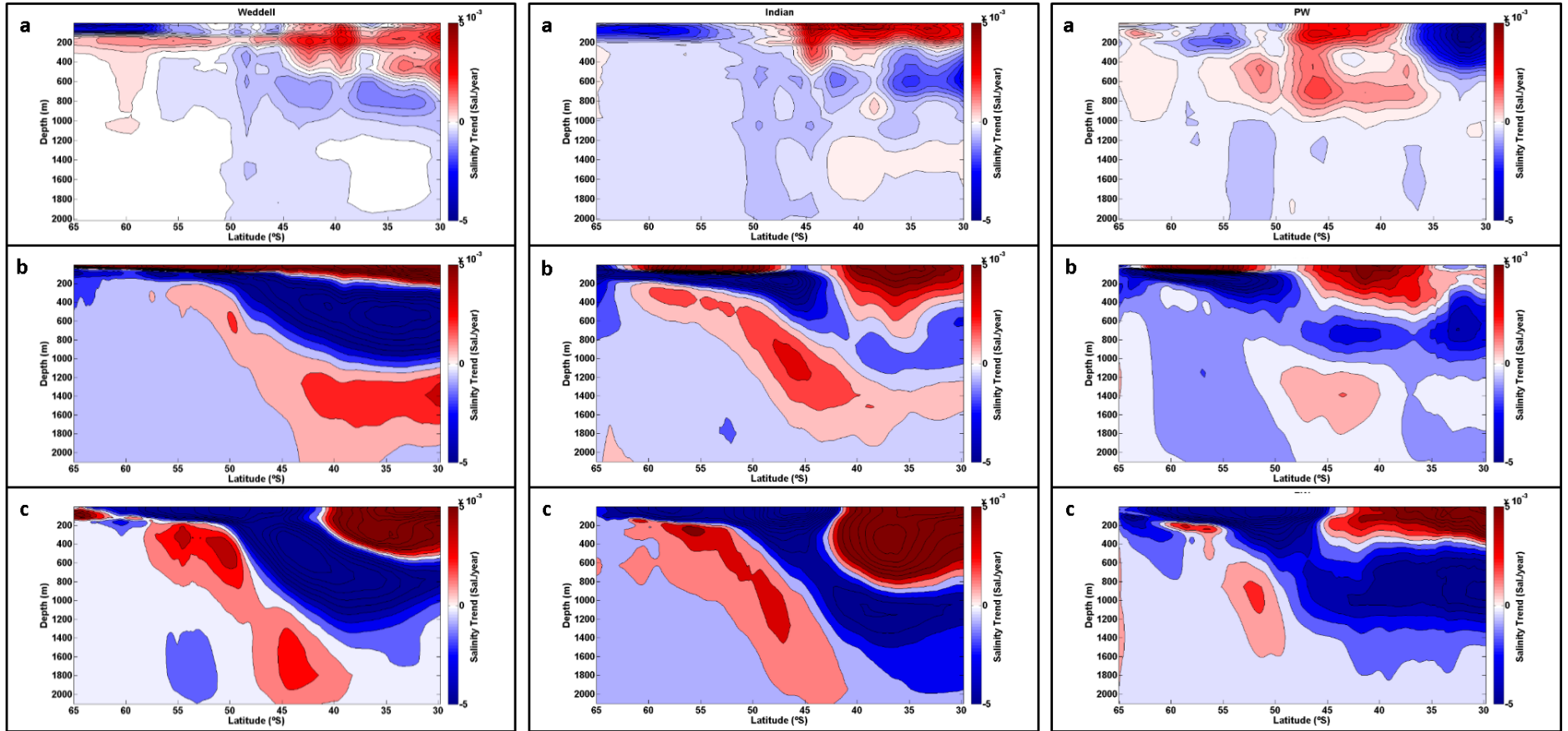


Figure 15.1: Salinity linear trends calculated for the entire period of each dataset for sectors Weddell Sea, Indian and Pacific West (PW); a: Argo (2004-2015); b: GLORYS2V3 (1994-2014); c: UR025.4 (1993-2010). Units: Salinity units/year.

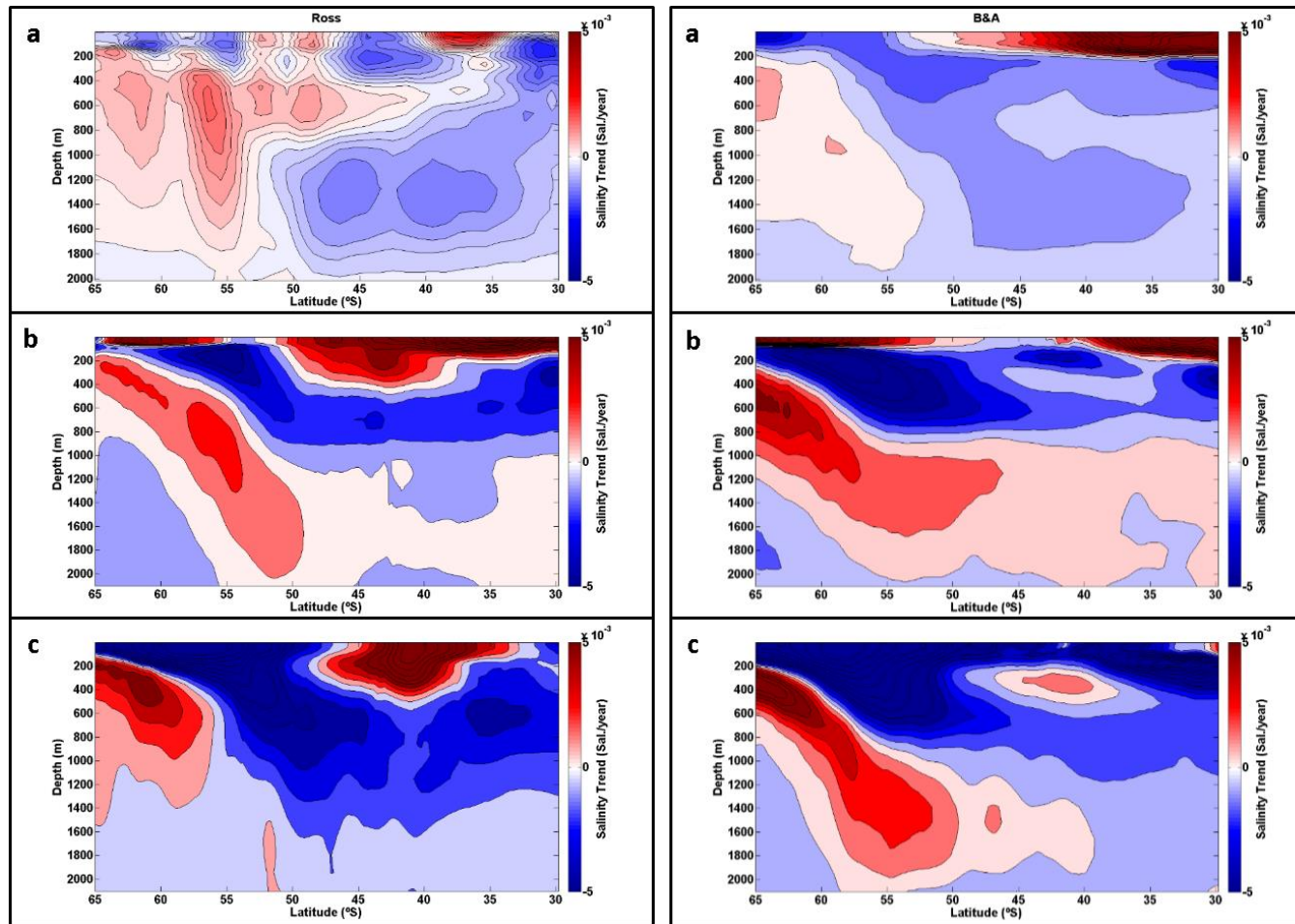


Figure 15.2: Same as Figure 15.1 for sectors Ross Sea and Bellingshausen and Amundsen Seas (B&A); **a**: Argo (2004-2015); **b**: GLORYS2V3 (1994-2014); **c**: UR025.4 (1993-2010). Units: Salinity units/year.

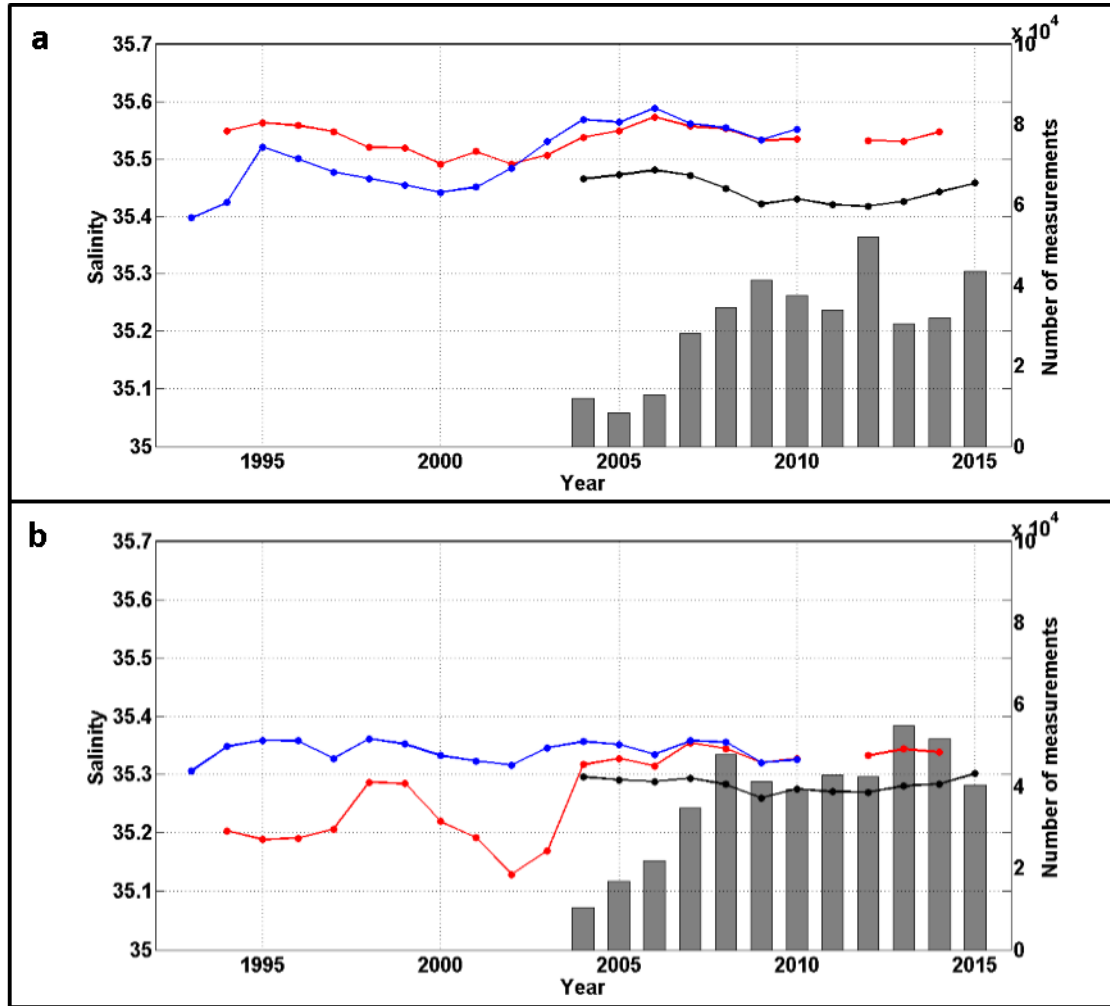


Figure 16: Temporal evolution of salinity for: a: PW sector; and b: Ross sector in the section 50°S-65°S, 0-200m. Black line: Argo; Red line: GLORS2V3 and Blue line: UR025.4. Gray bars represent the total of Argo measurements per year in the region averaged.

DISCUSSION

The main configuration differences between GLORYS2V3 and UR025.4 are the data assimilation method, the ocean model (UR025.4 uses a more recent version of NEMO) and the databases they assimilate. In both temperature and salinity fields distribution, UR025.4 displayed higher correlation with Argo than GLORYS2V3. Therefore, we can assume that UR025.4 is more suited to represent the thermohaline properties of the surface and mid depths of the SO.

Although GLORYS2V3 and UR025.4 differed in the databases assimilated, they both displayed high correlation with Argo (see Table 1). This is a direct consequence of the amount of data provided by Argo in comparison to other databases. As Argo surpassed the volume of data collected by others means, it became by far the most

important data assimilated by the reanalysis, thus reflecting that fact on the results. This stresses out how important Argo is for modern ocean studies.

Zonally averaged Southern Ocean

With respect to temperature, when comparing our results with the study by Böning et al. (2008), they found the strongest warming signal in the southern edge of the ACC near the surface along all its circumpolar extension and attributed it to eddy driven warming. Conversely, we found no signal of this phenomenon but instead our analysis reveals a cooling signal. Regarding salinity, however, our results unveil a spatial pattern that shows some resemblance to Böning et al. (2008), with most of the area experiencing a freshening trend. It is important to emphasize that our datasets cover a significantly smaller period, however, apart from the reanalysis, we used more than a decade of Argo data that alone surpass the amount of the four decades CARS climatology data (1960's-1990's). In fact, just the four years of Argo data used in Böning et al. (2008) study (2002-2006) did already surpassed the prior dataset. Böning et al. (2008) study dataset spanned more than four decades. In terms of longtime trends, this is an advantage; however, these data was mostly summer biased, as expected for any SO climatology due to viability of data collection. When Argo data is compared with season-biased data, the result can show some spurious trends (e.g. Roemmich & Gilson, 2009). On the other hand, the database we have used in this study is more limited on a time sense, but at least since the 2000's the issue with season bias is mitigated. Therefore, we have confidence that the dataset used is robust enough and provides a good representation of the current state of the SO.

The differences between our temperature trends and Böning et al. (2008) is likely to be the outcome of the difference in the period studied and perhaps from the data issues highlighted above. However, the warming south of ACC that Böning et al. (2008) attributed to the eddy driven warming is expected to take place just a few years after the strengthening of the winds related to SAM positive phase (Hogg et al., 2008). Moreover, even in the reanalysis we have used (which cover about two decades) we found no warming south of the ACC, although the SAM was in a positive trend during this time. That indicates that the warming found by Böning et al. (2008) can be the result of a long period trend caused by the resurgence south of ACC (Ferreira et al., 2015; Parise et al., 2015) rather than the eddy driven warming or the seasonal bias of the data. Despite the differences found in the temperature trends, our salinity results generally agree with Böning et al. (2008). The fact that one of the parameters analyzed agrees between both studies and the other does not is an interesting issue. However, Roemmich & Gilson (2009) and Riser et al. (2016) explain that salinity data was poorly collected before the

Argo era, so this lack of prior data could have shifted the weight of the analysis when Argo data became available.

The warming-cooling spatial pattern we found (Fig. 9) is consistent with the expected effects of the strengthening of winds in the SO associated with the positive trend of SAM (Sen Gupta & England, 2006; Fyfe et al., 2007; Gille, 2008; Screen et al., 2008; Spence et al., 2010; Armour et al., 2016). The warming north of 55°S from the surface to depths of over 1000 meters is a direct result of meridional ocean heat transport: the cool waters from higher latitudes absorb heat and are advected northwards to the ACC's northern boundary; the advection northwards prevents the heat from being stored in the southern edge of the ACC; when at the northern boundary of ACC, those waters experience subduction, enhancing the warming in this region and reducing the warming south of the ACC (Armour et al., 2016). On the other hand, the observed cooling is attributed to different mechanisms: enhanced northward Ekman transport south of the ACC, which is advecting cool waters from near the continent to lower latitudes (Ferreira et al., 2015; Armour et al., 2016; Kostov et al., 2017); reduction of radiative forcing by increased low-cloud reflectivity through enhanced wind-driven emissions of sea spray (Korhonen et al., 2010); and weakening of convection and vertical mixing caused by freshening of surface waters by melting of sea ice, which reduces the upward flux of heat from warmer waters on the subsurface (Kirkman & Bitz, 2011; Parise et al., 2015; Haid et al., 2017).

Figures 10b and 11b show fluctuations in temperature during its evolution in the time series. Meredith & Hogg (2006) and Hogg et al. (2008) mention a significant eddy kinetic energy (EKE) peak in 2003 and GLORYS2V3 shows a sharp peak in this period that could be a signal of this event (Fig. 10b). However, the resolution of GLORYS2V3 is only marginally eddy permitting, therefore we cannot affirm that our data captured that variability, and the peaks displayed by the reanalysis may be intrinsic model oscillations. Conversely, UR025.4 unveils smoother oscillations around the climatologic mean throughout the entire series, what reinforces the idea that what GLORYS2V3 showed were model oscillations.

The EKE peaks observed by Meredith & Hogg (2006) in the temperature of different depths lead to eddy-driven warming lagged by a few years from positive SAM events. This effect was mentioned by Screen et al. (2008), when analyzing models with different resolutions. They conclude that it is most evident in high latitude surface waters of the SO. The authors further argued that after the initial cooling caused by the strengthening of the winds, a warming period follows which persists and eventually surpasses the initial cooling. The strong warming in the upper-ocean south of the ACC found by Böning et al. (2008) was attributed to this eddy-driven mechanism as well.

However, what our potential temperature data shows are oscillations throughout the series, i. e., a peak in the temperature, followed by a decline, in contrast with the concept that the eddy-driven warming is a persistent and gradual process once it is triggered.

Kostov et al. (2017) analyzed the relationship between SAM and SST around Antarctica in various models from the Climate Modeling Intercomparison Project phase 5 (CMIP5) and their results showed that the SST response was quite variable between the models. All the models showed the initial cooling, probably related to the strengthening of the westerlies but their late response was basically in three forms: a transition from cooling to a warming trend after a few years; a transition to warming after a decade; and no transition at all, with the cooling trend persisting. Our results agreed more with the latter group of models, showing two peak- like features in the temperature of upper ocean, but maintaining the cooling trend until the end of the period.

Our results of the zonally averaged SO show that the eddy-driven warming process do not surpass the cooling in several years, instead, it happens in pulses and may only surpass the cooling in a much longer timescales than our data covers. However, Argo showed a surface warming trend in the Indian sector, agreeing with Zwally et al. (2002), Frenger et al. (2015), Hogg et al. (2015) and Masina et al. (2015), that mention high eddy activity in this region. Hence, we conclude that the eddy-driven warming is taking place regionally and currently it is not capable to drive the mean temperature signal in the zonally averaged SO.

Regarding the salinity, we attribute the salinity trends of the reanalysis being greater than Argo to the significant oscillations in those values. In fact, salinity fields in the reanalysis were oscillating significantly before the onset of Argo, which corroborates the idea that the salinities measures in the pre Argo era were too sparse and timely biased to properly represent SO variability (Roemmich & Gilson, 2009; Riser et al., 2016).

Our results show that salinity changes over time in our products display a pattern in which regions of higher (lower) salinity are becoming more (less) saline. This could be related to an intensification of the hydrological cycle, commonly associated to the recent anthropogenic induced climate changes (Durack & Wijffels, 2010; Helm et al., 2010; Liu & Curry, 2010; Durack et al., 2012; Skliris et al., 2014; Aretxabaleta et al., 2015). In agreement, some studies addressing the precipitation rates in mid-latitudes of the Southern Hemisphere have shown that there has been a decline in precipitation in this range of latitude that is partly attributed to the positive trend of SAM, which is constraining and strengthening the westerlies band to higher latitudes and shifting the associated precipitation belt with it (Meneghini et al., 2007; Kang et al., 2011; Cai et al., 2012; Purich et al., 2013; Delworth & Zeng, 2014). The freshening signal in the surface waters of high

latitudes in the SO (south of 50°S) is attributed to both increase in precipitation rates and glacial melting (the latter being active in waters adjacent to the continent, out of our study area). However, more recently, another explanation for the above pattern was suggested, as the two aspects aforementioned would not explain for all the freshening recorded in the SO.

Haumann et al. (2016) quantified the enhanced sea ice transport northward and proposed that it is the missing piece to fully explain the observed freshening south of the ACC. According to their study, the sea ice around Antarctica is being advected northward in an increasing rate from the recent decades due to strengthening of southerly winds coming from the continent. Thus, those winds would transport more freshwater from the coastal region to open ocean, around the sea ice edge, and melting there. This process was described by Kirkman & Bitz (2011), acting as a lateral conveyor of freshwater by extracting it from the coastal regions around Antarctica, where the sea ice forms, and releasing it at the northern edge of the sea ice, where the sea ice melts. This mechanism is largely responsible for the freshening signal on AAIW, thus, resulting in a feature that reinforces the idea that the hydrological cycle is intensifying, similar to what we found (Fig. 13).

Sectors

Although the zonally averaged trends of temperature in the SO are not homogeneous across the sectors, the warming signal north of ACC is present in all the sectors. That is also true for the surface cooling south of 55°S, except for the Indian sector. GLORYS2V3 cooling signal in the southern portion of the area seems to be exaggerated, when compared to Argo and UR025.4. This is likely due to the sharp decline in temperature over the years of 2003 to 2008, after the peak mentioned before (Fig. 10b). Moreover, the fluctuation in GLORYS2V3 is more expressive than UR025.4 and Argo (e.g., Figure 10), and leads us to believe that it overestimates the real values, thus, influencing in the linear trends at the end of the period. Less sampled areas as the higher latitudes of the SO play its role in the distinct trends, once they cause the values to oscillate, ultimately driving the trends in one way or another, considering we are analyzing a relatively small amount of time.

The Weddell and PW sectors exhibited a less expressive cooling south of 55°S. As mentioned earlier, the Indian sector is warming in the surface both in north and south of ACC due to mesoscale activity (Frenger et al., 2015; Hogg et al., 2015; Masina et al., 2015), so the neighbors sectors (Weddell and PW) might be going through the same process, yet currently not so strong.

The warming signal north of ACC is present in all the sectors and stands out as a robust circumpolar feature, as described in Böning et al. (2008) (Fig. 12). In most cases, the warming in Argo is more pronounced than in the reanalysis and it resembles the zonally averaged SO spatial pattern (Figs 9 and 12). Below 1000 m, Argo's warming signal remains, which generally is not the case for the reanalysis. This can be an indicative that either the reanalysis underestimate the warming or, because of the difference in the periods covered, Argo captured the warming which occurred in the last decade only. Conversely, the reanalysis trend was not sufficient to surpass the prior cooling trend yet, although capturing the same signal as Argo. The spatial pattern of the salinity trends in the sectors showed a general resemblance to the zonally averaged SO trend. The curious freshening area in the lower latitudes present in the PW sector in Argo and GLORYS2V3 is characterized by an oscillation that begin with a freshening in 1995-2000, a salinization from 2001-2006 and another decrease in the salinity that lasts until 2012. As the Argo time series is relatively short, it comprised the freshening from 2006 until 2012, which resulted in a negative trend at the end of the period. GLORYS2V3 showed a less intense freshening, and some salinization in this same region, probably because of the longer series (Fig. 11). UR025.4 trend, on the other hand, was characterized by two peaks in salinity values, one in 1995 and other in 2006, the latter being more intense. Even with the reducing amount of precipitation in this range of latitude, the decrease in salinity values over a period of some years is possibly related to some regional precipitation pattern.

On the freshening signal south of the ACC, both the reanalysis and Argo captured and represented it in some way. It was mostly depicted as freshening waters in the surface south of 50°S and increasing depths through lower latitudes, resembling the structure of the AAIW. There were some differences between the sectors, but the overall signal was present in every sector.

One interesting feature appeared in the Ross sector, which was expected to show the most expressive freshening signal. Haumann et al. (2016) found that in the Ross Sector there was the greatest contribution of transport of freshwater from the sea ice, following their proposal that this mechanism is fundamental for the freshening seen in the SO. Instead, we found that the surface freshening in this sector was one of the smallest and beneath 150m there is a wedge of water with a salinization trend. However, the higher latitudes of the SO count with a sparse coverage by Argo and mostly, the floats still cannot measure in sea ice covered waters. We did, however, find a stronger freshening in the B&A sector, which is neighbor of the Ross sector and showed a positive trend of transport in their study as well. In this sector, most of the glaciers are retracting, possibly releasing a significant amount of fresh water in that region of the SO. As the two

reanalysis assimilate sea ice data, it is possible that they were able to represent this feature in their models, as well as Argo did. It is important to mention that our area of study is limited in 65°S and the effects seen in Haumann et al. (2016) study were concentrated mostly in higher latitudes, so this may be the reason why we did not find the strong freshening signal in the Ross sector.

SUMMARY AND CONCLUSIONS

The oceans are especially important to the ongoing climate change given their capacity to store and redistribute heat throughout the planet. In this context, the SO is perhaps the less understood of the ocean basins because of the difficulty in logistics and sparse navigation routes. Since the 1960's, the SAM is in a positive trend, which is closely related to forcing that affect directly the SO like the strengthening and shifting position of the westerly winds belt. The expected effects in temperature of the SO is a warming in most of its area, with the surface of the higher latitudes displaying an initial cooling followed by the eddy-driven warming resultant of the increase of wind generated mesoscale activity. With respect to salinity, it is expected a shift of the rain belt from mid to higher latitudes, which would cause a freshening in most of SO area. Moreover, the recent warming climate is known to intensify the water cycle, which make less saline areas become even fresher and vice versa.

The SO is an inhospitable environment that make it difficult to maintain a continuous observation network. Thus, it is historically the less sampled ocean basin. Even with the efforts of various groups, the scarcity of data in the SO present as an unresolved problem that limited our understanding of this part of the climate system. Ocean Reanalysis are a recent tool developed to help in this task and they are indeed very useful in the ocean/climate research. In this study, we made use of this tool alongside with in situ data from the Argo system. The latter has revolutionized oceanography in the last two decades by providing an unprecedented robust dataset in both temporal and spatial sense. In this study, we analyzed data from about two decades to assess the recent trends in the vertical structure of the SO. We revisited the approach by Böning et al. (2008) study, but this time utilizing recent Ocean Reanalysis products and Argo data.

Our data analysis showed that the SO is warming in most areas, but a region of cooling is still present south of the ACC. Our results indicate that the proposed eddy-driven warming that happens several years following a positive SAM event has not been enough so far to reverse the cooling trend in higher latitudes. The warming signal in this region should be detected only after decades of gradual strengthening of the winds.

Although the northward sea ice transport might be an important agent in the freshening in higher latitudes (south of ACC), the salinity trend follows the spatial pattern that reinforces the idea of an enhanced hydrological cycle. We saw that the reanalysis were notably affected by Argo assimilation, which consolidate it as one of the most valuable tools in modern oceanography. UR025.4 showed higher correlation to Argo than GLORYS2V3 both in potential temperature and salinity, suggesting that it performed better in representing these fields in the SO. Further investigation with Argo data is imperative to a better understanding of the recent changes in the ocean, especially in high latitudes, where the data is historically sparse.

ACKNOWLEDGEMENTS

We thank the staff teams responsible for developing and making freely available the Ocean Reanalysis MyOcean GLORYS2V3 (Mercator Océan) and UR025.4 (University of Reading) on the Copernicus Marine Environment Monitoring Service website (<http://marine.copernicus.eu/services-portfolio/access-to-products/>). We acknowledge and thank the effort by D. Roemmich and J. Gilson in developing and maintaining updated the Argo Climatology, making it freely available and also for providing additional information on the product. This study is a contribution to the activities of the Brazilian High Latitudes Oceanography Group (GOAL) and the Brazilian National Institute of Science and Technology of the Cryosphere (INCT-CRIOSFERA 465680/2014-3). GOAL has been funded by the Brazilian Antarctic Program (PROANTAR) through the Brazilian Ministry of the Environment (MMA), the Brazilian Ministry of Science, Technology, Innovation and Communication (MCTIC), and the Council for Research and Scientific Development of Brazil (CNPq grant 405869/2013-4). J.F.A. Miranda thanks the financial support from the CAPES foundation, process number 1584000.

REFERENCES

* As referências serão listadas ao final deste documento, contendo todas as referências utilizadas nesta dissertação.

Capítulo IV: Conclusões e considerações

finais

Os resultados das comparações entre as Reanálises Oceânicas e a climatologia derivada do Argo mostraram que as reanálises conseguem reproduzir bem os campos de temperatura potencial e salinidade no Oceano Austral, como evidenciados pela Figura 4 do artigo científico (pág. 41). A Tabela 1 do artigo (pág. 47) complementa esta afirmativa ao mostrar alta correlação e baixos valores de p obtidos nos testes- t entre as reanálises e o Argo. Um aspecto importante é a distribuição espacial dos dados do Argo utilizados na climatologia, bem como a evolução no número de medições realizadas ao longo do tempo (Figs. 2 e 3 do artigo, pág. 39 e 40). As latitudes mais altas ainda sofrem com uma relativa baixa quantidade de medições enquanto que a faixa entre 30°-50°S já conta com uma amostragem mais robusta (Fig. 2 do artigo, pág. 39). Sobre a distribuição temporal dos dados Argo, constatamos que nos cinco primeiros anos utilizados o número de medições aumentou até chegar em uma estabilização, por volta de 2008, quando o sistema já havia alcançado uma distribuição global satisfatória [Riser *et al.*, 2016].

Concernente à tendência de temperatura potencial no Oceano Austral, os resultados refletem os efeitos causados por um aquecimento persistente e a tendência positiva do fenômeno SAM. Este fenômeno está causando uma intensificação e deslocamento do cinturão de ventos oeste para sul, o que, por sua vez, intensifica o transporte de Ekman para norte em latitudes mais altas. Como consequência, a região ao sul da CCA está sofrendo um resfriamento em superfície, já que recebe continuamente águas mais frias oriundas de próximo do continente Antártico, e a região ao norte de 55°S está passando por um aquecimento na superfície e em profundidade (alcançando mais de 1000 m). O aquecimento também é consequência da intensificação dos ventos, que intensificam o transporte de Ekman em direção a norte; durante este trajeto, essas águas absorvem calor e se aquecem até chegarem ao limite norte da CCA, onde sofrem subducção, levando este aquecimento para águas mais profundas [Armour *et al.*, 2016]. Este cenário pode ser visualizado na Figura 9 (pág. 50) do artigo científico.

É importante ressaltar que vários autores propõem que o resfriamento visto nas latitudes mais altas eventualmente é compensado por atividade de mesoescala após poucos anos. Esta, por sua vez, também é gerada em decorrência da maior intensidade dos ventos, transportando calor em direção a

sul pela subsuperfície [Meredith & Hogg, 2006; Fyfe *et al.*, 2007; Böning *et al.*, 2008; Hogg *et al.*, 2008; Screen *et al.*, 2008]; porém, neste estudo, nós não detectamos este sinal nos resultados referentes ao campo médio zonal do Oceano Austral. Os resultados mostraram que, ao longo do período analisado, o resfriamento ao sul da CCA é um processo persistente (Fig. 9 do artigo, pág. 50).

Em relação à salinidade do Oceano Austral, as reanálises apresentaram tendências com maior magnitude do que o Argo (Figs. 13 e 15 do artigo, pág. 59 e 61-62). Isto provavelmente aconteceu porque antes do sistema Argo, as medições de salinidade não eram confiáveis [Riser *et al.*, 2016], e nossos resultados mostraram que os valores de salinidade das reanálises no período anterior ao Argo tinham um comportamento oscilante e que depois do Argo, os valores tendem a se estabilizar (Figs. 14 e 16 do artigo, pág. 60 e 63). Os resultados mostraram que este padrão de distribuição de salinidade está se intensificando, ou seja, regiões mais salinas estão tendo a salinidade aumentada e regiões menos salinas estão passando por um processo de dessalinização.

Este cenário é compatível com a suposição de que o ciclo hidrológico terrestre está se intensificando devido às mudanças climáticas em curso e que isto produz o efeito na salinidade oceânica descrito acima. A tendência positiva do SAM também é um fator que contribui para a diminuição da salinidade em latitudes em torno de 50°S, pois o cinturão de ventos oeste está sendo deslocado para sul e por consequência, deslocando também a precipitação associada a ele. Mais recentemente, Haumann *et al.* [2016] também propuseram um mecanismo alternativo que também deve contribuir para a diminuição de salinidade em latitudes mais altas do Oceano Austral: o gelo marinho que circunda a Antártica (em latitudes mais altas que 65°S) está sendo transportado para norte, carregando assim uma maior quantidade de água doce, que futuramente é liberada no oceano após o derretimento do gelo. Segundo Haumann *et al.* [2016], só considerando este mecanismo junto com a intensificação do ciclo hidrológico é possível fechar o balanço de água doce que está causando a dessalinização desta região.

A análise se deu com a avaliação do desempenho das Reanálises Oceânicas ao compará-las com os dados Argo, num período que compreendeu 7 anos (de 2004 a 2010). As duas reanálises apresentaram altas correlações

com o Argo neste período (>0.99). Após isso, as tendências lineares de longo período das reanálises foram analisadas, em uma revisita à metodologia de Böning *et al.* (2008) concernente à temperatura potencial e salinidade, cobrindo cerca de duas décadas (UR025.4: 1993 a 2010; e GLORYS2V3: 1994 a 2014). As tendências lineares do Argo também foram analisadas, porém, com um período mais limitado, de 12 anos (2004 a 2015).

No contexto de que o Oceano Austral é o oceano historicamente menos amostrado, observou-se que as reanálises foram notavelmente afetadas pelos dados do sistema Argo, o que o consolida como uma das ferramentas mais valiosas da oceanografia moderna. As Reanálises Oceânicas estão sendo constantemente atualizadas e agregando melhoras em seus modelos e esquemas de assimilação, portanto também são ferramentas muito úteis para esse tipo de estudo, gerando resultados de anos passados, quando ainda não se tinha o sistema Argo. Investigações posteriores com dados do Argo são imperativas para uma melhor compreensão das recentes mudanças no oceano, especialmente em altas latitudes, onde os dados são historicamente escassos. Desta forma, recomenda-se uma revisita a esta pesquisa uma vez que os dados do sistema Argo tiverem um período maior para serem analisados. Os resultados gerados pelas reanálises cobriram cerca de duas décadas, portanto, um intervalo semelhante ou maior de dados Argo seria apropriado.

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