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Impacts of sea-surface salinity in an eddy-resolving semi-global OGCM[☆]

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ABSTRACT

To explore the impacts of sea-surface salinity (SSS) on the interannual variability of upper-ocean state, we compare two 10-year runs of an eddy-resolving ocean general circulation model (OGCM): in one, SSS is strongly restored toward a monthly climatology (World Ocean Atlas '98) and in the other, toward the SSS of a monthly gridded Argo product. The inclusion of the Argo SSS generally improves the interannual variability of the mixed layer depth; particularly so in the western tropical Pacific, where so-called "barrier layers" are reproduced when the Argo SSS is included. The upper-ocean subsurface salinity variability is also improved in the tropics and subtropics even below the mixed layer.

To understand the reason for the latter improvement, we separate the salinity difference between the two runs into its "dynamical" and "spiciness" components. The dynamical component is dominated by small-scale noise due to the chaotic nature of mesoscale eddies. The spiciness difference indicates that as expected from the upper-ocean general circulation, SSS variability in the mixed layer is subducted into the thermocline in subtropics; this signal is generally advected downward, equatorward, and westward in the equator-side of the subtropical gyre. The SSS signal subducted in the subtropical North Pacific appears to enter the Indian Ocean through the Indonesian Throughflow, although this signal is weak and probably insignificant in our model.

1. Introduction

1.1. Uncertainty in SSS

Freshwater flux into the ocean, mostly precipitation, river discharge, and sea-ice melt, is one of the least constrained parameters because the temporal or spatial scales of these phenomena are small (Boutin et al., 2016) and hence accurate global measurements are difficult. In numerical ocean models, uncertainty in freshwater flux translates to that in sea-surface salinity (SSS). Sea-surface temperature (SST) has similar uncertainty due to that in heat flux, but error in SST tends to be countered by anomalous heat flux of opposite sign (e.g., Bryan, 1986; Killworth et al., 2000), whereas no such negative feedback exists for error in SSS because SSS has little impact upon freshwater input or evaporation (e.g., Bryan, 1986). For this reason, sea-surface freshwater flux is often adjusted to avoid salinity drift in stand-alone ocean general circulation models (OGCMs) or in the oceanic components of coupled general circulation models either by directly modifying the flux itself or by restoring SSS to some observed values (e.g., Johns et al., 1997; Gordon et al., 2000; Masumoto et al., 2004; Oke et al., 2013; Storto et al., 2016).

For global or basin-scale simulations, this adjustment has, in turn, suffered from the paucity of SSS observation, especially before the Argo array (Gould et al., 2004): the best one can do has usually been to use a climatological SSS map based on in-situ observations, such as the World Ocean Atlas (e.g., Antonov et al., 1998a; Locarnini et al., 2013). As a result, interannual SSS variability is dampened or eliminated, which potentially causes inconsistency with the SST field or error in subsurface salinity. The potential impacts of this deficiency in climate prediction simulations are a concern.

One approach to improve the realism of the salinity field in ocean hindcast simulations (reanalyses) is to assimilate four-dimensional salinity observations such as those from the Argo array (e.g., Huang et al., 2008). Such ocean reanalyses are valuable resources for climate studies. They, however, require large human and computer resources to produce and maintain (e.g., Stammer et al., 2016). In

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addition, many assimilation schemes break conservation properties or dynamical balances (e.g., Stammer et al., 2016), rendering them less suitable for certain types of analysis than "free" model runs. Moreover, long integrations of global eddy-resolving ocean models are increasingly common and have been proved to be useful (e.g., Sasaki et al., 2004; Oke et al., 2013), but data assimilation that conserves scalars and maintains dynamical balances is a challenge for eddy-resolving ocean models. (That is obvious with respect to computer resources from the fact that most long-term assimilation products are on coarse grids.) For these reasons, free eddy-resolving OGCMs forced only from boundaries are useful tools. For such models, accurate sea-surface conditions are necessary.

1.2. Potential impacts of SSS

SSS impacts upon local surface density, affecting the local mixed-layer depth (de Boyer Montégut et al., 2004; Liu et al., 2009). The mixed-layer-depth change can in turn alter local SST. It can also generate dynamical responses such as Rossby and Kelvin waves, either through the density change itself or through its impact upon the vertical distribution of wind forcing. These waves can propagate and affect ocean state elsewhere. Another potential impact of SSS is on the *T–S* relation (watermass properties) in the mixed layer. Both these processes can influence the circulation and watermass properties in thermohaline overturning circulations, such as those associated with the North Atlantic Deep Water, Antarctic Bottom Water, and Sea-of-Okhotsk Dense Shelf Water (Matsuda et al., 2015, and references therein).

1.2.1. Subtropical Cells

The wind-driven subduction (Stommel, 1979; Nurser and Marshall, 1991; Marshall et al., 1993) is another mechanism by which the mixed-layer watermass properties impacts upon subsurface salinity. In the subtropical gyres of the South Indian, North and South Pacific, and North and South Atlantic, where the Ekman pumping is generally downward, surface water is subducted into the pycnocline, advected in the North or South Equatorial Current (NEC or SEC) of each ocean, and typically upwelled to the surface in the equatorial region, forming what is often called the "Subtropical Cell" (McCreary and Lu, 1994; Gu and Philander, 1997; Johnson and McPhaden, 1999; Zhang et al., 2003; Schott et al., 2004).

Pacific. In the North and South Pacific, the subducted water flows to the western boundary, while part of the subducted water reaches the equator in the South Pacific before it arrives at the western boundary (Lu and McCreary, 1995, and references therein). At the western boundary, the flow bifurcates equatorward and poleward; both branches form a western boundary current, the equatorward branch joining the Equatorial Undercurrent (EUC) and the poleward branch joining to the Subtropical Gyre (Lu and McCreary, 1995 and references therein; see also the review paper by Schott et al., 2004). The equatorial upwelling of the upper part of the EUC is a major sink of the subducted water (McCreary and Lu, 1994; Schott et al., 2004). Part of the equatorward western boundary current in North Pacific (the Mindanao Current) enters the Indian Ocean via the "Indonesian Throughflow" (e.g., Gordon, 1986; McCreary et al., 2007; Sprintall et al., 2014).

Atlantic. In the Atlantic, the subducted water flows in the NEC or SEC; in the Southern Hemisphere, much as in the Pacific, the SEC bifurcates poleward and equatorward at the western boundary and its equatorward branch (the North Brazilian Coastal Current) feeds into the Atlantic EUC (Metcalf and Stalcup, 1967; Schott et al., 1998, 2004). In the North Atlantic, most of the subducted water returns poleward along the western boundary because of the presence of the Atlantic deep meridional overturning circulation (known as the "Atlantic MOC" or "AMOC"; Schott et al., 2004).

Indian. Subtropical subduction is non-existent or weak in the North Indian Ocean whereas it occurs in the South Indian much in the same way as in the Pacific (Schott et al., 2004). Permanent equatorial upwelling or EUC does not exist in the Indian Ocean, however, and the subducted water crosses the equator in the western boundary current and upwells in the Northern Hemisphere mainly at the coast of Somalia and in an interior thermocline ridge in the Northern Hemisphere (Schott et al., 2004, 2009).

1.2.2. Subtropical water masses

Various subtropical water masses have been found to be advected in the Subtropical Gyres of the North and South Pacific, North and South Atlantic, and South Indian Oceans. A subtropical "Mode Water" is a thick (low-PV) water mass found in the pycnocline of the subtropics; it is formed at a deep mixed layer, subducted into the pycnoline, and advected by the flow associated with the Subtropical Gyre. There are numerous papers studying Mode Waters; see Talley (1999) or Hanawa and Talley (2001) for an overview and references therein for details. The variability of the subtropical Mode Water has also been extensively studied (see below).

More recently, another type of water mass, generally called "Subtropical Underwater" or "Tropical Water", has attracted some attention. It is lighter and hence is formed more equatorward than subtropical Mode Waters; it does not form a particularly thick (low-PV) layer, is associated with a salinity maximum, and is also subducted to the upper pycnocline and advected in the Subtropical Cell (O'Connor et al., 2005). The North Pacific Tropical Water (NPTW; e.g., Qu et al., 1999; Katsura et al., 2013) and South Pacific Tropical Water (e.g., Tsuchiya and Talley, 1996; O'Connor et al., 2002; Qu and Gao, 2017) both exist on the ~24.0–25.0 σ_θ isopycnal surfaces. The NPTW is found to enter the Indonesian Seas (Fine et al., 1994) and then the Indian Ocean (Ffield and Gordon, 1992) along the Indonesian-Throughflow pathway described above. Ffield and Gordon (1992) point out the watermass characteristics are diluted by mixing during the water's passage through the Indonesian Seas. In the tropical and subtropical Atlantic, where surface density is generally higher than in the Pacific, the corresponding high-salinity waters, the North and South Atlantic Underwaters, are identified on the 25.0–26.0 σ_θ isopycnal surfaces (e.g., Zhang et al., 2003; Qu et al., 2016). In the South Indian Ocean, the SSS maximum exists further poleward than in the other oceans and the Underwater is formed on ~25.5-σ_θ isopycnals (O'Connor et al., 2005).

1.2.3. Variability carried by the Subtropical Cells

Two mechanisms are possible to generate variability in subducted salinity. In one, interannual SSS variability directly translates to the local subsurface salinity variability via subduction. In the other, interannual variability in heat flux changes the location of the outcrop of an isopycnal surface, altering the SSS that the isopycnal surface is exposed to and leading to salinity variability on the isopycnal (Nonaka and Sasaki, 2007). (There have been extensive discussion on the generation of salinity anomalies in the pycnocline; see, for example, Bindoff and McDougall (1994), Johnson (2006), Yeager and Large (2007), Laurian et al. (2009), Kolodziejczyk and Gaillard (2013), and Kolodziejczyk et al. (2015). There are also studies on the variability of SSS maxima, which is the source water of the Tropical Water or Underwater; see, for example, O'Connor et al. (2002) and Qu et al. (2011).)

Once salinity signal is brought to subsurface, it is advected in the pycnocline, leading to the interannual variability of subsurface salinity (Nonaka and Sasaki, 2007; Sasaki et al., 2010; Katsura et al., 2013) and potentially impacting on remote (in time and space) ocean state (Gu and Philander, 1997; Schneider et al., 1999a; 1999b; Lazar et al., 2001; Schneider, 2004). Isopycnal and diapycnal diffusion spreads and weakens this signal (Sato and Suga, 2009; Sasaki et al., 2010; Kolodziejczyk and Gaillard, 2012). The next subsection reviews past