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Atmospheric gas-phase composition over the Indian Ocean

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S1. Atmospheric intraseasonal and interannual variability

Intraseasonal variability can impact atmospheric transport patterns over the Indian Ocean with the dominant mode being the eastward propagating Madden-Julian Oscillation (MJO). Equatorially trapped, baroclinic oscillations in the tropical wind field propagate slowly eastward across the Indian Ocean, Maritime Continent, and West Pacific with an intraseasonal cycle of 30–60 days (Madden and Julian, 1972). A typical MJO event exhibits large-scale convection anomalies where enhanced convection and rainfall develop over the western Indian Ocean with suppressed convection further east over the western Pacific (Zhang, 2005). The eastward propagation of the convection and circulation anomalies depends on the season and is strongest during the winter monsoon. The summer monsoon shows a north-eastward propagation of the anomalies into Southeast Asia in addition to the eastward propagation along the equator (Waliser, 2006). Among the many impacts of the MJO, strong interactions with ocean surface fluxes of mass, heat, and momentum have been observed (e.g., Matthews et al., 2010).

Similarly, modes of tropical interannual variability, such as the irregular oscillation of sea surface temperatures known as the Indian Ocean Dipole (IOD), play a role for Indian Ocean meteorology. The positive phase of the IOD is characterised by positive sea surface temperature anomalies in the western part of the Indian Ocean accompanied by negative anomalies in eastern part (Saji et al., 1999). The initial cooling off the coast of Sumatra–Java leads to a positive feedback mechanism via suppressed local convection, anomalous easterly winds, a shoaling thermocline, and stronger upwelling, which in turn reinforce the initial cooling with a peak from September to November (Cai et al., 2014). Extreme positive IOD events can also impact the equatorial ocean by inducing a north-westward extension of the south-easterly trades and drying along the equatorial Indian Ocean (Webster et al., 1999).

The dominant mode of interannual climate variability of the Pacific, the El Niño–Southern Oscillation (ENSO), can also impact Indian Ocean sea surface temperatures via anomalous wind stress forcing (Latif and Barnett, 1995). In addition, ENSO modulates the depth of the Indian Ocean thermocline and contributes to changes in salinity due to shifts in rainfall and evaporation. The potential impact of ENSO on the IOD is currently under discussion (Stuecker et al., 2017 and references therein).

S2. Regional Oceanic Transport

Below we will outline the major features of the equatorial and southern Indian Ocean (Fig. S1) and describe the influence of the seasonal monsoon on the physical processes in the northern Indian Ocean (Fig. S1).

Southern Indian Ocean

The South Equatorial Current (SEC) in the Indian Ocean carries water masses entering through the Indonesian passages, with a relative salinity minimum in the Indian Ocean environment, via broad zonal inflow westward. Driven by the southeast trades, the SEC supplies the western boundary currents east of Madagascar. Part of the throughflow water in the SEC forms the northern East Madagascar Current (EMC), which partly passes in southward moving eddies through the Mozambique Channel and merges into the Agulhas (Ridderinkhof and de Ruijter, 2003; Schouten et al., 2003).

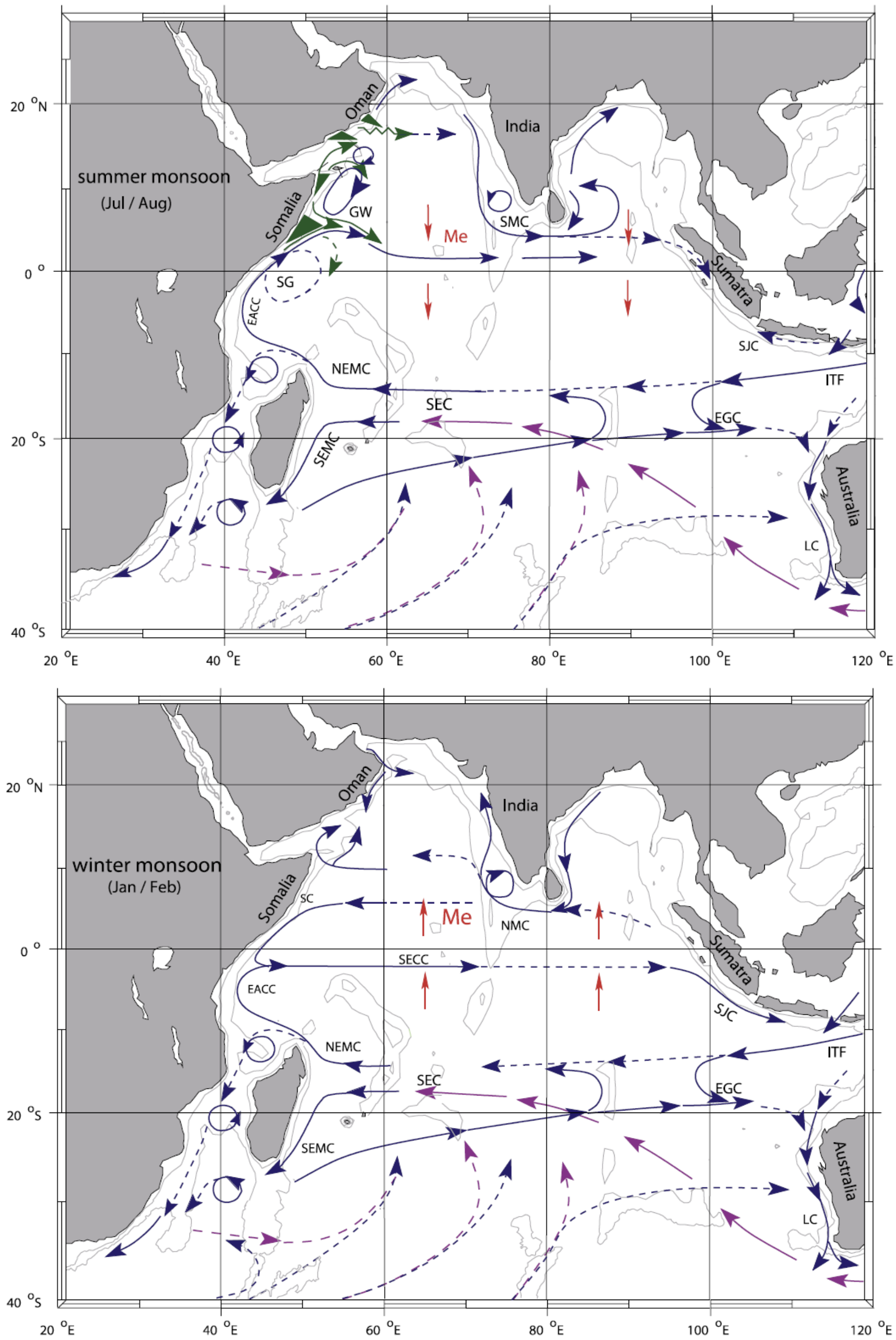

Figure S1. Schematic representation of identified oceanic currents during the summer monsoon (a) and winter monsoon (b). Current branches indicated are the South Equatorial Current (SEC), South Equatorial Countercurrent (SECC), Northeast and Southeast Madagascar Current (NEMC and SEMC), East African Coastal Current (EACC), Somali Current (SC), Southern Gyre (SG) and Great Whirl (GW) and associated upwelling wedges (green shades), Southwest and Northeast Monsoon Currents (SMC and NMC), South Java Current (SJC), East Gyral Current (EGC), and Leeuwin Current (LC). The subsurface return flow of the supergyre is shown in magenta. Depth contours shown are for 1000 m and 3000 m (grey). Updated representations are from SMC01; red vectors (Me) show directions of meridional Ekman transports. ITF indicates Indonesian Throughflow (from Schott et al., 2009, copyright 2009 by the American Geophysical Union, reproduced with permission).

Data from satellite altimetry suggest that the eastward South Indian Countercurrent (SICC) is already present in the Mozambique Basin, southwest of Madagascar (Siedler et al., 2006). The eastward frontal SICC coincides with the thermohaline front that separates the saline subtropical surface water from the fresher tropical surface water in the EMC in summer (Palastanga et al., 2007). The variability of SST and salinity is high in the warm waters south to south-east of Madagascar, likely due to eddy activity and upwelling. There is year-round coastal upwelling along the southern stretch of the oligotrophic EMC and in the shallower region just to the south of Madagascar, which leads to enhanced phytoplankton growth (Quartly et al., 2006). All productivity further from the island in bands of relatively high variability along 25°S and along the EMC are due to a combination of local upwelling caused by eddies and, more importantly, the advection of upwelled coastal waters around eddy features. The anticyclones moving through the region wrap both the warm EMC waters and the nutrient-rich upwelled waters into well-defined arcs. Occasionally strands of chlorophyll-rich water can stretch 500 km or more eastward, which are caused by the combined effects of both cyclonic and anticyclonic eddies (Quartly et al., 2006). The southward flowing EMC, as part of the bifurcated SEC, and the SEC form the western and northern boundary currents of the South Indian subtropical gyre, where saline surface water is formed, as there is more evaporation than precipitation in this region (Schott et al., 2009). The south-eastern Indian Ocean shows the strongest interannual to decadal variability of upper-ocean salinity in the Indian Ocean. Seasonality of the mixed layer salinity in the south-eastern tropical Indian Ocean is influenced by the annual cycles of the Indonesian Throughflow and the Leeuwin Current transports, freshwater forcing, and eddy fluxes (Zhang et al., 2016).

Open ocean upwelling associated with the Seychelles dome, a thermocline ridge in the southern tropical gyre can occur between 5 and 10°S, along the northern edge of the southeast trades, where Ekman divergence occasionally appears to be strong enough to upwell subsurface waters into the mixed layer (Schott et al., 2009). In this region, the South Equatorial Countercurrent (SECC) flows eastward year-round, fed by the East African Coastal Current (EACC) and forming the northern flank of the southern Indian Ocean tropical gyre. Low sea surface height is the signature of the Indian Ocean's tropical gyre, bounded in the north by the SECC, to the south by the SEC, and at the western boundary by the EACC.

Northern Indian Ocean

During the summer monsoon, the northward flowing Somali Current is supplied by the SEC and EACC. Once the Somali Current crosses the equator, a part of it turns offshore around 4°N and another part returns across the equator as a part of the southern gyre. A northern gyre occurs north of the Equator and occasionally a third gyre can be observed in many summer monsoons (Schott et al., 2009). These gyres influence the stability of the atmospheric planetary boundary layer, impacting surface wind stress and heat fluxes (Vecchi et al., 2004). Furthermore, the Southwest Monsoon Current flows towards the east, south of Sri Lanka, then turns to flow toward the north, bringing saltier Arabian Sea water into the Bay of Bengal (Jensen, 2003). In contrast, the Somali Current flows southward during the winter monsoon to meet the northward flowing EACC. They supply water for the eastward flowing SECC. The Northeast Monsoon Current flows toward the west, bringing fresher Bay of Bengal water into the Arabian Sea (Schott et al., 2009). In addition, model studies have suggested that Bay of Bengal water flows across the equator in the eastern basin in the winter monsoon (Han and McCreary, 2001; Jensen, 2003).

Unique to the Indian Ocean are strong eastward ocean surface jets during the inter-monsoon period, called Wyrtki Jets. They are produced by the semi-annual westerly equatorial winds and are important because they carry warm upper layer waters toward the east, which increases sea level and mixed layer depth in the east and decreases them in the west. These semi-annual westerlies are the reason for another unique Indian Ocean feature, namely the eastward Equatorial Undercurrent that is only present for a part of the year (i.e. February – June) when the winds have an easterly component (Schott et al., 2009; Reppin et al., 1999).

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