Seasonal and interannual Variability of the Subtropical South Indian Ocean Sea Surface Salinity Maximum

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Abstract

The sea surface salinity (SSS) maximum of the South Indian Ocean (the SISSS-max) is a high-salinity feature centered at 30°S, 90°E, near the center of the South Indian subtropical gyre. It is located poleward of a region of strong evaporation and weak precipitation. Using several different satellite and in situ datasets, we track changes in this feature since the early 2000's. The centroid of the SISSS-max moves seasonally north and south, furthest north in late winter and farthest south in late summer. Interannually, the SISSS-max has moved on a northeast-southwest path about 1500 km in length. The size and maximum SSS of the feature vary in tandem with this motion. It gets larger (smaller) and saltier (fresher) as it moves to the northeast (southwest) closer to (further from) the area of strongest surface freshwater flux. The area of the SISSS-max almost doubles from its smallest to largest extent. It was maximum in area in 2006, decreased steadily until it reached a minimum in 2013, and then increased again. The seasonal variability of the SISSS-max is controlled by the changes that occur on its poleward, or southern, side, whereas intereannual variability is controlled by changes on its equatorward side. The variations in the SISSS-max are a complex dance between changes in evaporation, precipitation, wind forcing, gyre-scale ocean circulation and downward Ekman pumping. Its motion correlated with SSS changes throughout the South Indian Ocean and is a sensitive indicator of changes in the basin's subtropical circulation.

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17	Key Points:
18 19	• We have studied the seasonal and interannual variability in the size and position of the South Indian Ocean sea surface salinity maximum
20	• The feature moves on a northeast-southwest track, with correlated changes in size
21 22	• Variability seems to be associated with changes in gyre-scale flows and wind forcing, not surface freshwater input/output

23 Abstract

- 24 The sea surface salinity (SSS) maximum of the South Indian Ocean (the SISSS-max) is a high-
- salinity feature centered at 30°S, 90°E, near the center of the South Indian subtropical gyre. It is
- 26 located poleward of a region of strong evaporation and weak precipitation. Using several
- 27 different satellite and in situ datasets, we track changes in this feature since the early 2000's. The
- 28 centroid of the SISSS-max moves seasonally north and south, furthest north in late winter and
- ²⁹ farthest south in late summer. Interannually, the SISSS-max has moved on a northeast-southwest
- path about 1500 km in length. The size and maximum SSS of the feature vary in tandem with
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- in the SISSS-max are a complex dance between changes in evaporation, precipitation, wind
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- 39 SSS changes throughout the South Indian Ocean and is a sensitive indicator of changes in the
- 40 basin's subtropical circulation.

41 Plain Language Summary

42 The ocean surface is saltiest in the mid-latitude subtropics where evaporation is strong and

- 43 precipitation is weak. Each ocean basin has such a region, centered 20-30° from the equator.
- 44 These regions are sensitive indicators of a balance between the effects of the wind, evaporation,
- 45 precipitation, and ocean currents. In this study, we focus on this salty region of the South Indian
- 46 Ocean. It is centered around 30°S, 90°E, west of the coast of Australia. We have found variations
- in the size, saltiness and position of the feature. It shifts over a northeast-southwest path on a
- 48 year-to-year basis and gets saltier and fresher at the same time. Our conclusion, is that this is
- 49 largely a result of changes in the wind field and the shape and strength of the underlying ocean
- 50 subtropical gyre. The motion we see is synchronized with similar motion of the analogous
- feature in the South Pacific, bringing up the likelihood of more global processes controlling both features.

53 **1 Introduction**

In five of the world's major ocean basins there is an area of the subtropical ocean 54 characterized by a horizontal maximum of sea surface salinity (SSS), situated typically around 55 25° latitude (Gordon et al., 2015). The classical view of these features (Worthington, 1976; 56 Gordon and Giulivi, 2014; Bingham et al., 2014; Katsura et al., 2013; Zhang and Ou, 2014; 57 Bingham et al., 2019) has them being produced as a result of poleward Ekman transport 58 59 underneath areas where evaporation greatly exceeds precipitation. At the latitude of the SSS maximum (the "SSS-max"), there is Ekman convergence and subduction as very salty water is 60 incorporated into the interior circulation of the equatorward part of the subtropical gyre (Schmitt 61 and Blair, 2015). These areas play a prominent role in the shallow overturning circulation 62 (McCreary and Lu, 1994; Gu and Philander, 1997; Nonaka and Sasaki, 2007; Kolodziejczyk and 63 Gaillard, 2012) which carries that salty water towards the equator, where it upwells and returns 64 at the surface. SSS-max areas are closely associated with a strong excess of evaporation over 65 66 precipitation (E-P), generally the strongest values in the global ocean (Schanze et al., 2010).

Thus, variability in the SSS maxima may be an indicator of changes in the global water cycle, or the magnitude of transfer of water from ocean to atmosphere. It may also indicate variability in internal ocean processes that are less well understood.

These SSS-max areas have been studied extensively in the northern hemisphere, especially in the North Atlantic (Lindstrom et al., 2015 and references therein), but have been less well characterized in the southern hemsiphere. The advent of satellite measurement of SSS (Lagerloef et al., 2008; Berger et al., 2002; Vinogradova et al., 2019), we can begin to understand how these areas move and change. There are suggestions that SSS in these areas may be increasing globally (Durack and Wijffels, 2010; Terray et al., 2012; Yu et al., 2020; Hosoda et al., 2009; Boyer et al., 2005) as the hydrologic cycle accelerates on a warming planet.

77 In the effort to understand the dynamics and variability of these features, we focus here on the SSS-max in the South Indian Ocean (the "SISSS-max") and its location within the greater 78 South Indian Ocean (SIO) and atmospheric circulation. The SISSS-max is a much more 79 80 elongated feature than the other ocean basins. The center is the farthest poleward of all the ocean basins (Gordon et al., 2015) at approximately (30°S, 90°E). Gordon et al. surmised that this is 81 due to the Australia-Asian monsoon that pushes the intertropical convergence zone into the 82 southern hemisphere, and to the injection of fresh water into the eastern Indian Ocean from the 83 Bay of Bengal and through the Maritime Continent. The SSS of the feature does not vary much 84 over the breadth of the SIO (Figure 1). 85

The main previous study of the SISSS-max is that of Wang et al. (2020 – henceforth 86 87 "W20"). That study divided the SISSS-max into three separate features, one in the east just off of Australia, one in the center of the basin and a third in the western part of the basin near Africa. In 88 the average picture of Figure 1, we do not detect an isolated SSS-max close to Australia and do 89 not look as far west as the coast of Africa, but we focus on what W20 call the central maximum. 90 91 It stretches from about 70°E to 110 °E and has SSS which reaches about 35.9 on average. The central maximum region identified by W20 starts at 90°E and stretches westward to 60°E, 92 encompassing about half of the region identified in Figure 1. Our SISSS-max is a sort of 93 combination of the eastern and central features of W20 as it encompasses the area shown in 94

95 Figure 1.

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scale is at right. The thin black contour line marks SSS of 35.772 (a value used by Gordon et al.,

2015). The wiggly black line going from west to east is the latitude of maximum SSS at eachlongitude.

The SISSS-max is embedded in the SIO surface circulation, which a number of studies 101 have described. As a typical example, Reid (2003) plotted the mean geostrophic flow. At 30°S, 102 where the SISSS-max is located, the geostrophic part of the flow is very weak. The paper plots a 103 104 meandering "S-shaped" flow more or less to the north through the SISSS-max. However, Reid notes that the surface circulation of the SIO is highly variable and that the type of averaging done 105 was not ideal. Many studies of the SIO focus primarily on the tropical circulation, and have little 106 to say about the flow in and around the SSS-max (e.g. Molinari et al., 1990; Han & McCreary, 107 2001; Menezes et al., 2013; Momin et al., 2015). Other studies of the subtropical SIO at the 108 latitude of the SISSS-max come to much the same conclusion as Reid (2003), indicating weak 109 flows at the surface, vaguely in the northward direction (W20; Stramma & Lutjeharms, 1997; 110 Siedler et al., 2006; Schott et al., 2009; Palastanga et al., 2007; Menezes et al., 2014; Schott et 111 al., 2002; Divakaran & Brassington, 2011). Maes et al. (2018), using an eddy-resolving model, 112 identify an area of surface convergence in the SIO cenered at (30°S, 94°E). They also describe 113 how the water from the region of the SISSS-max spreads from the South Indian into the South 114 Pacific, perhaps leading to the formation of the secondary SSS-max in the western part of that 115 basin (Gordon et al., 2015). 116

Below the surface, however, flows are better defined and more like what one might 117 expect. At 200 db, Reid's (2003) mean flow turns by 90° relative to the surface and moves 118 toward the northwest in a manner similar to what we might expect of a south equatorial current 119 as the return limb of a subtropical gyre. This is similar to what we find in other ocean basins (e.g. 120 Dohan et al., 2015; Bingham et al., 2019), and agrees with the sense of the wind-driven Sverdrup 121 transport (Schott et al., 2002; Menezes et al., 2014). This northwestward-flowing interior 122 circulation, however, does not seem to be associated with northwestward transport of salt. There 123 is little sign of a distinct equatorward-westward spreading subsurface salt tongue (Han & 124 125 McCreary, 2001) as is found in the North Atlantic (Schmitt & Blair, 2015), North Pacific (Katsura et al., 2013) or South Pacific (Kessler, 1999). Instead, the interior salinity distribution 126 of the SIO is dominated by the low-latitude input of fresh water from the Pacific, via the straits 127 and passages of Indonesia (Han & McCreary, 2001). 128

In contrast to the lack of well-defined surface circulation within the SISSS-max, areas to 129 the north and south have distinct flow features. To the south, the Antarctic Circumpolar Current 130 flows strongly to the east and also slants southward. This is visible in Figure 1 as a strong SSS 131 front at 40-45°S (e.g. W20; Stramma & Lutjeharms, 1997). To the north, a current known as the 132 133 South Indian Countercurrent (SICC) flows to the east in a highly variable banded pattern, with the southernmost band at around 25°S (Menezes et al., 2014; Menezes et al., 2016; Siedler et al., 134 2006; Palastanga et al., 2007; W20). In a contrasting view, Peng et al. (2015), using surface 135 drifter data, do not show much of a SICC, except possibly in December and January. The area in 136 the vicinity of the SISSS-max has relatively weak surface currents and mean and eddy kinetic 137 energy. It is one of strong convergence as indicated by the way that drifters congregate at the 138 139 very center of the SISSS-max (see their Figure 3).

The SISSS-max is the location of a minimum in mean wind stress (W20 – their Figure 2c). It is tucked between southeasterly trade winds, which reach down to around 25°S, and westerlies which come as far north as 35°S. It has positive wind stress curl throughout, indicating a prevalence of downward Ekman pumping (Qu et al., 2019). The wind stress pattern is relatively steady throughout the seasons in a climatological sense (Schott et al., 2002). As a

- result of this minimum of wind stress, the surface circulation appears to converge directly at the
- 146 latitude of the SISSS-max (Schott et al., 2002; Peng et al., 2015). This is in contrast to the all
- other ocean basins with SSS-maxima, where Ekman transport is poleward through the SSS-max
 (Gordon et al., 2015). The SIO has a larger eddy kinetic energy than the other southern
- 148 (Gordon et al., 2015). The SIO has a larger eddy kinetic energy than the other southern
- hemisphere ocean basins, and as a result has a large eddy flux of salt, and the SISSS-max is also a maximum of convergence of salt flux (Qu et al., 2019). Thus, horizontal eddy flux of salt plays
- a larger role in the SIO than in other ocean basins.

W20 give a basic description of the SISSS-max. It is situated well to the south of the 152 maximum of surface freshwater forcing which is around 10-20°S. SSS within their central 153 maximum has a seasonal cycle, with highest value in April, i.e. fall. They computed budgets for 154 the eastern, central and western SSS-maxima, both seasonally and interannually (2011-2015). 155 For the central maximum, defined as a box with limits (35-28°S, 60-100°E), the budget was not 156 closed in either case. The SSS tendency fluctuated strongly, but was not matched by a surface 157 forcing, advection or vertical entrainment term. The tendency computed from satellite (Aquarius) 158 data is very different from that computed from Argo data. The magnitude of tendency variability 159 - it fluctuates on a scale of approximately + 0.04 month⁻¹ – is similar to other ocean basins (e.g. 160 Dong et al., 2015; Katsura et al., 2013). 161

In this paper, we expand on the work of W20, to better define the seasonal cycle, and look at longer-term trends in the location and scope of the central SISSS-max. We relate the SISSS-max to the surface forcing and underlying subtropical gyre, in light of the results summarized above.

166 **2 Data and Methods**

Gordon et al. (2015) delineated the SISSS-max using the 35.772 isohaline at the surface, a convention we adopt here (Figure 1). This threshold isohaline value is derived from the MIMOC (Monthly Isopycnal/Mixed layer Ocean Climatology; Schmidtko et al. (2013)). We compute the area with this value of SSS or higher and the location of the centroid of this area in order to quantify the variability. We also compute and display values of surface flux in the region as well as the advection and entrainment terms in the salinity balance equation.

173 2.1 Data

See Acknowledgements section for details on version number and data access for alldatasets used.

There are several SSS datasets displayed, Two SMOS, two SMAP, one Aquarius, one L4 composite and two in situ gridded (Table 1). All SSS datasets where retrieved from the source

either as monthly averages, or averaged monthly after retrieval. The in situ data used are the EN4

- dataet of Good et al. (2013), and the Roemmich and Gilson (2009) dataset (the "RG" data).
- 180

Dataset name	Spatial grid size	Dates	Color in Figures 2-5
SMOS LOCEAN	0.25°	2010-December 2020	Yellow and black
SMOS BEC	0.25°	2010- December 2020	Red

SMAP JPL	0.25°	2015- December 2020	Green
SMAP RSS	0.25°	2015- December 2020	Black dashed
Aquarius	1°	2011-2015	Green
CCI - composite	0.25°	2010-2018	Black solid
EN4 – in situ	1°	2004*- December 2020	Blue
RG – in situ	1°	2004*-December 2020	Cyan

*EN4 and RG data go further back, but we chose to start at 2004.

182 Table 1. Names, spatial grid size and dates for SSS datasets used.

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184 A few other datasets are used. The EN4 data, mentioned above, has a subsurface 185 component, from which we compute dynamic height relative to 2000 m depth.

We used the OSCAR surface current dataset (Bonjean & Lagerloef, 2002) to determinesurface flows.

188 Wind data are from the NCEP/NCAR reanalysis (Kalnay et al., 1996).

189 Freshwater forcing is defined as

190
$$FWF = S_0 \frac{E - P}{h}$$

191 where S_0 is a constant, set to 35, E is evaporation, P precipitation and h the mixed-layer depth.

192 Evaporation data are monthly averages sourced from the OAflux dataset of Yu & Weller (2007).

193 Precipitation are monthly values from IMERG (Integrated Multi-satellitE Retrievals for GPM;

194 Skofronick-Jackson et al., 2018). Evaporation and precipitation data are interpolated onto a

195 1°X1° grid. We used a monthly climatological 1° mixed-layer depth product from MIMOC

(Monthly, Isopycnal/Mixed-layer Ocean Climatology; Schmidtko et al., 2013). This product
 computes the mixed-layer depth following the method of Holte & Talley (2009). We tried some

other non-climatological mixed-layer products and found them to be not useful for our purposes.

Vertical velocity values are computed from upwelling and the vertical motion of the
bottom of the mixed layer. Upwelling data were downloaded from NOAA Coastwatch.
Entrainment was computed by combining vertical velocity with the vertical salinity gradient

- following the method of Bingham et al. (2010).
- 203 2.2 Methods

The area of the SISSS-max is defined here as the area with SSS higher than the threshold in the central SIO (60-120°E, 20-45°S). The meridional (zonal) centroid is the latitude that half of the area is to the north (east) of in the central SIO. The meridional northern (southern) limit is the latitude that 95% of the area with SSS higher than the threshold is south (north) of. Similar definitions apply for the east/west limits of the feature. This calculation was done monthly.

We note here that there is a close relationship between average SSS (or maximum SSS) within the threshold isohaline and area. That is, when the area within the threshold isohaline is

- 211 large the water within it is also salty as can be seen in Figure 2. This close relationship holds
- better for small values of area and gets more scattered as the area gets larger. What Figure 2
- shows is that the isohaline area in the SIO is mainly a measure of how salty the water within the
- SSS-max is, both on a monthly and a yearly basis. On both monthly and yearly time scales the two are significantly correlated. This conclusion may seem self-evident, but it is worth
- confirming nonetheless.
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Figure 2. Mean SSS computed within the 35.772 isohaline vs. area with SSS>35.772 from EN4. Black symbols are monthly (areas are the same data displayed in Figure 6). Red symbols are

221 yearly averages (areas are the same data displayed in Figure 8).

222

223 **3 Results**

The area of SSS greater than 35.772 (Figure 3) shows a range of values and changes 224 among the different products. For the SMAP JPL product, the area appears to nearly quadruple 225 between 2015 and 2020 from 0.5 to 2.0X10⁶ km². The BEC product shows an increase, but not 226 to the same degree, from about 1.5 to 2.5X10⁶ km². The EN4 and SIO data have a maximum in 227 2017-2018, but generally increase from 2010 to 2020. The LOCEAN product has more variation 228 than any of the others, and tends to have larger values, but with a strong decrease from 2012 to 229 2020. The Aquarius, CCI and RSS SMAP products do not show much change over the time 230 period they are depicted in Figure 1. There is seasonal variability in the different products too, 231 with maximum SSS in summer (January-March) and minimum in winter (July-August) (Gordon 232 et al., 2015). This seasonality is more difficult to detect in the CCI, LOCEAN and BEC products, 233 but quite apparent in the EN4, SIO, Aquarius and the two SMAP products. 234



Date

Figure 3. Area with SSS greater than 35.772 as a function of time with units of 10⁶ km². The different colors represent different satellite and other products, with a color key in Figure 4. Note, the JPL SMAP and Aquarius products are the same color (green) and overlap by a couple of months in early 2015.

The different datasets are much more consistent when it comes to showing the changing 241 position of the feature. In the north-south direction (Figure 4) the datasets have consistent 242 intetrannual and seasonal changes. The SISSS-max moved steadily equatorward between 2010-243 2011 and 2020, with total motion of 0.5-1°. This is apparent in every dataset, but to different 244 degrees. The EN4 dataset starts out with the centroid at 30.5-31°S in 2010-2011, and it moves 245 northward to 29.5°S in 2020, with a large excursion southward in 2015. There is significant 246 247 seasonality as well in this north-south motion. The feature is furthest south in summer and north in winter, as seen consistently in all the datasets. The amplitude of the seasonal north-south 248 motion is $1-1.5^{\circ}$. 249



Figure 4. Latitude position of the centroid of the 35.772 isohaline in the SIO. The different

dataset are keyed to colors as shown at the bottom of the figure. The RSS-SMAP curve is
dashed. Note, the JPL SMAP and Aquarius products are the same color (green) and overlap by a

dashed. Note, the JPL SMAP acouple of months in 2015.

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The longitude position of the centroid (Figure 5) is more variable within products, but 257 again the different products are relatively consistent with each other. Between about 2011 and 258 2020, the position of the centroid moves significantly eastward, from about $87^{\circ}E$ to about $99^{\circ}E$. 259 a distance of over 1000 km. There are large excursions during this time. In 2016, the feature 260 moves far eastward, past 100°E. In 2013, the feature moved far waestward, to 80-85°E. This 261 westward motion is also detected in 2012, 2014 and 2018, but only by the JPL SMAP and 262 Aquarius products. Seasonal variability in the longitude position of the SISSS-max is not 263 apparent in this display. 264



Figure 5. Longitude position of the centroid of the 35.772 isohaline in the SIO. The different dataset are keyed to colors as shown in Figure 3. The RSS-SMAP curve is dashed. Note, the JPL SMAP and Aquarius products are the same color (green) and overlap by a couple of months in 2015.

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The in situ data give an idea of the trends in position and area over a longer time scale 272 (Figure 6), and a number of items can be noticed. The seasonal cycle in area changes in 273 amplitude. From 2004-2008, the range of the seasonal cycle is about $2 \times 10^6 \text{ km}^2$. After that, 274 there appears to be some kind of regime shift, where the range decreases to about $1 \times 10^{6} \text{ km}^{2}$ 275 and the area decreases, until about 2013. After that, the area increases again, and the range does 276 277 as well. The latitude shifts in tandem with the area. It starts out at close to 30°S. It then shifts southward for several years until about 2013, when it reaches a southward excursion of about 278 31.5°S. After that it again moves northward. The latitude has a seasonal cycle with a range of 1-279 1.5°, but it remains about the same amplitude throughout. The longitude position (lower panel) 280 does not have a visible seasonal cycle, but does have interannual variability in sync with the area 281 and latitude. The feature moves farthest west in 2013 to about 85°E. Before and after that it is 282 283 further east as far as 100°E in 2016.



Figure 6. From EN4 data. Top panel: Blue curve/left axis, area with SSS>35.772. Red
curve/right axis, latitude position of the centroid. Lower panel: Blue curve/left axis, area with
SSS>35.772, same as top panel. Red curve/right axis, longitude position of the centroid. Blue

curves are the same in each panel.

Putting the east-west and north-south motion together into an annual average (Figure 7), we see that the SISSS-max shifts substantially along an almost linear southwest-northeast path. The southwestern limit was reached in about 2013 (green contour) and the northeast limit in 2020 (black and yellow contour). 2016 was a bit of an exception: The SISSS-max was farther east, but shifted to the south as well. This is due to one event that occurred in March-April of that year as can be seen in Figure 6. The size is also correlated with these motions. As the feature moves to the northeast it gets larger and smaller when it moves to the southwest.

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The yearly average area (Figure 8) shows large changes in area over time. The area 305 ranges from a high of 2.6 X10⁶ km² in 2006 down to a low of just over 1.4 X10⁶ km² in 2013, a 306 decrease by a factor of almost 1/2 in 7 years. The area abruptly increased again to another 307 maximum in 2017 and another sharp decrease. The overall picture is of a feature with large 308 coherent interannual changes. Putting this change in area together with the motion in Figures 4-7, 309 the SISSS-max gets smaller as it moves to the southwest and larger as it moves northeast. 310

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We can learn more about what causes the observed variability of the SISSS-max by 314 looking at the limits of the feature (Figure 9). As noted before, the SISSS-max moves north and 315 south over the course of the year. It is clear from Figure 9a that most of that change is a result of 316 the motion of the poleward boundary, which has a large seasonal cycle of range about 3°. This 317 seasonal motion occurs every year, though the size of it changes, being larger in some years (e.g. 318 2016) and smaller in others (e.g. 2004). By contrast, the interannual variability of the SISSS-max 319 position is mainly determined by the equatorward boundary. This has no discernable seasonal 320 cycle, but large interannual changes. It moves from close to 25°S in 2005, down to about 29°S in 321 2013. It is hard to detect any seasonal cycle in the east-west motion of the SISSS-max (Figure 322 9b). It has interannual variability as discussed above, but that is not dominated by either the 323 eastern or western side. It does look like the western side of the feature is more highly variable in 324 position then the eastern side. 325 326



Figure 9. From EN4 data. a) Black curves: Latitude of the centroid of the SISSS-max. Solid curve is monthly, dashed curve is the yearly average. This is the same as the red curve in Figure 5 upper panel. Upper (lower) red curve: latitude of the 95th percentile of area. That is, 95% of the area with SSS>35.772 is south (north) of this latitude. b) As in panel a) but for the longitude of

the centroid and with time on the y-axis.

One can see how the SISSS-max fits into the larger scale variability of the SIO on an 332 333 interannual time scale by looking at the correlation between the area (Figure 8) and the SSS over the larger SIO (Figure 10). The pattern is quite striking. North of the SISSS-max, the correlation 334 is positive, with values as high as 0.8. South of the SISSS-max, the pattern is opposite, negative 335 correlations with some very low values. The boundary, with near-zero correlation, runs along the 336 northern edge of the SISSS-max. This explains the northeast-southwest translation shown in 337 Figure 7. As the SISSS-max moves to the northeast, the area gets larger and SSS within the 338 339 feature increases. As it moves to the southwest, the area gets smaller and the SSS decreases. The highest positive correlations are near the west coast of Australia. The SISSS-max moves closer 340 to there as it gets saltier and larger as seen in Figure 7. This picture puts the SISSS-max within a 341 large scale see-saw pattern in the SIO, high SSS in the lower latitudes corresponding with low 342 SSS in higher latitudes, and vice versa. It should be noted that the picture in Figure 10 is based 343 on only 17 years of data, so does not have a high degree of statistical confidence. 344





Figure 10. Unitless correlation between annual average area (Figure 8) and annual-average SSS
at each location in the SIO. Data are from the EN4 dataset over the 2004-2020 time period. Thin
black line is the mean 35.772 isohaline as in Figure 1.

As discussed above, the SISSS-max is embedded in the SIO circulation, and is impacted 350 by winds and freshwater forcing the surface. In the (2010-2020) mean, the SISSS-max sits within 351 352 a region that is evaporation-dominated (red area in Figure 11). The boundary between evaporation and precipitation-dominated regions crosses the study area diagonally from (27°S, 353 60°E) to (42°S, 120°E). The SISSS-max is to the northeast of this delineation, similar to the 354 South Pacific (Bingham et al., 2019). The feature is located to the southwest of where the 355 freshwater forcing is most strongly positive, which in Figure 11 is 20-25°S (see also Gordon et 356 al., 2015, Figure 1b). This placement is similar to that of the SSS-max in the South Pacific 357 (Bingham et al., 2019). Again as discussed in the introduction, the underlying geostrophic 358 circulation is very weak, especially poleward of the SISSS-max. It is more or less northward 359 from the Antarctic Circumpolar Current (ACC) at 40-45°S to the SISSS-max. At a latitude of 360 about 30°S, in the middle of the SISSS-max, the flow strengthens and takes a right-hand turn 361 towards the Australian continent. 362





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Figure 11. Averages over 2004-2019. Colors: freshwater forcing (see equation 1). Color scale is at right, with units of pss/s. Positive (red) values indicate freshwater forcing out of the ocean, i.e. net evaporation. Green contour lines: dynamic height at the surface relative to 2000 m from EN4 data, with units of dynamic-meters and a contour interval of 0.1. Arrows: mean winds from NCEP. A 5 m s⁻¹ scale arrow is displayed at right on top of the Australian continent. Light black line is the SSS=35.772 contour as in Figure 1. Small box (80-110°E, 26-28°S) is where the average in Figure 13 is taken from.

The wind field that impacts the SISSS-max varies with time. The most relevant variation occurs near the coast of Australia at (30°S, 110°E), with minimum seasonal speed in winter (Figure 12). The seasonal aspect of this variability has the SIO subtropical high depicted in Figure 11 getting stronger and weaker at this location, or, alternatively, moving equatorward and poleward. The high is furthest equatorward in winter, and thus winds are weak. This north-south

- 377 shifting of the winds may relate to the seasonal changes in the SISSS-max at its poleward edge.
- Perhaps when the winds are strongest there in summer, evaporation increases and so does the
- 379 SSS. The interannual variability at this location indicates weak winds in the 2011-2014 time
- 380 period, coincident with the minimum in area shown in Figure 8.



Figure 12. Northward wind at (30°S, 110°E). Variable black line is from monthly averages.
Smoother black line with symbols is a yearly average.

Given that the SISSS-max is closely linked to the surface forcing, it would be logical to conclude that variability of the forcing in the area equatorward of the feature is related to the area or motion. However, this does not seem to be the case. E-P averaged within the box in Figure 11 is quite variable on short time scales, but relatively steady interannually (Figure 13). There is a small dip in 2018 due to three anomalous months at the end of the year. Given this result, it seems variability of E-P just equatorward of the SISSS-max does not directly control SSS variability or the size or position of the feature.



Figure 13. E-P (m/yr) averaged over the box shown in Figure 11. Black dots are monthly values.
Black curve is yearly averages.

394 As shown in Figure 11, the gyre-scale geostrophic flow beneath the SISSS-max is northeastward, more or less opposite to the Ekman component. The geostrophic flow across 27°S 395 is indicated by the dynamic height between 80 and 110°E. The sea surface slopes generally 396 397 downward from west to east, consistent with net northward motion. There is an O(20 cm) height difference from west to east (Figure 14). The gradient across the breadth of the SISSS-max 398 varies from year-to-year, but comes to a minimum in the years 2011-2015. These are the same 399 years in which the area of the feature reached a minimum and it translated farthest to the 400 southwest. Thus, the large-scale gyre flow appears to have some control over (or is at least 401 correlated with) the position and size of the SISSS-max. 402



403

Figure 14. Yearly-averaged dynamic height (in dyn-m) from EN4 data along 27°S as a function
 of time.

We have computed the advection term in the salinity balance equation (Figure 15). The mean values are small (not shown), but the variability has an interesting distribution. The advection term is quite variable on the equatorward side of the SISSS-max, but there is much less variability within the feature and on the poleward side. This emphasizes the importance of eddy processes in bringing fresh water to the SISSS-max (Johnson et al., 2016) from the tropics and the salinification that accompanies that transport. On the other hand, eddy advection plays a much smaller role on the poleward side of the SISSS-max.





Figure 15. Standard deviation of the advection terms of the salinity balance equation. Light black line is the SSS=35.772 contour as in Figure 1.

The entrainment term of the salinity balance equation is more easily interpreted than the 416 advection. The term itself is very small in the mean compared to other terms (not shown), but the 417 418 distribution of variability relative to the SISSS-max is interesting (Figure 16). There is a local maximum in the amount of variability of the entrainment term at the poleward edge of the 419 420 SISSS-max. Examination of individual records (not shown) indicates that the poleward-edge variability is mainly seasonal, with upwelling peaking in winter. This is likely the source of the 421 seasonal changes observed at the poleward edge of the SISSS-max (Figure 9b). During the 422 winter upwelling mixes fresh water into the surface and decreases the observed size of the 423 SISSS-max, where as in summer, that process reverses and exchange with the interior goes in the 424 opposite direction, having little impact on the surface salinity balance. Variability of entrainment 425 426 at the equatorward edge of the SISSS-max is much smaller. Additionally, because of the vertical distribution of salinity, vertical entrainment at the equatorward edge of the SSS-max would add 427 salty water to the surface mixed layer, not fresh. Strong seasonal vertical entrainment at the 428 poleward edges of all the major SSS-max features has been noted before (Johnson et al., 2016). 429



Figure 16. Standard deviation of the vertical mixing term (pss/s) in the SIO. Light black line is the SSS=35.772 contour as in Figure 1.

433 **4 Discussion**

The SIO SSS-max has been shown to vary on seasonal and interannual time scales in its 434 position (Figures 4-7), size (Figures 3 and 6-8) and intensity (Figure 2). Its centroid moves in a 435 distinct northeast-southwest track (Figures 6 and 7) for reasons that are still not entirely clear, but 436 may relate to the balance between Ekman transport and the geostrophic flow of the subtropical 437 gyre. The flow of the subtropical gyre tends to push the feature to the northeast, while Ekman 438 transport pushes it to the southwest. The fact that the SISSS-max is situated to the northeast of 439 the minimum of the mean winds (Figure 11) bears this out. The apparent correlation between 440 position and size/intensity makes sense. As the feature moves northeastward, it moves into an 441 area more dominated by evaporation (Figure 11) and thus gets saltier. 442

Advection is small within the SISSS-max relative to surrounding areas (not shown). This makes sense as the SSS gradient becomes small near the meridional peak of SSS - advection is the dot product of the velocity and SSS gradient. So a determining factor in the size, position and intensity of the SISSS-max may be not so much the strength of evaporation at the center of the feature, but the evaporation imposed on the source waters as they flow towards it, and the amount of time that water spends underneath this strong evaporation while in transit (D'Addezio & Bingham, 2014; Bingham et al., 2014).

We have not explicitly addressed the role of eddy advection of salt in the variability of 450 the SISSS-max. Eddy processes may be more of a factor in the SIO than in other oceans due to 451 elevated eddy kinetic energy in the SIO, especially on the equatorward side. Qu et al. (2019) 452 emphasize this point showing a large divergence of the salt flux centered at the SISSS-max. 453 Johnson et al. (2016) also describe the importance of eddy over mean advection. Though the 454 eddy flux may be important in the mean location of the SISSS-max, it is not clear how or if eddy 455 processes may contribute to the variability of the position or size. Are there interannual changes 456 in the strength of eddy advection? 457

The main seasonal variation in the SISSS-max is expansion and contraction on the 458 459 poleward side (Figure 9a). We have discussed the likely role of seasonal variability in vertical entrainment in this. Vertical entrainment shifts from downwelling to upwelling and back again 460 over the course of the year. Vertical processes are driven by the curl of the wind stress and the 461 heaving of the base of the mixed layer. The prevailing winds (Figure 11) indicate that the mean 462 zero in wind stress is found south of the SISSS-max, at about 35°S. Seasonal shifting in the 463 strength and distribution of the wind stress curl may be the cause of the observed seasonality in 464 vertical entrainment (Figure 16) and thus the poleward edge of the SISSS-max. Bingham et al. 465 (2021) have shown that there is a strong seasonal cycle in the small-scale (<100 km) variance of 466 SSS in the vicinity of the SISSS-max, with maximum in the fall season. This is likely due to 467 seasonal variation of rainfall. How this might impact the expansion and contraction of the 468 SISSS-max on its poleward side is still an open question. 469

The close relationship of the SISSS-max to the wind field is emphasized in Figures 11 and 12. Varibility of the wind field can impact the SISSS-max in several different ways, through Ekman transport which advects water towards the feature, through Ekman convergence which determines the structure of the underlying subtropical gyre and also causes SSS-max water to subduct and enter the interior flow, and through changes in evaporation which is closely tied to wind speed. Future research can help sort out which of these is most important in helping to shape the structure of the SISSS-max.

The SISSS-max in the eastern Indian Ocean is also influenced by the input of low salinity 477 water from its equatorward side. The surface layer and thermocline off the northwest coast of 478 Australia has low salinity, mainly due to Indonesian Throughflow (ITF). This results in relatively 479 high sea level that induces a north to south pressure gradient off the west coast of Australia, 480 driving the southward flowing Leeuwin Current (LC) (Gruenberg, 2021). The poleward flowing 481 LC is an unusual subtropical gyre eastern boundary current, which in other oceans flows towards 482 the equator. The north-south pressure gradient is more effective in sending low salinity water 483 484 into the LC when the northward winds relax which truncates the eastern extension of the 35.772 isohaline. 485

486 Bingham et al. (2019) studied the SSS-max in the South Pacific in a similar way as we have done here, and found similar variability in the centroid. There was a minimum in area, but 487 1-2 years before the one we have shown in this paper in the South Indian. The fact that the two 488 SSS-maxima behave in similar ways suggests that their motion is a result of similar forces, or 489 that one influences the other. In the South Pacific Bingham et al. suggested that the variability is 490 linked to the Pacific Decadal Oscillation (PDO), and found significant correlation between the 491 492 PDO index and the annul-average area. There was a minimum in PDO in 2009, and a minimum in SSS-max area in 2011. Thus, the SSS-max area in the South Pacific lags the PDO by ~2 years, 493 and, by extension, the lag between PDO and SISSS-max area is ~3-4 years. Perhaps the 494 495 increased delay in the SIO results from the fact that the SISSS-max is 5° poleward of that of the South Pacific. Another possibility is the role of the ITF in connecting the Pacific and Indian 496 ocean basins that adds a time delay in the Indian Ocean response relative to the Pacific. 497 498 Regardless of the reason, the syncronicity of the motion of the centroid in the South Pacific and South Indian emphasizes the interconnectedness of the two ocean basins (Qu et al., 2019). 499

500 As stated above, the SISSS-max is the result of a delicate balance between a number of 501 competing and complementary processes, northeastward motion due to the underlying 502 subtropical geostrophic circulation, southwestward motion due to Ekman transport, vertical

- 503 entrainment variability at the poleward edge, eddy advection in the region equatorward of the
- 504 SISSS-max and a predominance of evaporation over precipitation which decreases towards the
- southwest. All of these have a role in determing the position, size, intensity and variability of the
- feature. The SISSS-max can change in response to changes in any of these processes. Thus, the
- 507 SISSS-max is a sensitive indicator of the climate of the SIO, and of the southern hemisphere
- subtropics in general. In order to understand the balance of forces affecting the interannual variability of the SISSS-max, one has to study not just the processes within it, but the variability
- of the source waters, the wind systems that drive Ekman transport and downwelling and the eddy
- 511 transport on the equatorward side.
- 512

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- NCEP/NCAR Reanalysis winds (Kalnay et al., 1996):
 <u>https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.derived.html</u>
- SMOS LOCEAN V5: <u>https://data.catds.fr/cecos-</u>
 <u>locean/Ocean_products/L3_DEBIAS_LOCEAN/L3_DEBIAS_LOCEAN_v5/debiasedSS</u>
 <u>S_09days_v5/</u>
- SMOS BEC: <u>http://bec.icm.csic.es/ocean-experimental-dataset-global/</u>
- 522 SMAP JPL: <u>https://doi.org/10.5067/SMP50-3TMCS</u>
- SMAP RSS: https://data.remss.com/smap/SSS/V05.0/FINAL/L3/monthly/
- Aquarius: https://doi.org/10.5067/AQR50-3YMCE
- CCI: <u>https://doi.org/10.5285/9ef0ebf847564c2eabe62cac4899ec41</u>
- EN4: <u>https://www.metoffice.gov.uk/hadobs/en4/download-en4-2-2.html</u>
- RG: http://sio-argo.ucsd.edu/RG_Climatology.html
- OAFlux: <u>https://oaflux.whoi.edu/data-access/</u>
- IMERG: https://gpm.nasa.gov/data/directory
- Ekman upwelling:
- 531 https://coastwatch.pfeg.noaa.gov/erddap/griddap/erdQAstressmday.html
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