Using sea surface salinity to foretell Australian rainfall

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The oceans contain 97% of all fresh water on Earth (Figure 1). As such, the oceans are the largest source of moisture to the atmosphere and hence for the global and regional water cycle. Of the total fluxes of fresh water at Earth's surface, 85% of evaporation is from the ocean and 77% of precipitation falls on the ocean.

The global water cycle is intensifying due to climate change as the atmospheric moisture content increases about 7% for every degree of atmospheric warming. Strikingly, this pattern of the intensified global water cycle is reflected in the changes we have seen in the sea surface salinity. We now know that we can use ocean salinity change as nature's rain gauge.

Recent advancements in measuring ocean salinity (sea surface salinity) through *in situ* instruments and satellite remote sensing have opened new avenues to use salinity

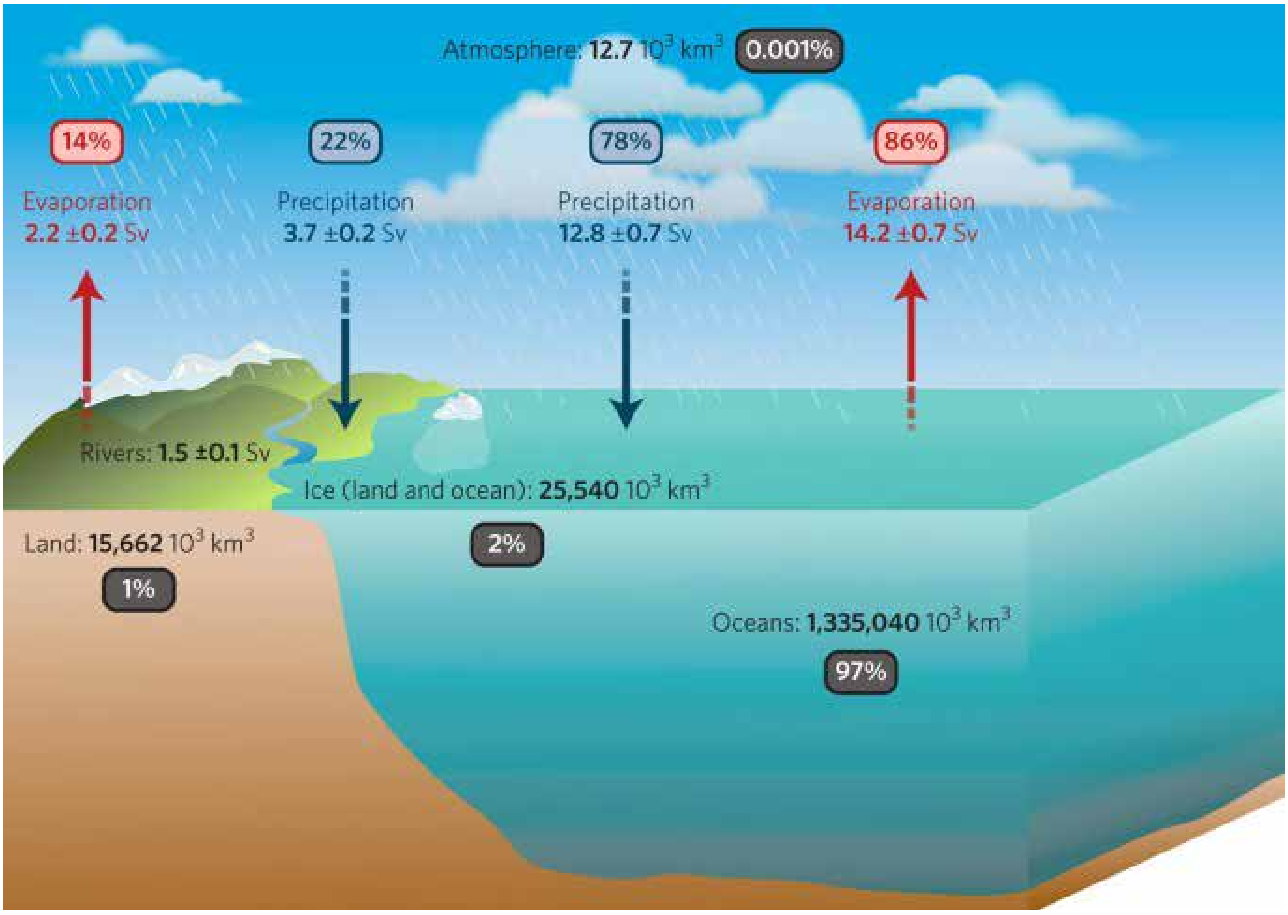

Figure 1. The global water cycle —the oceanic perspective. Reservoirs are represented by grey boxes with units 10^3 km^3. Fluxes are represented by arrows and the red and blue boxes with units of Sv (Sverdrups; $10^6 m^3 s^{-1}$). Source: (Durack et al., 2015).

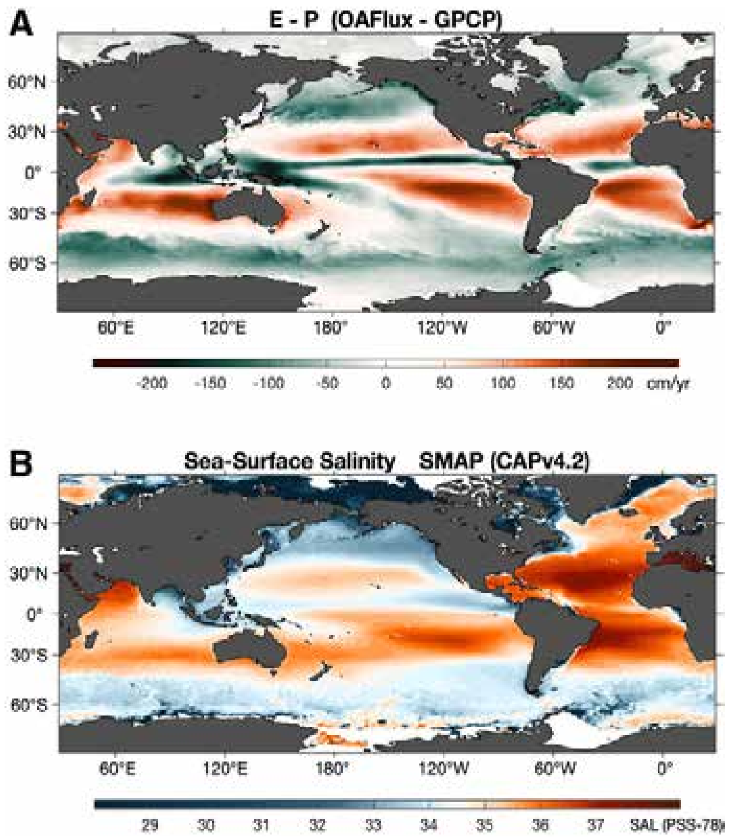

Figure 2. The mean evaporation-minus-precipitation (E–P) flux from OAFlux2 and GPCP. (B) Mean sea surface salinity observed from SMAP. The period of 2016 –2018 was used in constructing both mean fields. Source: (Yu et al., 2020).

as an important climate variable to monitor changes in the global and regional water cycle. Changes in the sea surface salinity are predominantly the net balance between Evaporation (E) and Precipitation (P) i.e., E–P.

In Figure 2, we see the remarkable match between patterns of E minus P (how much fresh water leaves the ocean) and sea surface salinity. The patterns are a 3-year average view that reveals the regions where the ocean persistently loses fresh water and hence is salty and regions where fresh water is returned to the ocean by excess precipitation. The salty regions are located primarily in the high evaporation subtropical latitudes between 25° and 35° in both hemispheres. The fresh regions are around the equator and at high latitudes. These patterns of sea surface salinity and E minus P are being amplified by global warming. Fresh regions are becoming fresher as precipitation intensifies and salty regions are becoming saltier as evaporation intensifies. These trends are illustrated in Figure 3 using long - term averages of measurements in the ocean and atmosphere. In regions that already have high precipitation (low E – P, Figure 3b) and a fresh surface (low salinity, Figure 3d), the trend in total precipitable water vapour is increasing (Figure 3a), as is the trend to an even fresher ocean surface (Figure 3c). The reverse is true for regions that have high evaporation and a salty surface. This scenario has been termed “rich getting richer and poor getting poorer”.

This remarkable, global scale relationship also raises the potential that we could use ocean salinity as a predictor for rainfall over land - since moisture must be taken up by the atmosphere (given up by the ocean) before it can be delivered as precipitation. Using this concept there are a few studies, including ours (Rathore et al. 2020, 2021) which investigate the links between sea surface salinity and rainfall over land.

Our investigation aims to use sea surface salinity as a precursor for Australian summer rainfall during December - February. We show that sea surface salinity can be used as a proxy for Australian rainfall variability on interseasonal to interannual timescale and identify the oceanic sources of moisture. We have shown that a characteristic sea surface salinity signature appears in spring to the north of Australia in the Indian and Pacific oceans. These regions act as a source of atmospheric moisture (signalled by increased salinity) prior to periods of enhanced rainfall over Australia, and a sink of moisture (sea surface freshening) prior to dry periods.

High salinity events in the southeast equatorial Indian and western equatorial Pacific (Figure 4 upper panel) occur during the negative phase of El Niño Southern Oscillation (i.e., La Niña) and negative Indian Ocean Dipole (-IOD). During such events, atmospheric moisture from evaporation in the Indian and Pacific Oceans converges over the ocean to the north of Australia and part of it is transported towards the Australian continent. Due to conducive atmospheric conditions over Australia, the incoming moisture converges and results in rainfall and anomalously wet conditions across Australia.

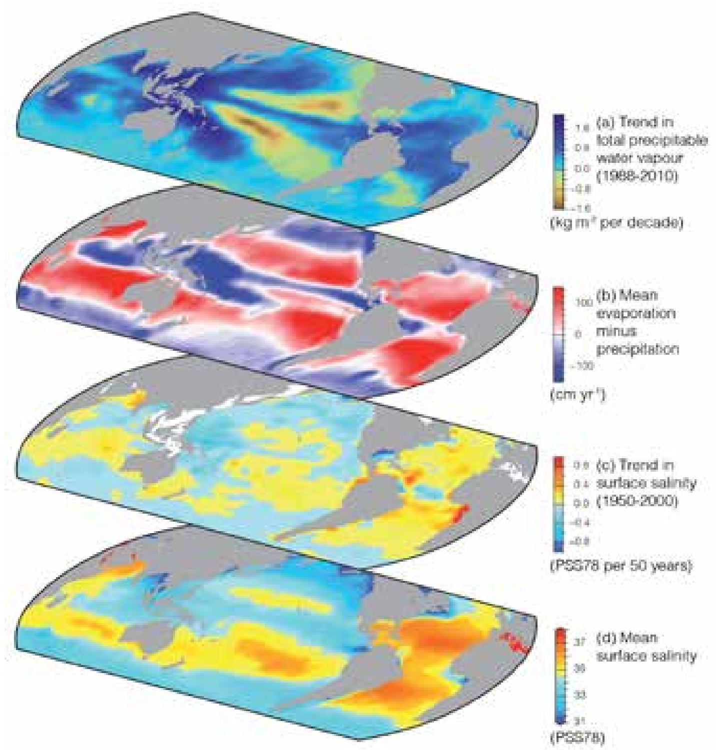

Figure 3. Changes in sea surface salinity are related to the atmospheric patterns of evaporation minus precipitation (E–P) and trends in total precipitable water: (a) Linear trend (1988–2010) in total precipitable water (water vapor integrated from the Earth’s surface up through the entire atmosphere) (kg m^2 per decade) from satellite observations (blues: wetter; yellows: drier). (b) The 1979 –2005 climatological mean net E–P (cm yr^{-1}) from meteorological reanalysis (National Centers for Environmental Prediction/National Center for Atmospheric Research) (reds: net evaporation; blues:net precipitation). (c) Trend (1950 – 2000) in surface salinity (PSS78 per 50 years) (blues freshening; yellows-reds saltier). (d) The climatological -mean surface salinity (PSS78) (blues: <35; yellows–reds: >35). Source: (Rhein et al., 2013).

In contrast, low sea surface salinity events over the Indian and Pacific Oceans (Figure 4 lower panel) occur during El Niño and +IOD events. During these events, moisture from evaporation north of Australia is transported away from the Australian continent, resulting in less rainfall and anomalously dry conditions across Australia.

Surface salinity also has relevance to short periods events like the devastating Brisbane flood event of summer 2010/11. These floods happened during a co-occurring La Niña and IOD event (as in Figure 4; upper panel). A robust signature of anomalously high sea surface salinity appeared in the southeast equatorial Indian and western equatorial Pacific Ocean during July - August 2010. The high sea surface salinity was accompanied by strong atmospheric moisture transport towards Australia. This moisture converged over Australia and resulted in heavy precipitation during November - December 2010 with widespread anomalously wet conditions observed over Australia, and an extreme event for Brisbane.

These physical and mechanistic links between sea surface salinity, atmospheric moisture transport and Australian rainfall motivate us to predict Australian summer (Dec-Feb) rainfall using sea surface salinity of prior seasons (Jul-Sep and Sep-Nov). We used a machine learning approach known as Random Forest Regression Analysis to predict rainfall over a large region of northeastern Australia and a relatively smaller region that surrounds Brisbane. In both cases, we have tested the effect of incorporating sea surface salinity in the southeast equatorial Indian and western equatorial Pacific Ocean along with other previously known and widely used predictors (i.e., ENSO index of Nino 3.4 region, IOD index, area-averaged local soil moisture). We used Jul - Sep and Sep-Nov values of theseindices to predict Dec-Feb rainfall over northeastern Australia (Figure 5) and the Brisbane region (Figure 6).

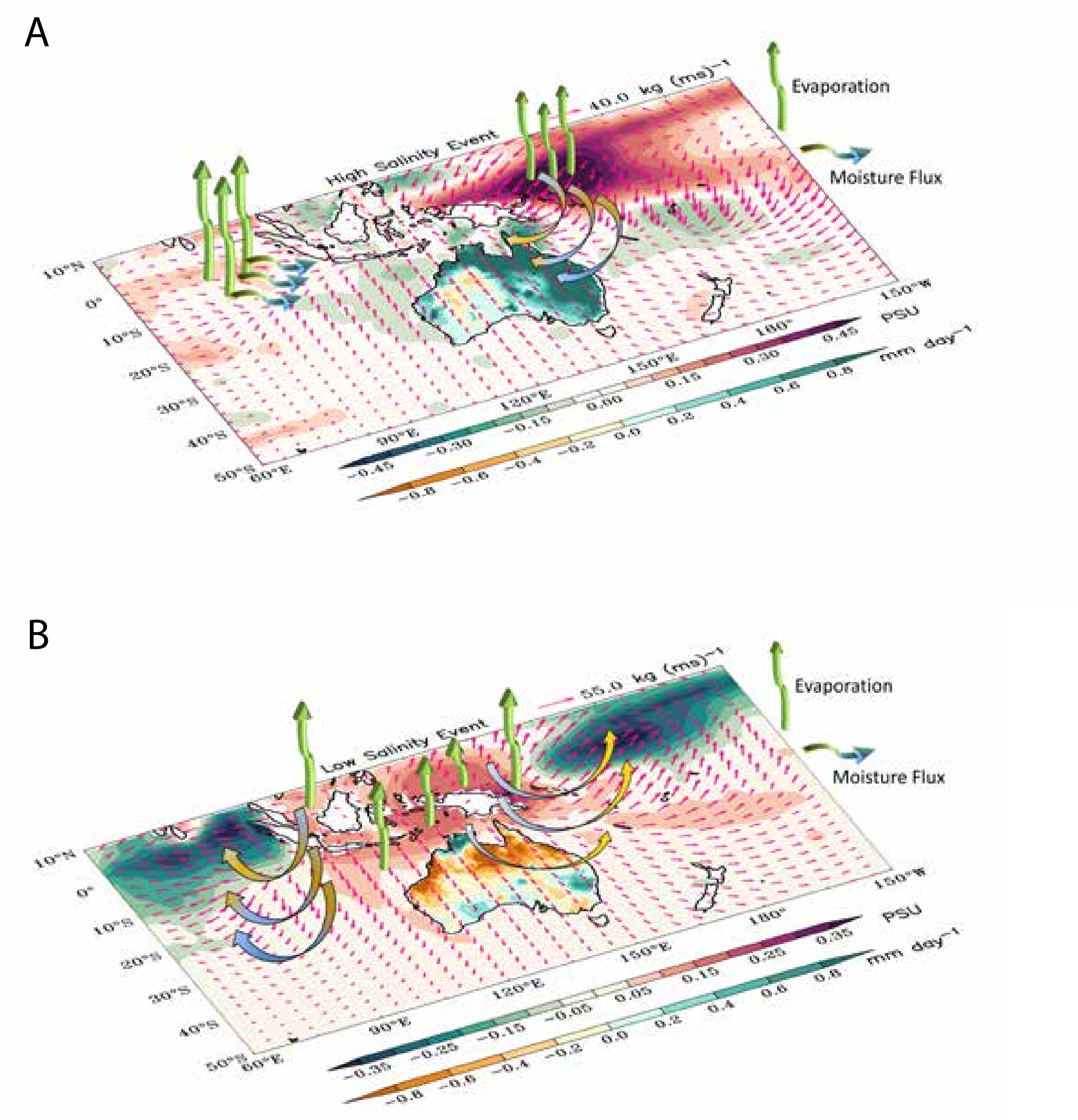

Figure 4. Schematic of high (upper panel) and low (lower panel) sea surface salinity event where magenta vectors represent moisture transport, green and red colour over the ocean represents low salinity (fresh region) and high salinity (salty region), respectively, brown and green colour over Australia represents low rainfall (dry region) and high rainfall (wet region), respectively, green arrows represent evaporation from the ocean surface, and coloured arrows represent moisture flux. Source: (Rathore et al., 2020, 2021)

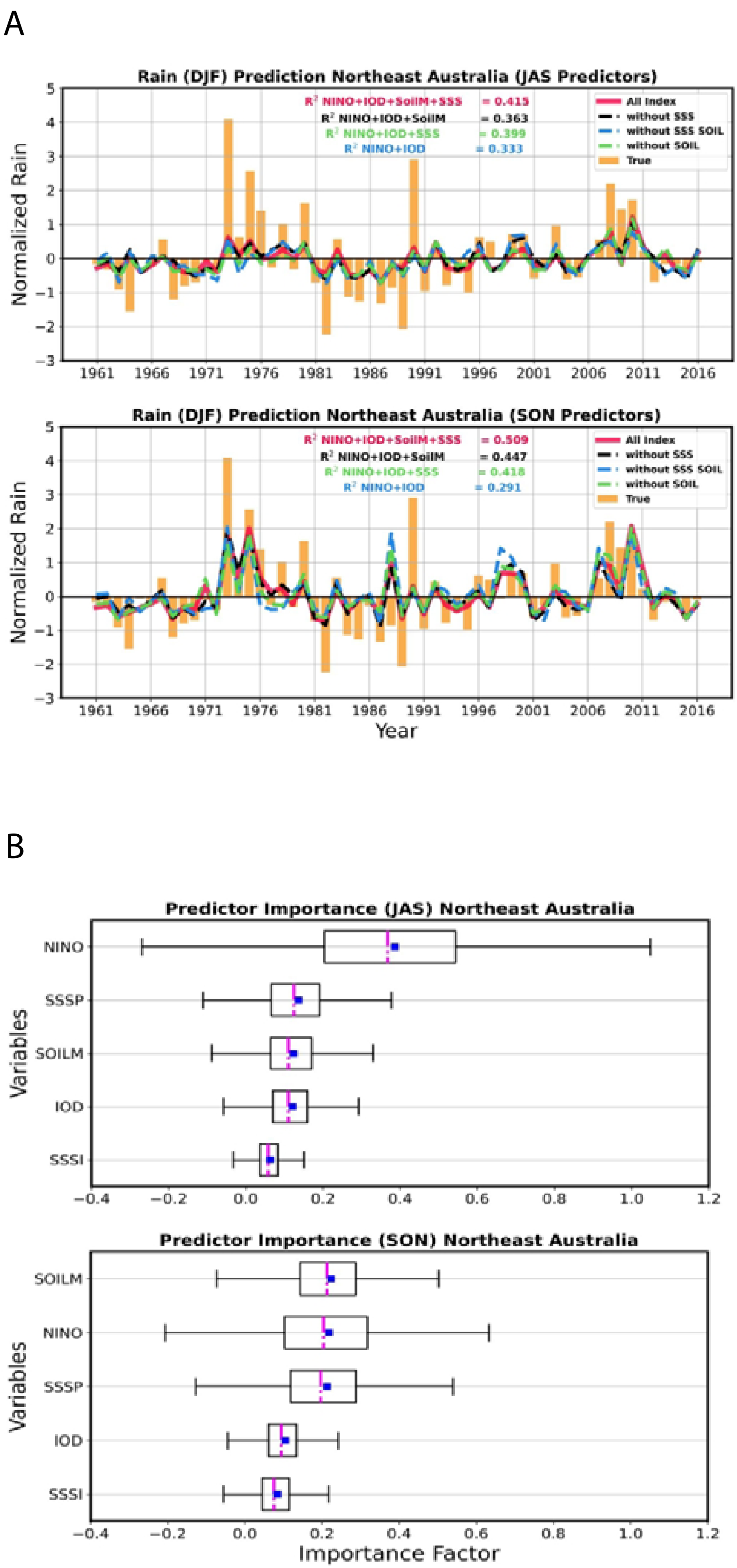

Figure 5. Normalized time series of DJF rainfall over northeastern Australia (130°-152°E and 25°-0°S) (yellow), predicted rainfall time series by incorporating the JAS and SON indices of SSSP, SSSI, Niño 3.4, DMI and Soil Moisture over northeastern Australia as predictors (red), predicted rainfall including all the predictors except SSSP and SSSI (black), predicted rainfall including all the predictors except soil moisture (green), and predicted rainfall without incorporating SSSP, SSSI and Soil Moisture indices (blue). The variance explained by the prediction model is shown as R2 Value. Importance of predictors during JAS and SON in predicting the DJF rainfall over northeastern Australia. Magenta line is the median and blue square is the mean. Source: Rathore et al., 2021)

The prediction of Dec - Feb rainfall over northeastern Australia shows an improvement in the explained variance by 6% when the prediction includes sea surface salinity along with other predictors. In the case of northeastern Australia, the local soil moisture and sea surface salinity of the western equatorial Pacific Ocean are equally important after ENSO and significantly improve the rainfall prediction when combined with ENSO and IOD. In contrast, for the Brisbane region, incorporation of sea surface salinity (R2 = 51% (Jul-Sep) and 46% (Sep-Nov) for ENSO + IOD + Sea surface salinity) shows a large improvement in the prediction as compared to the local soil moisture (R2= 41% (Jul-Sep) and 39% (Sep-Nov) for ENSO + IOD + Soil Moisture). Over the Brisbane region, ENSO and IOD together can explain 36% of the variance in rainfall. After ENSO, the sea surface salinity of the western equatorial Pacific Ocean is the second most important predictor for the rainfall over the Brisbane region and local soil moisture is the least important. Moreover, the Brisbane flood events of 1973/74 and 2010/11 are robustly captured by the random forest regression technique.

Hence, our study suggests that the continuous monitoring of sea surface salinity and its integration into numerical weather forecast systems will help make a better prediction of terrestrial rainfall.

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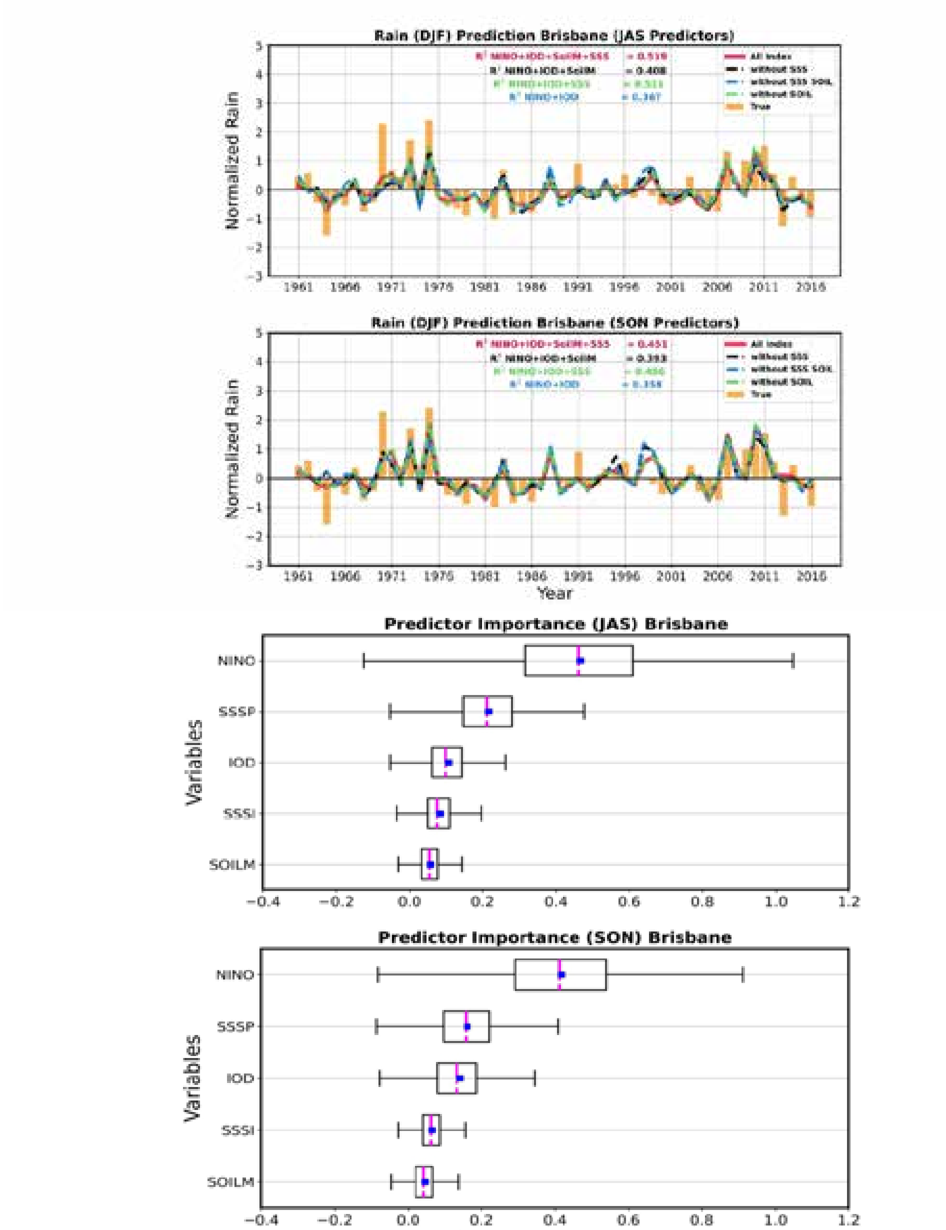

Figure 6. Normalized time series of DJF rainfall over Brisbane region (144o-154oE and 34o-24oS) (yellow), predictedrainfall time series by incorporating the JAS and SON indices of SSSP, SSSI, Niño 3.4, DMI and Soil Moisture over Brisbane region as predictors (red), predicted rainfall including all the predictors except SSSP and SSSI (black), predicted rainfall including all the predictors except soil moisture (green), and predicted rainfall without incorporating SSSP, SSSI and Soil Moisture indices (blue). The variance explained by the prediction model is shown as R2 Value. Importance of predictors during JAS and SON in predicting the DJF rainfall over Brisbane region. Magenta line is the median and blue square is the mean. Source: Rathore et al., 2021)