Anchoring Intraseasonal Air–Sea Interactions: The Moored Moist Static Energy Budget in the Indian Ocean from Reanalysis

ADAM V. RYDBECK, a JONATHAN A. CHRISTOPHERSEN, b MARIA K. FLATAU, b MATTHEW A. JANIGA, b TOMMY G. JENSEN, a CAROLYN A. REYNOLDS, b JAMES A. RIDOUT, b TRAVIS A. SMITH, a AND HEMANTHA WIJESEKERA a

a U.S. Naval Research Laboratory, Stennis Space Center, Mississippi
b U.S. Naval Research Laboratory, Monterey, California

(Manuscript received 17 March 2022, in final form 12 August 2022)

ABSTRACT: Moist static energy (MSE) and ocean heat content (OHC) in the tropics are inextricably linked. The processes by which sources and sinks of OHC modulate column integrated MSE in the Indian Ocean (IO) are explored through a reformulation of the MSE budget using atmosphere and ocean reanalysis data. In the reframed MSE budget, interfacial air–sea turbulent and radiative fluxes are replaced for information on upper ocean dynamics, thus “mooring” the MSE tendency to the subsurface ocean. On subseasonal time scales, ocean forcing is largely responsible for the amplification of MSE anomalies across the IO, with basin average growth rates of 10% day$^{-1}$. Local OHC depletion is the leading contributor to anomalous MSE amplification with average rates of 12% day$^{-1}$. Along the equator, MSE is amplified by OHC vertical advection. Ocean forcing only weakly reduces the propagation tendency of MSE anomalies ($-2\%$ day$^{-1}$), with propagation predominantly resulting from atmosphere forcing ($10\%$ day$^{-1}$). OHC in the IO acts as an MSE reservoir that is expended during periods of enhanced intraseasonal atmosphere convection and recharged during periods of suppressed convection. Because OHC is an MSE source during enhanced intraseasonal convection periods, it largely offsets the negative MSE tendency produced by horizontal advection in the atmosphere. The opposite effect occurs during suppressed convection periods, where OHC is a sink of MSE and counters the positive MSE tendency produced by horizontal advection in the atmosphere.

KEYWORDS: Indian Ocean; Madden-Julian oscillation; Energy transport; Reanalysis data; Intraseasonal variability; Tropical variability

1. Introduction

Intraseasonal variability in the Indian Ocean (IO) is characterized by large-scale, organized modes in the atmosphere and ocean. These include the Madden–Julian oscillation (MJO) (Madden and Julian 1971, 1972) and boreal summer intraseasonal oscillation (BSISO) (Yasunari 1979, 1980) that modulate rainfall in the atmosphere and ocean. Kelvin and Rossby waves that modulate the thermocline and heat content (McPhaden 1982). The processes by which these modes interact has been the focus of many recent research studies (Fu 2007; Nyadjro et al. 2020; Rydbeck et al. 2017, 2019a,b, 2021; Rydbeck and Jensen 2017; Webber 2012; Webber et al. 2010, 2012a,b, 2014; West et al. 2018, 2020). Using a reformulated moist static energy (MSE) budget, the goal of this study is to quantify changes in atmospheric intraseasonal oscillation (ISO) intensity forced by upper ocean heat content (OHC) variations.

Previous studies examining MSE sources and sinks have revealed tremendous insights into the variety of mechanisms that force the amplification and propagation of ISOS (Maloney 2009; Yu and Neelin 1994), particularly in the context of moisture mode theory, which emphasizes the interactive relationships among atmospheric moisture, cloud populations, and circulations on intraseasonal time scales and large spatial scales (e.g., Adames and Kim 2016; Adames and Maloney 2021; DeMott et al. 2019; Hagos et al. 2020). Observations obtained during CINDY/DYNAMO (Yoneyama et al. 2013) have shown that radiative and surface turbulent heat fluxes are the leading contributors to the maintenance of column integrated MSE anomalies in the central IO, with radiation also contributing to the initial increase of anomalous MSE during the transition to MJO enhanced convection (Adames et al. 2017; Ruppert and Johnson 2016; Sobel et al. 2014; Yokoi and Sobel 2015). MSE budgets are also used to scrutinize simulated ISOs and disentangle the effects of complex, intertwined physical processes. For example, in a superparameterized version of the NCAR Community Earth System Model and under conditions of a warmer climate.
MJO activity increased due to a reduced sink of MSE by surface latent heat fluxes and increased maintenance of MSE by vertical advection in the atmosphere (Arnold et al. 2015).

The state of the upper ocean is critical to the evolution of the sea surface during conditions of strong intraseasonal surface fluxes (e.g., DeMott et al. 2016; Maloney and Sobel 2004; Pujiana et al. 2018; Sobel and Maloney 2010). The anomalous energy of the thin sea surface layer would be depleted by fluxes in a matter of hours if not resupplied from below (e.g., Shroyer et al. 2021). Previous work has demonstrated that the subsurface ocean behaves in a conspicuously different manner than the surface during ISOs. Rydbeck et al. (2019b) showed that OHC anomalies in the central and western IO are anomalously enhanced during enhanced intraseasonal convection and suppressed during suppressed intraseasonal convection. SST anomalies, though, are generally suppressed during enhanced convection and enhanced during suppressed convection. To account for the disparity in behavior between SST and OHC anomalies, we develop a new framework, the moored MSE budget, to directly account for the effects of OHC sources and sinks on MSE.

The investigation is organized as follows. Section 2 describes the data used in the analysis. Section 3 shows the process for combining the respective tendency equations of MSE and OHC into the moored MSE budget. Section 4 examines the intraseasonal relationship of MSE and OHC when anomalous MSE is enhanced and suppressed in the central IO. Section 5 quantifies the various atmosphere and ocean contributions to the MSE tendency. Section 6 provides a summary of the main results.

2. Data

To analyze the intraseasonal variability of the tropical IO atmosphere and ocean system, we use atmosphere and ocean reanalyses as well as satellite observations. For the calculation of the MSE budget, data including daily temperature, winds, specific humidity, frozen condensate, geopotential height, longwave radiative flux, shortwave radiative flux, surface latent heat flux, and surface sensible heat flux are obtained from the European Centre for Medium-Range Weather Forecasts ERA5 reanalysis (0.25°) (Hersbach et al. 2020). Daily ocean variables used in the calculation of the OHC budget are obtained from the HYCOM reanalysis (0.08°) (Metzger et al. 2017) and are interpolated to the same horizontal grid as the atmosphere reanalysis. While HYCOM reanalysis uses surface forcing fields from the National Centers for Environmental Prediction Climate Forecast System Reanalysis (Saha et al. 2010), ERA5 fluxes are used throughout for consistency between the MSE and OHC budgets. Daily outgoing longwave radiation (OLR) is from the NOAA Climate Data Record (1.0°) (Lee and NOAA CDR Program 2011). Daily precipitation is from the Global Precipitation Climatology Project (1.0°) (Adler et al. 2003). All data span the period of the HYCOM reanalysis from 1994 to 2015 except for precipitation, which begins in 1996. Intraseasonal anomalies are calculated by removing the first three harmonics of the seasonal cycle and then bandpass filtering to isolate variability with periods of 30–120 days. The analyses are performed as a function of season, with boreal winter defined as November–April and boreal summer defined as May–October.

3. Derivation of the moored moist static energy tendency

The purpose of the moored MSE tendency derivation is to attain a unified formula that directly couples processes in the atmosphere and upper ocean, not simply the ocean surface. Here “moored” refers to the new connections made between atmospheric MSE sources and sinks and subsurface ocean processes. As previously discussed, the MSE budget is critical for determining the processes responsible for organized tropical convection, such as the MJO and BSISO. By combining the equation for the tendency of MSE with the tendency of OHC, ocean internal energy changes that result from ocean dynamics and heat uptake are shown to directly contribute to internal, latent, and potential (i.e., moist static) energy changes in the atmosphere. Previous MSE process studies examining the role of the ocean have relied on detailed examinations of surface fluxes. This new formulation circumvents this step to create a direct link between ocean dynamics and MSE shifts. The expression can also be arranged to solve for the tendency of OHC, whereby processes throughout the depth of the troposphere impact the internal energy of the ocean. To begin, we describe the respective vertically integrated MSE and OHC tendency equations.

a. Moist static energy budget

The vertically integrated tendency of MSE is expressed as

\[
\begin{align*}
\frac{\partial [\text{MSE}]}{\partial t} &= -\left(\text{MSE horizontal advection} + \text{MSE vertical advection} + \text{net longwave radiative flux} + \text{net shortwave radiative flux} + \text{surface latent and sensible heat fluxes}\right) \\
&= \left(\text{MSE} \text{ horizontal advection - MSE vertical advection - net longwave radiative flux - net shortwave radiative flux - surface latent and sensible heat fluxes}\right),
\end{align*}
\]

where \( m = c_{ap} T_a + g z_f + L_a q_f - L_f q_f \), \( c_{ap} \) is the specific heat of dry air at constant pressure, \( T_a \) is the atmospheric temperature, \( z_f \) is the geopotential height, \( g \) is the acceleration due to gravity, \( L_a \) is the latent heat of vaporization, \( L_f \) is the latent heat of freezing, \( q_f \) and \( q_a \) are the mass of water vapor and ice per kilogram of dry air, \( \nabla \cdot \mathbf{u}_h \) is the horizontal wind, \( \omega \) is the vertical wind, \( p \) is the pressure, \( LW \) is the longwave radiative flux, \( SW \) is the shortwave radiative flux, \( LH \) is the surface latent heat flux, and \( SH \) is the surface sensible heat flux. Surface fluxes are positive when the ocean is supplying energy to the atmosphere. Surface fluxes are negative when the ocean is removing energy from the atmosphere. Vertical advection is the sum of large and competing contributions and is calculated as the residual of all other budget terms in Eq. (1). Square brackets indicate the mass-weighted vertical integral in the atmosphere \( \int d p \) from the surface to 100 hPa. The units of the MSE tendency and forcing terms are watts per square meter (W m\(^{-2}\)).
b. Ocean heat content budget

The tendency of OHC is expressed as

\[
\frac{\partial (OHC)}{\partial t} = OHC_{\text{storage}} - OHC_{\text{horizontal advection}} - OHC_{\text{vertical advection}} - OHC_{\text{diffusion}}
\]

where \( T_o \) is the ocean excess temperature \((T - T_{\text{reference}})\), \( v_{o,h} \) is the ocean horizontal current, \( w_o \) is the vertical current \((w_o = dz/dt + w|_{z=H})\), \( z \) is the depth, and \( A_h \) and \( A_z \) are the horizontal and vertical eddy diffusivities. Surface fluxes are positive when the ocean is supplying energy to the atmosphere. Surface fluxes are negative when the ocean is removing energy from the atmosphere. Angle brackets indicate the mass-weighted vertical integral from the ocean surface to a specified depth (\( H \)). OHC is defined as the integrated temperature such that \( \text{OHC} \equiv \langle T_o \rangle = \rho_o c_o \rho H \int (T - T_{\text{reference}}) dz \), where \( c_o \rho \) is the specific heat of seawater at constant pressure and \( \rho_o \) is the seawater density. In our study, OHC is defined in the same manner as tropical cyclone heat potential such that \( T_{\text{reference}} \) is 26°C and \( H \) is the depth of the 26°C isotherm, which averages between 40 and 85 m over much of the tropical IO. Vertical advection is calculated as the residual of all other terms in Eq. (2), and any discrepancies that might arise from using ERA5 surface fluxes with HYCOM reanalysis are captured in this term. The units of the OHC tendency and forcing terms are \( \text{W m}^{-2} \).

c. Moored moist static energy budget

To characterize the interactions between the internal energy of the ocean and the MSE energy of the atmosphere, Eqs. (1) and (2) are summed. In doing so the air–sea interfacial fluxes cancel one another, and we arrive at

\[
\frac{\partial (MSE)}{\partial t} = -\langle v_{o,h} \cdot \nabla m \rangle - \omega \frac{\partial m}{\partial p} - (SW|_{100hPa} - LW|_{100hPa})
\]

or alternatively

\[
\frac{\partial \langle T_o \rangle}{\partial t} = -\langle v_{o,h} \cdot \nabla T_o \rangle - \omega \frac{\partial T_o}{\partial z} - \langle A_h \nabla^2 T_o \rangle - \left\langle \frac{1}{H} A_z \frac{\partial T_o}{\partial z} \right\rangle,
\]

Equation (3) represents the tendency of MSE owing to atmospheric processes such as advection and net radiative heating, as well as the local depletion, advection, and mixing of OHC. Equation (4) represents the role of atmospheric MSE processes in modulating the OHC tendency. These processes are summarized in Fig. 1. In Eq. (3), if the sum of OHC depletion and ocean dynamics is positive, then the net ocean forcing acts as a source of MSE. If negative, ocean forcing acts as a sink of MSE. In this way, ocean dynamics can modulate the MSE tendency. Although Eqs. (3) and (4) do not explicitly include surface turbulent and radiative fluxes, imbalances between OHC depletion and ocean dynamics are physically realized as surface turbulent and radiative fluxes. A primary utility of Eq. (3) is that processes involving complex ocean mixing and advection are directly linked to changes in MSE. For our purposes, this reveals new insights into the role of ocean dynamics during periods of strong atmospheric intraseasonal variability in the IO.

4. Moist static energy and ocean heat content

The intraseasonal relationship between MSE and OHC in the IO is explored in this section. Because the leading modes
of intraseasonal variability have distinct characteristics based on season, boreal summer and boreal winter are examined separately.

a. Mean and variability

Intraseasonal variability of precipitation in the IO is strongly modulated by changes in MSE (e.g., Benedict and Randall 2007; Johnson et al. 2015; Kemball-Cook and Weare 2001; Li et al. 2015; Ruppert and Johnson 2015; Sobel et al. 2014; Tian et al. 2006; Wu and Deng 2013; Zhao et al. 2013). More recently, intraseasonal variability of precipitation has also been linked to marked changes in OHC (Azaneu et al. 2021; Moum et al. 2016; Rydbeck et al. 2019b, 2021). To better understand the relative scales and locations of these variations as a function of season, Fig. 2 shows the mean and intraseasonal standard deviation of precipitation (Figs. 2a,b), vertically integrated MSE (Figs. 2c,d), and OHC (Figs. 2e,f).

During boreal summer (i.e., southwest monsoon), the local maxima of mean precipitation along the western facing coasts in the Northern Hemisphere are associated with local maxima of intraseasonal precipitation variability as well (Fig. 2a). The local maximum of mean precipitation along and south of the equator is likewise associated with a local maximum of intraseasonal precipitation variability. During boreal winter, maximum precipitation variability is largely confined to the eastern and central tropical IO, with the largest values mostly occurring between 15°S and 5°N. The standard deviation of anomalous precipitation is approximately 40%–70% of the mean in the equatorial IO during summer and winter. Throughout the tropical IO, the maxima of mean precipitation and intraseasonal variability are predominantly collocated.

Unlike precipitation, maxima of the standard deviation of intraseasonal MSE and OHC anomalies are not collocated with their respective means. Mean MSE maximizes in the northern Bay of Bengal during summer and just south of the equator during winter with values of 313 and 310 kJ cm\(^{-2}\), respectively (Figs. 2c,d). Local maxima of the standard deviation of intraseasonal MSE anomalies are generally located in regions of mean horizontal MSE gradients. The intraseasonal MSE standard deviation is \(~0.3\%–0.4\%\) of the mean. Mean OHC is a maximum in the eastern equatorial IO with a westward extension of the maximum into the central and western IO during the summer with a slightly weaker pattern in winter (Figs. 2e,f). OHC variability is concentrated in off-equatorial regions at and poleward of 3°N/S. The standard deviation of intraseasonal OHC anomalies is \(~5\%–15\%\) of the mean, and
approximately an order of magnitude larger than the standard deviation of intraseasonal MSE anomalies.

b. Coherence

The relationship between MSE and OHC on intraseasonal time scales is explored by calculating their coherence and phase for boreal summer and winter, respectively. For periods of 30–70 days, in which spectral power of atmospheric tropical intraseasonal variability is strongest, OHC generally leads MSE by 90°–135° of phase (~15 days) in the summer hemisphere, indicating that enhanced OHC leads enhanced MSE and suppressed OHC leads suppressed MSE (Figs. 3a,c). This is similar to the well-documented phase relationship of SST and atmosphere convection in the MJO and BSISO (DeMott et al. 2015, and references therein). There are exceptions to this behavior, like along the coast of Sumatra, where OHC

![Fig. 2. The mean (contours) and intraseasonal standard deviation (shading) of (a),(b) GPCP precipitation (mm day\(^{-1}\)), (c),(d) vertically integrated MSE (kJ cm\(^{-2}\)), and (e),(f) OHC (kJ cm\(^{-2}\)) anomalies are shown as a function of season.](image-url)
and MSE are out of phase, indicating that suppressed OHC occurs during enhanced MSE, and enhanced OHC occurs during suppressed MSE. Previous work has suggested that reflecting oceanic equatorial waves initially forced by intraseasonal wind stress are responsible for this out of phase behavior (Rydbeck et al. 2019b, 2021).

When examining the low-frequency tail of intraseasonal variability characterized by periods of 70–120 days, OHC and MSE are much more coherent and display a multifarious and complex pattern of phasing across the tropical IO (Figs. 3b,d). During summer, OHC generally leads MSE by 90° in the Bay of Bengal and Arabian Sea, similar to the behavior observed for 30–70-day periods. During winter, OHC also leads MSE by ~90° in much of the tropical IO to the south of the equator, like the 30–70-day period phasing. However, the western equatorial IO is characterized by an in-phase relationship, such that enhanced OHC anomalies occur simultaneously with enhanced MSE anomalies and suppressed OHC anomalies occur with suppressed MSE anomalies. In narrow portions of the central equatorial IO, MSE leads OHC by ~90° of phase, such that enhanced OHC occurs after enhanced MSE, regardless of season. This is contrary to what might be inferred from archetypical atmosphere flux forcing of the upper ocean. During both seasons, OHC and MSE are largely out of phase near the coast of Sumatra, like the pattern for 30–70-day periods.

We use the white reference boxes in Fig. 3 as averaging areas to create time series of enhanced and suppressed MSE periods. The averaging regions are defined as 0°–10°N, 83°–93°E for boreal summer and 0°–10°S, 83°–93°E for boreal winter. These locations are selected due to the strong coherence and quasi-consistent phase displayed across each season and frequency band. Periods of enhanced and suppressed intraseasonal MSE anomalies are used to define events because we are interested in the processes that generate and maintain these anomalies as revealed by Eq. (3). To ensure the suitability of this method for capturing propagating modes of intraseasonal variability in the IO as a function of season, we first perform a simple analysis. Coherence and phase are calculated between intraseasonal MSE averaged over the reference box and MSE anomalies at each point in the tropical IO for summer and winter, respectively. The objective of this test is to confirm that the intraseasonal variability of MSE within the boxes is associated with the eastward propagating MSE anomalies during boreal winter and eastward/northward propagating anomalies during boreal winter, consistent with the MJO and BSISO, respectively. A failing indicator would result if the box-averaged MSE anomalies are incoherent with
their surroundings, and/or the phasing is incongruous with neighboring regions.

**Figure 4** shows the coherence and phase between box-averaged MSE anomalies and those in the rest of the tropical IO. During summer, MSE anomalies in the western IO lead by 90° and those in the northern Arabian Sea and the Bay of Bengal lag by 45°–90°, consistent with the eastward and northward propagating components of the BSISO (Fig. 4a). During winter, MSE anomalies in the western IO lead those in the reference box by 90° and gradually become more phase aligned in the central and eastern IO (Fig. 4b), consistent with eastward MJO propagation. MSE anomalies in the southwestern IO lag those in the reference box by 45°–90°, indicating propagation over the Maritime Continent also consistent with the MJO. It is notable that there is some blending of the MJO/BSISO that is evident in the coherence and phase vectors due to the inclusion of seasonal transition months in the calculations. Nonetheless, this analysis ensures that the area averages of anomalous MSE are capturing well-known characteristics of the seasonally propagating modes of intraseasonal variability and not trivial, locally pulsating modes.

c. Composites

Atmosphere and ocean variables are composited for days when box-averaged MSE anomalies are enhanced and suppressed, respectively. Enhanced MSE days are defined as those when the MSE is greater than or equal to 1 standard deviation, and suppressed MSE days are defined as those when the MSE is less than or equal to −1 standard deviation.

**Figure 5** shows composites of intraseasonal MSE, OLR, OHC, and SST anomalies. During boreal summer, positive MSE anomalies in the IO are collocated with negative OLR anomalies, indicating enhanced convection (Fig. 5a). Positive OHC anomalies are generally located in the western, central, and northern IO with negative OHC anomalies located along the coast of Sumatra (Fig. 5c). Maximum OHC anomalies are located to the north of the MSE maximum, in the direction of the BSISO propagation. Warm SST anomalies are located in the Bay of Bengal and the northern Arabian Sea, similar to the location of enhanced OHC anomalies (Fig. 5d). SST anomalies are negative along most of the equatorial IO, while OHC anomalies are only negative in the eastern IO. The out-of-phase relationship of SST and OHC anomalies in the central and parts of the western IO is similar to that documented in Rydbeck et al. (2019b).

During suppressed MSE periods, the patterns are mostly reversed with positive OLR anomalies, indicating suppressed convection, associated with negative OHC anomalies in much of the northern, central, and western IO (Figs. 5b,d). Positive OLR anomalies are collocated with positive OHC anomalies in the eastern IO. The behavior of OHC anomalies contrasts with that of SST in the central and western equatorial IO (Fig. 5f). The sea surface warming during anomalously suppressed MSE periods is consistent with reduced latent heat fluxes and enhanced incoming solar radiation during suppressed convection. The negative OHC anomalies have previously been hypothesized to result from the cooling effect of ocean dynamics, specifically meridional and vertical advection, driven by ocean equatorial waves that counters the warming effect of net surface flux forcing (Rydbeck et al. 2021).

During winter, the overall behavior is similar to that for summer but shifted to the Southern Hemisphere (Fig. 6). There are, however, a few notable differences. The anomalous MSE maximum/minimum is weaker by ~10% (Figs. 6a,b), and the OHC and SST maxima and minima are ~25%–50% weaker (Figs. 6c–f). The horizontal SST gradients are also greatly reduced.

Differences in the patterns of OHC and SST anomalies during suppressed and enhanced MSE periods during both seasons suggest different sensitivities to intraseasonal forcing mechanisms. Many studies have documented the role of intraseasonal surface fluxes in regulating mixed layer temperature and SST anomalies in the IO (Drushka et al. 2012; Duvel et al. 2004; Halkides et al. 2015; Han et al. 2007; Jayakumar et al. 2011; Jensen et al. 2015; Li et al. 2016; Roxy et al. 2013; Sengupta and Ravichandran 2001; Zhang 1997). The phasing and interactions between OHC and MSE anomalies require a more careful treatment because they do not strictly follow the
FIG. 5. For boreal summer, composites of the intraseasonal (a),(b) OLR (W m$^{-2}$), (c),(d) OHC (kJ cm$^{-2}$), and (e),(f) SST ($\times10^{-1}$ K) anomalies for (left) enhanced and (right) suppressed periods of MSE in the tropical IO are shaded. Line contours show the intraseasonal MSE (kJ cm$^{-2}$) anomaly associated with the respective enhanced or suppressed periods. Positive contours are solid, and negative contours are dashed with a contour interval of 0.15 kJ cm$^{-2}$. The zero MSE contour is in bold. The number of days in each composite are shown above (a) and (b).
typical flux forcing paradigm of the sea surface and mixed layer temperature. Recent studies have suggested that OHC anomalies in the tropical IO are primarily forced by ocean dynamics associated with large-scale planetary waves initially generated by intraseasonal wind stress (Azaneu et al. 2021; Rydbeck et al. 2019b, 2021). Under these conditions, the SST can decrease while the integrated temperature (i.e., the OHC) increases. An analogy is integrating the area under a temperature versus depth curve. The peak of the curve can decrease while the total area under the curve increases. On intraseasonal time scales, surface flux forcing is very effective at modulating the maximum temperature, while ocean dynamics, under

Fig. 6. As in Fig. 5, but for boreal winter.
FIG. 7. For boreal summer, composites of the intraseasonal moored MSE budget terms including (a),(b) MSE tendency (W m$^{-2}$), (c),(d) horizontal advection of MSE (W m$^{-2}$), (e),(f) vertical advection of MSE (W m$^{-2}$), (g),(h) boundary radiation fluxes (W m$^{-2}$), and (i),(j) ocean forcing (W m$^{-2}$), which includes the sum of ocean heat depletion, and ocean dynamics are shown during (left) enhanced and (right) suppressed periods of MSE in the tropical IO. Line contours show the intraseasonal MSE (kJ cm$^{-2}$) anomaly associated with the respective enhanced or suppressed periods. Positive contours are solid, and negative contours are dashed with a contour interval of 0.15 kJ cm$^{-2}$. The zero MSE contour is in bold. Area averages (15$^\circ$S–15$^\circ$N, 50$^\circ$–100$^\circ$E) are shown in each panel description.
certain conditions, are effective at modulating the integrated temperature. An unresolved question is the degree to which sources and sinks of integrated temperature (i.e., OHC) modulate MSE. Using the moored MSE equation, we next examine how sources and sinks of OHC modulate MSE in the atmosphere.

5. Moored moist static energy budget

The moored MSE budget considers the troposphere and upper ocean as a combined system, eliminating the interfacial fluxes between the two. In this framework, an MSE tendency from ocean forcing results when local OHC depletion and ocean dynamics are unbalanced. For instance, a positive tendency from ocean dynamics that is not balanced by a local OHC increase manifests as an MSE increase. In this section, each term of the MSE budget is examined as a function of season. Many detailed examinations of the standard MSE budget have been performed in previous studies. To permit a more focused assessment of the previously unexplored role of OHC in modulating the MSE, we focus on the ocean forcing terms and limit in depth treatments of atmosphere forcing terms.

a. Boreal summer

In addition to eastward propagation, the BSISO is characterized by slow northward propagation of ~1° latitude day$^{-1}$, consistent with the positive MSE tendencies in the northern Bay of Bengal located to the north of the MSE maximum and negative tendency along the equator during enhanced periods (Fig. 7a). The leading contributor in the composite budget is horizontal advection of MSE that is more than double (>25 W m$^{-2}$) the amplitude of the MSE tendency (Fig. 7c). Horizontal advection is largely responsible for the northward propagation while also weakly damping the maximum MSE amplitude.

The phase relationship between vertical advection of MSE and MSE anomalies varies across the IO (Figs. 7e,f). Away from the coastline in the Arabian Sea, they mostly lead to an enhancement of anomalous MSE there. Along the equator, vertical advection damps MSE anomalies. The net radiation, which is defined as the sum of the shortwave and longwave radiation at the top of the atmosphere less the radiation that penetrates the base of the ocean’s 26°C isotherm (Figs. 7g,h), generally supports anomalous MSE intensification in the tropical IO.

The magnitude of ocean forcing is comparable to that of MSE horizontal advection throughout much of the IO but is opposite in sign (Figs. 7i,j). Ocean forcing is partly in phase with the MSE anomalies, indicating that it intensifies them while also resisting the off-equatorial propagation forced by MSE horizontal advection. This is similar to the role of SST anomalies in the context of surface latent heat fluxes, which tend to pull MSE anomalies toward the equator as described in DeMott et al. (2016). In the northern Bay of Bengal, ocean forcing weakens MSE and opposes its northward propagation. MSE horizontal advection is stronger than the combined effects of MSE vertical advection and ocean forcing, resulting in overall northward propagation. Apart from weak contributions made by net radiative heating, ocean forcing is the only other term in the moored MSE budget responsible for anomalous MSE intensification during periods of enhanced and suppressed MSE.

The ocean forcing term shown in Figs. 7i and 7j is the sum of OHC depletion and ocean dynamics, which are shown in Fig. 8. Ocean dynamics includes horizontal advection, horizontal mixing, vertical advection, vertical mixing, and entrainment of OHC. For simplicity, horizontal mixing is included in the horizontal advection term, and vertical mixing and entrainment are included in the vertical advection term. The mixing terms are of second-order importance. It is useful to remember that OHC depletion can arise from two main processes. When OHC depletion is positive, OHC is either transferred upward out of the ocean and realized as MSE increases, and/or OHC is transferred horizontally/ downward out of the ocean column by ocean dynamics. When OHC depletion is negative (i.e., ocean is storing energy), either MSE is transferred downward into the ocean, resulting in MSE decreases, and/or OHC is transferred into the ocean column by ocean dynamics.

OHC depletion is the largest term in the moored MSE budget and is mostly in phase with MSE anomalies in off-equatorial regions during enhanced and suppressed MSE periods, respectively (Figs. 8a,b). It is generally greater in magnitude than ocean dynamics (Figs. 8c,d), except along the equator, with values exceeding ±60 W m$^{-2}$. Along the equator, ocean dynamics are a source of MSE during enhanced periods and a sink of MSE during suppressed periods. In these locations, there is a net increase of anomalous MSE by ocean forcing (see Figs. 7i,j) because ocean dynamics are greater than OHC depletion. While ocean dynamics include many processes, the largest contributor to ocean dynamics along the equator is vertical advection (Figs. 8g,h) and this is perhaps related to downwelling and upwelling Kelvin waves (e.g., Pujiana and McPhaden 2020). For instance, a westerly surface wind stress along the equator associated with ISO convection generates Ekman convergence and downward motion in the ocean. This can trigger downwelling Kelvin waves. The wave’s downward motion transports warm water in the upper ocean to deeper layers such that vertical advection increases OHC, all else being equal. If the ocean does not store the entirety of the OHC generated by vertical advection, the remainder is realized as an atmospheric MSE increase. Horizontal advection is less spatially coherent, limiting its interpretation (Figs. 8e,f). The magnitude of horizontal advection is a maximum near 5°N, 90°E and damps anomalous MSE there.

While anomalous OHC is expended during enhanced MSE periods in off-equatorial regions, it is replenished during suppressed periods (Figs. 8a,b). The anomalous OHC depletion/storage is generally between ±15 and ±60 W m$^{-2}$, comparable to the mean net surface heat fluxes observed during MJO events in TOGA COARE and CINDY/DYNAMO (de Szoeke et al. 2015). The anomalous storage of OHC (i.e., negative OHC depletion) during suppressed periods in the Arabian Sea and the southern Bay of Bengal is partly explained by ocean dynamics, but the ocean is storing...
FIG. 8. For boreal summer, composites of the intraseasonal moored MSE budget terms including (a),(b) OHC depletion (W m$^{-2}$), (c),(d) ocean dynamics (W m$^{-2}$), (e),(f) the sum of horizontal advection and mixing of OHC (W m$^{-2}$), and (g),(h) the sum of vertical advection, mixing, and entrainment of OHC (W m$^{-2}$) are shown for (left) enhanced and (right) suppressed periods of MSE in the tropical IO. Line contours show the intraseasonal MSE (kJ cm$^{-2}$) anomaly associated with the respective enhanced or suppressed periods. Positive contours are solid, and negative contours are dashed with a contour interval of 0.15 kJ cm$^{-2}$. The zero MSE contour is in bold. Area averages (15°S–15°N, 50°–100°E) are shown in each panel description.
energy faster than can be supplied by those processes alone (Figs. 8b,d). The remaining recharge of OHC occurs at the expense of MSE, further intensifying the negative MSE anomaly during suppressed MSE periods (see Fig. 5d). While not explicitly in the budget, this is accomplished by net surface fluxes. To note, this does not necessarily result in a positive OHC anomaly at this time, simply a positive OHC tendency. The resupply of OHC across much of the tropical IO by ocean dynamics, namely vertical advection and, to a lesser degree, OHC horizontal advection, during suppressed MSE periods demonstrates the important role of ocean dynamics in preconditioning the upper ocean during suppressed phases.

To quantify the role of each process in forcing MSE anomalies, a new metric is presented. Previous studies have used a fractional contribution to quantify the role of particular terms \( F_i \) in changing the MSE (Andersen and Kuang 2012; Arnold et al. 2015; DeMott et al. 2016; Wing and Emanuel 2014; Wolding et al. 2016). The fractional contribution is based on the correlation coefficient squared and the formulas for both are as follows:

\[
\text{correlation coefficient}^2_{F_i} = \frac{[m|F_i|^2]}{[m]^2 [F_i]^2}, \tag{5}
\]

\[
\text{FC}_{F_i} = \frac{[m|F_i|^2]}{[m]^2} \times 100 \times 86400 \text{ s day}^{-1}, \tag{6}
\]

where \( F_i \) is a term of the moored MSE budget and \( \text{FC}_{F_i} \) is the percent of anomalous MSE growth forced by that term in units of percent per day. One shortcoming of this metric is that it does not distinguish whether the growth results in an amplification or propagation of MSE at a local point. To extract this information, we derive a new metric based on the formula for coherence squared:

\[
\text{coherence}^2_{F_i} = \frac{\text{cospectrum}^2_{m|F_i|^2} + \text{quadrature spectrum}^2_{m|F_i|^2}}{\phi_{mm}^2} \times 100 \times 86400 \text{ s day}^{-1}, \tag{7}
\]

amplifying \( \text{FC}_{F_i} = \frac{\text{cospectrum}_{m|F_i|^2}}{\phi_{mm}} \times 100 \times 86400 \text{ s day}^{-1}, \tag{8} \)

propagating \( \text{FC}_{F_i} = \frac{\text{quadrature spectrum}_{m|F_i|^2}}{\phi_{mm}} \times 100 \times 86400 \text{ s day}^{-1}, \tag{9} \)

where amplifying \( \text{FC}_{F_i} \) is the fractional contribution of a term \( F_i \) to MSE amplification. When amplifying \( \text{FC}_{F_i} \) is positive, the term contributes to the amplification of anomalous MSE. When amplifying \( \text{FC}_{F_i} \) is negative, the term contributes to the damping of anomalous MSE. To note, the sum of all amplifying fractional contribution terms must equal zero, otherwise it would imply a runaway amplification or damping of intraseasonal MSE. Propagating \( \text{FC}_{F_i} \) is the fractional contribution of a particular tendency term to MSE propagation. When propagating \( \text{FC}_{F_i} \) is positive, the term contributes to the propagation of anomalous MSE. When propagating \( \text{FC}_{F_i} \) is negative, the term contributes to the retardation of anomalous MSE.

Figure 9 shows the amplifying fractional contribution of each term during all boreal summer days, without consideration to the enhanced/suppressed MSE index. The average (15°S–15°N, 50°–100°E) effect of the atmosphere forcing is to damp MSE anomalies at a rate of \(-11\% \text{ day}^{-1}\) (Fig. 9a). This is mainly due to MSE horizontal advection (Fig. 9c) with damping contributions from MSE vertical advection in the eastern and central IO as well (Fig. 9e). Net boundary radiation weakly amplifies MSE anomalies in off-equatorial regions (Fig. 9g).

Ocean forcing amplifies MSE anomalies at an average rate of 11% day\(^{-1}\) (Fig. 9b). The amplification of anomalous MSE is largely the result of OHC depletion, which is the strongest contributor of any term in the budget with a basin average rate of 14% day\(^{-1}\) (Fig. 9h). OHC vertical advection amplifies MSE along much of the equatorial IO but has a damping effect in many off-equatorial regions (Fig. 9f). OHC horizontal advection is spatially noisy, with no clear patterns evident (Fig. 9d). When averaged over the basin, OHC vertical advection contributes \(-4\% \text{ day}^{-1}\) and horizontal advection contributes 2% day\(^{-1}\) to MSE amplification.

Figure 10 shows the MSE propagating fractional contribution. Atmosphere processes are overwhelmingly responsible for the propagation of MSE anomalies (Fig. 10a) of which MSE horizontal advection is the leading contributor (Fig. 10c). MSE vertical advection assists propagation in much of the central IO (Fig. 10e). Contributions from radiation to the propagation are comparatively modest (Fig. 10g). The ocean forcing resists MSE propagation in much of the IO, although the basin averaged value is a modest \(-2\% \text{ day}^{-1}\) (Fig. 10b). The contribution by OHC horizontal advection is spatially noisy with no clear large-scale pattern (Fig. 10d). Contributions to propagation by OHC depletion and vertical advection are oppositely signed but of comparable magnitude, with largest magnitudes in the eastern equatorial IO. This suggests that any propagating effect by the depletion of OHC is somewhat offset by the retarding effect of vertical advection there. The overall role of ocean forcing to the propagation of MSE anomalies is weak \((-2\% \text{ day}^{-1})\) during summer.

\textit{b. Boreal winter}

Terms of the moored MSE budget during winter are shown in Fig. 11. By definition, the MSE maximum is located in the southeast IO during enhanced phases, and the MSE minimum is located in the southeast IO during suppressed phases. Horizontal advection (Figs. 11c,d) is the largest contributor to the MSE tendency (Figs. 11a,b). During enhanced periods, horizontal advection of MSE is negative in the western and central equatorial IO with values reaching \(-25 \text{ W m}^{-2}\) (Fig. 11c). Horizontal advection propagates positive MSE away from the central equatorial IO, while also weakening the MSE maximum. Similar but oppositely signed behavior is observed during suppressed periods (Fig. 11d). Vertical advection of MSE damps the MSE anomaly at average
rates of 5–6 W m$^{-2}$ (Figs. 11e,f). Radiation supports the growth of MSE anomalies at average rates of 2–3 W m$^{-2}$ (Figs. 11g,h). Ocean forcing contributes to the growth of anomalous MSE and resists the southeastward propagation of the MSE maximum and minimum at basin average rates of 8 and –7 W m$^{-2}$ during enhanced and suppressed MSE periods, respectively (Figs. 11i,j).

It is the largest contributor to the growth of MSE anomalies, and its role is to amplify intraseasonal MSE anomalies along the equator and resist their eastward propagation. The positive ocean forcing also occurs during anomalously enhanced convection (i.e., negative OLR anomalies) (see Fig. 5a). The effects of ocean forcing are damped by MSE horizontal advection and MSE vertical
advection such that MSE anomalies do indeed propagate away from the central equatorial IO. For any particular intraseasonal event, strongly unbalanced competition between these atmosphere and ocean forcings would significantly modulate the phase speed and/or amplification of anomalous MSE and convection.

Figure 10 shows the components of the ocean forcing term, including OHC depletion and ocean dynamics. OHC depletion is the largest contributor with magnitudes of 50 W m$^{-2}$. Ocean dynamics are predominantly out of phase with OHC depletion with magnitudes of 50 W m$^{-2}$ (Figs. 12c,d). Ocean dynamics are stronger than OHC depletion along the equator and also reduce the
FIG. 11. As in Fig. 7, but for boreal winter.
net effect of OHC depletion in off-equatorial regions. The growth of MSE anomalies by ocean forcing along the equator (Figs. 11i,j) is mainly due to vertical advection (Figs. 12g,h). Similar to boreal summer, the strong equatorial signal of vertical advection is suggestive of Kelvin wave dynamics. Horizontal advection is spatially noisy, with no discernible large-scale patterns (Figs. 12e,f).

The amplifying fractional contribution to MSE by each term of the budget during winter is shown in Fig. 13. The total atmosphere forcing damps MSE anomalies across most of the IO, with minimum MSE growth rates from −20% to −40% day$^{-1}$ in the central equatorial IO. MSE horizontal advection (Fig. 13c) contributes the most to atmosphere forcing and is strongest.
in the central and western IO. In the western IO, MSE vertical advection generally opposes the pattern of horizontal advection with positive growth rates. Vertical advection contributes to negative growth rates in the eastern equatorial IO. Radiation is positive over most of the IO with maximum growth rates of 5%–10% day$^{-1}$ in off-equatorial regions.

The basin-averaged (15$^\circ$S–15$^\circ$N, 50$^\circ$–100$^\circ$E) amplification of MSE by ocean forcing is 9% day$^{-1}$, balancing the equal but opposite damping effect of atmosphere forcing (Figs. 13a,b). The primary contributors to ocean forcing are OHC depletion and vertical advection with maximum amplitudes of 20%–40% day$^{-1}$ along 5$^\circ$S/N and the equator (Figs. 13f,h). OHC depletion has the largest amplifying effect of any term in the budget with a basin average value of 11% day$^{-1}$, compared to ~4% day$^{-1}$ from vertical advection. The patterns of vertical advection and OHC depletion in
the equatorial IO are consistent with known waveguides of oceanic equatorial wave activity, such as equatorial Kelvin waves and equatorial Rossby waves. The amplification of MSE by OHC horizontal advection has locally large amplitudes but is dominated by higher wavenumber spatial variability (Fig. 13d).

Figure 14 shows the propagating fractional contribution during winter. Atmosphere forcing contributes to propagating MSE over the basin at an average rate of 10% day$^{-1}$, like its role during summer (Fig. 14a). MSE horizontal advection is the leading contributor to MSE propagation with an average rate of 8% day$^{-1}$ (Fig. 14c). MSE vertical advection also contributes to propagation over much of the IO with an average rate of 2% day$^{-1}$. Net boundary radiation is noisy with a weak overall contribution. (Figs. 14e,g).

The fractional contribution of net ocean forcing to MSE propagation is relatively weak with a basin average value of $-2\%$ day$^{-1}$ (Fig. 14b). A few discernible patterns are evident
in OHC vertical advection and depletion (Figs. 14f,h). OHC depletion assists propagation in parts of the southwest, equatorial, and eastern IO, with vertical advection largely opposing it in those regions. The competition between the two generally results in a muted net effect. OHC horizontal advection does not appreciably contribute to the large-scale propagation of MSE anomalies, although roles for localized and small-scale contributions may exist.

6. Summary

We present a framework for examining sources and sinks of MSE that include detailed treatments of ocean dynamics. The processes by which the ocean forces subseasonal MSE energy exchanges have previously been limited to examinations of surface fluxes. While these studies have yielded significant insight into the dynamics of ISOs, they relegate the role of ocean dynamics to those processes that modulate the SST and, by extension, surface fluxes. The moored MSE budget reframes these interactions such that the roles of ocean processes, like OHC depletion, advection, and mixing, are directly quantified.

Coherence between intraseasonal MSE and OHC anomalies in the IO increases with increasing period such that the strongest relationship occurs in the low-frequency band of subseasonal time scales. Their phase relationship is also highly regional, such that they are in phase in portions of the equatorial western IO, but out of phase in the equatorial eastern IO. During periods of enhanced MSE, OHC anomalies are positive in the western and central IO, and negative in the eastern IO. The behavior of OHC is a departure from that of SST, which anomalously cools in much of the equatorial IO. The unconventional behavior of OHC suggests that it supports MSE growth during periods of enhanced intraseasonal convection. The modulation of MSE by OHC is explored using the moored MSE budget.

The moored MSE budget reveals many new insights of intraseasonal air–sea interactions. In off-equatorial regions, OHC generally acts as a reservoir of anomalous MSE that is filled during suppressed MSE periods and drained during enhanced MSE periods. Along the equator, OHC and MSE are simultaneously amplified by OHC vertical advection. In simple terms, during enhanced MSE periods, the OHC generated by OHC vertical advection exceeds that which is stored in the ocean, leading to atmosphere uptake. We provide the following description as an example of how this might occur. Westerly surface winds associated with enhanced ISO convection can trigger downwelling equatorial Kelvin waves in the ocean. The westerly winds force Ekman convergence along the equator, which, by continuity, forces downward currents that advect warm water near the surface to deeper levels. In the moored MSE budget, any OHC generated by vertical advection that is not stored in the ocean generates MSE in the atmosphere. Along the equator during periods of suppressed MSE, OHC is decreased by vertical advection. This depletion is somewhat mitigated by the transfer of MSE into the ocean.

The moored MSE budget can also be used to concisely quantify the processes in the atmosphere and ocean that regulate MSE amplification and propagation. The fractional contribution of each term in the budget to the growth and propagation of MSE anomalies is shown for all seasons in Fig. 15. Vertical OHC advection damps MSE amplification (−4% day\(^{-1}\)) and retards MSE propagation (−5% day\(^{-1}\)), horizontal OHC advection weakly contributes to amplification (2% day\(^{-1}\)) and negligibly contributes to propagation, and OHC depletion strongly amplifies (12% day\(^{-1}\)) and weakly enhances propagation (3% day\(^{-1}\)). As a result, the net ocean forcing amplifies MSE anomalies by 10% day\(^{-1}\) and slows their propagation by −2% day\(^{-1}\).

Individual intraseasonal events may depart from these composite results, and processes like OHC horizontal advection may at times have coherent large-scale patterns of MSE.
forcing that are obfuscated by the averaging techniques used in this investigation. Moreover, the role of ocean forcing may be qualitatively different for primary versus successive intraseasonal events, especially when considering the forced response of the ocean, which may feed back onto consecutive events (e.g., Moum et al. 2016; Webber et al. 2010). While this study has focused on intraseasonal time scales, the moored MSE budget may also prove useful for investigating other modes of organized convection that are sensitive to changes in OHC, such as El Niño–Southern Oscillation and tropical cyclones. Future work involves analyzing the moored MSE budget of individual intraseasonal events using in situ observations as well as coupled models that output online calculations of budget terms.

Acknowledgments. This work was supported by the U.S. Naval Research Laboratory 6.1 project IRCSOME and ONR department research initiatives MISO-BoB and PISTON. We appreciate comments from three anonymous reviewers and help from Charlotte Demott, Brandon Wolding, James Ruppert, and Matt Igel.


REFERENCES


Jensen, T. G., T. Shinoda, S. Chen, and M. Flaatau, 2015: Ocean response to CINDY/DYNAMO MJOs in air–sea-coupled...


