Intraseasonal Variability and Seasonal March of the Moist Static Energy Budget over the Eastern Maritime Continent during CINDY2011/DYNAMO

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Abstract

This study analyzes radiosonde observations and other datasets to examine variability in the moist static energy (MSE) budget over the eastern Maritime Continent during the CINDY2011/DYNAMO field campaign of October 2011–March 2012. During this period, five events bearing key characteristics of the Madden–Julian oscillation (MJO) are identified. Our analysis focuses on both these events and longer-term seasonal evolution.

On the seasonal time scale, the characteristics of column-integrated MSE budget are different between periods before and after the Australasian summer monsoon onset in early December. Both the net source term (the sum of surface turbulent fluxes and radiative heating) and the net advection term (the sum of horizontal and vertical advection of MSE) have small magnitudes before the onset. After the onset, the source term becomes large and positive, while the advection term becomes large and negative.

On the intraseasonal scale, both the source and advection terms fluctuate as the MJO events come and go. The surface fluxes and radiative heating contribute to the maintenance of the amplitude of column-integrated MSE anomaly and thus to the intensity of MJO. The vertical advection term, along with horizontal advection term, seems to contribute to the phase progression and eastward propagation of MJO, mainly because of lower-tropospheric descent after the precipitation and MSE maxima, presumably associated with rain re-evaporation.

This study also examines how the MSE budget would be different if key components of the budget were parameterized by two assumptions used in recent idealized models of MJO: (1) the column-integrated radiative heating anomaly is considered proportional to the column water vapor anomaly and (2) the normalized gross moist stability is considered constant. We find that the former tends to speed up the phase progression of MJO, while the latter tends to slow it down.

Keywords MJO; Maritime Continent; moist static energy budget; CINDY2011/DYNAMO; Australasian monsoon

1. Introduction

Since its discovery in 1971, Madden–Julian oscillation (MJO; Madden and Julian 1971, 1972) has posed one of the central problems of tropical meteorology. Since MJO has a widespread impact on daily weather not only in the tropics but also in the extratropics and
since MJO has an intraseasonal (30–60 day) time scale that is longer than the typical synoptic scale of midlatitude weather, we may expect that improvements in MJO prediction may lead to improvements in medium-range weather forecasts (Gottschalck et al. 2010). On the other hand, dynamical understanding of MJO’s essential mechanisms, which we expect to be important for improving prediction skill, is still elusive despite much research. Various different idealized models have been proposed to explain the dynamics underlying MJO’s intraseasonal time scale, planetary horizontal scale, and eastward propagation speed.

One school of thought holds that MJO is a moisture mode, meaning a mode that depends on a prognostic moisture equation; thus, it has no counterpart in a dry atmosphere (Fuchs and Raymond 2002, 2005, 2007; Majda and Stechmann 2009; Sugiyama 2009a, b; Sobel and Maloney 2012, 2013; Sobel et al. 2014, and others). We advocate the view that MJO in particular is a moisture mode in which the interactions of surface turbulent fluxes and atmospheric radiation with cumulus convective activity are important (Sobel et al. 2008, 2010). Because these processes are sources of column-integrated moist static energy (MSE) or moist entropy, it may be useful to focus attention on the budget of that quantity as it varies in association with MJO events. The column-integrated MSE and moist entropy budgets have been studied using numerical simulation outputs (Maloney 2009; Andersen and Kuang 2012; Hannah and Maloney 2014; Benedict et al. 2014; Wang et al. 2015) and reanalysis datasets (Kiranmayi and Maloney 2011; Kim et al. 2014).

The necessary data to examine the MSE budget in detail can be sought in the results of several field campaigns conducted in the tropics. The Tropical Ocean Global Atmosphere program Coupled Ocean-Atmosphere Response Experiment (TOGA COARE; Webster and Lukas 1992) conducted a field campaign over the equatorial western Pacific in 1992/93 austral summer, and the Cooperative Indian Ocean Experiment on Intraseasonal Variability in the Year 2011 (CINDY2011)/Dynamics of the MJO (DYNAMO) project conducted a field campaign focusing on central Indian Ocean in 2011/12 austral summer (Yoneyama et al. 2013). While there have been a number of studies performing budget analyses of dry static energy (DSE) and moisture using data obtained during these campaigns (Lin and Johnson 1996a, b; Johnson and Ciesielski 2000, 2013; Johnson et al. 2015, and others), only a few studies have focused on MSE budget (Sobel et al. 2014; Inoue and Back 2015). Sobel et al. (2014, hereafter SWK) examined the column-integrated MSE budget over the Indian Ocean using datasets collected by the CINDY2011/DYNAMO project together with complementary data. Their results were broadly consistent with the view of MJO as a moisture mode whose growth and maintenance depend on the surface fluxes and radiation, while its propagation depends on horizontal moisture advection, and to some extent, vertical advection of MSE as well.

Between the western Pacific and Indian Ocean lies the Maritime Continent (MC) region. MC covers the equatorial band from 90°E through 160°E and is characterized by a complicated geography with tremendous islands of various shapes and sizes. These islands certainly alter the structure and behavior of MJO, although different studies emphasize different mechanisms by which they do so. Peatman et al. (2014) revealed that the convective response to MJO has different features over land and ocean; active convection over land tends to precede that over the surrounding ocean by about a week. The structure of circulation anomalies associated with MJO is also modulated by topography (Hsu and Lee 2005). The diurnal cycle in convective activity over and around islands (Mori et al. 2004) interacts with MJO (Ichikawa and Yasunari 2008; Rauniyar and Walsh 2011; Peatman et al. 2014), which may contribute to its eastward propagation (Ichikawa and Yasunari 2007). On the other hand, the view of MJO as driven by surface fluxes and radiation implies that the low heat capacity of the land surface should cause MJO-related intraseasonal variability in convection to weaken over land, consistent with what is observed (Sobel and Gildor 2003; Sobel et al. 2010). Because of these differences between MJO’s properties over MC and those over the Indian Ocean and western Pacific, it seems worth examining the MSE budget over MC. However, MC has received less attention so far than the ocean basins to its west and east, presumably because of the shortage of adequate observations. The CINDY2011/DYNAMO project collected raw data of routine radiosonde observations at stations over MC (Fig. 1) during the field campaign period. During this period, several MJO events developed and traveled across MC (Yoneyama et al. 2013; Gottschalck et al. 2013). Although the sounding interval is 12 h, longer than that over western Pacific during TOGA COARE and over Indian Ocean during CINDY2011/DYNAMO, it is still worth attempting to perform budget analysis using the radiosonde data.
over MC and comparing the results with those of previous studies, which are the main purposes of this study.

The MSE budget equation is further used to develop mathematical models of MJO. Sobel and Maloney (2012, 2013, hereafter SM) used a variant of the column-integrated MSE budget equation as the single prognostic equation in a simplified mathematical model. In designing such mathematical models, we usually make a number of assumptions to simplify the governing equations, making possible analytical treatment of the models. While the validity of these assumptions is usually tested by the statistical relationship, we expect that field observation campaigns are good opportunities to further test the validity through detailed case studies. This study will use the radiosonde data collected during CINDY2011/DYNAMO to test assumptions about radiative heating and vertical advection that were made, for example, by SM.

The reminder of this paper is organized as follows. In Section 2, we describe the datasets and analysis method. We present the overall characteristics of the observations during the target period in Section 3.1 and the MSE budget in Section 3.2. Section 3.3 presents results of the validity test of the assumptions about the radiative heating and vertical advection. Finally, a summary is presented in Section 4.

2. Data and methods

2.1 Data

We analyzed radiosonde sounding data obtained at eight stations marked by the letters A–H in Fig. 1 and listed in Table 1. Stations A–G constitute a heptagonal sounding array with station H located near its center.

![Radiosonde stations](image)

**Table 1.** Name, location, and altitude of radiosonde stations.

<table>
<thead>
<tr>
<th>ID</th>
<th>Station name</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Manado</td>
<td>124.92°E</td>
<td>1.54°N</td>
<td>80 m</td>
</tr>
<tr>
<td>B</td>
<td>Biak</td>
<td>136.10°E</td>
<td>1.19°S</td>
<td>10 m</td>
</tr>
<tr>
<td>C</td>
<td>Merauke</td>
<td>140.41°E</td>
<td>8.52°S</td>
<td>3 m</td>
</tr>
<tr>
<td>D</td>
<td>Darwin</td>
<td>130.89°E</td>
<td>12.42°S</td>
<td>30 m</td>
</tr>
<tr>
<td>E</td>
<td>Kupang</td>
<td>123.67°E</td>
<td>10.18°S</td>
<td>137 m</td>
</tr>
<tr>
<td>F</td>
<td>Makassar</td>
<td>119.53°E</td>
<td>5.06°S</td>
<td>12 m</td>
</tr>
<tr>
<td>G</td>
<td>Palu</td>
<td>119.91°E</td>
<td>0.92°S</td>
<td>84 m</td>
</tr>
<tr>
<td>H</td>
<td>Ambon</td>
<td>128.10°E</td>
<td>3.71°S</td>
<td>10 m</td>
</tr>
</tbody>
</table>

While MC is characterized by complicated geography with several very large islands, more than 90% of the array area is covered with ocean. Twice-daily (00UTC and 12UTC) observations for the period from October 1, 2011 to March 31, 2012 were analyzed. Observations were performed four times daily at station D; however, we did not use the 06UTC and 18UTC data, for consistency with the other stations. Variables analyzed include pressure, horizontal wind, geopotential height, temperature, and relative humidity. The mean sea level pressure was also analyzed, which was calculated using the hydrostatic equation and assuming constant potential temperature.

While the observed data were stored at 2-second (station D) or 1-second (other stations) intervals, we averaged them into 10-hPa bins and then applied vertical interpolation to fill in any missing data. Furthermore, there are about 5% of soundings that data were almost wholly missing. We applied temporal interpolation to fill in the missing data in this case. Before applying temporal interpolation, we calculated 7-day running mean for 00UTC and 12UTC data separately and subtracted the difference between them (running mean for 00UTC minus that for 12UTC) from the 00UTC data to diminish the diurnal cycle component. After the interpolation, we added the difference to the 00UTC data. These interpolation procedures enable us to examine the MSE budget over the entire 6-month target period, except for short periods in late November 2011 and in early January 2012.

In addition to the radiosonde observations, we analyzed data from the European Centre for Medium-Range Weather Forecast (ECMWF) Interim Reanalysis (ERA-Interim; Dee et al. 2011) and Japan Meteorological Agency (JMA) 55-Year Reanalysis (JRA-55; Kobayashi et al. 2015) for comparison. The horizontal resolution of ERA-Interim is 0.75°, while that of JRA-55 is 1.25°. Both are available at 6-hour time intervals. The three-dimensional distributions of...
horizontal wind, vertical wind, temperature, geopotential height, and specific humidity as well as mean sea level pressure from these data were analyzed.

We used the Tropical Rainfall Measurement Mission (TRMM) 3B42 version 7A (Huffman et al. 2007) and Global Precipitation Climatology Project 1-Degree Daily Combination version 1.2 (GPCP-1DD; Huffman et al. 2009) data to calculate precipitation averaged over the sounding area. We also used data from Clouds and Earth’s Radiant Energy System (CERES; Wielicki et al. 1996) to calculate area-averaged column-integrated radiative heating, Objectively Analyzed air-sea Fluxes (OAFlux; Yu et al. 2008) to calculate area-averaged column-integrated moisture. Note that OAFlux and SSMIS data are available only over the ocean.

2.2 Methods

MSE, \( h \), is defined as \( h \equiv s + q \), where \( s \equiv C_p T + g z \) is DSE, \( q \) is the specific humidity having the energy unit \([J \text{ kg}^{-1}]\) after multiplication by the specific heat of vaporization \( L = 2.5 \times 10^6 \text{ [J kg}^{-1}]\); \( C_p = 1004 \text{ [J kg}^{-1} \text{ K}^{-1}]\) is the specific heat with constant pressure, \( T \) is temperature, \( g = 9.8 \text{ [m s}^{-2}]\) is the gravitational acceleration, and \( z \) is the geopotential height. The budget equations of column-integrated DSE, moisture, and MSE are

\[
<\partial_t s> + <u \cdot \nabla s> + <\omega \partial_p s> =<R> + P + H \equiv<Q_1>,
\]

\[
<\partial_t q> + <u \cdot \nabla q> + <\omega \partial_p q> = E - P \equiv -<Q_2> \tag{2}
\]

and

\[
<\partial_t h> + <u \cdot \nabla h> + <\omega \partial_p h> =<R> + E + H \equiv<Q_1 - Q_2>, \tag{3}
\]

respectively, where \( u \) is the horizontal wind vector, \( \omega \) is the vertical pressure velocity, \( R \) is the radiative heating, \( P \) is precipitation, \( H \) is SHF, and \( E \) is LHF. \( Q_1 \) and \( Q_2 \) are the so-called apparent heat source and apparent moisture sink, respectively (Yanai et al. 1973). The angle brackets indicate mass-weighted vertical integration over the troposphere:

\[
<>() \equiv \frac{1}{g} \int_{p_h}^{p_t} () dp, \tag{4}
\]

where \( p_t \) is pressure at a nominal constant tropopause pressure and \( p_h \) is the mean sea level pressure. Here we assume \( p_t = 100 \text{ [hPa]}\).

Equation (3) states that the tendency of column-integrated MSE \( <\partial_t h> \) is caused by horizontal advecton \( (<u \cdot \nabla h>) \), vertical advection \( (<\omega \partial_p h>) \), and the net source \( (<q_1 - q_2>) \), the latter of which consists of the sum of column-integrated radiative heating, LHF and SHF. The tendency, horizontal advection, and vertical advection terms are estimated from radiosonde sounding data or reanalysis data, while radiative heating is obtained from the CERES dataset, and LHF and SHF are obtained from the OAFlux dataset.

Besides the fact that the MSE budget is central to the moisture mode view as introduced in Section 1, there is another advantage of examining the MSE budget over the DSE and moisture budgets, as demonstrated in Fig. 2. This figure shows the amplitude of the intraseasonal anomalies of column-integrated DSE, moisture, and MSE budget terms over the target period, measured by the standard deviation. Here, the intraseasonal-scale anomaly is defined as the sum of terms in the Fourier series corresponding to frequencies of 3, 4, 5, and 6 cycles in 183 days (30.5–61-day periods). The amplitudes are normalized by those of the vertical advection terms in the individual equations. For the DSE budget (Fig. 2a), the vertical advection and apparent heat source terms dominate, with amplitudes more than 10 times larger than those of the tendency and horizontal advection terms. This justifies the application of the weak temperature gradient approximation (Charney 1963; Sobel et al. 2001) to the intraseasonal variability. The moisture budget (Fig. 2b) is similar, with tendency term’s amplitude only slightly greater than 10 % of those of the vertical advection and apparent moisture sink terms. In short, the DSE and moisture budget equations primarily represent balances between vertical advection and source/sink terms, and the smallness of the tendency terms implies that these terms are negligible to first order in their respective budgets. Therefore, it is hard to assess the mechanisms for the temporal evolution of DSE and moisture through analysis of the budget equations. The MSE tendency term, on the other hand, has an amplitude that is approximately 50 % of those of vertical advection and source terms (Fig. 2c) and is thus not negligible in the MSE budget equation. This simplifies the attribution of MSE variations to terms in the budget, including allowing us to understand how different terms contribute to growth and maintenance vs. propagation.
of the MSE anomalies.

Figures 2a, b further show that precipitation has much larger amplitude than LHF and SHF. Since the precipitation term cancels out when combining Eqs. (1) and (2), the amplitudes of the source term in the MSE budget equation becomes considerably smaller than those of the apparent heat source and moisture sink terms in the DSE and moisture budgets, respectively. Of the components of the column-integrated MSE source term \(\langle Q_1 - Q_2 \rangle\), LHF has the largest amplitude, and radiative heating takes second place, while SHF is much smaller.

Hereafter, time series of variables and budget terms shown in figures and used for regression analyses are 5-day running averages unless otherwise stated.

3. Results and discussion

3.1 Overall characteristics

Before presenting the MSE budget results, we present an overview of convective activity and atmospheric conditions during the target period (October 2011–March 2012). The longitude-time distribution of daily-mean TRMM 3B42 precipitation averaged over the 15°S–5°N band is shown in Fig. 3. The most striking signal propagating eastward from the Indian Ocean to the western Pacific is found during February–March 2012. It passes over the sounding array in the first half of March. Three additional eastward-propagating signals pass over the sounding array in early November, early December, and late December 2011, although the precipitation resulting from these events over the array is much smaller than that resulting from the February–March event. These four events were identified as MJO events by Yoneyama et al. (2013), while Gottschalck et al. (2013) did not consider the third event as an MJO event. Whether a certain event is an MJO event or not is sometimes debatable as there is no universally recognized definition.

In addition to these four events, there are three heavy precipitation signals in January 2012 at around 110°E, 130°E (middle of the sounding array), and 160°E, which seem to be associated with an eastward-propagating signal. Local phase relationships over the sounding array between moisture, precipitation, and wind associated with this signal are reminiscent of MJO, as will be shown later. Furthermore, the multivariate MJO index (Wheeler and Hendon 2004) shows eastward propagation from MC to the western Pacific with non-negligible amplitude (Fig. 11 of Gottschalck et al. 2013). Based on these diagnostics, we consider this event to be an additional MJO event.
although previous studies did not. In total, during the target period, there are five MJO events, which are shown by ellipses with a bold dashed line in Fig. 3. Note that MJO-5 (the fifth event) in this study was referred to as MJO-4 in Yoneyama et al. (2013).

Precipitation time series averaged over the sounding array are plotted in Fig. 4a. Precipitation estimated from Eq. (2) with the use of radiosonde data and OAFlux LHF agrees well with GPCP-1DD and TRMM 3B42. Maxima in precipitation are observed when the five MJO events pass over the sounding array, indicated by dashed vertical lines. Among the five MJO events, MJO-5 is associated with the heaviest precipitation. In addition to the precipitation maxima apparently associated with these events, there are several other maxima in late October, late November, and February. The time intervals between these and MJO-related maxima suggest that precipitation over the sounding array has a component with a quasi-biweekly time scale, particularly during November–January.

Figure 4b presents the column water vapor averaged over the sounding array, showing that the radiosonde data agree well with SSMIS. It exhibits an increasing trend over October–December, followed by a near-zero trend through March. The precipitation maxima associated with the five MJO events are accompanied by column water vapor maxima, with
precipitation slightly lagging water vapor. This phase relationship between precipitation and column water vapor has been reported previously (Yasunaga and Mapes 2012; SWK). In addition, several non-MJO precipitation maxima are accompanied by column water vapor maxima. Similar to precipitation, column water vapor seems to have a quasi-biweekly component. This quasi-biweekly feature is intriguing and deserves further research, although this is beyond the scope of the present paper.

Figure 5 shows vertical profiles of various variables averaged over the sounding array as observed by the radiosondes. Zonal wind (Fig. 5a) in the lower troposphere is dominated by easterlies in October–November, followed by an abrupt shift to westerlies in early December, which is associated with the passage of MJO-2. This shift can be interpreted as the onset of the Australasian summer monsoon (Holland 1986; Hendon and Liebmann 1990a). After the onset, westerly winds last until early February, and then weak easterlies are observed until early March, followed by strong westerlies.

On the intraseasonal time scale, lower-tropospheric westerly wind strengthens, or easterly wind weakens, indicating westerly anomalies compared with the longer-term mean after the precipitation maxima associated with the MJO events. In the upper troposphere, easterly winds amplify after the precipitation maxima do, except in the case of MJO-3. These result in increases in easterly vertical shear. The phase lag between lower tropospheric zonal wind and precipitation is consistent with the statistical study of sounding data at Darwin by Hendon and Liebmann (1990b), and it is a characteristic of MJO in the Indian Ocean rather than in the western Pacific (Zhang 2005).

The vertical profile of meridional wind (Fig. 5b) in the lower troposphere is characterized by amplification of northerly wind after the precipitation maxima of MJO-2, MJO-3, MJO-4, and MJO-5. The height of the strongest northerly wind is below that of the westerly wind maxima. The northerly wind was also pointed out by Hendon and Liebmann (1990b), although they reported no phase lag between meridional wind and precipitation.

The seasonal march of relative humidity (Fig. 5c) is characterized by increases from October through November, particularly in the lower free troposphere above the 800-hPa level. During December–March, periods with high relative humidity coincide with precipitation maxima. Relative humidity variability associated with MJO-5 exhibits the largest amplitude of the period and shares several aspects with MJO events reported in previous studies. Lower-tropospheric moisture increases gradually during the period from February 24 to March 4, about 1–2 weeks before the precipitation maximum. The middle troposphere then moistens quickly, close to the time of the precipitation maximum. After the maximum, rapid drying is observed in the 800–600-hPa layer. These features are consistent with those observed in previous studies using field campaign data over the Indian Ocean (Johnson and Ciesielski 2013) and the western Pacific (Lin and Johnson 1996a) and satellite data (Tian et al. 2006). The other MJO events exhibit similar temporal evolution but weaker amplitude.

Precise estimation of the vertical pressure velocity is essential for the estimation of the vertical advection of MSE because it is sensitive not just to the magnitude but also to the detailed structure of the vertical profile of vertical pressure velocity. Figure 5d shows the vertical profile of vertical pressure velocity estimated from radiosonde data. Periods of strong, deep ascent coincide with precipitation maxima associated with the five MJO events. In MJO-5, shallow ascent in the lower troposphere first appears in February 25–March 4, followed by deep ascent during the precipitation maximum. Following this, lower-tropospheric descent emerges beneath the remaining ascent. Similar features can also be observed in MJO-2, MJO-3, and MJO-4. Results from reanalysis data are broadly similar (Fig. 6), although they exhibit smaller fluctuation than the radiosonde data in the lower troposphere. Similarity and difference in resultant vertical advection of MSE will be examined in the next section.

Consistent with the vertical pressure velocity, the evolution of the horizontal divergence profile associated with MJO-5 is characterized by elevation of horizontal convergence from the lower troposphere (around February 25) through the middle troposphere (around March 20), with shallow divergence in the lower troposphere after the precipitation maximum. These are well-known features of MJO events, as pointed out by a number of studies, and are considered to be associated with the transition from shallow congestus to deep convection, followed by stratiform precipitation (Lin and Johnson 1996b; Kemball-Cook and Weare 2001; Sperber 2003; Kikuchi and Takayabu 2004; Lin et al. 2004; Kiladis et al. 2005; Mapes et al. 2006). In the stratiform precipitation regime, lower tropospheric descent is considered to be an adiabatic response to cooling associated with the re-evaporation of rainfall. On the other hand, the coexistence of surface divergence and lower-tropo-
Fig. 5. Vertical profiles of (a) zonal wind, (b) meridional wind, (c) relative humidity, (d) vertical pressure velocity, and (e) horizontal divergence derived from radiosonde data averaged over the sounding array. Information of contour interval is shown at the upper right of each panel. Solid (dashed) contours represent positive (negative) values. Gray tone indicates missing data. Vertical dashed lines are the same as those in Fig. 4.
spheric westerly wind, which can be found not only after MJO-5 but also after MJO-3 and MJO-4, is reminiscent of frictional divergence. The surface convergence ahead of the precipitation maxima, however, may not be frictional (Ekman) in origin because the lower tropospheric wind is either westerly or at most weak easterly, except in the case of MJO-1.

3.2 MSE budget

In this section, the temporal evolution of the column-integrated MSE budget is examined. First, we compare time series of variables estimated from radiosonde data with those estimated from reanalysis, CERES, and OAFlux data. The red line in Fig. 7a shows the column-integrated MSE derived from radiosonde data, and Fig. 7b shows those derived from two reanalysis datasets. Apart from systematic offsets, these three time series exhibit quite similar features. Figures 7c–f show time series of various terms in the column-integrated MSE budget Eq. (3). The red line in Fig. 7c shows the source term estimated from radiosonde data, while the blue line shows that calculated from CERES and OAFlux. While the former is noisy compared with the latter in October–November, they are in good agreement during December–March. The horizontal advection term estimated from radiosonde data (red line in Fig. 7e) is also generally in good agreement with that from reanalysis datasets (black and blue lines), although the former has a positive bias compared with the latter throughout the period. For the vertical advection term (Fig. 7f), radiosonde data are in good agreement with JRA-55, while ERA-Interim seems to have smaller amplitude of its fluctuation associated with MJO. The column-integrated MSE exhibits an overall increasing trend during October–December and then decreases back to its early December level in January and February, followed by an intraseasonal-scale fluctuation in March associated with MJO-5. It can be said that MSE before the monsoon onset in early December is characterized by an increase trend, while that after the onset is dominated by subseasonal variability with almost no seasonal-scale trend. These features are broadly consistent with those in column water vapor (Fig. 4b).

The seasonal characteristics of the MSE budget, like those of MSE itself, are different before and after the monsoon onset in early December. Before
the onset, both the source and advection terms are very small (Fig. 7c). The source term becomes large and positive after the onset because of increases in both the radiative heating and LHF with comparable magnitude (Fig. 7d). The advection term becomes large and negative after the onset, primarily because of the vertical advection term (Fig. 7f). These results mean that during the summer monsoon season, atmospheric circulation vigorously exports MSE that is supplied by surface fluxes and decreased radiative cooling.

Figure 8b shows vertical profiles of the source term estimated from radiosonde data. Before the monsoon onset, negative values are found in the lower troposphere below the 700-hPa level and positive values above, nearly canceling in the vertical integral. The negative values are primarily due to positive apparent moisture sink (Fig. 9b). On the other hand, after the onset, the source term increases both in the lower and upper troposphere. In the upper troposphere, both the apparent heat source (Fig. 9a) and moisture sink increase; the apparent heat source increases more rapidly. In the lower troposphere, the apparent heat source does not change significantly, but the apparent moisture sink decreases.

Before the onset, the vertical advection term estimated from radiosonde data (Fig. 8d) exhibits positive values in the lower troposphere below 600 hPa and negative values above, which nearly cancel in the integral. After the onset, the term in the upper tropo-
Fig. 8. The same as that in Fig. 5, but (a) MSE tendency, (b) source term \((Q_1 - Q_2)\), (c) horizontal advection term, and (d) vertical advection term of MSE budget equation (Eq. 3). Note that the contour interval in (a) is a half of the other panels.
sphere tends to become more negative. This difference between periods before and after the onset is due to differences in the vertical profile of vertical pressure velocity; the profile after the onset is more top-heavy than that before the onset (Figs. 5d, 6).

On the subseasonal time scale, while the fluctuations of column-integrated MSE have a significant quasi-biweekly component, particularly during October–January, its maxima are approximately coincident with the precipitation maxima of MJO-1, MJO-2, MJO-4, and MJO-5. As for MJO-3, although a local MSE minimum is observed at the precipitation maximum, an intraseasonal-scale increase occurs in the second half of December, followed by a decrease in the first half of January. Consistently, the tendency of column-integrated MSE tends to be positive before the precipitation maxima and negative after them. These positive and negative tendencies tend to have a vertically in-phase structure (Fig. 8a).

The source term (Fig. 7c) increases in the buildup to the MJO events’ precipitation maxima and reaches its own maxima approximately simultaneously, with the exception of MJO-1. After the precipitation maxima associated with the latter four MJO events, the source term decreases. For MJO-3, MJO-4, and MJO-5, this decrease seems to be more gradual than the increase just before it. For example, associated with MJO-5, the source term increases from nearly zero in late February, when MSE minimum is found, to approximately 120–130 W m\(^{-2}\) at the time of the precipitation maximum and then remains nearly constant for 10 days. LHF and column-integrated radiative heating (Fig. 7d) contribute to these features with comparable magnitude. The fact that the source term tends to co-vary with MSE fluctuations associated with MJO suggests that this term contributes to the maintenance of the amplitude of MSE anomalies and thus to the intensity of MJO. On the other hand, the more gradual decreases later suggest that this term tends to hinder the phase progression of the MSE.

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Fig. 9. The same as that in Fig. 5, but (a) apparent heat source \(Q_1\) and (b) apparent moisture sink \(Q_2\) terms.
anomaly and thus the eastward propagation of MJO.

The advection term varies nearly oppositely to the source term (Fig. 7c). For all of the five MJO events, this term decreases before the precipitation maxima and increases later, and the increase tends to be more gradual than the decrease. The horizontal advection term (Fig. 7c) decreases at and around the time of precipitation maxima; it is more negative after the precipitation maxima than before them. This means that this term co-varies with the MSE tendency; thus, assuming that the tendency is associated more with phase progression than with disturbance growth, this term contributes to the phase progression of the MSE anomalies in all the MJO events. The negative values after the precipitation maxima are particularly found in the lower free troposphere between 900 and 500 hPa (Fig. 8c).

On the other hand, the vertical advection term (Fig. 7f) decreases before the precipitation maxima of all five MJO events. After that, this term remains large and negative for MJO-3 and MJO-4 and decreases further for several days in the case of MJO-5. The vertical profile (Fig. 8d) reveals that after the precipitation maxima of MJO-3, MJO-4, and MJO-5, negative values are observed not only in the upper troposphere but also in the lower troposphere, with a secondary negative maximum at around 900 hPa. The lower-tropospheric negative values are caused by descending motion (Fig. 4d) because MSE decreases with height in the lower troposphere. Note that these negative values are also found in results of the reanalysis datasets (figure not shown) but with smaller amplitude, which is due to weaker descent in the reanalysis datasets (Figs. 5d, 6). These mean that the vertical advection term opposes the maintaining effect of the source term for all of the MJO events and furthermore tends to contribute to the phase progression for MJO-3, MJO-4, and MJO-5.

To summarize the contribution of the individual budget terms on the maintenance of the amplitude of MSE anomaly, we calculated regression coefficients of the column-integrated budget terms on column-integrated MSE during the period of Australasian summer monsoon (December 7, 2011 to the end of the target period), shown in Fig. 10a. Both radiative heating and LHF have large and positive values, indicating that they contribute to the maintenance, with the former having slightly larger magnitude than the latter. On the other hand, the vertical advection term has a negative value, indicating that it opposes the maintaining effect. Coefficients of the horizontal advection and SHF have much smaller magnitude.

Figure 10b shows regression coefficients of the column-integrated budget terms on column-integrated MSE tendency, which measure contribution of the terms on phase progression of the MSE anomaly. It is shown that both advection terms contribute to the phase progression, with vertical advection having slightly larger magnitude than horizontal advection. On the other hand, radiative heating and LHF tend to hinder the phase progression, although their hindering effects are considerably weaker than the speeding effects of the advection terms.

These results are qualitatively very similar to those of SWK and confirm the idea that radiative heating
and LHF are important for the maintenance of intra-seasonal MSE anomalies associated with MJO, while the advection term contributes to the phase progression and eastward propagation (Sobel et al. 2008, 2010; Maloney 2009; Kiranmayi and Maloney 2011; Andersen and Kuang 2012; SM; Kim et al. 2014; Benedict et al. 2014; Kerns and Chen 2014). In addition, consistently with SWK, we find that both horizontal and vertical advection terms contribute to phase propagation.

### 3.3 Impact of assumptions for simplification

In this section, we examine two assumptions sometimes made in idealized models of tropical dynamics, including that of SM for MJO.

The first one is that the column-integrated radiative heating anomaly is proportional to the precipitation anomaly, which is further assumed to be proportional to the column water vapor anomaly. This assumption is justified by a statistically significant linear relationship between radiative heating and precipitation anomalies (Bretherton and Sobel 2002; Lin and Mapes 2004) and a linearized representation of the nonlinear relationship between precipitation and column water vapor (Bretherton et al. 2004; Peters and Neelin 2006). However, the well-known transition feature of convective characteristics over the course of the MJO phase (Lin and Johnson 1996b; Kemball-Cook and Weare 2001; Kikuchi and Takayabu 2004; Lin et al. 2004; Mapes 2006) suggests that the statistical relationship between them varies over the course of the MJO phase as a broad upper-tropospheric cloud deck in the stratiform regime is expected to cause a larger reduction rate of the radiative cooling per unit precipitation anomaly during this regime than during the preceding congestus and deep convection regimes.

To examine the validity of this assumption in the MSE budgets shown above, we calculated anomalies from the seasonal march, defined here as the sum of the time mean, linear trend, and first two harmonics (with 183- and 92.5-day periods) of the 6-month time series. Following this, we calculated linear regression coefficients between the column-integrated radiative heating anomaly from CERES data and the column water vapor anomalies from both radiosonde and reanalysis data (second column of Table 2). Using these values, the anomaly of column-integrated radiative heating is estimated from its seasonal march and column water vapor anomaly. Figures 11a–c compare the column-integrated radiative heating from the CERES data alone (black) and that estimated using the relationship to the water vapor anomaly as just described (red). The estimated radiative heating follows that observed well during October–early November, while fluctuating with smaller amplitude than that observed during December–February. When focusing on MJO-5, we can find that while the estimated radiative heating using both radiosonde and reanalysis data have a maximum value at the precipitation maximum, which is close to that of the original one, an overestimation and underestimation are found before and after, respectively, the precipitation maximum. Similar features can also be found during the other MJO events. A pair of such overestimation and underestimation can be observed for the precipitation maximum of MJO-1, although their magnitudes are smaller than those associated with MJO-5. After the MJO-4 precipitation maximum, another maximum of original radiative heating in early February is not reproduced by the estimated one, resulting in underestimation. The maximum values around the time of the precipitation maxima are reasonably estimated for MJO-1, MJO-4, and MJO-5. For MJO-2 and MJO-3, this assumption does not represent the fluctuation of the radiative heating well because the radiative heating anomalies are larger than those estimated from water vapor.

The overestimation before the precipitation maximum and underestimation after it indicate that making this assumption in an idealized model will cause the model to lack the retarding effect on phase propagation that the radiative heating anomalies are found to have in our results. This argument is

<table>
<thead>
<tr>
<th></th>
<th>(&lt; R &gt;) and column water vapor</th>
<th>(-\langle \omega \partial_p h \rangle) and (-\langle \omega \partial_p s \rangle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiosonde</td>
<td>3.9</td>
<td>0.16</td>
</tr>
<tr>
<td>ERA-Interim</td>
<td>4.2</td>
<td>0.14</td>
</tr>
<tr>
<td>JRA-55</td>
<td>5.1</td>
<td>0.18</td>
</tr>
</tbody>
</table>
confirmed by the fact that the regression coefficient of the estimated radiative heating using column water vapor anomaly of the radiosonde data on column-integrated MSE tendency (the triangle in Fig. 10b) is no longer negative.

SM also assumed that the normalized gross moist stability (NGMS; Neelin and Held 1987; Raymond et al. 2009) is constant. Their definition of NGMS is the ratio between the anomaly of column-integrated vertical advection of MSE to that of DSE. Testing this assumption is complicated by the difficulty of precisely estimating NGMS from observations; however, several modeling and observational studies indicate that NGMS significantly varies with the MJO phase (Benedict et al. 2014; SWK; Wang et al. 2015; Inoue and Back 2015). SWK found that NGMS increases as the MJO convective active phase passes. This will cause underestimation (overestimation) of the vertical advection term before (after) the precipitation maximum.

To examine the validity of this assumption, we first calculated the NGMS averaged over the 6-month period. To perform a stable calculation, we estimated it as a linear regression coefficient between the anomaly of column-integrated vertical advection of MSE and that of DSE over the period. The resulting
regression coefficients for radiosonde and two reanalysis datasets are shown in the 3rd column of Table 2. These values are close to NGMS averaged over the region covering the eastern Indian Ocean and western MC and over the November–April period of 1989–2004 estimated experimentally by Yokoi (2015) using JRA-55. Using these values, the column-integrated vertical advection of MSE is estimated as the sum of its seasonal march and the anomaly of column-integrated vertical advection of DSE. Note that we parameterize only the anomaly of the MSE vertical advection to focus our discussion on the variability associated with the MJO events. The column-integrated vertical advection of MSE thus estimated is compared with that observed in Figs. 11d–f. Although the estimated advection is broadly consistent with the original one, a peculiar difference is found around the time of the MJO-5 precipitation maximum for all the three estimates. Underestimation is found before the precipitation maximum, particularly for radiosonde data, and overestimation is found after that. The overestimation is also observed after the precipitation maxima of MJO-1 and MJO-2 for the two reanalysis datasets and of MJO-4 for the estimates with all three datasets. The regression coefficient of the estimated MSE vertical advection using the radiosonde data on the column-integrated MSE tendency (the circle in Fig. 10b) is no longer positive, suggesting that the assumption does not represent the contribution of vertical advection to MJO’s phase progression. These results are consistent with the above argument based on the result of SWK. Figure 10b also suggests that the effect of the assumption of the constant NGMS is stronger than the effect of the assumption of radiative heating.

The regression coefficients of estimated radiative heating and MSE vertical advection on the column-integrated MSE are shown by a triangle and circle, respectively, in Fig. 10a. It seems that these assumptions do not have much influence on the aspect of the MSE budget associated with the maintenance of MJO’s intensity.

4. Summary

We have examined the MSE budget over the eastern Maritime Continent using upper air sounding data obtained at eight radiosonde stations during the CINDY2011/DYNAMO extended observing period of October 2011–March 2012 and other contemporary datasets including reanalysis products, CERES, OAFlux, TRMM 3B42, and GPCP-1DD. Seven of the eight stations constitute a heptagonal sounding array located at approximately 12.5°S–2.5°N, 120°–140°E, while the eighth is near the center of the heptagon. During the 6-month period, five MJO events traversed MC.

Since the radiosonde data were available at time intervals as long as 12 hours, as opposed to the 6-hour or shorter intervals that are desirable and most often used in sounding budget studies, and since the islands in the region lead to considerably non-uniform surface conditions and produce strong diurnal cycles, it is of scientific interest to ask whether we can perform budget analysis using these radiosonde data with enough accuracy to be relevant for MJO dynamics. We compared the results with those from reanalysis data and independently estimated radiative heating and surface flux data to confirm that the source term and horizontal and vertical advection terms of MSE estimated by the radiosonde data agree well with those of other datasets, although several disagreements are also found.

We focus not only on intraseasonal-scale phenomena but also on the difference in seasonal features before and after the Australasian summer monsoon onset. The onset occurs in early December, associated with the second MJO event (MJO-2), when low-level easterly winds are replaced with westerly winds and relative humidity increases abruptly. Column water vapor and column-integrated MSE show overall increasing trends before the onset, while their time series are dominated by subseasonal components with almost no seasonal trend after the onset. The gross characteristics of the MSE budget are also different before and after the onset. Before the onset, both the source term and advection term have small magnitudes. After the onset, the source term becomes large and positive, with comparable contributions from radiative heating and LHF, and the advection term becomes large and negative, primarily due to the vertical advection term. This means that during the summer monsoon season, the atmospheric circulation exports MSE from the atmospheric column, while surface fluxes and decrease in radiative cooling compensate the export.

Precipitation signals associated with five MJO events pass over the sounding array in early November (MJO-1), early December (MJO-2), late December (MJO-3), during the second half of January (MJO-4), and the first half of March (MJO-5). While the classification of the third and fourth events as MJO events may be debatable, we include them as such as they show both eastward propagation and local phase relationships among variables.
that are consistent with a typical MJO. Although there are several differences among these five events, the majority of them share several characteristics over the sounding array:

- **Column water vapor and column-integrated MSE tend to co-vary with precipitation**, exhibiting maxima approximately coincident with the precipitation maxima of MJO events.
- **The net diabatic source of MSE (the sum of surface fluxes and radiative heating)** also tends to co-vary with precipitation, while its decreases after the precipitation maxima tend to be more gradual than its increases before the precipitation maxima. The LHF and column-integrated radiative heating contribute to the fluctuations of the source term with comparable magnitude, whereas the amplitude of the SHF fluctuation is much smaller. These results suggest that the source term contributes to the maintenance of the amplitude of MJO’s MSE anomaly, while hindering its phase progression and eastward propagation.
- **The column-integrated horizontal advection term tends to co-vary with column-integrated MSE tendency and exhibits larger negative values after the precipitation maxima than before them**, suggesting that this term contributes to phase progression. The large negative values after the precipitation maxima are primarily due to the advection in the lower troposphere (900–500-hPa levels).
- **The column-integrated vertical advection term tends to co-vary with precipitation in the opposite direction to the source term.** It decreases before the precipitation maxima, achieving large negative values close to the time of those maxima. After the precipitation maxima, it increases at a smaller rate than the preceding decrease or keeps decreasing for several days, mainly due to the negative values in the lower troposphere below the 800-hPa level. These negative values result from descending motion, perhaps an adiabatic response to cooling associated with re-evaporation of rainfall in the stratiform precipitation regime following the deep convection regime (Lin et al. 2004; Kiladis et al. 2005; Mapes et al. 2006). The descent may also be due to frictional divergence at the surface. This term thus counterbalances the maintenance effect of the source term while contributing to MJO’s phase progression.

These results are broadly consistent with those of SWK. Similarities between the present study and SWK include contributions of the radiative heating and LHF on the maintenance of the amplitude of MSE anomaly with comparable magnitude, opposing effect of the vertical advection term on the maintenance, and contributions of the vertical and horizontal advections of MSE on the phase progression of MSE anomaly with comparable magnitude. On the other hand, there are several differences as well. First, this study points out that the radiative heating and LHF tend to hinder the phase progression, which was not clearly observed in SWK. Second, the overall amplitude in the fluctuation of the budget terms of the present study is smaller than that of SWK; the difference between the maximum and minimum in the source and advection terms (Fig. 7c) is about 150 W m$^{-2}$, which is about 60–70 % of that of SWK (their Fig. 3c), which is consistent with the difference in precipitation amount and MSE amplitude between two studies.

These results confirm the view that MJO is a moisture mode destabilized by surface fluxes and radiative heating and that phase progression and eastward propagation is achieved by advective effect (Sobel et al. 2008, 2010; Sugiyama 2009a, b; Maloney 2009; Kiranmayi and Maloney 2011; Anderson and Kuang 2012; SM; Kim et al. 2014; Benedict et al. 2014; Kerns and Chen 2014; SWK). Not only the horizontal advection term but also the vertical advection term contributes to the phase progression.

We further used the MSE budget results to test the assumptions made in some idealized dynamical models that (1) the column-integrated radiative heating anomaly is proportional to the column water vapor anomaly and (2) the normalized gross moist stability is constant. We found that these assumptions seem to have only a small impact on the aspects of the budget associated with the maintenance of MJO’s intensity. On the other hand, the former assumption implies an underestimate of the hindrance effect of the column-integrated radiative heating on phase progression, while the latter one implies an underestimate of the positive effect of the vertical advection term on phase progression. Quantitatively, the error in the second assumption is greater than that in the first one, implying that a model that makes both assumptions will underestimate the eastward phase speed of MJO.

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