Seasonal and Subseasonal Variability of Potential Energy Injected into the Tropical UTLS by Convective and Tropical Cyclone Outflow

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ABSTRACT

This study employs 40 years of ERA-Interim data to quantify the periodic behavior of the integral amount of potential energy stored in the tropical upper UTLS (upper troposphere and lower stratosphere) originally placed there by high-entropy outflow of deep convection and tropical cyclones (TCs). The upper UTLS is defined to be isentropic layers above the level of zero net radiation (LZNR) in the tropics. Once there, the trapped high-entropy air mass must flow into the extratropics where radiative loss will allow it to subside back to lower-entropy levels. Mean poleward fluxes of isentropic mass are prevented by an inertial wall associated with Earth's rotation. This causes the mass of these isentropic layers to build up, creating a bubble of high potential energy. Periodic releases of this mass into the extratropics in the form of tropical plumes (TPs) help drain the bubble of its mass buildup over time. We present a metric to quantify the energy trapped and stored in this bubble to be the jet available potential energy (JAPE), in reference to the availability of this energy to fuel the kinetic energy of the subtropical jet stream (STJ), which bounds the tropical JAPE bubble (TJB) on its poleward extremities. We also calculate the isentropic mass M , which measures the isentropic thickness. Results of a 40-yr-time-series analysis of upper-UTLS JAPE and M show that the TJB features periodicity in the buildup and release of JAPE and M .

1. Introduction

Latent heat energy released into air parcels within the tropics enables the moist adiabatic conversion of low-level free energy (proportional to pressure) into geopotential energy at the convective or TC outflow level. Via these energy conversions, air parcels are lifted from near the surface and deposited into outflow residing at isentropic layers corresponding to the moist entropy of the updraft source level (Anthes and Johnson 1968). Generally, the outflowing mass returns to low levels through dry subsidence, crossing isentropic surfaces by diabatic radiative cooling. However, for the case of tropical deep convection and tropical cyclones, the outflow level may be in the upper troposphere–lower stratosphere (UTLS) region where the effects of radiative transfer are less likely to drive compensating subsidence. In the UTLS, deposited potential energy is more likely to build up over time (Lorenz 1955; Krishnamurti 1961a,b).

Due to the radiative effects of stratospheric ozone, there exists a vertical level in the tropics where radiative

loss to space is matched by radiative warming. This results in a level of zero net radiation (LZNR), which lies at approximately 356 K (Fig. 1) in the tropics, and is found in the upper UTLS. As a consequence, convective outflow mass deposited in isentropic layers near or above the LZNR is radiatively trapped in the tropical upper UTLS, and so accumulates there unless transported into the extratropics where the LZNR is at a much higher isentropic level.

Earth's rotation and the conservation of angular momentum prevent the free exchange of the potential energy trapped in the UTLS with the extratropics by zonally mean meridional transport of the Hadley circulation. In the zonal mean, the UTLS potential energy is instead held in the tropics behind what is effectively an “inertial wall,” typically near 30° latitude.

Because the potential energy of convective outflow into the tropical UTLS is trapped there against both vertical and horizontal movement, outflow mass inserted into the upper UTLS builds up over time, forming a “bubble” of increased potential energy. The tropospheric part of this so-called bubble contains isentropic layers of expanded vertical thickness. The stratospheric portion of the bubble above the tropical tropopause is

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FIG. 1. Zonally averaged cooling rate based on ERA-Interim for 1 Dec 2016. The approximate level of zero net radiation (LZNR) is drawn for reference. The area with white shading averages above zero net radiation heating tendency. Note that the LZNR moves to higher elevations poleward of about 30° latitude on average in the winter hemisphere and poleward of around 20° latitude in the summer hemisphere.

composed mainly of vertically lifted isentropic layers having anomalously elevated density for their height (Folkens et al. 2000). These are not outflow layers and so have no increased isentropic mass. Figure 2 depicts a

sample meridional cross section depicting the potential energy bubble as the tropical JAPE bubble (TJB); the jet available potential energy (JAPE) will be defined in the next section.

Despite the lack of explicit flow, global isentropic analysis (Johnson 1989; Pauluis et al. 2008) has consistently shown that although the mean meridional poleward outflow of the Hadley circulation does not move past the inertial wall, if one considers the zonally mean isentropes as energy tracers, then UTLS outflow from the tropical convection is somehow flowing into the extratropics intermittently. The meridional circulation moving convective outflow mass to the extratropics is consistent with the Brewer–Dobson circulation (Brewer 1949; Dobson 1956), which is thought to occur through the action of atmospheric waves. Many studies have also considered transport by Eliassen–Palm eddy fluxes of heat along usually pressure surfaces. Perhaps more consistent with the reported results of isentropic analysis, and a long history of observed activity, is the possibility that tropical plumes (TPs) in the upper UTLS burst poleward from the potential energy bubble. Given their low potential vorticity and high potential energy, such self-propelled “plumes of energy” might be more akin to conditionally unstable bursts of vertical convection than a slow baroclinic eddy mixing process, where the inertial wall

FIG. 2. Meridional cross section based on ERA-Interim of 6 Dec 2016. Color shading depicts the absolute magnitude of PV on a log scale, with near-zero PV having dark gray shading. Isentropes are shown in blue (<356 K) and red (>356 K) at intervals of 10 K. Isotachs of westerly winds greater than 30 m s^{-1} are shown at 10 m s^{-1} intervals to depict jet streams as labeled. The heavy yellow contour depicts the 2500 J kg^{-1} boundary of the JAPE bubble. The green contour depicts the approximate position of the tropopause as defined by the 1.5-PVU ($1 \text{ PVU} = 10^{-6} \text{ K kg}^{-1} \text{ m}^{-2} \text{ s}^{-1}$) PV everywhere except near the equator. The “upper” and “lower” UTLS are defined to be those parts of the UTLS above or below the tropopause. Generally, the JAPE in the upper UTLS results from the upward displacement of the stratospheric isentropic surfaces, while the lower UTLS results from the diabatic injection of entropy into isentropic layers from convective activity or radiative heating above the LZNR.

FIG. 3. Tropical plumes present at 0000 UTC 16 Jan 2017, labeled on global map displaying the (a) 2000 J kg^{-1} JAPE surface and (b) PV magnitude along the 340-K isentropic surface. Also shown is the 40 m s^{-1} westerly wind speed isotach colored by $\log(\text{PV})$.

would play the role of the burst inhibition. In this study, we examine the long-term behavior of the tropical energy bubble, by monitoring the amount of energy and isentropic mass held in the bubble. By doing so, we can learn if there is a significant temporal pattern of energy build up and release and if the release appears to be triggered by a critical amount of energy buildup, or is triggered by a breakdown of the inertial wall, perhaps induced from extratropical waves.

For the purposes of this study, we define a TP to be a (horizontal convective) burst of potential energy (PE) emanating from the TJB. This definition is a different take on what is likely the same phenomenon discussed by McGuirk et al. (1987), McGuirk et al. (1988), and McGuirk and Ulsh (1990), based on satellite imagery and extended and by Knippertz (2005), Knippertz and

Wernli (2010), and Frohlich et al. (2013). Our definition is more consistent with that of Mecikalski and Tripoli (1998), who similarly showed that inertial instability of convective outflow can give rise to a poleward directed TP in the UTLS. Here we explicitly define a TP to be a plume that breaches the inertial wall of the TJB and moves poleward into extratropical latitudes. As defined here, the TP is longitudinally wider than the TPs defined in earlier studies, based on satellite evidence from cloud patterns. Instead, our definition of a TP would typically span several hundred to over a thousand kilometers in width. Similar to previous definitions, a subtropical jet (STJ) is associated with a TP, but in the present definition it bounds the poleward periphery of a TP, creating a poleward “arched” appearance to the STJ. Figure 3 depicts the global system of TPs depicted

Zonally Averaged Meridional Angular Momentum Fluxes

FIG. 4. Zonally averaged meridional angular momentum fluxes for (a) zonally mean transport and (b) eddy transport, based on ERA-Interim of 1 Dec 2016, plotted as a function of potential temperature. As expected, the mean circulation confines significant angular momentum transport equatorward of around 20° – 25° latitude, while the eddy angular momentum transport is stronger and significant poleward of 20° , particularly in the winter hemisphere.

as both protrusions of the potential energy and as low-potential-vorticity (PV) plumes, showing the relationship to the STJ.

The TP, as defined here, represents a poleward surge of cold dense air initially rooted in the TJB. In response, a deep anticyclonic circulation will typically extend downward toward low tropospheric levels, appearing as a ridge of high heights on an isobaric map. Associated poleward (and eastward)-oriented cloud bands would be expected to be located on the western and poleward boundaries of the TPs defined here, resulting from low-level frontogenesis along the western boundary of the plume's anticyclone. These bands are sometimes defined as tropical plumes in other studies.

Although potential energy is not strictly conserved by advection like PV or entropy mass, TPs can and do move much of the anomalously high potential energy of the TJB poleward in the plume by advecting the isentropic layer mass, and also by wave propagation processes responding to the mass anomalies. Although TPs have not been observed to move all the way to the poles in the previous definitions based on cloud patterns, the TPs defined here by conserved dynamic and thermodynamic properties of their origins may be different. Examination of these plumes on a daily basis over 40 years has shown that these plumes occasionally cross the Arctic and Antarctic circles at isentropic levels in the UTLS. These plumes have been reported on by published studies such as [Lang and Martin \(2013\)](#), where they have been discussed as convectively forced ridges of high

pressure and low PV, rather than TPs. In some cases, convection in the extratropics can add some JAPE to these plumes, but usually not at the high isentropic layers of the upper TJB that require equivalent potential temperatures not attainable outside of occasional TCs recurving into the extratropics.

Figure 4 depicts the meridional angular momentum flux by mean transport and eddy fluxes in the UTLS for 2016. As expected, there is a net positive (negative) transport of angular momentum into the Northern (Southern) Hemispheric extratropics by eddy fluxes, and on a scale much larger and to deeper heights than the zonally mean transport. The elevation of the transport maximum suggests that eddy transport is likely initiated at high elevations by tropical plumes near 340 K, which is near the height of the STJ core. This suggests that, on average, Eliassen–Palm (E–P) fluxes are initiated by TPs at the base of the UTLS, but then deepen downward as the plume moves poleward, perhaps by a combination of baroclinic forcing below, and of radiational cooling as the LZN is higher at higher latitudes. Note the asymmetry of transport between the northern (winter) and southern (summer) hemisphere where the winter hemisphere fluxes go farther poleward and where the inertial wall is more frequently breached by interaction with the Rossby wave train (RWT) ([Mecikalski and Tripoli 1998](#)).

The eddy momentum transport can be expected to be reconciled within the RWT by surface friction particularly in extratropical storms and by mountain wave drag.

Likewise, radiative processes and diabatic mixing induced by extratropical weather systems eventually resolve the net poleward isentropic fluxes of PV and entropy mass into the extratropics.

2. Definition of JAPE

The available potential energy anomaly discussed above can be approximated by comparing the density of the tropical atmosphere at a given height to the density typical of a typical extratropical atmosphere at the same elevation. For a reference density, we use the density of the “U.S. standard atmosphere” (COESA 1976). The jet available potential energy is then defined to be

$$\text{JAPE} = \frac{\rho'}{\rho} g z, \quad (2.1)$$

where ρ is the air density, z is the geopotential height, g is the acceleration of gravity, and the prime refers to the difference between the local density and a reference density, which we will take to be the density at the equivalent elevation in the reference sounding. Since the reference sounding is only a function of height, JAPE is *not* the energy available relative to a relaxed state of the atmosphere, as is available potential energy (APE), defined by Lorenz (1955), but simply a measure of how anomalous the suspended mass field is relative to a constant known reference. This makes JAPE a convenient diagnostic for comparing tropical stored energy across time and space against a stationary reference. It is also a rough approximation to the relative amounts of potential energy locally available to accelerate the STJ. The units of JAPE are joules per kilogram, and so can be integrated with density over a volume to find total jet available potential energy. These units are also the same units which CAPE and kinetic energy are typically defined, which makes the comparison easy. The elevated isentropic layers of the tropical UTLS where JAPE is positive constitute the definition that we use for the tropical JAPE bubble (TJB).

The TJB appears as a global, 3D, closed surface between 10 and 18 km above mean sea level (MSL) encircling the globe over the tropics. It is bound by the subtropical jets on its poleward edges in the lower UTLS, as seen in Fig. 5. Note that the TJB encircles the globe at all longitudes, with some poleward extensions associated with strong tropical plumes. Additionally, note that the TPs are associated with poleward excursions of low PV.

Figure 6 depicts the meridional variation of the magnitude of zonally averaged JAPE bubble. Note that its peak intensity on average lies just below the LZN, and

FIG. 5. The 2500 J kg^{-1} surface of the global JAPE bubble at 1200 UTC 30 Dec 2016 viewed from the west and above with three meridional cross sections cut through the bubble depicting the isentropes, major westerly isotachs $>30 \text{ m s}^{-1}$, and shading of PV on a log scale as shown in Fig. 2 for the 12.5°E cross section. Surface topographical features and geography are shown for reference. The JAPE bubble is shaded by the 356-K JAPE values above and the 340-K JAPE values on the visible inner side of the JAPE bubble. This figure shows the global extent of the JAPE bubble and the existence of plume-like features that extend poleward from the bubble that are the base of the tropical plumes that vent the JAPE poleward. Refer to Fig. 2 for color scale.

its upward extent extends about 3–4 km into the lower stratosphere. Its lower extent in the tropics is about 10 km, roughly equivalent to the extratropical tropopause. Lower-magnitude tails extend downward and poleward from the tropical JAPE maximum, coinciding with the mean position of the tropical tropopause fold, seen at 12.5°E in Fig. 2.

Note also that the STJs portrayed in Fig. 2 occur in the lower extremities of the TJB, because this is the centroid of where the conversion to kinetic energy takes place. This energy conversion produces a jet maximum centered at around the LZN, or about 356 K. The air trajectories entering the STJ from the equatorward side carry low PV along isentropic surfaces, turning to the right, paralleling the jet as they merge into the airstream. Because geopotential increases upward with lowering pressure much more in the tropical UTLS than at the

FIG. 6. Total zonal sum of JAPE as a function of isentropic level (ordinate) and latitude (abscissa) for the same time as Figs. 2 and 4. Note that JAPE is maximized at about 352 K. The uppermost level of significant JAPE is about 400 K or near 18 km MSL as seen in Fig. 2, which resides in the upper UTLS, which is in the lower stratosphere. The tropopause in Fig. 2 is about 370 K, around the height of the third pink contour, showing that the majority of the JAPE bubble mass resides in the upper troposphere of the tropics. The LZNR, shown in Fig. 1 to be 356 K, tends to run through the level of maximum JAPE.

same isobaric height poleward of the TJB, a frontogenesis process ensues along the poleward boundary of the TJB. This steepens the isentropic surface and is capable of folding the tropical tropopause over the extratropical tropopause. The resulting enhanced baroclinic, JAPE, and PV gradients build an STJ, featuring low TJB PV on the equatorward side of the jet.

An outline of the remainder of this paper is as follows. Section 3 will describe the data and metrics to be used. Section 4 describes the 40-yr time series derived from ERA-Interim and the types of variability that can be seen qualitatively. Section 5 will describe an extensive spectral analysis of the time series that quantitatively evaluates its variability. Section 6 will discuss implications of these results and then present some brief conclusions and suggestions for further study.

3. Data and volume integration

This study focuses on the positive JAPE anomalies associated with the elevated tropical tropopause, from ERA-Interim 6-hourly data spanning the 40-yr period from 0000 UTC 1 January 1979 through 1800 UTC 31 December 2018 (Dee et al. 2011). To simplify analysis, leap days have been removed from the dataset. The spatial resolution of the data is approximately $1^\circ \times 1^\circ$.

All JAPE time series have been calculated from the ERA-Interim datasets using analysis tools in the University of Wisconsin Nonhydrostatic Modeling System (UW-NMS) (Tripoli and Smith 2014a,b). Data processing in the UW-NMS includes calculations of variables of interest and formatting for data analysis. The analysis calculates the long-term evolution of the integrated amount of potential energy stored in the elevated JAPE bubble. The integral, performed on a latitude–longitude or spherical grid, is

$$[\text{JAPE}] = R_e^2 \int_{\varphi_1}^{\varphi_2} \int_{\lambda_1}^{\lambda_2} \int_{\theta_1}^{\theta_2} \max(\text{JAPE}, 0) \frac{dz}{d\theta} d\theta \cos\varphi d\lambda d\varphi, \quad (3.1)$$

where $[\text{JAPE}]$ is the mass-weighted integral of JAPE, ρ is the air density, R_e is the radius of Earth, φ is the latitude angle in radians, and λ is the longitude angle in radians. The subscripts refer to a range of latitudes, longitudes, and potential temperature over which we integrate.

The portion of the JAPE bubble contained in a given isentropic layer is suspended over underlying isentropic layers, which themselves are typically bowed upward relative to a standard extratropical standard atmosphere. Overall, positive JAPE is found over most of the tropics above 10 km MSL although only the JAPE above about 12.5 km (~ 356 K) is totally radiatively trapped. Monitoring the temporal variability of total mass stored in the isentropic layers of the TJB is an additional diagnostic of the buildup of trapped entropy mass in the JAPE bubble. Similar to the isentropic JAPE, total isentropic layer mass is computed as

$$[M] = R_e^2 \int_{\varphi_1}^{\varphi_2} \int_{\lambda_1}^{\lambda_2} \int_{\theta_1}^{\theta_2} \rho \frac{dz}{d\theta} d\theta \cos\varphi d\lambda d\varphi, \quad (3.2)$$

where $[M]$ is the integral isentropic mass, φ is the latitude angle in radians, λ is the longitude angle in radians, and θ is the potential temperature in kelvins. This results in a measurement of the total mass contained between isentropic layers (θ_1, θ_2) of the JAPE bubble. The total storage within prescribed isentropic layers will be confined to the tropical troposphere above the level of zero net radiation at 356 K and below 420 K, a layer representative of the UTLS. Unlike Eq. (3.1), $[M]$ includes mass outside the positive JAPE bubble. Rather than a strict measure of integrated anomalous energy, $[M]$ should be interpreted as a measure of Montgomery energy, which is related to the total entropy storage. More than JAPE, $[M]$ depicts the reservoir of what quantity is actually trapped in the upper UTLS. Interestingly, we will show that $[M]$ behaves much the

same as JAPE in the tropics, but displays some contrasting advantages in the extratropics.

These integrations were taken over four separate volumes spanning the following ranges: The range of longitude λ is taken to be the entire zonal belt of the globe. Each of the four volumes spans the isentropic layers between 356 and 420 K. We define this to be the upper UTLS, which lies entirely above the LZNR in the tropics. The four integration volumes are distinguished from each other by their meridional ranges: 1) 30°–60°N (“north midlatitudes”), 2) 60°–30°S (“south midlatitudes”), 3) 30°S–30°N (“tropics”), and 4) 60°S–60°N (“nonpolar region”). By integrating JAPE and M , using Eqs. (3.1) and (3.2) over each of these areas, we attain the total stored JAPE in joules and stored mass in kilograms resident in each of the four volumes. The nonpolar volume is the total of volumes 1–3. We include it to get a sense of how the total global JAPE and M in upper UTLS varies, and to show it is dominated by that stored in the tropical JAPE bubble.

Except for recurring tropical cyclones, it would be rare for moist convection to produce potential temperatures high enough to inject mass into the upper UTLS outside the tropics. Nevertheless, the midlatitude upper-UTLS budgets of JAPE and M are important to consider due to the extratropical interactions with the tropical JAPE bubble that allow JAPE and M to breach the inertial wall and produce occasional plumes of JAPE and expanded isentropic thickness to extend poleward of 30° latitude. Because JAPE will typically be near zero or negative poleward of the TJB, the extent to which any JAPE exists in volumes 1 and 2 is indicative of an extension of tropical conditions into the extratropics. This can happen either by a simple expansion of the TJB poleward of 30° latitude or by a plume of JAPE flowing into the extratropics.

Significant short time scale variability in the mass of the volumes 1 and 2 would also likely come from extensions of the JAPE bubble into the extratropics. The isentropic mass of each volume is conserved over adiabatic processes, but JAPE can change due to changes in the height of the layer. This would likely be case when JAPE is converted to kinetic energy adiabatically. This suggests that isentropic mass may track the tropical air flowing in a TP slightly better than JAPE, where JAPE is being depleted.

In this study, we will focus on the temporal variability of the TJB in each of the four analysis volumes over the 40-yr period between 1 January 1979 and 31 December 2018. Of particular interest will be the time scales over which the integrated JAPE and M vary in the tropics and how that variability is reflected in the amount of JAPE and M present in the extratropics.

4. Time series analysis

The fluctuations in the amount of JAPE and layer mass over the course of 40 years integrated over volumes 1–3 are depicted in Fig. 7. Significant variability of [JAPE] and $[M]$ is evident, as is the annual cycle. Although there seems to be some effect of the El Niño cycle on the overall amplitude of the JAPE and M fluctuations, it appears that the strongest [JAPE] and $[M]$ happen just after the conclusion of an El Niño event, rather than during the event. This suggests that enhanced deep convection in the west Pacific following the breakdown of El Niño is more likely to increase [JAPE] than El Niño-based convection.

Note that the amount of stored JAPE is much higher in the tropics than in the midlatitude volumes 1 and 2. This is somewhat by design, since JAPE is defined as the excess of mass compared to an extratropical standard sounding and we discard negative JAPE values.

The integrated isentropic mass $[M]$ is larger in the tropics as is [JAPE], but less so. Perhaps more important, the amplitude of the $[M]$ fluctuations in the tropics (volume 3) is even stronger compared to the middle latitudes (volumes 1 and 2) than is JAPE. An explanation for this is that JAPE tends to be consumed by adiabatic conversion to kinetic energy, while M does not, depleting JAPE faster in the extratropical environment than M is depleted. As mentioned, the existence of any JAPE in regions 1 and 2 might be viewed as measure of the extent to which tropical conditions extend into the extratropics.

It is also evident, upon initial inspection that the upper-UTLS [JAPE] and $[M]$ have variance features with much higher frequencies of variability in the tropics than in the extratropics. A closer example of this variability is given by Fig. 8, isolating a 2-yr period over the horizontal area the tropics but limited to an isentropic layer limited to 360–370 K. First, a strong annual cycle of JAPE stands out, but in addition strong periodicity in subannual frequencies centered somewhere around 45 days, corresponding to the MJO, also appears to stand out. JAPE deposited at 364 K must come from upward mass fluxes featuring particularly high equivalent potential temperature, not typical of even most tropical convection outside tropical cyclones, the more extreme convection of the MJO, and the very-high-entropy South Asian monsoon and monsoon cyclones. Hence, the hypothesis that 45-day cycle of recharging the TJB with isentropic mass and JAPE release from MJO-related convection during its maximum intensity may be reasonable if we can show this 45-day cycle to be robust over the 45 years of the ERA-Interim dataset. TCs and convection of the SAM would also likely be a

FIG. 7. (a) Time series of isentropic JAPE over the 40-yr period from 0000 UTC 1 Jan 1979 to 1800 UTC 31 Dec 2018. Tropical JAPE for the upper UTLS (356–420 K) is depicted in red, and the lower UTLS (330–355 K) is depicted in blue. The total extratropical JAPE in the upper UTLS for 30°–60°N (gray) and 60°–30°S (yellow) is also shown. The light shading depicts El Niño periods. (b) As in Fig. 8, but depicting isentropic mass in all the same regions in the lower UTLS.

strong contributor of mass and energy to the TJB and are more likely to occur with seasonal or subannual periods, which also seem to be important in Fig. 8. Overall, inspection of the full 40-yr dataset suggests that although the 45-day period of variability seen in Fig. 8 appears strikingly common, it does not occur every year or always throughout entire years in all periods. On the other hand, a seasonal cycle of [JAPE] and [M] is apparent from Fig. 7 every year.

Diurnal variability is also important, for obvious reasons such as the movement of atmospheric tides and the

diurnal cycle of ozone warming. For this study, however, we are interested on the energy buildup and release cycle of the TJB on seasonal and subseasonal time scales, leading to responses in tropical plume activity that may influence extratropical weather. We pose this overarching question: “Is there evidence for a climatological cycle of seasonal and subseasonal variability in the upper UTLS?” We now present additional time series analysis and then spectral analysis to answer this question quantitatively.

Figure 9 presents a Hovmöller diagram of the zonally averaged JAPE and M at 364 K, corresponding to the

FIG. 8. Total tropical JAPE (latitudes less than 30°) stored in the 360–370-K isentropic layer as a function of time for the years 2004–05. Note the apparent 45-day cycle of JAPE buildup and release.

Total Zonal JAPE Hovmöller

Year=2005, $\theta=364$

Total Zonal M Hovmöller

Year=2005, $\theta=364$

FIG. 9. Hovmöller diagram of the (a) JAPE bubble and (b) M bubble as it varies with time (vertical axis) and latitude (horizontal axis), found at a height of 364 K. Units of time are in days from 1 Jan 2005.

isentropic layer depicted in Fig. 8 centered in the upper-tropospheric portion of the UTLS. The 45-day oscillation apparent in Fig. 8 is again apparent in both the JAPE and M here. Also, note here that when we view zonally averaged JAPE or M as a function of latitude in Fig. 10, we can see a strong seasonal cycle, shifting poleward in the summer hemisphere, with the maximum shift about 1 month following the solstice. Also, standing out is the stronger amplitude of an

FIG. 10. Annual variation of (a) [JAPE] (10^{20} J) and (b) $[M]$ (10^{15} kg) integrated over the latitudinal bands: (i) TML (60°S – 60°N), (ii) T (30°S – 30°N), (iii) NML (30° – 60°N), and (iv) SML (30°S – 30°N).

apparent 45-day cycle relative to total M compared to that relative to total JAPE in the tropics during the late Northern Hemisphere summer.

Note also that the poleward shift of the JAPE bubble in the Northern Hemisphere is considerably stronger than that in the Southern Hemisphere. Moreover, the poleward shifted JAPE bubble in the Northern Hemisphere shows a secondary latitudinal maximum of JAPE and M on top of the tropical JAPE max. This secondary maximum is associated with the deep intense convection of the South Asian monsoon (SAM). Because this secondary maximum is poleward of the equator, it leads to the formation of the tropical easterly jet near 16–18 km AGL and 5° – 10°N latitude.

Note also the periodic behavior of JAPE in the extratropics poleward of the extent of the TJB, featuring a low-amplitude oscillation. An inspection of M fluctuations, shown in Fig. 9b, also shows that periodic fluctuations of M in the extratropics poleward of 30° latitude are less apparent. This suggests that the extratropical negative JAPE fluctuations are primarily related to the vertical lifting and descent of isentropic layers by vertically propagating waves, rather than the conserved penetration of tropical plumes. Further investigation of the coherence between the tropical and extratropical subseasonal cycles will be presented in the next section.

As suggested in Figs. 8 and 9, overall variability of [JAPE] appears to be dominated by the annual cycle. Figure 10 depicts the 40-yr averaged annual cycle for [JAPE] and [M] integrated over four volumes spanning the latitude bands: tropical plus midlatitude (TML) (60°S–60°N), tropical (T) (30°S–30°N), north midlatitude (NML) (30°–60°N), and south midlatitude (SML) (30°S–30°N). The annual TML JAPE variation depicts a double annual maximum occurring on 7 February (Southern Hemisphere summer) and 7 August (Northern Hemisphere summer). The August maximum spans a considerably longer period than the February peak, not just because of the SAM but likely also as the consequence of a more robust and sustained TC season occurring in the Northern Hemisphere.

A single annual broad maximum of tropical [JAPE] occurs during the Northern Hemisphere late winter and early spring, with a sustained minimum of tropical [JAPE] lasting from 18 July to 2 December. Note that from 15 May to 15 August, the *tropical* [JAPE] decreases while, at the same time, the *total* [JAPE] is increasing, likely with the input from the SAM. It is not until mid-November that the tropical [JAPE] begins to increase in step with the total global [JAPE]. Examination of daily weather maps of the TJB and STJ activity (not shown) reveals that the period from mid-May to mid-November is a period rich with almost continuous tropical plume activity in the Southern Hemisphere with usually three to five tropical plumes active at any given time. These are likely fluxing [JAPE] and [M] out of the TJB and into the southern wave train. This happens much less during the Northern Hemisphere winter, where tropical plumes tend to be less frequent, primarily due to the dominance of more blocking or stationary upper-level wave patterns. Tropical and total [M] are mostly consistent with the [JAPE] variability, except that the amplitude is reduced, because [M] is not compared to a reference state as is [JAPE].

In both hemispheres the amounts of extratropical [JAPE] and [M] are maximized during the summer months in part because of poleward extensions of the TJB, such as during the SAM. Note that the NML summer maximum extends into November and the SML maximum extends into May. This is likely, at least in part, because of the periodic extension of the TJP and TPs associated with the recurvature of TCs.

5. Spectral analysis

For this analysis, our primary interest is the periodic exchange of energy between the TJB and the extratropics

that inspection of Figs. 7–9 suggest is occurring on sub-seasonal time scales of weeks to months. Power spectrum analyses of [JAPE] and [M] performed on all four volumes [including now 4, the nonpolar volume] are shown in Figs. 11 and 12 respectively. Below we discuss each result.

a. JAPE

To focus on longer periods, we initially filter periods less than the diurnal period from the data. The spectrum of [JAPE] observed in the north midlatitudes (Fig. 11a) contains significant variance at annual and semiannual periods, as well as subharmonics at periods 1/3 and 1/4 of the annual cycle. The spectrum of [JAPE] in the south midlatitudes (Fig. 11b) appears similar with significant spectral peaks at annual and semiannual periods, although subharmonics of the annual cycle are not as clear in the Southern Hemisphere. These peaks would likely correspond to the seasonal shift of the TJB toward the edge of tropical latitudes during the hemispheric summer seasons. Figures 9 and 10 suggests that the shift is considerably stronger in the Northern Hemisphere, consistent with Fig. 11a and 11b. More study of the [JAPE] annual cycle and its subharmonics in the extratropics presents a fascinating challenge for future research.

It is noteworthy that the first-order autoregressive [AR(1)] null hypothesis does not fit the power spectrum particularly well in the extratropics with deseasonalized data (seasonal cycles removed). In both spectra, numerous periods between about 6 and 50 days exceed the expected variance from an AR(1) process, while variations with periods shorter than about 4 days exhibit significantly less variance than the AR(1) process. We fit a second-order autoregressive process to the data (not shown), which fits better but generally underestimates variability with synoptic time scales between about 6 and 14 days. We interpret these results to reflect well-known synoptic to subseasonal variability in the midlatitudes.

Spectral analysis of the tropical and nonpolar regions yields a slightly different picture. While significant periods are still seen for the annual cycle, the semiannual cycle is (interestingly) weak, and the third harmonic (1/3 of the annual cycle period) is nearly statistically significant. The annual cycle in the tropics is likely due to the impact of the SAM on JAPE production, clearly evident in Fig. 10. With the seasonal cycle removed, and similar to midlatitudes, the AR(1) null hypothesis still does not fit closely the observed spectra, the latter of which exhibits a broad band of significant variability with time scales between about 16 and 70 days that is consistent with the

Power Spectra, JAPE

FIG. 11. Power spectra of JAPE for (a) northern midlatitudes (30° – 60° N), (b) southern midlatitudes (60° – 30° S), (c) tropics (30° – 60° N), and (d) nonpolar regions (60° S– 60° N). For each panel, the solid black curve represents the spectrum of deseasonalized data, the dashed curve represents the spectrum of “de-meanned” data, the white line indicates the best-fit AR(1) null hypothesis to the deseasonalized data, and the shading extends from the 0.1% to the 99.9% confidence limits on the AR(1) null hypothesis.

Madden–Julian oscillation (MJO) time scale (Madden and Julian 1971). The AR(1) process also overestimates variability with periods shorter than about 6 days. The enhanced variability at MJO time scales suggests that the MJO may play an important role in subseasonal variations of tropical [JAPE].

b. Layer mass

Spectral analysis of isentropic layer mass [M] confirms the similarities and differences discovered with time series analysis in section 4. Like the [JAPE] time series spectra, the northern and southern midlatitudes spectra of [M] (Fig. 12) exhibit significant spectral peaks at periods of the annual cycle and its harmonics, an enhancement of variance at synoptic to subseasonal time scales, and an overall poor fit to the AR(1) null hypothesis (though the fit in the Southern Hemisphere is better than that in the Northern Hemisphere). In the tropics and nonpolar regions, the observed spectra of isentropic mass exhibit strong annual and semiannual variability (interestingly, stronger semiannual variability than seen with JAPE) and enhanced variability

at MJO time scales. Again, the strong variability at MJO time scales suggests a role for the MJO in influencing variations of isentropic mass in the tropical UTLS.

Coherence between the deseasonalized power spectrum of both [JAPE] and [M] (not shown) suggests that the periodicity of the TJB and extratropical [JAPE] are not part of the same dynamic process. Since the existence of [JAPE] in the extratropical upper UTLS is likely to be tied to TP activity by virtue of the high entropy involved, it is suggested that the buildup cycle is somewhat independent of the release cycle driven by the TP process. Because the extratropical [JAPE] and [M] have a significant peak on shorter synoptic and subsynoptic time scales compared to the subseasonal time scales of the TJB, it is suggested that the release cycle into the extratropics is more continuous, while the buildup occurs with less frequent specific production mechanisms such as the MJO and TCs. This is consistent with the hypothesis that extratropical waves, and particularly long waves, are triggering the eruption of TPs out of the JAPE bubble.

Power Spectra, MASS

FIG. 12. Power spectra of MASS for (a) northern midlatitudes (30° – 60° N), (b) southern midlatitudes (60° – 30° S), (c) tropics (30° – 60° N), and (d) nonpolar regions (60° S– 60° N). For each panel, the solid black curve represents the spectrum of deseasonalized data, the dashed curve represents the spectrum of “de-meaned” data, the white line indicates the best fit AR(1) null hypothesis to the deseasonalized data, and the shading extends from the 0.1% to the 99.9% confidence limits on the AR(1) null hypothesis.

6. Discussion and conclusions

The results suggest that JAPE and mass stored in the TJB of the upper-UTLS TJB contain significant variability, broadly centered around a period of 45 days. The periods of intraseasonal variability of $[M]$ and $[JAPE]$ agree closely with each other in the tropics, due to their close relationship to the same source mechanism of high-entropy vertical mass fluxes associated with very deep convection and tropical cyclone outflow and the reliance on the same primary sink mechanism of meridional transport out of the tropics.

There is published research presenting evidence that there is MJO involvement in the extratropical weather. One study found strong coherence between the subtropics and the tropics, supporting the suggestion that planetary wave baroclinic instability and the MJO are interconnected (Straus and Lindzen 2000). Another study found that, in all phases of the MJO, modeling and observational studies revealed that 300-hPa height anomalies formed part of an MJO-like global wave train. (Barrett and Henley 2015). Additional work has

indicated that the structure and evolution of mid-latitude setups are statistically connected to tropical convection on a 30–60-day time scale (Schubert and Park 1991; Hsu 1996). In the present study, we did find that in the northern extratropics, there was barely significant subseasonal periodicity [JAPE], but no significant coherency with the tropics. This may suggest that the MJO connection is likely more of a wave connection rather than a physical entropy or mass exchange via TPs as we are studying here.

Another previously published study, also similar to what was performed here, sought to produce a time series of significant subseasonal variability in APE in the Northern Hemisphere and identify synoptic-scale variability from that dataset (Wintels and Gyakum 2000). The study found a 3-day cycle in APE generation, while the time scale of depletion events remained consistent with that of baroclinic instability observations of developing synoptic eddies, particularly in the troposphere. Our results do not exhibit such short time scale periodic behavior of [JAPE] in the tropical upper UTLS. However, we do see an interesting significant

spectral peak of [JAPE] (and to a slightly lesser extent [M]) at synoptic periods of about 6–20 days in the extratropics of both hemispheres. We have interpreted this as evidence of tropical plumes in the UTLS interacting with longwave troughs in the westerlies. We envision that this is the effect of poleward arched STJs plumbing low-PV and high-JAPE air poleward on the east side of troughs.

A notable difference in the average annual periods of [JAPE] between the north and south midlatitudes lies in the size of amplitude of each annual cycle. The north midlatitudes feature a much larger difference between the maximum and minimum values of [JAPE] than the south midlatitudes. The apparent reason for this is the tendency for the TJB to extend slightly into the extratropics of the summer hemisphere. The effect is stronger in the Northern Hemisphere, mainly because of the SAM and a more intense TC season compared to the Southern Hemisphere.

It was shown that the SAM-associated convection and TCs produce so much JAPE that the SAM creates a secondary monsoon JAPE bubble (MJB) within the overall TJB north of the equator. Inertial adjustment to the MJB forms not only an enhanced STJ, but also the tropical easterly jet (TEJ) on its southern side at altitudes centered near 16 km AGL. Krishnamurti et al. (2018) showed that the STJ and TEJ driven by SAM outflow send energy westward across Africa into the Atlantic in tropically confined plumes and eastward and poleward toward the Aleutians in tropical plumes. They also showed, more recently, that 17 of 21 category 4 or 5 Atlantic TCs have occurred under the TEJ, emanating from the SAM. The movement of plumes containing enhanced JAPE within the tropics and their impact on tropical weather is a subject of future research.

The participation of TCs in the [JAPE] budget is also an important area for future study. The role of TCs in the general circulation of the atmosphere is not well appreciated as significant, but this study has underlined apparent routine connections between STJs entering the extratropics and [JAPE] via TPs in the UTLS. Moreover, the unique ability of TCs to recurve poleward allows them to inject JAPE and M poleward or near the inertial wall, enhancing the extratropical interaction. Circumstantial evidence presented in this study suggests that TPs play an important role in extratropical weather of all types, and there is further evidence that TCs enhance that connection. This begs the question: Do TCs enhance the Hadley circulation and force a stronger connection with the extratropics through enhanced TPs? Bosart et al.'s (2012) studies of predecessor rain events arguably point in that direction.

We conclude that [JAPE] and [M] provide useful measures of the integrated potential energy and entropy injected into the upper UTLS by intense convection and tropical cyclones occurring primarily across the tropics. Because these quantities exhibit periodicity consistent with a process of buildup and release, it is suggested that global monitoring these quantities may be providing a measure of the potential for tropical plume eruptions and periods of intense extratropical weather fueled by energy transfer of [JAPE] to extratropical weather.

These results also suggest that the specific isentropic layers in which tropical convection and TCs insert their outflow mass are critical to evaluating their impact on the buildup of trapped tropical energy that is required to be transported to the extratropics to complete the global energy cycle. Results here suggest a significant periodicity to the buildup and release cycles of tropical [JAPE], but dynamic processes leading to extratropical release should be documented specifically with more investigation. Moreover, the processes producing the buildup of the TJB from convection and TCs should also be documented with some detail in future studies.

Global change may be influencing the portion of outflow energy and mass inserted into these critical layers of the upper UTLS, leading to change in the reliance of the energy cycle on the transfer of energy into the extratropics for global equilibrium to be reached. This is a topic of potential importance that will require greater study to evaluate its significance.

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APPENDIX

Acronyms

AM	Absolute angular momentum
APE	Available potential energy
AR	Autoregressive
E-P	Eliassen–Palm (flux)
ENSO	El Niño–Southern Oscillation
ERA-Interim	ECMWF interim reanalysis
CAPE	Convective available potential energy
JAPE	Jet available potential energy
LZNR	Level of zero net radiation
<i>M</i>	Isentropic mass or isentropic thickness
MJO	Madden–Julian oscillation
MLN	North midlatitude bands
MSL	Mean sea level
PE	Potential energy
PJ	Polar jet
PNJ	Polar night jet
PV	Ertel potential vorticity
RWT	Rossby wave train
SAM	South Asian monsoon
SML	South midlatitude bands
STJ	Subtropical jet
T	Tropical latitude bands
TC	Tropical cyclone
TJB	Tropical JAPE bubble
TML	Tropical plus both midlatitude bands
TP	Tropical plume
UTLS	Upper troposphere–lower stratosphere
UW-NMS	University of Wisconsin Nonhydrostatic Modeling System

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