


Observational evidence of the downstream impact on tropical rainfall from stratospheric Kelvin waves

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Abstract Analysis of one continuous decade of daily, high-vertical resolution sounding data from five proximate islands in the western equatorial Pacific region reveals eastward and downward propagating Kelvin waves in the tropical stratosphere, with a zonal wave number one structure and a period of ~15 days. By defining an initiation index, we find that these waves are primarily generated over the western Pacific warm pool and South America–tropical Atlantic sector, consistent with regions of frequent deep convection. The zonal phase speed of the stratospheric Kelvin waves (SKWs) is relatively slow (~10 m s⁻¹) over the initiation region due to coupling with deep convection, and becomes much faster (~30–40 m s⁻¹) once decoupled from the downstream troposphere. SKWs have significant impacts on downstream tropical rainfall through modulation of tropopause height. The cold phase of SKWs at tropopause leads to higher tropopause heights and more convection in tropics—with opposite impacts associated with the warm phase. Downstream tropical precipitation anomalies associated with these SKWs also propagate eastward with the same speed and zonal scale as observed SKWs. Interannual variability of the amplitude of the SKWs is shown to be associated with the Quasi-Biennial oscillation (QBO); implications for predictability are discussed.

Keywords Stratosphere · Kelvin waves · Tropopause · Tropical convection · Sounding observations · Intraseasonal variability · Precipitation

1 Introduction

Many studies have shown that stratospheric anomalies can influence tropospheric circulation and convection (e.g. Gray et al. 1992; Ho et al. 2009; Hu et al. 2012; Garfinkel and Hartmann 2011; Huang et al. 2012), and much attention has been paid to the dominant mode of interannual variability of the equatorial stratosphere, i.e., quasi-biennial oscillation (QBO) (Yasunari 1989; Baldwin et al. 2001; Hamilton 2002; Garfinkel and Hartmann 2007; Taguchi 2010; Kawatani and Hamilton 2013; Yuan et al. 2014). In both observations and numerical simulations, it has been demonstrated that the QBO can affect tropical convection (Gray et al. 1992; Knaff 1993; Randel et al. 2000; Liess and Geller 2012; Nie and Sobel 2015). Two hypotheses of the QBO modulation of tropical convection have been put forward (e.g. Reid and Gage 1985; Collimore et al. 2003). One is through the influence of the stratospheric temperature anomalies on upper tropospheric static stability and tropopause height (Collimore et al. 1998), and the other is related to changes in the vertical wind shear in the lower stratosphere and upper troposphere associated with the QBO zonal wind anomalies (Gray et al. 1992). Collimore et al. (2003) compared the relative importance of the two mechanisms and pointed out that the QBO fluctuations of convection in the tropical region are primarily associated with tropopause height anomalies. These studies clearly show prominent impacts of stratospheric anomalies on tropical convection.

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In addition to the QBO, subseasonal stratospheric waves have been identified in previous studies. Yanai and Maruyama (1966) found 5-day wind oscillations in the tropical stratosphere that propagate westward and downward, based on upper-air observation network over the central Pacific. Later, Wallace and Gousky (1968) discovered synoptic-scale wave motions in the equatorial stratosphere with a period of around 15 days by analyzing radiosonde data from three tropical stations. These waves propagate eastward, similar to an equatorial Kelvin wave. Holton (1972) found that these waves are primarily generated by tropospheric heating sources.

Due to observational limitations, these subseasonal stratospheric waves have not yet been thoroughly examined, including their characteristics and potential impacts on the troposphere. In this study, the stratospheric waves are analyzed, using both sounding and reanalysis data sets. We find subseasonal stratospheric variability associated with stratospheric Kelvin waves (SKWs), which are excited by the deep convection over the tropical western Pacific and South America regions. The SKWs propagate eastward and create significant impacts on downstream tropical precipitation by modulating the tropopause height.

2 Data and methods

Atmospheric sounding data from five proximate Micronesian islands situated within the western Pacific warm pool region are analyzed in this study, the domain of which is marked in Fig. 5. The islands are Palau, Yap, Truk, Ponape, and Majuro, and their daily soundings are available at <http://weather.uwyo.edu/upperair/sounding.html>. Daily profiles of air temperature from 2002 to 2011 at all five islands are linearly interpolated to the same vertical resolution. Raw sounding data have irregular vertical spacing ranging from 30 to 300 m; we interpolate all soundings to a regular 10 m interval between the surface and 30 km. We then average all five soundings into a single profile representing the regional atmosphere. Such an approach effectively filters out small-scale weather noise.

With global coverage and consistent spatial and temporal resolution, reanalysis data sets provide additional information, so daily air temperature from National Centers for Environment Predictions (NCEP) reanalysis 2.0 dataset (Kanamitsu et al. 2002) is also analyzed. As will be shown, the reanalysis dataset well reproduces the subseasonal variability present in the raw sounding data. Daily precipitation data from both Global Precipitation Climatology Project (GPCP) (Huffman et al. 2001) and Tropical Rainfall Measuring Mission (TRMM) satellite products (Huffman et al. 2007) are used to analyze the impact of the subseasonal stratospheric variability on tropical rainfall. All datasets

used in this study cover at least the same time period as the sounding data (2002–2011). To obtain the 5–30 day variability, a simple band-pass filter, which is based on differences between the 5- and 30-day running means, is applied to both air temperature and precipitation fields. The relationship between the QBO and interannual variability of amplitude of high-frequency stratospheric waves is also discussed below, with the QBO index commonly defined as the 180-day low-pass filtered zonal mean 30 hPa zonal wind at the equator (retrieved from <http://www.esrl.noaa.gov/psd/data/correlation/qbo.data>).

3 Results

3.1 Characteristics and identification of subseasonal stratospheric waves

A vertical Hovmöller diagram of regionally averaged, 5–30 day filtered air temperature anomalies reveals very clear subseasonal variability of amplitude 1–2 K (Fig. 1). A single year (2004) is shown to better illustrate the main features of the stratospheric waves; results are very similar for other years. Alternating positive and negative air temperature anomalies are shown to propagate downward in the stratosphere (Fig. 1). The period of the oscillation is around 15 days, and it takes about the same length of time for temperature anomalies at 25 km to reach the tropopause. Opposite temperature anomalies appear in the troposphere when the stratospheric temperature anomalies reach the tropopause. The opposite changes in air temperature in the stratosphere and the troposphere must lead to changes in the tropopause height, which is defined as the level of minimum air temperature. Indeed, in the warm (cold) phase of the stratospheric waves, the tropopause is lowered (lifted). Results from the NCEP2 reanalysis are very similar to Fig. 1 (not shown), despite having much lower vertical resolution.

In addition to their vertical propagation, the horizontal structure of the observed stratospheric waves is explored through analysis of the NCEP2 reanalysis. A zonal Hovmöller diagram of the filtered stratospheric temperature anomalies shows that the stratospheric waves not only propagate downward, but also eastward in the equatorial band (Fig. 2). The zonal phase speed is relatively slow over the warm pool region (90°E–180°E), and becomes faster over the eastern Pacific. The characteristics of these stratospheric waves are the same as the equatorial Kelvin waves (Gill 1980), which are generated by the tropical heating source in the troposphere (Holton 1972). Hence, even though the phases of the SKWs propagate downward, the energy actually propagates upward. It is noted that the amplitude of the SKWs is relatively weak during 2004 and

Fig. 1 Hovmöller diagram of the 5–30 day filtered, five islands-averaged air temperature anomalies in 2004 (unit: K). Black (grey) shading represents positive (negative) 5–30 day filtered tropopause height anomalies on top of the climatological tropopause height (unit: m)

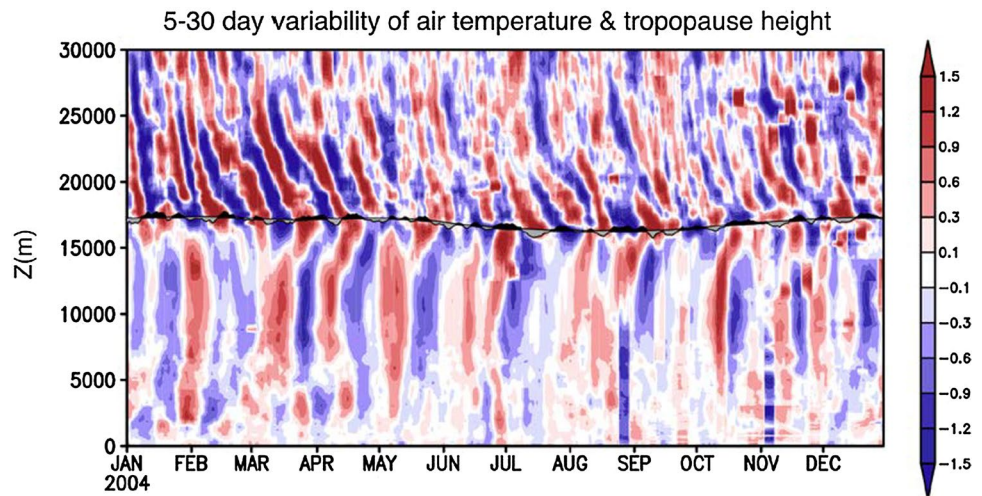
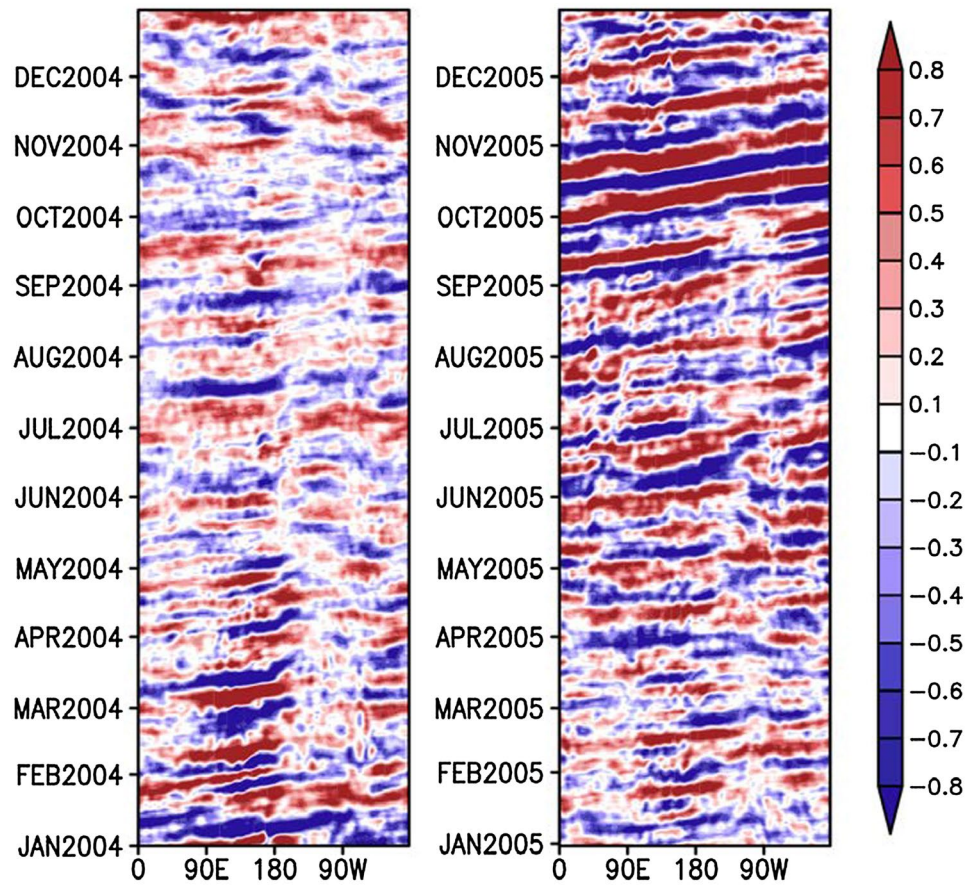


Fig. 2 Hovmöller diagram of 5–30 day filtered 30 hPa air temperature anomalies averaged between 5°N and 5°S in 2004 and 2005 from the NCEP2 reanalysis (unit: K)

Filtered 30hPa air temperature anomaly (5°N-5°S, NCEP2)

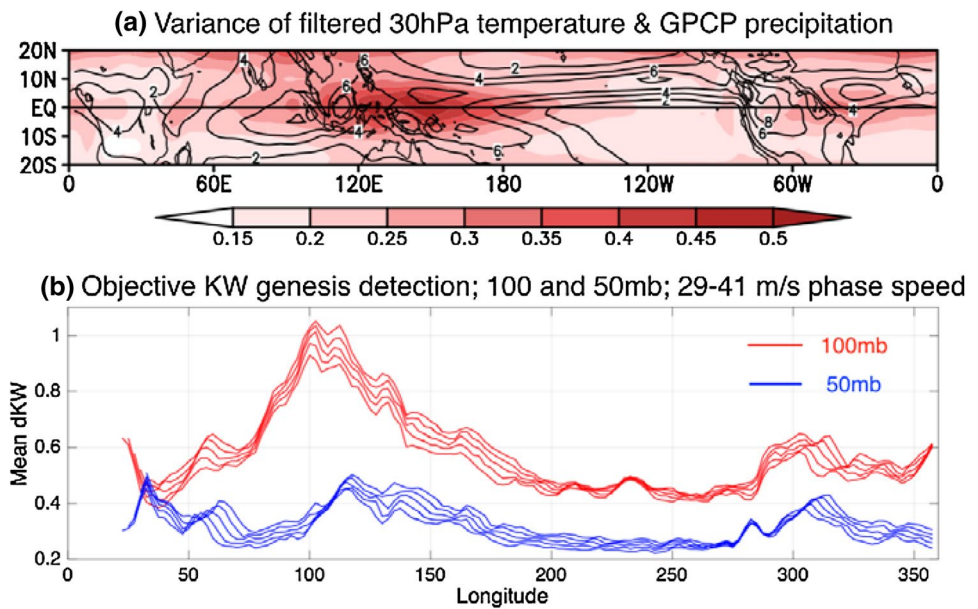


early 2005, while it becomes much stronger toward the end of 2005. The interannual variability of the SKWs is discussed in Sect. 3c.

Temperature anomalies associated with the SKWs are larger over the western Pacific warm pool region (90°E-180°E) and equatorial Atlantic (60°W-0°), where

tropical deep convection is typically located (Fig. 2). Variance of the 5–30 day filtered 30 hPa temperature anomalies indeed reaches a distinct maximum over these two regions (Fig. 3a). Such a spatial distribution is related to the initiation of the SKWs, which is represented by an initiation index defined as $(T_{t,x} * T_{t+\Delta t,x+c*\Delta t})/abs(T_{t,x})$ where $T_{t,x}$

Fig. 3 **a** Variance of the 5–30 day filtered 30 hPa temperature anomalies (shading, K^2) and climatological annual mean precipitation (contours, mm/day). **b** Initiation index (reversed sign) defined at different heights (red for 100 mb and blue for 50 mb) with different phase speeds (bottom line to top line: 29–41 $m s^{-1}$ at a 3 $m s^{-1}$ interval)



denotes the temperature anomalies at time t and longitude x , and $T_{t+\Delta t, x+c*\Delta t}$ denotes the temperature anomalies at the next time increment ($\Delta t = 1$ day) and to the east by the distance $c*\Delta t$. The index is parameterized by the zonal phase speed c (estimated as 30–40 $m s^{-1}$). Results are not sensitive to the choice of the value of the zonal phase speed c . A large negative initiation index value indicates that the temperature anomaly changes sign and grows rapidly in one day. The time-average of the initiation index reveals that SKWs are commonly initiated over the western Pacific warm pool and South America-Atlantic sector (Fig. 3b). Also note that peak of the initiation index shifts eastward at a higher altitude, which is consistent with the eastward energy propagation (Fig. 3b).

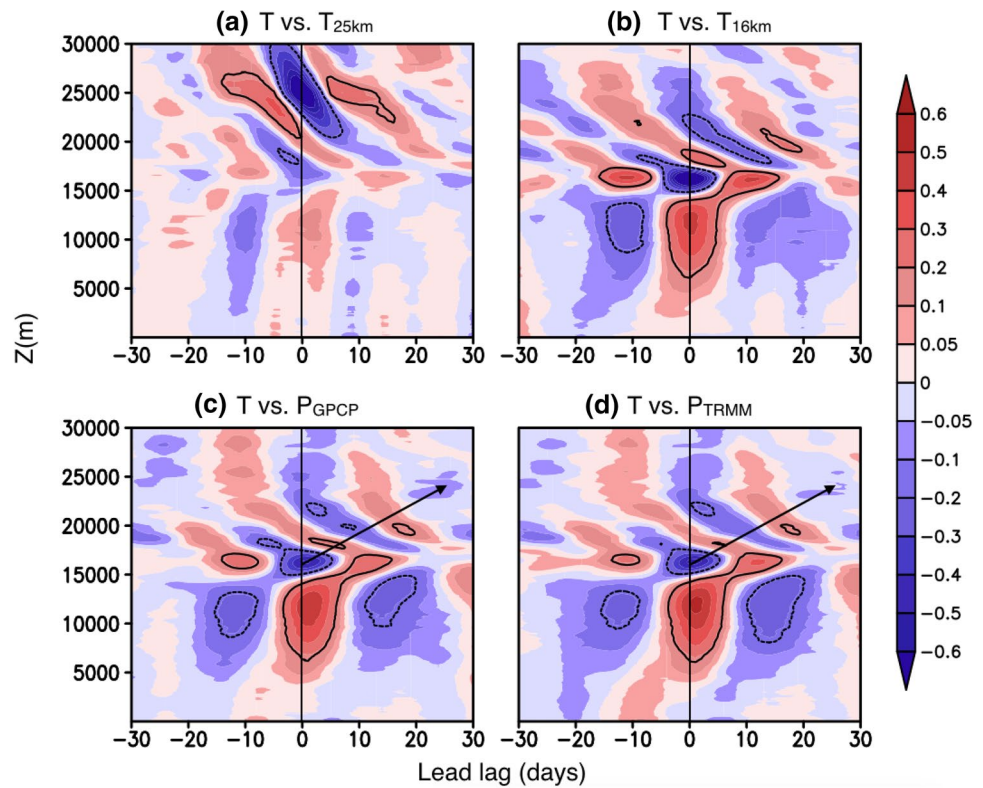
Initiation of SKWs by the tropical heating source is also evident in lead-lag correlation structure between filtered 25 km (16.25 km) air temperature index and air temperature anomalies at different heights from the sounding data (Fig. 4). Warm and cold subseasonal anomalies in the tropical stratosphere clearly alternate and propagate downward to the tropopause, which is at around 16–17 km (Fig. 4a, b). Opposite air temperature anomalies appear in the troposphere, and as a result, the tropopause is lifted (lowered) in the cold (warm) phase of the SKWs. More importantly, the stratospheric temperature anomalies are found to be closely related to the tropical rainfall anomalies. The lead-lag correlation between precipitation and temperature anomalies at different heights over the western Pacific warm pool region shows that after the tropical rainfall anomaly reaches maximum in day 0, which leads to warmer troposphere and higher tropopause, the energy propagates upward from the troposphere into the mid-stratosphere, generating alternating positive and negative temperature anomalies (Fig. 4c,

d). Precipitation anomalies over the Indian Ocean and western Pacific warm pool region that initiate the SKWs could be associated with the Madden Julian Oscillation (MJO).

3.2 Downstream impact of SKW on tropical rainfall

Lead-lag regression analysis confirms the eastward propagation of SKWs (Fig. 5). Positive days are associated with 30 hPa temperature lagging the temperature index, which is defined for the two primary SKW initiation regions, i.e., the region of the five proximate islands in the western Pacific and the South America-Atlantic sector. In Fig. 5a, the stratospheric warm anomalies are located over the Maritime Continent region in day 0. The warm anomalies propagate eastward in the following days, first at a relatively slow phase speed over the western Pacific warm pool region, then faster once over the eastern Pacific (Fig. 5b–d). The slow phase speed over the warm pool region is due to the strong coupling between SKWs and deep convections, similar to MJO-initiated Kelvin waves (e.g. Wang and Rui 1990). Once SKWs propagate away from the initiation region and decouple from the substantial tropospheric heating source, the phase speed becomes much faster. The zonal phase speed of the SKWs is estimated to be $\sim 14 m s^{-1}$ over the tropical western Pacific and $\sim 55 m s^{-1}$ over tropical eastern Pacific (Fig. 5). Similarly, for the SKWs initiated over South America, the zonal phase speed is slow over the Atlantic and becomes faster until reaching the western Pacific warm pool region (Fig. 5e–h). Also note that the temperature anomalies associated with SKWs are not confined in the equatorial region, but widely spread in tropics to nearly 40°N and S.

Fig. 4 Lead-lag correlation between five islands-averaged air temperature anomalies at, **a** 25 km and **b** 16.25 km and five islands-averaged air temperature anomalies at different heights. Signs in **a, b** are reversed. Lead-lag correlation between domain averaged (20°S–20°N, 90°E–180°E) precipitation from **c** GPCP and **d** TRMM and five islands-averaged air temperature anomalies. *Black arrows* denote the energy propagation. Negative (*positive*) days are associated with the index lagging (leading) air temperature anomalies. Contours represent the 95% confidence level



30hPa air temperature regression (NCEP2)

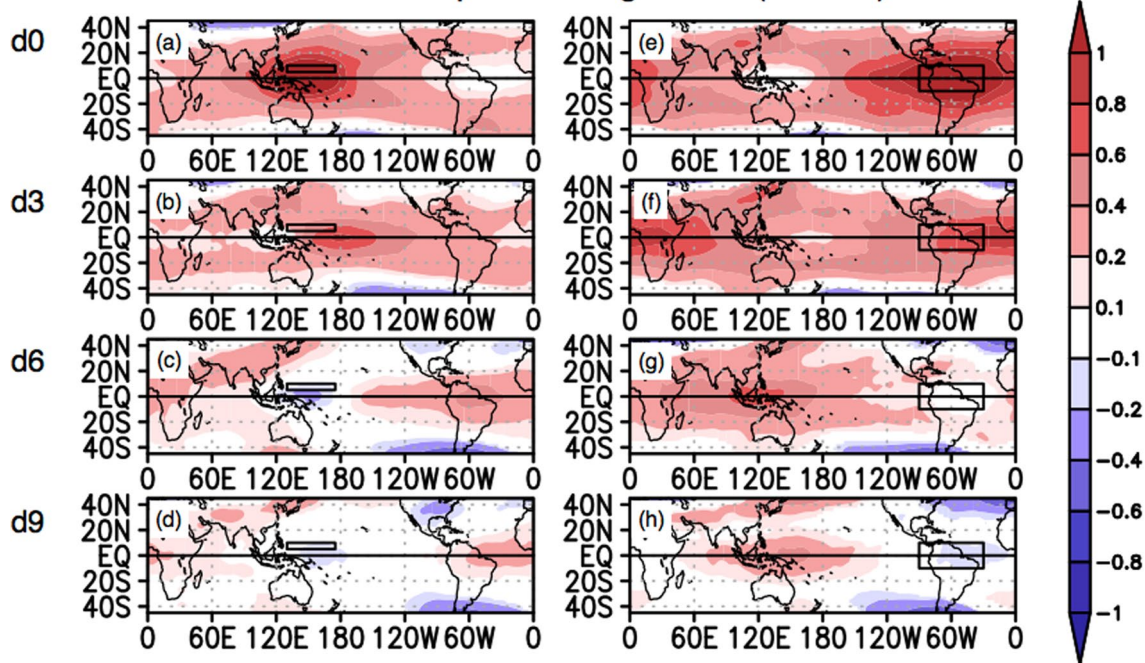


Fig. 5 Lead-lag regression of 30 hPa air temperature anomalies onto domain averaged 5–30 day filtered 30 hPa air temperature anomalies with a 3-day interval (units: $K K^{-1}$). Positive days are associated with the index leading 30 hPa air temperature anomalies. **a–d** For tem-

perature index defined for the domain over the western Pacific warm pool region (5°N–10°N, 130°E–175°E), and **e, h** for the domain (10°S–10°N, 90°W–30°W). Shown are signals that are statistically significant at the 95% confidence level

In the light of the eastward and downward propagation of the observed SKWs, the associated temperature anomalies may have impacts on the downstream tropopause, which may further influence the tropical rainfall. Figure 6 shows lead-lag regression maps of precipitation anomalies from the GPGP dataset onto stratospheric temperature anomalies at 16.25 km. Similar results are also obtained using the TRMM rainfall dataset (not shown). Positive days are associated with the temperature index leading precipitation anomalies. Prominent negative rainfall anomalies appear over the Indo-Pacific sector in day 0 when the 16.25 km warm anomalies reach a maximum (Fig. 6a), which also confirms the initiation of SKWs by the anomalous heating source in the troposphere. Over the downstream region, the stratospheric warm (cold) anomalies associated with the SKWs lowers (lifts) the tropopause, which then leads to negative (positive) rainfall anomalies. Indeed, we find that dry signals propagate eastward at a relatively fast phase speed, along with warm anomalies in the stratosphere (Fig. 6). This process appears to be a sub-seasonal analog to the QBO modulation of tropical rainfall by forcing tropopause height anomalies (Collimore et al. 2003). The latitudinally averaged results clearly reveal the close relationship between eastward propagating SKWs and associated precipitation anomalies (Fig. 6e–h). Note

that the downstream stratospheric temperature anomalies associated with the observed SKWs are associated with anomalous precipitation over the 3 day lag period (Fig. 6). The response of tropical rainfall is slightly delayed compared to the 30 hPa temperature anomalies because it takes several days for the stratospheric temperature anomalies to reach the tropopause (as evident in Figs. 1, 6).

3.3 Interannual variability of SKWs and the QBO

A clear year-to-year variation in the amplitude of the SKWs is also evident in both the observational and reanalysis data, which turns out to be closely related to the dominant mode of interannual variability in the tropical stratosphere, i.e., the QBO. The low-frequency temperature anomalies associated with the QBO and 180-day running variance of 5–30 day filtered air temperature make the case quite clear (Fig. 7). Both the QBO-related anomalies and the high-frequency variance exhibit significant interannual variability and their phases both propagate downward in the stratosphere. It is also interesting that the interannual variation in the amplitude of the SKWs are in quadrature with the LF temperature signals associated with the QBO, i.e., high variance signals are found after (before) the cold (warm) QBO phases (Fig. 7b). One can see a clear

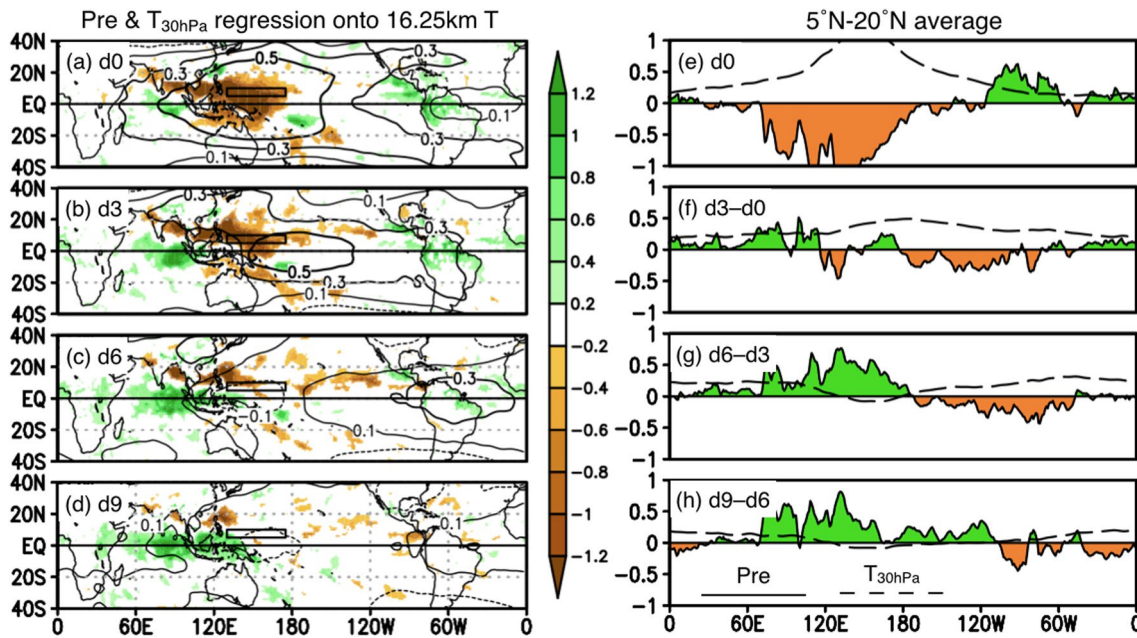


Fig. 6 a–d Lead-lag regression of GPCP precipitation anomalies onto five islands-averaged temperature anomalies at 16.25 km with a 3-day interval (shading, $\text{mm day}^{-1} \text{K}^{-1}$). Contours are for lead-lag regression of 30 hPa temperature anomalies onto domain averaged 5–30 day filtered 30 hPa air temperature anomalies (units: K K^{-1}). Positive days are associated with temperature index leading precipitation and temperature anomalies. The box in the western Pacific warm

pool region denotes the domain in which the islands are located. Shown are precipitation anomalies that are statistically significant at the 95% confidence level. e–h As in a–d but for 5°N–20°N averaged regression of 30 hPa temperature (dashed line) and precipitation (solid line) with a 3-day interval. Shown in f–h are difference of precipitation from the previous 3 days

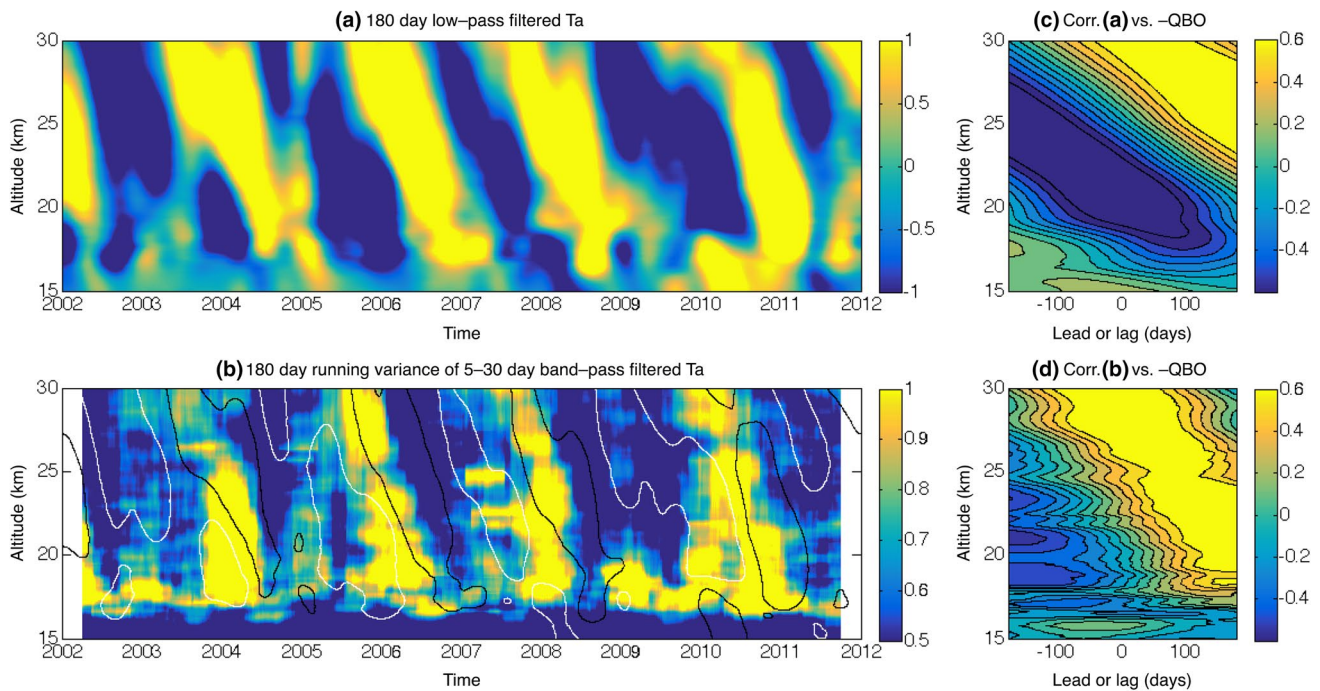


Fig. 7 **a** 180-day low-pass filtered air temperature from sounding data (unit: K). **b** 180-day running variance of 5–30 day band-pass filtered air temperature (*shading*, K^2). *Black (white)* lines are the +1 (–1) contours of 180-day low-pass filtered air temperature. **c** Lead-

lag correlation between 180-day low-pass filtered air temperature and the QBO index. **d** Lead-lag correlation between 180-day running variance of 5–30day filtered air temperature and the QBO index. Signs in **c**, **d** are reversed

downward propagation of the variance signals in lead-lag correlations between the variance of the SKWs and the QBO index (Fig. 7b). The QBO is in a cold (warm) phase before (after) the SKW amplitude reaches a maximum, and in a neutral phase when the SKW amplitude peaks in day 0. These results suggest that the amplitude of SKWs are tightly linked to the QBO. Such a result is confirmatory, given that Kelvin waves in the stratosphere have long been suggested as one of the primary drivers of the QBO (Holton and Lindzen 1972). We also found that the characteristic precipitation anomaly associated with the SKW is stronger when the SKW amplitude is relatively large after the cold QBO phase.

4 Summary and discussion

Our analysis of the subseasonal temperature variability in both high-vertical resolution sounding data from proximate islands in the western Pacific warm pool region and the NCEP2 reanalysis dataset confirms the presence of eastward and downward propagating high-frequency stratospheric waves, with a zonal wavenumber 1 structure, phase speeds of 30–40 m/s and a period of around 15 days. It takes about 15–20 days for the temperature anomalies at 25 km to reach the tropopause (16–17 km). These results

suggest that these waves are Kelvin waves in the equatorial stratosphere, as previously discovered by Wallace and Kousky (1968).

The SKWs are primarily generated by substantial heating sources in tropics, particularly over the western Pacific warm pool region and South America-Atlantic sector. The wave energy propagates upward from the troposphere into the stratosphere, but the phase propagation of the SKWs is downward in the stratosphere. Due to the strong coupling with tropical deep convection, the zonal phase speed of SKWs is relatively slow over the initiation region. Once SKWs propagate away from the substantial tropical heating sources, their phase speed becomes faster.

The stratospheric temperature anomalies associated with SKWs have prominent impacts on the downstream tropical rainfall anomalies by modulating the tropopause height. In the cold (warm) phases of the observed SKWs, tropopause height is lifted (lowered) once the temperature anomalies reach the tropopause. As a result, tropical convection anomalies occur in conjunction with the passage of these waves. Consistent with the eastward wave propagation in the stratosphere, the associated wet (dry) tropospheric anomalies also propagate eastward at the same phase speed as SKWs. It is interesting to note that, in contrast to the stratospheric temperature anomalies that are symmetric about the equator (Fig. 4), the tropical precipitation anomalies associated

with SKWs propagate along the climatological mean precipitation centers, i.e. Indian Ocean-western Pacific warm pool sector, intertropical convergence zone (ITCZ) and tropical South America (Fig. 6). In regions where the mean precipitation is small, e.g. the eastern equatorial Pacific, the tropopause modulation of tropical convection is insignificant.

The observed impact of SKWs on downstream tropical rainfall described herein suggests a new potential source of predictability at the subseasonal (10–30 day) timescale, which may help close the gap between medium-range numerical weather prediction (~10 days) and 30–60 day intraseasonal oscillations in tropics (e.g. MJO). Indeed, it is encouraging that the NCEP2 reanalysis is shown to be capable of capturing the tropopause modulation of tropical convection. Moreover, we find that SKWs exist in an atmospheric general circulation model experiment forced by climatological sea surface temperature field as well, which will be the subject of a forthcoming study.

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