GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L02710, doi:10.1029/2009GL041020, 2010

Scale interaction between tropical instability waves and low-frequency oceanic flows

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Received 22 September 2009; revised 23 November 2009; accepted 10 December 2009; published 30 January 2010.

[1] Tropical instability waves (TIWs), prevailing in the tropical Pacific and Atlantic Oceans, interact with the low-frequency oceanic flow. It is known that TIWs act as negative feedback to ENSO through a thermal process. In this study, we examine the dynamical eddy feedback of TIWs. We show that in terms of physical processes, the dynamical TIW feedback is very similar to the atmospheric synoptic eddy feedback in the extratropics. For example, the mean seasonal eddy vorticity flux of TIWs can be largely explained by the left-hand rule, which states that eddy vorticity fluxes are predominantly directed toward the left-hand side of the oceanic flow. Therefore, they act as positive feedback to the low-frequency oceanic flow. We also show that the positive eddy feedback is obtained from eddy structure changes induced by the low-frequency flow. **Citation:** Kug, J.-S., Y.-G. Ham, F.-F. Jin, and I.-S. Kang (2010), Scale interaction between tropical instability waves and low-frequency oceanic flows, *Geophys. Res. Lett.*, *37*, L02710, doi:10.1029/2009GL041020.

1. Introduction

[2] Tropical instability waves (TIWs) are unique features of the tropical Pacific and Atlantic Oceans [*Legeckis*, 1977; *Weisberg and Weingartner*, 1988]. It is known that TIWs develop from shear instability in an equatorial current system [*Philander et al.*, 1986] and baroclinic instability in strong meridional temperature gradients [*Wilson and Leetmaa*, 1988]. This indicates that TIW variability is closely related to the basic mean flows. On the other hand, several studies have reported that TIWs influence the tropical climate state by modifying the mixed layer heat budget [*Jochum and Murtugudde*, 2004; *Seo et al.*, 2006; *An*, 2008b]. This indicates that there are two-way interactions between TIWs and low-frequency oceanic flows.

[3] On an interannual time scale, TIW variability interacts with tropical low-frequency oceanic variation. The TIW variation is closely related to the variation in the cold tongue. TIW activity is suppressed during El Nino because of the reduced meridional temperature gradient [*Vialard et al.*, 2001; *Yu and Liu*, 2003]. On the other hand, *An* [2008b] showed from a heat budget analysis that TIWs act as negative feedback to ENSO because the TIW activity is suppressed and induces an anomalous cooling due to the reduced meridional mixing.

[4] However, most studies that have focused on the impact of TIWs on large-scale tropical variability have been limited to their thermal feedback. They may overlook the impact of TIWs on large-scale mean flows because they do not consider dynamical feedback. In contrast, we will consider the dynamical feedback of TIWs and will emphasize that TIWs act as positive feedback to the low-frequency flow; this is possibly in opposition to the effect of their thermal feedback.

[5] It is well known that extratropical atmospheric synoptic eddies act as positive feedback to the low-frequency flow through their dynamical feedback [*Lau*, 1988]. Recently, *Kug and Jin* [2009] suggested that the synoptic eddy feedback can be explained by a simple relationship with the low-frequency flow based on theoretical and observational analyses. They call this relationship the *left-hand rule*; it states that the vorticity flux of synoptic eddies tends to be directed toward the left-hand side of the low-frequency flow. *Ren et al.* [2009] further revealed that the left-hand rule can be derived from a kinematic mechanism between the low-frequency flow and the synoptic eddies. According to the left-hand rule, the synoptic eddy feedback plays a positive role in enhancing the low-frequency flow [*Kug and Jin*, 2009; *Kug et al.*, 2009].

[6] The first goal of the present paper is to test whether or not the left-hand rule works in interactions on an oceanic scale. Furthermore, we will illustrate the dynamical feedback of TIWs; this feedback plays a positive role in enhancing the low-frequency ocean current system, similar to the role played by the atmospheric synoptic eddy feedback.

2. Model and Data

[7] The use of ocean reanalysis data may be problematic because the data assimilation technique and coarse observational network may fail to realistically simulate TIWs and TIW activity [*Ham and Kang*, 2010]. Therefore, in this study, we used seasonal prediction data from the Seoul National University coupled general circulation model (SNU CGCM) [*Kug et al.*, 2008]. The zonal grid spacing of the oceanic model is 1.0°, and the meridional grid spacing between 8°S and 8°N is 1/3°.

[8] The seasonal prediction data are adopted from those of *Ham and Kang* [2010]. To initialize the oceanic and atmospheric variables, GODAS and ERA40 data are nudged into the forecast model. Given the initial conditions, 20-yr hindcasts with 4-month lead forecast are carried out, starting from 1st May for the period 1981–2000. In this experiment, three-dimensional TIW perturbations that are obtained from free integration are added to the initial

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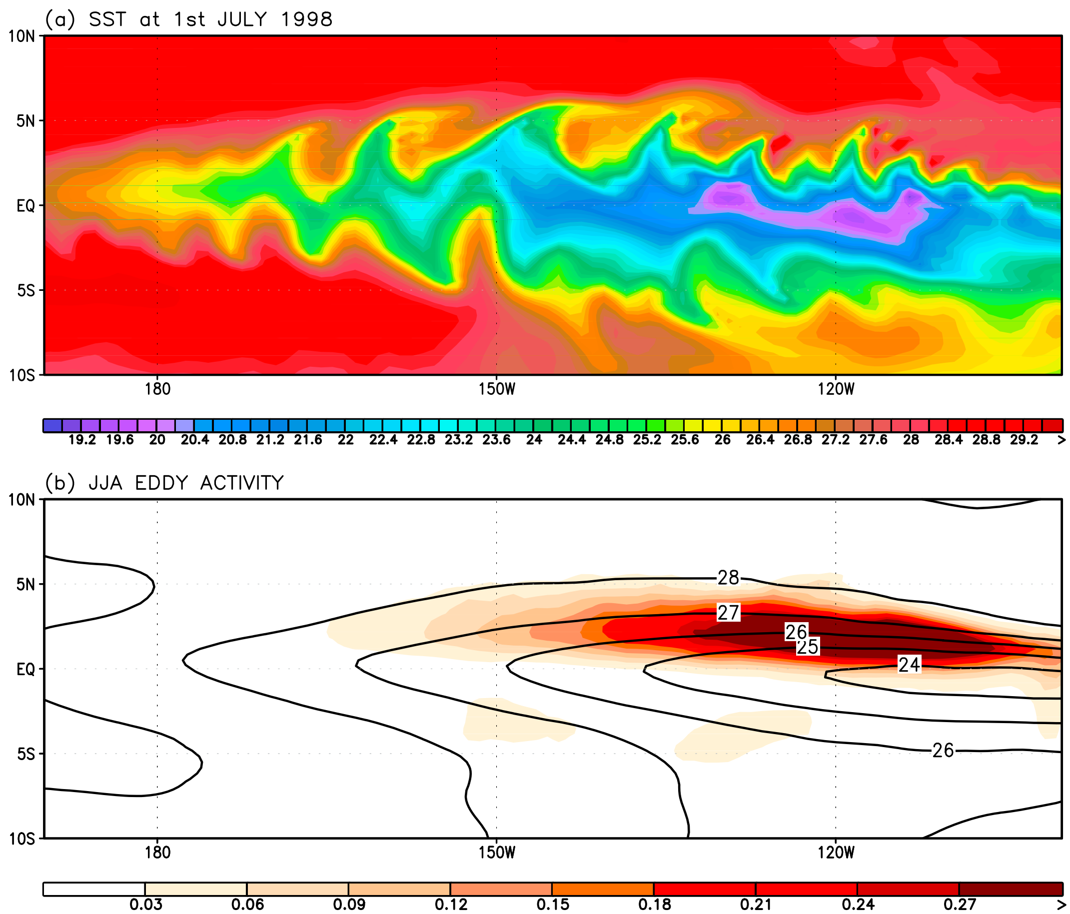

Figure 1. (a) SST snapshot at 1st July 1998 and (b) JJA SST eddy variance (Unit: $^{o}C^{2}$). Note that TIWs are defined as perturbations whose zonal scale is smaller than less than 10°; high-pass filters in the zonal direction are applied to remove larger perturbations.

condition in order to achieve the right TIW intensity. Ham and Kang showed that the forecasting of ENSO is significantly improved when a small-scale perturbation is added.

[9] Figure 1a shows a daily mean snapshot of the tropical Pacific SST and TIW variance from June to August (JJA). In this study, TIWs are defined to be perturbations whose zonal scale is less than 10°; high-pass filters in the zonal direction [*Roundy and Frank*, 2004] are applied to remove larger perturbations. Note that the filtered data have a dominant time scale of 40–50 days, and zonal-scale of the perturbations in high-pass filtered data is mostly between 5–10 degree with power spectrum results (not shown). Cusp-like SST perturbations are clearly seen along the edge of the cold tongue region where the meridional SST gradient is strong. This suggests that our model has the ability to simulate TIWs. As shown in Figure 1b, our model simulates a strong eddy variance in the northern part of the equatorial cold tongue region, which is consistent with the observed variance [*Contreras*, 2002; *An*, 2008a].

[10] To measure the dynamical feedback of TIWs, convergence of eddy-vorticity fluxes (VFC) is defined as follows:

$$VFC = -\left(\frac{\partial \overline{u'\varsigma'}^{a}}{\partial x} + \frac{\partial \overline{v'\varsigma'}^{a}}{\partial y}\right)$$

where u', v', and ς' denote the zonally high-pass filtered zonal currents, meridional currents, and vorticity. The overbar indicates the monthly (or seasonal) mean. The superscript *a* indicates an interannual anomaly from the mean monthly climatology. A positive (negative) VFC value indicates the cyclonic (anticyclonic) vorticity tendency of the low-frequency flow. Because the rotational component of the eddy vorticity flux does not influence the low-frequency flow, only the divergent component is examined here.

3. Results

[11] As mentioned in the Introduction, the left-hand rule states that in the extratropical atmosphere the eddy vorticity flux of synoptic eddies tends to be directed toward the left-hand side of the low-frequency flow. To test whether or not the left-hand rule works in the ocean, we calculate the correlation between the mean monthly zonal current and the monthly meridional vorticity flux of TIWs. Because the meridional current is quite weak in this region, we focus only on the zonal current. As shown in Figure 2a, there is a strong positive correlation over the central-eastern Pacific in the Northern Hemisphere (0–5N). This strong positive correlation indicates that the eastward (westward) currents tend to accompany the northward (southward) eddy vorticity

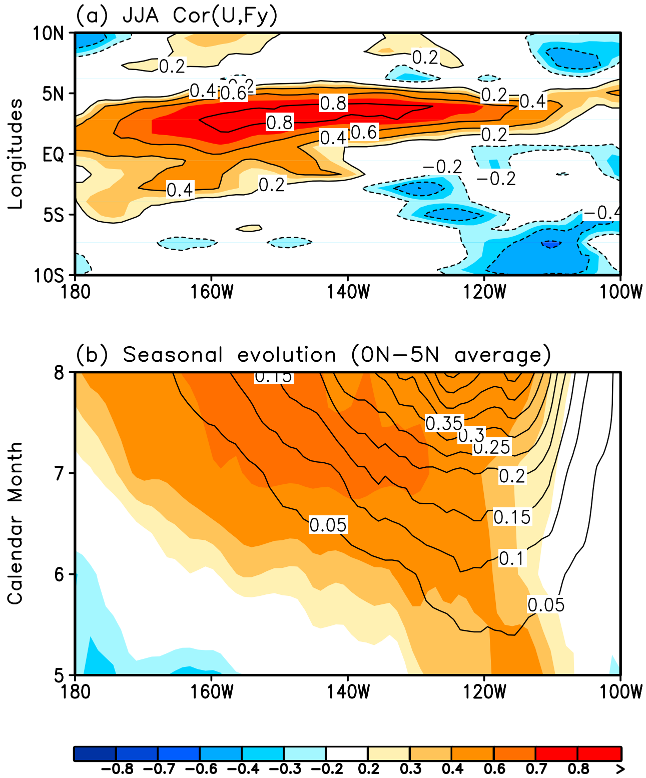

Figure 2. (a) Correlation between JJA averaged zonal currents and meridional vorticity flux. (b) Seasonal evolution of eddy variability (contour) and correlation between zonal currents and meridional vorticity flux (shading).

flux, indicating that the eddy vorticity flux is mostly to the left-hand side of the low-frequency oceanic current.

[12] Note that the maximum correlation coefficients are more than 0.8. It is interesting that the maximum correlation region is located over 180–120W, while as shown in Figure 1b the maximum eddy variance is located over 150–90W, indicating a westward shift. Note that TIWs develop in the eastern Pacific and propagate westward with a slow decay. When TIWs are developing by extracting energy from the low-frequency oceanic flow, the left-hand rule does not work well because the in-quadrature eddy feedback is dominant [*Robinson*, 1991; *Jin*, 2009]. However, when the eddy is decaying, the in-phase eddy forcing is overwhelming and so the left-hand rule works well [*Jin*, 2009]. These features are clearly shown in observed synoptic eddy forcing [*Kug and Jin*, 2009]. These authors showed that the left-hand rule works very well over the downstream region of the Pacific storm track, whereas it does not work over the east Asia region where the synoptic eddies are generated and developed [see *Kug and Jin*, 2009, Figure 2]. Therefore, the westward shift of the maximum correlation in relation to the variance can be explained by the life cycle of the TIWs.

[13] Figure 2b shows the seasonal evolution of the variance and correlation. The seasonal variation of TIWs is closely related to seasonal changes in the cold tongue [*Yu et al.*, 1995; *An*, 2008b]. When the cold tongue is colder, TIW activity is stronger, while during the warm season of the cold tongue TIW activity is weak. It seems that our model also simulates well the seasonal variation in the eddy variance. The variance becomes gradually stronger as the cold tongue develops. It is clear that the correlation between the zonal current and meridional vorticity flux gets higher when the eddy activity becomes stronger, indicating that strong eddy activity leads to a robust left-hand rule. In addition, it is shown that except in May the maximum correlation region is consistently shifted to the west of the strong activity region.

[14] The left-hand rule leads to positive eddy feedback to the low-frequency flow. Under a cyclonic shear in the NH, the eddy vorticity fluxes of TIWs converge into the center of the cyclonic shear according to the left-hand rule, so the eddy-vorticity convergence intensifies the cyclonic shear. In the same manner, an anticyclonic flow is intensified by a divergence of eddy-vorticity fluxes, indicating positive eddy feedback. To illustrate this relationship, Figure 3a shows a scatter diagram of the JJA mean meridional shear of the zonal currents and the VFC of TIWs from an individual ensemble member. The values are averaged over 160°W–140°W, 2°N–5°N, where the correlation between low-frequency oceanic flows and vorticity flux is maximal. To a large extent, a cyclonic (anticyclonic) shear leads to a positive (negative) VFC. The correlation coefficient is −0.76, which is significant at the 99% confidence level. As shown in Figure 3b, the regression coefficients become larger as the eddy variance increases, indicating that stronger eddy activity leads to stronger positive eddy feedback.

[15] So far, we have shown that eddy vorticity fluxes of TIWs can be explained by the left-hand rule, and that they play a positive role in enhancing the low-frequency oceanic current. It is important to know exactly how TIWs interact with the low-frequency flow. Recently, *Ren et al.* [2009] analyzed the way in which the NAO-related flow induces positive eddy feedback by satisfying the left-hand rule. They suggested a kinematic mechanism for positive eddy feedback: the NAO-related flow anomalies systematically deform and tilt the structure of the recurring synoptic eddies, so that the tilted eddies generate eddy-vorticity flux anomalies directed toward the left-hand side of the NAO-related flow. They used a three-point covariance method to depict the structure changes in the synoptic eddies.

[16] In our study, we applied a one-point covariance method. Firstly, we selected strong and weak VFC cases from the data (20 years and 4 ensemble members) using a certain criterion. Based on one-standard-deviation criterion, 20 are strong and 16 are weak. Note that our results are quite robust with slightly different criterion (0.8 and 1.2 standard deviation). Secondly, one-point covariance maps were calculated from the filtered data for these strong and weak cases. Figure 4a shows the resulting one-point covariance maps. In Figure 4a, the base one-point is 150W, 3N, which is where the correlation is the highest in Figure 2a. The one-point covariance field shows a wave-packet-like structure for the TIW. The amplitude of the packet naturally decays as the distance from the base point increases. Overall, it exhibits a slightly tilted structure due to the off-equatorial counter current (eastward) and the equatorial surface current (westward).

[17] However, there is a systematic difference between the strong and weak cases. The TIW structure for the strong case is systematically less tilted than that for the weak case. The difference in the mean seasonal mixed-layer current

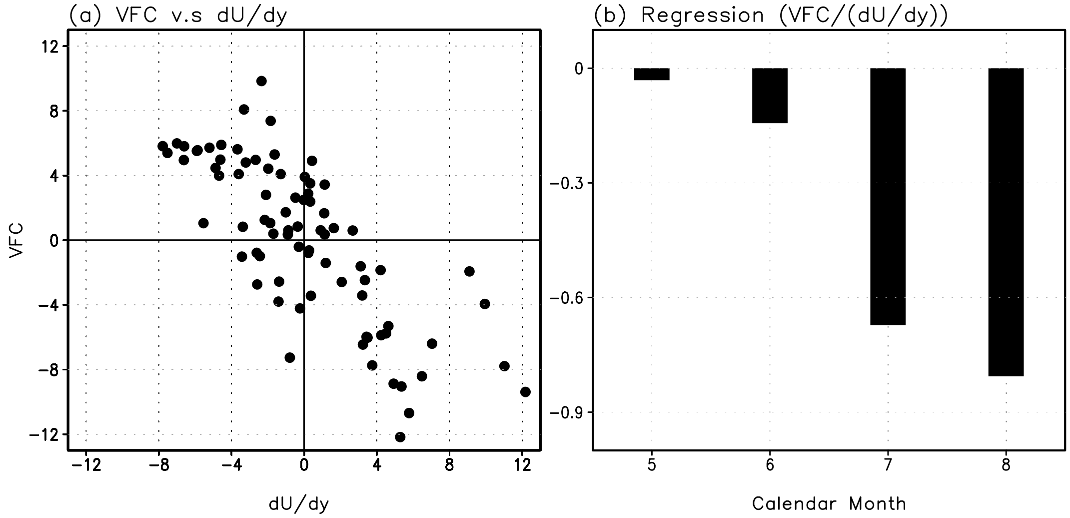

Figure 3. (a) Scatter diagram of JJA averaged VFC (vorticity flux convergence) and meridional shear of zonal currents. (b) Regression coefficient of VFC with respect to meridional shear of zonal currents. Units of VFC and meridional shear are 10^{-10} s^{-2} and 10^{-5} s^{-1}, respectively. The values are averaged over 160°W–140°W, 2°N–5°N, where the correlation between low-frequency oceanic flows and vorticity flux is maximal.

between the two cases (vector) clearly shows a cyclonic flow, i.e., eastward (westward) anomalies in the equatorial (off-equatorial) region. This indicates that the current anomalies systematically deform the TIWs. *Kug and Jin* [2009] and *Ren et al.* [2009] suggested that the differential vorticity advection of the anomalous low-frequency flow can change the eddy structure. That is, an anomalous cyclonic (anticyclonic) shear leads to a cyclonic (anticyclonic) tilting of the eddy structure; this is consistent with the features shown in Figure 4a.

[18] The different tiltings of the eddy structure produce different eddy feedbacks. To examine this, lead-lag one-

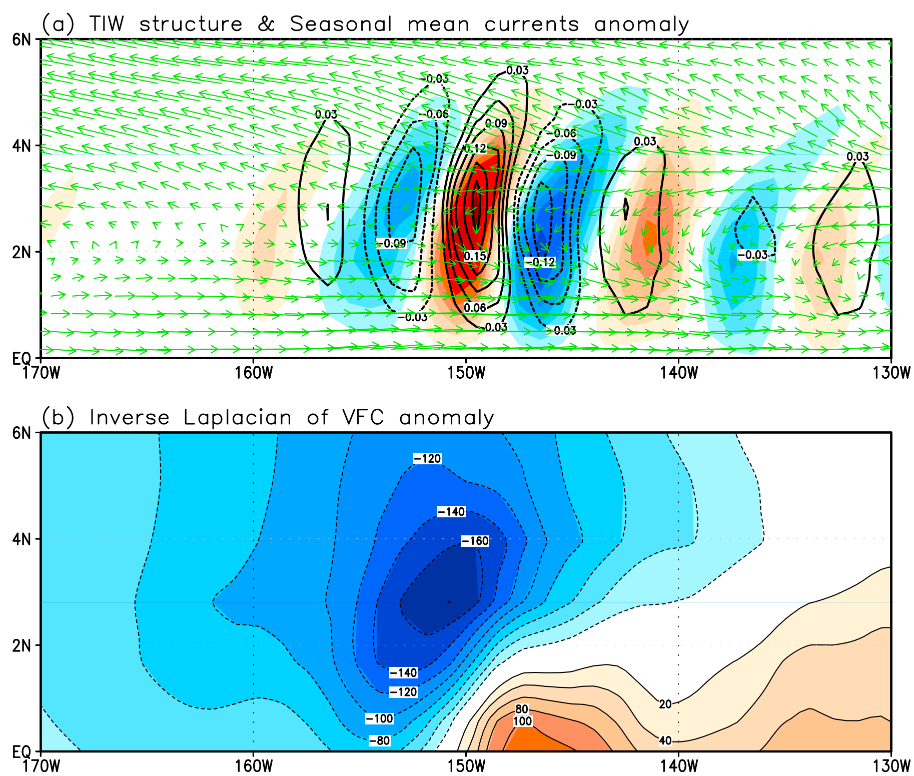

Figure 4. (a) TIW structure calculated from one-point covariance during strong VFC (contour) and weak VFC (shading) cases, and JJA mean current difference (vector). (b) Inverse Laplacian of VFC difference (strong–weak VFC cases). The unit of the inverse Laplacian of VFC is m^2/s^2.

point maps are calculated to capture the statistical life cycle of the TIWs for both the strong and weak cases. The eddy-vorticity flux is calculated from the lead-lag one-point covariance map, and the eddy forcings ($-\nabla^{-1} \cdot \vec{F}$) for the two cases are compared. Note that the eddy forcing is defined to be the inverse Laplacian of the VFC, whose positive (negative) value is related to the anticyclonic (cyclonic) flows. The inverse Laplacian is taken to smooth out the VFC fields and show the eddy forcing difference more clearly. This methodology is similar to that of *Ren et al.* [2009]. The advantage of using one-point covariance statistics is that the reconstructed eddy structure and the corresponding eddy forcing can provide a simple explanation for the positive eddy feedback.

[19] Figure 4b shows the differences in the eddy forcings ($-\nabla^{-1} \cdot \vec{F}$), derived from the eddy structure changes in the one-point covariance map. The eddy forcings are averaged values from 10 day lag to 10 day lead (a total of 21 days). The differences show an overall cyclonic streamfunction tendency (negative values) near the one-point, although an anticyclonic tendency (positive values) exists over the southeastern regions. The cyclonic tendency indicates that the eddy feedback tends to enhance the cyclonic shear of the oceanic current for the strong cases, and to enhance the anticyclonic shear for the weak cases, which is consistent with Figure 3a. Although we used only a one-point covariance map, the calculation captures the observed positive eddy feedback. This indicates that the positive eddy feedback is related to the eddy structure changes controlled by the low-frequency flow.

4. Summary and Discussion

[20] In this study, we have examined the dynamical eddy feedback of TIWs to the low-frequency oceanic flow. We have demonstrated that the mean seasonal eddy vorticity flux of TIWs can be largely explained by the left-hand rule, which states that the eddy vorticity fluxes are predominantly directed toward the left-hand side of the oceanic flow. Therefore, they play a positive role in enhancing the low-frequency flow. A one-point covariance analysis has revealed that the positive eddy feedback is related to the eddy structure changes induced by the low-frequency flow. It is striking that there are great similarities between atmospheric and oceanic phenomena in the dynamical eddy feedback process. We have found that the major dynamical processes, previously revealed for the interaction of atmospheric synoptic eddies and the low-frequency flow [*Kug and Jin*, 2009; *Ren et al.*, 2009], are also applicable to the interaction of TIWs and low-frequency oceanic flows.

[21] Although we have presented the evident TIW feedback, our study has obvious limitations. Firstly, our analyses were carried out using data covering one season and a few ensemble members due to availability of the data. However, TIW activity is strongly seasonal [*Yu et al.*, 1995; *An*, 2008a]; therefore, feedback will vary with season. Secondly, our results are based on a particular climate model and may therefore be model-dependent. Future research should use a multi-model analysis or high-resolution observational evidence.

[22] In this study, we showed the left-hand rule is working well in tropical ocean, implying that the dynamical TIW feedback plays a positive role like the role of synoptic eddies in the extratropical atmosphere. Therefore, TIW feedback tends to increase interannual oceanic anomalies over the equatorial Pacific. However, the net effect of the TIWs on oceanic variability can be different, compared to that of synoptic eddies, because the environmental conditions, i.e., baroclinicity) are quite different between tropical ocean and extratropical atmosphere. For example, previous studies observed that TIWs act as negative feedback to interannual variability (i.e., ENSO) through a thermal process. Therefore, the dynamical and thermal feedback will compete and cancel out each other. Because our analysis focused only on the qualitative relationship, it was difficult to determine the exact role of TIWs. It will be very useful to know the collective effect of TIWs on interannual oceanic variability, and further research can provide more detailed modeling and analysis.

[23] **Acknowledgments.** This work was supported by grant KSC-2009-S03-0002 from Korea Institute of Science and Technology Information. J.-S. Kug is partly supported by KORDI (PE98445, PE98511, PE98512). In-Sik Kang was supported by the second stage of the Brain Korea 21.

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