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Projected changes of wintertime synoptic-scale transient eddy activities in the East Asian eddy-driven jet from CMIP5 experiments

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Key Points:

- The East Asian eddy-driven jet will be intensified in a warming climate
- The enhancement is related to the surface stability and the historical state
- CMIP5 models exhibit large model diversities and independencies

Supporting Information:

- Figures S1–S4 and Table S1

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Abstract The wintertime East Asian eddy-driven jet (EAEJ) responding to climate change in the 21st century is studied using model outputs from the Coupled Model Intercomparison Project phase 5 (CMIP5). Compared to the location displacement in oceanic eddy-driven jets, the magnitude change of synoptic-scale transient eddy activities, measured by eddy kinetic energy (EKE), is a more striking feature in EAEJ. An intensified EKE is projected unanimously by CMIP5 models, suggesting that potential strong winter storm events are likely to happen in East Asian midlatitude in a warming climate. The future change of EKE in EAEJ can be understood in terms of growing baroclinicity wave. The upper level EKE is highly correlated to the low-level static stability, Brunt-Väisälä frequency (BVF). CMIP5 models generally project an intensified upper evel EKE with a reduced low-level BVF ($\Delta\mathrm{EKE} \propto -\Delta\mathrm{BVF}$). Meanwhile, the enhancement of EKE is also constrained by its historical state ($\Delta\mathrm{EKE} \propto -\mathrm{EKE}$). Intermodel variabilities among CMIP5 models reveal a similar but weaker relationship between ΔBVF (or EKE) and ΔEKE, indicating relatively large model diversities and independencies among CMIP5 models.

1. Introduction

The extratropical atmospheric general circulation is characterized by the prevailing circumpolar westerlies, which act as the dominant west-to-east motion of the atmosphere in both hemispheres. In East Asia, two splitted jets are located at the southern and northern flanks of the Tibetan Plateau, namely, East Asian subtropical jet (EASJ) and East Asian polar front jet (also known as eddy-driven jet, EAEJ), which are brought by the unique mechanical and thermodynamic conditions in East Asian region (Figure S1 in the supporting information) [*Zhang et al.*, 2008; *Ren et al.*, 2010]. The former is a result of angular momentum transport by the thermally direct Hadley circulation, while the latter is driven by the eddy momentum convergence that develops in regions of enhanced baroclinicity [*Held*, 1975; *Held and Hou*, 1980; *Zhang et al.*, 2006; *Li and Wettstein*, 2012; *Xiao and Zhang*, 2012]. The eddy-driven jet is of great significance in understanding the weather and climate variability in midlatitude; thus, the future projection of jet location and intensity plays a crucial role in assessing regional and global climate change impacts.

The poleward shift of the eddy-driven jet and associated storm tracks has been evidenced in observation [*Thompson and Solomon*, 2002; *Fu et al.*, 2006] and projected to continue throughout the 21st century [*Lorenz and DeWeaver*, 2007; *Chang et al.*, 2012], especially in the Southern Hemisphere. Compared with the zonal symmetry and intermodel consensus in the Southern Hemisphere, however, the location displacement and magnitude change of the jet responding to global warming exhibit not only intermodel spread but also spatial inhomogeneity in the Northern Hemisphere [*Yin*, 2005; *Kidston and Gerber*, 2010; *Barnes and Polvani*, 2013]. Due to the complexity of the topography-induced thermodynamic condition in East Asia, the eddy-driven jet varies distinctively in this region. Most previous works were conducted from a global or hemispheric perspective, while less attention was paid to East Asian region.

Multimodel ensemble projection by *Ihara and Kushnir* [2009] indicated that midlatitude westerlies in the North Hemisphere would be undergoing an intensity enhancement but with regional dependence. *Zhang and Huang* [2011] compared the climatological jet position between 1980–2004 and 1958–1979 and found that the jet in the North Atlantic had experienced a significant poleward shift but not in East Asia. In this study, a special effort is devoted to the eddy-driven jet over East Asia with regard to a regional response to the global warming.

2. Data and Methods

Daily and monthly outputs from 14 models of the Coupled Model Intercomparison Project phase 5 (CMIP5) data set are used [*Taylor et al.*, 2012] in this study. The detailed model descriptions are listed in the supporting information (Table S1). We compare the historical simulation from 1970 to 2000 and the Representative Concentration Pathway 4.5 (a midrange mitigation emissions scenario) projection from 2070 to 2100 in winter (December, January, and February) from all models. In addition, the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis [*Kalnay et al.*, 1996] is also utilized to compare with historical simulations. The circulation data for the latest three decades were chosen because the reanalysis covering the modern satellite era is more reliable and homogeneous than the presatellite period [*Bromwich et al.*, 2007].

Compared to EASJ which is featured with the prevailing westerly jet axis and center, EAEJ is not as stable and strong as EASJ and experiences quite wide location variations in the polar front zone where EAEJ is characterized by enhanced synoptic-scale transient eddy activity [*Zhang et al.*, 2008; *Ren et al.*, 2010]. In this study, the historical simulation and the future projection of EAEJ in CMIP5 models are investigated with emphasis on its transient characteristic. Similar to the definition of storm track [*Blackmon*, 1976; *Hoskins and Hodges*, 2002], the transient eddy kinetic energy (EKE) on 300 hPa is calculated to represent the synoptic-scale transient eddy activity of EAEJ from the following equation:

$$\mathrm{EKE} = \overline{u'^2 + v'^2} \tag{1}$$

where u and v are the zonal and meridional wind components, respectively, the prime denotes 2–8 day band-pass filtering, and the overbar means temporal average in winter (Figure S2). The intensity of EKE in EAEJ is defined as the area average in the rectangle (60–120°E, 50–65°N) where EAEJ frequently occurs (Figure S1, the definitions of jet locations are provided in the supporting information), and the location is the latitude of maximum EKE in the meridional direction. The strong upper level EKE in EAEJ is associated with intensified low-level baroclinicity (Figure S3) [*Ren et al.*, 2010]. The baroclinicity can be expressed in terms of the Eady growth rate maximum (EGRM) [*Eady*, 1949; *Hoskins and Valdes*, 1990], which provides a quantitative estimate of the growth rate of baroclinic eddies

$$\sigma_{B1} = 0.31 \frac{f}{N} \frac{\partial |V|}{\partial z} \tag{2}$$

$$N^2 = \frac{g}{\theta} \frac{\partial \theta}{\partial z} \tag{3}$$

where f is the Coriolis parameter, N the Brunt-Väisälä frequency (BVF), V the time-mean horizontal wind, θ the potential temperature, and z the vertical height. The EGRM is regulated by the static stability and the vertical shear. Given that the mean state of wind velocity remains steady, the future change of low-level baroclinicity, EGRM, is mainly caused by the static stability, BVF. Here the BVF is vertically averaged between 1000 hPa and 850 hPa.

3. Results

The projected changes of zonal mean EKE for individual model and multimodel ensemble mean (MME) are shown in Figure 1. For a given model curve where the maximum of EKE change (ΔEKE) is on the poleward side of the dot (historical location), there will be a poleward shift of EKE and vice versa. The MME projects the ΔEKE peak at the southern side of MME dot, indicating that EAEJ will experience a slight equatorward displacement, differing from the poleward shift of oceanic storm tracks [e.g., *Yin*, 2005]. Every model reproduces two maximum EKE in the meridional direction over East Asia, corresponding to the EASJ around 30°N and EAEJ around 55°N, respectively. While CMIP5 models performance differently in the projection of EASJ, all models unanimously project a strengthening EKE in EAEJ in the warming scenario. In MME, the maximum ΔEKE can reach as large as 13 $\mathrm{m^2\,s^{-2}}$, accounting for more than 10% enhancement of 20 century climatology. In the following subsections, we will focus on the magnitude increase of EKE from the perspectives of the low-level static stability and its historical mean state.

Figure 2a illustrates the relationship between ΔEKE and the static stability change (ΔBVF). The future change of EKE and BVF are calculated as 2071–2100 projections annually minus 1971–2000 simulations. So, each

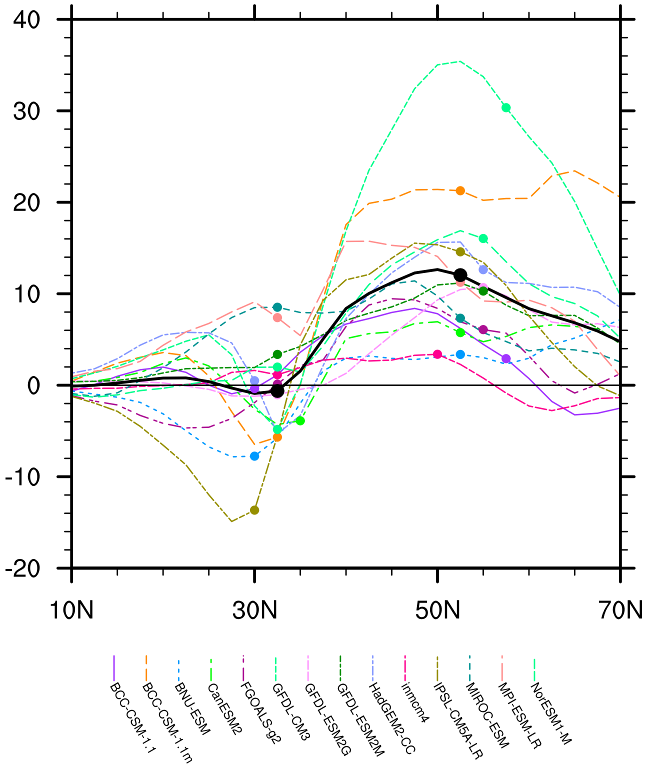

Figure 1. The projected change (2071–2100 minus 1971–2000) of eddy kinetic energy (EKE, units: $m^2 s^{-2}$) zonally averaged in East Asia. The thick black line denotes the multimodel ensemble mean. The dots on each line represent the latitude of the maximum EKE in the 1971–2000 climatology.

model contains 29 winter pairs of ΔEKE and ΔBVF. Obviously, there is a strong relationship between ΔEKE and ΔBVF, with a correlation coefficient of −0.543 calculated from all model scatter points, implying that the synoptic-scale activity in EAEJ will be intensified in a more unstable low-level environment. Studies from both previous CMIP3 [*Kidston and Gerber*, 2010] and current CMIP5 [*Barnes and Polvani*, 2013] found that the future response of jet location is strongly related to its historical position. Similarly, the relationship between ΔEKE and the historical intensity of EKE, ΔEKE versus EKE, is then examined (Figure 2b). An even stronger relationship occurs between ΔEKE and EKE, with a correlation coefficient of −0.593. Models underestimating EKE in the historical simulation are favorable to strengthen EKE under global warming. Comparing the ranges of ΔEKE and EKE in MME also indicates that the magnitude of the projected change is larger than the historical interannual variability. Meanwhile, for the model validation, the EKE is underestimated in all models except for the high-resolution BCC-CSM-1.1m. From this point of view, accurate simulation of midlatitude dynamics over East Asia still remains as a considerable modeling challenge. The relationships between ΔEKE and EKE, ΔBVF for individual model are specified in Table 1. Even though the simulated EKE in EAEJ differs significantly among each model, the projected relationship between ΔEKE and EKE becomes robust. Compared with EKE, the relationship between ΔEKE and ΔBVF reveals a strong intermodel spread. In MME, the correlation coefficient of ΔEKE versus ΔBVF (−0.49) is similar to that of ΔEKE versus EKE (−0.62).

In addition to the annual change of EKE which is related to the historical status and the low-level static stability, the corresponding intermodel variability is then explored. In Figure 3, the ΔEKE (ΔBFV) is defined as the projected climatology (2071–2100) EKE (BVF) minus the historical climatology (1971–2000). The similar relationships of ΔEKE versus ΔBVF and ΔEKE versus EKE still exist among CMIP5 models but are much weaker than those in individual model. Considering the substantial bias in simulating EKE and complex surface topography in East Asia, the model uncertainty becomes particularly notable in this area. Compared with the former CMIP3, the new CMIP5 models tend to be developed with more diversity and independence. The intermodel variability of jet magnitude change in East Asia is much less than that of jet location displacement in Southern Hemisphere as shown in *Kidston and Gerber* [2010]. In another way, due to the larger independence, the multimodel ensemble result from CMIP5 models is more reliable.

4. Discussion and Conclusions

In the study, we revisit the topic of eddy-driven jet's response to a warming climate but focus on the East Asian section, a distinctive region with the uniquely elevated plateau on the Earth. Even though remarkable improvements are achieved in state-of-the-art CMIP5 models, accurately reproducing the midlatitude dynamic in East Asia still remains a considerable challenge in contemporary ear. The eddy-driven jet and

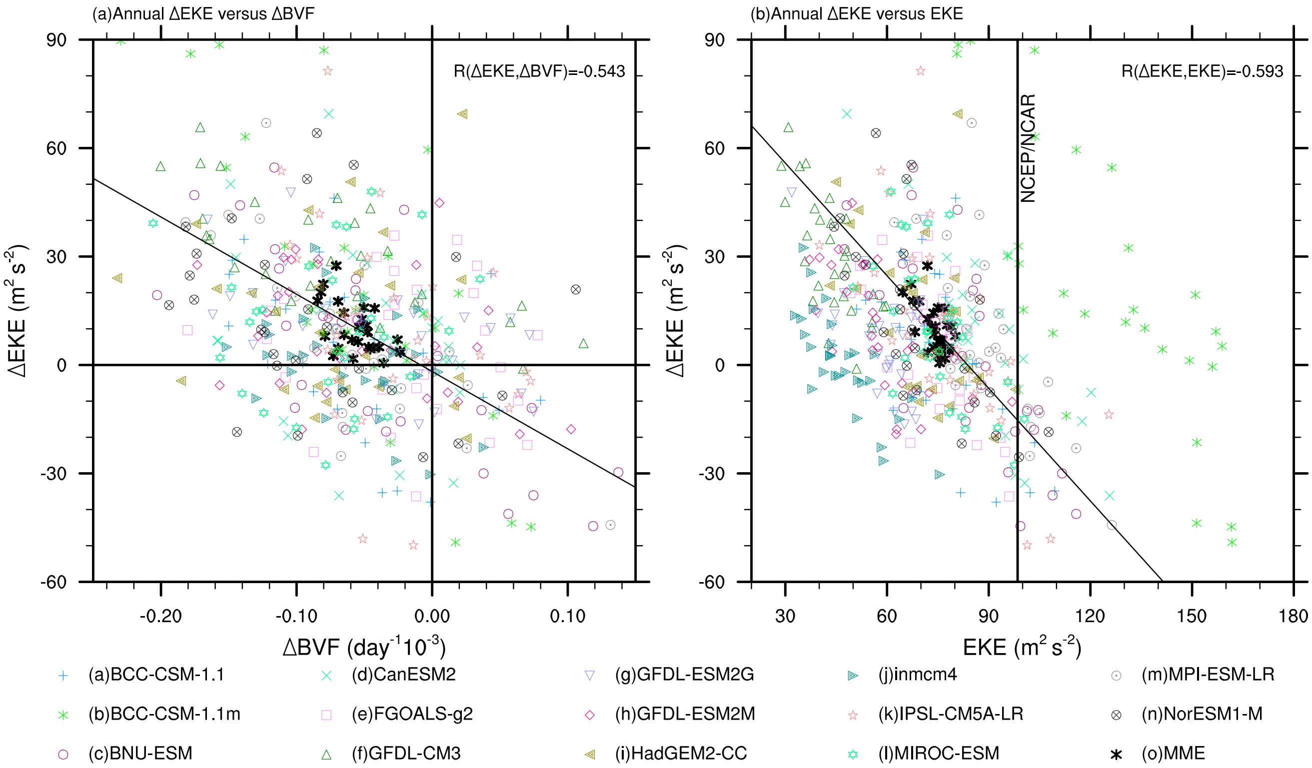

Figure 2. (a) Change (2071–2100 projection annually minus 1971–2000 simulation) of eddy kinetic energy (ΔEKE) versus the corresponding change of low-level static stability (ΔBVF) in East Asia eddy-driven jet. (b) Same as Figure 2a but for ΔEKE versus the corresponding historical intensity (EKE). The climatological EKE intensity in NCEP/NCAR reanalysis is the vertical line.

associated winter storms usually, from a synoptic view, bring severe weather around their routes, and more importantly from a climatologic view, cause anomalies in general circulation via heat, moisture, and momentum transfer [*Blackmon et al.*, 1977; *Yin*, 2005].

A robust response of the eddy-driven jet over East Asia to climate change is revealed from the CMIP5 models with emphasis on the magnitude enhancement which is quantified by transient EKE. We have highlighted that EKE response (ΔEKE) to global warming is highly correlated with low-level static stability change (ΔBVF) and the historical mean status of EKE. Our main findings are summarized as follows:

1. Compared with the location displacement of eddy-driven jet over the oceanic region, the eddy-driven jet over East Asia is characterized by the magnitude increase of EKE, which is unanimously projected by all 14 models (Figure S4).
2. For individual model, the future change of EKE which is projected to be embedded in a destabilized boundary layer measured by Brunt-Väisälä frequency is also constrained by the historical climatology. The EKE simulated by the model with a larger underestimation tends to be strengthened more in the future climate.
3. Intermodel variability among CMIP5 models manifests a similar but much weaker relationship between ΔBVF and ΔEKE, while the relationship between EKE and ΔEKE becomes statistically insignificant, indicating large model diversities and independencies in CMIP5.

Table 1. The Correlation Coefficient Between ΔEKE and EKE, ΔBVF for Each Model (From 1 to 14), and MME[a]

Model	1	2	3	4	5	6	7	8	9	10	11	12	13	14	MME
EKE	−0.60	−0.79	−0.78	−0.74	−0.61	−0.61	−0.32	−0.65	−0.52	−0.79	−0.69	−0.78	−0.75	−0.69	−0.62
ΔBVF	−0.41	−0.80	−0.71	−0.19	−0.05	−0.72	−0.52	−0.30	−0.15	−0.35	−0.34	−0.26	−0.67	−0.24	−0.49

[a] Absolute value of correlation coefficient larger than 0.355 is statically significant at 95% confidential level based Student's *t* test.

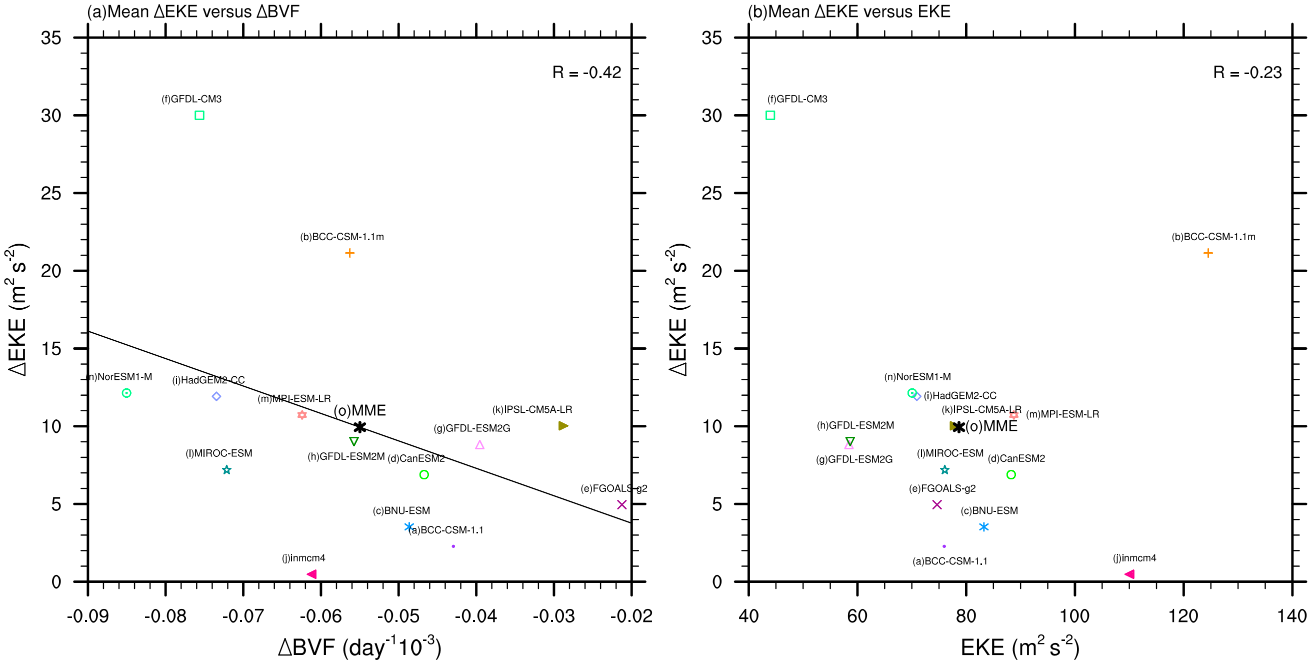

Figure 3. (a) Change (mean 2071–2100 minus mean 1971–2000) of eddy kinetic energy (ΔEKE) versus change of low-level static stability (ΔBVF) in East Asia eddy-driven jet. (b) Same as Figure 3a but for ΔEKE versus the corresponding historical climatology (EKE).

Similar with the relationship between poleward shift of jet and its historical location [*Kidston and Gerber*, 2010], the correlation between ΔEKE and EKE can be interpreted in the term of model internal mechanisms. Since the historical EKE is underestimated in CMIP5 models, the strong enhancement of EKE in future warming climate is favorable to happen in the model with weak EKE. The change in the low-level static stability is brought by the surface process in East Asia. According to the formula of BVF, the decrease in BVF can be caused by the decrease of potential temperature contrast ($\Delta\theta$) or the increase of height interval (Δz). Given that the height interval is relatively stable [*Ren et al.*, 2010], the BVF change is thus mainly altered by the vertical distribution of penitential temperature. In East Asia which is covered by arid or semiarid land use, in addition with the complex terrain, the near-surface layer is warmed to a larger extent than the middle-to-upper layer, resulting in vertical decrease of $\Delta\theta$, which leads to a destabilization in BVF. The change in low-level static stability is accompanied by the anomalies of cyclone and cold surge activities. Recent study [*Mizuta*, 2012] documented that the intense surface cyclone is projected to increase in the next century. Our results reaffirm that, with intensification EKE, more wintertime extreme storm events would like to happen in a warming climate in East Asia.

As a part of the global jet system, the East Asian jet can be affected by upstream anomalies or even by teleconnections from remote systems. The zonally locational vibrations of oceanic storm tracks will cause downstream effects and thus change the EKE intensity in EAEJ. Meanwhile, the intensity change will also follow the location shift of EAEJ. Thus, a thorough examination of all the factors contributing the future EKE change in EAEJ is worthy of continuing efforts.

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