Current Climate Change Reports (2019) 5:233–244
https://doi.org/10.1007/s40641-019-00134-x

INTERNAL CLIMATE VARIABILITY (S-P XIE, SECTION EDITOR)

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The Eurasian Jet Streams as Conduits for East Asian Monsoon Variability

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Published online: 10 June 2019

Abstract

Purpose of Review This article gives a brief review on how the jet streams over the Eurasian continent influence the East Asian monsoon on intraseasonal to interdecadal time scales and discusses the seasonal predictability and change.

Recent Findings The wave train along the Eurasian jet streams is found to be crucial for East Asian monsoon variability. Interaction of the upper-level Rossby wave train with the Siberian High causes changes in winter monsoon climate over East Asia. In the case of summer, the Silk Road pattern, embedded in the Asian jet in association with western North Pacific circulation and the Pacific-Japan pattern, alters the strength and phase of the monsoon. Current coupled models showed limited skills in seasonal prediction of the Eurasian jet variations and their influences on the East Asian monsoon variability.

Summary The Eurasian jets as conduits for East Asian monsoon variability involve multiple feedbacks. Its interaction with low-level circulation mostly determines the degree of strength of variations in the monsoon climate. Global warming projections based on RCP 4.5 and 8.5 in the CMIP5 (the Coupled Model Intercomparison Project phase 5) models indicate that the mean Asian jet strengthens in future during winter, but no change is reported during summer.

Keywords Asian jet · Polar front jet · East Asian monsoon · Precipitation · Pacific-Japan pattern · Silk Road pattern · Western North Pacific

Introduction

The East Asian monsoon is one of the most important climate systems, having a profound influence on the economy in the heavily populated regions in the world [1–5]. This subtropical monsoon system covers a large area which includes Korea, Japan, much of China, and the Western North Pacific (WNP). The East Asian Winter Monsoon (EAWM) system during December to February (DJF) is characterized by a prevailing low-level strong northwesterlies along the east flank of the Siberian High and northeasterlies over the South China Sea [6, 7]. The most prominent features of the EAWM are cold-core Siberian High and a warm-core Aleutian Low [6–9]. Winter monsoon extremes can cause severe weather events over East Asia, such as rain and snow storms, freezing rain, and cold waves [10, 11]. During boreal summer (June to August; JJA), the East Asian Summer Monsoon (EASM) causes heavy rainfall over East Asia [12, 13]. The EASM features strong humid low-level southerlies from the Philippine Seas and southwesterlies from the Bay of Bengal and leads to abundant rainfall over East Asia. Strong southerly winds entering East Asia are associated with the WNP subtropical anticyclone in the lower troposphere, while strong westerlies extending from mid-latitudes to the tropical region (till 25° N) associated with the Asian jet play an important role in the evolution of the EASM.

The variations of the EAWM/EASM at different time scales are affected not only by tropical forcing such as El Niño-Southern Oscillation (ENSO) and sea surface

This article is part of the Topical Collection on *Internal Climate Variability*

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temperature (SST) over the tropical Indian Ocean (TIO) [14–16] but also by high-latitude forcing such as Arctic sea ice [17–19], Eurasian snow cover [20], the Siberian High [21, 22], and the disturbances along the subtropical Asian jet and polar front jet over Eurasia [23–27]. Indeed, many researchers have extensively documented the impacts of ENSO and TIO SST on the EAWM/EASM variability and well explained the associated physical mechanisms [14, 28–32]. By contrast, the high-latitude influence through the jets has been recognized relatively recently, and a growing body of studies is emerging. The present study provides a review on how the Eurasian jets influence the East Asian Monsoon (both winter and summer).

The Asian jet is a Eurasian portion of the subtropical jet and blows from North Africa through East Asia. To the north of the Asian jet forms the polar front jet. The Asian jet is characterized by variabilities on a wide range of time scales and exerts substantial impacts on the weather and climate over East Asia. Jet stream features large horizontal and vertical wind shear throughout the troposphere and lower stratosphere. On the synoptic scale, the jet is closely linked to many phenomena such as cyclogenesis, frontogenesis, blocking, storm track activity, and the development of other atmospheric disturbances [33]. At longer time scales, the jet acts as a waveguide for quasi-stationary Rossby waves [34, 35], promoting disturbances in the Euro-Atlantic sector to propagate efficiently to East Asia. In East Asia, jet meanders are associated with the shift of precipitation bands in the EASM/EAWM [36–40]. Previous studies [41, 42] suggested that the association of the Asian jet with ENSO is weak, but its association with extra-tropical North Pacific SSTs is notable. Furthermore, it has been reported that the Asian jet is linked to variations of the Hadley circulation [43–45], suggesting the importance of the interaction with tropical convective activities [46, 47]. The latitudinal variation of the Asian jet over the East Asian region is obvious in winter and summer seasons (Fig. 1). The present review aims to summarize the recent progress in studying how the Eurasian jets could exhibit a strong impact on the EASM and EAWM climate and addresses the seasonal predictability and change of the jets.

The Eurasian Jets and EAWM

An active winter monsoon is accompanied by frequent cold air outbreaks, known as the cold waves or cold surges, from the source region—the Siberian cold dome. The cold surges along with northwesterly monsoon sweep China, Korea, Japan, and surrounding regions, leading to abrupt temperature and precipitation changes [7]. In winter, the Asian jet blows around 25° N (south of Tibet) while the polar front jet is located around 55° N [48]. The geographically fixed planetary wave trough over the Far East makes the two jet streams merge over Japan to form the single Pacific jet [48].

Although the low-level EAWM is located at a different altitude from the Asian and polar front jet cores, change of the jets often occurs with variations of winter monsoon and thereby can be used as a measure of the EAWM [49]. Observed evidence shows that when the Asian jet is strong, the Asian winter monsoon strengthens, and colder and drier conditions prevail in East Asia [42, 50]. Meanwhile, a southward shift of the polar front jet often accompanies a cold winter in northern East Asia [51]. The linkage between the variability of winter monsoon and the jets is likely because both are affected by geographically fixed stationary planetary waves forced by large-scale orography and land-sea thermal contrasts. On the interannual timescale, both the Asian jet and the EAWM become weak when the upward propagation of planetary waves from the troposphere into the stratosphere is weaker, but their equatorward propagation in the middle and upper troposphere is stronger, and vice-versa [52]. Similar phenomena and mechanism can also be observed on the interdecadal timescales [53]. The change of external forcing such as snow cover over the Eurasia continent [53, 54] and the Arctic sea ice [18, 19] may lead to change in the winter

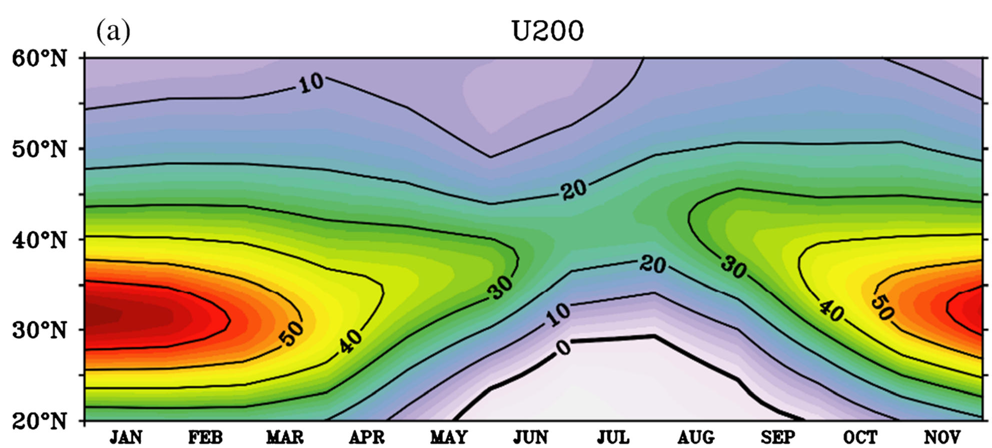

Fig. 1 Latitude-time plot of 200-hPa mean zonal wind (Climatology; m/s) averaged over the region 100° E to 160° E. This figure based on ERA-interim (Dee et al. 2011 [118]) data for the period 1979 to 2014

monsoon as well as in the Asian and polar front jets simultaneously via modulating stationary planetary waves.

Along the polar front jet, a recurrent wave train known as the Eurasian teleconnection pattern [55, 56] can lead to the intraseasonal amplification of the Siberian High [27, 48]. When an equivalent barotropic anticyclonic anomaly associated with the wave train appears over central Siberia and Mongolia, the circulation could create a cold surface high ahead of the upper-level anticyclone by enhancing surface cold advection. The surface cold high anomaly, in turn, may strengthen the upper-level anticyclone by advecting low potential vorticity poleward. The mutual intensification between the upper-level Rossby wave train and lower-tropospheric thermal anomalies can strengthen the cold Siberian High, which in turn enhances the EAWM circulation and leads to East Asian cold anomalies [27, 57]. On the interannual timescales, the Eurasian pattern is associated with the variability of the EAWM most tightly among the known atmospheric teleconnections [16]. On the interdecadal timescales, the EAWM switched from strong to weak epochs in the late 1980s and from weak to strong epochs in the early 2000s [58]. These transition times are quite consistent with those of the Eurasian pattern [56], implying its crucial role in the interdecadal variations of the EAWM.

Wave trains along the Asian jet waveguide also exert significant influence on the EAWM. Some extreme wintertime rainfalls [59•, 60], snowfalls [61], and temperature anomalies [26••, 62] in East Asia are associated with wave train-like circulation anomalies along the Asian jet. North Atlantic Oscillation (NAO)–induced divergence over the Mediterranean is considered as an important source for the wave train [63]. When the NAO induces anomalous upper-level convergence over the Mediterranean Sea, perturbations along the subtropical Asian jet form a wave train with a zonal wavelength of approximately 75° (Fig. 2). There is a cyclone over South China and an anticyclone over Japan, which may lead to persistent rainfall and anomalous warmth in respective regions [26••, 63].

Wave activities in the two waveguides arise mainly due to atmospheric internal variability. But some observed studies suggest that the external forcing such as SST [26••, 64], sea ice [18], and snow cover [19, 54] anomalies may also contribute to the formation of the wave trains. For example, SST anomalies in the equatorial eastern Pacific [26••] and east-west SST contrast in the North Atlantic [66] may help in the formation of the wave train into the Asian jet. The SST anomalies in the mid-latitude North Atlantic may excite the Eurasian pattern along the polar front jet by altering the low-level baroclinicity and synoptic high-frequency eddies [56, 65••]. Further analysis should be carried out to identify the external factors for the wave activities in the two waveguides, as they are useful for predicting the EAWM.

The Eurasian Jets and EASM

In summer, the Asian jet blows along the northern periphery of the upper-tropospheric Tibetan/South Asian high and is centered on 40° N (Fig. 3a). Seasonal northward migration of the Asian jet in the East Asian sector from early to mid-summer significantly affects rainfall locally. The north–south displacement of the Asian jet is thus a reliable indicator of Asian monsoon onset and retreat [66]. Over East Asia, the jet stream is identified with the surface front that produces extensive Meiyu (in China), Changma (in Korea), and Baiu (in Japan) rains [12, 67–69]. The Asian jet co-varies with the location of the Meiyu–Changma–Baiu rain band over East Asia. This jet anchors the zonally prolonged rain band by advection of warm air, organizing ascending motions and directing transient weather disturbances from the upstream [70]. In addition, the ageostrophic secondary circulation associated with the upper-tropospheric jet promotes convection to its south, forming the rain band [71]. Intraseasonal anomalies of 200-hPa zonal wind manifest in the weak and slightly southward extension of the jet over East Asia during the active phase of the WNP rainfall, and vice-versa for monsoon breaks [72, 73]. Meridional displacements of the Asian jet over East Asia are associated with day-to-day variability in mid-tropospheric temperature advection because the upper-tropospheric jet stream traps the transient eddies, leading to enhanced rainfall in the Yangtze-Huaihe River valley [74].

On interannual timescales, many studies have suggested that the meridional displacement of the East Asian jet bears a close relationship to the EASM precipitation [38–40]. An equatorward displacement of the Asian jet causes precipitation to increase over south-central China, while a poleward shift of the jet brings heavier precipitation over north China [37, 75–77]. The equatorward (poleward) jet displacement is also accompanied by southward retreat (northward extension) of the surface subtropical high over the WNP, bringing the anomalously cold (warm) condition to Korea and Japan [78]. Summer time tropical cyclone activity over the WNP is closely related to the location and intensity of the Asian jet on the interannual time scale [79].

An important external driver of the East Asian jet and the EASM is the wave-like pattern embedded in the Asian jet, called the Silk Road pattern (SRP, Fig. 3b) [24]. The SRP can be regarded as the Eurasian sector of the summertime circumglobal teleconnection pattern [80]. Yet, instead of a free Rossby wave train, the SRP can maintain itself through its efficient extraction of kinetic and available potential energy from the background flow through barotropic and baroclinic energy conversions, leading to the dominance of a particular zonal phase [81, 82]. The SRP has an equivalent barotropic structure with significant circulation anomalies reaching the lower troposphere to affect the WNP subtropical high and the EASM rainfall [81, 83]. Various studies have indicated that

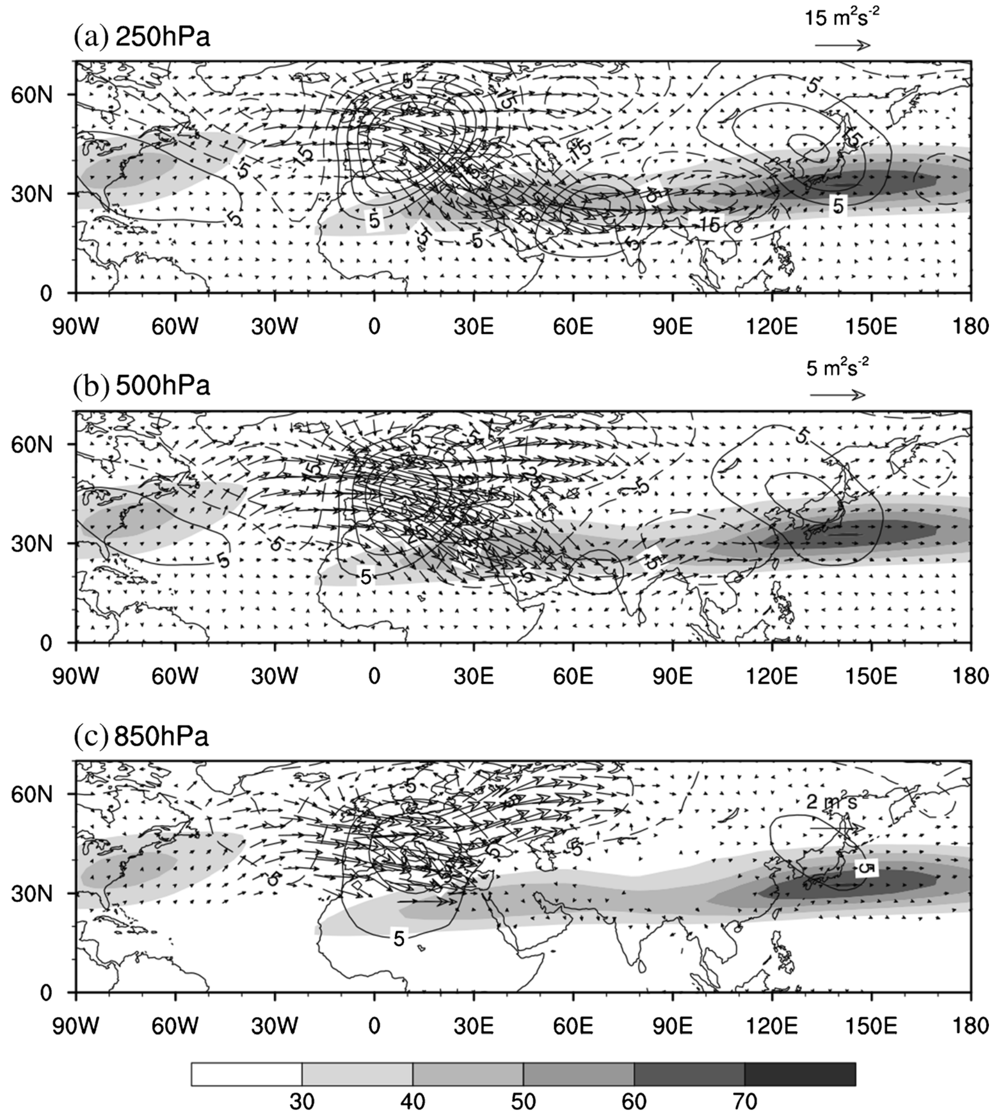

Fig. 2 The regression of geopotential height (contours; m) at 250-hPa (**a**), 500-hPa (**b**), and 850-hPa (**c**) on the PC1 of the EOF modes of 250-hPa monthly *v* (December, January, and February) in the domain (0–45° N, 0–120° E) from 1979 to 2013 in NCEP-DOE reanalysis (Kanamitsu et al. 2002 [119]). Vectors are the wave fluxes. Shades denote the climatological zonal wind speed (m/s) at 200 hPa. The figure is similar to that of Hu et al. (2018) [26••]

the SRP significantly affects climate over China, Korea, and Japan on the interannual timescales [24, 80, 84–87]. The Arctic sea ice change is an important source of the wave train along the Asian Jet waveguide, which can, in turn, influence the EASM. Some studies found that the reduced spring Arctic sea ice leads to an enhancement of summer rainfall in northeast China [88], central China between the Yangtze River and the Yellow River [89], Indochinese Peninsula, and the Philippines and decreased rainfall over Meiyu–Changma–Baiu front zone [90]. The aforementioned studies suggested that spring Arctic sea ice anomalies modulate the atmospheric circulation via Eurasian wave train and influence the EASM.

On the interdecadal timescales, the SRP features a barotropic wave train along the Asian jet, resembling its interannual counterpart, with a secondary weak wave train along the polar front jet [91•]. As a result, the meridional scale of the interdecadal SRP is larger than its interannual counterpart. The SRP shows two regime shifts in the mid-1970s and late-1990s [91•, 92••]. The latter shift explains over 40% of the observed rainfall reduction and warming over Northeast Asia, highlighting its crucial role in the recent decadal climate variations over East Asia [87, 91•, 93]. The mid-1970s shift is suggested to have arisen from the favorable background state after the mid-1970s that projects more onto the SRP via the positive feedback between the SRP and the rainfall over subtropical South Asia. The interdecadal variations of the SRP show some linkage to North Atlantic SST, but the mechanism of this linkage remains unclear [92••]. The interdecadal changes in northeast Asia climate are associated with the propagation of an atmospheric Rossby wave along the Asian Jet, and this interdecadal circumglobal teleconnection is closely associated with the AMO [91•, 93–95]. However, it has been suggested that SST in the North Atlantic and the North Pacific may indirectly affect the decadal variations in SRP by modulating South Asian rainfall [92••]. Further, in-phase Pacific Decadal Oscillation (PDO) and

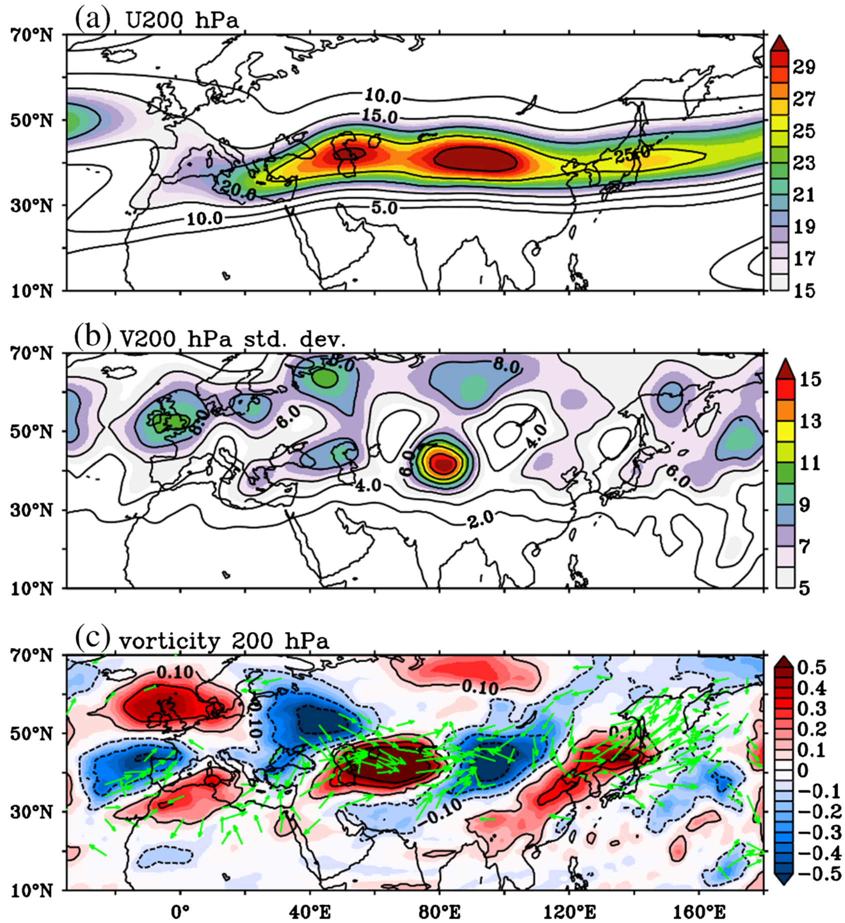

Fig. 3 **a** Climatological mean zonal wind (m/s), **b** interannual standard deviation of meridional wind (m/s), and **c** the vorticity anomalies regressed onto the PC1 of 200-hPa meridional wind over [20°–60° N, 30°–130° E]. All at 200 hPa for JJA. Green arrows show wave-activity flux formulated by Takaya and Nakamura (2001) [120]. Data used here is based on ERA-interim for 1979–2014. Reproduced from Kosaka et al. (2009) [81] with updated data

AMO with opposite sign of SST anomalies alter the waveguide in the eastern Mediterranean region and modulate the Indian summer monsoon rainfall anomalies [96]. These rainfall anomalies, in turn, interact with the teleconnection wave train induced by the PDO and AMO, leading to a meridional dipole mode of interdecadal precipitation anomalies over eastern China.

As in winter, the polar front jet in summer also allows wave trains to propagate along [97, 98]. Previous studies noticed that the amplification of the surface Okhotsk high and anomalously cool summer over Japan and Northeast Asia are often associated with some wave-like disturbances along the summertime polar front jet over Eurasia [82, 97]. The British–Baikal Corridor (BBC) pattern is a teleconnection pattern with a meridionally confined, zonal wavenumber-5 structure that extends from the North Atlantic to Siberia [99••]. It affects climate along its route including precipitation over East Asia. Internal atmospheric dynamics dominate interannual variability of the BBC pattern, including barotropic energy conversion and the multiscale interactions among the climatological mean flow, the low-frequency anomalies, and the synoptic-scale transient eddies. No clear external forcing for the BBC pattern has been identified so far.

Predictability of the Eurasian Jet Variability and Impacts

Coupled ocean-atmospheric general circulation models (CGCMs) are useful for the prediction of the interannual variation of the Asian jet [100] and impact on East Asia monsoon [101, 102]. CGCMs show good skills in predicting the first two empirical orthogonal function (EOF) modes of summer upper-tropospheric circulation in the Northern Hemisphere [103]. Here, we examine hindcast data from seasonal prediction models participating in the APEC Climate Center (APCC) seasonal forecast to study the predictability of summer and winter Asian jet and its influence on East Asian monsoon. Table 1presents a brief summary of the models used in the study. Multi-model ensemble (MME) mean is defined as a simple average of the model runs with equal weighting. One-month lead forecasts initialized in May and November are used to evaluate summer and winter predictability, respectively. An EOF analysis of the 200-hPa zonal wind over the region (40° E to 160° E and 20° N to 60° N) is used to identify the major modes of the Asian jet variability both in winter and summer for the observations and MME mean.

Most of the models simulate well the major mean circulation features related with the EAWM such as the upper

Table 1 Details of the APCC models used in this study

Model	Organization	Resolution	Ensemble size
CCSM3	APCC/Korea	T85L26	10
MSC	MSC/Canada	T63/L31	10
CANCM3	MSC/Canada	T63/L31	10
CANCM4	MSC/Canada	T63/L31	10
GMAO	NASA/USA	288 × 181 grid L72	11
CFSV2	NCEP/USA	T62/L64	20
PNU	PNU/Korea	T42L18	5
POAMA	BOM/Australia	T47L17	33

troposphere jet stream, the sea level pressure contrast between the cold Siberian High and the warm Aleutian Low, and the prominent low-level northerly wind along the eastern coast [104]. The leading mode (EOF-1) of 200-hPa zonal wind in DJF in the observations is dominated by a positive loading along the jet axis extending from the Tibetan Plateau to the WNP and with negative loading on either side. In observations, this leading mode accounts for 32% of the total variance and is related to the variation in Asian winter jet intensity [105] (Fig. 4a). A strong Asian winter jet is associated with an intensified EAWM. Associated with an anomalous low-level anticyclone over East Asia in EOF-1, dry conditions are seen over south-central China (Fig. 4c). None of the models including the MME mean can properly represent the leading EOF pattern associated with the winter Asian jet (Fig. 4b). Positive loading along the jet axis and negative loading to the south are somewhat captured by MME but signals are completely missing to the north. This mode accounts for 74% of the MME mean-variance. Rainfall patterns over East Asia associated with EOF-1 are somewhat different in the MME mean and individual models than in observations. Correlation of the corresponding principal components (PC1s) between models and observations (Fig. 4e) is marginally significant in some models (Table 1), consistent with [104]. Although most models capture the main seasonal mean circulation over East Asia reasonably well, they still suffer from difficulty in predicting the interannual variability of the EAWM.

Figures 5 a and b show the spatial patterns of the leading EOF mode (EOF-1) of JJA 200-hPa zonal wind in the observations and the MME mean, both of which feature meridional displacements of the Asian jet. These modes account for 28% and 69% of the total variance in the observations and the MME mean, respectively. However, the magnitude of EOF-1 signals is weak in the MME mean compared to the observations, suggesting the dominance of the variability unpredictable at monthly to seasonal leads. The wave-like pattern along the Asian jet from central Asia to Japan is apparent in meridional wind anomalies. This wave train pattern is embedded with anomalous anticyclonic, cyclonic, and anticyclonic circulations along the jet, similar to the SRP. The anomalous

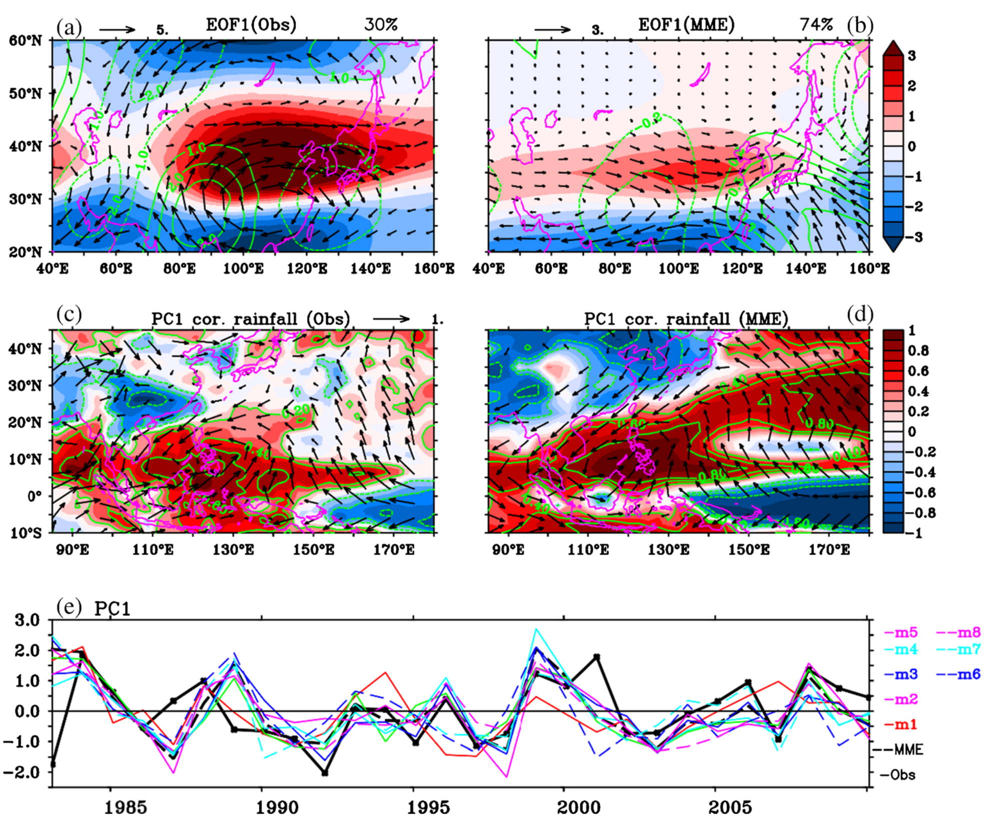

Fig. 4 **a** The first EOF pattern of 200-hPa zonal wind (shaded) along the Asian Jet during winter (DJF) and correlation of PC-1 with 200-hPa winds (vectors) and meridional wind component (green contours) and **c** correlation of PC-1 with precipitation (shaded) and 850 hPa winds (vectors) for observations. **b** Same as in (**a**) but for MME and **d** same as in (**c**) but for MME. **e** PC-1 corresponds to the EOF-1 for the observations, individual models, and MME

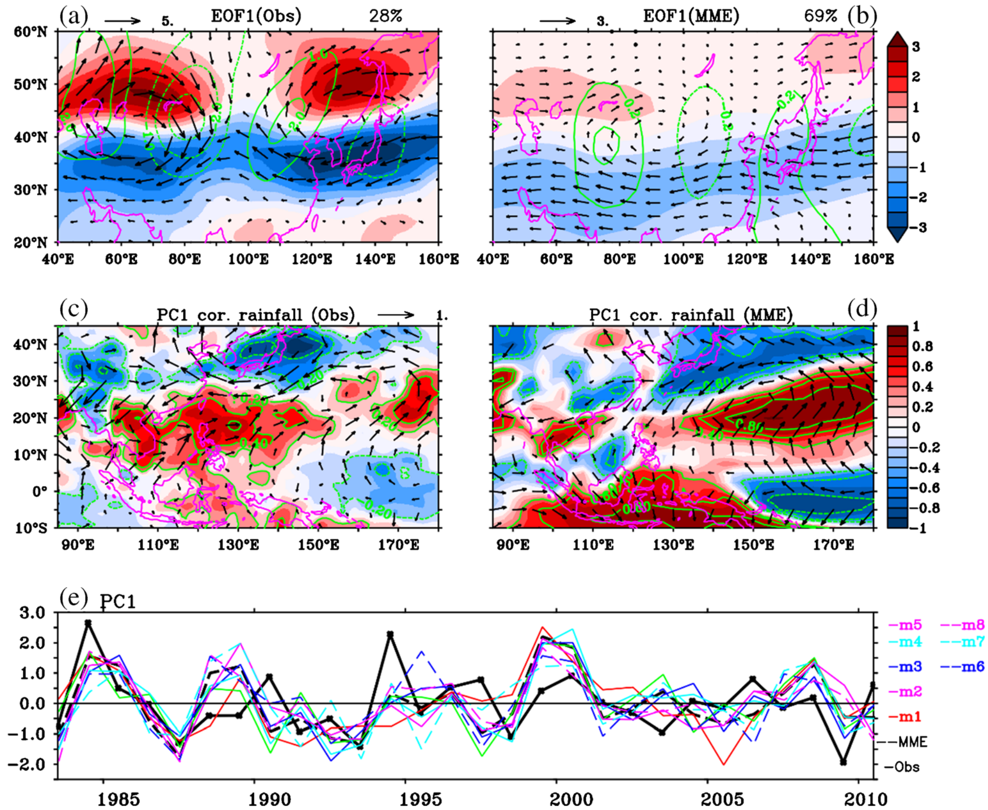

Fig. 5 Same as in Fig. 4 but for the boreal summer season (JJA)

upper-level anticyclone associated with SRP over Japan and central and north China [83] extends to the lower level with an equivalent barotropic structure, with local reduction of rainfall (Fig. 5c). The MME zonal wind anomalies and the wavetrain pattern are apparently displaced southward and eastward, respectively, compared to the observational counterparts (Fig. 5a and b).

In association with the shift of the jet, changes in low-level circulation and precipitation patterns are noted in the MME mean. Individual models also show such shifts in precipitation and low-level circulation (figure not shown). South of the low-level anticyclonic circulation is a strong cyclonic circulation, covering parts of the WNP and South China Sea (Fig. 5c). The meridional alignment of these circulation anomalies over the WNP region is similar to the Pacific–Japan (PJ) pattern [106, 107]. It is notable that in all the models and the MME mean the Asian jet anomalies, SRP, and the PJ pattern are displaced from observational counterparts. These unrealistic shifts limit the skill in predicting the EASM rainfall variations associated with the Asian jet. Furthermore, only two out of eight models (POAMA and MSC_CANCM4) show reasonable skill in predicting the Asian jet variation, as shown by the PC-1 (Fig. 5e) correlation between models and observations (Table 2). Previous studies noted that current coupled models have very limited skills in predicting the SRP even at one-month lead forecast [102, 108]. This would limit the skills of CGCMs in predicting variability of the Asian jet in summer.

Overall, most of the coupled models examined show certain skill in predicting the variability of the Asian jet during summer but fail during winter. As a consequence of poor winter prediction, the model rainfall patterns over East Asia are disorganized.

Future Projections in CMIP5 Simulations

This section discusses the Coupled Model Intercomparison Project phase 5 (CMIP5) [109] MME ability in simulating the Asian jet in the present climate and its changes in Representative Concentration Pathway (RCP) 4.5 and RCP8.5 scenarios based on 24 models (Table 3). The MME

Table 2 Observed PC-1 correlation with individual models and MME for both winter and summer seasons for the period 1983–2010

Model	JJA	DJF
APCC	0.36	0.41
MSC_CANCM3	0.32	0.46
MSC_CANCM4	0.43	0.13
MSC	0.39	0.22
NASA	0.32	0.13
NCEP	0.25	0.38
PNU	0.31	0.39
POAMA	0.43	0.29
MME	0.43	0.33

Table 3 Details of 24 CMIP5 models used for the analysis with respective centers, model names, and their grid sizes. One (r1i1p1) ensemble for each model is used in this study

S. No	Modeling center (or group)	Model name	Grid size
1	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology (Australia)	ACCESS1.0	192 × 144
2	Beijing Climate Center (China)	BCC-CSM1-1	128 × 64
		BCC-CSM1-1-m	320 × 160
3	College of Global Change and Earth System Science, Beijing, Normal University (China)	BNU-ESM	128 × 64
4	Canadian Centre for Climate Modelling and Analysis (Canada)	CanESM2	128 × 64
5	Centre National de Recherches Météorologiques (France)	CNRM-CM5	256 × 128
6	Commonwealth Scientific and Industrial Research Organization (Australia)	CSIRO-Mk3.6.0	192 × 96
7	NOAA Geophysical Fluid Dynamics Laboratory (USA)	GFDL-CM3	144 × 90
		GFDL-ESM2G	144 × 90
		GFDL-ESM2M	144 × 90
8	NASA Goddard Institute for Space Studies (USA)	GISS-E2-H	144 × 89
		GISS-E2-H	144 × 89
9	Met Office Hadley Centre (UK)	HadGEM2-AO	192 × 144
		HadGEM2-ES	192 × 144
10	Institute for Numerical Mathematics (Russia)	INM-CM4	180 × 120
11	Institut Pierre-Simon Laplace (France)	IPSL-CM5A-LR	96 × 96
		IPSL-CM5A-MR	96 × 96
12	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (MIROC) (Japan)	MIROC5	256 × 128
		MIROC-ESM	128 × 64
		MIROC-ESM-CHEM	128 × 64
13	Max Planck Institute for Meteorology (Germany)	MPI-ESM-LR	192 × 96
		MPI-ESM-MR	192 × 96
14	Meteorological Research Institute (Japan)	MRI-CGCM3	320 × 160
15	Norwegian Climate Centre (Norway)	NorESM1-M	144 × 96

mean simulates jet characteristics very well in the historical period both in winter and summer (not shown). MME projections show that the mean jet strengthens along 45° N just north of jet core by 4 to 5 m/s (3 to 4 m/s) in RCP 8.5 scenarios at the end (middle) of the twenty-first century during winter over East Asia (Fig. 6a and b). As a result, a slight poleward shift in the jet core is apparent in future projections. This shift may influence the wave train along the jet and hence the EAWM. A poleward shift in the future projection of westerly jet over the North Pacific has been reported earlier and is attributed to latitudinal temperature gradient [110].

In summer, the MME shows no significant change in jet strength under RCP 8.5 over East Asia (Fig. 6c and d). A recent study points out that the future change in the continental Meiyu precipitation location is insignificant, which is related to weak changes in the jet position [111•]. Some changes are notable in the strength of westerlies south of jet core west of the Tibetan Plateau, indicating an equatorward shift. However, its robustness needs to be confirmed. In the mid-range scenario (RCP4.5), changes in the mean Asian jet are similar to RCP8.5 but weaker. CMIP5 models display large inter-model spread in simulations of the East Asian jet [112]. CMIP5 MME captures the spatial pattern of the Asian jet variability but underestimates the magnitude [113], affecting rainfall change uncertainties over East Asia. Recent studies also suggested the presence of uncertainty in projected changes in Asian–Australian monsoon circulation, which has been attributed to the inter-model difference of western Pacific SST warming [114, 115]. In addition, the significant bias in the tropical SST and related teleconnection characteristics can cause uncertainty in the CMIP5 future projections of the Northern Hemisphere boreal summer upper-level circulation [116]. This indicates that projected future changes in mean jet must be considered with caution due to the involvement of large uncertainties in CMIP5 models.

Conclusions

The main purpose of this study is to provide an overview of the current understanding of the Eurasian jet streams' influence on the East Asian monsoon variability. Predictability of the winter and summer Eurasian jet variations and impacts are discussed. Further, the mean Asian jet changes in global warming scenarios using CMIP5 MME are presented.

The wave train patterns along the Asian jet are crucial for the East Asian monsoon variability. The wave activities along the jet are caused by atmospheric internal variability

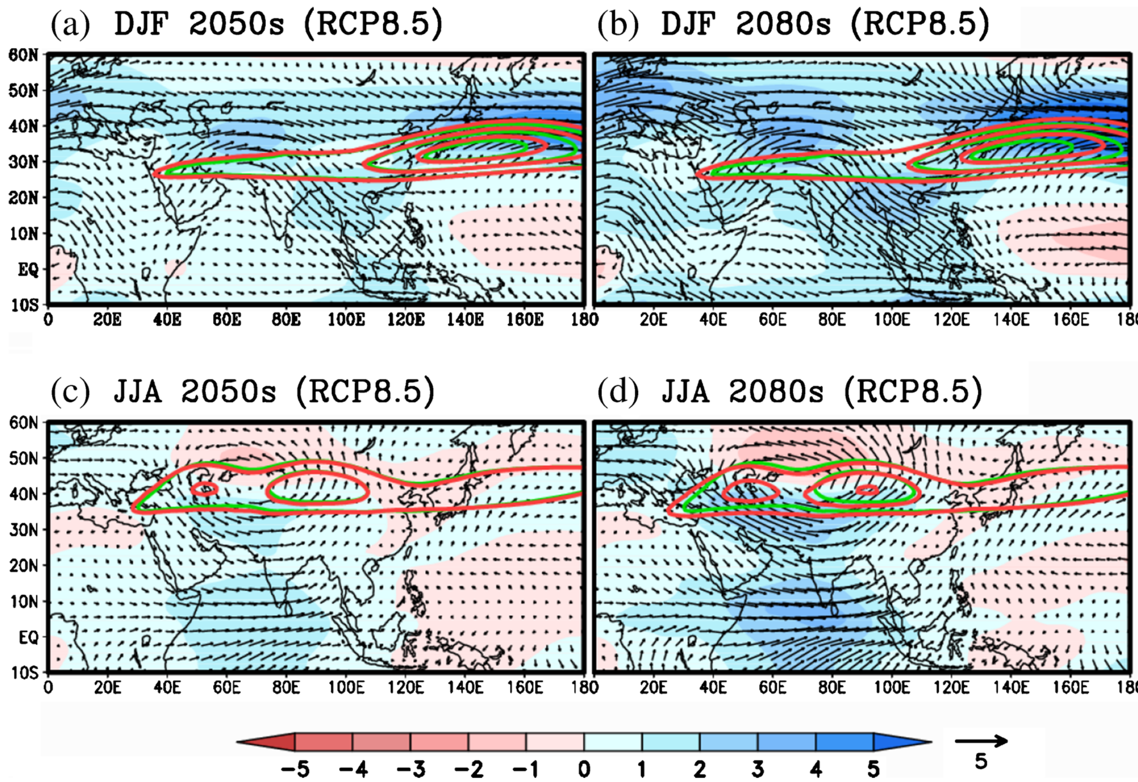

Fig. 6 Projected changes in the mean zonal wind (shaded; m/s) at 200 hPa and vectors (m/s) (the Asian Jet) during the 2050s (mean of 2040 to 2069) and 2080s (mean of 2070 to 2099) using MME of 24 CMIP5 models based on RCP8.5 scenarios. Changes are with respect to the climatology for the period of 1976–2005 in historical simulations for **a** and **b** DJF and **c** and **d** JJA. Green contours (zonal wind above 50 m/s for DJF and 20 m/s for JJA) indicate the mean jet core for present-day climate and red contours for future projections

and external forcing such as NAO, Indian summer monsoon, and Atlantic Nino [80, 117]. The EAWM variations associated with the polar front jet emerge through interactions of the upper-level Rossby wave train with the Siberian High. On the other hand, the EASM is affected by the SRP and the PJ pattern through the Asian jet [70, 71, 83, 102]. The Asian Jet interaction with low-level circulation is important in determining monsoon variations. Coupled models simulate mean jet features fairly well both in winter and summer but they, individually and in MME mean, show limited skills in predicting Asian jet variations and their impacts on the EAWM/EASM. In spite of the considerable progress made in the sub-seasonal to seasonal predictions of monsoon climate, seasonal predictions of the Asian jet variability and associated impacts are still inadequate. Future projections based on 24 CMIP5 models indicate that the mean jet strengthens slightly in RCP 4.5 and 8.5 scenarios in winter, with little change noticed in summer. Further investigations are needed into variations of the Eurasion jet streams and their impact on the East Asian monsoon rainfall.

Acknowledgments JSC thank the Director, Earth System Sciences Organization (ESSO)—Indian Institute of Tropical Meteorology (IITM) for support and infrastructure. We thank the editor and reviewers for careful reading and constructive suggestions which helped us to improve the manuscript. We thank Drs. C. Gnanaseelan, Anant Parekh, and D. Ramu for discussions and help.

Funding JSC is fully supported by IITM and GS is supported by INCOIS. YK is funded by Japan Society for the Promoting Science (Grant Number 18H01278), Japan Science and Technology Agency through Belmont Forum CRA "InterDec." LW is funded by the National Natural Science Foundation of China (Grant Number 41721004). KK fellowship (NPDF) is supported by DST.

Compliance with Ethical Standards

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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- • Of importance
- •• Of major importance

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