Physical mechanisms of surface wind variability at Incheon Airport

Hyung-Ju Park | Kwang-Yul Kim

School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea

Correspondence
Kwang-Yul Kim, School of Earth and Environmental Sciences, Seoul National University, Seoul 08826, South Korea.
Email: kwang56@snu.ac.kr

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Abstract
The mechanisms of surface wind variability observed by Aerodrome Meteorological Observation System at Incheon International Airport (IIA), located near the western coast of the Korean Peninsula, are investigated using cyclostationary empirical orthogonal function (CSEOF) analysis. Despite the complex nature of surface wind, as various factors contribute to its variance, distinct features of surface wind variability are separated reasonably into CSEOF modes. The physical interpretation of each mode using the ERA-Interim reanalysis data is accomplished through regression analysis in CSEOF space. In essence, three atmospheric features dominate the surface wind variability: East Asian monsoon, land–sea breeze, and baroclinic waves. East Asian monsoon, the first mode, explains ~12% of the total variance of the surface wind at IIA. The annual reversal of the monsoon circulation due to the thermal contrast between the Asian continent and the western Pacific is captured as the single most dominant source of surface wind variability at IIA. The second CSEOF mode reveals that zonal circulation induced by land–sea breeze dominates the diurnal variation of the surface wind at IIA, and explains ~8% of the total variance. The largest fraction of variability is associated with baroclinic waves, which is separated into many CSEOF modes due to their irregular phase and wavelength, and the locations of vortex centre. Modes 3–10 are all associated with baroclinic waves and they together explain ~42% of the total variance. Baroclinic waves are amplified as they move over the ocean due to strong turbulent flux from the ocean surface induced by the associated upper tropospheric vortices.

KEYWORDS
CSEOF analysis of surface wind variability, physical mechanisms of surface wind variability, surface wind variability

1 | INTRODUCTION

Understanding atmospheric conditions that affect the air traffic and accidents is important as air travel is becoming more commonplace. According to the Korean Aviation-Railway Accident Investigation Board, there had been 394 aviation accidents during 1957–2009. Of these, 28 accidents (7.1%) are associated with the atmospheric conditions, and 57% of these accidents are due to the wind. Flight Safety Foundation also reported that rear winds and side winds on runways are responsible for 33% of the accidents during takeoff and landing (Flight Safety Foundation, 1999). Therefore, understanding...
the nature of wind variability, which is ever-present potential hazard to aircraft, is important for the enhancement of aviation safety. Among many crowded airports, the Incheon International Airport (IIA) is selected as the target of this study; IIA is located near the western coast of the Korean Peninsula with complex characteristics of surface winds.

As one of the most accurate representations of local wind variation, observational data at a station near IIA is used in the present study. Various studies used station data to represent a local wind environment, the most active field being wind resource evaluation. Since wind energy production is proportional to the cubic power of wind speed, focus has been in producing annually or seasonally calculated statistics such as probability distribution, mean, and variance (e.g., Lun and Lam, 2000; Weisser and Foxon, 2003; Akpinar and Akpinar, 2005; Ko et al., 2010). Diurnal statistics are also widely calculated if a target region is close to water mass or mountain (Weisser and Foxon, 2003; Ko et al., 2010; Belu and Koracin, 2013). When wind direction is investigated, wind rose is frequently used (Kim and Kim, 2016; Ramadan, 2017; Nedaie et al., 2018).

To fully understand the nature of local wind variability, however, direct linking with various scales of atmospheric circulation is required as emphasized in many studies (Greene et al., 2010; Belu and Koracin, 2013; Millstein et al., 2018; Soukissian et al., 2018). For that purpose, relationship between surface wind and long-term climatological variation of atmospheric condition has been probed in some studies. Berg et al. (2012), Enloe et al. (2004), and Harper et al. (2007) revealed the impact of El Niño–Southern Oscillation (ENSO) on surface wind speed; they consistently showed that wind speed is enhanced over the United States during a warm phase of ENSO and that ENSO effect is more prominent in winter. Hamlington et al. (2015) also showed that the effect of modulated annual cycle and ENSO on the variation of wind speed could be up to 30% at individual wind farm sites over the United States. Yu et al. (2015) examined temporally and regionally varying effect of various climate modes on wind speed based on empirical orthogonal function analysis.

Many studies reported a trend in wind speed in many areas including United States (Yu et al., 2015), Europe (Pryor et al., 2006; Poupkou et al., 2011; Tobin et al., 2014; Soukissian et al., 2018), China (Wu et al., 2018), and South Korea (Kim and Paik, 2015). See also the reviews by Greene et al. (2010), Pryor and Barthelmie (2010), and Schaeffer et al. (2012). There are many potential causes for a trend in wind speed, such as enhancement of surface roughness, reduction of surface pressure gradient force, etc. However, there is still much lack of knowledge in terms of quantifying the contribution of each.

Most studies on daily, weekly, monthly, and yearly-scale variations rely typically on simple statistical analysis. Since this short-term variability takes up a significant fraction of a wind power spectrum, more comprehensive and physically based analysis should be implemented (Belu and Koracin, 2013). Some studies investigated atmospheric phenomena, which may serve as driving mechanisms of short-term surface wind variability. For example, seasonal cycle of solar radiation and differential heating of land and ocean results in the seasonal cycle of atmospheric variables including wind. Lim et al. (2002), Kim et al. (2010), and Roh et al. (2012) investigated the detailed evolution features of atmospheric variables associated with the East Asian summer monsoon. Kim and Roh (2010) and Kim et al. (2013) delineated the mechanism of winter monsoon in terms of the evolution of atmospheric conditions.

One factor that complicates the surface wind variability over the Korean peninsula is that it is located in the latitude band of maximum north–south temperature gradient. Due to strong baroclinicity, four to eight extratropical depressions are typically observed in this latitude band, which reduce the meridional contrast of the available potential energy; this is an important role of the mid-latitude weather system. They can induce significant variation of surface wind at IIA. Composite analysis, case studies, and modelling experiments have been used to understand the genesis and development of mid-latitude storms (Park and Lee, 1987; Whitaker et al., 1988; Bullock and GyaKum, 1993; Park and Lee, 1998; Gray and Dacre, 2006; Dacre and Gray, 2009; Graf et al., 2017). In particular, storms passing through the Korean peninsula, which is located at the East Asian coastal region, are known to show a rapid development due to the interaction with the marginal seas (Chen and Dellosso, 1987; Chen et al., 1992). Interaction with the marginal seas is also reported as a primary factor for the generation of low-level wind shear at the IIA (Kang et al., 2010), which can result in such risks as abrupt loss of air speed or microburst. Therefore, analysis of climatological characteristics of wind variation induced by them would serve as the basic information for the aviation safety.

Land/sea breeze is also an important phenomenon that dominates the variation of wind strength and direction in the course of a day, particularly for the airports located near the coastline including IIA. Since land/sea breeze is a medium-scale feature, it exhibits localized characteristics. For this reason, numerical experiments have been carried out under various conditions. Mahrer and Pielke (1997), Kikuchi et al. (1981), and Miao et al. (2003) showed that topography could modulate the structure of sea breeze front and produce more intense circulation. Freitas et al. (2007) and Dandou et al. (2009) reported that heat island effect could further strengthen or deform sea breeze. Since IIA is located on the
western coast of the Korean Peninsula with many islands and small mountains nearby, and is close to Seoul, capital of Korea, land/sea breeze is affected by surface topography and heat island effect. There are also several experiments that strength of geostrophic wind could significantly affect the formation and strength of land/sea breeze (Estoque, 1962; Arritt, 1989; 1993; Bechtold et al., 1991; Kim and Jhun, 1992; Zhong and Takle, 1993; Gilliam et al., 2004). Modulation of land/sea breeze by synoptic waves is also investigated in this study, and the modulation characteristic and physical mechanism are presented.

Surface winds at IIA may vary in association with large-scale monsoons and extratropical cyclones, as well as small-scale breezes affected by local terrain and water mass nearby. These are the primary weather and climatological systems considered for forecasting surface winds at airports together with localized terrain and geographical characteristics. In the studies and reports discussed so far, numerical experiments, mean, and composite analysis have been used to understand variability of local winds. No comprehensive analysis has yet been conducted to delineate various mechanisms and the degree of their contributions to wind variability. This study deals with surface wind variability by directly linking it with synoptic and climatic features in a physically meaningful fashion. Then, it will be possible to delineate how climatic and synoptic features affect surface wind variability at a local station and their contributions to total wind variability. The cyclostationary empirical orthogonal function (CSEOF) analysis is applied to the station data in order to investigate how the monsoons, land/sea breezes, and the extratropical storms affect the magnitude and direction of the low-level wind at IIA. Reanalysis data are also used to understand the synoptic- and climatic-scale atmospheric patterns and mechanisms for each CSEOF mode identified from the station data.

This study is organized as follows. Data and method of analysis are addressed in section 2. Section 3 includes the results of analysis, followed by discussion and conclusions in section 4.

2 | DATA AND METHOD OF ANALYSIS

2.1 | Data

In this study, surface wind variability is analysed primarily in terms of speed and direction. Surface wind observed by Aerodrome Meteorological Observation System (AMOS) located at IIA (126.43°E, 37.47°N, 7 m above sea level) on the Korean Peninsula is the key variable. Seventeen years (2001–2017) of AMOS data are acquired from the Korea Aviation Meteorological Agency (https://amo.kma.go.kr/eng). AMOS is a basic instrument installed near the runway complex in all airports in South Korea and provides real-time measurements of weather conditions. Wind is measured every minute and is transmitted to the main processing unit to perform quality control such as physical limit test, internal consistency test, persistence test, and climate range test. In order to eliminate micro-scale physics, hourly mean wind is used in the present study.

The reanalysis data from the European Centre for Medium-Range Weather Forecasts Interim Re-Analysis (ERA-Interim; Dee et al., 2011) is used for the same period (2001–2017). Variables used include the 6-hourly geopotential (GP), air temperature (T), horizontal wind (U, V), vertical (pressure) velocity (ω), potential vorticity (PV), and specific humidity (q) at the 23 levels from 1,000 to 200 hPa over East Asia (20°–80°N, 60°–180°E) with a horizontal resolution of 1.5°. The 3-hourly surface variables of 10 m wind, 2 m air temperature, sensible heat flux (SHF), and latent heat flux (LHF) are also used over the same horizontal domain.

2.2 | Method of analysis

The CSEOF technique is employed to analyse the data in the present study (Kim et al., 1996; Kim and North, 1997). In CSEOF analysis, space–time data are decomposed as

\[
T(r,t) = \sum_{n} B_n(r,t) T_n(t), \tag{1}
\]

where \(B_n(r,t)\) are time-dependent cyclostationary loading vectors (CSLVs) and \(T_n(t)\) are corresponding principle component (PC, amplitude) time series. Unlike empirical orthogonal function (EOF) analysis, CSEOF loading vectors are periodic in time with the period of \(d\), which is called the nested period,

\[
B_n(r,t) = B_n(r,t+d). \tag{2}
\]

CSLVs depict temporal evolutions of the physical variable under investigation and are orthogonal to one another in space and time (i.e., in terms of the physical evolutions they represent). PC time series are uncorrelated with (and often independent of) one another. Thus, CSEOF analysis is viewed as a decomposition of a variable into physically distinct and temporally uncorrelated (independent) spatiotemporal evolutions.

When several variables are analysed, one-to-one correspondence should be established between two or more sets of CSEOFs so that they can be interpreted in a physically consistent manner. One-to-one correspondence is established by conducting the so-called regression analysis in CSEOF space (Kim et al., 2015). Let us consider CSEOF analysis of another variable,
and predictor variables can be written as \( P(r, t) = \sum_n C_n(r, t) P_n(t), \) (3)

where \( C_n(r, t) \) and \( P_n(t) \) are the CSLVs and PC time series of \( P(r, t) \). Regression analysis is conducted between the PC time series of the “target” variable, \( T_n(t) \), and those of the “predictor” variable, \( P_n(t) \). That is,

\[
T_n(t) = \sum_{m=1}^{M} \alpha_m^{(n)} P_m(t) + \varepsilon_m^{(n)}(t), \quad n = 1, 2, \ldots, (4)
\]

where \( \{ \alpha_m^{(n)} \} \) are regression coefficients, \( \varepsilon_m^{(n)}(t) \) are regression error time series, and \( M \) (=50 in the present study) is the number of predictor PC time series used for regression. Then, a new set of CSLVs are constructed for the predictor variable as

\[
C_n^{(reg)}(r, t) = \sum_{m=1}^{M} \alpha_m^{(n)} C_m(r, t), \quad n = 1, 2, \ldots, (5)
\]

which are called the “regressed” CSLVs. Then, the target and predictor variables can be written as

\[
\{T(r, t), P(r, t)\} = \sum_n \{B_n(r, t), C_n^{(reg)}(r, t)\} T_n(t). \quad (6)
\]

That is, two loading vectors \( B_n(r, t) \) and \( C_n^{(reg)}(r, t) \) are controlled by the same PC time series \( T_n(t) \), which ensures that the evolutions described in \( B_n(r, t) \) and \( C_n^{(reg)}(r, t) \) are physically and dynamically consistent. As a result of regression analysis, the entire dataset can be written as

\[
\text{Data}(r, t) = \sum_n \{B_n(r, t), C_n^{(reg)}(r, t), \ldots, Z_n^{(reg)}(r, t)\} T_n(t). \quad (7)
\]

For each \( n \), the terms in curly braces represent a spatio-temporal evolution as manifested in different physical variables.

3 | RESULTS AND DISCUSSION

CSEOF analysis is conducted on the AMOS wind with the nested period \( d = 168 \) hr (7 days). This choice for the nested period is to resolve synoptic waves with periods of 7 days and less. The first 10 CSEOF modes explain about 62% of the total surface wind variability (see Table 1). Then, regression analysis in CSEOF space is conducted on all predictor variables with the AMOS wind as the target variable. Figure 1 shows the \( R \) values of regression for all the pressure-level predictor variables for the first four CSEOF modes. The regression coefficients primarily show how closely predictor variables are connected with the AMOS wind for each CSEOF mode, although the distinct nature of the target variable (observed) and the predictor variables (modelled) deteriorates the regression fit to some degree.

| Mode | % Var | \( R \) |
|------|------|------|
| 1    | 12.08| 0.818|
| 2    | 8.18 | 0.863|
| 3    | 7.26 | 0.751|
| 4    | 6.62 | 0.749|
| 5    | 6.18 | 0.726|
| 6    | 5.52 | 0.709|
| 7    | 5.07 | 0.704|
| 8    | 4.38 | 0.544|
| 9    | 3.87 | 0.529|
| 10   | 3.26 | 0.504|
| Total| 62.43|      |

Table 1 Percent variance of the first 10 PC time series of the AMOS wind (2001–2017) and regression coefficients \( R \) using the ERA-Interim 10 m wind as the predictor variable.

For the first CSEOF mode, all the tropospheric variables are linked significantly with the evolution of the AMOS wind. For the second mode, long-term variations of air temperature, potential vorticity, and vertical (omega) velocity are fairly consistent with that of the AMOS wind up to 550 hPa. Then, the variation of pressure variables becomes disparate with that of the AMOS wind except for the vertical velocity. It is interesting to note that the tropospheric wind is quickly disconnected with the AMOS wind as elevation increases. The pressure-level variables in the lower troposphere are all moderately linked with the AMOS wind for the third CSEOF mode. No abrupt transition of regression coefficients is seen in the troposphere except for potential vorticity. Potential vorticity exhibits a stronger correlation with the AMOS wind above 400 hPa. For the fourth mode, strong connectivity of predictor variables is traced throughout the troposphere.

Figure 2 shows the CSLVs of the AMOS wind (solid line) and regressed loading vectors of the ERA-Interim surface (10 m) wind at the grid point nearest IIA (dashed line; \( R = 0.82, 0.86, 0.75, \) and 0.75 for modes 1–4). Zonal wind is depicted in red and meridional wind in blue. The corresponding PC time series and their spectral density functions are depicted in Figure 3. Each loading vector shows the variation of wind during a 1-week period. For example, the first loading vector shows predominantly southerly winds with weaker zonal winds (Figure 2a). The time-averaged regressed patterns of the 850-hPa geopotential and wind in Figure 4a show that the wind pattern in Figure 2a is associated with a land/ocean pressure...
The 250-hPa potential vorticity also indicates that warm and humid air resides over the Asian continent (Figure 4b). The corresponding PC time series shows a conspicuous seasonality with negative amplitudes in winter and positive in summer (Figure 3a; see also Figure S1a). Thus, the wind associated with the first CSEOF mode is...
predominantly northerly in winter and is southerly in summer. This annual reversal of wind is due to the East Asian monsoon (Lim et al., 2002; Kim and Roh, 2010; Kim et al., 2013; 2014).

The second loading vector exhibits primarily the diurnal variation of wind, particularly the zonal component, with weak inter-daily variation (Figure 2b). Figure 5 is the diurnal pattern of the regressed 2 m air temperature and 10 m wind for the second CSEOF mode. The difference in specific heat results in temporally distinct response to the diurnal solar variation, which is the driving force for land/sea breezes. During the heat of the day conspicuous westerly develops, while easterly is seen at night. Figure 6a shows the diurnal structures of 950 hPa vertical velocities (−\(\omega\); blue), 950 hPa air temperatures (red) and 800 hPa air temperatures (black) over land (solid line; 127.5°E, 37.5°N) and over the sea (dashed line: 124.5°E, 37.5°N) close to IIA. In mode 2, air temperature contrast (land minus ocean) is positive at 15 LST (UTC+9) and as a result land is heated (Figure 6a). This generates an upwards motion over land and a downwards motion over the sea, driving a zonal thermal circulation from the sea to land (Figure 6b). At 03 LST, temperature contrast is reversed with a warmer temperature over the sea (Figure 6a) causing a reversal of the zonal wind anomaly from land to sea (Figure 6b). Since land/sea breeze is a local circulation near the surface, 800 hPa air temperature does not show such diurnal variations (Figure 6a).

The corresponding PC time series shows a nonzero mean, suggesting that this mode is indeed the diurnal cycle of wind (Figure 3b; see also Figure S1b). The positive mean value of the PC time series implies that the phase of the loading vector in Figure 2b is not reversed in the mean sense. The diurnal cycle is particularly strong in March (Figure S1b). On the other hand, negative values of the PC time series are
often seen during July–September (Figure 3b); this implies that the diurnal cycle is reversed. The reversal of the diurnal cycle, most likely, is associated with inclement weather events such as heavy rains and typhoons. There is a conspicuous annual peak, suggesting that the strength of the diurnal cycle of surface wind exhibits a strong seasonal dependency with some asymmetric seasonal structure (causing a small semi-annual peak; Figure S1b).

The third loading vector shows weekly variation of wind without substantial diurnal variation (Figure 2c). The local wind depicts wind direction change from northwesterly to southeasterly and back to northwesterly. Figure 7 shows the regressed patterns derived from the ERA-Interim reanalysis variables. A successive passage of cyclone and anticyclone is clearly portrayed in the regressed loading vectors of 850-hPa geopotential and wind. A cyclone is developed over the ocean and northwesterly is seen at IIA (Days 1–2, Figure 7). Then an anticyclone is developed over the eastern coast of the Asian continent and it produces southeasterly as it leaves the airport (Days 5–7, Figure 7). Then, another cyclone begins to form over the sea (Day 7, Figure 7). Positive PV is seen at the trailing edge of the cyclone, whereas negative PV is seen at the trailing edge of the anticyclone.

Judging from the distance from the ridge to the trough, the wavelength is approximately 6,000 km and the period is

![Figure 4](image_url)

**Figure 4** The averaged patterns of the regressed loading vectors for the first CSEOF mode: (a) 850-hPa geopotential height (shading) and wind (vector) and (b) 250-hPa potential vorticity (shading) and 850-hPa geopotential height (contour)

![Figure 5](image_url)

**Figure 5** The diurnal pattern of the regressed loading vector for the second CSEOF mode: 2 m air temperature (shading) and 10 m wind (vector). Daily mean is removed from the loading vectors to show the diurnal variation. The red dot represents the location of IIA (124.5°E, 37.5°N)
**FIGURE 6**  (a) The diurnal cycles of 950-hPa vertical velocity (−ω; red), 950-hPa air temperature (blue), and 800-hPa air temperature (black) at IIA (solid line; 127.5°E, 37.5°N) and over the sea (dashed line; 124.5°E, 37.5°N) of the second CSEOF mode. (b) The diurnal cycle of zonal (red) and meridional (blue) winds (solid: AMOS, dotted: ERA-Interim 10 m) for the second CSEOF mode. Daily mean is removed from each loading vector in order to show the diurnal cycle clearly.

**FIGURE 7**  The daily averaged patterns of the third CSEOF loading vector: (left column) 850-hPa geopotential height (shading) and wind (vector), and (right column) 250-hPa potential vorticity (shading) and 850-hPa geopotential height (contour).
~7 days. These are the characteristic length and time scales of the planetary Rossby waves. The dispersion relationship of the barotropic Rossby waves is given by

\[ \omega = Uk - \frac{\beta k}{k^2 + l^2}, \]  

where \( \omega \) is the angular frequency, \( k \) and \( l \) are the zonal and meridional wavenumbers, \( U \) is mean zonal wind, and \( \beta \) is the beta parameter (meridional gradient of the Coriolis parameter \( f \)). When \( l \) is assumed to be equal to \( k \), the corresponding mean wind speed is about 18 m/s, which is roughly consistent with the mean upper tropospheric wind speed in this region.

The vertical structure of the waves developing over the ocean is investigated in Figures 8 and 9. The vertical structures of (a) PV, (b) omega, (c) meridional wind, (d) air temperature, (e) specific humidity, (f) relative vorticity, and (g) divergence are depicted on top of the vertical structure of geopotential (contour) along the latitude 37.5°N on Days 1 and 2. These two time steps show the enhancement of a baroclinic system as it moves over the ocean. LHF s and SHFs are shown as dashed and solid lines (sum in red) in Figures 8h and 9h. In (a)–(g), the area masked out by grey shading denotes the ERA-Interim topographic height. The grey shading in (h) represents the land area. As can be seen, this mode depicts a baroclinic system intensified by oceanic emission of heat flux following the upper-tropospheric

**Figure 8** Vertical structure of geopotential (contour), and (a) PV, (b) omega, (c) meridional wind, (d) air temperature, (e) specific humidity, (f) relative vorticity, and (g) divergence (shade) along the latitude 37.5°N on Day 1 for CSEOF mode 3. The red lines are the ridge (trough) lines representing \( v = 0 \). The solid and the dashed lines in Figure 9h are the sensible and latent heat fluxes (sum in red). The area masked out by grey shade in (a–g) represents the ERA-Interim topographic height. Land area is shaded in grey in (h). The red (blue) dots are the locations of ridge (trough), while the red (blue) triangles are the leading (trailing) edge of the ridge.
Rossby waves passing over the Korean Peninsula. The baroclinic structure and quasi-geostrophic (QG) relationship among the variables are clearly demonstrated (Holton, 1992).

In Figure 8, geopotential anomaly shows that an upper-level ridge is fully developed near 150°E (red dots). The ridge line represented by $v = 0$ (red line) beneath the negative PV aloft clearly displays westward tilting. The upwards motion (Figure 8b) at the trailing edge of the negative PV (Figure 8a) coupled with upper-level divergence (Figure 8g) represents the secondary circulation, which is a crucial condition for the maintenance of a baroclinic system. The meridional wind at the trailing edge near 130°E is positive (Figure 8c), which transports warm subtropical air to higher latitudes. Thus, the signs of air temperature anomaly (Figure 8d) and specific humidity anomaly (Figure 8e) are roughly consistent with that of the meridional wind. The polewards warm advection indicates that available potential energy is converted into kinetic energy, further amplifying the baroclinic system (Figure 8f).

It is noteworthy that westwards tilting is more prominent near the surface. Negative air temperature and specific humidity anomalies leading the ridge cause sensible and latent heat flux to increase (Figure 8h), which elevates energy in the lower troposphere (Kim et al., 2012). The increased heat flux enhances buoyancy near the surface and pushes the isobaric surface upwards, which results in
positive geopotential anomaly near the surface. This results in a more inclined vertical structure near the surface.

The trough at 110°E is more strongly developed as it moves eastwards to ~125°E roughly corresponding to the speed of ~18 m/s (Figure 9). It should be noted that the ridge and trough as they approach the mountain range show essentially barotropic structures in Figure 8. As the system moves eastwards, however, they exhibit more baroclinic structures (Figure 9) by the mechanism mentioned above. Specifically, negative geopotential anomaly is now clearly seen at the leading edge of the trough (Figure 9a), together with warmer and more humid lower tropospheric conditions (Figure 9d, e). The meridional wind is positive at the leading edge (Figure 9c), fortifying the cyclonic circulation around the trough (Figure 9f). At the trailing edge of the trough, situation reverses. In particular, turbulent heat flux increases at the trailing edge of the trough (Figure 9h), which is instrumental in the development of a ridge following the trough.

It is confirmed that the oceanic response to Rossby waves amplifies a baroclinic system. As can be seen in Figure 10a, potential vorticity is amplified significantly as waves enter the oceanic region and surface wind variability at IIA is increased (Figure 7). In turn, the secondary circulation induced by turbulent heat flux at the trailing edge strengthens the baroclinic system behind. Thus, turbulent heat flux is an important mechanism of linking upper-level Rossby waves and surface weathers. This result is consistent with Kim et al. (2012) (see Figure 11).

**FIGURE 10** The time-longitude plot of turbulent heat flux (sensible+latent; shade) and potential vorticity (PVU = 1 ×10^{-6} s^{-1}; contour) for modes 3–10.
The PC time series exhibits two conspicuous peaks at approximately 8-year period and 1-year period (Figure 3c). The 8-year peak is outside the cone of influence and may not be significant. The peak at 1-year period is due to the seasonal dependency of the amplitude of the PC time series (Figure S1c). In the mean sense, variability of the PC time series is stronger in winter and spring (Figure S1c).

The fourth loading vector exhibits a weekly variation together with a somewhat damped diurnal cycle of wind (Figure 2d). Both the zonal and meridional components of wind switch signs and form an anticyclonic evolution during a 1-week period. The loading vector shows that the diurnal cycle is affected by this mode. Due to the in-phase relationship of the diurnal cycle in modes 2 and 4, the diurnal cycle is strengthened (weakened) when mode 4 is in a positive (negative) phase (see also Figure S2).

Figure 11 depicts the physical mechanism associated with mode 4. A weekly variation of wind at IIA is mainly associated with a negative PV. A negative PV is first seen over the Korean Peninsula (Day 4), which strengthens as it migrates slightly to the east of the airport. Then, southeastern anomaly develops over the Korean Peninsula (Days 5–7). Temperature and specific humidity increase significantly at the trailing edge of the negative PV (see Figure S3). This results in decreased heat flux, more significantly over the sea than over land. Thus, the atmosphere is cooler and land breeze is intensified during the night-time amplifying the diurnal cycle (see also Figure S2).
The corresponding PC time series shows that the amplitude of the fourth mode is affected on various time scales from several weeks to 1 year (Figure 3d). The amplitude tends to be stronger in fall and weaker in spring (see Figure S1d). A significant non-zero mean in the PC time series throughout the year except in late winter/early fall implies that anticyclones are more likely than cyclones. Also, a significant trend suggests that the occurrence frequency of this mode increases from March through September in the record (Figure S1d).

The rest of the modes up to mode 10 exhibit surface wind variability associated with eastwards propagation of synoptic patterns and the subsequent strengthening of synoptic patterns over the ocean (Figure 10). The separation of these modes is due to variable phase, speed, and wavelength of synoptic patterns. In particular, mode 5 displays a quadrature relationship with mode 4 with fairly similar physical mechanisms (see also Figure S4). These two modes together explain an arbitrary phase of the development of synoptic patterns within the nested period. Similarly, modes 6 and 7 seem to represent higher-frequency shorter-wavelength synoptic patterns with variable phases.

Figure 12 represents the climatological (17-year averaged) annual variation of wind, which summarizes the patterns and the subsequent strengthening of synoptic patterns over the ocean (Figure 10). The separation of these modes is due to variable phase, speed, and wavelength of synoptic patterns. In particular, mode 5 displays a quadrature relationship with mode 4 with fairly similar physical mechanisms (see also Figure S4). These two modes together explain an arbitrary phase of the development of synoptic patterns within the nested period. Similarly, modes 6 and 7 seem to represent higher-frequency shorter-wavelength synoptic patterns with variable phases.

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seasonal dependency of the relative contribution of each mode discussed above. The abscissa (x) and the ordinate (y) represent the time of the day and the day of the year, respectively. The first and the second columns are obtained, respectively, from the raw data and the reconstructed data based on the 10 CSEOF modes. Their diurnal and annual structures of variability coincide with each other.

The sign reversal of the meridional wind between summer and winter due to monsoonal circulation is reasonably explained by the first CSEOF mode (Figure 12b third column). The diurnal cycle due to land/sea breeze is faithfully captured by the second CSEOF mode (Figure 12a fourth column). The second CSEOF mode represents the diurnal cycle due to land/sea breeze associated with the proximity of IIA to the marginal sea (fourth column). Since the coastline stretches in the north–south direction, the diurnal variation of the surface wind is more prominent in the zonal direction. The intensity of the diurnal variation is most intense in spring, when the diurnal temperature range is largest.

The propagation of synoptic patterns is clearly seen in all higher CSEOF modes. Wave signals are smoothed significantly upon averaging due to their irregular phases; thus, standard deviation of wind variability is overlaid in the fifth (modes 4 + 5) and the last (modes 3 + 6–10) columns to show the intensity of wave signals. The diurnal cycle of wind is affected by the fourth and the fifth modes (Figure 12a column 5). Synoptic system causes the vacillation of land/sea breezes, which is particularly intense in autumn. The strong surface wind variability induced by the rest of the CSEOF modes, all of which are associated with eastwards propagating synoptic patterns, can be found in the last column. The contribution of Rossby waves is, in general, more intense in winter than in summer because of strong baroclinicity. According to our results, surface wind variability, particularly the meridional component of variability, induced by Rossby waves on average is intensified in November and March (Figure 12b column 6) rather than mid-winter; this result is consistent with the double peaks in late fall and early spring of the Pacific storm track activity (Nakamura, 1992).

4 | SUMMARY AND CONCLUDING REMARKS

Variability of surface wind at IIA located on the western coast of the Korean Peninsula is investigated in terms of distinct physical characteristics. This goal is accomplished by conducting regression analysis between the AMOS wind (station measurements) and the ERA-Interim wind in CSEOF space. Understanding the physical mechanisms of surface wind variability is a first step towards an improved forecast system and aviation safety. It appears that the ERA-Interim product is reasonable in understanding the physical mechanisms of surface wind variability at IIA.

The leading CSEOF modes indicate that surface wind at IIA is affected primarily by the East Asian monsoon and the diurnal cycle associated with land/sea breeze. The monsoonal effect causes primarily the annual reversal of the meridional component of winds, whereas the breeze effect mainly causes the daily reversal of the zonal component of winds at IIA. The rest of the CSEOF modes (up to mode 10 investigated in the present study) are all associated with eastwards propagating synoptic patterns (Rossby waves). The surface wind variability associated with synoptic patterns explains ~42% of the total variability and is decomposed into a number of CSEOF modes because of varying phase, frequency and wavelength. As Rossby waves leave the Asian continent, strong baroclinicity is developed due to turbulent heat flux from the sea, and Rossby waves are amplified. As a result, strong surface wind variability is induced at IIA.

Seasonal dependency of the PC time series in terms of their mean and variance indicates that surface wind variability varies strongly following the time of the year. In fact, all the PC time series of the leading modes exhibit strong power at 1-year period, suggesting that their amplitudes vary significantly throughout the year. The effect of monsoon is stronger in winter than in summer. Land and sea breezes are intensified in different seasons due to the influence of synoptic patterns (modes 4 and 5); sea breeze is intensified most strongly in spring and land breeze in autumn. Rossby wave signals are stronger in winter, when meridional temperature gradient is sharper, than in summer. More intense wave activity appears in early spring and late fall when storm track activity peaks in the western Pacific. The inter-annual component of variability is relatively weak compared to the seasonal and sub-annual variation of the amplitude of the leading modes. The seasonal dependency is an important aspect of surface wind variability, which was not fully addressed in the present research; future research should focus on the seasonal dependency of the physical mechanisms causing surface wind variability.

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ORCID

Hyung-Ju Park https://orcid.org/0000-0002-7061-9453
Kwang-Yul Kim https://orcid.org/0000-0001-8526-6737
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