Measurement, simulation, and meteorological interpretation of medium-range transport of radionuclides to Korea during the Fukushima Dai-ichi nuclear accident

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A B S T R A C T

Two radionuclides (131I and 137Cs) were measured and simulated over the Korean Peninsula during the Fukushima Dai-ichi nuclear accident, and the resulting meso-scale meteorological characteristics were explored in order to interpret the medium-range transport of radionuclides from the site of the Fukushima Dai-ichi nuclear accident to the Korean Peninsula. Peak concentrations of radionuclides were detected across all sites in Korea for a period of April 2–8, 2011, with maximum concentrations of 131I and 137Cs at 3.12 mBq/m³ (on April 6), and 1.25 mBq/m³ (on April 7), respectively; the highest levels on record in Korea since measurements began. The multi-particle Lagrangian model, the FLEXPART simulation based on the National Centers for Environmental Prediction/Global Forecast System (NCEP/GFS), successfully explored these high radionuclide peaks resulting from long- and medium-range transport processes from the accident site.

The meteorological feature of the medium-range transport exploited in this study is the veering meso-scale circulation, in association with the presence of a blocking anticyclone, and its subsequent evolution with propagation eastwards over northeast Asia, which was one of the important factors in explaining the advection and redirection of radionuclides from the accident site to the Korean Peninsula. The blocking situation of the anticyclone, centered on the Korean Peninsula, lasted for two days (on April 4–5, 2011), and the northwesterlies and subsequent northerlies advected the radionuclides from the accident site to the southern Sea of Japan. They were then redirected towards Korea due to the veering circulations produced by the blocking anticyclone. The position-evolution of the anticyclone was concurrent with the timing of the transport of the highest level of 137Cs concentrations recorded in Korea. The vertical meteorological structure of the blocking anticyclone was also well featured to maintain its position due to the persistent compensation provided by being aloft a convergence zone, which is in good accordance with the location of the ridge on the 500 hPa level.

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1. Introduction

The Fukushima Dai-ichi nuclear accident, which occurred on March 11, 2011, is one of the largest nuclear disasters since the Chernobyl disaster of 1986, and the second disaster (after Chernobyl) to be given the Level 7 event classification of the International Nuclear Event Scale. During and after the Fukushima Dai-ichi nuclear accident occurred, numerous measurements and numerical studies have been carried out in order to understand the harmfulness and damages, along with how the radionuclides have been transported from the accident area since the accident (Mathieu et al., 2012; Park et al., 2013; Estournel et al., 2012; Momoshima et al., 2012; Long et al., 2012; Christoudias and Lelieveld, 2013). In Korea, the Korea Institute of Nuclear Safety (KINS) has been operating a monitoring program, and peak concentrations of 131I and 137Cs were detected across almost all sites in Korea during the period of April 2–8, 2011. These peaks are believed to be directly transported from the accident site through medium-range transport processes. Continuously, incident-related
radionuclides were detected until mid-April in many other monitoring sites and intermittently until the end of April.

In East Asia, the most frequent direction of atmospheric movement is from west to east, following the predominant upper air stream over mid-latitudes. Therefore, westerly winds are prevalent and can transport emitted radionuclides from East or Central Asia to North America with their seasonal variations of strength. The westerly winds are stronger in winter than summer and, therefore, radionuclides are transported at greater speeds and over greater distances during the winter months. In summer, the easterlies extend their influence northward so that the North American and Asian summer monsoons develop and drive surface emissions of radionuclides northward (UNECE, 2010). Therefore, the location of the quasi-persistent anticyclone in predicting the transport pathways by providing the proper interpretation of the meso-scale meteorological features that have been favored due to the features of wind fields around the flank of the quasi-persistent anticyclone. Since this transport pathway is associated with the presence of a quasi-persistent location, it was able to be identified by simply inspecting the weather maps; two synoptic weather maps of both the lower (850 hPa level) and upper atmosphere (500 hPa height fields) were employed for the identification of meteorological features that have been favored by the relevant transport process. Other information, such as streamline patterns and meso-scale meteorological dynamics, that were present during April 2–8, 2011, has also been discussed. By illustrating this sequence, we will point out the dominant role of the anticyclone in predicting the transport pathways by providing the proper interpretation of the meso-scale meteorological features over northeast Asia.

2. Measurements and modeling study

2.1. Measurement

In Korea, the KINS has been continuously monitoring both environmental radiation and the associated dose rates throughout Korea. When KINS first detected the incident signal at one monitoring station on March 28, 2011, it reinforced the extent of the monitoring program, and has monitored during and after the Fukushima accident.

Fig. 1 depicts the locations of the 12 Korean monitoring stations used in this study. The monitored data has also been used in the previous study (Lee et al., 2015). The radionuclide samples were collected at 01:00 UTC every morning and were analyzed every day during the study period. All samples were analyzed by a high purity germanium detector for 24 h, and prepared for gamma spectrometry. The samples were analyzed together with IAEA reference materials, and then analytical results were compared with values of the reference materials for the quality control of measurement results in gamma spectrometric analysis. The Minimum Detectable Concentration of 137Cs and 131I were ranging from 0.02 to 0.1 mBq/m³, and 0.03 to 0.1 mBq/m³, respectively (Lee et al., 2015). Other information on the radionuclide sampling is described by Lee et al. (2015) and Kim et al. (2012).

2.2. Model simulations

As the key simulation components, the two radionuclides (131I and 137Cs), were selected in light of their potential harmfulness to human health (UNSCAR, 2014). The FLEXPART model was used to simulate the transport and dispersion processes in this study. FLEXPART was driven by the National Centers for Environmental Prediction/Global Forecast System (NCEP/GFS) wind fields with a
temporal resolution of 3 h, horizontal resolution of 0.5° × 0.5° (globally), and 26 vertical levels. The source terms for 131I and 137Cs were taken from Stohl et al. (2012), and Terada et al. (2012), respectively. The emission rates of both 131I and 137Cs for the study period were shown in Fig. 2, and these source terms had been well documented (Christoudias and Lelieveld, 2013; UNSCEAR, 2014). As a model configuration, more than 2,000,000 particles were assumed to be released per each simulation, and the radioactive decays of 8.02 day and 30.17 year for 131I and 137Cs, were used here, respectively. In addition, as FLEXPART does not have plum rise modules, three release heights; 0–50 m, 50–300 m, and 300–1000 m above ground were used (Lee et al., 2015).

Weather maps for the 850 and 500 hPa levels during the study period, have been employed. The synoptic weather map of the 850 hPa level is a typical lower level weather chart while the 500 hPa height chart represents typical upper atmosphere, well representing motion in the middle troposphere. The 500 hPa height fields over the Northern Hemisphere lead to surface systems that are valued in the weather forecast and used for an extended forecast, analyzing long- and short-wave data in the middle troposphere, which is the level of non-divergent atmosphere. Both these weather maps were provided by the Korea Meteorological Administration (KMA).

Streamline distributions over the Northern Hemisphere, provided by the KMA, were also used to exploit the characteristics of wind direction changes that are dependent on the varying position of the surface anticyclones and cyclones. It appears appropriate, therefore, to speculate that the presence and absence of anticyclones and their locations control the medium-range transport pathways starting from accident area to the Korean Peninsula.

3. Results
3.1. Radionuclide measurement

Figs. 3 and 4 showed the spatial and temporal distributions of monitored concentrations of 131I and 137Cs, respectively. According to the radionuclide sampling analysis, two radionuclides of 131I and 137Cs were both detected for the first time on March 28, 2011. Lee et al. (2015) argued that these are due to intercontinental scale long-range transport processes such as semi-hemispherical transport processes and/or global-scale transport processes. We did not analyze in detail the distributions and attributions from intercontinental scale long-range transport processes during the period before April, 2011. Instead, we investigated the spatiotemporal variations of radionuclides since April 3, focusing on interpreting the direct impact of medium-range transport processes.

Since 131I was first detected on March 28, 2011, at Chuncheon monitoring station, located in northeast South Korea (Fig. 1), it was observed continuously or intermittently until early April. The 137Cs was observed on a less extensive scale relative to 131I, but appeared intermittently at most stations until early April (KINS, 2011).

However, as indicated in Fig. 3, the 131I was observed at all stations, with a sharp increase over April 5–7 all across the Korean Peninsula, reaching greater than 3 mBq/m³ at some stations, due probably to both the intercontinental scale transport and the subsequent medium-range transport process, as will be addressed later. During this period, the maximum concentrations of 131I, recorded on April 6 at most stations, were measured in the range of 0.44–3.12 mBq/m³, with the lower concentrations over southeast region such as Daegu, Andong and Busan stations. The maximum concentration, 3.12 mBq/m³, the highest and record-breaking level since KINS has measured in Korea, was observed on April 6 at Gunsan station, located in the west coast of the Korean Peninsula. On April 5, the Daegu and Andong stations, located in the east of the Korean Peninsula, in the inland region, had maximum values of 1.12 and 0.689 mBq/m³, respectively. Busan station, on the south coast of the Korea Peninsula, showed a maximum value of 1.32 mBq/m³ on April 7, and these high levels of radionuclide concentrations rapidly decreased on April 8.

The 137Cs was observed relatively more intermittently at most stations until April 4 (Fig. 4). On April 7, as indicated in Fig. 4, the higher concentrations of 137Cs were recorded as 0.55, 1.25, and 0.417 mBq/m³, at Jeju, Busan, and Gwangju, respectively. The peak value of 137Cs was observed at Busan station, with a maximum value of 1.25 mBq/m³. This was, again, the highest value on record since measurements began in Korea. While the maximum concentration of 137Cs was measured in the range of 0.131–1.25 mBq/m³, the arrival time of this peak is comparable with those of 131I. The maximum concentration of 137Cs was measured at most stations on April 7, with the exception of the Cheongju and Gangneung stations. Cheongju station had a maximum value of 0.197 mBq/m³ recorded on April 6 (Fig. 4) and Gangneung station, near the center of the Korean Peninsula, had a peak of 0.259 mBq/m³ on April 9 (not shown here). These shark increases of radionuclide concentrations imply the impact of medium-range transport processes on the radionuclide levels recorded in the Korean Peninsula, as will be explained in the later chapter.

The concentration levels of 131I and 137Cs increased at all stations until April 7, and the concentration levels of 131I were considerably higher than those of 137Cs. Furthermore, the maximum concentrations of 131I were observed a day earlier than those of 137Cs, although their temporal patterns were similar to each other. The current analysis revealed that relatively higher levels of 131I concentrations were observed on April 6, over the northern stations of the Korean Peninsula such as Chuncheon, Gangneung, and Gunsan (Fig. 1), as compared to the southern stations (Fig. 3), suggesting that one day earlier peak of 131I is attributable to its intercontinental scale transport process as described by Lee et al. (2015). Further relevant sensitivity tests for source and removal processes of each of the radionuclides during the intercontinental transport process would be need to explain this issue in detail.

From the spatial distribution of 137Cs component (Fig. 4), the medium-range transport process is one of the important factors to explain the sudden shift of 137Cs concentrations over southern stations of the Korean Peninsula such as Jeju and Busan, as indicated in Fig. 1. We assumed that the radionuclide plumes moved southwest of Japan, arriving inland of the Korean Peninsula, and some stations measured a higher value than usual for the period of early April. At this time, it would be worthwhile looking further into how to explain and elucidate the transport of higher concentrations of radionuclides from the accident site to neighboring regions by the meso-scale meteorological circulations.
3.2. FLEXPART modeling

Figs. 5 and 6 show the FLEXPART simulations of $^{131}$I and $^{137}$Cs concentrations, respectively, over northeast Asia for the period of April 2–8, 2011. As indicated in both Figs. 5 and 6, the simulated $^{131}$I and $^{137}$Cs moved to southeast direction due to the northwest-wind flow around accident site, being transported from accidental site towards the east Sea of Japan on April 2–3. Thereafter, $^{131}$I and

Fig. 3. Spatial and temporal variation of the 24 h mean measured concentrations of $^{131}$I for the period of April 3–April 8.
$^{137}$Cs are continuously transported to the south of Korea due to weak north and northwesterly flows on April 3–5. On April 6, however, a small percentage of $^{131}$I and higher levels of $^{137}$Cs arrived in Korea due to the southerlies that prevailed over the south Sea of Korea and east China, which was redirected by the veering mesoscale wind circulations. At this time, the maximum concentrations of $^{131}$I and $^{137}$Cs were recorded and also simulated according to both the actual measurements and model results, as shown in Figs. 3–6.

Both modeled and measured $^{137}$Cs component indicated the effects of the medium-range transport process, being recorded maximum over the southern area of the Korean Peninsula on April
7, 2011, as shown in Figs. 4 and 6. However, the $^{131}$I component exhibited the highest value in many monitoring stations one day earlier (on April 6, 2011) than $^{137}$Cs as indicated in Figs. 3 and 4. This is believed to be due to the different advection activities of $^{131}$I component, originating from northwestern area of the Korean Peninsula such as intercontinental-scale and global-scale transport processes prevailed on 5–6 April, 2011. In Fig. 5, the intercontinental scale transported plum of $^{131}$I was continuously transported
from northwest to southeastern area of the Korea Peninsula during April 5–6. Lee et al. (2015) described the pathway of intercontinental scale transport plume from accident site: released since mid-March 2011, transported to the north, passed through Kamchatka Peninsula/South Russia, and arrived at northwest area of Korean Peninsula on late March–early April 2011. As a result, high levels of $^{131}I$ were detected on 5–6 April, 2011, with relatively higher levels over the northern part (entrance area) of the Korean Peninsula as compared with southern area. This is also seen in the elevated concentration levels over South Korea (Fig. 5). As indicated Fig. 5, the elevated $^{131}I$ concentrations in 1000–3000 m height on 2–5 April (three upper panels in Fig. 5) as well as higher surface concentrations for 3–4 April over northern area of South Korea (Figs. 3 and 5). Our modeling study induced a considerable change
in $^{131}$I concentrations over northern part of South Korea, and measurements were also most likely due to the intimate involvement of north-westerlies of long-range transport through the intercontinental or semi-hemispheric scale transport processes. Further relevant and detailed sensitivity tests would be needed to quantitatively explain why the distribution features and maximum concentration of $^{131}$I component occurred one day earlier than $^{137}$Cs component.

Scatter plots of observations versus simulations for both $^{131}$I and $^{137}$Cs components are presented in Fig. 7. As illustrated in Fig. 7, the $^{131}$I results showed overall a good correlation ($r = 0.70$ and $p < 0.01$) at 12 monitoring stations, but model tends to underestimate for high $^{131}$I concentrations (i.e., observations of above 0.3 mBq/m$^3$). The average values of FA5 and FA10 for all stations were 67.6% and 81.8%, respectively. Here, the values of FA5 and FA10 denoted the percentage of simulations within factors of 5 and 10 for the measurements, respectively. The value of FA10 for $^{131}$I concentrations ranged from 66.7 to 100%, with a correlation coefficient of 0.67–0.92, confirming a good correlation between observations and simulations for $^{131}$I concentrations. However, $^{137}$Cs concentrations showed relatively more scattered pattern with 58.3% (FA5) and 71.7% (FA10), and tends to overestimate in a relatively high concentration range (i.e., model results for above 0.3 mBq/m$^3$). The $^{137}$Cs concentrations observed over the entrance area of advection of activity such as Jeju and Busan (Fig. 1), both located over southern part of South Korea, were in good agreement relative to other sites, with a correlation coefficient above 0.84 ($p < 0.01$) for two stations. Other statistical parameters such as bias, MAE (Mean Absolute Error), RMSE (Root Mean Square Error), and IOA (Index of Agreement) denoted by Lee et al. (2015), showed no critical values. The results of IOA showed 0.87 (for $^{131}$I) and 0.53 (for $^{137}$Cs), suggesting that the emission estimate of $^{131}$I is more accurate than that of $^{137}$Cs for the given period.

### 3.3. Meteorological features

#### 3.3.1. Synoptic features of the lower atmosphere

Figs. 8 and 9 depict the synoptic weather maps of the 850 hPa level, and simulated geopotential height fields by WRF model, respectively, and Fig. 10 illustrated the stream-lines distributions during the study period. Overall the simulated pressure patterns are quite similar to the observed ones (Figs. 8 and 9), and it is found that an intense anticyclone formed over northeast China on April 3, 2011, while low pressure existed over the north of Japan (Figs. 8 and 9), inducing the strong pressure gradient driving north-westerlies over the accident area (Fig. 10). As the high pressure system advected, it slowed steadily, with the center traversing eastern China until April 4. On April 4–5, we clearly see the veering circulations (or distinctly slow-moving) extended high pressure centered on the Korean Peninsula (Figs. 8 and 9).

Under the condition of this blocking anticyclone, which lasted two days, the persistent northerly and northeasterly wind fields were induced by the eastern flank of the stagnating anticyclone over accident area and the southeastern Sea of Japan: the advection zone from the accident site covering a longitudinal and latitudinal area of 138–141$^\circ$E and 33–35$^\circ$N, respectively (Fig. 10). From April 6, it was slowly migrating eastward, and on April 7, it was elongated eastward, stretching from the center of Japan to the eastern Sea of Japan (Figs. 8 and 9). The wind direction over the advection zone (now the southern Sea of Japan covering 128–132$^\circ$E and 29–33$^\circ$N) then turned by almost 90 degrees and forced radionuclides to migrate to the Korean Peninsula due to air flow along the southern edges of the quasi-stationary anticyclone on April 7 (Fig. 9).

In Fig. 10, streamlines are well governed by the high pressure located in the center of the study period (Figs. 8 and 9). On April 3, the high pressure system formed, moving eastward until it was centered over the Korean Peninsula. It led to the prevailing northwesterlies at the accident site, which then turned to northerlies and northeasterlies on both April 4 and 5. This veering wind field prevailed for two days over the eastern flank of the slowly migrating and stagnating anticyclone, the center of which traversed northeast Asia to the Korean Peninsula. Streamlines on April 4–5 provided the meteorological conditions, which were well favored by medium-range transport processes.

On April 6, high pressure was widely located over central Japan, yielding southeast winds blowing towards the Korean Peninsula, then moved to the Pacific Ocean on April 8–10. During this period, the high pressure system with strong pressure gradient slowly extended eastward on April 6 and veering circulations occurred over the advection zone of the southern marine area of Japan. This circulation redirected the wind flows, continuously driving the transport of radionuclides by southerlies from southern marine area of Japan (Fig. 10), which was also simulated well, as indicated in Figs. 5 and 6. Therefore, this quasi-stationary anticyclone that prevailed over the advection zone of southern Japan maintained the veering circulations that were persistently conducive to the downwind transport of radionuclides to the Korean Peninsula.
3.3.2. Synoptic features of upper atmosphere

Fig. 11 shows the 500 hPa geopotential height fields over the northern hemisphere for our analysis period. The 500 hPa weather map generally shows wave air motion at 5–6 km above the sea level pressure. In Fig. 11, strong waves formed in the 500 hPa level with undulating and meandering upper airflow forming in Jet stream generally found over the entire study period. Prevailing wind fields, from the west to the east, were found in the upper level in the middle latitude, between 30 and 60 degrees, including East Asia. However, it should be noted that a large ridge overlies much of central China, whereas two troughs are influencing both west China and east Japan, as shown in Fig. 8. For two days, from April 4–5, the ridgeline remained quasi-stationary (Fig. 11) and its location is correlates well with the locations of the stagnating anticyclone in the lower atmosphere, as illustrated in Figs. 8 and 9. Meanwhile, the right region of the ridgeline creates convergence and the subsiding air aloft it provides the surface diverging anticyclone, compensating for the air mass maintaining the long standing anticyclone system.

This interdependency is illustrated in the schematic diagram, shown in Fig. 12. This shows the relationship over the vertical air column between the stagnant anticyclone position (the divergence zone) in the lower air and the quasi-stationary convergence zone above this accounts for the stagnating high pressure centered on

Fig. 8. Synoptic weather chart at 850 hPa 00:00 UTC.

Fig. 9. Simulated geopotential height fields at 850 hPa 00:00 UTC.
Fig. 10. Streamlines and isotach (>25 knots) at 850 hPa 00:00 UTC. Star (★) denotes Fukushima accident site.

Fig. 11. Geopotential height fields of 850 hPa over the northern hemisphere. Star (★) denotes Fukushima accident site, and dashed lines indicate the ridgelines around the accidental site.
east China (Figs. 8 and 9). As indicated in both Figs. 8–9 and 11, the position of the quasi-stationary anticyclone in the 850 hPa level (Fig. 8 and Fig. 9) concurs well with the position (right wing) of the ridgeline (Fig. 11) for the period from April 4–5, as illustrated in Fig. 12. This quasi-stationary ridge exists during the study period (i.e., April 4–5) and has an influence on sustaining the anticyclone in the lower atmosphere, blocking the eastward migration. It persistently remained stagnant while deriving veering circulation from the surface anticyclone. From the center of this anticyclone, surface winds blow away clockwise, driving northerlies over the accident site (on April 3), advecting the radionuclides by northeasterlies (on April 4–5) along with the subsequent southerlies (on April 6) over the advection zone of the southern Sea of Japan. Over the next two days, the ridge maintained its strength as it moved eastward. This implied that the location of the 500 hPa quasi-stationary ridgeline played an important role in the presence of the blocking anticyclone in the lower atmosphere, resulting in the long-lasting veering meso-scale circulation during the Fukushima Dai-ichi nuclear accidents.

In summary, tracer particles are continuously released from the Fukushima accident site as indicated in Fig. 1. The radionuclides are continuously transported southeastwards around the accident site due to the slowly moving high pressure that prevailed from east China to Korea on April 2–3. As this high pressure stagnated over the Korean Peninsula on April 4–5, which results from the stagnated ridgelines, the particles were advected by northerlies to the advection zone, in the southeastern Sea of Japan. A stagnant ridgeline of upper atmosphere led to the blocking of the surface anticyclone, resulting from upper-atmospheric convergence/subsidence, advected particles southeastwards to the southeastern Sea of Japan (Figs. 5 and 6). From there, slowly moving eastwards, the veering characteristics redirected the advection of radionuclides from the southern Sea of Japan to the Korean Peninsula by the southerlies produced from along the edges of quasi-stationary anticyclone.

Therefore, the location of the anticyclone played an important role in the transport of radionuclides to Korea. That is, the blocking anticyclone, with the veering circulation that prevailed over east China and Korea, was conducive to the downwind medium-range transport of radionuclides to Korea.

Over the mid-latitude, the common and predominant wind direction is westerlies, and this prevailing wind fields have caused transport patterns of emitted radionuclides with their seasonal variations of strength. Thus, from the viewpoint of general atmospheric circulations, the westward transport process such as the Fukushima Dai-ichi nuclear accident for the period of April 2–8, 2011, had fairly small potentiality of transport pattern. However, the stagnating or distinctly slow-moving anticyclone along with the vertical pressure structure up to 500 hPa appears to be an important factor to feature the westward medium-range transport process of radionuclides on a regional scale over Northeast Asia, as investigated in this study.

4. Summary and conclusion

In this study, observations of radionuclides over the Korean Peninsula, the results of the Lagrangian particle dispersion model FLEXPART, and meteorological data, were all used to interpret the medium-range transport of 131I and 137Cs radionuclides to the Korean Peninsula during the Fukushima Dai-ichi nuclear accident. The observed 131I and 137Cs components showed peak values at most monitoring stations in Korea between April 6 and 7, 2011, respectively, due to the influence of the characterized transport features over the whole study period. The model showed the effects of medium range transport process on both 131I and 137Cs components. The modeled 137Cs showed maximum on 7 April, due to the direct effect of medium-range transport process, and the 131I exhibited more complicated conditions, showing the highest value one day earlier than that of 137Cs as a result of intercontinental-scale transport that occurred prior to the medium range transport process. The meteorological features present during the medium-range transport showed that the measured high concentrations of radionuclides, especially for 137Cs, originated from the plumes released and transported on a regional scale. The meso-scale wind circulations were in accordance with the stagnant high pressure: as the high pressure slowly approached the Korean Peninsula, the wind fields changed from northeasterlies to northerlies. This veering circulations over the east and south of Japan advected the radionuclides to the southeast of Japan, which lasted for 2 days due to the influence of a stagnant high-pressure center over the Korean Peninsula. In turn, as the anticyclone slowly moved eastwards, southerlies redirected the radionuclides towards the Korean Peninsula from the southern Sea of Japan on April 6–7. The meso-scale veering circulations were well explained by the blocking anticyclone, whose position is lasted for a long time due to the persistent compensation provided by being aloft a convergence zone in association with the location of the ridge on the 500 hPa level.

Admittedly, the stagnating anticyclone viewpoint may not completely explain the meteorological characteristics controlling the presence and transport of radionuclides, but its role appears to be more important than that of the migrating anticyclone or of the cyclone, as gained from the present study. Our results mainly serve the more practical purpose of studying the role of the blocking anticyclone, and its association with meteorological circulations under synoptic patterns, for use in emergency response situations. As part of this, dynamic, thermodynamic, and physical characteristics, under the indicated meso-scale meteorological features, must concurrently be studied based on the meaningful measurement of radionuclides over the given domain, as featured in this study.

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Fig. 12. A plan view of upper-level sinusoidal isobars superimposed on lower-level circular isobars and the resulting vertical distribution of divergence, modified from Hess (1959).
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