Amphidromic Lines in the Atmosphere: An Example of Global Pressure Field Annual Harmonic

Enjin Zhao1,2, Lin Mu1,3, and Haoyu Jiang1,2

1Hubei Key Laboratory of Marine Geological Resources, China University of Geosciences, Wuhan, China, 2Laboratory for Regional Oceanography and Numerical Modeling, Pilot Qingdao National Laboratory for Marine Science and Technology, Qingdao, China, 3College of Life Sciences and Oceanography, Shenzhen University, Shenzhen, China

Abstract Amphidrome refers to an oceanic point where the amplitude of one harmonic constituent of the tidal system is zero, and the phase of the harmonic constituent is undetermined. The concept of amphidrome can also be used in climatological studies because of the existence of annual amphidromes, points of zero amplitude, and ill-defined phase of annual cycle. This study investigated the global atmospheric geopotential height from the ERA-interim to identify annual amphidromes at different isobaric altitudes. Many well-defined annual amphidromes were identified. These amphidromic points appear always as twins with different rotating directions with respect to phases. This phenomenon can be explained mathematically with the basic theory of spherical algebraic topology, suggesting amphidrome twins as a common feature for periodic variables in the atmosphere. Due to the spatial continuity of atmospheric parameters, amphidromes at different isobaric altitudes can be concatenated into amphidromic lines. Amphidromic lines have a three-dimensional structure with both clockwise and anticlockwise vertical branches connected by one or two horizontal components. Particularly, some amphidromic lines in the atmosphere can be closed loops when they are connected by two horizontal components. The rotary phases around the amphidromic loops are similar to the magnetic induction lines around a closed electromagnetic coil.

Plain Language Summary Amphidrome refers to an oceanic point that is encircled by one harmonic constituent of rotary tides. The amplitude of the amphidromic point is zero and its phase is undetermined. Recent studies showed that an amphidrome is not a tide-only phenomenon but widely exists in oceanic and atmospheric systems. This study investigated annual amphidromes in the atmospheric pressure field. Many well-defined amphidromic points can be found at different heights, and four interesting features of these amphidromes were identified: (1) Amphidromes are very common in many periodic atmosphere features and always appear in pairs of two amphidromes that rotate in opposite directions, termed amphidromic twins. (2) The location of amphidromes in different layers changes slowly with height forming so-called amphidromic lines. (3) Amphidromic lines have a three-dimensional (3D) structure with both clockwise and anticlockwise vertical branches, connected by one or two horizontal components. The amphidromic twins are, in fact, only two vertical branches. (4) The 3D structure of specific amphidromic lines, sometimes, can be a closed loop named amphidromic loop. The phase rotating around this loop is similar to magnetic induction lines around a closed electromagnetic coil.

1. Introduction Periodicity is an important characteristic of many variables of oceanic and atmospheric systems. The behavior of these periodic cycles is, to some extent, similar to the periodic ebb and flow of the tidal system. Therefore, there can be many analogies of concepts between the oceanic/atmospheric system and the tidal system, and amphidrome is one of them. In the oceanic tidal system, an amphidrome refers to an oceanic point which has zero tidal amplitude and undetermined tidal phase for one harmonic constituent (e.g., the semidiurnal tidal constituent with a period of 12 h) of the tide. The harmonic constituent of the rotary tides runs around the corresponding amphidromes. About a dozen well-defined amphidromic points have been identified for semidiurnal and diurnal tides have been discovered, which form a fundamental feature of the global tidal system (Cartwright, 2001).
Based on the exploration of available satellite data, Chen and Quartly (2005) reported that an amphidrome is not only linked to tides in the ocean system but is also a rather common feature in the ocean. They identified a number of well-defined annual amphidromes in the data of sea surface temperature and sea level anomaly (SLA). Accordingly, annual SL amphidromes are invariant points where the SL amplitudes of the annual harmonic component are zero, and the annual phases are undetermined. Such a phenomenon of annual SLA amphidromic points is also found marginal seas such as the South China Sea, as reported by Zhang et al. (2006). Then, the characteristics of annual phase and amplitude of sea level pressure (SLP) and precipitation were studied to explore the amphidromic points in the atmosphere (Zhang et al., 2008). After that, dozens of annual/semiannual and clockwise/anticlockwise amphidromic points were found in the atmosphere-ocean system (e.g., Chen et al., 2012). Based on these findings, Chen et al. (2014) identified four annual amphidromic columns of sea temperature with different thicknesses across tropical ocean, taking advantage of the global Argo sea temperature data. This work extends the concept of amphidrome into a three-dimensional (3D) concept.

Since amphidromic columns have been identified in the ocean, it is natural to ask whether such a phenomenon also exists in the atmospheric 3D structure. This study attempted to identify amphidromic columns in the atmosphere. Using the data of global pressure field, we found that a phenomenon similar to the amphidromic column does exist in the atmosphere. However, some features of this phenomenon in the atmosphere seem to be different from those in the ocean. The location of amphidromic points changes with height, and we call this phenomenon amphidromic lines to emphasize the difference from amphidromic columns. The remainder of this study is structured as follows: The data and method we use are briefly described in Section 2. The main results are described in Section 3, followed by the discussion in Section 4. Section 5 is concluding remarks.

2. Data and Methods

In this study, we used the global pressure field as an example to investigate the 3D structure of amphidromes in the atmosphere. The pressure field is one of the most useful tools of the synoptic in diagnosing atmospheric circulation, therefore, is of great importance in weather forecast and climate studies. The data of pressure field used in this study is the atmospheric geopotential height (AGH) data from the ERA-interim data archive of the European Centre for Medium Range Weather Forecasts (ECMWF). ERA-interim provides global atmospheric products from January 1979 to August 2019 with a spatial resolution of 0.75° and a temporal resolution of 6 h (at 0000, 0600, 1200, and 1800 UTC) on 37 vertical levels from the surface up to 1 hPa. Global air temperature (AT) field from ERA-interim over the same period and with the same resolution was also used in this study to show that 3D structure of amphidromes also exists in other atmospheric variables. More detailed information on this dataset can be obtained from Berrisford et al. (2011), and the dataset is available from the Copernicus Climate Change Service (ECMWF, 2011). This dataset is sufficient to represent most annual and semiannual variability in the oceanic and atmospheric systems.

Based on the data described above, the global harmonic spectrum of AGH can be calculated using the spatial harmonic analysis method proposed by Chen (2006). An AGH anomaly series at a given geographical location (x, y) and height (isobaric altitude) z, \(d(x, y, z, t)\), can be obtained from the original time series of AGH, \(D(x, y, z, t)\), by removing the mean and the trend. Then, the annual harmonics of the AGH for a given point, \(P(x, y, z, t)\), can be derived via Fourier analysis of the anomaly series:

\[
P_a(x, y, z, t) = A_a(x, y, z) \cdot \cos(2\pi t / T_a + \phi_a(x, y, z))
\]

where \(A_a\) represents the amplitude of the annual harmonic, \(\phi_a\) represents the phase that indicates the time when the annual harmonic peaks, and \(T_a\) represents the period of annual harmonic (12 months). The harmonic can also be expressed as the sum of the sine and cosine components:

\[
P_a(x, y, z, t) = S_a(x, y, z) \cdot \sin(2\pi t / T_a) + C_a(x, y, z) \cdot \cos(2\pi t / T_a)
\]

where \(S_a\) and \(C_a\) represent the amplitudes of sine and cosine components, respectively. Either the combination of \(A_a\) and \(\phi_a\) or the combination of \(S_a\) and \(C_a\) is able to express the full information of the annual
harmonic. According to the definition, an amphidrome is visible in the phase map as a fixed point around which all 12 months appear as a rotary feature. Therefore, distributions of amplitude were not used in this study. However, the phase distributions might be chaotic in many cases (large variability of phase within a small spatial range, e.g., Chen et al., 2014; Chen & Wang, 2016), which might impact the identification of amphidromic points. It is noted that both \( S_a \) and \( C_a \) at an amphidromic point are also zero. Therefore, the locations of amphidromic points on different isobaric surfaces can also be identified as the intersection of the \( S_a = 0 \) contours and \( C_a = 0 \) contours. This feature is helpful for a better identification of amphidromic points.

### 3. Annual Amphidromic Twins and Amphidromic Lines

The global distribution of the phase of annual AGH variations on different isobar surfaces derived from ERA-interim is shown in Figure 1, where the colors indicate the months during which the annual AGHs peak. The zero amplitude contours of the sine and cosine components of the annual AGH variations are represented by solid and dashed lines, respectively. An amphidromic point can be identified via both nodes of its cophase lines and intersections of solid and dashed lines. Due to the space limitation of static figures, only phase maps of 15 selected pressure levels are shown here, and an animation that shows the evolution of the phase maps in all 37 different pressure levels is available in the supplementary material (Movie S1). The phase distribution of AGH generally varies slowly with altitude. In the lower layers of atmosphere, the phase patterns of AGH are relatively chaotic compared to the upper layers of atmosphere due to the impact of the Earth's surface. However, they are much clearer than the annual phase patterns of the deep ocean presented in Chen et al., (2014), because seasonal variability is significant in the AGH from the bottom to the top of the atmosphere. Because the signal of annual cycle is significant and robust, the differences among different versions of ERA datasets are small with respect to the phase distributions of annual cycle. For example, Figure S1 in the supplementary material shows the phase distribution of AGH annual harmonic at 1000-hPa isobaric altitude from ERA5 dataset. The pattern is almost identical with that from ERA-interim. The pattern at 1000-hPa isobaric altitude is also similar to the SLP annual phase distribution shown in Zhang et al. (2008) and Chen et al. (2012), because the 1000-hPa isobaric surface is close to the sea surface and their physical meanings are closely related.

Not surprisingly, the phase distributions of annual AGH in the many isobaric layers are dominated by a series of complex, yet clearly defined amphidromic systems as commonly seen in cophase line maps of oceanic tides. However, compared to Zhang et al. (2008) and Chen et al. (2012), more amphidromic points can be identified here because the land data are not blocked in the ERA-interim. It is noted that the AGH data at lower layers and SLP data in the ERA-interim dataset are artificial in high elevation regions, such as the Himalayas and Antarctica, because some of the isobaric surfaces in Figure 1 might be below the land surface in these regions. The data in these regions from the ERA-interim dataset are computed by taking into account the standard variation of pressure with height and the influence of temperature variations with height on the pressure assuming an adiabatic lapse rate under elevated terrain. After including the data for the land region, more amphidromic points are identified in Figure 1a than are reported by Zhang et al. (2008) and Chen et al. (2012), and amphidromic points in all altitudes always appear as twins with phases rotating in opposite directions (clockwise/anticlockwise), sharing several cophase lines, an \( S_a = 0 \) contour, and a \( C_a = 0 \) contour in common. Here, this phenomenon is defined as *amphidrome twins* to emphasize this twinned characteristic of amphidromic points in the atmosphere. The reason for this phenomenon is discussed in the following section.

With the increase of height, the annual phase distribution of AGH becomes increasingly hemispherically divided and zonally distributed due to less impact from the underlying surface. In the layers between 500-hPa and 100-hPa isobaric surfaces, the phase distribution becomes generally hemispherically divided and the AGH peaks around June, December, and September in major parts of the northern hemisphere, the southern hemisphere, and tropical regions, respectively. In the layers above the 100-hPa isobaric surface, the phases of the tropical region generally become similar to those of the northern hemisphere. However, less but well-defined amphidromic points are still observed, and they also appear as twins. Therefore, the rotational pattern of the phase of the annual cycle, amphidrome twins, also exists in the stratosphere.
Chen et al. (2014) showed that the locations of annual sea temperature amphidromic points are stable at different depths so that they can form *amphidromic columns* extending to a maximum oceanic depth of 120 m. However, the locations of AGH annual amphidromic points in the atmosphere vary significantly with isobaric altitudes, and are therefore not as stable as the amphidromic column in the ocean. This phenomenon is named *amphidromic lines* here to emphasize this feature of unstable locations. For instance, at 1000-hPa pressure level, four amphidromes (labeled A1-A4) form two pairs of amphidrome twins. A1 and A3 (A2 and A4) have a clockwise (anticlockwise) phase propagation around them, and are marked with circles (triangles) in Figure 1. With the increase of height, the locations of both A1 and A2 have a southward trend and the distance between A3 and A4 decreases (which might be more clearly observed in the Movie S1 in the supplementary material). At the 750-hPa level (Figure 1f), the A1-A2 pair still remains well defined, while the A3-A4 pair disappears. At the 650-hPa level (Figure 1g), the A1-A2 pair also disappears but a new pair of amphidromes, B1 and B2, is generated, although both of them are strongly distorted at this height.

![Figure 1](image-url)

**Figure 1.** Annual phase distributions of AGH variations over the global atmosphere at 15 pressure levels. The color bar indicates the calendar month during which the annual AGHs peak. The symbols “○” and “Δ” indicate clockwise and anticlockwise amphidromes, respectively. Most amphidromic points are not labeled to keep the figure clear. The zero amplitude contours of sine and cosine component of the annual AGH variations are shown as gray and black lines, respectively.
With increasing isobaric altitude, both B1 and B2 are observed to shift eastward with increasing distance between them, and they become increasingly well defined. At the levels between 300 hPa and 100 hPa, B1 and B2 are the only identified pair of amphidromes globally and rotatory patterns around them (clockwise for B1 and anticlockwise for B2) are very clear. The distance between B1 and B2 becomes smaller at the 100-hPa level (see Movie S1 in the supplementary material), and these amphidromes cannot be observed at the 70-hPa level, which is similar to the evolution of the A3-A4 pair. At the 70-hPa level, another new pair of distorted amphidromic points, C1 and C2, can be observed. However, C1 and C2 are located in the zonal region, which can be regarded as a “boundary” between the two dominated phases. The annual amplitude is very small along this zonal region because the \( S_a = 0 \) contour and the \( C_a = 0 \) contour almost overlap in this region. Therefore, both the pair of C1-C2 and the pair at the 10-hPa level (D1-D2) are distorted and the amphidromic lines are not clear at the upper layers (i.e., 100 hPa and above). It is noted that D1-D2 and C1-C2 are different amphidrome twins, which can be identified using the 50-hPa level in Movie S1.

4. Discussion

The amphidromic twins and amphidromic lines in this study were found in the global atmospheric pressure field. The pattern of global annual cycle of atmospheric pressure has been widely studied in the last century, especially for the lower atmosphere, and the patterns have been well known (e.g., Hsu & Wallace, 1976; Yulaeva et al., 1994). But the phenomena of amphidromic twins and amphidromic lines were not discussed explicitly in these early studies, maybe because most previous studies focus more on the dynamics instead of mathematical features of the pressure field. Chen et al. (2012) presented a detailed analysis on the annual/semiannual cycle of SLP in terms of a joint pattern of amplitude and phase over the world’s oceans using a 2° × 2° SLP data, finding some annual/semiannual amphidromes and showing that the SLP phase pattern of annual/semiannual cycle in the lower atmosphere is not only zonal but also rotational. This study validated this conclusion with a different data set and found that such a rotational pattern does not only exist in the sea level but also in other different levels of the atmosphere. It is also found that the amphidromes in the same level (or the same altitude) always appear as twins, bringing some new insights into the atmospheric “amphidromic system”. The reasons for the formation of amplitude/phase patterns of annual cycle in the global pressure field had been widely discussed in previous studies (e.g., Chen et al., 2012), thus, were not discussed in this section. In this section, we mainly discuss the common features of amphidromic twins/lines in different fields from a mathematical point of view.

Adjacent amphidromes always appear as twins with different rotating directions. Moreover, amphidromes with the same rotary direction never share any cophase line or the contour of \( S_a = 0 \) or \( C_a = 0 \) without passing through an amphidrome of the other type. These features of amphidromic twins can be explained using the basic theory of spherical algebraic topology: a contour of \( S_a = 0 \) or \( C_a = 0 \) on the Earth’s surface (which is spherical) can always be regarded as a closed loop, and amphidromes are actually the intersections of two such “loops” as mentioned above. The condition of tangency of two loops cannot be treated as an amphidrome because it will not be related to a rotating system. Moreover, strict tangency between the two contours rarely happens in the real world. The number of intersections between two closed loops is always an even number, and if a direction is assigned to one of the loops, an intersection will correspond to either this loop going in or going out of the other loop, and every “going in” intersection will have a corresponding “going out” intersection. Therefore, the number of amphidromes at a pressure level in the atmosphere is also always even. Two adjacent amphidromes will have opposite rotational symmetry because they correspond to these two different types of intersections (the aforementioned “going in” and “going out” intersections).

Zhang et al. (2006, 2008) tried to explain the amphidromes in the oceanic and atmospheric system using empirical orthogonal function analysis. It is noted that if the empirical orthogonal function is applied to the reconstructed data from annual harmonic instead of the original dataset (to avoid the obscuringness of other periods), the first two modes will be exactly the sine and cosine components of the harmonic and will explain 100% of the annual harmonic. According to Equation 2, the spatial distribution of a harmonic can be regarded as the superposition of two standing waves with the same period on a two-dimensional surface. Therefore, these amphidromes can also be seen as the common nodes of these standing waves.
For oceanic variables (land variables), due to the existence of land (ocean), some of the cophase lines and $S_a = 0$ and $C_a = 0$ contours might be overlaid by land. Therefore, these lines do not have to be loops (or several potential amphidromes may be covered by ocean or land) so that the number of amphidromes does not have to be even. That is also why previous literature might have reported odd numbers of amphidromes and ignoring the feature of amphidrome twins. However, even for ocean-only or land-only variables, two adjacent amphidromes (that share cophase lines) still have to show different rotating directions due to the aforementioned reason. A deduction that can be derived from these amphidromic lines is that horizontal amphidromic points are also very common in vertical profiles of AGH in the atmosphere, similar to horizontal amphidromic points in the ocean (Chen & Wang, 2016). The reason is that the vertical and horizontal amphidromic points can be regarded as the horizontal and vertical profiles of amphidromic lines, respectively. Many zonal and meridional profiles are inspected to test this deduction, and the results confirm it. An example is shown in Figure 2, which shows the AGH annual phase patterns at the 180° longitude profile. Three well-defined horizontal amphidromes are found at (300 hPa, 15°N), (100 hPa, 15°N), and (50 hPa, 23°S), with the middle one having opposite rotating direction with the other two.

The formation of amphidromic lines can also be explained by extending the above discussion to 3D. The annual amphidromic lines are simply the intersections of the $S_a = 0$ isosurface and the $C_a = 0$ isosurface in a 3D space. The intersecting lines between two surfaces do not have to be vertical and therefore, it is not surprising that the location of the amphidromes varies with height and profile. It is noted that the intersections of two surfaces with limited area can be either an open line or a closed loop. Therefore, theoretically, these annual amphidromic lines might be either a line with endpoints or a closed loop. To better show the feature of these amphidromic lines, all identified horizontal and vertical amphidromic points at different layers were plotted in a 3D space, as shown in Figure 3 from different view angles. Corresponding data of the figure is available is attached in the supplementary material. Readers can draw them using softwares with an interactive user interface to get a better view. Both types of amphidromic lines can be observed in Figure 3. For example, it can be observed that the amphidromic lines A3 and A4 are, in fact, two branches of the same “n”-shaped amphidromic line. When the distance between the two amphidromes decreases, they will merge into a horizontal amphidromic point (which can also be observed via the variation of phase near A3-A4 from Figures 1c–1f). The two amphidromic points in the lower boundary of the atmosphere (1,000-hPa pressure level) are simply two endpoints of this amphidromic line. The amphidromic line corresponds to D1-D2 systems (the red line in Figure 3) is also an “n”-shaped one, but with a very long horizontal branch almost around the globe.

When the amphidromic line does not intersect with the upper or lower boundary of the atmosphere, it should be a closed loop, which is a special case of the amphidromic line. Here, this special case of amphidromic lines is named amphidromic loop. A very well-defined case of an amphidromic loop can be observed in the center of each subplot in Figure 3. This amphidromic loop corresponds to the B1-B2 twin system in the annual AGH phase distributions in Figure 1 and the two adjacent horizontal amphidromes, (300 hPa, 15°N) and (100 hPa, 15°N), in Figure 2. Therefore, it is simple to recognize that both the vertical amphidrome
twins B1-B2 and the two horizontal amphidrome twins at (300 hPa, 15°N) and (100 hPa, 15°N) are simply the horizontal and vertical profile of an amphidromic loop, respectively. A different type of amphidromic loop is the orange line at ∼50 hPa altitude in Figure 3, which also corresponds to the C1-C2 system in Figure 1. It appears as a big loop around the globe at ∼30°S. One can imagine that the physical image of the AGH annual phase rotating around the amphidromic loop is similar to the magnetic field (magnetic induction lines) around a closed electromagnetic coil (with only one lap).

Moreover, the discussion above is also applicable for other atmospheric parameters and other harmonics. Therefore, aforementioned features of phase rotating, including amphidromic twins and amphidromic lines, might not only exist in the annual harmonic of the atmospheric pressure field, but also other harmonics of other atmospheric fields. This hypothesis was validated using the phase distributions of semiannual harmonic of AGH and annual/semiannual harmonic of AT at different pressure levels obtained from the ERA-interim data (Movies S2-S4 in the supplementary material). The results still indicate that the aforementioned phenomena of amphidromes are common features in the phase patterns of periodic cycles for many geophysical variables in the atmosphere.

5. Concluding Remarks

The successful identification of annual amphidromic columns in the ocean by Chen et al. (2014) encouraged us to search for amphidromic columns for different variables and periods in the atmosphere. Utilizing a 3D atmospheric model hindcast which provides AGH and AT data from isobaric altitudes of 1000-hPa to 1-hPa on the global scale, effort has been made to identify and locate annual and semiannual amphidromic points and amphidromic lines of AGH and AT at different pressure levels. From the AGH annual phase distributions (also from the AGH semiannual phase distributions and the AT annual/semiannual phase distributions), several interesting and inspiring phenomena are identified as listed in the following:

1. Amphidromes in all isobar surfaces on the Earth's surface always appear together as twins with opposite directions of rotation. This phenomenon is named amphidrome twins to emphasize their twinned characteristic. The inevitability of this twinned characteristic is proved mathematically using the basic
theory of spherical algebraic topology, which indicates that this is a common feature for all periodic variables of the atmospheric system.

2. The amphidromes at different pressure levels can also form a 3D structure; however, the locations of most amphidromes shift significantly with height. Therefore, this structure is named atmospheric amphidromic lines instead of amphidromic columns to emphasize this drifting feature.

3. The existence of amphidromic lines indicates that horizontal amphidromic points are also very common in the vertical profiles of the atmosphere. Vertical and horizontal amphidromic points are horizontal and vertical profiles of amphidromic lines, respectively.

4. One type of amphidromic lines is a line with endpoints at the upper or lower boundary of the atmosphere. If both endpoints are at the upper (lower) boundary, the amphidromic line will be an n-shaped curve with both clockwise and anticlockwise branches.

5. Another type of amphidromic lines is the amphidromic loop, which mostly appears between the lower and upper boundary of the atmosphere: the phase rotates around this loop similar to magnetic induction lines around a closed electromagnetic coil.

The annual and semiannual cycles are the two most dominant periods of atmospheric oscillation and are typically regarded as well-understood variability for common variables, such as atmospheric pressure and temperature. However, the main findings of this study, including the existence of these amphidrome twins, amphidromic lines, and amphidromic loops in the phase domain of the 3D atmosphere, seem not to have been reported in previous studies. Phenomena such as amphidrome twins and amphidromic lines are proved to be mathematically inevitable and are also observed in other atmospheric geophysical variables. Since these phenomena can be found in many geophysical variables and harmonics, it can be deduced that the basic phase pattern for most periodic variability of geophysical variables in the ocean and atmosphere is a combination of zonal distribution (which is already well known) and rotatory distribution.

A point in an amphidromic line can be reckoned as ideal locations for the observation of other climatic signals such as interannual variability and long-term trends, because the seasonal signal which is usually energetic has been filtered naturally at these locations. These amphidromic lines can also be used as benchmarks for the validation of numerical climate models. Besides, we believe that amphidromic twins, lines, and loops themselves are interesting phenomena worth reporting, and their identification should be helpful for a better understanding of periodic oscillations in the atmospheric system.

Data Availability Statement

The ERA-interim dataset is available from Copernicus Climate Change Service (ECMWF 2011).

References

Berrisford, P., Dee, D. P., Poli, P., Brugge, R., Fielding, K., Fuentes, M., et al. (2011). The ERA-Interim archive, version 2.0. Retrieved from https://www.ecmwf.int/file/21498/download?token=cr31Wrx8

Cartwright, D. E. (2001). Tides: A scientific history. Cambridge University Press.

Chen, G. (2006). A novel scheme for identifying principal modes in geophysical variability with application to global precipitation. *Journal of Geophysical Research, 111*, D11103. https://doi.org/10.1029/2005jd006233

Chen, G., Qian, C., & Zhang, C. (2012). New insights into annual and semiannual cycles of sea level pressure. *Monthly Weather Review, 140*, 1347–1355. https://doi.org/10.1175/mwr-d-11-00187.1

Chen, G., & Quartly, G. D. (2005). Annual amphidromes: A common feature in the ocean? *IEEE Geoscience and Remote Sensing Letters, 2*, 423–427. https://doi.org/10.1109/lgrs.2005.854205

Chen, G., & Wang, X. (2016). Vertical structure of upper-ocean seasonality: Annual and semiannual cycles with oceanographic implications. *Journal of Climate, 29*, 37–59. https://doi.org/10.1175/jcli-d-14-0085.1

Chen, G., Zhang, H., & Wang, X. (2014). Annual amphidromic columns of sea temperature in global oceans from Argo data. *Geophysical Research Letters, 41*, 2056–2062. https://doi.org/10.1002/2014gl059430

European Centre for Medium-range Weather Forecast (ECMWF). (2011). The ERA-Interim reanalysis dataset, *Copernicus Climate Change Service*. Retrieved from https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-datasets/era-interim

Furu, C.-P. F., & Wallace, J. M. (1976). The global distribution of the annual and semiannual cycles in sea level pressure. *Monthly Weather Review, 104*, 1597–1601. https://doi.org/10.1175/1520-0493(1976)104<1597:gdota>2.0.co;2

Yulaeva, E., Holton, J. R., & Wallace, J. M. (1994). On the cause of the annual cycle in tropical lower-stratospheric temperatures. *Journal of the Atmospheric Sciences, 51*, 169–174. https://doi.org/10.1175/1520-0469(1994)051<0169:otaca>2.0.co;2

Zhang, C., Chen, G., & Qiu, F. (2008). Annual amphidromes observed in the atmosphere with remote sensing data. *Journal of Geophysical Research, 113*, D16112. https://doi.org/10.1029/2008jd009864

Zhang, C., Wang, B., & Chen, G. (2006). Annual sea level amphidromes in the South China Sea revealed by merged altimeter data. *Geophysical Research Letters, 33*, D16112. https://doi.org/10.1029/2006gl026493

Acknowledgments

The ERA-interim dataset is downloaded from ECMWF using the Web API. This work is jointly supported by the Key-Area Research and Development Program of Guangdong Province (No. 2020B111020005), the National Natural Science Foundation of China (41806010, U2006210), Laboratory for Marine Science and Technology Modeling, Qingdao National Laboratory for Marine Science and Technology (Grant No. JCYJ20200109110220482), and Shenzhen Fundamental Research Program (Grant No. JCYJ20200109110220482).