Chapter 2
Wind and General Circulation

Wind is the directional motion of air particles. The general circulation is a representation of climatic state of wind, which is a linear and delayed response of periodic solar radiation forcing. The timescale of general circulation is from diurnal cycle to seasonal cycle, while its spatial scale ranges from a small peninsula to continent and basin. The study of general circulation has a long history since Halley (1686) and Hadley (1735) to Maury (1855) and Ferrel (1856), from the single-cell model, the two-cell model, and to the three-cell model. In 1921, V. Bjerknes proposed the four-cell model based on his theoretical speculation. Using four sets of reanalysis products and a climate model simulation, the four-cell model has been confirmed through zonally averaged calculation from basic atmospheric variables. The fourth cell located over the two polar areas are, respectively, named as the Arctic cell in the Northern Hemisphere and the Antarctic cell in the Southern Hemisphere. The Hadley, Ferrel, Polar, and Arctic/Antarctic cells exist in each hemisphere but their intensities vary from day to day and from month to month. The result of an aqua control experiment further identifies the existence of eight cells in the global atmosphere.

2.1 Diurnal-Cycle General Circulation

Traditionally, the general circulation of the atmosphere includes the totality of motions that characterizes the global-scale atmospheric flow. It is to identify average structures of the wind field along with other meteorological variables including temperature, humidity, pressure, and phenomena such as precipitation. Thus, the general circulation can be considered to consist of the flow averaged over a period of time sufficiently long for months and seasons, which can remove the random variations associated with individual weather systems. We here believe that
the general circulation is climatic winds or prevailing winds with various spatiotemporal scale subcomponents caused by regular forcing from solar radiation and surface conditions.

Land and sea breezes are such climatic winds with local spatial-scale component caused by regular diurnal-cycle forcing. Without large-scale climatic wind and wind anomalies, a sea breeze or onshore breeze is a gentle wind that develops over bodies of water near land due to differences in air pressure created by their different heat capacities. It is a common occurrence along coasts during the morning as solar radiation heats the land more quickly than the water. Land breezes or offshore breezes have a reverse effect, caused by land cooling more quickly than water in the evening. Sea breezes dissipate and wind blows from the land toward the sea. Offshore wind refers more generally to any wind over open water.

The cause is that the sea has a greater heat capacity than land, so the sea surface warms up slower than the land’s surface during the daytime. As the temperature of the land surface rises, the land heats the air above it by conduction (sensible heat flux). Warm air is less dense and so it expands, decreasing the pressure over the land near the coast. The air above the sea has a relatively higher pressure, causing air near the coast to flow toward the lower pressure over land. The strength of the sea breeze is directly proportional to the temperature difference between the land and the sea.

Atmospheric moisture rises at a place of wind convergence near the surface. Sea-breeze fronts are such convergence systems created by sea breezes. Cold air from the sea meets warm air from the land and creates a boundary like a shallow cold front. If the air is humid and unstable, cumulonimbus clouds and even showers can be formed along the mesoscale front.

At night, sea breezes usually change to land breezes, due to reversal of the sea–land temperature gradient. During night, the land cools off faster than the ocean due to differences in their heat capacity, which forces the dying of the daytime sea breeze as the temperature of the land approaches that of the ocean. If the land becomes cooler than the adjacent sea surface temperature, the air pressure over the water will be lower than that over the land, setting up land breezes blowing from the land to the sea, as long as the environmental surface wind pattern is not strong enough to oppose it. If there is sufficient moisture and the atmosphere is unstable, land breezes can cause showers, or even thunderstorms, over the water. Land breezes die once the land warms up again the next morning.

The reversal wind directions on the surface and rising–sinking flows between land and sea crossing the coastline form two opposite overturning circulations from day and night. The intensity of this local closed circulation can be quantitatively described by mass stream function, which is locally associated with the solar radiation and the surface sea–land condition. The intensity of circulation should be
delayed to the solar radiation in the diurnal timescale. Its surface zonal wind \( \tilde{u}(t) \) crossing the coastline can be, according to Eq. (1.3.1), written as

\[
\frac{\partial \tilde{u}(t)}{\partial t} = \tilde{\Theta}(t) - (L + D)\tilde{u}(t), \tag{2.1.1}
\]

where the term \( \tilde{\Theta}(t) \) is the solar forcing and the term \( -(L + D)\tilde{u}(t) \) is the delayed factor depending upon the linear relationship and dissipative effect \( -(L + D) \). If the solar radiation forcing \( \tilde{\Theta}(t) \) approaches its maximum at noon, the maximum wind \( \tilde{u}(t) \) and other weather phenomena such as shower should appear in the afternoon. The diurnal cycle of this local circulation and the surface wind and regular weather is a climatic phenomenon which does not need to be predicted but should be identified. This reversal circulation caused by sea–land heating contrast with diurnal cycle can also be referred as daily sea breeze and daily land breeze during day and night, respectively.

From Eq. (1.5.1), the local wind is written as

\[
u(p, t) = \tilde{u}(p, t) + u'(p, t). \tag{2.1.2}\]

It is clear that only wind anomalies \( u'(p, t) \), which may be caused by anomalous cyclone and anomalous anticyclone, need to be predicted. And, mountain and valley breezes are also local climatic circulation with a diurnal cycle.

### 2.2 Seasonal-Cycle General Circulation

Solar insolation has an obvious seasonal cycle besides the diurnal cycle. Therefore, apart from sea and land breezes as shown in Fig. 2.1, the general circulation should also have a seasonal cycle. This seasonal-cycle general circulation is directly associated with the seasonal change in solar radiation over adjacent continent and ocean. The reason is that the land responds to the seasonal changes in solar radiation much more quickly than the ocean does. Therefore, this seasonal-cycle general circulation of continent–ocean contrasts is a large-scale sea breeze. The direct response to the solar radiation is land rather than ocean, which occur when the temperature on land is significantly warmer in summer or cooler in winter than the temperature of the ocean. These temperature imbalances happen because oceans and land absorb heat in different ways. Over oceans, the air temperature remains relatively stable for two reasons: water has a relatively high heat capacity and because both conduction and convection will equilibrate water temperature in the vertical direction (up to 50 m). In contrast, dirt, sand, and rocks have lower heat capacities over land and they can only transmit heat into the earth by conduction and not by convection. Therefore, the bodies of water stay at a more even temperature, while land temperatures are more variable.
During summer, sunlight heats the surfaces of both land and oceans, but land temperatures rise more quickly. As the land’s surface becomes warmer, the air above it expands and an area of low pressure develops. Meanwhile, the ocean remains at a lower temperature than the land, and the air above it retains a higher pressure. This difference in pressure causes seasonal sea breeze to blow from ocean to land, bringing moist air inland. This moist air rises to a higher altitude over land and then it flows back toward the ocean, completing a closed circulation. However, when air rises, and while it is still over the land, the air cools. This decreases the air’s ability to hold water, and this brings precipitation over the land (Fig. 2.2a).

In winter, the cycle is reversed. Land cools faster than ocean and the air over the land has higher pressure than air over the ocean. This causes the air over the land to flow to the ocean, namely seasonal land breeze. When humid air rises over the ocean, it cools. This causes precipitation over the oceans. Cool air then flows toward the land to complete a closed circulation (Fig. 2.2b).

Similar rainfall occurs when moist ocean air is lifted upwards by mountains, surface heating, with convergence at the surface and divergence aloft. It should be noted that this circulation has a seasonal cycle but its spatial scale diversifies from a small island to peninsular and continental scales. It can appear in any latitudes even near the two polar areas on the Earth. In many places, this circulation is not reality of monsoon particularly in high latitudes. One can easily obtain the seasonal-cycle general circulation and its normal weather procedure caused by the land–ocean contrast locally.
2.3 History of Trade Circulation

The diurnal-cycle and seasonal-cycle circulations occupy two timescales. On the other hand, one finds that the prevailing wind direction does not change with season in many places over the Earth. The trade winds are the prevailing pattern of easterly surface winds found in the tropics, in the lower troposphere near the Earth’s
The trade winds blow predominantly from the northeast in the Northern Hemisphere (NH) and from the southeast in the Southern Hemisphere (SH). Historically, the trade winds help captains of sailing ships to cross the world’s oceans for centuries, and enable the expansion of European empire into America and the trade routes established across the Atlantic and Pacific oceans.

The term trade wind originally derived from the late Middle English word “trade,” meaning “path” or “track” (Braham et al. 2001). The Portuguese recognized the importance of the trade winds in navigation over both the North and South Atlantic Ocean as early as the fifteenth century (Muelder 2007). They learned that in order to reach South Africa, they needed to go far out in the ocean, head for Brazil at around 30°S, and then go eastward again. In the Pacific Ocean, the full wind circulation, which includes both the trade wind (easterlies) and higher latitude westerlies, was unknown to Europeans until Andres de Urdaneta’s voyage in 1565 (Hayes 2001). The ancient captain of a sailing ship sought a course along which the winds can be expected to blow in the direction of travel. It is clear that the trade wind has been applied in sailing across an oceanic basin for many centuries.

Except some captains collected enough information to create prevailing wind and current charts, meteorologists attempted to explain the spatial pattern or structure of circulation. One of the most famous scientists was Hadley (1735), who explained the trade winds and prevailing westerly winds by noting that the heating should produce a direct meridional cell in each hemisphere (Lorenz 1967). Prior to Hadley’s time, Edmund Halley (1686), an astronomer, presented a detailed and methodical account of the trade winds as observed in three separate oceans, and sought a common cause for them. In concordance with Halley, Hadley concluded that the distribution of solar heating would lead to a general rising motion in lower latitudes and a sinking motion in higher latitudes, the circuit completed by the equatorward motion at low levels and poleward motion aloft. This circulation carries more angular momentum, since the westerly winds aloft are stronger. It also carries more sensible heat and internal energy, if the stratification is stable.

Hadley himself presented no figures, but Lorenz (1967) later introduced the Hadley’s circulation schematically as shown in Fig. 2.3. In Hadley’s picture, the horizontal transports needed to satisfy the balance requirements that are accomplished by the simplest possible mechanism: A meridional circulation where the uniform poleward current at one elevation carries a different amount of each transported property from the uniform equatorward current at another elevation. Near the surface, northeast trade winds and southeast trade winds are clearly pictured in the tropical regions of the two hemispheres. The surface northwesterly winds in the NH and the surface southwesterly winds in the SH show an unstable observation that they originate from the polar highs. Therefore, this picture has not entirely described the spatial dynamical relation between surface winds and meridional circulations. In the NH, the surface northwesterly winds proposed by Hadley began to cast some doubt due to growing evidence that the prevailing westerly winds in the NH tended to blow from somewhat southwesterly rather than northwesterly winds.
After Hadley’s work in 1735, similar explanation was also proposed by other savants during more than half century because the scientific community was generally unaware of this work. Figure 2.3a pictures a single circulation model from

Fig. 2.3 Schematic representations of the general circulation model of the atmosphere as envisioned by a Hadley (1735), b Dove (1837), c Maury (1855), d Ferrel (1856), e Thomson (1857, 1892), and f Ferrel (1859). Sourced from Lorenz (1967)
the equator to the high latitudes. Large-scale eddies such as cyclones are absent in this picture because eddies influence the zonally averaged motion by transporting some property from one latitude band to another. One hundred years later, Dove (1837) modified the previous model (Fig. 2.3b). He made two modifications on Hadley’s explanation. One is that southwesterly winds and northeasterly winds vary with moving eddies in middle latitudes. Another is that the single circulation shrinks within tropics. It implies that a vertical circulation exists in meridional section in the tropics while transient southwesterly winds and northeasterly winds with moving eddies are horizontally active in middle latitudes. In his southwesterly winds and northeasterly winds, the effect of Earth rotation contributed by Coriolis in 1835 is visible.

Matthew Maury, a naval officer, was one of the most diligent compliers of weather observations. He charted of the winds over the oceans and began to consider the reduction in the normal sailing times between distant points. About 120 years after Hadley, Maury (1855) proposed a model shown in Fig. 2.3c. It followed Dove’s circulation and trade winds in the tropics and proposed a second meridional circulation in the vertical direction over the mid-high latitudes. The new cell is an opposite current beside Dove’s circulation. The effect of the Earth rotation was well considered in his scheme where trade winds were below the tropical meridional circulation and southwesterly winds were under the second circulation. Therefore, there were two cells: A direct cell like Hadley’s within the tropics and an indirect cell in higher latitudes. This picture correctly showed that the two direct cells in the tropics rose in the doldrums along the equator while the direct cell and indirect cell combined to form a sinking flow in the horse latitudes. However, the indirect cell had not been explained.

Maury’s book is extremely readable. It became rather popular and instrumental in initiating some of the more rational theories which were to follow. A school teacher, William Ferrel, was one of those readers. He first learned that normal pressure was not uniform over the Earth’s surface, but higher in the horse latitudes, and lower in the doldrums and especially in the two polar regions. He disagreed with some of Maury’s ideas, particularly the crossing of the meridional currents. In the following year, Ferrel came forth with a theory of his own and proposed a spatial circulation pattern as shown in Fig. 2.3d. The circulation which he envisioned was somewhat like Maury’s, except that there were now three cells in each hemisphere, which he felt were demanded by the observations. Unlike Maury, however, Ferrel believed that he could present a complete explanation for the three cells. Ferrel’s great contribution was the introduction of a “new” force, the meridional component of the Coriolis force acting on winds. He definitely believed that proper consideration of this new force would account for the previously unexplained features not only of the general circulation but also of cyclones and smaller disturbances as well. Ferrel was the first person who presented to the meteorological world a correct account of the Coriolis force, a quantitative description of the geostrophic wind, and a partial explanation for its occurrence.

In the spatial circulation pattern of Ferrel’s model, the third cell was respectively located in two polar regions. This should be a direct cell and its surface winds
should be northeasterly flow due to the Earth’s rotation or the Coriolis effect. Two surface convergence zones were, respectively, located along the equator and in high latitude while a surface high zone was in the horse latitudes. Ferrel (1859) revised his meridional cells by two closed currents vertically located in two layers but the indirect cell limited in the lower layer of middle latitudes (Fig. 2.3f). The revised pattern may be influenced by Thomson (1857)’s model (Fig. 2.3e), which can also explain the two northeasterly zones, respectively, in the tropics and two polar regions while a southwesterly zone in NH middle latitudes. Ferrel’s original version has been popular till nowadays, but his revision has not been accepted.

2.4 Modern General Circulation

In the Ferrel era, the general circulation was identified using mainly theoretical speculation, with less observations. In that era, eddies were only considered by Dove (1837) in high latitudes of his circulation picture but they did not exist in the Ferrel (1856)’s model. Since the early twentieth century, many observations in high latitudes can be obtained. A school group led by V. Bjerknes particularly focused on the study of observed cyclones in NH middle latitudes. Then, J. Bjerknes (1919), the son of V. Bjerknes, identified observational cyclones as waves on the polar frontal surface. These cyclones, as some disturbances growing upon a preexisting flow pattern, required a consideration of the preexisting pattern itself. This preexisting pattern is the general circulation. In the discussion of the general circulation, V. Bjerknes (1921) noted the difficulties in deducing a zonally symmetric circulation from a pure theory, and based his picture upon the combination of theory and observation. His theoretical result is illustrated in Fig. 2.4a. Then, he noted that this circulation appeared to be unstable, and that cyclones should develop, ultimately leading to the distribution of asymmetric circulation, as shown in Fig. 2.4b. For the symmetric scheme, he described that on each hemisphere there are four circulations, running as toothed wheels, the circulations of the trades, the circulation of the temperate zone, the circulation of the easterly polar zone, and the circulation of the theoretically introduced westerly polar zone. The first and the third of these circulations represent thermodynamically direct cells, in which the motion is maintained by heat energy. But the temperate cell is an indirect one, by which kinetic energy is transformed into heat, and this is also the case for the westerly polar zone. In his symmetric scheme (Fig. 2.4a), the fourth cell is the smallest one, so its westerly polar zone was not plotted.

The scheme of symmetric circulations gives two zones with descending motion, where very limited precipitation should be expected, namely a zone around the pole, and a zone near subtropical calms; and further two zones with ascending motion and abundant precipitation, one along the equator and one along the polar front, situated on the polar side of it. Finally, a third theoretical zone of precipitation should be at the pole itself (Fig. 2.4a).
The first direct cell in the tropics stably exists in symmetric and asymmetric schemes. However, many transient eddies are active in mid-high latitudes and make other three meridional cells unstable (Fig. 2.4b). Cyclones and anticyclones are introduced in proper places as essential links in the mechanism of circulation, drawing the supply of cold air from the polar circulation and the supply of warm air from the inversely going temperate circulation. We now understand that the symmetric cells occupy their climatic features while the asymmetric scheme shows the transient systems as horizontal vortices and vertical stream lines. It is clear that Fig. 2.4a is a climatic chart and Fig. 2.4b is a total-based field chart. In Fig. 2.4b, two cyclone families have been plotted in mid-high latitudes.

In the last part of Bjerknes (1921), he gave a detailed description of the two circulations in the polar region. The two will be mixed and the stronger one will gain. It showed that the two polar circulations were combined into one, which has the direction of the thermodynamic tendency. But the effect will to some extent be checked by the tendency toward the formation of the polar cyclone. He said that “we have introduced it to remind the reader of this checking effect.” We all know that the polar cyclone does not exist in daily synoptic chart because the diurnal and seasonal general circulations and transient eddies caused by sea–land contrast coexist.

The fourth cell in the polar region is seldom mentioned in the literature. One reason is that it is not important to daily weather and climate in mid-low latitudes.
Another is the lack of observations to prove its existence. Beyond 80°N, the historical radiosonde observations are sparse with about five stations from the beginning of record through 1987 (Kahl et al. 1992). To examine the intensity and extent of meridional cells, stream line and stream function (or mass stream function) were used to indicate the existence of meridional cells in previous studies. Some calculation covered the 60 latitudes (Peixoto and Oort 1992). Reanalysis products are available since the late twentieth century (Kalnay et al. 1996). Using the NCEP/NCAR reanalysis product, Li (2001) calculated the zonally averaged vertical velocity in the pressure-latitude section. As indicated by Bjerknes (1921), there are three ascending flows in the NH along the equatorial zone, the polar frontal zone and near the poles. Near the North Pole, the center of ascending motion is located round 850 hPa while the center near the South Pole is at upper troposphere in Li’s (2001) atlas.

2.5 The Arctic Cell and the Four-Cell Model

The traditional three-cell model was first proposed by Ferrel (1856) and has been widely accepted in the past century. The model describes that the Hadley cell ranges from the equator to about 30°N latitude, the Polar cell covers from about 60°N to the poles, and the Ferrel cell exists between them in the NH. Ferrel believed that the three meridional cells are equally crossing about 30 latitudes in each hemisphere. However, the Polar cell, in theory, cannot cross latitudes as many as the Hadley cell does in the lower latitudes because a larger decrease in the rotational radius will cause a larger increase in westerly velocity aloft according to the conservation of angular momentum (Ahrens 2012).

Recently, Qian et al. (2015a) proposed a fourth meridional cell, named the Arctic cell, based on the analyses of meridional-vertical section flow and meridional-mass stream function. The Arctic cell was found existing in the troposphere to the north of 80°N, and its intensity is very weak compared with other three cells. Due to the sparse long-term atmospheric radiosonde observations in the Arctic troposphere (Kahl et al. 1992), researches on the Arctic cell by observational datasets, climate model simulations as well as visualized methods are few. Therefore, more analyses based on different datasets and simulations are required to prove the existence of the Arctic cell.

Figure 2.5 shows annual mean zonally averaged meridional cells depicted by vertical sections of flow and zonal velocities averaged over 30 years (1981–2010) using four different reanalysis products and the CESM1-CAM5 model simulation. The meridional flow is simply drawn using the monthly mean wind components $v(\varphi, p, t)$ and $\omega(\varphi, p, t)$. Five centers of meridional cells covering between 30°S and

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1Modified article originally published in Qian et al. (2015a). *The Arctic and Polar cells act on the Arctic sea ice variation.* Tellus A, 67: 27692. Published with kind permission of © 2015 W. Qian et al. All Rights Reserved.
90°N are clearly obtained from each of the datasets in Fig. 2.5. The two Hadley cells are well defined from around 30°S to 30°N with an ascending flow in the tropics and two descending flows in the two subtropical zones. The northeasterly trade wind in the tropical NH and the southeasterly trade wind in the tropical SH are commonly observed in the tropical lower troposphere from five datasets. The flow in the NH is characterized by westerly jet with the maximum zonal velocity (a core) at about 35°N near the tropopause. A shallow layer northeasterly wind is centered below the Polar cell while a southwesterly wind is located below the Arctic cell near the polar region. In the NH, four meridional cells can be identified from the four reanalysis products and a model simulation. The fourth cell named by the Arctic cell is located beyond 80°N with its center at 850 hPa (Qian et al. 2015a).
Fig. 2.7  Same as in Fig. 2.5 except for annual mean MSFs (yellow-red shading for positive and green shading for negative). The MSF interval is $25 \times 10^6$ tons$^{-1}$ between $30^\circ$S–$30^\circ$N, $5 \times 10^6$ ton s$^{-1}$ between $30^\circ$N–$62.25^\circ$N and $1 \times 10^6$ ton s$^{-1}$ between $62.25^\circ$N–$90^\circ$N. Red and blue arrows indicate ascending and descending pressure velocities ($-0.015$ Pa s$^{-1}$) respectively. Sourced from Wu (2016)
To examine the seasonal features, Fig. 2.6 shows vertical sections of climatic seasonal-mean flow and westerly (or easterly) averaged over 30 years (1981–2010) using the ERA-Interim product in the four boreal seasons. It is noted that the central locations of the four cells vary with different seasons. The centers of two Hadley cells have the largest seasonal migration. In the boreal spring, the Ferrel cell even splits into two in the NH, probably because the Ferrel cell is an indirect circulation caused mainly by eddies. The Polar and Arctic cells are always limited in the high latitudes between 60°N and 90°N. The easterly flow is stably observed in the tropical troposphere associated with the Hadley cell, but the westerly flow in the polar region is highly unstable because there are strong interactions between the meridional cells and the synoptic eddies, as well as the influences from the topographic, frictional and diabatic processes. The same result can also be illustrated from other reanalysis products and model simulations.

As we mentioned, while the flow clearly depicts the spatial structures and basic patterns of the four meridional cells in the NH, the mass stream function (MSF) can quantitatively illustrate the intensity of each cell. Five zonally averaged meridional cells illustrated by the vertical section of climatic annual mean MSFs averaged over 30 years (1981–2010) are shown in Fig. 2.7 using the four reanalysis products and one model simulation. Four meridional cells are commonly observed in the NH,
With comparable central intensities and locations from all five datasets. The intensity ratios of the Ferrel, Polar, and Arctic cells to the Hadley cell are approximately 1:3, 1:13, and 1:80, respectively, while the intensity ratio of the Arctic cell to the Polar cell is approximately 1:6 (Qian et al. 2015a). The Arctic cell exists next to the Polar cell as a weak opposite circulation and is centered at 850 hPa and 80°N.

Five zonally averaged meridional cells illustrated by the vertical section of climatic seasonal-mean MSFs averaged over 30 years (1981–2010) are shown in Fig. 2.8 using the ERA-Interim product in the four boreal seasons. The central intensities and locations of two Hadley cells, as expected, vary with seasons. The Hadley cell in the NH has the minimal (maximal) MSF value $25 \times 10^6$ ton s$^{-1}$ ($200 \times 10^6$ ton s$^{-1}$) and the northernmost (southernmost) latitude in the boreal summer (winter). The central MSF value gradually reduces from the Ferrel cell to
the Polar and Arctic cells, so the MSF interval is drawn as $25 \times 10^6$ ton s$^{-1}$ between $30^\circ$S–$30^\circ$N, $5 \times 10^6$ ton s$^{-1}$ between $30^\circ$N–$62.25^\circ$N and $1 \times 10^6$ ton s$^{-1}$ between $62.25^\circ$N–$90^\circ$N. It is noted that the Arctic cell is influenced by the Polar cell in terms of intensities and locations. The central location of the Arctic cell is generally lower than that of the Polar cell. In the boreal winter, when the intensity of the Polar cell reaches its maximum, however, the central location of the Arctic cell is entirely located beneath the Polar cell (Fig. 2.8d). In contrast, the Arctic cell stands alongside the Polar cell in summer when the Polar cell is relatively weak (Fig. 2.8b). Similar distributions of MSFs can also be observed from other reanalysis products and model simulations.

Two pairs of meridional cells in the NH are well defined using the two 4D-VAR ERA-Interim and JRA-55 reanalysis products in Fig. 2.9. The first pair is the Hadley and Ferrel cells, whose monthly mean intensities have a climatic seasonal cycle and opposite in phase (Fig. 2.9a). The MSF difference between the Hadley
and Ferrel cells is maximum in January and minimum in July. Similarly, the intensity difference between the second pair (the Polar and Arctic cells) is also maximum in January and minimum in July (Fig. 2.9b).

In the symmetrical circulation scheme proposed by Bjerknes (1921), there should be a descending flow in the subpolar zone (70°–80°N) and an ascending flow in the polar region (Fig. 2.4a). Figure 2.10 shows the intensities of the descending and ascending flow branches in the NH high latitudes. The descending zone is concentrated from 69°N to 82°N while the ascending flow zone is located beyond 83°N. The strongest descending flow is climatologically observed in the boreal winter (Fig. 2.10d).

Two descending zones with limited precipitation and three ascending zones with plentiful precipitation speculated by Bjerknes (1921) in his scheme of symmetric circulations are also confirmed in Fig. 2.11. In the Arctic, higher precipitation rate is mainly concentrated in summer from pentads 29 to 45. During this period, the precipitation rate is more than 1 mm day$^{-1}$ in the Arctic, while in the subpolar there is a dry zone with the precipitation rate less than 1 mm day$^{-1}$ (Fig. 2.11a). In the Arctic, there is a year-round low center of climatic geopotential height at 850 hPa, whereas there is a high-pressure zone in the subpolar region (Fig. 2.11b). The low center in geopotential height and the higher precipitation rate in the Arctic are closely linked to an ascending flow region at 850 hPa (Fig. 2.11c). In the traditional three-cell model, the Polar cell ranges from 60°N to 90°N. In that case, the limited precipitation rate, the high-pressure system and the descending flow are expected to exist climatologically in the Arctic, which is inconsistent with the new results. Figure 2.11 gives additional evidences challenging the traditional three-cell model.

Theoretically, there should be southwesterly wind below the center of Arctic cell. Figure 2.12 shows climatic winds at 2 m level and surface air temperature in the NH high latitudes. On an average, there is southerly wind beyond 80°N. It means that the regional-mean southerly is climatologically larger than that of northerly. But as illustrated in Sect. 2.2, seasonal-cycle general circulation caused by sea–land contrast has a large deviation relative to the zonally averaged winds. Seasonally, there are three pairs of southerly and northerly centers. The strongest pair is caused by Greenland and the Greenland Sea. Other two pairs are associated with the two continents and seas in the high latitudes. In boreal summer, the surface air temperature is relatively higher beyond 80°N with southwesterly winds.
In a study of the frontal development, Bergeron (1928) found the necessity to introduce a model of the general circulation, so he proposed a three-cell meridional circulation, somewhat similar to the one which Ferrel introduced. It has been widely reproduced and it marked the beginning of the general acceptance of the three-cell model. The middle-latitude indirect cell has come to be known as the Ferrel cell since then. Figure 2.13 illustrates the traditional three-cell model and the new four-cell model. Their difference appears only in the polar region beyond 60°N, where an additional cell exists over the Arctic. Their climate effects should be completely different in the polar region.

Fig. 2.12 Climatic winds (m/s) at 2 m level and surface air temperature (K, the red line is 273 K) of a spring, b Summer, c Autumn, and d Winter in the NH polar region using a 30-year average (1981–2010) of the ERA-Interim product. Gray shading denotes land area. Sourced from Qian et al. (2016) © 2016 John Wiley & Sons, Inc., with permission
2.6 Eddy Heat Flux and Eddy Momentum Flux

In the NH, there should be two direct cells and two indirect cells along the meridional direction. The two indirect cells are associated with eddies. We here illustrate the eddy heat flux and eddy momentum flux. Monthly mean wind vector

$$
\mathbf{\tilde{V}}_m(\lambda, \varphi, p, t) = \mathbf{\tilde{u}}_m(\lambda, \varphi, p, t) + \mathbf{\tilde{v}}_m(\lambda, \varphi, p, t) + \mathbf{\tilde{k}\omega}_m(\lambda, \varphi, p, t)
$$

consists of three components: zonal wind velocity $u$, meridional wind velocity $v$, and vertical pressure velocity $\omega$ (positive downward) or z-vertical velocity $\mathbf{\tilde{k}\omega}_m(\lambda, \varphi, p, t)$ (positive upward). The zonally averaged monthly mean climatic wind vector $\mathbf{\tilde{V}}_m(\varphi, p)$ at a specific month of a year $t$ is calculated by

$$
\mathbf{\tilde{V}}_m(\varphi, p) = \sum_{t=1}^{N} \sum_{\lambda=1}^{K} \mathbf{\tilde{V}}_m(\lambda, \varphi, p, t)/(K \times N),
$$

where $N = 30$ years from 1981 to 2010, $K$ is the total grid number along a zonal circle, and $m$ represents the month. Similarly, the zonally averaged seasonal-mean and annual mean climatic wind vectors can also be calculated from the monthly mean climatic wind vector. The zonally averaged deviation of climatic monthly mean wind vector is

$$
\mathbf{\tilde{V}}_m^*(\lambda, \varphi, p) = \mathbf{\tilde{V}}_m(\lambda, \varphi, p) - \left[ \mathbf{\tilde{V}}_m(\varphi, p) \right].
$$

Fig. 2.13  a The traditional three-cell model and b the new four-cell model

2.6 Eddy Heat Flux and Eddy Momentum Flux

In the NH, there should be two direct cells and two indirect cells along the meridional direction. The two indirect cells are associated with eddies. We here illustrate the eddy heat flux and eddy momentum flux. Monthly mean wind vector $\mathbf{\tilde{V}}_m(\lambda, \varphi, p, t) = \mathbf{\tilde{u}}_m(\lambda, \varphi, p, t) + \mathbf{\tilde{v}}_m(\lambda, \varphi, p, t) + \mathbf{\tilde{k}\omega}_m(\lambda, \varphi, p, t)$ consists of three components: zonal wind velocity $u$, meridional wind velocity $v$, and vertical pressure velocity $\omega$ (positive downward) or z-vertical velocity $\mathbf{\tilde{k}\omega}_m(\lambda, \varphi, p, t)$ (positive upward). The zonally averaged monthly mean climatic wind vector $\mathbf{\tilde{V}}_m(\varphi, p)$ at a specific month of a year $t$ is calculated by

$$
\mathbf{\tilde{V}}_m(\varphi, p) = \sum_{t=1}^{N} \sum_{\lambda=1}^{K} \mathbf{\tilde{V}}_m(\lambda, \varphi, p, t)/(K \times N),
$$

where $N = 30$ years from 1981 to 2010, $K$ is the total grid number along a zonal circle, and $m$ represents the month. Similarly, the zonally averaged seasonal-mean and annual mean climatic wind vectors can also be calculated from the monthly mean climatic wind vector. The zonally averaged deviation of climatic monthly mean wind vector is

$$
\mathbf{\tilde{V}}_m^*(\lambda, \varphi, p) = \mathbf{\tilde{V}}_m(\lambda, \varphi, p) - \left[ \mathbf{\tilde{V}}_m(\varphi, p) \right].
$$

---

2 Modified article originally published in Qian et al. (2015a). The Arctic and Polar cells act on the Arctic sea ice variation. Tellus A, 67: 27692. Published with kind permission of © 2015 W. Qian et al. All Rights Reserved.
The two components, $\tilde{u}_m^*$ and $\tilde{v}_m^*$, can produce the stationary meridional eddy transport $[\tilde{v}_m^* \tilde{u}_m^*]$. It is well-known that the Hadley cell is thermally driven and its boundary is set by the conservation of angular momentum, while the Ferrel cell is eddy driven (Holton 2004). The zonally averaged momentum and thermodynamic energy equations for quasi-geostrophic motions on the middle latitude $\beta$ plane can be written as

$$\frac{\partial [\tilde{u}]}{\partial t} - f_0 [\tilde{v}] = -\frac{\partial [\tilde{u}^* \tilde{v}^*]}{\partial y} + [X], \quad (2.6.3)$$

$$\frac{\partial [\tilde{T}]}{\partial t} + N^2 HR^{-1} [\tilde{w}] = -\frac{\partial [\tilde{v}^* \tilde{T}^*]}{\partial y} + \frac{[J]}{c_p}, \quad (2.6.4)$$

where $[\tilde{u}]$, $[\tilde{v}]$ and $[\tilde{w}]$ are the zonally averaged climatic westerly, southerly and z-vertical components of velocity, $[\tilde{T}]$ is the zonally averaged climatic temperature, $[\tilde{v}_m^* \tilde{T}_m^*]$ and $[\tilde{v}^* \tilde{u}^*]$ are the zonally averaged stationary eddy heat fluxes and eddy momentum fluxes, $[X]$ and $[J]$ are the zonally averaged climatic turbulent drag and diabatic heating rate, $N$ is the buoyancy frequency defined by $N^2 \equiv \frac{k}{H} \left( \frac{\kappa T}{H} + \frac{dT}{dz} \right)$, in which $H$ is scale height, $R$ is the gas constant of dry air, and $c_p$ is the specific heat of constant pressure.

If $[\tilde{u}]$ and $[\tilde{T}]$ are steady, namely $\frac{\partial [\tilde{u}]}{\partial t} = \frac{\partial [\tilde{T}]}{\partial t} = 0$, the zonally averaged climatic direct circulation $([\tilde{v}]_d$ and $[\tilde{w}]_d)$ is mainly forced by the zonally averaged climatic turbulent drag and diabatic heating rate

$$-f_0 [\tilde{v}]_d = [X], \quad (2.6.5)$$

$$N^2 HR^{-1} [\tilde{w}]_d = \frac{[J]}{c_p}, \quad (2.6.6)$$

while the indirect circulation $([\tilde{v}]_i$ and $[\tilde{w}]_i$) is mainly driven by the zonally averaged stationary eddy heat fluxes and momentum fluxes

$$N^2 HR^{-1} [\tilde{w}]_i = -\frac{\partial [\tilde{v}^* \tilde{T}^*]}{\partial y} \quad (2.6.7)$$

$$f_0 [\tilde{v}]_i = \frac{\partial [\tilde{u}^* \tilde{v}^*]}{\partial y}. \quad (2.6.8)$$

The two terms, $[\tilde{v}^* \tilde{T}^*]$ and $[\tilde{u}^* \tilde{v}^*]$, can be calculated using reanalysis products while $[X]$ and $[J]$ are difficult to obtain directly. The four terms together contribute to form the total circulation.

Using four reanalysis products and one model simulation, we have revealed that there are four meridional cells in the NH from individual monthly mean, climatic
seasonal-mean flows, and MSFs (Qian et al. 2015a). The dynamical explanations and additional evidence will be given here to support the existence of the Arctic cell. It is noted that the Hadley, Ferrel and Polar cells have complex structures. They may split, shift, and merge in a complicated manner. Near the surface, topographic, frictional, and diabatic processes also affect these circulations.

The number of meridional cells existing in the NH troposphere can be illustrated by MSFs. The tropical Hadley cell is dynamically and thermally driven by the zonally averaged turbulent drag force $\overline{X}$ and diabatic heating rate $\overline{J}$ while the Ferrel cell is believed to be contributed mainly by the zonally averaged stationary eddy heat flux $\overline{\nabla^v \overline{T}^*}$ and eddy momentum flux $\overline{\nabla^u \overline{v}^*}$ (Holton 2004). Figure 2.14 shows the northward eddy heat flux $\overline{\nabla^v \overline{T}^*}$ calculated from the ERA-Interim product in October, November, December, and January. As expected, positive and strong centers of the eddy heat flux exist in the middle latitudes (30°N–60°N) while weak and negative centers are found in the tropics. From the negative weak center (H) to the positive strong center (F), $-\frac{\partial \overline{\nabla^v \overline{T}^*}}{\partial y} < 0$, i.e. $[\overline{w}]_i < 0$, so there is a descending branch (blue dashed arrow) between them. From the positive strong center (F) to a negative weak center (P), there is an ascending branch (red-dashed arrow) because $\frac{\partial \overline{\nabla^v \overline{T}^*}}{\partial y} > 0$, i.e. $[\overline{w}]_i > 0$. Thus, if the Hadley cell forms in the

![Fig. 2.14 Northward eddy heat flux ($\overline{\nabla^v \overline{T}^*}$), yellow-red shading for positive and green for negative, 2 °C m s$^{-1}$ interval in mid-low latitudes and 0.5 °C m s$^{-1}$ interval in the Arctic) calculated from a 30-year (1981–2010) average of ERA-Interim product in the NH in a October, b November, c December, and d January. Letters “H”, “F”, “P” and “A” are central locations of eddy circulation near the Hadley, Ferrel, Polar and Arctic cells respectively. Sourced from Qian et al. (2015a) © 2015 W. Qian et al., with permission](image-url)
tropics, the reversed and closed loop next to it should be the Ferrel cell in the middle latitudes. It can be identified that the Ferrel cell is mainly contributed by the stationary eddy heat fluxes.

In previous studies, no detailed comparison between the high and mid-low latitudes stationary eddy heat fluxes was made. As shown by Fig. 2.14, there are two pairs of negative and positive centers of eddy heat flux respectively in mid-low latitudes and high latitudes. The first pair is indicated by “H” and “F” while the second pair denoted by “P” and “A,” although the latter is weaker and smaller than the former. In Fig. 2.14, these four centers of eddy flux are near the centers of the Hadley, Ferrel, Polar, and Arctic cells.

Similarly, Fig. 2.15 shows the northward stationary eddy momentum flux $\left[ \tilde{v} \tilde{u}^* \right]$ in October, November, December, and January in the NH. From an ascending flow (red-dashed arrow) to a descending flow (blue dashed arrow), $\frac{\partial \tilde{u} \tilde{v}^*}{\partial y} > 0$, i.e. $\tilde{v}_y > 0$, so there is a southerly wind component (white dashed arrow). Otherwise, there should be a northerly component. There are also two pairs of cells described by the eddy momentum flux, respectively, in mid-low and high latitudes. The first pair indicated by “H” and “F” is, respectively, near the centers of the Hadley cell

![Fig. 2.15](image)

**Fig. 2.15** Same as in Fig. 2.14 except for the northward eddy momentum flux $\left[ \tilde{v} \tilde{u}^* \right]$ (yellow-red shading for positive and green for negative, 4 m$^2$ s$^{-2}$ interval in mid-low latitudes and 0.5 m$^2$ s$^{-2}$ interval in the Arctic) calculated from a 30-year (1981–2010) average of ERA-Interim product in the NH in a October, b November, c December, and d January. Sourced from Qian et al. (2015a) © 2015 W. Qian et al., with permission
and the Ferrel cell, while the second pair denoted by “P” and “A” is near the centers of the Polar cell and the Arctic cell. Similar distributions as shown in Figs. 2.14 and 2.15 can also be observed from the other three reanalysis products and the model simulation.

### 2.7 Global Eight Meridional Cells

Theoretically, there should be eight meridional cells globally. Using the four reanalysis products and a model simulation, Fig. 2.16 shows zonally averaged flow and westerly velocity climatologically during 1981–2010. For the westerly, all data show that there is only one center at the upper troposphere near 35°N while two centers exist, respectively, in 30°S and 50°S. It shows that the subtropical high-level jet stream and the polar frontal jet stream can be separated from the annual mean climatology in the SH, but they are not for the NH. The easterly is weak and unsteady below the Polar cell in the NH but is relative strong in the high latitudes of SH. We particularly concern the meridional cells in the SH. The two NCEP reanalysis products show that there are also four meridional cells in the SH. The fourth cell over the Antarctic has been referred to as the Antarctic cell (Qian et al. 2015b). The center of the Antarctic cell is located in the upper troposphere while the center of the Arctic cell is in the lower troposphere (Fig. 2.16a, b). But the Antarctic cell is not so clear from the analysis of other two products and model simulation (Fig. 2.16c–e).

The MSF analysis from all the five datasets shows that the intensities of the traditional three (Hadley, Ferrel and Polar) cells in the SH are stronger than those in the NH (Fig. 2.17). That may be the reason why the intensity of the Antarctic cell is so weak. This is because the Polar cell in the SH is largely stronger than the Antarctic cell. The intensity ratio of the Antarctic cell to the Polar cell in the SH is approximately 1:12 (Qian et al. 2015b).

Under the Antarctic cell, there should be northerly with convergence. Figure 2.18 shows climatic winds at 2 m level and surface air temperature in the SH high latitudes. The northerly is averagely larger than that of southerly wind beyond 80°S. The Antarctic is a continent surrounded by several peninsulas so the seasonal-cycle sea–land heating contrast forms zonal climatic deviation. Therefore, several pairs of northerly and southerly contrast exist over the Antarctic. The sea ice extent has seasonal variability with temperature.

Although we have not found a closed Antarctic cell from its annual mean climatology (Fig. 2.16c), it can be observed in an individual month. Figure 2.19 gives a profile of meridional cells in September 2004 in the SH. The four cells including the Antarctic cell are clearly observed in the SH.
Fig. 2.16  Same as in Fig. 2.5 except flow and zonal velocities between the two poles globally
Fig. 2.17  Same as in Fig. 2.7 except between the two poles globally. Symbols “H”, “F”, “P” and “A” indicate the central locations of the Hadley, Ferrel, Polar and Arctic (Antarctic) cells. The MSF interval is $10 \times 10^6$ ton s$^{-1}$ between 90°S–60°N while it is reduced to $1 \times 10^6$ ton s$^{-1}$ between 62.5°N–90°N. Red and blue arrows indicate ascending and descending pressure velocities ($-0.015$ Pa s$^{-1}$), respectively.
Fig. 2.18  Same as in Fig. 2.12 except climatic winds at 2 m level and surface air temperature in the SH polar region. The shading covers the maximum sea ice extent.

Fig. 2.19  Same as in Fig. 2.5 except flow and zonal velocities in September 2004.
2.8 Hemispheric Height and Vorticity

Are the four cells certainly existing in each hemisphere? If yes, they should be visible not only in wind field but also in zonally averaged pressure (geopotential height) and vorticity fields. Even at an isobaric level, we should also find their basic zonal features. We take the climatic annual mean height and vertical pressure velocity at 700 hPa and avoid the Antarctic terrain. In the SH, a zone with higher height gradient is concentrated in the middle latitudes, while in the Antarctic and tropics heights are relatively homogeneous (Fig. 2.20). This implies that there is strong westerly zone in the middle latitudes over the SH. Three zones of ascending velocity (blue shading) indicated by dashed line, dash-dotted line, and dotted line are clearly observed in the tropics, high latitude, and in the polar area. The zones of higher height gradient and ascending pressure velocity at 700 hPa should be symmetric in the NH (Fig. 2.20a). The asymmetric distribution is influenced by the sea–land contrast in the NH. Many troughs of height and individual ascending areas are thus exhibited. A fan-type area without the influence of sea–land contrast in the central North Pacific is taken to examine their zonal features. Three zones of ascending velocity can be comparable in the central North Pacific and the central South Pacific. Although the ascending area in the two polar areas is very small, it is the evidence to indicate the Arctic cell in the NH and the Antarctic cell in the SH.

On daily synoptic chart, there are always two low vortices near two polar regions and two longitudinal high zones in the subtropics, especially in the middle-upper troposphere. Figure 2.21 shows the climatic distribution of vorticity at 300 hPa in the NH in four seasons. In spring, positive (or negative) vorticity indicates that there

![Fig. 2.20](image-url) Climatic annual mean geopotential height (contour, 10 gpm) and vertical pressure velocity (0.05 Pa s\(^{-1}\)) at 700 hPa in a the NH and b the SH. *Shading grade* (0.05 Pa s\(^{-1}\) interval) and *dashed lines* denote the ascending and descending velocities, respectively. The heavy *blue line* denotes the height trough at 700 hPa. Heavy *blue dashed, dotted and dashed-dot lines* are axes of ascending velocity respectively in lower, high and middle latitudes. *Two red lines* cover the central North (South) Pacific between 150°E and 150°W. Sourced from Qian et al. (2015b) © Springer-Verlag Wien 2015, with permission
are two spiral bands extending from the north-polar region to middle and lower latitudes. The two spiral bands become weaker in summer, autumn and winter. The negative vorticity indicating the subtropical high at 300 hPa is the strongest in spring (Fig. 2.21a). For the two special days on March 4 and June 18, positive vorticity shows that there are about four spiral bands extending from the north-polar region to middle and lower latitudes (Fig. 2.22).

Differences are found in the SH, where there are three climatic spiral bands of positive vorticity, extending from the south-polar region to middle and lower latitudes. The two spiral bands become weaker in summer, autumn and winter. The negative vorticity indicating the subtropical high at 300 hPa is the strongest in spring (Fig. 2.21a). For the two special days on March 4 and June 18, positive vorticity shows that there are about four spiral bands extending from the north-polar region to middle and lower latitudes (Fig. 2.22).

**Fig. 2.21** Climatic vorticity (shading, $1 \times 10^{-5}$/s) at 300 hPa in the NH in boreal **a** spring, **b** summer, **c** autumn, and **d** winter. Heavy dashed line indicates the bands of positive vorticity
latitudes in four seasons (Fig. 2.23). For the two special days on March 4 and June 18, positive vorticity shows that there are four spiral bands (Fig. 2.24).

It is noted that spiral vorticity bands, extending from the two polar regions to middle and lower latitudes, exist in the two hemispheres. But their strengths and bands in the two hemispheres change with days and seasons. These structures of vorticity rely on topography, thermal contracts, and temporal periods as well. The spiral vorticity structures in the two hemispheres are similar to those of a super typhoon in Fig. 1.1a, the Milky Way galaxy in Fig. 1.1b and the mesoscale vortex (MV) in Fig. 1.6.

We also found that the spiral convective bands exist in extra-tropical cyclones. Figure 2.25a shows the surface pressure superimposed on combined reflectivity factor of radar echo at 0000 UTC 20 July 2016. Four spiral convective bands are clearly indicated by the combined reflectivity factor of radar echo at 0000 UTC 20 July 2016. This extra-tropical cyclone caused 130 deaths and 110 missed. The four spiral convective bands of reflectivity factor (Fig. 2.25a) are consistent with the four shears of anomalous flow at 700 hPa (Fig. 2.25b).

2.9 An Aqua Control Experiment

The topography distribution is asymmetric in the Earth’s two polar areas. We can always find the Arctic cell in the NH but the Antarctic cell is not always observed. So, are the two cells associated with the topography? We here give the results of an aqua control experiment of CCSM4 model. It is the fourth version of the...
Community Climate System Model (CCSM) consisting of atmosphere, land, ocean, and sea ice components that are linked through a coupler that exchanges state information and fluxes between the components (Gent et al. 2011). An aqua control experiment removed land and sea ice components and only remained ocean. The data of the aqua control experiment is derived from website www.earthsystemgrid.org/dataset/cmip5.output1.NCAR.CCSM4.aquaControl.mon.atmos.Amon.r1i1p1.html#variablesTab.

Fig. 2.23 Same as in Fig. 2.21 except the climatic vorticity at 300 hPa in the SH in boreal a spring, b summer, c autumn, and d winter. Heavy dashed line indicates the bands of positive vorticity.
The zonally averaged flow and zonal velocities by the five-year mean are given in Fig. 2.26. The meridional cells are clearly found in the SH with the Antarctic cell at the middle-upper troposphere. In the NH, the fourth circulation is not closed but the ascending flow is observed beyond 80°N. Five ascending zones and
four descending zones are well simulated in the aqua control experiment but the centers and intensities of circulation are not symmetric in the two hemispheres. This may be caused by eddies. The spatial distribution of MSF is shown in Fig. 2.27. Although there are eight areas of MSF, their intensities are really not symmetric.

For the aqua control experiment, northward eddy heat flux is shown in Fig. 2.28. The maximum of eddy heat flux is found over the indirect Ferrel cell. Its center shifts northward to 65°N in Fig. 2.28b when comparing with reanalysis in Fig. 2.14b. The intensities of northward eddy heat flux are not stable to indicate the Polar and Arctic cells. This situation is also found in the northward eddy momentum flux (Fig. 2.29). Two positive areas of the northward eddy momentum flux are clearly observed in Fig. 2.29c, d, but not in Fig. 2.29a, b. This indicates that the eddies are also frequently produced in the aqua experiment. The intensity of eddies is not steady through the model’s forcing and the boundary condition are determined in symmetry in the two hemispheres. This difference indicates that it is difficult to obtain a climatic state from the aqua model.
2.9 An Aqua Control Experiment

Fig. 2.28 Same as Fig. 2.14 except the result (northward eddy heat flux) of an aqua control experiment in a October, b November, c December, and d January

Fig. 2.29 Same as Fig. 2.15 except the result (northward eddy momentum flux) of an aqua control experiment in a October, b November, c December, and d January
Questions

1. Give some examples of diurnal-cycle and seasonal-cycle general circulation.
2. What are the climatic differences in the two hemispheres between the three-cell model and the four-cell model?
3. Why can an aqua control experiment produce asymmetric meridional cells in the two hemispheres?
4. Why did V. Bjerknes propose the four-cell model in 1921? How to confirm that the four-cell model is correct?

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