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To cite this article: Ruizhe Liu 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **658** 012003

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# Latest Trends of Atmospheric Cells under Global Warming

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**Abstract** Four atmospheric cells, Hadley cell, Ferrel cell, polar cell and Walker cell, were introduced and latest trends of Hadley cell and Walker cell were given in this paper. From previous studies, a significant intensification of the Hadley cell is shown statistically by the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP/NCAR), NCEP1 and the European Center for Medium-Range Weather Forecast (ECMWF) Re-analyses (ERA40). In contrast, no clear change in the period is shown in the NCEP2 reanalysis while great differences of the structure of the Hadley cell from ECMWF and NCEP/NCAR reanalyses are shown. A poleward expansion and strong weakening of the Hadley cell was found given the increased greenhouse gas (GHG) forcing. The inhomogeneous sea surface temperature (SST) change has become the most important factor on interannual timescales. The stronger Hadley cell will happen when the more central Pacific El Niño events happen. The stronger the Walker cell is, the more frequently the eastern Pacific El Niño events occur. In this paper, the changes of the cells under global warming are discussed. Global warming may cause the width of the Hadley cell to increase, exacerbating global warming in turn. Stronger Walker cell leads to El Niño happening more frequently, doing harm to agriculture production.

## 1. Introduction

In 1865, U.S. meteorologist William Ferrel proposed a three-cell model to explain how the atmosphere moves [1]. According to this model, each hemisphere consists of three distinct cells (circulation): Hadley cell (circulation), Ferrel cell (circulation) and polar cell (circulation). Among them, the Hadley cell plays a heat-driven role in the air between the tropics and subtropical latitudes. The Ferrel cell covers air in the middle latitudes and the polar cell circulates air in the high latitudes. Each cell is composed of a belt of sinking air with surface high pressure, one zone of upward air with low surface air pressure, an airflow zone with high pressure to the west with low pressure, and a wind zone in the upper atmosphere where the air flows from the zone of upward air to the zone of downward air. Oceans play an important role in the transfer of moisture and heat to the atmosphere. The motions and temperature changes of oceans are exceedingly slower than those in the atmosphere, which is used to forecast long-term climate. Some examinations on significant relationships between the ocean and the atmosphere such as La Niña and El Niño are closely linked with the Walker cell. In recent years, trends of atmospheric cells are causing concern on the development of global warming. In this paper, the latest studies are mentioned and objects of research are discussed.

## 2. The Hadley Cell

The air at the equator tends to diverge toward the poles and move upward, creating a zone of low pressure at the equator called the intertropical convergence zone (ITCZ) [2]. In the upper troposphere, the air within the Hadley cell expands poleward to the subtropical zone (20° to 30° latitude), acquiring



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increasing west-to-east motion. Upon reaching the subtropics, the air in the Hadley cell moves downward the surface to form large bands of high surface pressure called subtropical highs.

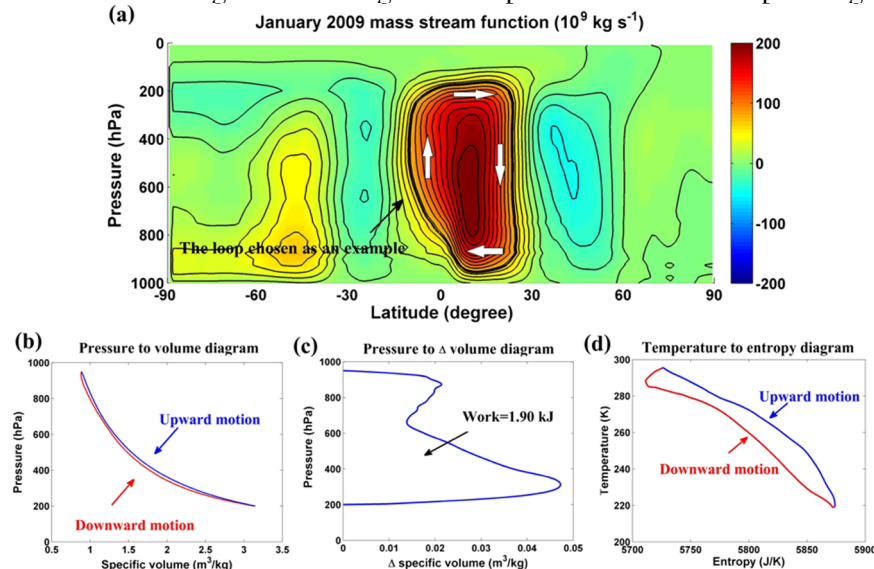


Figure.1 The average meridional atmospheric cell in January 2009. (a) Color shading refers to the mass streamfunction values of  $10^9 \text{ kg s}^{-1}$ . The loop circled in a thick black sign with a constant mass streamfunction value ( $70 \times 10^9 \text{ kg s}^{-1}$ ) is chosen, where white arrows illustrate the direction of the air motion. The characters of an air parcel with the example mass streamfunction value are shown in the (b) P-V, (c) P- $\Delta V$ , and (d) T-S diagrams[2].

Huang et al. (2014) selected a segment shown in Fig.1a to study the changes in the process of traveling around one loop of the Hadley cell. The pressure-volume diagram in Fig.1b presents properties of 1kg of air completing travel around this loop. At a certain pressure, the specific volume (red line) of the air parcel with downward motion is always lower than the one of upward motion (blue line). The specific volume change between the ascending motion and the descending motion is identified on a horizontal axis in Fig. 1c which presents the corresponding pressure- $\Delta$ volume (P- $\Delta V$ ) diagram. The temperature-entropy (T-S) diagram (Fig.1d) illustrates the changes in specific entropy and temperature over a thermodynamic cycle. The temperature-entropy cycle corresponding to the downward motion (the red portion) is quite close to the cycle corresponding to the descending motion (the blue portion), presenting a small thermodynamic efficiency.

The investigations of the latest trend of the Hadley cell under the recent warming climate are collected [3][4]. The evidence of variability in decades of the radiation budget of the tropical atmosphere is provided through recent satellite observations [3]. The observations suggest that the long-wave radiation from Earth increased by  $5 \text{ W m}^{-2}$  while the short-wave reflective radiation reduced by approximately  $2 \text{ W m}^{-2}$  from 1985 to 2000. These changes are related to intensifying circulation in the tropic atmosphere, especially the Hadley cell. The increasing upward motion in stronger tropical motion would cause an increase of upper-level humidity and the cloudiness at the equator and a decreasing trend of cloudiness of the subtropical area, however. NCEP1 and ERA40, two major reanalyses projects, suggest that the Hadley cell tends to be stronger during the last decades, which is consistent with the observation from the satellite. (Table 1) A significant intensification of the Hadley cell in that period is shown statistically by NCEP/NCAR and ECMWF reanalyses. In contrast, no clear change in the period is shown in the NCEP2 reanalysis while great differences of the structure of the Hadley cell from ECMWF and NCEP/NCAR reanalyses are shown. The same result is also shown in the global rawinsonde observations. Hence, some existing questions make the signal be inconsistent with all of the used data sets. This should be considered to obtain long-term trends of the Hadley cell.

Nguyen indicates that all reanalyses to the Hadley cell suggest a significant expansion in both hemispheres at an average rate of  $0.55^\circ \text{ decade}^{-1}$  during summer and autumn [4]. However, intensifying

inconsistency exists among the datasets particularly. The influence of annular modes and El Niño-Southern Oscillation(ENSO) to the Hadley cell is provided by the correlations between variability in tropical and extratropical large-scale motion and the Hadley cell. A shrink trend of the cell appears in the low phase of the annular modes and the warm phase of ENSO while there would be an expanding trend in the cold phase of ENSO and the high phase of the annular modes. ENSO appears to only lead to the intensity during winter for the northern cell and during spring for the southern hemisphere.

Table.1 Reanalysis dataset mentioned in this paper. [4]

	Data	Source	Length	Reference	Temporal resolution	Spatial resolution
NCEP-1	National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) Global Reanalysis 1	NCEP-NCAR	1958–present	Kalnay et al. 1996	6 h	$2.5^{\circ} \times 2.5^{\circ} \times 17$ levels
NCEP-2	NCEP/Department of Energy Global Reanalysis 2	NCEP-DOE	1979–present	Kanamitsu et al. 2002	6 h	$2.5^{\circ} \times 2.5^{\circ} \times 17$ levels
CFSR	Climate Forecast System Reanalysis	NCEP	1979–present	Saha et al. 2010	1 h	$0.5^{\circ} \times 0.5^{\circ} \times 36$ levels
ERA-40	European Centre for Medium-Range Weather Forecasts (ECMWF) data 40-yr ECMWF Re-Analysis	ECMWF	1957–2002	Uppala et al. 2005	6 h	$2.5^{\circ} \times 2.5^{\circ} \times 23$ levels
ERA-Interim	ECMWF Interim Re-Analysis	ECMWF	1979–present	Dee et al. 2011	6 h	$0.75^{\circ} \times 0.75^{\circ} \times 37$ levels
MERRA	Modern Era Retrospective-Analysis for Research and Applications	NASA	1979–2009	Rienecker et al. 2011	3 h	$2/3^{\circ} \times 1/2^{\circ} \times 42$ levels
JRA-25	Japanese 25-yr Reanalysis	JMA	1979–2009	Onogi et al. 2007	6 h	$1.25^{\circ} \times 1.25^{\circ} \times 23$ levels
20CR	National Oceanic and Atmospheric Administration (NOAA)-Cooperative Institute for Research in Environmental Sciences (CIRES) Twentieth-Century Reanalysis version 2	NOAA-CIRES	1871–2008	Compo et al. 2011	6 h	$2^{\circ} \times 2^{\circ} \times 24$ levels

In simulations of the 21th century through the A2 scenario of the IPCC AR4 project, a poleward expansion and strong weakening of the Hadley cell was found given the increased greenhouse gas(GHG) forcing.[5] Lu indicates that the width of the Hadley cell on both longer and interannual time scales affect the extratropical tropopause height, a good factor of the gross static stability. Baroclinic instability as a critical parameter controlling the limits of the outer boundaries of the Hadley cell is suppressed when the gross stability around the subtropics increases. The extratropical stabilization makes the thermally driven cell reach higher latitudes by inhibiting breakdown of the cell, allowing the poleward expansion of the Hadley cell. However, the conclusion based on this simple scaling analysis is tentative because only the annual means analyzed are provided and the assumption exists in the process.

### 3. Ferrel Cell and Polar Cell

According to the three-cell model, the Ferrel cell accounts for the distribution and movement of air flanking the Hadley cell, between the subtropical higher belt and lower belt in the subpolar area, or the zones with low pressure. In the Northern Hemisphere, the air near the equator side of the Ferrel cell is propelled poleward by the pressure gradient force and produces a wind belt called westerlies in the influence of Coriolis force. Likewise, air flowing northward away from the Southern Hemisphere subtropical high can also create a zone of westerlies as a result of a substantial deflection. Unlike the Hadley cell, the differences in heating of the Ferrel Cell is caused by the Hadley cell and polar cell. In other word, it is a thermally indirect cell. Baroclinicity donates the region of the Ferrel cell while it hardly occurs in the zone of the Hadley cell.

In Fig.2a, a specific segment accounted for the Ferrel cell is selected with a constant mass stream function value of  $-20 \times 10^{-9} \text{kg/s}$ . The diagram with the relationship of pressure-volume in Fig. 2b presents properties of 1kg of air completing travel around this loop. In contrast to the Hadley circulation, the

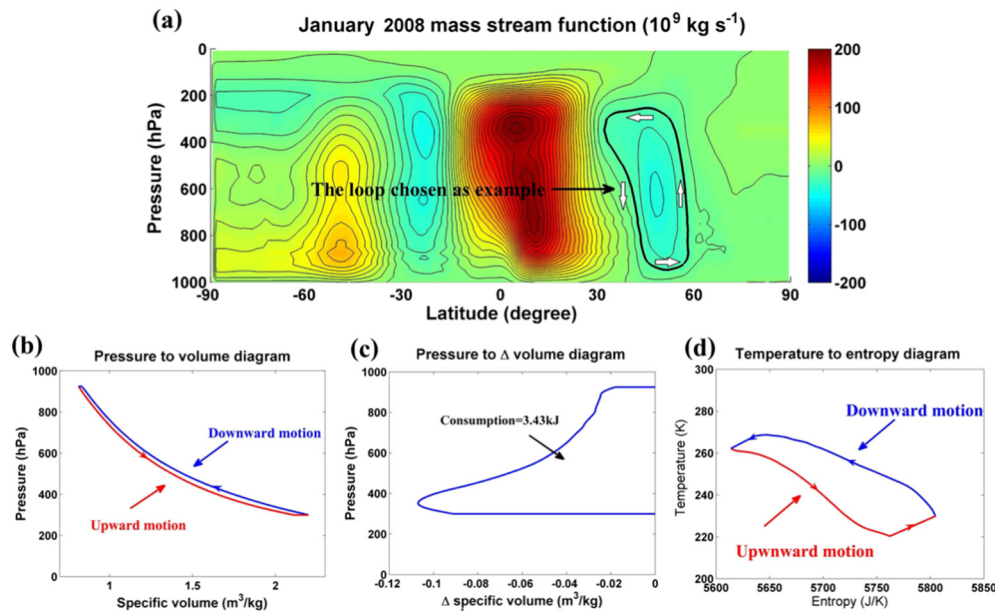


Figure.2 As in Fig. 1, but for an emphasis on the meridional Ferrel cell in January 2008 with the loop circled in thick black sign having a streamfunction value of  $-20 \times 10^9 \text{ kg s}^{-1}$ . [2] specific volume of upward motion (red line) is always smaller than the one (blue line) when the air parcel is experiencing downward motion. Fig. 2c presents the corresponding pressure– $\Delta$ volume ( $P-\Delta V$ ) diagram. The temperature–entropy ( $T-S$ ) diagram (Fig. 2d) illustrates the changes in specific entropy and temperature over a thermodynamic cycle, which is much rounder than Fig. 1d. It indicates the greater efficiency of consumption of kinetic energy in the Ferrel cell, given the stronger contrast on temperature at midlatitudes. Hence, the Ferrel cell has an opposite effect to the Hadley cell that converts thermal heat to kinetic energy. Ferrel cell is thought to play an important role in modulating mid and high latitude climate, however limited investigation on examining the variability of the Ferrel cell comparing to extensive effort on the Hadley cell.

In the polar cell, the air flows from the polar highs to the subpolar lows. It is also a thermally direct cell like the Hadley cells. The relatively warmer air at subpolar locations causes lower surface pressure and rising trend. Quite cold conditions at both poles make the low-level movement toward the equator with high surface pressure. Huang et al. indicate that the polar meridional is so weak that its effect cannot be computed as the procedure adopted by Hadley and Ferrel cells. Given that it's a thermally direct cell, thus it could create a net source of kinetic energy.

#### 4. Walker cell

Unlike the Hadley cells, the Walker cell is oriented east-west (zonal) in the tropical Pacific. It moves upward over the western Pacific and downward over the eastern Pacific, exerting an influence on the global climate through atmospheric teleconnections. Furthermore, the Walker cell affects socioeconomic status including ecosystems, severe weather and agricultural production. Phillips finds that El Niño can make the maize yield lower relative to neutral years [6]. Given the enhanced plant productivity due to ENSO-induced pulses, open dryland ecosystem could be changed into permanent woodland [7]. Callaghan and Power indicates that the decline of tropical cyclones landfall over eastern Australia can also partially account for the weakening of the Walker cell [8].

Plenty of factors could influence the intensity of Walker cell containing the atmospheric homogeneous warming with height, the inhomogeneous sea surface temperature (SST) change and the homogeneous warming in internal variability including the Pacific decadal oscillation, interdecadal Pacific oscillation, and the El Niño–Southern oscillation. [9] Among them, given the spatially inhomogeneous SST structure of the tropical Pacific basin strongly interacts with the overlying atmospheric



cell via atmosphere-ocean coupled processes, it has become the most important factor on interannual timescales. Corresponding to global warming, the role for the Walker cell leading to SST changes has been suggested through the Coupled Model Intercomparison Project Phase 5 (CMIP5) and 3 (CMIP3) climate models. It is estimated that  $50\% \pm 20\%$  of the weakening of the Walker cell observed in the 20th century accounted for external forcing with internal climate variability. At the same time, recent studies suggest that regional changes in the land-sea thermal contrast, for example, a heating over the land associated to the ocean lead to the spatially inhomogeneous temperature changes. Hence, the Walker cell was influenced by the large-scale contrast in sea level pressure in the tropics.

### 5. Hadley cell and Walker cell

Two types of interannual SST variability, eastern Pacific type and central Pacific type, happen in the tropical Pacific.[10][11] The anomaly center exists in the central Pacific is central Pacific type while the anomaly center exists in the eastern Pacific type is eastern Pacific type. The dominance of central Pacific type and eastern Pacific type was dependent on the intensity of the Hadley and Walker cell. The increasing influence on tropical central Pacific SST variations was related to the strengthening of the Hadley cell. The stronger Hadley cell will happen when the more central Pacific El Niño events happen. The CP El Niño development depends on the atmospheric forcing formed through the downward part of the Hadley cell over the subtropical area. Given the seasonal footprint mechanism, the effect of the subtropical atmospheric forcing in the central Pacific at the equator is extended via the wind-evaporation-SST(WES) feedback mechanism. Furthermore, the seasonal foot-printing mechanism as well as the zonal advection feedback including oceanic dynamics is a critical factor in exciting the central Pacific El Niño. The interaction between the thermocline at the equator and the Walker cell is invoked by a Bjerknes feedback mechanism, which develops the EP El Niño. The stronger Walker cell can cause more influentially the EP El Niño events.

### 6. Conclusion

An introduction to atmospheric cells—Hadley cell, Ferrel cell, polar cell and walker cell—and latest trends of Hadley cell and Walker cell under global warming was given. A significant intensification of the Hadley cell in that period is shown statistically by NCEP/NCAR, NCEP1, ERA40 and ECMWF reanalyses. In contrast, no clear change in the period is shown in the NCEP2 reanalysis while great differences of the structure of the Hadley cell from ECMWF and NCEP/NCAR reanalyses are shown. A poleward expansion and strong weakening of the Hadley cell was found given the increased greenhouse gas(GHG) forcing. the inhomogeneous sea surface temperature(SST) change has become the most important factor on interannual timescales. The stronger Hadley cell will happen when the more central Pacific El Niño events happen. The stronger the Walker cell is, the more frequently the eastern Pacific El Niño events occur. Global warming may cause the width of the Hadley cell to increase, exacerbating global warming in turn. Stronger Walker cell lead El Niño happens more frequently, doing harm to agriculture production.

Though the three-model hardly adequately explains the patterns in the real world, some important clues still have been found. Global warming may cause the width of the Hadley cell to increase. With the expansion of the Hadley cell, the heat driven can influence more areas in the relatively high latitudes and the areas of the Ferrel cell and polar cell will decrease. Furthermore, The effect of global warming will have a further development and then continue to expand the width of the Hadley cell. Hence, global warming will develop more rapidly in this cycle pattern, making us be aware of the extreme change and come up with some ideas such as greenhouse gases(GHGs) limitation, or advanced technologies with less emission of GHGs to stop it. As for the Walker cell, stronger Walker cell lead El Niño to happen more frequently. Although the cell is becoming weaker, global warming would make the El Niño stronger and more frequent. Terrestrial ecosystem prediction in long-term trends is complicated to do in the influence of the El Niño, though it can make dryland change into woodland. Less agricultural production is likely to happen with the El Niño coming, making the population not only be in severe weather but also in starvation conditions.

I want to show deep gratitude to prof. Wenhong Li and my assistant teacher, who let me learn about atmosphere cell. Furthermore, thank her advice and textbook when I met trouble during finishing this paper.

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