Introduction

Our understanding of the global circulation of the atmosphere is very incomplete, but improving at a brisk pace. The last several decades have brought huge advances. During the past 20 years or so, global circulation research has become a sub-discipline within the much broader field of climate research. At the same time, the scientific foundations of global circulation research have become deeper and more intellectually challenging.

Overwhelming evidence shows that the Earth’s climate is rapidly changing due to the accumulation of anthropogenic greenhouse gases in the atmosphere (IPCC, 2013). As a result, the global circulation of the atmosphere will be significantly different in the coming decades, and some trends have already become apparent in the observations. By studying the response of the circulation to the ongoing anthropogenic perturbation, we will learn more about how the circulation works. This closing chapter briefly discusses current trends and expectations for the future.

Temperature

The most widely known climate trend is a roughly 1 K warming of the globally averaged surface air temperature since the 19th century. The near-surface warming is strongest near the poles, especially the North Pole, which implies that the low-level meridional temperature gradient is becoming weaker, especially in the Northern Hemisphere. The near-surface warming is strongest in the winter, and greater at night than during the day (Vinnikov et al., 2002; Vose et al., 2005).

The troposphere above the surface is also warming. In the tropics, where the lapse rate is constrained by convection to be close to its moist-adiabatic value (Chapter 6), an increase in the surface temperature is expected to be accompanied by a larger increase in the troposphere above, simply because the moist adiabatic lapse rate is smaller at warmer temperatures (see Fig. 6.1).

At the same time, the stratosphere is cooling, much faster than the troposphere is warming. The cooling of the stratosphere is a direct radiative consequence of the increasing CO₂ concentration of the atmosphere.

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The height of the tropopause is increasing (e.g., Santer et al., 2003; Añel et al., 2006; Lorenz and DeWeaver, 2007), and tropical tropopause temperatures are decreasing (Wang et al., 2012). An increase in the height of the tropopause is consistent with a cooling of the stratosphere, and also with an increase in the heights of the tops of deep convective clouds.

**Hydrologic cycle**

As mentioned in Chapter 2, for typical current surface temperatures the saturation vapor pressure increases at the rate of 7% per Kelvin (Held and Soden, 2006). The slope will become even larger in a future, warmer climate. Because the actual vapor pressure near the surface is closely coupled to the saturation vapor pressure at the sea surface, a warmer atmosphere will contain much more water vapor. Observations show an upward trend in the atmosphere’s water vapor content over the past few decades (Wentz et al., 2007; Jin et al., 2007).

On the other hand, the globally averaged rate of precipitation is strongly linked to the rate at which the atmosphere cools radiatively; again, this was mentioned in Chapter 2. An increase in temperature, water vapor, and CO$_2$ concentrations favors stronger atmospheric emission of infrared radiation, i.e., more rapid radiative cooling. The precipitation rate is also constrained by supply of energy available to evaporate water from the surface. An increased downward emission of radiation to the Earth’s surface can encourage faster evaporation, and is therefore consistent with stronger precipitation.

For these reasons, the hydrologic cycle is expected to run faster in a warmer climate, and observations suggest that this is already occurring (e.g., Durack and Wijffels, 2010; Durack et al., 2012).

**Winds**

As discussed in Chapter 2, we can consider that the vigor of the global circulation is that required to maintain the speed of the hydrologic cycle, so that the global energy budgets of the atmosphere and surface can be balanced by phase changes of water.

Because the hydrologic cycle is accelerating more slowly than the water vapor content of the atmosphere is increasing, the overall strength of the circulation is expected to decrease (Held and Soden, 2006). In particular, the Hadley cells, the Walker circulation and the monsoon circulations are expected to slow down, even though rainfall is expected to increase in the ITCZ and the monsoons regions (Held and Soden, 2006; Hsu and Li, 2012; Hsu et al., 2013; Kitoh et al., 2013).

Notwithstanding the theory, observations show that the Hadley and Walker circulations have intensified during the first decade of the twenty-first century (l’Heureaux et al., 2013; England et al., 2014). This intensification is believed to be associated with a low-frequency mode of coupled ocean-atmosphere variability called the Interdecadal Pacific Oscillation (e.g., Alexander and Deser, 1995; Meehl et al., 2013).

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Observations show that the Hadley cell has expanded toward the poles in recent decades (e.g., Seidel and Randel, 2007; Seidel et al., 2008; Hu and Fu, 2007; Lu et al., 2009). As discussed in Chapter 5, theory suggests that the width of the Hadley cell is determined by the thermal Rossby number, which depends on the meridional temperature gradient. According to the theory, the expected reduction in the tropospheric meridional temperature gradient would favor a widening of the Hadley cell, as observed.

As discussed in Chapters 3 and 5, conservation of angular momentum suggests that a widening of the Hadley cell should be accompanied by a poleward shift and intensification of the subtropical jet streams (Chapter 5). Such changes have been observed (Strong and Davis, 2007; Barton and Ellis, 2009; Fu and Lin, 2011). In addition, the North Atlantic storm track is shifting poleward (Cornes and Jones, 2011), as was predicted in simulations of a future warmer climate (Change et al., 2012).

As discussed in Chapter 8, the physical processes that give rise to the MJO are still controversial, and many of today’s global atmospheric models have difficulty in simulating the MJO. Climate-change simulations with models that are able to simulate the present-day MJO with some fidelity suggest that the MJO will be much more active in the warmer, more humid world of the future (e.g., Schubert et al., 2013; Arnold et al., 2014). If true, this will have major consequences for the tropical climate system and the people who live in that part of the world.

**Methods**

Numerical modeling of the global circulation is still a rapidly changing field, but it has reached a level of maturity. It is now the standard tool for medium-range weather forecasting, climate-change simulations, and a wide range of academic studies. We are entering the era of cloud-resolving global atmospheric models, with horizontal resolutions of just a few kilometers.

The atmospheres of the planets and moons of our solar system are increasingly well observed. Our understanding of the Earth’s atmosphere is challenged as we attempt to apply it to these other planetary circulations. Over the past decade, many planets have been detected outside our solar system. Eventually we will have information about a very large number of planetary atmospheres, some of which may resemble our own more than any of the other planets in our solar system.