Journal of Hydro-environment Research 21 (2018) 109–117

Contents lists available at ScienceDirect

Journal of Hydro-environment Research

journal homepage: www.elsevier.com/locate/jher

Study on sky rivers: Concept, theory, and implications

Guangqian Wang[a,b,*], Deyu Zhong[a,b,*], Tiejian Li[a,b], Yu Zhang[b], Changqing Meng[b], Mingxi Zhang[b], Xiaolong Song[b], Jiahua Wei[a,b], Yuefei Huang[b]

[a] *Joint-Sponsored State Key Laboratory of Plateau Ecology and Agriculture, Qinghai University, Xining 810016, China*
[b] *State Key Laboratory of Hydro-science and Engineering, Tsinghua University, Beijing 100084, China*

ARTICLE INFO

Keywords:
Sky river
Atmospheric water
Water cycle
Characteristic surface

ABSTRACT

Presented in this paper is an introduction to the study on sky rivers, especially the concept, theory, and implications. A sky river is in essence a generalization for a rich variety of meteorological systems including tropical cyclones, extratropical frontal cyclones, shear lines and others from the viewpoint of fluid mechanics. All these meteorological systems share a common feature that, there exists a contacting surface between two air masses with contrasting velocities, temperatures, humidity, and pressures. Under the forces caused by large gradients of state variables normal to the contacting surfaces and other forces, concentrated water vapor flows along paths on the contacting surfaces like river channels on earth surface, characterized by cloud and precipitation processes along the paths. A simplified and direct approach to identify the sky rivers is proposed on the basis of their physical interpretation. Results show that the sky rivers globally exist and have close relations with precipitation. In mathematics, the sky rivers are the discontinuity surfaces of the governing equations for atmospheric flows, and they are formulated in this study as the characteristic surfaces where the characteristic values are real and the derivatives normal to the surface do not exist by means of general theory for partial differential equations to provide a description for time–space evolution of the sky rivers. Finally, future study areas regarding the sky rivers are discussed.

1. Introduction

Water affects every aspect of life on Earth. Development, utilization, and protection of water resources have long been the central tasks of human societies. However, shortage of fresh water is a serious natural and social problem. According to the report by World Resources Institute (Luo et al., 2015), currently 33 countries of the world are facing extremely high water stress, and this number will be expanded to as much as 59 in 2040. In China, water issues are even more complicated. The country is now suffering from severe water shortage, with the 28% of the world average per capita availability of water resources and 75% of the world average per capita annual consumption of water resources to feed 1/5 of the world's population. Meanwhile, the traditional water management techniques now almost reach their upper limits. For example, more than 85,000 reservoirs have been completed in China since the 1950s (Yu, 2011). Particularly, in the basin of the Yellow River, the total reservoir capacity exceeds annual runoff (Xia et al., 2014). Therefore, seeking new measures to alleviate water stress is of significance for the countries suffered from severe shortage of water resources.

Development of atmospheric water resources may be a potential solution. Since 1950s, numerous studies and experiments of cloud-water utilization have been conducted in China and the rest of the world to alleviate drought issues. But it is far from efficient. For instance, the total incoming water vapor of China is close to 20 trillion m^3 per year (Cai, 2008), approximately 4 times of average annual rainfall; while the increment of water resources by cloud-water utilization is only about 50 billion m^3 (National Development and Reform Commission, China Meteorological Administration, 2014). In the current practice, atmospheric water resources are still classified as unconventional water resources and cannot be fully brought into the water resources management systems, and thus resulting in the failure of coupling with conventional surface water resources to achieve a comprehensive development of atmosphere-surface water resource.

Therefore, what are the key factors that lead to the difficulty in exploiting atmospheric water resources? In addition to developing efficient cloud-seeding techniques, it is necessary to recognize that there still exist several theoretical issues that are not completely resolved in the utilization of atmospheric water. For instance, as a type of natural water materials, what makes atmospheric water as a resource must be

---

* Corresponding authors at: River Research Institute, Tsinghua University, Beijing 100084, China.
E-mail addresses: dhhwgq@tsinghua.edu.cn (G. Wang), zhongdy@tsinghua.edu.cn (D. Zhong).

https://doi.org/10.1016/j.jher.2018.09.003

well-defined. However, the stochastic feature of cloud and precipitation processes causes difficulties in providing a reasonable definition of atmospheric water resources. It seems like a meteorological or hydrological issue but actually beyond that. First, it is necessary to understand which part of atmospheric water could be potentially transformed into surface water, and then analyze its temporal and spatial variation. Here, our primary interest is not only on short-term processes, such as synoptic processes, but also on the long-term (i.e. usually on a century scale) evolution dynamics spanning the life cycles of water resource configuration infrastructure. Second, as a natural resource like others, the ownership of atmospheric water resource must be well clarified. For this purpose, we have to figure out whether there exists a concept of "basin" in the atmospheric water resources. And if so, where is the "basin"? How do atmospheric water flow between the "basins"? Obviously, these two problems make the atmospheric water resources development no longer a simple meteorological issue.

Numerous studies have been conducted regarding the mechanisms of atmospheric water vapor transport (see the comprehensive review by Gimeno et al., 2014), and have achieved great progress, especially since the concept of "Atmospheric Rivers" (ARs) was raised (Zhu and Newell, 1998). Most studies focused on the meteorological processes related to the occurrence of ARs; a few works are devoted to exploring the role of ARs in extreme events (extreme precipitation and flood). Indeed, studies on ARs may help shed light on the transport of atmospheric water; however, as explained before, it is still insufficient to have a full picture of long-term cycle of the atmospheric water resource.

Within this context, we proposed a concept of "Sky River" in 2015 (Wang et al., 2016) to explain how the atmospheric water could be utilized. Presented in this paper is a follow-up work reported by Wang et al. (2016). In this paper, we begin with the description of the concept of the sky rivers (Section 2). In Section 3, a simple method to identify the global sky rivers is proposed, followed by a case study of the extreme precipitation event occurred in Beijing on July 21, 2012 to illustrate the relationship between the sky rivers and precipitation. Then mathematical formulation of the sky rivers is given in Section 4 to describe the dynamics of the sky rivers and the simplified equations are also given to describe the major features of the governing equations of the sky rivers. Finally, a short summary of this paper and the future study as well as its implications are presented in Section 5.

2. Concept of sky river

It is no doubt that state-of-the-art research concerning each of the meteorological phenomena is highly valuable in weather forecasting, additional to its scientific importance in understanding the nature we live on. However, when we consider the cloud and precipitation processes from the angle of global water cycle using the principles of fluid mechanics, our immediate concern is not only on the details of the phenomena, but also on their general behaviors and underlying mechanisms as well.

If we take a more careful examination into the mechanisms related to cloud processes and possible precipitation as the results of tropical cyclones, extratropical cyclones or frontal cyclones, and gust fronts in deep convections, regardless of the differences in their names, their occurrence frequencies, and their temporal and spatial scales, we may learn from the descriptions in text books of meteorology that they all are marked by a most common feature. That is, all of them are closely related to the contacts of air masses within the fields of density, velocity, temperature, pressure, and humidity different from each other (Wallace and Hobbs, 2006; Barry and Chorley, 2009). Furthermore, in every case when two different air masses meet each other in the atmospheric flows, the ascending of the warm and moist air mass usually causes water vapor to condense and results in a variety of types of clouds and possible rainfalls.

For instance, extratropical fronts or frontal cyclones are typical synoptic phenomena in atmospheric flows due to the contact of two air masses with different temperature, velocity, pressure, and humidity. Baroclinic instability leads to ageostrophic vertical circulation and accompanied updraft of warm air at frontal zones. Meanwhile, the airflows there are affected considerably by the temperature gradient and thus geostrophic wind is significantly changed by the wind shear due to thermal wind, resulting in concentrated water vapor flows along the lines of fronts toward the lows, which are usually referred to as Prefrontal Low Level Jets (FLLJ) (Carbone, 1982) with nearly saturated air flows accompanied by heavy rainfalls (Bao et al., 2006; Cordeira et al., 2013). Tropical cyclone is another example of which high rate of evaporation occurs in the vicinity of the "eyewall", then warm and moist air ascends to meet ambient cooler air, which is also the key mechanism to develop intense storms (Anthes, 2016). The rise and sink of air at the "eyewall" and "eye" of a tropical cyclone can also be treated as a contacting system of different air masses.

Therefore, it can be concluded that typical phenomena regarding cloud and precipitation processes result from the contacts of different air masses, no matter they are found in tropical cyclones, extratropical frontal cyclones, and shear lines, among many others. In other words, the contacting surface separating two different air masses in the atmospheric flows is in essence the region where water vapor changes into cloud droplets possibly leading to rainfalls. For this reason, from a viewpoint of hydrology, the contacting surfaces between different air masses and the processes occurring there are exactly our study of interest in the water cycle. Usually, the contacting surfaces exhibit as narrow cloud or rain bands along which intensive transport of atmospheric water are found, behaving in a similar manner as river channels on the surface of the earth. For this reason, we termed the contacting surfaces as the sky rivers. By this definition, it is inferred that the atmospheric water flowing in the sky rivers has high potential to reach the surface of the ground through precipitation.

3. Identification and spatial distribution of sky rivers

3.1. Identification of sky rivers

According to the physical nature of the sky rivers, they are formed through the contact between air masses with different velocity, pressure, temperature, and humidity. Based on the knowledge of fluid mechanics, fluids in different states, especially those with different densities and temperatures, contact each other to form a discontinuity at the contacting interface with the lighter and warmer fluids uplifted. Under steady state conditions, the continuous equation of atmospheric water (mainly water vapor) can be written as

$$\alpha w_1 - \alpha w_0 = -\int_{z_0}^{z_1}\left(\frac{\partial \alpha u}{\partial x} + \frac{\partial \alpha v}{\partial y}\right)\mathrm{d}z \tag{1}$$

where u and v is the horizontal wind component, w_1 and w_0 is the vertical wind component at z_1 and z_0, and α is the specific humidity. From Eq. (1), when $\partial\alpha u/\partial x + \partial\alpha v/\partial y < 0$, it implies that convergence of the flow occurs and atmospheric water within $[z_0, z_1]$ is more likely to be uplifted, i.e., $\alpha w_1 - \alpha w_0 > 0$. Therefore, from a viewpoint of fluid mechanics, updraft is always linked to the convergence in a given flow filed. Consequently, a succinct way to find the discontinuity surfaces or the sky rivers is to analyze the convergence in the flow field. In fact, analysis on the convergence of the flow fields is also a common method in meteorology to diagnose precipitations (Simmonds et al., 1999; Banacos and Schultz, 2005; Lavers et al., 2014).

When considering the distribution of the sky rivers in a large scale, it is advisable to analyze vertically integrated atmospheric water transport flux and identify the convergence lines in the atmospheric flows, which is given by

$$\boldsymbol{Q} = \frac{1}{g}\int_{p_s}^{0} \alpha \boldsymbol{u}\,\mathrm{d}p \tag{2}$$