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Shiyan Tao and the history of indigenous meteorology in China

Abstract

This paper gives an account of some of the indigenous characteristics of China's atmospheric sciences. We use the contributions of Academician Shiyan Tao to demonstrate how scientific advances in an international context were adapted to the evolving field of meteorology in China. The article outlines the major scientific contributions of Shiyan Tao, pays specific attention to his academic career in an international context, and highlights the possible implications of his achievements to the meteorological field in China. Tao came into meteorology while studying at the National Central University (NCU) in 1938. In 1944, he entered the Institute of Meteorology of Academia Sinica (IMAS), and in 1950 he joined the Joint Center for Weather Analysis and Prediction (JCWAP), where he furthered his experiences in weather prediction. In 1958, he published, with coauthors Tu-cheng Yeh and Chen-chao Koo, three important articles in *Tellus*, giving wider access to his academic contributions in the areas of satellite meteorology, rainstorms in China, East Asian Monsoon, and Tibetan atmospheric research. In this paper, we outline how the indigenous innovations of Tao integrated many international meteorological ideas into the Chinese setting, thereby promoting the development of atmospheric sciences in China. His successes benefited greatly from the desire to: pursue Chinese national requirements, integrate international advances into Chinese meteorology, coordinate research groups, and undertake practical research. He created a Practical School of Atmospheric Science in China and helped mold it with distinctive characteristics indigenous to contemporary China. By virtue of his position, Tao also trained numerous other Chinese meteorologists.

Keywords

Shiyan Tao, indigenous meteorology, academic trajectory, practical observation, scientific contribution

Disciplines

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SHIYAN TAO AND THE HISTORY OF INDIGENOUS METEOROLOGY IN CHINA

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ABSTRACT

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This paper gives an account of some of the indigenous characteristics of China's atmospheric sciences. We use the contributions of Academician Shiyan Tao to demonstrate how scientific advances in an international context were adapted to the evolving field of meteorology in China. The article outlines the major scientific contributions of Shiyan Tao, pays specific attention to his academic career in an international context, and highlights the possible implications of his achievements to the meteorological field in China. Tao came into meteorology while studying at the National Central University (NCU) in 1938. In 1944, he entered the Institute of Meteorology of Academia Sinica (IMAS), and in 1950 he joined the Joint Center for Weather Analysis and Prediction (JCWAP), where he furthered his experiences in weather prediction. In 1958, he published, with coauthors Tu-cheng Yeh and Chen-chao Koo, three important articles in *Tellus*, giving wider access to his academic contributions in the areas of satellite meteorology, rainstorms in China, East Asian Monsoon, and Tibetan atmospheric research. In this paper, we outline how the indigenous innovations of Tao integrated many international meteorological ideas into the Chinese setting, thereby promoting the development of atmospheric sciences in China. His successes benefited greatly from the desire to: pursue Chinese national requirements, integrate international advances into Chinese meteorology, coordinate research groups, and undertake practical research. He created a Practical School of Atmospheric Science in China and helped mold it with distinctive characteristics indigenous to contemporary China. By virtue of his position, Tao also trained numerous other Chinese meteorologists.

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1. INTRODUCTION

1.1 The composition of the modern meteorological knowledge system

The late nineteenth century and early twentieth century witnessed the institutionalization of atmospheric sciences. In general, the atmospheric sciences seek to understand the atmosphere both locally and globally. Globally, for instance, Rossby wave theory describes the behavior of the atmosphere at planetary or global scales, whilst cold air outbreaks are a common feature in the winter time at synoptic scales. However, the atmospheric sciences can also be influenced by the regional underlying land surface and the distribution of human populations. In this context, the theoretical system of the atmospheric sciences should combine both the basic global framework theories and regional atmospheric theories.

Thus, in China, modern atmospheric sciences are the product of global framework theories (generally developed internationally) with regional atmospheric theories that were developed in China and influenced by regional topography, population distribution, and history. It can be argued that the advances made regionally in China have informed international atmospheric sciences theory with the potential for greater understanding of local atmospheric science analysis

applied in other parts of the world.

1.2 The whole picture of Shiyao Tao

Shiyao Tao (1919–2012) (also referred to as Shih-Yen Tao or Shih-Yen Dao) was born in Jiaying, Zhejiang Province, eastern China (Figure 1). During a long life he became a prominent meteorologist and was made an Academician of the Chinese Academy of Sciences (CAS) in 1980. During a career spanning 70 years he published 170 journal articles and thirty other publications including monographs, co-authored books and translations (see Table 1; Ding 1992; Xu 2011; Chen and Yang 2014). His research efforts principally focused on atmospheric science at the planetary scale to mesoscale.

Figure 1. Picture of Academician Tao in his nineties (1919–2012)

Table 1. Tao's publications and books arranged by research area.

Research area	Number of published articles (including co-authored items)	Number of published books (including co-authored and translations)	Total
Weather prediction methods	4	3	7
Cold air intrusion studies	5		5
General atmospheric circulation	21	5	26
Satellite meteorology	3	2	5
Rainstorms & Meiyu (or Plum Rain) in China	40	5	45
Eastern Asian monsoon	14	1	15
Tibetan meteorology	8	6	14
Climate change	10	3	13
Meteorological disasters	6		6
Others	25	4	29
Total	136	29	165

From 1978 to 1984 Tao held the position of deputy and acting superintendent of the Institute of Atmospheric Physics (IAP) of the Chinese Academy of Sciences, the premier institution of atmospheric science in China. For his contributions to China, he was appointed committeeman of the Chinese People's Political Consultative Conference. He was simultaneously selected as the vice-chairman of the Chinese Meteorological Society in 1982, a Society of which he became chairman in 1987. He gained many other important honors during his long life.

In the contemporary Chinese meteorology community, Shiyao Tao and Tu-cheng Yeh were of nearly equal academic reputation. Tu-cheng Yeh was the winner of the 2005 State Supreme Science and Technology Award, known as China's Nobel Prize (with a cash value of RMB

5,000,000). In contrast, Tao was a home-grown meteorologist since he did not study abroad and did not have a Masters or Ph.D. degree. His highest academic degree was a Bachelor of Science. Given his limited education, how was Tao able to make such important contributions over a wide range of topics central to the development of Chinese meteorology?

Obviously, Tao's research was closely related to local weather characteristics of China and it largely focused on Chinese weather cases. His research trajectory and achievements represents the indigenous, or home-grown, model of contemporary Chinese atmospheric science, also followed by many other scholars. Here, indigenous meteorology refers to the successful application of advanced atmospheric science theories and applied techniques developed internationally, for example by the Chicago School, to weather forecasting practice in China. In addition, indigenous meteorology refers to the development within China of mathematical theories and applied forecasting skills based on Chinese observations and unique physical geography. These advances in Chinese meteorology have largely enriched the atmospheric sciences in general and provided valuable models for the development of indigenous meteorology in other regions.

In contrast to indigenous meteorology, another research approach in Chinese atmospheric science was established by Tu-cheng Yeh, and it relied on applying internationally developed mathematical theories to China (e.g. the Rossby wave theory) and on understanding physical processes of the atmosphere, especially in weather dynamics.

Despite a lifetime of rich achievements, little is known outside of China regarding the academic career of Tao, nor of the indigenous characteristics of the Chinese atmospheric science that he practiced. His research findings have been widely applied to weather forecasting and meteorological hazard prediction within China (Tao 2005; Xu 2011; Chen *et al.* 2011; Chen and Yang 2014), but their linkage to developments in international meteorological science has not previously been fully assessed. Furthermore, Tao's academic progression might be considered to have created an "indigenous innovation effect", by shaping the research agenda of many Chinese meteorologists. Therefore, an integrated analysis of the domestic and international influence of Tao's research is warranted.

In this paper, we analyze Tao's professional contributions in order to evaluate his influence on other Chinese meteorologists and to characterize the possible reasons for this influence. To achieve this objective, comprehensive surveys and analysis of Shiyao Tao's academic career have been undertaken, with emphasis placed on the implications of his work on other meteorologists.

2. ACADEMIC TRAJECTORY FOLLOWED THE FRONTIER

Tao's research trajectory kept pace with developments in atmospheric science throughout the world. This made up for his not having studied abroad. Furthermore, he advanced knowledge by applying those new developments to the practice of weather analysis in China.

2.1 First generation of atmospheric science undergraduates in China

In 1938 Shiyao Tao, being regarded as a conscientious student, was recommended to one of the best Chinese universities, National Central University (NCU, nowadays Nanjing University). One year later, the young Tao developed a consuming interest in meteorological science, and this led to his switching from Hydrological Engineering to Meteorology. At the time, meteorology was a relatively small and young discipline in China, with only four students, including Chen-chao Koo, Shiyao Tao, Shisong Huang, and Qigong Chen, engaging in major studies in meteorology at NCU (Figure 2). These four became the first group of meteorologists to graduate in China. In 1942, at the age of twenty-three, Tao received his degree of Bachelor of Meteorology with a thesis on isallobaric wind (the wind velocity whose Coriolis force exactly balances a locally accelerating geostrophic wind (Haurwitz 1941; Glickman 2000)).

Figure 2. First group of students majoring in meteorology in the early 1940s, showing (left to right) Chen-chao Koo, Shiyan Tao, Shisong Huang, and Qigong Chen. Image provided by Tao's secretary, Professor Jie Wei.

After making a start on further studies of the isallobaric wind, Tao instead turned to a professional career as an assistant meteorologist, specializing in the application of the theories of the Chicago School to weather prediction. After graduating in 1942, his classmates went abroad for further study: Shisong Huang and Qigong Chen went to the USA for Masters degrees, while Chen-chao Koo undertook a Ph.D. with Carl-Gustaf Arvid Rossby in Sweden. Because of illness, Tao failed to attend the selection examination for studying abroad. Nevertheless, even 70 years later, he never regretted missing this opportunity since this lack of overseas study experience had little effect on his subsequent scientific research. Instead, in Tao's own opinion, it was the opportunities offered by the new China that allowed him to develop his career.

2.2 Three important articles in *Tellus*

Because of the imposition of the "Bamboo Curtain" in the 1950s, most international meteorological communities knew little about Chinese meteorological research. Nonetheless, Tao and his group displayed an ability to convince international meteorology colleagues and administrators that their research results were of high caliber.

In 1958, Tu-cheng Yeh, Chen-chao Koo, and Shiyan Tao published three important papers in *Tellus* a high impact meteorology journal founded by Rossby. The articles investigated the general atmospheric circulation over Eastern Asia (Staff Members of Academia Sinica 1957, 1958a, 1958b). These aroused interest in the international meteorological community and initiated significant contacts with the Chinese meteorologists.

The first paper provided a summary sketch of the atmospheric circulation over the Far East. It described the mean field of motion in the lower troposphere and discussed mean cross sections for winter and summer as well as for different latitudes. At the same time, the paper analyzed the seasonal circulation variation over East Asia (Staff Members of Academia Sinica 1957). The second paper studied the principal weather systems over East Asia in the different seasons. It documented the influence of the Tibetan Plateau on the circulation over East Asia and the weather over China (Staff Members of Academia Sinica 1958a). The last paper made some important contributions including the computation of averaged vertical motion, heat sources and sinks for the normal maps for January and July, and the interpretation of perturbations in the westerlies due to large-scale heat sources and sinks and topography (Staff Members of Academia Sinica 1958b).

These three papers became widely known, and showed that Tao, Yeh and Koo possessed a remarkably clear insight into the meteorological situation in China. The publication of these three papers had an important influence on the field of meteorology, and opened a wide window for

INDIGENOUS METEOROLOGY IN CHINA

foreign scientists to know more about Chinese meteorology in the 1950s. The papers also introduced the authors to the international scientific community and established their reputations. Furthermore, these scientific publications showed some of the real problems confronting Chinese meteorology, with a desire to reach a precise resolution for China. They also showed that Chinese meteorology during the 1950s and 1960s had been keeping close pace with advances in meteorology in the Western world. The core ideas of atmospheric circulation over Eastern Asia introduced in these papers were eventually recognized by the National Science Congress in 1978, and awarded the First Prize of National Natural Science in 1987.

2.3 Extending to East Asian monsoon research and Tibetan meteorology

Early in the 1950s the influence of the East Asian monsoon on the cycle of drought and flooding in China had come to Tao's attention, and he had proposed the concept of the East Asian monsoon circulation mutation. In 1980 Tao initiated and organized the Southeast Asian Summer Monsoon Research Program. During the late 1980s, he further developed his ideas on the East Asian Monsoon System (Tao and Chen 1987), and subdivided the Asian monsoon into two independent but interrelated subsystems, the Indian Monsoon and the East Asian Monsoon (including China and Japan). Tao argued that the India monsoon and East Asian monsoon have their own heat sources, heat sinks, and circulation systems, respectively. This reversed the traditional idea within the meteorological community that the whole of Asia, including southern India, China, and Japan, all belonged to the same summer wind circulation system (*i.e.* the Indian monsoon system). In 1987, Tao's article 'A Review of recent research on the East Asia summer monsoon in China' was published in *Monsoon Meteorology* (Tao and Chen 1987), and has since been very widely cited. He also revealed the response mechanism between East Asian monsoon circulation and ENSO. He extended his interest to the interaction between the ocean, atmosphere, and land surface in the evolution of the East Asian monsoon circulation, further improving the prediction of short-term climate and the East Asian monsoon circulation in China. In particular, Tao established the conceptual model for prediction of widespread flood disasters in the East Asian monsoon areas, largely accelerating accurate flood predictions in the Yangtze and Huaihe River drainage basins.

In addition, beginning in the 1950s, Tao spent a large part of his research time on the high Tibetan Plateau (Yang *et al.* 1960). In May to August 1998, Tao and another academician, Lianshou Chen, were in charge of the second Tibetan Plateau Experiment of Atmospheric Sciences. These programs collected large amounts of data and have since provided a valuable resource for China, East Asia, and the rest of the world, for the prediction of weather disasters and for monitoring climate change (see Tao *et al.* 2002, *The Second Tibetan Plateau Experiment of Atmospheric Sciences TIPEX-GAME/TIBET* (3 volumes in both Chinese and English)). The research results of Tao's group indicated that the atmospheric dynamics, thermal structure, and water vapor processes on the Tibetan Plateau should be the pivotal factors to monitor for any successful prediction of disastrous weather in China and the rest of East Asia. This finding demonstrated that monitoring conditions over an upstream mountain range would benefit the prediction of severe weather immediately downstream of the mountain. This finding can be applied to other regions of the world.

3. KEEPING PACE WITH CHINA'S INDIGENOUS METEOROLOGY

Tao's research program to a large degree paralleled the development of China's modern atmospheric sciences. In the second half of the twentieth century, China's atmospheric sciences were in an accelerated phase of development, providing favorable conditions for Tao's innovative work. China's atmospheric sciences developed its own indigenous characteristics because of the unique geography of China.

3.1 Academic training with China local characteristics

At the end of 1942 Tao was recruited as an assistant to teach and conduct research in the NCU Department of Geography. Because of his knowledge of modern meteorology, Tao was recommended at the end of 1944 to Jeou-jang Jaw, the executive director of the Institute of Meteorology of Academia Sinica (IMAS), by Chang-wang Too, a professor from the NCU Department of Geography. This invitation to work in IMAS became the first important turning point in Tao's academic career. Both Jeou-jang Jaw and Chang-wang Too were influential meteorologists who introduced advanced Western meteorological theories to China.

IMAS (Figure 3) is the predecessor of the present Institute of Atmospheric Physics of the Chinese Academy of Sciences, and was established in Nanjing in 1928 by Co-ching Chu. Chu was one of the founders of modern meteorology in China and had received a Ph.D. in meteorology from Harvard University in 1918. On his return to China, Chu did everything he could to develop Chinese meteorology, and IMAS became the top academic institute in China at that time. It subsequently became the cradle of numerous Chinese meteorologists, including Tao. Tao always attributed his contributions to meteorology to his teachers and helpful friends at IMAS (Tao 1990).

Figure 3. Photograph of Beijige, IMAS Nanjing, where Tao worked from 1944 to 1949. Photo taken in the 1980s. Image provided by Tao.

Tao's interest in meteorology was greatly inspired by his time at IMAS. It was there that he met the renowned scholars Co-ching Chu, Jeou-jang Jaw, and Chang-wang Too who brought the theories of the Chicago School to IMAS. Tao, together with several assistants, began to apply Rossby's theory to drawing local weather charts for China. Although his name did not appear on most of the published IMAS reports during the years he was there, Tao did contribute some good ideas in the area of Chinese indigenous meteorology, including the preliminary understanding of the effects of cold air intrusion and impacts of topography on meteorological patterns in China. He was also called upon to give a variety of academic presentations, including ones concerning weather analysis at the time of the Battle of Midway Island (Figure 4a; presented on Dec 27, 1945), and on the variability of atmospheric circulation in Eurasia (Figure 4b; presented on May 8, 1945). His strict academic training during this period aided and cemented his scientific foundation for his later work on indigenous Chinese atmospheric science.

Figure 4. Notices of an academic presentation given by Tao on 27 December 1945 whilst at IMAS. Figure 4a (left) concerns a weather analysis at the time of the Battle of Midway Island. Figure 4b (right) concerns the types of atmospheric circulation in Eurasia (from The Second Historical Archives of China).

3.2. Contributions to rainstorm studies in China

The study of rainstorms in China is a good example of indigenous Chinese meteorology. In the early 1950's, Shiyan Tao had already discovered that rainstorms in the Yangtze drainage basin were closely associated with the atmospheric circulation in East Asia in particular, and the northern hemisphere in general, including snowy areas at high latitudes. Tao began to delve into the subject of heavy rainstorms in China in the mid-1970s. From then through the 1980s he systematically studied the activity patterns, mechanisms and prediction of severe rainfall events within China. He investigated the concept of multi-scale interactions in the shaping of rainstorms, and expanded heavy rainfall forecasting methods in susceptible regions.

In August 1975, 1,600 millimeters of precipitation fell in just three days in the upper Huaihe River region and led to a 100-year flood. This floodwater then emerged into Zhumadian and resulted in the death of tens of thousands of people, and the destruction of numerous reservoirs, railways and buildings. This calamity was a great shock for the Chinese meteorological community. As a result, Tao gathered an outstanding group of China's leading meteorologists and graduate students to more deliberately study such severe rainstorm events. They eventually developed a heavy rain *drop-zone* prediction method, which predicted the areas most likely to be impacted by heavy rain.

Early in the 1970s, Tao started to interpret the rainstorms occurring in the drainage basins of some megarivers, including the Yangtze River, as the result of the focusing mechanism (an atmospheric process or phenomena that produces enhanced low-level convergence of warm-moist air over a mesoscale region) and an unstable atmosphere supportive of sustained convection, which was later confirmed by many international scholars. Tao believed that these rainstorms were mesoscale phenomena, but would maintain or strengthen into an extreme rainstorms due to the complex interaction among air flows of different scales. Circulation in the northern hemisphere is generally considered unstable for a given location. This is due to disturbances that originate on a frequent basis. These comprise major low-level troughs or ridge-transform systems migrating through a region. Rarely, frontal zones and rainfall belts become concentrated in certain areas, thus producing persistent rainstorms and widespread flooding. The idea proposed by Tao

was widely applied to heavy rainfall prediction in China. Furthermore, Tao attached great importance to the correlation between mesoscale systems and large scale basic flow, terrain, and drop area forecasts. According to his theories, many meteorological hazards like the “75.8” *rainstorm* happened because of the abnormal atmospheric circulation, distinctive topography and land use. Because of the densely populated region where the storm occurred, the impacts were severe which helped spur the development of indigenous meteorology of China in response to this natural disaster.

These studies led to what may be considered another of Tao’s most important works (Tao *et al.* 1979b; Tao 1980; Tao and Ding 1981; Tao *et al.* 1989). He systematically summarized the subject of rainstorms and showed insight into the severe problems besetting the prediction of these events. Tao’s 1980 monograph entitled *Rainstorms in China* (Tao 1980) was based on many years of research and study. For this contribution, he was awarded the First Prize of Natural Science of the Chinese Academy of Sciences in 1992.

3.3 Focusing on national requirements

In the twentieth century, the mission of meteorology in China was to “serve the national interest and cater for the public demand”. When reviewing his lifetime, Tao believed that every task he did arose from an imperative to serve the nation (see Table 1 and Figure 6). The development of atmospheric science in China can be roughly divided into two periods, before and after 1949. Tao always insisted that he largely benefited from, and was grateful for, the opportunities given since 1949 when the new Republic of China was founded (Chen 2011; Chen and Yang 2014).

Beginning in 1949 the new China needed better weather forecasting. As a result, meteorologists from the Institute of Geophysics, the Chinese Academy of Sciences, and the Central Military Commission Meteorological Bureau were merged into the Joint Center on Weather Analysis and Prediction (JCWAP) in December 1950. Chen-chao Koo was appointed as Director and Shiyan Tao as Deputy Director. This was another significant step for Tao (Chen 2011).

Tao entered the JCWAP because of the need for improved weather prediction to meet national requirements (Ren *et al.* 2007; Chen 2011) (see Figure 6). In the early 1950s it was difficult to make accurate weather forecasts in China because of a scarcity of domestic meteorological data, compounded by a weak research base. Also, the direct adoption of some foreign forecasting methods into prediction practice was often inappropriate in China because of the influence of local factors. However, Tao creatively combined foreign meteorological theory with Chinese practice, thereby improving the accuracy of weather prediction in China.

The Chinese policies of “Reform and Opening-Up” after 1978 promoted the diversification of meteorology and independent Chinese innovation (see Figure 6). During the 1980s, Tao made many contributions to the understanding of rainstorms in China and the East Asian monsoon, and made advances in understanding Tibetan atmospheric sciences and various meteorological hazards in the 1990s. He concentrated on the river floods of 1998 and 2007, the hot summer of 2006, and the extreme cold and snow event at the beginning of 2008, all of which had indigenous characteristics and impacted the social structure and national requirements of China.

4. A PARADIGM FOR INDIGENOUS INNOVATION

Because of its dense population and long history of human occupation and development, China is particularly subject to weather-related natural disasters. In order to mitigate those hazards, the influence of local factors on weather needed to be better understood. As a result, an indigenous form of meteorology became established.

INDIGENOUS METEOROLOGY IN CHINA

4.1 Rooted in China's meteorological practice

As mentioned previously, there are many differences between the atmospheric sciences and other natural sciences. For example, the atmospheric sciences incorporate lessons learned from applied practice into fundamental research. Tao in particular paid close attention to weather forecast practice. In his career of more than 70 years, Tao always recognized the key problems in the practice of meteorology in topics such as atmospheric circulation in East Asia, the monsoon, climate, cold air outbreaks, heavy rain forecasting, and meteorological satellite applications, thereby significantly improving the weather forecasting level and prescription in China (Table 1).

Tao had realized that it was important to validate in practice the advanced theory of the Chicago School, because he felt that this theory must be considered in order to solve a number of problems in Chinese meteorology. So he devoted his time and effort to establishing and summarizing various weather forecasting methods developed through practice, and successfully issued a succession of accurate predictions about cold air intrusions. For instance, Tao had systematically distinguished four possible cold air intrusion paths in China, consequently enhancing greatly the forecast accuracy of cold air intrusions and extending the forecast time to about three days. These successes considerably advanced Chinese weather prediction practices (Dao 1953, 1957).

At the beginning of the New China in 1949, many Chinese regarded the Soviet Union as a good role model, and this resulted in a *one-sided tendency* that focused on assimilating ideas generated in the Soviet world rather than elsewhere. Tao thought that Soviet meteorology, and the Advection Momentum Theory in particular, was inappropriate for Chinese meteorological practice. Unlike theories advanced by the Bergen School or Chicago School, the Advection Momentum Theory primarily focuses on the correlation between the ground temperature and the high-altitude dynamic change. As such, the upper deformation field would greatly influence and determine the cyclonic and anticyclonic oscillations, possibly generating some reasonable interpretation to a certain degree. However, it can't correctly explain the essence of frontal cyclone as well as anticyclone fluctuations, not to mention atmospheric long waves at the planetary scale. So, under the leadership of Tao, the Central Meteorological Observatory instead carried out weather prediction according to the Chicago School theory. In 1954, Tao, encouraged by Chang-wang Too, bravely made a report to a Chinese national meteorology conference that pointed out the deficiencies of the Advection Momentum Theory. His assessment was later proven to be correct (Dao and Yang 1965).

Tao remained in the JCWAP for five years during which he accumulated considerable experience with practical weather forecasting in China. This provided him with a strong foundation for his future studies. Many articles generated from his practical experience in the JCWAP were published from the late 1950s to early 1960s, including ideas about the cold air path (Dao 1957), the abrupt change of circulation over the Northern hemisphere, and the rainy season of the Yangtze River region (Yeh *et al.* 1959; Dao *et al.* 1965).

4.2 Initiating Chinese satellite meteorology during the Cultural Revolution

The Cultural Revolution between 1966 and 1976 significantly affected China economically and socially. Due to the Cultural Revolution, a lot of research programs were delayed and under-funded. Simultaneously, most meteorologists (such as Tu-cheng Yeh, Jeou-jang Jaw) were stopped from undertaking research work largely due to having had an overseas study background. In contrast, Tao was a home-grown meteorologist, and mostly remained away from any political activities. Therefore, his research program was not adversely affected in the midst of this turmoil. Instead Tao was able to dig deeper than ever into his scientific work and turned all his attention to the study of applied meteorology.

During this time, Tao obtained a temporary appointment as senior meteorologist to

perform military weather forecasting for Chinese atomic bomb tests and missile launches. Weather prediction for military applications was quite difficult at that time due to the weak economy and the lack of modern equipment. Nonetheless, Tao's activities helped indirectly to initiate China's own satellite meteorology program.

Tao and his assistants also made some attempts to establish an effective method for cirrocumulus prediction, a challenging task. It was vital to make those predictions because cirrocumulus can obscure the observation of rocket attitudes as they take off and land. These activities necessitated significant organizational administration, a new responsibility for Tao. The successful way in which he handled these duties presaged his later promotions and future career successes. Because of his outstanding performance in these efforts in military meteorology, he was awarded the Merit Award Class II in May 1965 and the Great Merit Award in 1966 (see Figure 5).

Figure 5 Tao's Great Merit Certificate (1966) for his significant contributions to military meteorology (courtesy of Professor Jie Wei).

After the USA launched the TIROS-1 weather satellite in 1960, the international meteorological community regularly began to utilize satellite data in weather analysis and forecasting. The Chinese government had decided to receive and utilize foreign meteorological satellite data before it launched its own weather satellites, and Tao, in his 50s, was one of the first Chinese meteorologists to be assigned this research work. He led the Chinese meteorological community in the study of satellite cloud images, and developed a satellite cloud image identification and application method which quickly spread across China. This method greatly improved the level of China's short-term forecasting, and quickly became an important tool in Chinese weather prediction and research.

Under the leadership of Tao, Chinese satellite meteorology made many other achievements. For example, the *China Satellite Cloud Imagery Manual* was published in 1975 (Tao *et al.* 1975), and ideas and information were shared with international colleagues (Tao *et al.* 1979a).

4.3 Promoting international cooperation between China and other countries

The paradigm of indigenous innovation not only needs the contribution from Chinese meteorologists but also contributions from talented scientists all over the world. As one of China's most eminent meteorologists, Tao had initiated and promoted a large number of exchanges and collaborations between China and the wider international meteorological community. One interesting example was an American Meteorological Society delegation which visited China in 1973 (Kellogg *et al.* 1974), during which Tao invited them to eat the famous Beijing roast duck.

INDIGENOUS METEOROLOGY IN CHINA

Between 1977 and 1986, Tao also served as a chief Chinese representative to the United Nations World Meteorological Organization (WMO), and was simultaneously China's chief scientist in the joint Sino-US research on climatic effects of atmospheric CO₂. During this time, Tao was invited many times by institutions in the United States, Japan, France and other countries to conduct academic exchanges and make professional presentations.

In October 1978, the World Meteorological Organization held an international conference on typhoons in Shanghai. The conference was successfully organized and chaired by Tao, and typhoon experts from more than fifty countries were invited to share their ideas. Tao later organized a number of similar conferences, and through such activities the Chinese meteorology community was strengthened, and the academic standing of Chinese meteorologists promoted internationally after the Cultural Revolution.

Based on Tao's work on the East Asian monsoon, an important example of scientific cooperation between China and the United States occurred in 1982, when Academician Tao, as China's chief representative scientist from 1982–1990, paid a three-month visit to the National Center for Atmospheric Research in Boulder, CO. This was Tao's longest stay in a foreign country. In 1985 Tao promoted major cooperation between China and the Japanese Ministry of Education on the analysis of the Asian monsoon system. This international collaboration later expanded in 1998 to cooperation between China, Japan and Korea. From 1988 to 1992, Tao, following Tu-cheng Yeh, was invited to be a representative on the Joint Scientific Committee of the World Meteorological Organization and the International Council of Scientific Unions to engage in the formulation of the World Climate Research Programme. Participation in such important scientific programs improved the opportunities for meteorological scholars to speak internationally (Riches *et al.* 1992, 2000). Tao made good use of such international cooperation to promote China's meteorological research.

5. DISCUSSION AND CONCLUSIONS

5.1 *Always in the forefront of disciplinary development*

Unlike some other Chinese meteorologists Tao did not study or travel abroad for extended periods, yet he was always at the forefront of Chinese meteorology. Tao thought of himself as belonging to the Chicago School, because his adoption of that School's theories as a young man had a profound influence on his career. In the 1917–1950 periods, there were notable developments in atmospheric science due to the contribution from both the Bergen School and Chicago School, which had major impacts on meteorology globally and in China (Ding 1992; Chen and Yang 2014) (see Figure 6). Chinese students studying abroad, including Tu-cheng Yeh, Yibing Xie, and Chen-chao Koo, brought advanced theories back with them on their return. Those theories were applied to the practical problems in China, thereby producing advancement in Chinese modern meteorological science. In addition, the academic style and spirit of the Bergen School and Chicago School, as well as the mode of training talented people, generated a strong influence on China's meteorological sciences. At the same time, the meteorological theories of Russia were also introduced into China. However, due to the different indigenous conditions, many of these theories were not fully applicable in China. Therefore, during his university studies, Tao learned the meteorological theories of the Bergen and Chicago Schools. Several years later, when Tao was at IMAS, he received encouragement from Professor Jeou-jang Jaw, who urged him to explore, as much as possible, the Chicago School's theories (Figure 6).

After the establishment of the new China in 1949, when Tao was working in JCWAP, and later at the Institute of Atmospheric Physics at the Chinese Academy of Sciences, the Chicago School theory was introduced under the leadership of Co-ching Chu, Jeou-jang Jaw, Chang-wang Too and other senior academics, and many advances were made. Some years later, Tu-cheng Yeh, a student of Rossby, became responsible for the Institute. Within the context of those international

and domestic influences, Tao made significant contributions to atmospheric sciences (Ding 1992; Ren *et al.* 2007; Xu 2011; Chen and Yang 2014) (see Figure 6). Tao was not only receptive to a number of the world's most advanced atmospheric science theories and techniques (e.g. the Chicago School, numerical prediction, and satellite meteorology), but he also applied those ideas and techniques to the Chinese setting and conditions, modifying them where necessary to suit the local conditions. This led to many significant indigenous contributions to Chinese meteorology.

Figure 6. Integration diagram showing the correlation of Tao's academic career path with the historic environment of China and the international background. The horizontal arrows indicate major events in Chinese history and advances in meteorology internationally through time. The dotted arrows show how political and economic factors influenced scientific and technology policy, which in turn influenced patterns of individual scientific research. The bold arrows indicate the impact from both the domestic and international factors on the development of indigenous meteorological concepts in China. The dotted ellipse refers to the Tao's major contributions.

5.2 Importance of practice in meteorological forecasting

Although Tao did not study abroad nor did he have a graduate degree, he consistently combined, throughout his seventy year career, weather observation and forecasting theories with their practical applications (Ding 1992; Ren *et al.* 2007). Tao thought that professional success depended on practical research. Some of those who studied under him have said they respected him for his applied meteorology (Xu 2011). For example, the contributions Tao made to understanding the atmosphere circulation in East Asia, the monsoon system, cold air intrusions, severe rainstorm prediction, and satellite meteorology were his major contributions emanating from his practical work.

5.3 The fruits of diligence

In evaluating the contributions of Shiyan Tao it must be recognized that his success as a meteorologist resulted from his applied research perspective, his insight and understanding of his field, his abundant practical experience and his diligence, (Ding 1992; Li 2001; Ren *et al.* 2007; Chen 2011; Chen and Yang 2014). In particular, he always stepped up to answer the needs of his country, emphasized practical observation and research, and promoted the exchange of ideas between meteorologists. As one of the major figures in the history of Chinese meteorology, inspiration can be drawn from his academic growth and contributions.

Although he had retired by the beginning of the twenty-first century, Tao continued to support and advise his doctoral students, to participate in meetings, and to write articles until he was nearly ninety. He learned four foreign languages, namely English, German, Russian and Japanese. In 2004, at the age of eighty-five, he even participated in a long field investigation, travelling over 1,000 km in the rugged Taklimakan Desert of western China. He personally directed the disaster analysis investigations in 2008 when an unexpected cold rain and snow event occurred in southern China, causing a major and costly disaster.

Tao remained a hard worker to the end, including a paper analyzing the impact of Rossby Waves on China published in 2010 (Tao *et al.* 2010). In 2012, at the age of ninety-three, he remained clear and quick in his thinking, and retained concerns about the frontiers of atmospheric science. As late as 2012, just before he died, he continued to give significant assistance to his research group. Throughout his career, he focused on scientific research and did not interfere with the affairs of administration.

5.4 Some conclusions

In the history of contemporary Chinese atmospheric science and technology, Tao was an outstanding innovator in the field of indigenous atmospheric science. Our research indicates that Tao was a consistent advocate for the Rossby wave theory and that he was familiar with a broad range of topics on the frontier of international atmospheric science. The key feature of Tao's academic career was that he applied those international principles to the study of China's atmospheric processes thereby developing an indigenous weather forecasting system. Tao consistently served his country, and in doing so was at the forefront of every stage of meteorological and atmospheric science development in modern China. Most of Tao's scientific contributions resulted from applying modern meteorological theory to local Chinese conditions in order to improve weather prediction. As a consequence, his insights had a large influence on the development of meteorology in China, in particular through the development of an indigenous Chinese school of practical atmospheric science. His rigorous academic training and valuable help from his teachers and friends during his career produced a scientist with keen insight, deep philosophical thinking, and outstanding research techniques. All these have allowed him to combine deeper scientific principles with practical observation. For these reasons, we can conclude that Tao's atmospheric science research was strongly indigenous in character. As one of China's leading meteorologists, Shiyan Tao's academic career and contribution to indigenous innovation offers insight into the history of meteorology in China. His academic path is emblematic of the history of development of contemporary Chinese meteorology. This is not to say that Tao was the only meteorologist practicing an indigenous form of the science. It may be worth examining the contributions of other meteorologists, both in China and elsewhere, to see how the history of meteorology was influenced by indigenous characteristics in other countries such as India and Russia. For these reasons, we should continue to pay attention to the history of the atmospheric sciences in the future.

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INDIGENOUS METEOROLOGY IN CHINA

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