Advances in Atmospheric Sciences
Impact Factor: 3.158
E-alert
ISSN 0256-1530
CN 11-1925/O4

Contributions of Fuqing ZHANG to Predictability, Data Assimilation, and Dynamics of High Impact Weather: A Tribute

Zhiyong MENG, Eugene E. CLOTHIAUX

Citation: Meng, Z. Y.,, E. E. Clothiaux, 2022: Contributions of Fuqing ZHANG to Predictability, Data Assimilation, and Dynamics of High Impact Weather: A Tribute, *Adv. Atmos. Sci.*, In press. doi: 10.1007/s00376-021-1362-x.

View online: https://doi.org/10.1007/s00376-021-1362-x

ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 39, MAY 2022, 676–683

• In Memoriam •

Contributions of Fuqing ZHANG to Predictability, Data Assimilation, and Dynamics of High Impact Weather: A Tribute※

Zhiyong MENG*[1] and Eugene E. CLOTHIAUX[2]

[1]*Department of Atmospheric and Oceanic Sciences*, *School of Physics*, *Peking University*, *Beijing* 100871, *China*

[2]*Department of Meteorology and Atmospheric Science*, *The Pennsylvania State University*, *University Park*, *Pennsylvania* 16802, *United States*

(Received 12 September 2021; revised 24 November 2021; accepted 26 November 2021)

ABSTRACT

This article reviews Fuqing ZHANG's contributions to mesoscale atmospheric science, from research to mentoring to academic service, over his 20-year career. His fundamental scientific contributions on predictability, data assimilation, and dynamics of high impact weather, especially gravity waves and tropical cyclones, are highlighted. His extremely generous efforts to efficiently transmit to the community new scientific knowledge and ideas through mentoring, interacting, workshop organizing, and reviewing are summarized. Special appreciation is given to his tremendous contributions to the development of mesoscale meteorology in China and the education of Chinese graduate students and young scientists.

Key words: predictability, dynamics, data assimilation, high impact weather, Fuqing ZHANG, contributions, tribute

Citation: Meng, Z. Y., and E. E. Clothiaux, 2022: Contributions of Fuqing ZHANG to predictability, data assimilation, and dynamics of high impact weather: A tribute. *Adv. Atmos. Sci.*, **39**(5), 676–683, https://doi.org/10.1007/s00376-021-1362-x.

Through just a 20-year career before his premature death in 2019, Fuqing ZHANG made outsized fundamental contributions to a wide range of topics in atmospheric science, including, but not limited to, predictability and dynamics of multiscale weather, ensemble-based data assimilation and prediction, tropical cyclones, mesoscale gravity waves, and midlatitude weather (Fig. 1). He was able to accomplish so much in such a short time because of his drive and his unparalleled curiosity that would often morph into boundless passion on a topic. He uniquely integrated elements of seemingly diverse subdisciplines into a wholistic understanding of atmospheric dynamics and prediction, always with a dedicated focus on addressing high-impact weather forecast challenges.

Fuqing ZHANG graduated from Nanjing University, China, in 1994 and obtained his Ph.D. degree from North Carolina State University in 2000. After one year of post-doctoral research at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, he started his career at Texas A&M University in 2001 as a tenure track assistant professor. In 2008, he joined Pennsylvania State University and became a tenured full professor in the Department of Meteorology and Atmospheric Science and a year later received a joint appointment with the Department of Statistics. From 2001 through July 2019, he fully met each and every one of the criteria on which the achievements of scientists are judged: from research to mentoring to academic service.

Fuqing ZHANG's outstanding scientific accomplishments are attested to at least, in part, by both the quality and the impact of his stellar record of publications. In addition to one book and six book chapters, he authored 275 peer-reviewed journal papers by 22 January 2022 (listed in the supporting information) with 224 collected by ISI Web of Science by 4 September 2021 (Figs. 2 and 3). As tracked by Web of Science and Google Scholar, these works have received 9950 and 14 930 total citations with an h-index of 54 and 68, respectively, by 4 September 2021 (Fig. 3). The top 50 most cited journal papers authored by Fuqing ZHANG are listed in Fig. 4, which shows that predictability, gravity waves, data assimilation, and tropical cyclones are the top four areas where Fuqing ZHANG made substantial contributions.

Predictability of multiscale weather systems

One significant contribution that Fuqing ZHANG made to atmospheric science is on the basic problem of predictabil-

※ This paper is a contribution to the special issue on Predictability, Data Assimilation and Dynamics of High Impact Weather —In Memory of Dr. Fuqing ZHANG.

* Corresponding author: Zhiyong MENG
Email: zymeng@pku.edu.cn

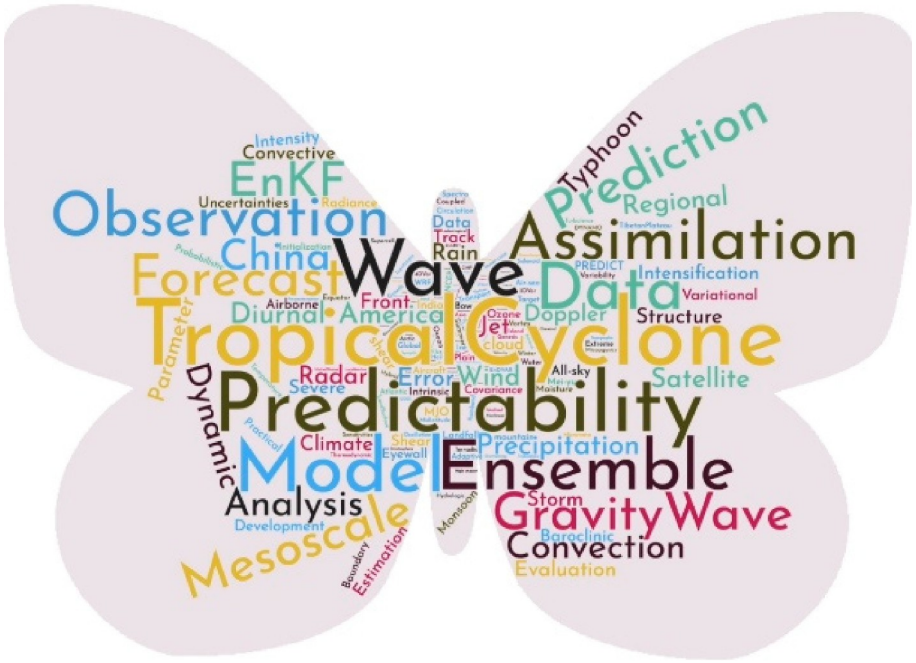

Fig. 1. Frequencies of occurrence of key words in the titles of Fuqing ZHANG's publications, revealing the major and widespread topics of his research. Larger sizes denote higher frequencies. (Produced by Ruoqi GAO, currently a graduate student at the University of Virginia and formerly of Pennsylvania State University.)

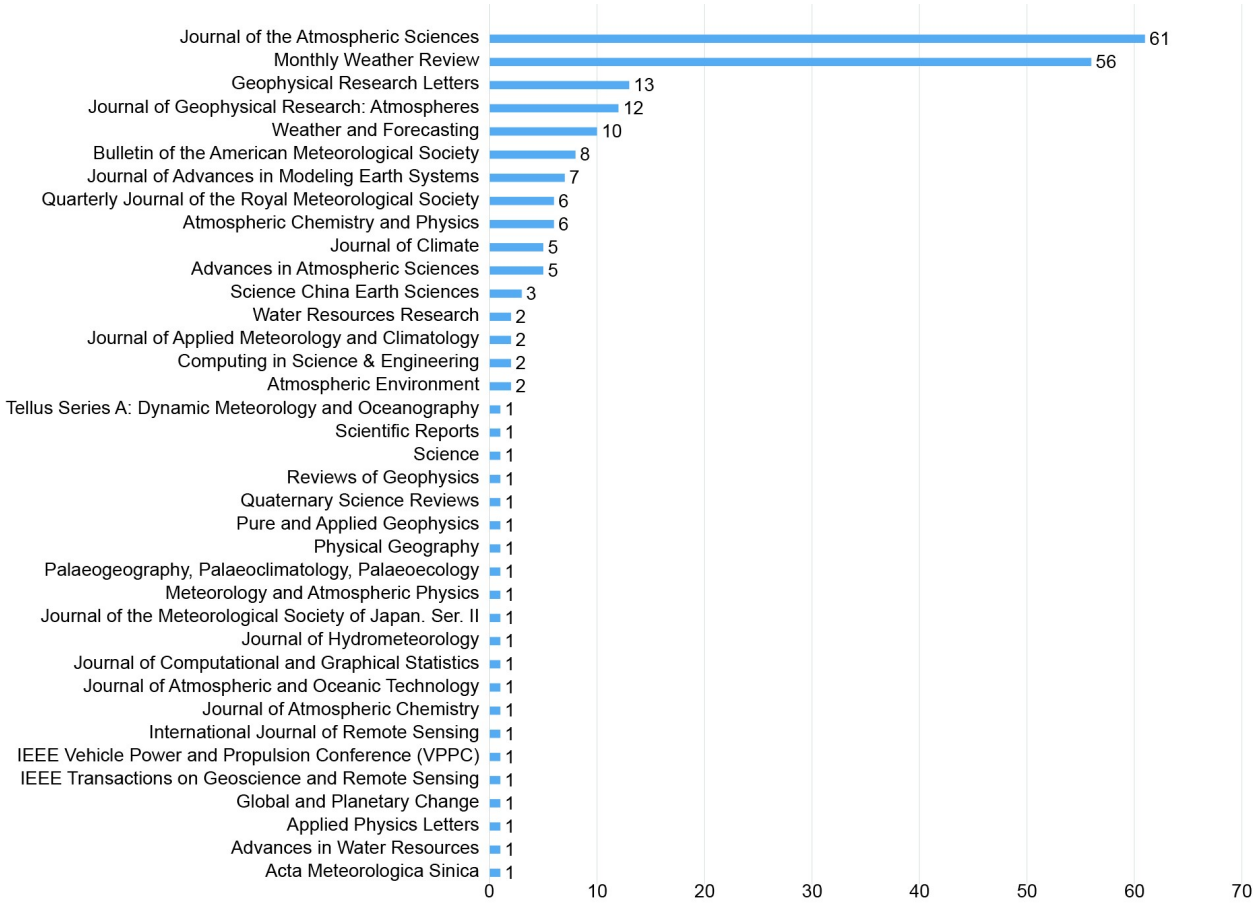

Fig. 2. A list of journals in which Fuqing ZHANG's papers were published up to 4 September 2021.

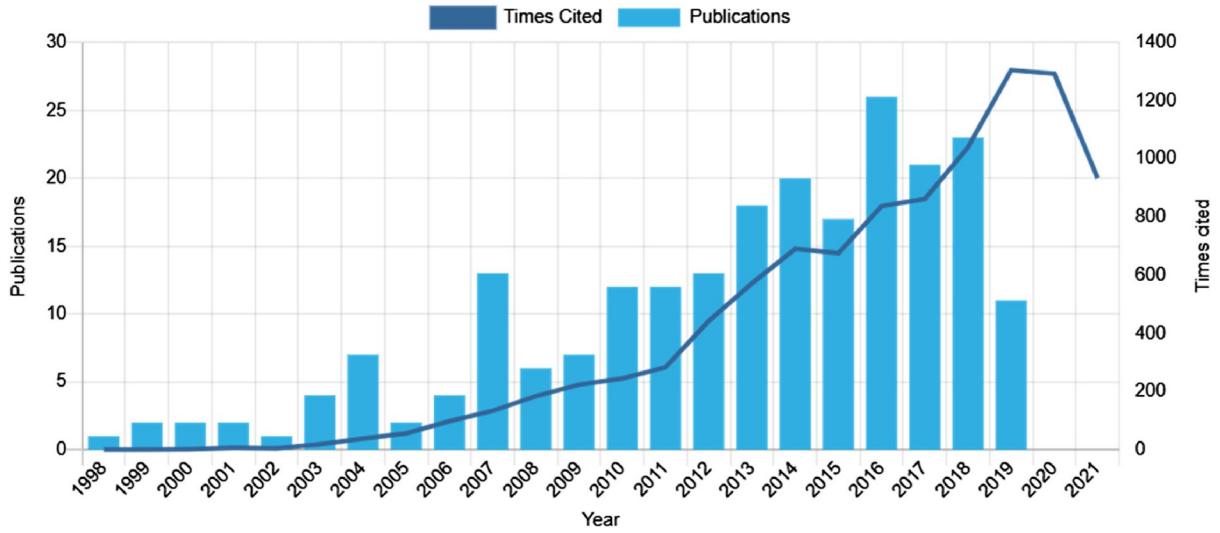

Fig. 3. Fuqing ZHANG's impact over time up to 4 September 2021 (adapted from Web of Science).

ity. He was the first to demonstrate that upscale growth of initial model errors through moist convective processes may limit the predictability of severe weather and related mesoscale processes (Zhang et al., 2002, 2003; Zhang, 2005). He further highlighted the impact of moist processes on atmospheric predictability in a conceptual model of multiscale multistage error growth (Zhang et al., 2007) and in different flow regimes such as tropical cyclones (e.g., Sippel and Zhang, 2008, 2010; Zhang and Sippel, 2009; Zhang and Tao, 2013; Melhauser and Zhang, 2014; Tao and Zhang, 2014, 2015) and mesoscale convective systems (e.g., Zhang et al., 2006; Melhauser and Zhang, 2012). He and his students demonstrated with high-resolution simulations that moist convection and/or gravity waves are able to generate the observed −5/3 mesoscale power spectrum slope (Sun and Zhang, 2016; Sun et al., 2017). His paper on "What is the Predictability Limit of Midlatitude Weather?" (Zhang et al., 2019a) represents our most comprehensive knowledge to date on global weather predictability, and it generated wide public, academic, and media interest.

Dynamics of gravity waves associated with jets and fronts

Fuqing ZHANG was the world's leading expert on the dynamics of gravity waves associated with jets and fronts (see the tribute to him on these topics by Ruppert et al., 2021, in the *Bulletin of the American Meteorological Society*). He was the first to propose and demonstrate spontaneous balance adjustment regarding the generation of gravity waves in highly baroclinic situations (Zhang, 2004), supported by a series of rigorous demonstrations (Plougonven and Zhang, 2007; Wang and Zhang, 2007, 2010; Lin and Zhang, 2008; Wang et al., 2009, 2010). He further extended the balance adjustment framework to examine gravity waves in moist baroclinic jet-front systems and systematically disentangled the roles of baroclinic versus convective instabilities (Wei and Zhang, 2014, 2015). These findings have aided in parameterizing the effects of jet-front gravity waves in global models (Wei et al., 2016). He was the chairperson of the 2016 Stratosphere-troposphere Processes And their Role in Climate (SPARC) international gravity wave symposium and a co-leader of SPARC gravity wave activities as part of the World Climate Research Program.

Ensemble-based data assimilation techniques

Fuqing ZHANG was the first to successfully implement the ensemble Kalman filter (EnKF) in assimilating radar data into a cloud-scale model (Snyder and Zhang, 2003; Zhang et al., 2004). He led the development and application of EnKF techniques for combating sampling errors and model uncertainties such as covariance inflation through relaxation to the prior perturbation (Zhang et al., 2004) and adaptive relaxation to the prior spread (Ying and Zhang, 2015), successive covariance localization (Zhang et al., 2009a), multi-physics-scheme ensembles (Meng and Zhang, 2007, 2008a, b), and simultaneous state and parameter estimation (Aksoy et al., 2006a, b; Hu et al., 2010a, b). He was among the first to develop the coupling of EnKF and 4D-Var (Zhang et al., 2009b, Zhang and Zhang, 2012; Poterjoy and Zhang, 2014). The Pennsylvania State University (PSU) ensemble data assimilation system that his group developed is made freely available online and is now widely used for both research (e.g., the United States, Australia, China, and Korea) and operations (e.g., U.S. Naval Research Laboratory and the Meteorological Observatory of Anhui, China) around the world.

Tropical cyclone intensity forecasts

An especially important contribution of Fuqing ZHANG was his efforts in improving tropical cyclone intensity forecasts. The hurricane prediction system he lead-

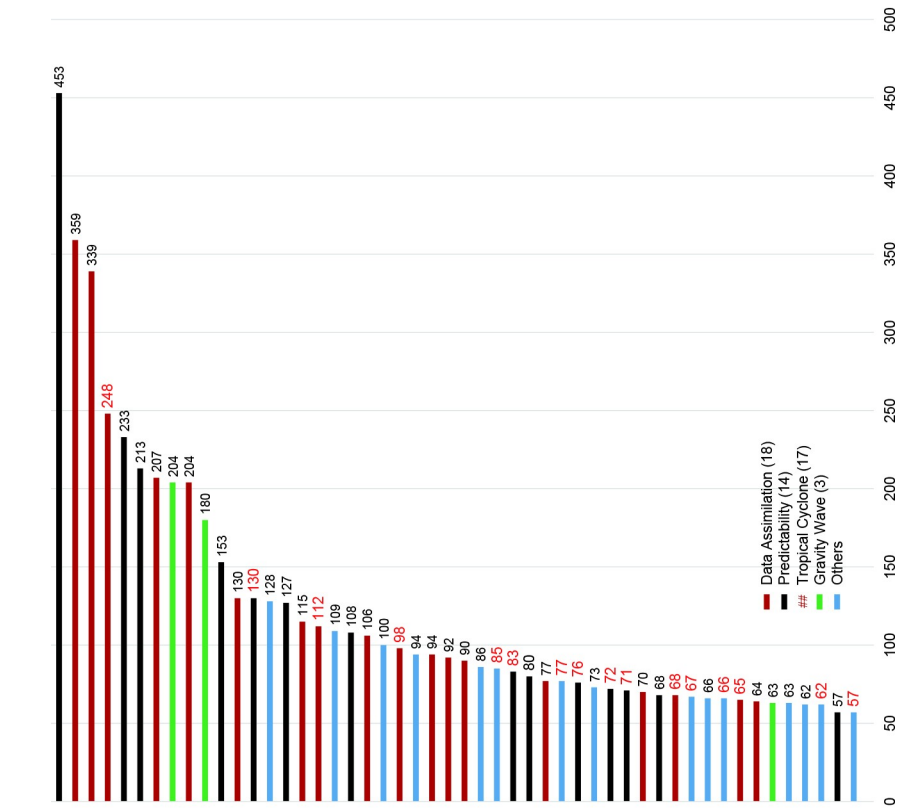

Fig. 4. Top 50 most cited journal papers authored by Fuqing ZHANG up to 4 September 2021. Topics on data assimilation, predictability, and gravity waves are in maroon, black, and green bars, respectively, with the number of papers in each area given within parentheses. The numbers after each bar denote the citation times from Web of Science. Tropical cyclone papers are denoted by the bars with citation times printed in red.

developed using EnKF to assimilate airborne Doppler radar observations in real time showed an improvement in the skill of tropical cyclone intensity forecasts by ~30% over the official National Hurricane Center forecasts (Zhang et al., 2011; Zhang and Weng, 2015). This, in turn, resulted in the operational implementation of the methodology in the use of airborne Doppler radar by NOAA since 2013. In addition to airborne Doppler radar observations, he also led the development of EnKF in assimilating all-sky satellite radiance (Zhang et al., 2016; Zhang et al., 2019b) and reconnaissance aircraft observations (Weng and Zhang, 2016) for tropical cyclone prediction. This breakthrough has been widely regarded as the first real advance in tropical cyclone intensity forecasts to date, which is not only an important scientific achievement but also a very significant contribution to social welfare.

With so many ground-breaking scientific achievements, as listed but not limited to those above, Fuqing ZHANG received numerous awards, best exemplified by two major research awards from the American Meteorological Society (AMS): the 2009 Clarence Leroy Meisinger Award "for outstanding contributions to mesoscale dynamics, predictability and ensemble data assimilation" and the 2015 Banner I. Miller Award "for valuable insights into incorporating real-time airborne Doppler radar measurements via ensemble data assimilation, leading to improvements in forecasts of tropical cyclone track and intensity." He was awarded the prestigious Pennsylvania State University Faculty Scholar Medal in 2018 "for his innovating and pioneering research on data assimilation" and soon thereafter the title of distinguished professor. He was awarded the Joanne Simpson Medal by the American Geophysical Union (AGU) in December 2019 "for significant contributions to the Earth and space sciences by an outstanding mid-career scientist". He became an elected AMS fellow in 2015 and AGU fellow in 2018.

Over all of his professional years, Fuqing ZHANG attached great importance to scientific exchanges and collaborations. He always paid full attention to talks and lectures during meetings, seldom opening a laptop. He often went to meetings without taking a backpack but always with a focused mind with endless critical questions during meeting sessions and active interactions with colleagues after sessions (Fig. 5). He gave nearly 300 keynote or invited talks at various institutions and meetings. He participated in five field experiments: the Bow-echo And MCV EXperiment (BAMEX), the Stratosphere-Troposphere Analyses of Regional Transport (START08), the PRE-Depression Investigation of Cloud-systems in the Tropics (PREDICT), the Hurricane and Severe Storm Sentinel (HS3), and the Intensity Forecasting EXperiment (IFEX). He also held visiting appointments at various prestigious institutions, including Peking University, Nanjing University, NCAR, Naval Research Laboratory (NRL), NOAA Hurricane Research Division (HRD), Laboratoire de Météorologie Dynamique (LMD), and École Normale Supérieure of Paris. He was selected as the 2015 Rossby Fellow of the International Meteorological Institute of Sweden, a Houghton Lecturer at MIT during his 2015 fall sabbatical, the Nordenskjöld Lecturer at University of Gothenburg in 2016, the 2017 Burgers Keynote Lecturer at University of Maryland, and the GoCAS Distinguished Chair to lead the 2018 Gothenburg Chair Programme for Advanced Studies.

Fig. 5. Fuqing ZHANG asking questions at the Multiscale Convection Summer School from 27–30 May 2019 held at Peking University in Beijing, China. This summer school was co-organized by Zhiyong MENG and Fuqing ZHANG.

In addition to his outstanding scientific achievements, Fuqing ZHANG also made great contributions to the atmospheric science community. He mentored more than 60 graduate students, including the first author of this review, and another 60 or so postdoctoral, visiting, and research scientists from all over the world. Many of his mentees have now emerged as leaders in their own respective subdisciplines. He helped to organize 45 national and international workshops and conferences, including 8 EnKF workshops. He served on numerous expert panels or advisory boards for NSF, NASA, NOAA, Office of Naval Research (ONR), AMS, and the National Academies. On 14 November 2017, he was part of the expert panel that gave a congressional briefing on *Science's Impact on Weather Prediction and Economy* organized by the University Corporation of Atmospheric Research (UCAR). He served as editor of several professional journals, including six years as editor of *Monthly Weather Review*. He was an editor for the newest (2nd) edi-

tion of the *Encyclopedia for Atmospheric Sciences* (six volumes, with a total of 2998 pages), as well as a reviewer of articles for more than 30 professional journals and of grant applications for more than 20 funding agencies.

Over the years, Fuqing ZHANG made tremendous contributions to the development of mesoscale meteorology in China and the education of Chinese graduate students and young scientists. Most of the younger generation of scientists in China in the areas of mesoscale meteorology, tropical meteorology, synoptic meteorology, atmospheric predictability, and data assimilation, including all of the lead and corresponding authors of papers in this special issue, were greatly influenced by him, either through direct mentorship or through numerous summer schools and workshops that he organized and ran. He supervised or co-supervised 20 graduate students from 7 universities and 45 visitors from 16 universities, research institutes, and operational meteorological agencies in China. He helped them in both science and life, leading each of them to greater progress in their careers. He acted as a key liaison between China and the world in the field of mesoscale meteorology. He co-organized international summer schools and conferences seven times with Nanjing University, Peking University, the Institute of Atmospheric Physics, and the Chinese Academy of Meteorological Sciences. He invited top scientists in the world to give lectures at the summer schools and conferences, which made China see the world and the world see China. As an editor of the *Journal of Science China Earth Sciences*, he made enormous contributions in improving the quality of the journal. Fuqing's passing is a monumental loss for atmospheric science in China.

All in all, Fuqing ZHANG was an outstanding, incredibly prolific scientist in the atmospheric sciences worldwide. He will be remembered not only for his groundbreaking scientific contributions to a broad range of topics in atmospheric predictability and dynamics, as well as ensemble-based data assimilation for advanced prediction of severe weather and tropical cyclones, but also for his generosity in putting energy and time into efficiently transmitting to the community the new scientific knowledge and ideas that he helped to grow. He helped to shape the careers and lives of many students and mentees in wonderful ways. Even when he was poking holes in his mentees' research, his laugh, mirth, and kindness were never far away. Fuqing ZHANG's dedication to science and his attitude towards life have been, and will continue to be, a great inspiration to many, many people.

Acknowledgements. The authors were inspired to write this review by the important role that Fuqing ZHANG played in their careers and lives. Zhiyong MENG met Fuqing in 1991 and became his Ph.D. student in 2003 at Texas A&M University. Ever since, Zhiyong MENG's career and life have been shaped for the better by him. To Zhiyong MENG, ZHANG was not only a mentor, but also a great friend and as close as family. Eugene E. CLOTHIAUX thoroughly enjoyed all of his years as Fuqing's next-door neighbor on the 6th floor of the Walker Building at the Pennsylvania State University. Fun, delightful, energetic, passionate, and smart scientists from all over the world were Fuqing's constant companions, and he shared them all with all of his neighbors all of the time. Finally, we would like to acknowledge and thank Yunji ZHANG (currently at the Pennsylvania State University and formerly of Peking University) for assembling a complete list of publications and citations of Fuqing ZHANG. Zhiyong MENG was supported by the Natural Science Foundation of China (Grant Nos. 42030604, 41875051, and 41425018) during the writing of this review.

Electronic supplementary material: Supplementary material is available in the online version of this article at https://doi.org/10.1007/s00376-021-1362-x.

REFERENCES

Aksoy, A., F. Q. Zhang, and J. W. Nielsen-Gammon, 2006a: Ensemble-based simultaneous state and parameter estimation in a two-dimensional sea-breeze model. *Mon. Wea. Rev.*, **134**, 2951–2970, https://doi.org/10.1175/MWR3224.1.

Aksoy, A., F. Q. Zhang, and J. W. Nielsen-Gammon, 2006b: Ensemble-based simultaneous state and parameter estimation with MM5. *Geophys. Res. Lett.*, **33**, L12801, https://doi.org/10.1029/2006GL026186.

Hu, X.-M., F. Q. Zhang, and J. W. Nielsen-Gammon, 2010a: Ensemble-based simultaneous state and parameter estimation for treatment of mesoscale model error: A real-data study. *Geophys. Res. Lett.*, **37**, L08802, https://doi.org/10.1029/2010GL043017.

Hu, X.-M., J. W. Nielsen-Gammon, and F. Q. Zhang, 2010b: Evaluation of three planetary boundary layer schemes in the WRF Model. *J. Appl. Meteorol. Climatol.*, **49**, 1831–1844, https://doi.org/10.1175/2010JAMC2432.1.

Lin, Y. H., and F. Q. Zhang, 2008: Tracking gravity waves in baroclinic jet-front systems. *J. Atmos. Sci.*, **65**, 2402–2415, https://doi.org/10.1175/2007JAS2482.1.

Melhauser, C., and F. Q. Zhang, 2012: Practical and intrinsic predictability of severe and convective weather at the mesoscales. *J. Atmos. Sci.*, **69**, 3350–3371, https://doi.org/10.1175/JAS-D-11-0315.1.

Melhauser, C., and F. Q. Zhang, 2014: Diurnal radiation cycle impact on the pregenesis environment of Hurricane Karl (2010). *J. Atmos. Sci.*, **71**, 1241–1259, https://doi.org/10.1175/JAS-D-13-0116.1.

Meng, Z. Y., and F. Q. Zhang, 2007: Tests of an ensemble Kalman filter for mesoscale and regional-scale data assimilation. *Part II: Imperfect model experiments. Mon. Wea. Rev.*, **135**, 1403–1423, https://doi.org/10.1175/MWR3352.1.

Meng, Z. Y., and F. Q. Zhang, 2008a: Tests of an ensemble Kalman filter for mesoscale and regional-scale data assimilation. *Part III: Comparison with 3DVAR in a real-data case study. Mon. Wea. Rev.*, **136**, 522–540, https://doi.org/10.1175/2007MWR2106.1.

Meng, Z. Y., and F. Q. Zhang, 2008b: Tests of an ensemble Kalman filter for mesoscale and regional-scale data assimilation. *Part IV: Comparison with 3DVAR in a month-long experiment. Mon. Wea. Rev.*, **136**, 3671–3682, https://doi.org/10.1175/2008MWR2270.1.

Plougonven, R., and F. Q. Zhang, 2007: On the forcing of inertia-

gravity waves by synoptic-scale flows. *J. Atmos. Sci.*, **64**, 1737–1742, https://doi.org/10.1175/JAS3901.1.

Poterjoy, J., and F. Q. Zhang, 2014: Intercomparison and coupling of ensemble and four-dimensional variational data assimilation methods for the analysis and forecasting of Hurricane Karl (2010). *Mon. Wea. Rev.*, **142**, 3347–3364, https://doi.org/10.1175/MWR-D-13-00394.1.

Ruppert, J. H. Jr., S. E. Koch, X. C. Chen, Y. Du, A. Seimon, Y. Q. Sun, J. H. Wei, and L. F. Bosart, 2021: Mesoscale gravity waves and midlatitude weather: A tribute to Fuqing Zhang. *Bull. Amer. Meteor. Soc.*, https://doi.org/10.1175/BAMS-D-20-0005.1.

Sippel, J. A., and F. Q. Zhang, 2008: A probabilistic analysis of the dynamics and predictability of tropical cyclogenesis. *J. Atmos. Sci.*, **65**, 3440–3459, https://doi.org/10.1175/2008JAS2597.1.

Sippel, J. A., and F. Q. Zhang, 2010: Factors affecting the predictability of hurricane Humberto (2007). *J. Atmos. Sci.*, **67**, 1759–1778, https://doi.org/10.1175/2010JAS3172.1.

Snyder, C., and F. Q. Zhang, 2003: Assimilation of simulated doppler radar observations with an ensemble Kalman filter. *Mon. Wea. Rev.*, **131**, 1663–1677, https://doi.org/10.1175//2555.1.

Sun, Y. Q., and F. Q. Zhang, 2016: Intrinsic versus practical limits of atmospheric predictability and the significance of the butterfly effect. *J. Atmos. Sci.*, **73**, 1419–1438, https://doi.org/10.1175/JAS-D-15-0142.1.

Sun, Y. Q., R. Rotunno, and F. Q. Zhang, 2017: Contributions of moist convection and internal gravity waves to building the atmospheric -5/3 kinetic energy spectra. *J. Atmos. Sci.*, **74**, 185–201, https://doi.org/10.1175/JAS-D-16-0097.1.

Tao, D. D., and F. Q. Zhang, 2014: Effect of environmental shear, sea-surface temperature, and ambient moisture on the formation and predictability of tropical cyclones: An ensemble-mean perspective. *Journal of Advances in Modeling Earth Systems*, **6**, 384–404, https://doi.org/10.1002/2014MS000314.

Tao, D. D., and F. Q. Zhang, 2015: Effects of vertical wind shear on the predictability of tropical cyclones: Practical versus intrinsic limit. *Journal of Advances in Modeling Earth Systems*, **7**, 1534–1553, https://doi.org/10.1002/2015MS000474.

Wang, S. G., and F. Q. Zhang, 2007: Sensitivity of mesoscale gravity waves to the baroclinicity of jet-front systems. *Mon. Wea. Rev.*, **135**, 670–688, https://doi.org/10.1175/MWR3314.1.

Wang, S. G., and F. Q. Zhang, 2010: Source of gravity waves within a vortex-dipole jet revealed by a linear model. *J. Atmos. Sci.*, **67**, 1438–1455, https://doi.org/10.1175/2010JAS3327.1.

Wang, S. G., F. Q. Zhang, and C. Snyder, 2009: Generation and propagation of inertia-gravity waves from vortex dipoles and jets. *J. Atmos. Sci.*, **66**, 1294–1314, https://doi.org/10.1175/2008JAS2830.1.

Wang, S. G., F. Q. Zhang, and C. C. Epifanio, 2010: Forced gravity wave response near the jet exit region in a linear model. *Quart. J. Roy. Meteor. Soc.*, **136**, 1773–1787, https://doi.org/10.1002/qj.676.

Wei, J. H., and F. Q. Zhang, 2014: Mesoscale gravity waves in moist baroclinic jet-front systems. *J. Atmos. Sci.*, **71**, 929–952, https://doi.org/10.1175/JAS-D-13-0171.1.

Wei, J. H., and F. Q. Zhang, 2015: Tracking gravity waves in moist baroclinic jet-front systems. *Journal of Advances in Modeling Earth Systems*, **7**, 67–91, https://doi.org/10.1002/2014MS000395.

Wei, J. H., F. Q. Zhang, and J. H. Richter, 2016: An analysis of gravity wave spectral characteristics in moist baroclinic jet-front systems. *J. Atmos. Sci.*, **73**, 3133–3155, https://doi.org/10.1175/JAS-D-15-0316.1.

Weng, Y. H., and F. Q. Zhang, 2016: Advances in convection-permitting tropical cyclone analysis and prediction through EnKF assimilation of reconnaissance aircraft observations. *J. Meteor. Soc. Japan*, **94**, 345–358, https://doi.org/10.2151/jmsj.2016-018.

Ying, Y., and F. Q. Zhang, 2015: An adaptive covariance relaxation method for ensemble data assimilation. *Quart. J. Roy. Meteor. Soc.*, **141**, 2898–2906, https://doi.org/10.1002/qj.2576.

Zhang, F. Q., 2004: Generation of mesoscale gravity waves in upper-tropospheric jet-front systems. *J. Atmos. Sci.*, **61**, 440–457, https://doi.org/10.1175/1520-0469(2004)061<0440:GOMGWI>2.0.CO;2.

Zhang, F. Q., 2005: Dynamics and structure of mesoscale error covariance of a winter cyclone estimated through short-range ensemble forecasts. *Mon. Wea. Rev.*, **133**, 2876–2893, https://doi.org/10.1175/MWR3009.1.

Zhang, F. Q., and J. A. Sippel, 2009: Effects of moist convection on hurricane predictability. *J. Atmos. Sci.*, **66**, 1944–1961, https://doi.org/10.1175/2009JAS2824.1.

Zhang, F. Q., and D. D. Tao, 2013: Effects of vertical wind shear on the predictability of tropical cyclones. *J. Atmos. Sci.*, **70**, 975–983, https://doi.org/10.1175/JAS-D-12-0133.1.

Zhang, F. Q., and Y. H. Weng, 2015: Predicting hurricane intensity and associated hazards: A five-year real-time forecast experiment with assimilation of airborne Doppler radar observations. *Bull. Amer. Meteor. Soc.*, **96**, 25–32, https://doi.org/10.1175/BAMS-D-13-00231.1.

Zhang, F. Q., C. Snyder, and R. Rotunno, 2002: Mesoscale predictability of the "surprise" snowstorm of 24–25 January 2000. *Mon. Wea. Rev.*, **130**, 1617–1632, https://doi.org/10.1175/1520-0493(2002)130<1617:MPOTSS>2.0.CO;2.

Zhang, F. Q., C. Snyder, and R. Rotunno, 2003: Effects of moist convection on mesoscale predictability. *J. Atmos. Sci.*, **60**, 1173–1185, https://doi.org/10.1175/1520-0469(2003)060<1173:EOMCOM>2.0.CO;2.

Zhang, F. Q., C. Snyder, and J. Z. Sun, 2004: Impacts of initial estimate and observation availability on convective-scale data assimilation with an ensemble Kalman filter. *Mon. Wea. Rev.*, **132**, 1238–1253, https://doi.org/10.1175/1520-0493(2004)132<1238:IOIEAO>2.0.CO;2.

Zhang, F. Q., A. M. Odins, and J. W. Nielsen-Gammon, 2006: Mesoscale predictability of an extreme warm-season precipitation event. *Wea. Forecasting*, **21**, 149–166, https://doi.org/10.1175/WAF909.1.

Zhang, F. Q., N. F. Bei, R. Rotunno, C. Snyder, and C. C. Epifanio, 2007: Mesoscale predictability of moist baroclinic waves: Cloud-permitting experiments and multistage error growth dynamics. *J. Atmos. Sci.*, **64**, 3579–3594, https://doi.org/10.1175/JAS4028.1.

Zhang, F. Q., Y. H. Weng, J. A. Sippel, Z. Y. Meng, and C. H. Bishop, 2009a: Cloud-resolving hurricane initialization and prediction through assimilation of Doppler radar observations with an ensemble Kalman filter. *Mon. Wea. Rev.*, **137**, 2105–2125, https://doi.org/10.1175/2009MWR2645.1.

Zhang, F. Q., M. Zhang, and J. A. Hansen, 2009b: Coupling ensemble Kalman filter with four-dimensional variational data assimilation. *Adv. Atmos. Sci.*, **26**, 1–8, https://doi.org/10.1007/s00376-009-0001-8.

Zhang, F. Q., Y. H. Weng, J. F. Gamache, and F. D. Marks, 2011: Performance of convection- permitting hurricane initialization and prediction during 2008–2010 with ensemble data assimilation of inner-core airborne Doppler radar observations. *Geophys. Res. Lett.*, **38**, L15810, https://doi.org/10.1029/2011GL048469.

Zhang, F. Q., M. Minamide, and E. E. Clothiaux, 2016: Potential impacts of assimilating all-sky infrared satellite radiances from GOES-R on convection-permitting analysis and prediction of tropical cyclones. *Geophys. Res. Lett.*, **43**, 2954–2963, https://doi.org/10.1002/2016GL068468.

Zhang, F. Q., Y. Q. Sun, L. Magnusson, R. Buizza, S. J. Lin, J. H. Chen, and K. Emanuel, 2019a: What is the predictability limit of midlatitude weather. *J. Atmos. Sci.*, **76**, 1077–1091, https://doi.org/10.1175/JAS-D-18-0269.1.

Zhang, F. Q., M. Minamide, R. G. Nystrom, X. C. Chen, S. J. Lin, and L. M. Harris, 2019b: Improving Harvey forecasts with next-generation weather satellites: Advanced hurricane analysis and prediction with assimilation of *GOES-R* All-Sky Radiances. *Bull. Amer. Meteor. Soc.*, **100**, 1217–1222, https://doi.org/10.1175/BAMS-D-18-0149.1.

Zhang, M., and F. Q. Zhang, 2012: E4DVar: Coupling an ensemble Kalman filter with four-dimensional variational data assimilation in a limited-area weather prediction model. *Mon. Wea. Rev.*, **140**, 587–600, https://doi.org/10.1175/MWR-D-11-00023.1.