Prologue: Tropical Meteorology 1960–2010—Personal Recollections

TAROH MATSUNO

Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan

This volume consists of some papers presented at the AMS Symposium held to honor the memory of the late Professor Michio Yanai as well as additional works inspired by his research. By the nature of this volume, many of the contributed papers describe the development of tropical meteorology over the past half-century or so in connection with Professor Yanai's influence on it. While most of the chapters address specific areas and discuss timely issues, in this prologue I will describe some of Professor Yanai's contributions during the early period of his career from my own point of view. As this is a personal reminiscence, I would like to emphasize how Professor Yanai influenced me.

Both Professor Yanai and I became graduate students at the University of Tokyo to begin our career as meteorologists in 1956 and 1957, respectively. Since we studied and worked together so closely for a long time, in this article I will call him Yanai-san as I have done in our personal interactions.

1. Emergence of CISK and convection parameterization

Operational numerical weather prediction (NWP) began in the late 1950s, within a decade from the first successful computer-generated 500-mb (1 mb = 1 hPa) height prediction (Charney et al. 1950). The Japan Meteorological Agency (JMA) started routine NWP in 1959, following in the footsteps of Sweden (1954) and the United States (1955). In November 1960, the International Symposium on NWP was held at Tokyo. It was very timely, and the world's prominent figures in the field attended. Looking back at the proceedings (Syono et al. 1962), we can see that the symposium represents an important landmark concerning the dynamics and numerical modeling of tropical cyclones and convection. Since the successful realization of NWP implies that the baroclinic instability theory of extratropical cyclones had been verified through practical applications, the tropical cyclone became the next major target of dynamic meteorology and numerical modeling.

Professor Shigekata Syono of the University of Tokyo, our supervisor and the symposium organizer, had published a paper in *Tellus* early in 1953 discussing the formation mechanism of tropical cyclones using linear theory (Syono 1953). He tried to explain the formation in terms of the static instability, which must be correct considering its energy source. When a computer became available, he directly applied this theory of typhoon formation via numerical simulation, with the help of a young graduate student named Takao Takeda, who subsequently published a paper on the mechanism of the long-lasting convection cell or squall line (Takeda 1971).

At the symposium, Professor Syono reported the result, showing that the initially specified, slow upward motion over a 300-km region did not intensify uniformly; instead, extremely strong vertical motion was concentrated in a 15-km central region. Just prior to this

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Corresponding author address: Taroh Matsuno, Principal Scientist, Japan Agency for Marine-Earth Science and Technology, 3173-25, Showamachi, Kanazawaku, Yokohama 236-0001, Japan.
E-mail: matsuno@jamstec.go.jp

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presentation, Dr. Akira Kasahara from the University of Chicago talked about results of his numerical experiments that were almost identical with Professor Syono's, except that he had used a linear stability analysis to show that the maximum growth rate was at the smallest possible scale. Questions and intensive discussions followed, which included contributions by Professor Jule Charney.

Charney commented that the dominance of the smallest scale was nothing but a manifestation of Bénard-like convection owing to conditional instability, which corresponds to cumulus clouds in the real atmosphere. Then he talked about his ongoing study with Dr. Yoshimitsu Ogura, suggesting that they had encountered a similar difficulty that they were currently working to overcome. Charney stated that ''a typhoon and the cumulus clouds do not compete but they cooperate . . . actually cooperate to maintain the energy of the large-scale system.'' Then he identified the crux of the problem: ''But . . . cumulus clouds are very small-scale phenomena. How do you handle that in the numerical prediction scheme? Isn't it very difficult to deal with both small and large scales?'' For more about this and the origin of cumulus parameterization, see Kasahara (2000).

Following this, Yanai-san made a presentation on a detailed analysis of the formation process of Typhoon Doris, which was a part of his doctoral thesis. An interesting discussion followed, but more important was conversation and discussion that took place when Professor Charney visited Professor Syono at the University of Tokyo prior to the symposium. Later, Yanai-san talked often about this visit, recalling that he was surprised and deeply impressed that Charney, the field's top theoretician, had showed a keen interest in his detailed analysis of this complicated, real-world phenomenon. Considering that Professor Charney was in the midst of a struggle concerning how to handle cumulus clouds as part of larger-scale dynamics, Yanai-san's work must have represented what he most wanted to know. In any event, Yanai-san was thankful that, as a result of Charney's interest, Professor Syono had changed his evaluation of Yanai-san's work, which he had thought did not include enough dynamics.

As to Yanai-san's thoughts on this problem, I do not have clear memory. However, as another part of his thesis work, he wrote a paper titled ''Dynamical aspects of typhoon formation'' (Yanai 1961), in which he proposed inertial instability, found at upper levels near the center of a typhoon, as integral to the large-scale dynamics of tropical cyclone development. In the conclusion of this paper, he wrote that the ''actual condensation process takes place in individual cumulus clouds, and their horizontal sizes are utterly different from large scale of the pre-existing vertical motion. Therefore . . . in the dynamics of typhoons, some artificial modification in treatment seems to be necessary'' (Yanai 1961, p. 304). In this way, Yanai-san was involved in the birth of both cumulus parameterization and conditional instability of second kind (CISK).

It was a few years after the symposium that these key concepts of the new tropical meteorology emerged in the papers by Ooyama (1964) and Charney and Eliassen (1964). The work of Dr. Ooyama was presented in early 1963 at an international symposium, and its content had a great impact on Japanese meteorologists, including myself. Collaborating with a new graduate student, Masanori Yamasaki, we began a numerical experiment of typhoon formation, based on the primitive equations and a cumulus parameterization scheme which we discovered later to be similar to H. L. Kuo's scheme. By conducting two (or three) integrations with different sea surface temperature (SST) conditions, we concluded that typhoons can develop under the initial conditions represented by the Jordan (1958) tropical atmosphere when the SST exceeded 27°C. We reported our results to Professor Syono, asking to present the result at the Berkeley International Union of Geodesy and Geophysics (IUGG) meeting, but he declined because he was still sticking with the original experiment, questioning the use of parameterization.

As noted previously, there were many important papers concerning tropical meteorology and convection presented at the Tokyo NWP symposium. In the ''Mesoscale Phenomena'' session, Professors Ogura and Chaney presented their early results, entitled ''A numerical model of thermal convection in the atmosphere,'' which used the nonhydrostatic equations to examine convection caused by a moving head of a cold front. It was soon after this that the paper by Ogura and Phillips (1962) on the anelastic approximation appeared. Professor

Kuo's presentation was titled ''On cellular convection and heat transfer,'' which was a finite amplitude theory of Bénard convection, a cutting-edge problem in fluid mechanics at that time. Although he could not come to the symposium, Professor Yoshi Sasaki contributed the paper ''Effects of condensation, evaporation and rainfall on development of mesoscale disturbances: A numerical experiment.'' As this title suggests, this was perhaps the first study to discuss the mechanisms underlying the typical features of mesoscale systems known from observation by performing a numerical experiment. Thus, the early 1960s was the time that a new stream in the study of tropical meteorology and convection emerged following the success of NWP.

2. Equatorial waves in the stratosphere

While he was affiliated with the Meteorological Research Institute of the JMA, Yanai-san spent two years at Colorado State University at the invitation of Professor Herbert Riehl. Soon after returning to Japan, in April 1965, he was appointed as an associate professor of meteorology at the University of Tokyo, where I was working as a research associate. As a new university professor, he looked for something new to study with his graduate students. In those days, the stratosphere was a research frontier in meteorology. New and unique phenomena were being discovered owing to expansion of the routine radiosonde observations up to the 100-mb level. The opening of the ''space era'' by the launch of Sputnik on 4 October 1957 also drew the attention of meteorologists to the upper atmosphere.

In the upper atmosphere, two mysterious phenomena stood out: sudden stratospheric warmings (SSWs) and the quasi-biennial oscillation (QBO) of zonal winds at equatorial stratosphere. Working in tropical meteorology, Yanai-san decided to address the mechanism of the QBO. The core of the mystery concerns how and why the zonal winds alternate directions over the equator. Among a limited number of possibilities, the eddy transport of momentum was supposed to be most likely, and for that there must be ''eddies.'' Thus, Yanai-san started to search for eddies from observational data, with his graduate student Taketo Maruyama.

As luck would have it, a dataset very well suited for this study already existed, consisting of special observations conducted by the U.S. Army to monitor winds up to high levels over the Pacific for nuclear weapon tests. In his thesis work on the analysis of typhoon formation, Yanai-san used those data printed and bound in books that were found on a bookshelf. Thus, in a very short time, the westward movement of disturbances having north–south wind fluctuations was discovered in the raw data plots. The first result was submitted for publication in July 1966, about a year after Yanai-san moved to the University of Tokyo (Yanai and Maruyama 1966).

It is interesting that almost at the same time, across the Pacific at the University of Washington in Seattle, similarly young, new faculty members Professors James Holton and John M. (Mike) Wallace began to investigate the mechanism of the QBO along with Professor Richard Lindzen of the University of Chicago, and their diagnostic study indicated the need for momentum forcing. Thus, a search for disturbances in the equatorial stratosphere as the source of momentum began, involving a graduate student named Kousky. They discovered another kind of disturbance with only zonal wind fluctuations and identified it as an equatorial Kelvin wave (Wallace and Kousky 1968). The research activities of these two groups and their search for tropical waves are described briefly in a story (Madden and Julian 2005) about the discovery of the Madden–Julian oscillation (MJO). In the biographical memoir of the late Professor Holton published quite recently, an early history of investigation of the QBO mechanism is vividly described, including those analysis studies to search for waves (Wallace 2014).

During the period 1965–66, I was working on the theoretical analysis of wave motions at equatorial latitudes where the Coriolis force becomes extremely small and changes sign as my thesis work for my doctorate degree. The motivation for this study was a theoretical interest in the dynamics under this particular condition, which had not been discussed while midlatitude geostrophic dynamics was the major player in the early NWP era. By treating a simple shallow water model on the equatorial β plane, some normal mode solutions were found to have characteristics unique to the equatorial latitudes (Matsuno 1966). They are now known as the (equatorial) Kelvin wave and mixed Rossby–gravity (MRG) wave.

The MRG wave is westward propagating and characterized by meridional wind fluctuations, so I considered that the wave found by Yanai and Maruyama must correspond to this mode. [Maruyama also quickly identified them as MRGs; see Maruyama (1967).] However, in those days I was anxious about the discovery of the equatorial Kelvin wave in the real atmosphere or ocean, as that would become decisive proof of the correctness of the theory. The Wallace and Kousky paper that reported the discovery came out in 1968, after I moved to Kyushu University. Although Yanai-san was occupied with his QBO research, he was very kind to read the draft of my paper and gave me valuable advice to help me to finish the thesis and publish it in time to meet a requirement for my getting a new job at Kyushu University. Thus, at the time of the first report (Yanai and Maruyama 1966), identification of the newly found wave with a mode in the equatorial wave theory was not a top priority.

3. GARP

The greatest innovations in modern atmospheric science and weather prediction are NWP and satellite observation. In the late 1960s, considering the emergence of these two powerful new tools, the world's leading scientists led by Professor Charney created a vision for the future of global-scale weather prediction and discussed how to realize it. This led to the establishment of the Global Atmospheric Research Programme (GARP), to be implemented by international cooperation. As part of its participation, Japan (JMA) decided to launch one of five Geostationary Meteorological Satellites designed to survey the whole globe starting from the First GARP Global Experiment (FGGE) period, 1977–78.

From an early stage (1967), Yanai-san worked actively to contribute to the planning of GARP as a tropical meteorology expert. He proposed a special field observation program to be conducted in the Marshall Islands area in the Pacific, tentatively called the Tropical Meteorology Experiment (TROMEX). Implementation proved difficult owing to the international political situation, and it was replaced by the GARP Atlantic Tropical Experiment (GATE), to be conducted in the tropical Atlantic. Owing to the relocation of the tropical field project, and also because of difficulties at the university because of students' rioting, Yanai-san decided to leave Japan to join the University of California, Los Angeles (UCLA), as a professor.

Soon after arriving at UCLA, Yanai-san actively worked on GATE and, at the same time through cooperation with UCLA Professor Akio Arakawa, he made an analysis of the heat and water vapor budgets in regions of cloud clusters and easterly waves. Collaborating with new graduate students, he first applied basically the same analysis method but to diagnose the ''cloud mass flux'' following Professor Arakawa's new formulation (Yanai et al. 1973). It was very timely that Dr. Tsuyoshi Nitta, Yanai-san's eldest former student, visited UCLA and devised a novel calculation scheme to quantify spectral mass fluxes with different cloud-top heights from observed data. He applied it to the GATE data to obtain reasonable results, suggesting a need for including cloud downdrafts (Nitta 1977). These series of works by Yanai-san's colleagues and students established the method to diagnose the role of convective clouds in various types of tropical weather systems as a standard analysis tool. It has been applied in many studies, and the notations Q_1 and Q_2 originally used in Yanai-san's doctoral thesis work became a common language among tropical meteorologists, as reviewed in Johnson et al. (2016, chapter 1).

As part of his GARP activity, in 1968 Yanai-san worked as a member of an ad hoc Study Group on Tropical Disturbances, along with Professors P. R. Pisharoty and Tetsuya Fujita. They examined the then very new satellite images of tropical clouds and attempted a classification of them. According to the report, they identified three types: ''cloud clusters,'' "monsoon clusters," and "popcorn cumulonimbi." At this time, Yanai-san was still in Japan and I listened to his explanations, which stimulated my special interest in cloud clusters.

4. Twinkling cloud clusters—What are you?

In the mid-1960s, when cloud imagery by satellite observation became available to meteorologists for the first time, some cloud images appeared as anticipated but some others were previously unimaginable. To me, clouds associated with extratropical cyclones and fronts looked very much like those drawn in many textbooks based on the cyclone model of the Bergen school. In contrast to this, the appearance of cloud clusters in the tropics was completely beyond imagination, at least for me. Their sizes are 100–500 km or even larger, which are comparable to tropical cyclones or smallest extratropical cyclones, so that they must represent some kind of as-yet-unknown weather system. I was shocked and puzzled by their existence. After a while, I came to think that they must represent a kind of mesoscale convective system and confirmed that by asking specialists in this field.

However, another question arose. In midlatitudes, mesoscale convective systems develop in small areas under limited conditions where the vertical stratification becomes a state of (large) latent instability, perhaps because of particular situations of the larger-scale flow fields. In contrast to this, cloud clusters are ubiquitous in the tropics. They develop everywhere and every day are scattered over tropical areas around the world, just as extratropical cyclones are seen always occupying mid- and high-latitude areas.

Noting this comparison, we come to consider that cloud clusters are nothing but the manifestation of convective activity transporting energy upward to compensate for radiative energy loss aloft. Usually in textbooks this function is attributed to "convective clouds" or "cumulus and cumulonimbus clouds," but actually, these clouds are not distributed individually and uniformly as Bénard cells, nor are all of them organized by larger-scale, well-defined disturbances like tropical cyclones. Most convective clouds always aggregate by themselves to create bigger and very unique cloud systems having their own mechanism and life cycle. Needless to say, the special mechanism for producing mesoscale convective systems originates from the coupling of hydrodynamical and cloud physical processes unique to Earth's atmosphere.

Bearing this point in mind, and recalling that in most general circulation models midlatitude baroclinic waves are treated explicitly by the dynamical equations, I came to think that the generation and dynamics of tropical cloud clusters should also be treated explicitly.

Such thoughts went back to the mid- to late 1960s, when the ubiquitous nature of cloud clusters became apparent. The first question was whether and why tropical cloud clusters must be formed naturally and inevitably when the atmosphere undergoes differential heating. To answer this question, a long-term integration over a large area would be required and, because of computing limitations, I postponed trying to do that. After about 20 years, in the 1980s when computing resources at the University of Tokyo became available for conducting numerical experiments for this purpose, a graduate student Kensuke Nakajima (currently at Kyushu University) developed a 2D cloud dynamics model and performed several experiments with and without some cloud physical processes. From the results, we concluded that if all of a minimum set of cloud physical processes operating within mesoscale convective systems are included, cloud-cluster-like convective patterns appear, but they do not develop when some of the processes are missing. Instead, in those cases, convection of different types appears, including Bénard convection (Nakajima and Matsuno 1988).

I recall that I heard from someone who visited the United States sometime in the 1960s that Dr. Douglas Lilly was also wondering the same thing and said that the best way to answer the question was to perform a numerical experiment. I agreed with this view because it seemed impossible to make a laboratory experiment corresponding to cloud cluster formation, and it also seemed impossible to prove theoretically that the cloud cluster type of convection should occur under the given conditions, in the manner of the theory of Bénard convection or the baroclinic instability theory of extratropical cyclones.

In the course of this research, in 1985 I visited the NASA Goddard Space Flight Center (GSFC) and talked about this. At this time I first met Dr. W.-K. Tao, who, like us, was engaged in development of cloud dynamics models to be used for a wide area of long-term integrations. Since then, he continued his research as one of the leaders in this field (e.g., Tao and Moncrieff 2009). The director of Dr. Tao's branch was Dr. Joanne Simpson, who was truly the founder of atmospheric convection modeling. She published the first paper on the numerical simulation of the motion of a buoyant bubble in the Rossby memorial volume (Malkus and Witt 1959), which got me to recognize that numerical experimentation would become a powerful tool in various fields of atmospheric sciences.

5. TRMM, Earth Simulator, and NICAM

Soon after we met at GSFC, Dr. Simpson and I worked together toward the realization of a U.S.–Japan joint space program, the Tropical Rainfall Measuring Mission (TRMM), as representatives of each side's group of scientists. After a few years, I passed that role to Professor Tsuyoshi Nitta, a former student of Yanai-san and then the most active tropical meteorologist representing Japan. At an early stage, we meteorologist colleagues—Nitta, Sumi, and I—worried that the original plan for the inclination of the satellite orbit, 28°, would be too low to cover the baiu precipitation zone and requested the space agency people to change it to 35°. Since we were so naïve concerning the space program, we were afraid that our request regarding a most basic element of the satellite might be difficult to accept. Regardless of our anxiety, they readily consented to our request. The TRMM satellite was successfully launched on 27 November 1997 and is only now reaching the end of its mission at the time I write these words, after a 17-yr-long operation surpassing many times the originally planned lifespan of 3 years. Tao et al. (2016, chapter 2) describe the latest achievements utilizing the TRMM data by the collaborative team. Currently, the leader of Japan's science team is Professor Yukari Takayabu [coauthor of Takayabu et al. (2016), chapter 3], who was a student of the late Professor Nitta, and so is a grand-student of Yanai-san, as it were.

In the late 1990s, I participated in committees for research projects; one was to develop the world's fastest supercomputer, which was named the Earth Simulator (ES), completed in 2002, and another was a project to promote modeling of the global environment and prediction of global environmental changes. Until this time, meteorologists in Japan had been suffering from a shortage of computer resources for a long time. By my own very crude estimate, we were 10 years or more behind the United States with regard to our computing environment. Suddenly we were going to be given the best computer in the world! To respond to this situation, we would have to challenge ourselves with a new problem of great scientific value, something that was made possible only by the world's most capable computer.

Consulting with Professor Akimasa Sumi, my closest colleague who was working together in leading these projects, I proposed a global atmospheric model with a horizontal mesh size of less than 5 km that could resolve tropical cloud clusters as one of the targets for model development. The 5-km mesh size is marginal for resolving the 10-km-wide upward motion areas typically found in convective systems. However, it was twice the resolution of the formal target (10 km) employed as the reference for the computer architecture design, based on which the maximum effective speed was determined to be 5 teraFLOPS (floating-point operations per second). Doubling the resolution meant increasing the computing time by a factor of 10. Thus, it seemed daunting to run the models at the kind of resolutions that could produce really new, significant results. However, lucky for us that the estimate was wrong! When completed, the ES ran 3 times faster than the officially declared target.

A new model, the Nonhydrostatic Icosahedral Atmosphere Model (NICAM; Satoh et al. 2008), was developed from scratch starting in the year 2000, and the first scientifically significant result was an aquaplanet experiment that came out in early 2005 (Tomita et al.

2005). More lucky and essential for this achievement than the faster computer speed was that young, talented scientists led by Masaki Satoh came to join this ambitious project, dedicating themselves to a work without knowing whether it would produce results accepted by the community or not.

To evaluate the effects of increasing the model's resolution aimed at a fundamental improvement in climate modeling, the Athena project was conducted in 2009–10 under the leadership of Professor Jagadish Shukla. NICAM was adopted as a global atmospheric model with explicit convection as well as the European Center for Medium-Range Weather Forecast's highest-resolution model with parameterized convection. Results of the project are reported in Dirmeyer et al. (2012) and Kinter et al. (2013). Some recent results using NICAM are described in Oouchi and Satoh (2016, chapter 14).

6. Midlatitude versus tropical meteorology

It may be fair to say that the aquaplanet experiment corresponds to a tropical version of Norman Phillips' numerical experiment of the midlatitude general circulation published in 1956 (Phillips 1956). Prior to the NICAM experiment, there was another aquaplanet experiment by Hayashi and Sumi (1986), which was based on a (hydrostatic) primitive equation model including parameterized convection. Results of these two aquaplanet experiments are more or less similar, except that in the NICAM experiment individual cloud clusters of $O(100)$-km size were reproduced correctly. That is, they have mesoscale convective system structure. Thus, the NICAM experiment established that cloud cluster in the tropics is a fundamental structure of the convective system that naturally emerges under realistic conditions, just as baroclinic waves emerged naturally in Phillips' experiment.

In addition to this, both aquaplanet experiments produced active convection areas of $O(1000)$-km size and, at the same time, a wavenumber-1 modulation of them encircling the equator. Both of these large-scale structures moved eastward at about $15\,\mathrm{m\,s^{-1}}$ along the equator (taking 30–35 days for one cycle). The $O(1000)$-km size convection area was named the "super (cloud) cluster," whose observed counterpart was identified in satellite cloud imageries by Nakazawa (1988).

More systematic analysis of the space–time variability of convective clouds in the tropical belt by Takayabu (1994) led to a finding that a major part of the variability follows the dispersion relation of equatorial waves. By use of a novel technique, Wheeler and Kiladis (1999) have succeeded in showing the existence of this variability clearly, which is now referred to as convectively coupled equatorial waves (CCEWs; Kiladis et al. 2009). Through comparison with observational studies of the tropics, we recognize that the aquaplanet experiment can successfully reproduce (Kelvin type) CCEWs in addition to cloud clusters.

Originally, the Hayashi–Sumi aquaplanet experiment was conducted with an anticipation that the MJO might appear naturally as a free oscillation of the tropical atmosphere coupled with convection, and the result was once taken to support this idea. However, owing to the discovery of CCEWs, the MJO is now considered to be a different entity both from the dispersion diagram and structures. As to the background stationary fields, trade winds and an ITCZ located just over the equator are also seen in the model results.

This situation is quite different from the case of Phillips' experiment. In his case, almost all of the major phenomena of meteorologists' interest—the generation of extratropical cyclones, the three-cell structure of the zonal mean meridional circulation, and the strong westerly flow (the jet stream)—were reproduced, solving many long-standing open questions with just one experiment. In contrast to this, in the tropics case, there are many more important phenomena, such as tropical cyclones, easterly waves, and the MJO, that are not found in the aquaplanet experiments. The lack of tropical cyclones and easterly waves is considered to be due to the lack of background vorticity fields. Namely, in the aquaplanet experiment, the trade wind field has complete symmetry about the equator, so that the ITCZ that appears just over the equator is not associated with vorticity, whereas in the real situation the ITCZ is found at off-equatorial latitudes having vorticity. Though it is not yet clear, perhaps the existence of the warm water mass extending from the Indian Ocean to the Maritime Continent area may be a necessary condition to the generation of the MJO. Although they appear in nature, the monsoon circulation and the Walker circulation, which are important in tropical meteorology, are also (understandably) missing. From this comparison, we realize that understanding and simulation of the tropical weather and circulation are more difficult and complicated.

Perhaps the ultimate origin of this dissimilarity lies in the difference of the scales of energy sources. In midlatitude dynamics, the energy source for circulations is in the baroclinic instability that produces waves whose scales are several thousand kilometers. Finer structures like jet streams and fronts are generated from the largest-scale energy-containing eddies. Further, because of the stable stratification, all dynamical evolution of flow and temperature fields is constrained by potential vorticity conservation, which give us a feeling that their evolution is ''stiff.''

In contrast, in the tropics the ultimate energy source is vertical instability that first produces convective clouds with a 10-km horizontal size. Then, via coupling with other processes, larger-scale structure and flows are generated. The generation of the cloud cluster is the first level in the size hierarchy above the individual cloud scale. If there is a background vorticity field with the proper configuration, cloud clusters may couple with it to strengthen the rotational motion. The surface inhomogeneity is much more influential in the generation of tropical convection and associated circulations compared with its effect on large-scale baroclinic waves in the midlatitude.

Working as a meteorology professor for a long time, I have experienced that giving lectures in an organized style is easy for midlatitude dynamics but difficult for the tropics. Thus, even how to discuss tropical dynamics is a challenge, which is now presented as ''multiscale convection-coupled systems'' in this volume.

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REFERENCES

Charney, J. G., and A. Eliassen, 1964: On the growth of the hurricane depression. *J. Atmos. Sci.*, **21**, 68–75, doi:10.1175/1520-0469(1964)021<0068:OTGOTH>2.0.CO;2.

——, R. Fjörtoft, and J. von Neumann, 1950: Numerical integration of the barotropic vorticity equation. *Tellus*, **2**, 237–254, doi:10.1111/j.2153-3490.1950.tb00336.x.

Dirmeyer, P. A., and Coauthors, 2012: Simulating diurnal cycle of rainfall in climate models: Resolution versus parameterizaion. *Climate Dyn.*, **39**, 399–418, doi:10.1007/s00382-011-1127-9.

Hayashi, Y.-Y., and A. Sumi, 1986: The 30–40 day oscillations simulated in an ''aqua-planet'' model. *J. Meteor. Soc. Japan*, **64**, 451–467.

Johnson, R. H., P. E. Ciesielski, and T. M. Rickenbach, 2016: A further look at Q_1 and Q_2 from TOGA COARE. *Multiscale Convection-Coupled Systems in the Tropics: A Tribute to Dr. Michio Yanai*, *Meteor. Monogr.*, No. 56, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0002.1.

Jordan, C. L., 1958: Mean soundings for the West Indies area. *J. Meteor.*, **15**, 91–97, doi:10.1175/1520-0469(1958)015<0091:MSFTWI>2.0.CO;2.

Kasahara, A., 2000: On the origin of cumulus parameterization for numerical prediction models. *General Circulation Model Development: Past, Present and Future*, D. A. Randall, Ed., Academic Press, 199–224.

Kiladis, G. N., M. C. Wheeler, P. T. Haertel, K. H. Straub, and P. E. Roundy, 2009: Convectively coupled equatorial waves. *Rev. Geophys.*, **47**, RG2003, doi:10.1029/2008RG000266.

Kinter, J. L., III, and Coauthors, 2013: Revolutionalizing climate modeling with Project Athena. *Bull. Amer. Meteor. Soc.*, **94**, 231–245, doi:10.1175/BAMS-D-11-00043.1.

Madden, R. A., and P. R. Julian, 2005: Historical perspective. *Intraseasonal Variability in the Atmosphere–Ocean Climate System*, W. K. M. Lau and D. E. Waliser, Eds., Springer, 1–18.

Malkus, J. S., and G. Witt, 1959: The evolution of a convective element: A numerical calculation. *The Atmosphere and Sea in Motion*, Rockefeller Institute Press, 425–439.

Maruyama, T., 1967: Large-scale disturbances in the equatorial lower stratosphere. *J. Meteor. Soc. Japan*, **45**, 391–408.

Matsuno, T., 1966: Quasi-geostrophic motions in the equatorial area. *J. Meteor. Soc. Japan*, **44**, 25–43.

Nakajima, K., and T. Matsuno, 1988: Numerical experiment concerning the origin of cloud clusters in the tropical atmosphere. *J. Meteor. Soc. Japan*, **66**, 309–329.

Nakazawa, T., 1988: Tropical super-clusters within intraseasonal variations over the western Pacific. *J. Meteor. Soc. Japan*, **66**, 823–839.

Nitta, T., 1977: Response of cumulus updraft and downdraft to GATE A/B-scale motion systems. *J. Atmos. Sci.*, **34**, 1163–1186, doi:10.1175/1520-0469(1977)034<1163:ROCUAD>2.0.CO;2.

Ogura, Y., and N. A. Phillips, 1962: Scale analysis of deep and shallow convection in the atmosphere. *J. Atmos. Sci.*, **19**, 173–179, doi:10.1175/1520-0469(1962)019<0173:SAODAS>2.0.CO;2.

Oouchi, K., and M. Satoh, 2016: A synoptic-scale cold-reservoir hypothesis on the origin of the mature-stage super cloud cluster: A case study with a global nonhydrostatic model. *Multiscale Convection-Coupled Systems in the Tropics: A Tribute to Dr. Michio Yanai*, *Meteor. Monogr.*, No. 56, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0008.1.

Ooyama, K., 1964: A dynamical model for the study of tropical cyclone development. *Geofis. Int.*, **4**, 187–198.

Phillips, N. A., 1956: The general circulation of the atmosphere: A numerical experiment. *Quart. J. Roy. Meteor. Soc.*, **82**, 123–164, doi:10.1002/qj.49708235202.

Satoh, M., T. Matsuno, H. Tomita, H. Miura, T. Nasuno, and S. Iga, 2008: Nonhydrostatic icosahedral atmospheric model (NICAM) for global cloud resolving simulations. *J. Comput. Phys.*, **227**, 3486–3514, doi:10.1016/j.jcp.2007.02.006.

Syono, S., 1953: On the formation of tropical cyclones. *Tellus*, **5**, 179–195, doi:10.1111/j.2153-3490.1953.tb01047.x.

——, and Coauthors, Eds., 1962: *Proceedings of International Symposium on Numerical Weather Prediction in Tokyo, 1960*. Meteorological Society of Japan, 656 pp.

Takayabu, Y., 1994: Large-scale wave disturbances associated with equatorial waves. Part 1: Spectral features of cloud disturbances. *J. Meteor. Soc. Japan*, **72**, 433–449.

——, G. N. Kiladis, and V. Magaña, 2016: Michio Yanai and tropical waves. *Multiscale Convection-Coupled Systems in the Tropics: A Tribute to Dr. Michio Yanai*, *Meteor. Monogr.*, No. 56, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0019.1.

Takeda, T., 1971: Numerical simulation of a precipitating convective cloud: The formation of a ‘‘long-lasting’’ cloud. *J. Atmos. Sci.*, **28**, 350–375, doi:10.1175/1520-0469(1971)028<0350:NSOAPC>2.0.CO;2.

Tao, W.-K., and M. W. Moncrieff, 2009: Multi-scale cloud system modeling. *Rev. Geophys.*, **47**, RG4002, doi:10.1029/2008RG000276.

——, and Coauthors, 2016: TRMM latent heating retrieval: Applications and comparisons with field campaigns and large-scale analyses. *Multiscale Convection-Coupled Systems in the Tropics: A Tribute to Dr. Michio Yanai*, *Meteor. Monogr.*, No. 56, Amer. Meteor. Soc., doi:10.1175/AMSMONOGRAPHS-D-15-0013.1.

Tomita, H., H. Miura, S. Iga, T. Nasuno, and M. Satoh, 2005: A global cloud resolving simulation: Preliminary results from an aqua planet experiment. *Geophys. Res. Lett.*, **32**, L08805, doi:10.1029/2005GL022459.

Wallace, J. M., 2014: James R. Holton, 1938–2004, U.S. National Academy of Sciences Biographical Memoirs, 27 pp. [Available online at http://nasonline.org/publications/biographical-memoirs/.]

——, and V. E. Kousky, 1968: Observational evidence of Kelvin waves in the tropical stratosphere. *J. Atmos. Sci.*, **25**, 900–907, doi:10.1175/1520-0469(1968)025<0900:OEOKWI>2.0.CO;2.

Wheeler, M. C., and G. N. Kiladis, 1999: Convectively coupled equatorial waves: Analysis of cloud and temperature in the wavenumber-frequency domain. *J. Atmos. Sci.*, **56**, 374–399, doi:10.1175/1520-0469(1999)056<0374:CCEWAO>2.0.CO;2.

Yanai, M., 1961: Dynamical aspects of typhoon formation. *J. Meteor. Soc. Japan*, **39**, 282–309.

——, and T. Maruyama, 1966: Stratospheric wave disturbances propagating over the equatorial Pacific. *J. Meteor. Soc. Japan*, **44**, 291–294.

——, S. Esbensen, and J.-H. Chu, 1973: Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. *J. Atmos. Sci.*, **30**, 611–627, doi:10.1175/1520-0469(1973)030<0611:DOBPOT>2.0.CO;2.