Idealized Numerical Experiments on the Space-time Structure of Cumulus Convection Using a Large-domain Two-dimensional Cumulus-Resolving Model

Kensuke Nakajima

Center for Global Environmental Research
National Institute for Environmental Studies, Japan
Idealized Numerical Experiments on the Space-time Structure of Cumulus Convection Using a Large-domain Two-dimensional Cumulus-Resolving Model

Kensuke Nakajima

Center for Global Environmental Research

National Institute for Environmental Studies, Japan
Supercomputer Steering Committee (FY2010):
Yasumasa Kanada (University of Tokyo)
Shoji Kusunoki (Meteorological Research Institute)
Koki Maruyama (Central Research Institute of Electric Power Industry)
Akira Noda (Japan Agency for Marine-Earth Science and Technology)
Takashi Imamura (NIES)
Kunio Kohata (NIES)
Kazumi Kishibe (EIC/NIES)
Yukihiro Nojiri (CGER/NIES)

Coordination for Resource Allocation of the Supercomputer
Center for Global Environmental Research
National Institute for Environmental Studies

Maintenance of the Supercomputer System
Environmental Information Center
National Institute for Environmental Studies

Operation of the Supercomputer System:
NEC Corporation

Editorial Board:
Center for Global Environmental Research

Copies of this report can be obtained by contacting:
Center for Global Environmental Research
National Institute for Environmental Studies
16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan
Fax: +81-29-858-2645
E-mail: www-cger@nies.go.jp

The report is also available as a PDF file.
See: http://www.cger.nies.go.jp

Copyright 2011:
NIES: National Institute for Environmental Studies

This publication is printed on paper manufactured entirely from recycled material (Rank A), in accordance with the Law Concerning the Promotion of Procurement of Eco-Friendly Goods and Services by the State and Other Entities.
Foreword

The Center for Global Environmental Research (CGER) at the National Institute for Environmental Studies (NIES) was established in October 1990. CGER’s main objectives are to contribute to the scientific understanding of global change and to identify solutions for pressing environmental problems. CGER conducts environmental research from interdisciplinary, multi-agency, and international perspectives, provides an intellectual infrastructure for research activities in the form of databases and a supercomputer system, and makes the data from its long-term monitoring of the global environment available to the public.

CGER installed its first supercomputer system (NEC SX-3, Model 14) in March 1992. That system was subsequently upgraded to an NEC Model SX-4/32 in 1997, and an NEC Model SX-6 in 2002. In March 2007, we replaced that system with an NEC Model SX-8R/128M16 in order to provide an increased capacity for speed and storage. We expect our research to benefit directly from this upgrade.

The supercomputer system is available for use by researchers from NIES and other research organizations and universities in Japan. The Supercomputer Steering Committee evaluates proposals of research requiring the use of the system. The committee consists of leading Japanese scientists in climate modeling, atmospheric chemistry, ocean environment, computer science, and other areas of concern in global environmental research. In the 2010 fiscal year (April 2010 to March 2011), twelve proposals were approved.

To promote the dissemination of the results, we publish both an Annual Report and occasional Monograph Reports. Annual Reports give the results for all research projects that have used the supercomputer system in a given year, while Monograph Reports present the integrated results of a particular research program.

This Monograph Report presents the results of two-dimensional numerical cumulus convection model. The simplified model setup helps us understand the physical process of cumulus convection, whose treatment in an atmospheric general circulation model has been a serious problem. It is hoped that this report will contribute to the numerical research on cumulus convection and the improvement of an atmospheric general circulation model.

In the years to come, we will continue to support environmental research with our supercomputer resources and disseminate practical information on our results.

January 2011
Preface

The present volume of CGER’S SUPERCOMPUTER MONOGRAPH REPORT series is the 16th publication of research results achieved by users of the supercomputer facilities at the Center of Global Environmental Research (CGER) of the National Institute for Environmental Studies (NIES). Computer resources have been provided to Kensuke Nakajima, who has been affiliated with the Center for Climate System Research (CCSR) of the University of Tokyo from 1992 to 1995 and with the Faculty of Sciences, Kyushu University, from 1995 to the present. From the research supported by the computer resources, this volume summarizes the results directly concerning cumulus convection in the earth's tropical atmosphere. The other topics, which concern convection in the ocean, convection in the atmosphere of the other planets, and the development of numerical models, will be described elsewhere.

Cumulus convection, which is the central theme of this volume, plays various indispensable roles in shaping the earth’s climate systems, for example, via the water cycle, by driving atmospheric circulation by latent heating, and by effect on the radiative energy balance. In spite of the tremendous importance of cloud convection, its treatment in numerical modeling constitutes a history of continuous struggle, mainly because of its small scale compared to the earth’s atmosphere as a whole, and the complexity of its physical processes. The establishment of massively parallel supercomputers such as the Earth Simulator has finally achieved the ambition of “cloud system-resolving” global modeling, while true “cloud-resolving climate simulation,” i.e., 100-year simulation with 1-km grid resolution, is still in our future. Moreover, such calculation would produce so tremendous amount of data that the analysis and the interpretation of the results would be quite formidable task; the complexity of the behavior of the modeled cloud system, without a doubt, would also be hard for us to understand in a simple framework.

The numerical experiments collected in this volume were performed using two-dimensional models and are therefore, compared to such calculations in three dimensions, quite compact. Moreover, the setup was kept as simple as possible, so that the results would remain within the reach of our understanding.

The author hopes that this publication will contribute to further progress in global environmental change research, especially as it relates to global warming.

January 2011

Kensuke Nakajima
Faculty of Sciences,
Kyushu University
"cloud-resolving climate simulation," i.e., 100-year simulation with 1-km grid resolution, is finally achieved the ambition of "cloud system-resolving" global modeling, while true
The establishment of massively parallel supercomputers such as the Earth Simulator has
compared to the earth's atmosphere as a whole, and the complexity of its physical processes.
modeling constitutes a history of continuous struggle, mainly because of its small scale
balance. In spite of the tremendous importance of cloud convection, its treatment in numerical
by driving atmospheric circulation by latent heating, and by effect on the radiative energy
indispensable roles in shaping the earth's climate systems, for example, via the water cycle,
the atmosphere of the other planets, and the development of numerical models, will be
this volume summarizes the results directly concerning cumulus convection in the earth's
University, from 1995 to the present. From the research supported by the computer resources,
the University of Tokyo from 1992 to 1995 and with the Faculty of Sciences, Kyushu
Nakajima, who has been affiliated with the Center for Climate System Research (CCSR) of
Environmental Studies (NIES). Computer resources have been provided to Kensuke
Center of Global Environmental Research (CGER) of the National Institute for
the 16th publication of research results achieved by users of the supercomputer facilities at the
complexity of the behavior of the modeled cloud system, without a doubt, would also be hard
that the analysis and the interpretation of the results would be quite formidable task; the
quite compact. Moreover, the setup was kept as simple as possible, so that the results would
two-dimensional models and are therefore, compared to such calculations in three dimensions,
for us to understand in a simple framework.
Cumulus convection, which is the central theme of this volume, plays various
environmental change research, especially as it relates to global warming.

Preface…...........................................................................................................................................

List of Figures ....................................................................................................................................
List of Tables ........................................................................................................................................

Contents

Foreword..............................................................................................................................................i
Preface..................................................................................................................................................ii
Contents...............................................................................................................................................iii
List of Figures ........................................................................................................................................v
List of Tables.......................................................................................................................................vii

Abstract................................................................................................................................................2

Section 1 General Introduction

1.1 Difficulties of cumulus research in the climate context .................................................................3
1.2 Multi-scale structure of moist convection .......................................................................................3
1.3 Deficiency of the “scaled approach” to moist convection ..............................................................4
1.4 Approach of this study ..................................................................................................................6

Section 2 Description of the Numerical Model

2.1 Introduction ..................................................................................................................................8
2.2 Dynamical framework ....................................................................................................................8
2.3 Parameterization of cloud microphysics .......................................................................................9
2.4 Substitute for radiative cooling ....................................................................................................10
2.5 Parameterization of subgrid-scale turbulence .............................................................................10
2.6 Surface fluxes ..............................................................................................................................11
2.7 Finite difference ..........................................................................................................................11
2.8 Basic state and initial conditions .................................................................................................11
List of Symbols ..................................................................................................................................12

Section 3 Cloud Clusters

3.1 Specifications of the experiments.................................................................................................14
3.2 Standard experiments ..................................................................................................................14
3.3 Dependence on the surface flux specifications .............................................................................16
3.4 Dependence on the evaporation of rain .......................................................................................18
3.5 Remarks ......................................................................................................................................19

Section 4 Organization Forced by Large-scale Inhomogeneity

4.1 Specifications of the experiments.................................................................................................20
4.2 Inhomogeneous initial conditions ...............................................................................................20
4.3 Inhomogeneous SST ..................................................................................................................23
4.4 Inhomogeneous radiative cooling ...............................................................................................25

iii
Section 5  Wave-CISK

5.1 Initial note ....................................................................................................................................... 26
5.2 Brief summary of gravity wave-CISK theory ................................................................................. 26
5.3 Setup of the numerical experiments ............................................................................................... 29
5.4 Dependence on the radiative cooling profile .................................................................................. 30
5.5 Wave-CISK with a more complex profile of cumulus heating ....................................................... 35
5.6 Wave-CISK with enhanced rain evaporation .................................................................................. 37
5.7 Wave-CISK over “half-desert” ....................................................................................................... 37

Section 6  Behavior of Wave-CISK on a Planetary Scale

6.1 The purpose, setup, and unexpected results of the extended experiments ...................................... 40
6.2 Preferred scale of wave-CISK and the emergence of planetary scale concentration ...................... 40
6.3 The mechanism of stationary concentration of cloud activity ......................................................... 43
6.4 Sensitivity experiments on the concentration of cloud activity ......................................................... 46
6.5 Possible condition for the emergence of a large-scale stationary mode .......................................... 50

Section 7  Wind-Evaporation Feedback

7.1 Brief introduction to WISHE .......................................................................................................... 52
7.2 Specifications of the experiments .................................................................................................... 52
7.3 Prototypes of WISHE disturbance .................................................................................................. 53
7.4 Sensitivity to the vertical heating profile ......................................................................................... 56
7.5 Vacillation of WISHE ..................................................................................................................... 58
7.6 Remarks ........................................................................................................................................... 62

Section 8  Concluding Remarks .......................................................................................... 63

Plates ..................................................................................................................................................... 65

References ............................................................................................................................................ 71
List of Figures

Section 1

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>&quot;Telescoping network&quot; employed in GATE</td>
<td>5</td>
</tr>
<tr>
<td>1.2</td>
<td>Schematic picture of the idealized tropical atmosphere of the earth</td>
<td>7</td>
</tr>
</tbody>
</table>

Section 2

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Vertical profiles of radiative cooling used in the experiments</td>
<td>10</td>
</tr>
<tr>
<td>2.2</td>
<td>Staggered grid employed for discretization</td>
<td>12</td>
</tr>
</tbody>
</table>

Section 3

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Temporal evolution of the rainfall intensity in case H0</td>
<td>15</td>
</tr>
<tr>
<td>3.2</td>
<td>Temporal evolution of rainfall intensity in a limited region of case H0</td>
<td>15</td>
</tr>
<tr>
<td>3.3</td>
<td>Temporal evolution of heat flux from the ocean in the same limited region of case H0 as in Fig. 3.2</td>
<td>16</td>
</tr>
<tr>
<td>3.4</td>
<td>Space–time spectrum of the rainfall intensity in case H0</td>
<td>16</td>
</tr>
<tr>
<td>3.5</td>
<td>Temporal evolution of the rainfall intensity in case N0</td>
<td>17</td>
</tr>
<tr>
<td>3.6</td>
<td>Temporal evolution of the heat flux from the ocean in case N0</td>
<td>17</td>
</tr>
<tr>
<td>3.7</td>
<td>Temporal evolution of the rainfall intensity in case C2V300</td>
<td>18</td>
</tr>
<tr>
<td>3.8</td>
<td>Temporal evolution of the rainfall intensity in case NRE</td>
<td>19</td>
</tr>
<tr>
<td>3.9</td>
<td>Space–time spectrum of the rainfall intensity in case NRE</td>
<td>19</td>
</tr>
</tbody>
</table>

Section 4

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Temporal evolution of the rainfall intensity in case IT</td>
<td>21</td>
</tr>
<tr>
<td>4.2</td>
<td>Temporal evolution of the rainfall intensity in case IHL</td>
<td>22</td>
</tr>
<tr>
<td>4.3</td>
<td>Temporal evolution of the rainfall intensity in case IHM</td>
<td>22</td>
</tr>
<tr>
<td>4.4</td>
<td>Horizontal distribution of SST anomaly used in case ST2 and ST2V0</td>
<td>23</td>
</tr>
<tr>
<td>4.5</td>
<td>Temporal evolution of the rainfall intensity in case ST2</td>
<td>24</td>
</tr>
<tr>
<td>4.6</td>
<td>Temporal evolution of the rainfall intensity in case ST2V0</td>
<td>24</td>
</tr>
<tr>
<td>4.7</td>
<td>Temporal evolution of the rainfall intensity in case IR</td>
<td>25</td>
</tr>
</tbody>
</table>

Section 5

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Schematic structure of the mechanism of wave-CISK</td>
<td>26</td>
</tr>
<tr>
<td>5.2</td>
<td>The structures of the vertical velocity and heating in usual wave-CISK</td>
<td>28</td>
</tr>
<tr>
<td>5.3</td>
<td>The structures of the vertical velocity and heating in the new type of wave-CISK</td>
<td>29</td>
</tr>
<tr>
<td>5.4</td>
<td>Temporal evolution of the rainfall intensity in case RH</td>
<td>30</td>
</tr>
<tr>
<td>5.5</td>
<td>Temporal evolution of the rainfall intensity in case RL</td>
<td>31</td>
</tr>
<tr>
<td>5.6</td>
<td>Space–time spectrum of the rainfall intensity in case RH</td>
<td>31</td>
</tr>
<tr>
<td>5.7</td>
<td>Space–time spectrum of the rainfall intensity in case RL</td>
<td>32</td>
</tr>
<tr>
<td>5.8</td>
<td>Temporal evolution of the rainfall intensity in case R5H</td>
<td>32</td>
</tr>
<tr>
<td>5.9</td>
<td>Space–time spectrum of the rainfall intensity in case R5H</td>
<td>33</td>
</tr>
<tr>
<td>5.10</td>
<td>The structure of the wavenumber 1 disturbance in case RH</td>
<td>34</td>
</tr>
<tr>
<td>5.11</td>
<td>Temporal evolution of the rainfall intensity in case RHL</td>
<td>35</td>
</tr>
<tr>
<td>5.12</td>
<td>The structure of the wavenumber 1 disturbance in case RHL</td>
<td>36</td>
</tr>
</tbody>
</table>
5.13 Temporal evolution of the rainfall intensity in case SFR ............................................................ 37
5.14 Temporal evolution of the rainfall intensity in case DS .............................................................. 38
5.15 Temporal evolution of the rainfall intensity in case DSNRE ...................................................... 39

Section 6

6.1 Temporal evolution of the rainfall intensity in case R5H32 ....................................................... 41
6.2 Temporal evolution of the domain-integrated kinetic energy in case R5H32. ............................... 41
6.3 Temporal evolution of the rainfall intensity in case R5L32 ....................................................... 42
6.4 Temporal evolution of the rainfall intensity in case R5HNRE16 ............................................... 42
6.5 Temporal evolution of the rainfall intensity in case R5HL32V30 .............................................. 43
6.6 Temporal evolution of the rainfall intensity in case SFR16 ...................................................... 43
6.7 Eigenvalue (complex phase velocity squared) of the two-level wave-CISK problem ................ 44
6.8 Scattering diagram showing the relationship between the low wavenumber Fourier amplitudes of vertical velocity at \( z=1.42 \) km (abscissa) and rain water mixing ratio at \( z=0.36 \) km (ordinate) in case R5H32 .......................................................................................... 45
6.9 Scattering diagram showing the relationship between the high wavenumber Fourier amplitudes of vertical velocity at \( z=1.42 \) km (abscissa) and rainwater mixing ratio at \( z=0.36 \) km (ordinate) in case R5H32 .......................................................................................... 45
6.10 Square of coefficient of proportionality of the Fourier amplitude of rainfall regressed to those of the vertical velocity at \( z=1.42 \) km in case R5H32 (green) and case R5L32 (red) for various wavenumber (abscissa) .......................................................................................................................... 46
6.11 Temporal evolution of the rainfall intensity in case R5H32C1V10 ............................................ 47
6.12 Temporal evolution of the rainfall intensity in case R5H32C4V10 ............................................ 47
6.13 Temporal evolution of the rainfall intensity in case R5H32C6V10 ............................................ 48
6.14 Temporal evolution of the rainfall intensity in case R5H32C6V30 ............................................ 48
6.15 Temporal evolution of the domain-integrated kinetic energy in experiments similar to R5H32 with different radiative cooling strengths .......................................................... 49
6.16 Temporal evolution of the domain-integrated kinetic energy in experiments similar to R5H32 with different radiative cooling strengths and surface wind speeds used in the flux calculations .................................................................................................................. 49
6.17 The vertical distribution of three important terms in the heat budget equation before and after the establishment of the planetary-scale stationary structure in case R5H32 ..................... 51

Section 7

7.1 Schematic structure of the WISHE mechanism .......................................................................... 52
7.2 Temporal evolution of the rainfall intensity in case W ............................................................... 53
7.3 Space–time spectrum of the rainfall intensity in case W ........................................................... 54
7.4 The structure of the wavenumber 1 disturbance in case W ....................................................... 55
7.5 Temporal evolution of the rainfall intensity in case W32I1 ....................................................... 56
7.6 Temporal evolution of the rainfall intensity in case WRH32 ................................................... 57
7.7 Temporal evolution of the rainfall intensity in case WRL32 ................................................... 57
7.8 Temporal evolution of the rainfall intensity in case W32 ........................................................ 58
7.9 Temporal evolution of various domain-integrated quantities in case W32 .................................. 59
7.10 Temporal evolution of the normalized total kinetic energy in models with different domain sizes ........................................................................................................................ 60
7.11 Temporal evolution of the normalized total kinetic energy in sensitivity experiments ............ 61
7.12 Temporal evolution of the rainfall intensity in case WNRE32 ................................................ 61
List of Tables

Section 3
3.1 Specifications of the experiments ................................................................. 14

Section 4
4.1 Specifications of the experiments ................................................................. 20

Section 5
5.1 Specifications of the experiments ................................................................. 29

Section 6
6.1 Specifications of the experiments ................................................................. 40
6.2 Specifications of the sensitivity experiments ................................................ 46

Section 7
7.1 Specifications of the experiments ................................................................. 52

List of Plates

1 and 2 Structure of cloud activity in the subdomain extending 2,800 km at two selected times ..... 66
3 Temporal evolution of cloud clusters in the subdomain extending 6,160 km at time intervals of 12 h ................................................................. 67
4 Variables in the full 65,536 km domain ............................................................ 67
5 Temporal evolution of the rainfall intensity ....................................................... 68
6 Temporal evolution of evaporation from the sea surface ................................... 68
7 Temporal evolution of low-level temperature .................................................. 69
8 Temporal evolution of low-level horizontal wind ............................................. 69
9 Temporal evolution of the water vapor mixing ratio in the mixed layer ............ 70
10 Temporal evolution of the water vapor mixing ratio in the middle troposphere ....... 70
Idealized Numerical Experiments on the Space-time Structure of Cumulus Convection Using a Large-domain Two-dimensional Cumulus-Resolving Model

Kensuke Nakajima

Faculty of Sciences, Kyushu University
6-10-1 Hakozaki, Higashi-ku, Fukuoka, 812-8581 Japan

Guest Investigator of NIES
16-2 Onogawa, Tsukuba, Ibaraki, 305-8506 Japan
Abstract

A numerical modeling study of tropical moist convection hierarchy using a very large domain (4,096–65,536 km) two-dimensional cumulus convection model is summarized. Each model run is continued for about 10–100 days in the presence of heat and moisture fluxes from an underlying water surface and body cooling mimicking the effect of radiation. So-called “large-scale forcing,” which is often used in convectional cumulus ensemble modeling, is intentionally excluded.

In almost all cases, the cumulus convection exhibits “double-scale” structure: cumulus elements spontaneously organize into mesoscale or cloud cluster-scale structures that are $O(100)$ km in space and $O(10)$ h or longer in time. The average activity of the convection at larger and longer scales, however, differs significantly depending on the specifications of the experiment.

In cases with horizontally uniform initial and boundary conditions, the averaged convective activity is statistically uniform. Initial moisture inhomogeneity in the middle troposphere is found to strongly modulate the convection over a period longer than several days. Horizontal inhomogeneity of sea surface temperature or radiative cooling is also found to be effective in shaping the large-scale distribution of the convection.

Under conditions that favor upper level enhanced cumulus heating, propagating modulation and standing oscillation, associated with large-scale wave motion, were found in the convective activity. The overall structure resembles that predicted by linear wave-CISK (Conditional Instability of the Second Kind) theory.

In the presence of mean surface wind, evaporation-wind feedback is found to operate effectively, resulting in amplification of the synoptic-scale waves associated with strong modulation of convective activity in accordance with the predictions of WISHE (Wind-Induced Surface Heat Exchange).

In very large domains, the cloud fields exhibit considerable spatial and temporal vacillations. Although some properties of these vacillations resemble the intraseasonal variability in the real atmosphere, the correspondence between the behavior of the highly idealized model presented here and that of highly complicated nature remains to be investigated.

Keywords: Cumulus convection, CISK, Cumulus-resolving model, WISHE
Section 1  General Introduction

1.1 Difficulties of cumulus research in the climate context

The importance of cumulus convection in the energetic and hydrological cycles of the atmosphere cannot be overemphasized. It thus should be investigated as an indispensable part of the earth's climate system. However, such an investigation meets with great difficulties in both diagnostic and prognostic directions.

Direct measurement of the contribution of cumulus convection to general circulation is almost impossible because it requires an observation that is both dense enough to resolve individual cumulus clouds and large enough to cover the whole earth. The role of cumulus clouds has therefore been indirectly estimated from residuals in the thermal and moisture budgets in large-scale observations (e.g., Riehl and Malkus, 1958). Each of these estimations requires a kind of “process model” of cumulus clouds. The results depend on which model is used, so that some ambiguity cannot be avoided.

The direct incorporation of cumulus convection in numerical general circulation models (GCMs) suffers from the same resolution/coverage difficulty: a climate simulation run of a “cumulus-resolving GCM” would require at least 1,000,000 times the computational resources needed for a convectional GCM. Thus, in current atmospheric GCMs the effects of cumulus clouds are parameterized using various schemes. Unfortunately, the climate output by these GCMs differs significantly depending on which cumulus parameterization scheme is used, indicating that the parameterization schemes are far from being perfect. Of course, one can “tune” such schemes so as to produce a result that matches an observation, but the validity of tuned schemes in the prediction of unknown climate states, such as a possible CO2-induced warm period in the near future or in the climate of the geological past, remains unclear.

1.2 Multi-scale structure of moist convection

One of the significant characteristics of cumulus convection is its multi-scale spatial and temporal structure, which can be summarized as follows:

1. Individual cumulus clouds are quite often organized in “mesoscale systems,” whose spatial and temporal scales are about an order of magnitude larger than those of cumulus clouds.
2. Mesoscale systems are often organized into “cloud clusters,” whose scales are again about an order of magnitude larger than those of mesoscale systems.
3. Cloud clusters are generally produced in various synoptic-scale disturbances, whose spatial and temporal scales are at least a few times larger than those of cloud clusters.
4. The activity of synoptic-scale disturbances, which is called “intraseasonal variability,” is modulated on a time scale of 30–60 days and on a global spatial scale.
5. Time-averaged cloud activity shows significant geographic inhomogeneity, such as ITCZ (Intertropical Convergence Zone).

The existence of such a hierarchy strongly implies that the statistical properties of convection are far from random. For this reason, the global properties of moist convection may not successfully be derived by extrapolation from a limited number of observations using standard statistical techniques; each of the scale classes should be investigated carefully.
1.3 Deficiency of the “scaled approach” to moist convection

The multi-scale nature of moist convection has implicitly affected the way it is thought of and the framework of research into it. One example can be seen in the design of observational networks in the tropics. Fig. 1.1 summarizes the hierarchical network employed in the Global Atmospheric Research Project (GARP) Atlantic Tropical Experiment (GATE) in summer 1974. The network consisted of an A-scale array for large-scale disturbances, an A/B-scale array for African waves, a B-scale array for cloud clusters, and a C-scale array for cumulonimbus (International and Scientific Management Group for GATE, 1974). Moreover, the existence of a hierarchy in moist convection introduced a scale hierarchy into moist convection research, i.e., subdivisions of research corresponding to each of the scale classes of convection. One such example in the field of numerical modeling is the combination of GCMs, which cover the range of classes from synoptic disturbances to global circulation, and cumulus ensemble models, which cover the range of classes from individual clouds to cloud clusters. Such a scaled approach is, of course, useful and efficient. At the same time, however, it has the following few pitfalls:

1. Motivated by such scale hierarchy, there is a tendency to think that smaller classes are controlled by larger classes. This may be true in some situations such as convective clouds in hurricanes, but it may not be true in other cases such as cloud clusters in weak tropical disturbances. Nevertheless, in some cumulus ensemble modeling studies, cloud activities are treated as a “response” to “large-scale forcing.”

2. By putting too much stress on the differences among the scales of each class, one tends to forget about the differences in physical processes of the various classes. In fact, some recent GCMs can resolve the horizontal scale of cloud clusters. Then it is tempting to label the grid-scale rainfall events in such models as “cloud clusters.” This characterization is inadequate because most of these models do not include cloud microphysics, which is generally thought crucial to the dynamics of cloud clusters. This argument is also supported by the high sensitivity of the behavior of such grid-scale convective activities to the cumulus parameterization (e.g., Numaguti and Hayashi, 1991ab).

3. If one assumes the existence of such a hierarchy a priori, one cannot investigate its origin. This is not only of metaphysical concern. Some cloud systems, in fact, appear to begin as a few convective clouds and grow through mesoscale systems into cloud clusters of considerable size; this sort of continuous upgrading of the scale hierarchy cannot be investigated with models that include a priori assumptions about scale separation.
Deficiency of the "scaled approach" to moist convection

The multi-scale nature of moist convection has implicitly affected the way it is thought of and the framework of research into it. One example can be seen in the design of observational networks in the tropics. Fig. 1.1 summarizes the hierarchical network employed in the Global Atmospheric Research Project (GARP) Atlantic Tropical Experiment (GATE) in summer 1974. The network consisted of an A-scale array for large-scale disturbances, an A/B-scale array for African waves, a B-scale array for cloud clusters, and a C-scale array for cumulonimbi (International and Scientific Management Group for GATE, 1974). Moreover, the existence of a hierarchy in moist convection introduced a scale hierarchy into moist convection research, i.e., subdivisions of research corresponding to each of the scale classes of convection. One such example in the field of numerical modeling is the combination of GCMs, which cover the range of classes from synoptic disturbances to global circulation, and cumulus ensemble models, which cover the range of classes from individual clouds to cloud clusters. Such a scaled approach is, of course, useful and efficient. At the same time, however, it has the following few pitfalls:

1. Motivated by such scale hierarchy, there is a tendency to think that smaller classes are controlled by larger classes. This may be true in some situations such as convective clouds in hurricanes, but it may not be true in other cases such as cloud clusters in weak tropical disturbances. Nevertheless, in some cumulus ensemble modeling studies, cloud activities are treated as a "response" to "large-scale forcing."

2. By putting too much stress on the differences among the scales of each class, one tends to forget about the differences in physical processes of the various classes. In fact, some recent GCMs can resolve the horizontal scale of cloud clusters. Then it is tempting to label the grid-scale rainfall events in such models as "cloud clusters." This characterization is inadequate because most of these models do not include cloud microphysics, which is generally thought crucial to the dynamics of cloud clusters. This argument is also supported by the high sensitivity of the behavior of such grid-scale convective activities to the cumulus parameterization (e.g., Numaguti and Hayashi, 1991ab).

3. If one assumes the existence of such a hierarchy a priori, one cannot investigate its origin. This is not only of metaphysical concern. Some cloud systems, in fact, appear to begin as a few convective clouds and grow through mesoscale systems into cloud clusters of considerable size; this sort of continuous upgrading of the scale hierarchy cannot be investigated with models that include a priori assumptions about scale separation.

---

**Fig. 1.1 “Telescoping network” employed in GATE.** (top) The A-scale array, covering the entire tropics in the western hemisphere and enhanced by a number of research vessels in the Atlantic ocean, observed the behavior of synoptic-scale disturbances such as African waves and large-scale systems including the evolution of the ITCZ. (bottom) The A/B-scale array, consisting of six research vessels at the corners of a hexagon placed within the Atlantic ITCZ, examined the details of African waves and the associated convective activity. (next page) The B-scale array, consisting of five ships placed at the corners of a pentagon, and the C-scale array, consisting of a number of ships and buoys scattered around the small triangle at the center, attempted to observe mesoscale convective activity and individual convective clouds, respectively.
1.4 Approach of this study

To complement the deficiencies of the scaled approach discussed above, some sort of “continuous” approach is evidently necessary. Comparison of observational and numerical modeling suggests that the difficulties of the latter are less severe. In fact, recent developments in massively parallel supercomputers have finally allowed the execution of “cloud system-resolving” numerical modeling of the global atmosphere (Satoh et al., 2005). They are, however, extremely costly in the consumption of computational resources, so that the opportunities for very long time integration (longer than O(100) days) or the execution of a large number of experiments are still limited. Therefore, until around 1990, when the present research was started, conducting cumulus-resolving experiments on a scale covering the Pacific Ocean was possible only by using a two-dimensional model, which still remains useful, in particular for theoretically oriented numerical experiments. The results of such two-dimensional experiments will of course be different in various aspects from the behavior of the real three-dimensional atmosphere. Nevertheless, one can obtain information or hints about real systems, which can be valuable for planning future research directions.

In this paper, I present a summary of such attempts to run large-domain two-dimensional cumulus models. The domain sizes of the models range between 4,096 and 65,536 km, which is more than an order of magnitude larger than conventional cumulus ensemble models (CEM), and the time integrations continue as long as 10–100 days. The experiments are not designed following particular observed situations, but simulate various types of idealized, “clean” situations that allow the natural behavior of cloud convection hidden in the actual complex circumstances of the real world to be uncovered. In short, the aim of this research is to clarify how clouds would behave over a uniform ocean, including the interaction with the large-scale motion driven by the clouds themselves (Fig. 1.2).
Section 1  General Introduction

1.4 Approach of this study

To complement the deficiencies of the scaled approach discussed above, some sort of "continuous" approach is evidently necessary. Comparison of observational and numerical modeling suggests that the difficulties of the latter are less severe. In fact, recent developments in massively parallel supercomputers have finally allowed the execution of "cloud system-resolving" numerical modeling of the global atmosphere (Satoh et al., 2005). They are, however, extremely costly in the consumption of computational resources, so that the opportunities for very long time integration (longer than $O(100)$ days) or the execution of a large number of experiments are still limited. Therefore, until around 1990, when the present research was started, conducting cumulus-resolving experiments on a scale covering the Pacific Ocean was possible only by using a two-dimensional model, which still remains useful, in particular for theoretically oriented numerical experiments. The results of such two-dimensional experiments will of course be different in various aspects from the behavior of the real three-dimensional atmosphere. Nevertheless, one can obtain information or hints about real systems, which can be valuable for planning future research directions.

In this paper, I present a summary of such attempts to run large-domain two-dimensional cumulus models. The domain sizes of the models range between 4,096 and 65,536 km, which is more than an order of magnitude larger than conventional cumulus ensemble models (CEMs), and the time integrations continue as long as $10-100$ days. The experiments are not designed following particular observed situations, but simulate various types of idealized, "clean" situations that allow the natural behavior of cloud convection hidden in the actual complex circumstances of the real world to be uncovered. In short, the aim of this research is to clarify how clouds would behave over a uniform ocean, including the interaction with the large-scale motion driven by the clouds themselves (Fig. 1.2).

In addition to the domain size, the length of time integration, and the setup, there is another important difference between the approach of this type of study and that of CEMs. As mentioned earlier, CEM experiments are performed by imposing so-called large-scale forcing, which is horizontally uniform cooling and moistening estimated from the budget analysis of observations. In fact, it has often been reported that such large-scale forcing is indispensable for realization of cloud activity in these models. In this study, however, such large-scale forcing is not used because, as noted earlier, it may introduce a reversal of cause and effect. Instead, following Nakajima and Matsuno (1988), the model troposphere is cooled at a rate comparable to the radiative cooling intensity, and the underlying ocean supplies heat and moisture. This combination induces convective instability in the model, which some amount of convection is expected to balance. As is described in this paper, continuous convective activity did occur during the simulation. Furthermore, the activity exhibited a hierarchy from individual convective clouds to synoptic-scale waves extending over the full extent of the domain.

The organization of this paper is as follows: In section 2, the numerical model is described. In section 3, the results of experiments in horizontally homogeneous conditions are presented. Spontaneous generation of cloud clusters is also discussed. In section 4, cases with various large-scale horizontal inhomogeneities are described. In section 5-7, the results of experiments concerning the interaction between cumulus clouds and large-scale internal gravity waves are presented. Section 8 contains concluding remarks.
Section 2 Description of the Numerical Model

2.1 Introduction

The numerical model used in this study is simply a very large domain, two-dimensional cumulus convection model. The dynamical framework is an anelastic system, and warm rain cloud microphysical parameterization is incorporated. The model atmosphere is subject to an energy supply from the underlying warm ocean and a body cooling that is a very crude substitute for radiative processes. Symbol definitions are listed in the Appendix.

2.2 Dynamical framework

The dynamical framework follows that of Ogura and Phillips (1962). Slab symmetry is assumed in the y-direction, so that \( \frac{d}{dy} = 0 \) for any variable, and cyclic continuity is assumed in the x-direction. The domain extends \( 0 < z < 22.6 \) km in the vertical direction and either 4,096 or 16,384 km in the x-direction.

The equations of motion are

\[
\frac{du}{dt} - fv = -c_p \theta_0 \frac{\partial \pi}{\partial x} + D(u) \\
\frac{dv}{dt} + fu = -c_p \theta_0 + D(v) \\
\frac{dw}{dt} = -c_p \theta_0 \frac{\partial \pi}{\partial z} + b + D(w)
\]

where the Coriolis parameter \( f \) is assumed to be constant, \( \frac{d}{dt} \) is the material time derivative, \( D(\cdot) \) is the diffusion operator, and \( b \) is buoyancy:

\[
\frac{d}{dt} \equiv \frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + w \frac{\partial}{\partial z}
\]

\[
D(Y) \equiv \frac{\partial}{\partial x} \left( K \frac{\partial Y}{\partial x} \right) + \frac{1}{\rho_0} \frac{\partial}{\partial z} \left( \rho_0 K \frac{\partial Y}{\partial z} \right)
\]

\[
b \equiv g \left( \frac{\theta}{\theta_0} + 0.608 q_v - q_c - q_r \right)
\]

Representation of the turbulent diffusivity \( K \) is described below. The x and z components of the velocity are assumed to satisfy the anelastic continuity equation:

\[
\frac{\partial (\rho_0 u)}{\partial x} + \frac{\partial (\rho_0 w)}{\partial z} = 0
\]

This equation diagnostically determines the perturbation non-dimensional pressure in the equations of motion. The first law of thermodynamics is represented in terms of the potential temperature budget:
\[
\frac{d\theta}{dx} + w \frac{d\theta_0}{dz} = \frac{L}{c_p\rho_0} (C - E_r) + D(\theta + \theta_0) + Q_{rad}
\]

Water is divided into three categories: water vapor, cloud water, and rain water. Cloud and rain water are in liquid form, the latter of which falls downward relative to the motion of the air. Mixing ratios of the three water substances are computed by the following conservation equations:

\[
\frac{dq_v}{dt} = -C + E_r + D(q_v)
\]
\[
\frac{dq_c}{dt} = C - P_{rc} + D(q_c)
\]
\[
\frac{dq_r}{dt} = P_{rc} - E_r + D(q_r) - \frac{1}{\rho_0} \frac{\partial}{\partial z} (\rho_0 V_T q_r)
\]

The terms on the right-hand side are described in the following subsection.

### 2.3 Parameterization of cloud microphysics

The treatment of cloud microphysical processes follows the bulk parameterization by Kessler (1969) except for the autoconversion term.

The conversion from cloud to rain is computed as the sum of the autoconversion term, which represents the growth of cloud droplets into raindrop size, and the collection term, which represents the amount of cloud water captured by the descending raindrops:

\[
P_{rc} \equiv P_{auto} + P_{collect}
\]

The autoconversion term is calculated following Berry (1968) as

\[
P_{auto} = \frac{10^6 \rho_0 q_c^3}{60(2q_c + 2.66 \cdot 10^{-8} N_0/\rho_0 D_0)}
\]

\[
N_0 = 5.0 \times 10^7
\]

\[
D_0 = 0.366
\]

(The SI system of units is used in all of these formulae.)

The collection term can be computed by assuming an inverse exponential raindrop size distribution (Marshall and Palmer, 1948), combined with an exponential fitting to the terminal velocities of individual raindrops. The bulk terminal velocity of the rain water, and the bulk evaporation of the rain water, can be calculated in similar ways. The results are as follows:

\[
V_T = 12.2 q_r^{0.125}
\]
\[
P_{collect} = 2.2 q_c (\rho_0 q_r)^{0.875}
\]
\[
E_r = 4.85 \times 10^{-2} (q_v^* - q_v) (\rho_0 q_r)^{0.65}
\]

Finally, the condensation of water vapor into cloud water and the evaporation of cloud water into water vapor are calculated by saturation adjustment. Here, the dependence of the saturation vapor mixing ratio on the perturbation pressure is neglected for simplicity.


2.4 Substitute for radiative cooling

Body cooling is introduced in the model to mimic the effect of radiative cooling in the atmosphere. Its intensity is horizontally uniform, and it is calculated as the sum of a fixed component and a Newtonian damping component that is linear in the x-averaged temperature deviation :

\[ Q_{rad} \equiv \frac{\theta_0}{T_0} (Q_R(z) + D_R \overline{T}(z)) \]

There are several types of specification of the vertical profile of \( Q_R(z) \) as are shown in Fig. 2.1. In each experiment, one of these profiles is chosen and applied to the model.

![Fig. 2.1 Vertical profiles of radiative cooling used in the experiments.](image)

2.5 Parameterization of subgrid-scale turbulence

Turbulent diffusivity is calculated considering the subgrid-scale turbulent kinetic energy following Klemp and Wilhelmson (1978). The prognostic equation of the diffusivity is

\[
\frac{dK}{dt} = \frac{C_m^2}{2} (B + S) - \frac{C_e K^2}{2C_m L^2} + D(K)
\]

\[
S = \left( \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right)^2 + 2 \left\{ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial w}{\partial z} \right)^2 \right\}
\]

\[
B = \begin{cases} 
-g \frac{1}{\theta_0} \frac{\partial (\theta + \theta_0)}{\partial z} & \text{for } q_c = 0 \\
-g \frac{1}{\theta_0} \frac{\partial (\theta_{ei} + \theta_0)}{\partial z} & \text{for } q_c > 0 
\end{cases}
\]

\[
\theta_{ei} \equiv \theta + \frac{L q_v}{c_p \Pi_0} + \theta_0 (0.608 q_v - q_c - q_r)
\]

\[
C_m = C_e = 0.2
\]
The turbulent microscale is defined as
\[ l \equiv \min (\Delta z, z) \]

2.6 Surface fluxes

Momentum, heat, and moisture fluxes from the sea surface are calculated using the following standard bulk formulae:

\[
\begin{align*}
F_u &= -C_D V_{sfc} u \\
F_v &= -C_D V_{sfc} v \\
F_{\theta} &= -C_D V_{sfc} (T_{sfc} - T_{z=0}) \\
F_{q_v} &= -C_D V_{sfc} (q_{v,sfc} - q_{v,z=0}) \\
C_D &= 0.0015 \\
Q_{v,sfc} &= q_v^* (T_{sfc})
\end{align*}
\]

The wind speed at the sea surface is calculated as
\[ V_{sfc} \equiv (u_{z=0}^2 + v_0^2)^{1/2} \]
so as to assure some amount of flux even if the computed wind speed is very weak. The standard value of \( v_0 \) is 3 m/s.

2.7 Finite difference

The variables are differenced over a staggered grid (Fig. 2.2). The grid size is 2 km in x and variable in z, and the representative vertical resolution is about 600 m. A 4-th order differencing is used in advection terms to minimize the computational dispersion. Additional nonlinear diffusion is introduced to ensure stable computation. This enforced usage of 4-th order differencing is also applied to the continuity equation resulting in a slightly modified form of the discretized pressure equation, which can, however, be solved with the standard Fourier Transform method in the x-direction. This also violates energy conservation, but the error is smaller than the contribution of nonlinear dissipation terms.

2.8 Basic state and initial conditions

Temperature and humidity in the basic state are standard conditions in the tropical atmosphere; the specific values used are those of Yamasaki (1984)’s “wet” condition. These determine the initial conditions except for a small-amplitude random noise in the grids at \( z = 700 \) m, which is necessary to “seed” the convective activity in the course of the experiments. As described below, in some experiments, additional disturbances are introduced.
Section 2  Description of the Numerical Model

![Staggered grid](image)

**Fig. 2.2** Staggered grid employed for discretization.

### List of Symbols

- $b$: buoyancy
- $B$: generation of subgrid scale turbulence due to stratification
- $c_p$: Specific heat of dry air at constant pressure
- $C$: Source of cloud water due to condensation or evaporation
- $C_D$: Drag coefficient in surface flux calculation
- $C_{mm}$: Coefficient for momentum mixing in subgrid scale turbulence calculation
- $C_\varepsilon$: Coefficient for scalar mixing in subgrid scale turbulence calculation
- $D_0$: Dispersion of size distribution of aerosols
- $D_0$: Diffusion of prognostic variables
- $D_R$: Time constant of Newtonian cooling
- $E_r$: Evaporation of rain water
- $f$: Coriolis parameter
- $F_{qv}$: Flux of water vapor from the sea surface
- $F_q$: Flux of heat from the sea surface
- $F_u$: Flux of the x-component momentum from the sea surface
- $F_v$: Flux of the y-component momentum from the sea surface
- $g$: Acceleration of gravity
- $K$: Coefficient of subgrid scale diffusion
- $\kappa$: R/$c_p$
- $l$: Mixing length used in the calculation of subgrid scale mixing
- $L$: Latent heat of condensation of water
- $N_0$: Number density of aerosols
- $\rho_0$: Basic state density of air
\(P_{\text{autoconv}}\) generation of rain water due to autoconversion
\(P_{\text{collect}}\) generation of rain water due to collection of cloud water
\(P_{\text{rc}}\) total conversion of cloud water into rain water
\(\pi\) perturbation Exner function
\(\Pi_0\) basic state Exner function
\(P_0\) basic state pressure
\(P_R\) reference value of pressure (1000 hPa)
\(q_c\) mixing ratio of cloud water
\(q_{\text{d}c}\) saturation mixing ratio of water vapor at the sea surface
\(q_{\text{v}c0}\) mixing ratio of water vapor at the lowest level
\(q_r\) mixing ratio of rain water
\(q_v\) mixing ratio of water vapor
\(q_v^*\) saturation mixing ratio of water vapor
\(Q_{\text{rad}}\) intensity of radiative cooling
\(R\) gas constant of dry air
\(S\) generation of subgrid scale turbulence due to shear
\(t\) time
\(T_0\) basic state temperature
\(T_{\text{s}fc}\) temperature of sea or ground surface
\(T_{z=0}\) air temperature at the lowest level
\(\Theta\) horizontally averaged temperature
\(\theta\) potential temperature
\(\theta_{\text{li}}\) approximate liquid water potential temperature
\(\Theta_0\) basic state potential temperature
\(u\) x-component of wind velocity
\(v\) y-component of wind velocity
\(v_\text{t}\) minimum value of wind velocity in surface flux calculation
\(V_T\) terminal fall velocity of rain water relative to the air
\(V_{\text{s}fc}\) wind velocity at the surface in surface flux calculation
\(w\) z-component of wind velocity
Section 3  Cloud Clusters

3.1  Specifications of the experiments

This section describes the results of numerical experiments in which initial and boundary conditions are prescribed to be almost uniform horizontally. These experiments serve as the reference cases to which the modified cases are compared in later sections. Moreover, the behavior of convection in such perfectly uniform conditions is of considerable interest in itself, because such ideal conditions cannot be found in the real atmosphere and the only way to investigate them is by numerical experiments. In this respect, the experiments in this section are an extension of the study of Nakajima and Matsuno (1988), who investigated the behavior of convection in homogeneous conditions with a smaller (512 km) domain model. As is shown below, the most significant result is the spontaneous generation of mesoscale or cloud cluster-scale systems.

Table 3.1 summarizes the specifications of the experiments that are described in this section. The domain size of the model used is 4,096 km. Details are presented below.

<table>
<thead>
<tr>
<th>case</th>
<th>Radiative Cooling</th>
<th>V0[m/s]</th>
<th>Initial Disturbance</th>
<th>note</th>
</tr>
</thead>
<tbody>
<tr>
<td>H0</td>
<td>M</td>
<td>3</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>N0</td>
<td>M</td>
<td>0</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>C2V300</td>
<td>2M</td>
<td>300</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>NRE</td>
<td>M</td>
<td>3</td>
<td>Yes</td>
<td>No rain evaporation</td>
</tr>
</tbody>
</table>

3.2  Standard experiments

Case H0, an experiment under standard tropical conditions, is a simple extension of case F of Nakajima and Matsuno (1988). Time integration was continued for 9 days.

Fig. 3.1 shows the time evolution of the rainfall distribution in case H0 (2 cycles of the computational domain are shown). The large-scale averaged convective activity is fairly uniform in both space and time, but some structure is evidently present at the horizontal scale of O(100 km) and temporal scale of O(10 h). This space–time scale corresponds to the mesoscale or cloud cluster scale in the moist convection hierarchy.

Fig. 3.2 shows the space–time distribution of precipitation during the first 48 h in more detail. The “first generation” of cloud activity emerges at T = 6 h as a large number of clouds, which are separated from each other by around 50 km. Their intensity is not uniform: more intense clouds are found with mutual separations of 150–200 km. Their lifetime is no longer than a few hours. After termination of the first generation of cloud activity, the number of clouds greatly reduces, but individual clouds are more intense. More importantly, the convection exhibits a “double-scale” structure in space and time; that is, clouds occur in series whose horizontal and temporal scales are O(100 km) and O(10 h), respectively. This type of behavior is similar to that found by Nakajima and Matsuno (1988).

Inspection of Fig. 3.3, which shows the x-t distribution of sensible heat flux in the same time interval as Fig. 3.2, reveals the mechanism of the double-scale structure clearly. Each
strong precipitation is followed by an area of enhanced heat flux, which reflects the presence of a cold air mass at the sea surface. The fan-shaped pattern of the heat flux means that each cold air mass spreads out as a density current. During the spreading, the cold air mass becomes weak owing to the enhanced heat supply in it. In the final stage of its lifetime, each cold air pool triggers the formation of one or two new clouds, which generate new cold air pools. This sequence of events results in “double-scale” convection: cumulus convection that has O(10 km) horizontal scale and O(1h) lifetime occurs in series that has O(100–1,000 km) horizontal scale and O(1–10 day) lifetime.

Fig. 3.4 shows the space–time spectrum of rainfall in case H0. Focusing on the horizontal phase velocity, there are two types of signals: one type has a broad but smaller spatial scale (wavelengths of 1,000 km or smaller) and slow propagation speed (a few m/s), and the other has a larger scale (wavelengths of 500–4,096 km) and fast phase velocity (15–20 m/s). The former corresponds to cloud clusters, and the existence of the latter indicates that cloud activity is modulated by internal gravity waves. The interaction between clouds and gravity waves is more intense in the wave-CISK experiments discussed later (section 5).

<table>
<thead>
<tr>
<th>Case</th>
<th>Radiative Cooling</th>
<th>Initial Disturbance</th>
<th>C2V300</th>
<th>N0</th>
<th>NRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>H0</td>
<td>Yes</td>
<td>Yes</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>N0</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>C2V300</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>NRE</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
</tbody>
</table>

**Table 3.1: Specifications of the experiments.**

**Fig. 3.1  Temporal evolution of the rainfall intensity in case H0.** Two cycles of the computational domain are shown. More intense precipitation is represented by the dark color. Most of the domain is white; that is, precipitation occurs only within a number of small-scale convective clouds.

**Fig. 3.2  Temporal evolution of rainfall intensity in a limited region of case H0.** Clouds develop as slowly migrating series.
Section 3  Cloud Clusters

Fig. 3.3 Temporal evolution of heat flux from the ocean in the same limited region of case H0 as in Fig. 3.2. The dark color represents large heat flux, roughly corresponding to the locations of lower temperatures near the surface. The clouds produce cold air pools, which expand horizontally and trigger the next generation of clouds.

Fig. 3.4 Space–time spectrum of the rainfall intensity in case H0. The abscissa indicates the characteristic phase velocity in units of [m/s], and the ordinate is the horizontal wave number measured at the domain scale (i.e., 4,096 km).

3.3 Dependence on the surface flux specifications

Case N0 is similar to case H0 except for the specification of the wind speed used in the surface flux calculation. In case N0, $v_0$ is set to 0, so that the energy input from the ocean can be arbitrarily small. Time integration was continued for 6 days. Fig. 3.5 shows the x-t distribution of rainfall in case N0. In comparison with case H0 (Fig. 3.1), the cloud series are more evident, and they migrate more slowly. Thus, each cloud series is in this case more
easily recognizable. The cause of this difference is revealed by examining the surface fluxes. Fig. 3.6 shows the x-t distribution of sensible heat flux in case N0. Other than the areas of intense heat flux accompanying the cold air pools close to the convective clouds, one can note faster propagating transient areas of enhanced heat supply originating from strong convective cells. These are reminiscence of strong winds associated with internal gravity wave packets forced by strong heating in the clouds. Areas of such strong winds exist only within a few hundred kilometers from each convective cloud activity because of the detachment of gravity wave packets as a result of vertical dispersion. The collective effect of the localized strong wind, combined with the generation of cloud series by the cold air pool, is the enhancement of the energy supply from the sea near the cloud series. This feedback results in more persistent and stationary cloud series.

Fig. 3.5 Temporal evolution of the rainfall intensity in case N0. Two cycles of the computational domain are shown.

Fig. 3.6 Temporal evolution of the heat flux from the ocean in case N0. Two cycles of the domain are shown. The dark color represents a large heat flux. Other than the concentrated regions of strong flux corresponding to the cold air pools directly associated with cloud activity, fast-moving signals are observed to emanate from each cloud, which result from the strong wind driven by transient latent heating in clouds.
Fig. 3.7 shows the x-t distribution of rainfall in case C2V300, where the wind speed used in the calculation of surface flux was tremendously increased. Compared with case H0, the lifetime and horizontal scale of each convective element do not differ very much. However, we can note a difference in the properties of cloud clusters: the cloud series in case H0 migrate horizontally, but those in case C2V300 are almost stationary. In other words, convective clouds in case C2V300 occur close to the locations of previous clouds. Inspection of the low level temperature distribution reveals that the cold air pools, which are produced by the evaporation of rain as in case H0, disappear quickly because of the heat flux from the underlying ocean, so that the lateral spreading of cold air pools is not powerful enough to trigger new clouds at O(10–100) km distances from the original clouds. On the other hand, the quick dissipation of cold air pools allows the occurrence, or repetition, of new clouds at the same location as older clouds, where the full depth of the troposphere is more humid than the surrounding area. These two factors allow the persistence of narrow intermittent stationary series of convection in case C2M300.

3.4 Dependence on the evaporation of rain

Case E0 is similar to case H0 except that the evaporation of raindrops is switched off. Fig. 3.8 shows the x-t distribution of rainfall in case E0. Compared with case H0, the cloud series are stationary and persistent. In fact, the cloud lifetime is much longer than in cases that include rain evaporation, in which the cold air pool generated by the evaporation of rain kills each convective cloud. The space–time spectrum of precipitation (Fig. 3.9) reflects the stationary nature of the cloud activity: the component with wavelengths shorter than 1,000 km is almost stationary. Still, a weak, fast propagating signal having a phase velocity of about 20 m/s exists, as in case H0, suggesting that interaction between clouds and gravity waves is possible also in this setup.
Fig. 3.7 shows the x-t distribution of rainfall in case C2V300, where the wind speed used in the calculation of surface flux was tremendously increased. Compared with case H0, the lifetime and horizontal scale of each convective element do not differ very much. However, we can note a difference in the properties of cloud clusters: the cloud series in case H0 migrate horizontally, but those in case C2V300 are almost stationary. In other words, convective clouds in case C2V300 occur close to the locations of previous clouds. Inspection of the low level temperature distribution reveals that the cold air pools, which are produced by the evaporation of rain as in case H0, disappear quickly because of the heat flux from the underlying ocean, so that the lateral spreading of cold air pools is not powerful enough to trigger new clouds at O(10–100) km distances from the original clouds. On the other hand, the quick dissipation of cold air pools allows the occurrence, or repetition, of new clouds at the same location as older clouds, where the full depth of the troposphere is more humid than the surrounding area. These two factors allow the persistence of narrow intermittent stationary series of convection in case C2V300.

3.4 Dependence on the evaporation of rain

Case E0 is similar to case H0 except that the evaporation of raindrops is switched off. Fig. 3.8 shows the x-t distribution of rainfall in case E0. Compared with case H0, the cloud series are stationary and persistent. In fact, the cloud lifetime is much longer than in cases that include rain evaporation, in which the cold air pool generated by the evaporation of rain kills each convective cloud. The space–time spectrum of precipitation (Fig. 3.9) reflects the stationary nature of the cloud activity: the component with wavelengths shorter than 1,000 km is almost stationary. Still, a weak, fast propagating signal having a phase velocity of about 20 m/s exists, as in case H0, suggesting that interaction between clouds and gravity waves is possible also in this setup.

Fig. 3.8 Temporal evolution of the rainfall intensity in case NRE. Two cycles of the computational domain are shown.

Fig. 3.9 Space–time spectrum of the rainfall intensity in case NRE. Abscissa indicates characteristic phase velocity in the unit of [m/s], and ordinate is horizontal wave number measured by the domain scale (i.e., 4,096 km).

3.5 Remarks

Two remarks should be made about the results of the homogeneous condition experiments. First, a double-scale structure invariably occurred in all of the experiments. Its emergence without any specific forcing supports the viewpoint that the double-scale structure, which may correspond to mesosystems or cloud clusters in the moist convection hierarchy, is a “free-mode” behavior of moist convection. Second, the large-scale structure is quite sensitive to the surface flux specification. This agrees with recent arguments that stress the importance of surface flux (e.g., Emanuel, 1987). This point is also demonstrated section 6. The properties of mesoscale systems, which are known to be controlled by the behavior of cold air pools, might also be sensitive to surface wind.
Section 4  Organization Forced by Large-scale Inhomogeneity

4.1 Specifications of the experiments

In the real atmosphere, many types of large-scale inhomogeneity exist. At least some of them should be regarded as being OUTSIDE of the moist convection hierarchy. In this section, the experiments that demonstrate the effects of such large-scale inhomogeneities are presented. Table 4.1 summarizes the experiments described in this section. Details are explained below.

Table 4.1: Specifications of the experiments.

<table>
<thead>
<tr>
<th>case</th>
<th>Variables that is inhomogeneous in the domain</th>
<th>V0 [m/s]</th>
<th>Radiative cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>IT</td>
<td>Initial tropospheric temperature</td>
<td>3</td>
<td>M</td>
</tr>
<tr>
<td>IHL</td>
<td>Initial low-level humidity</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>IHM</td>
<td>Initial mid-level humidity</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>ST2</td>
<td>Surface temperature (2[K])</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>ST2V0</td>
<td>Surface temperature (2[K])</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>IR</td>
<td>Radiative cooling</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

4.2 Inhomogeneous initial conditions

In case IT, a large-scale, deep temperature anomaly, with a sinusoidal shape and a half wavelength of 15 km in the vertical direction and Gaussian with a standard deviation of 1,024 km in the horizontal direction, is introduced in the initial conditions. Fig. 4.1 shows the x-t distribution of rainfall in case IT. During the first 36 h, the rainfall is concentrated in the initially warm area. However, the concentrated cloud activity disperses rapidly. The rainfall on day 4 is actually less intense in the initially warm area, although it recovers around day 6. This behavior, characterized by stationary large-scale modulation of cloud activity, can be interpreted as the interaction of clouds with long-wavelength internal gravity waves emitted by the initial large-scale warm anomaly. It should be remarked that, although it much less evident compared with the concentrated cloud activity in the first 36 h, the frequency of convective clouds is higher in the initially warm area. This presumably results from the large-scale initial humidity anomaly in the middle troposphere, whose effect is quite persistent as is shown below, that is induced by the large-scale upward motion associated with lateral dispersion of the large-scale internal gravity waves at the start of the experiment.

In case IHL, the effect of large-scale inhomogeneity in low-level humidity is investigated, introducing a saturated region in the height range from z = 200 to 900 m extending 1,024 km horizontally. Fig. 4.2 shows the x-t distribution of rainfall in case IHL. Although strongly concentrated cloud activity occurs in the first 24 h in the initially moist region, the overall distribution of cloud activity thereafter is almost unaffected by the initial moisture distribution. This behavior can be explained as follows. In the low-level saturated region, a large number of convective clouds develop immediately. They produce a large amount of rain water, which evaporates, resulting in a cold air pool covering the area of initial saturation. By this sequence of events, the initially given low-level humidity anomaly is rapidly destroyed, so that the cloud activity at a later time is free from this initial distribution.
In case IHM, the effect of large-scale inhomogeneity in the initial moisture is examined. Specifically, the humidity in the middle troposphere \((z > 1,500 \text{ m})\) is set to zero outside a region with a width of 1,024 km in which standard tropical conditions are used. This initial condition may also be thought of as a kind of lateral boundary condition, as when inhomogeneous air over a boundary between desert and tropical forest is advected to the ocean. Fig. 4.3 shows the x-t distribution of the rainfall in case IHM. As in case IHL, convection immediately develops in the initially moist region. After that, however, it exhibits distinctly contrasting behavior to IHL, as the convection in the moist region continues actively for several days. In fact, active clouds occur almost exclusively in the initially moist region for several days. The result clearly demonstrates that a moisture field in the middle troposphere can very strongly and persistently modulate cloud activity.

How the moisture field controls the development of convective clouds can be understood if we consider the resistance that a convective element feels during the development from the planetary boundary layer entraining the surrounding air: the clouds in a more humid environment experience less drying and cooling than those in a dryer environment. Close inspection of the convective activity outside the initial moist region also exemplifies the importance of moisture: those clouds tend to form in the area where older convective clouds moistened the air column. This constitutes a positive feedback loop, but it is not necessarily very strong: each convective area, including that caused by the initial moisture field, shows a tendency toward lateral dispersion.

Fig. 4.1 Temporal evolution of the rainfall intensity in case IT. Two cycles of the computational domain are shown.
Section 4   Organization Forced by Large-scale Inhomogeneity

**Fig. 4.2 Temporal evolution of the rainfall intensity in case IHL.** Two cycles of the computational domain are shown.

**Fig. 4.3 Temporal evolution of the rainfall intensity in case IHM.** Two cycles of the computational domain are shown.
4.3 Inhomogeneous SST

In cases ST2 and ST2V0, the temperature of the underlying sea surface is set to vary with a half amplitude of 1 K (Fig. 4.4). The absolute value of the deviation of SST is proportional to the fourth power of $\sin(x/4,096[\text{km}])$. The surface wind speed is fixed to be 3 m/s irrespective of the calculated wind speed in case ST2, whereas it varies temporally and spatially as is written in section 2.6 in case ST2V0.

Fig. 4.5 shows the x-t distribution of rainfall in case ST2. In spite of the initial disturbance that was in the middle of the colder SST region, almost all of the cloud activity becomes concentrated in the warmer SST region. Moreover, as time goes on, the width of the convection region becomes narrower. A possible cause of this evolution is that the humidity becomes horizontally inhomogeneous and modulates the convective activity as in case IHM.

Interestingly, the rainfall evolution in case ST2V0 does not simply follow the SST distribution. As is shown in Fig. 4.6, the rainfall is most intense around the edge or shoulder of the SST distribution; there is a secondary minimum of rainfall in the area of warmest SST. This unexpected behavior results from the distribution of surface wind. As was demonstrated by Lindzen and Nigam (1987), low-level wind in the tropics is driven primarily by the horizontal gradient of the SST. In the present case, the SST-driven wind is significant at the shoulder of the warm SST area, but it is absent at the minima and maxima of the SST. The inhomogeneity of SST-driven low-level wind modulates the surface flux from the ocean, so that the surface flux is small at the maxima of SST, resulting in a minimum of precipitation.

![Fig. 4.4 Horizontal distribution of SST anomaly used in case ST2 and ST2V0.](image-url)
Fig. 4.5 Temporal evolution of the rainfall intensity in case ST2. Two cycles of the computational domain are shown.

Fig. 4.6 Temporal evolution of the rainfall intensity in case ST2V0. Two cycles of the computational domain are shown.
4.4 Inhomogeneous radiative cooling

Finally, in case IR, the body cooling that mimics the radiative processes is varied in sinusoidal form in the horizontal direction. Specifically, the cooling is strongest (1.5 K/day) at $x = 1,024$ km and weakest (0.5 K/day) at $x = 3,072$ km.

Fig. 4.7 shows the x-t distribution of surface precipitation in case IR. This time, the convective activity is concentrated in the region of weaker radiative cooling. There are two possible explanations for the large-scale modulation of convection in case IR: a temperature anomaly in the PBL due to radiation cooling inhomogeneity in the PBL, and a moisture anomaly in the middle troposphere resulting from the large-scale circulation caused by the anomaly component of the radiative cooling. Some supplementary experiments (not shown) were conducted to clarify this issue, and both of these were found to be important.

It is also noticed that the overall convective activity is not steady, but oscillates with a period of 2 days. Considering the domain size of 4,096 km, the temporal variability has a phase speed of about 20 m/s, which is similar to what was found to be the fast speed oscillation in the experiments in section 3. This demonstrates that the interaction between clouds and large-scale internal gravity waves, which is the focus of section 5, occurs even in an inhomogeneous environment.

Fig. 4.7 Temporal evolution of the rainfall intensity in case IR. Two cycles of the computational domain are shown.
Section 5  Wave-CISK

5.1 Initial note

In this section and in sections 6 and 7, we examine the organization of cloud convection in two set-ups that could be favorable to the emergence of large-scale organization through possible interaction between convection and large-scale waves. The first is wave-CISK (Convective Instability of the Second Kind) examined in sections 5 and 6, and the second is wind-evaporation feedback, or Wind-Induced Surface Heat Exchange (WISHE; Yano and Emanuel, 1991) examined in section 7.

There are features somewhat common between these two mechanisms: both predict instabilities in propagating disturbances, and the growth rate becomes infinitely large at the limit of zero wavelength. The latter point is problematic because the most unstable mode cannot be distinguished from individual convective clouds if we accept literally the prediction of wave-CISK or WISHE.

The investigation of wave-CISK and WISHE has two aims. The first is to clarify the structure and behavior of disturbances that could emerge through wave-CISK and WISHE, including whether those disturbances appear or not. The second is to find a way to distinguish the disturbances developing through wave-CISK and WISHE, which could be similar to each other.

5.2 Brief summary of gravity wave-CISK theory

Wave-CISK was first proposed by Hayashi (1970) in three-dimensional form on the equatorial beta-plane in an effort to explain the existence of large-scale equatorial waves. However, the essence of wave-CISK can be illustrated in a two-dimensional (x-z) framework. Fig. 5.1 illustrates how wave-CISK works. It is known that the instability property of wave-CISK is sensitive to the vertical structure of heating by cumulus convection; propagating unstable modes appear only when cumulus heating is stronger in the upper troposphere [e.g., Yamasaki (1969); Hayashi (1970); Lindzen (1974)]. However, in this section, another type of vertical heating profile is found to work, so we need to summarize the basics of wave-CISK before showing the numerical experiments.

![Fig. 5.1 Schematic structure of the mechanism of wave-CISK. Latent heating in convective clouds drives the circulation, part of which pulls down low-level moist air to trigger new cloud activity to the right.](image-url)
The governing equations of a small-amplitude hydrostatic disturbance in the stably stratified Boussinesq fluid driven by heating, which are the fundamentals of wave-CISK, are

\[
\begin{align*}
U_t &= -p_x \\
0 &= -p_x + g(\bar{\rho}/\bar{\theta})\theta \\
\theta_t &= -(d\bar{\theta}/dz)(W/\bar{\rho}) + \dot{Q} \\
0 &= U_x + W_z
\end{align*}
\]

Here \(\bar{\rho}\) and \(\bar{\theta}\) are the basic state density and potential temperature, respectively; \(\theta\) is potential temperature deviation; \(p\) is pressure deviation; and \((U,W) \equiv (u,w)\bar{\rho}\) are the horizontal and vertical components of the velocity, respectively. The subscripts denote partial derivative operation. \(\dot{Q} \equiv Q/(\frac{d\bar{\theta}}{dz})\) represents the heating due to condensation of water in cumulus convection, which is assumed to be parameterized as

\[
Q(z) = \eta(z)W(z_*)
\]

where \(z_*\) is the altitude of a controlling level. If it is assumed that all perturbations have the wav-like structure in time and horizontal direction, these equations can be separated into the horizontal structure equation (omitted here) and the vertical structure equation, which is

\[
N^2(W-Q) + c^2W_{zz} = 0
\]

where \(N^2 \equiv \left(\frac{\partial}{\partial z}\right)\left(\frac{d\bar{\theta}}{dz}\right)\) is the square of the buoyancy frequency. Combined with the boundary condition of no vertical motion at the upper and lower boundaries, the vertical structure equation constitutes an eigenvalue problem with the eigenvalue \(c^2\), which is the square of the complex phase velocity of disturbances.

In the absence of heating, the system has an infinite number of neutral modes:

\[
W(z) = \sin(n\pi z/H) \\
c = \pm (NH)/(n\pi)
\]

We can use these eigenfunctions to expand the heating function \(\eta\) and obtain

\[
\{N^2 - c^2(n\pi/H)^2\}W_n - \sum_{m=1}^{\infty} M_{mn}W_m = 0
\]

\[
M_{mn} \equiv \eta \sin(m\pi z_*/H)
\]

which shows that the heating by cumulus clouds can couple different vertical modes.

The heart of wave-CISK can be represented by the case where only two vertical modes interact with each other. In such a case, the condition in which eigenvalue \(c^2\) is complex (i.e., propagating instability occurs) can be represented as
\[
\left( \frac{N^2 - M_{ii}}{l_i^2} - \frac{N^2 - M_{jj}}{l_j^2} \right)^2 + 4 \frac{M_{ij} M_{ji}}{l_i^2 l_j^2} < 0
\]

where \( l_j \equiv \pi / H \) are the vertical wavenumbers.

The final equation suggests that a propagating instability of wave-CISK occurs when the phase speeds of the interacting two modes come close to each other by self-interactions, and, at the same time, the mutual interactions have different signatures. These conditions are met in the conventional wave-CISK by the combination of an upper-level enhanced heating profile and low \( z_* \) (Fig. 5.2), the latter of which is understood by considering that low-level convergence can trigger deep convection in the tropics, resulting in an unstable interaction between the first and second modes.

Another possibility of unstable interaction between the first and third modes can emerge if cumulus heating is strong in both the upper and lower troposphere and \( z_* \) resides in the middle troposphere (Fig. 5.3). Indeed, radiative cooling in the real tropical atmosphere, to which cumulus heating should adjust grossly, represents such a structure. Thus, if switching by the middle level vertical velocity is realized, the wave-CISK as modified above can occur.

![Diagram of vertical velocity and heating in usual wave-CISK](image)

**Fig. 5.2 The structures of the vertical velocity and heating in usual wave-CISK.** Left: The shapes of the first and second modes, both of which contribute positively to the vertical velocity at a low level \( z_* \). Right: The modal decomposition of top-heavy heating, showing that the contributions of the first and second modes are both positive.
Fig. 5.3 The structures of the vertical velocity and heating in the new type of wave-CISK. Left: The shapes of the first and third modes; the former contributes positively to the vertical velocity at the middle level $z^*$ and the latter contributes negatively. Right: The modal decomposition of heating that is strong at the low and high levels, showing that the contributions of the first and second modes are both positive.

5.3 Setup of the numerical experiments

Even in the cases described in sections 3 and 4, large-scale, fast-propagating signatures have been found. In a setup that is more preferable for wave-CISK setup, some kind of large-scale wave may appear more evidently. According to past linear wave-CISK theories, one such setup is that cumulus heating is more intense in the upper troposphere than in the lower levels. This section describes the results of experiments that examine such a situation. Table 5.1 summarizes the cases presented in this section. In all of these experiments, the surface wind velocity is fixed, causing the wind-surface flux feedback, which is, as will be shown later, very significant, to be turned off.

In this study, each time integration is continued for about 10 days, which is of the same order of the radiative equilibration time of the system, or longer. Therefore, cloud activity at least partially comes into a state of radiative convective equilibrium, so that the vertical profile of cumulus heating can be controlled by specification of the body cooling profile.

The vertical profile of the cooling in each experiment is shown in Fig. 2.2. According to the predictions of linear wave-CISK theories and the assumptions above, wave-CISK is preferred in cases RH and R5H, but not in RL.

Table 5.1: Specifications of the experiments.

<table>
<thead>
<tr>
<th>case</th>
<th>Radiative cooling profile</th>
<th>surface</th>
<th>Cloud physics</th>
<th>domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH</td>
<td>H</td>
<td>standard</td>
<td>standard</td>
<td></td>
</tr>
<tr>
<td>RL</td>
<td>L</td>
<td>standard</td>
<td>standard</td>
<td></td>
</tr>
<tr>
<td>R5H</td>
<td>5H</td>
<td>standard</td>
<td>standard</td>
<td></td>
</tr>
<tr>
<td>RHL</td>
<td>HL</td>
<td>standard</td>
<td>standard</td>
<td></td>
</tr>
<tr>
<td>SFR</td>
<td>M</td>
<td>standard</td>
<td>Rain falls slowly</td>
<td></td>
</tr>
<tr>
<td>DS</td>
<td>Half desert</td>
<td>standard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DSNRE</td>
<td>Half desert</td>
<td>No rain evaporation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.4 Dependence on the radiative cooling profile

Figs. 5.4 and 5.5 show the x-t distributions of rainfall in cases RH and RL, respectively. Comparison of the two figures shows that the signature of the propagating large-scale structure is much more noticeable in case RH. This contrast becomes more evident in the space–time spectral analysis. Figs. 5.6 and 5.7 show the power of precipitation in wavenumber-phase velocity space for cases RH and RL, respectively. Comparison between these two figures indicates that the power of the wavenumbers 1 to 3 is larger in RH: the power in case RL is an order of magnitude smaller than that in case RH. In short, the prediction of wave-CISK is shown to be correct. The enhancement of large-scale propagation (or standing oscillation) of cloud activity becomes even clearer in case R5H, whose rainfall realization and space–time spectrum are shown in Figs. 5.8 and 5.9, respectively. In fact, almost all of the convective activity is concentrated in the propagating pattern in this case.

Fig. 5.10 shows the composited structure of the propagating disturbance that appears in case RH. Note that the composite is done in the rightward propagating reference frame. In these figures, vertical tilts are noticeable in the horizontal velocity and temperature in accordance with the prediction of wave-CISK theories. The most important point is that the moisture anomaly precedes the precipitation. This suggests that the cloud activity is forced by the large-scale wave convergence.

**Fig. 5.4** Temporal evolution of the rainfall intensity in case RH. Two cycles of the computational domain are shown.
Section 5   Wave-CISK

5.4 Dependence on the radiative cooling profile

Figs. 5.4 and 5.5 show the x-t distributions of rainfall in cases RH and RL, respectively. Comparison of the two figures shows that the signature of the propagating large-scale structure is much more noticeable in case RH. This contrast becomes more evident in the space-time spectral analysis. Figs. 5.6 and 5.7 show the power of precipitation in wavenumber-phase velocity space for cases RH and RL, respectively. Comparison between these two figures indicates that the power of the wavenumbers 1 to 3 is larger in RH: the power in case RL is an order of magnitude smaller than that in case RH. In short, the prediction of wave-CISK is shown to be correct. The enhancement of large-scale propagation (or standing oscillation) of cloud activity becomes even clearer in case R5H, whose rainfall realization and space-time spectrum are shown in Figs. 5.8 and 5.9, respectively. In fact, almost all of the convective activity is concentrated in the propagating pattern in this case. Fig. 5.10 shows the composited structure of the propagating disturbance that appears in case RH. Note that the composite is done in the rightward propagating reference frame. In these figures, vertical tilts are noticeable in the horizontal velocity and temperature in accordance with the prediction of wave-CISK theories. The most important point is that the moisture anomaly precedes the precipitation. This suggests that the cloud activity is forced by the large-scale wave convergence.

Fig. 5.4 Temporal evolution of the rainfall intensity in case RH. Two cycles of the computational domain are shown.

Fig. 5.5 Temporal evolution of the rainfall intensity in case RL. Two cycles of the computational domain are shown.

Fig. 5.6 Space–time spectrum of the rainfall intensity in case RH. The abscissa indicates the characteristic phase velocity in units of [m/s], and the ordinate is the horizontal wave number measured by the domain scale (i.e., 4,096 km).

Fig. 5.6 Space–time spectrum of the rainfall intensity in case RH. The abscissa indicates the characteristic phase velocity in units of [m/s], and the ordinate is the horizontal wave number measured by the domain scale (i.e., 4,096 km).
Section 5  Wave-CISK

Fig. 5.7 **Space–time spectrum of the rainfall intensity in case RL.** The abscissa indicates the characteristic phase velocity in units of [m/s], and the ordinate is the horizontal wave number measured by the domain scale (i.e., 4,096 km).

Fig. 5.8 **Temporal evolution of the rainfall intensity in case R5H.** Two cycles of the computational domain are shown.
Fig. 5.9 Space–time spectrum of the rainfall intensity in case R5H. The abscissa indicates the characteristic phase velocity in units of [m/s], and the ordinate is the horizontal wave number measured by the domain scale (i.e., 4,096 km).
Fig. 5.10 The structure of the wavenumber 1 disturbance in case RH. Only the right-moving component is extracted.
5.5 Wave-CISK with a more complex profile of cumulus heating

As noted in the last paragraph of section 5.2, a new kind of wave-CISK is possible if cumulus heating is large in both the lower and upper troposphere, but small in the middle troposphere, and is positively correlated with vertical motion in the middle troposphere. Unlike in linear theory, we cannot directly specify the cumulus heating profile and its relationship with wave-related vertical motions. As noted earlier, we can expect that cumulus heating responds to the radiative cooling profile in a long-term integration. With this expectation in mind, we set the radiative cooling in case RHL to be smaller in the middle troposphere. As for \( z_* \) and the signature of correlation between the vertical motion and cumulus heating, we can only hope that middle level upward motion induces positive heating.

Fig. 5.11 shows the x-t distribution of rainfall in case RHL. It is evident that most of the convective activity is organized into the leftward propagating wavenumber 1 structure, demonstrating the operation of wave-CISK with the modified heating profile. Fig. 5.12 shows the structure of the disturbance. It is richer in the vertically higher mode than the structure of the disturbance in case RH (Fig. 5.10). Namely, the large contribution of the third vertical mode is notable in the horizontal wind and potential temperature. This also supports that the new kind of wave CISK works in case RHL.

![Fig. 5.11 Temporal evolution of the rainfall intensity in case RHL. Two cycles of the computational domain are shown.](image)
Fig. 5.12 The structure of the wavenumber 1 disturbance in case RHL. Only the left-moving component is extracted.
5.6 Wave-CISK with enhanced rain evaporation

Another setup that may prefer upper-enhanced cumulus heating is the artificial enhancement of rain water in the lower levels. In fact, this reduces the net heating in the lower levels, so that the second vertical mode is forced in the same sense as it is forced by the upper-enhanced cumulus heating. Enhancement of evaporation is, however, rather difficult to realize. Among several trial experiments, the largest amount of rain evaporation resulted when the bulk terminal velocity of the rain water was reduced.

Fig. 5.13 shows the x-t distribution of rainfall in case SFR, in which the rain water fall velocity is reduced to 1/5 of the standard value. Although it is less evident than in case R5H, organization of convective activity into a propagating large-scale structure is easily identified. The composite structure (not shown) of the wave number 1 disturbance is also similar to that in case R5H.

It should be noted that there are considerable differences between the mesoscale or cloud cluster-scale structure in this experiment and those in the previous cases. The cloud series in this case has a longer lifetime, larger horizontal scale, and faster propagation speed. Moreover, the lifetime of individual clouds is also longer. This supports the argument by Nakajima and Matsuno (1988) that the water recycle time determines the lifetime of clouds in connection with rain evaporation.

![Fig. 5.13 Temporal evolution of the rainfall intensity in case SFR. Two cycles of the computational domain are shown.](image)

5.7 Wave-CISK over “half-desert”

Another possible wave-CISK preferred setup is the “continental” condition. Namely, when the surface wetness is low, the PBL will be thick and latent heating will occur in the higher levels because the lifting condensation level is higher. Thus, the surface wetness is set to be 0.5 in case DS. This rather drastic change causes a large drift of the atmospheric structure from the initial conditions, so that the time integration was continued to 22 days.

Fig. 5.14 shows the x-t distribution of the rainfall in case DS. After a rather complex adjustment process in the first half of the experiment, convection becomes organized into a
Section 5   Wave-CISK

propagating structure whose wavenumber is 2. Its phase velocity is about 10 m/s, which is about half that in previous cases.

Because of the short wavelength of the propagating disturbance, the distinction between mesoscale systems and the wave-CISK disturbance is not so clear. Thus, the experiment was repeated with rain water evaporation switched-off (case DSNRE). As shown in Fig. 5.15, the results exhibit evident modulation of cloud activity, which constitutes standing oscillation of wave number 1 with a period similar to that of case DS. Each convection series in this experiment is stationary instead of the propagating mesosystem in case DS. Therefore, the wave-CISK oscillation is shown to be independent of the behavior of mesoscale systems strongly influenced by cloud microphysical processes.

Fig. 5.14 Temporal evolution of the rainfall intensity in case DS. Two cycles of the computational domain are shown.
Section 5  Wave-CISK

propagating structure whose wavenumber is 2. Its phase velocity is about 10 m/s, which is about half that in previous cases. Because of the short wavelength of the propagating disturbance, the distinction between mesoscale systems and the wave-CISK disturbance is not so clear. Thus, the experiment was repeated with rain water evaporation switched-off (case DSNRE). As shown in Fig. 5.15, the results exhibit evident modulation of cloud activity, which constitutes standing oscillation of wave number 1 with a period similar to that of case DS. Each convection series in this experiment is stationary instead of the propagating mesosystem in case DS. Therefore, the wave-CISK oscillation is shown to be independent of the behavior of mesoscale systems strongly influenced by cloud microphysical processes.

Fig. 5.14 Temporal evolution of the rainfall intensity in case DS. Two cycles of the computational domain are shown.

Fig. 5.15 Temporal evolution of the rainfall intensity in case DSNRE. Two cycles of the computational domain are shown.
Section 6  Behavior of Wave-CISK on a Planetary Scale

6.1 The purpose, setup, and unexpected results of the extended experiments

One important issue regarding wave-CISK is the preferred scale, for which linear theories cannot give a definite answer. In most of the cases in the section 5, the scale of the developed propagating disturbances is the largest possible scale in the model, so the preferred scale is not determined. Therefore, we repeat some of those cases with an even larger numerical model. The setup is summarized in Table 6.1. In the course of the extended experiments there appeared, surprisingly, very large-scale stationary disturbances. In this section, we try to interpret such behavior in the framework of wave-CISK.

Table 6.1: Specifications of the experiments.

<table>
<thead>
<tr>
<th>case</th>
<th>Cooling profile</th>
<th>Cloud physics</th>
<th>domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>R5H32</td>
<td>5H</td>
<td>standard</td>
<td>32,768 km</td>
</tr>
<tr>
<td>R5L32</td>
<td>5L</td>
<td>standard</td>
<td>32,768 km</td>
</tr>
<tr>
<td>RHL32</td>
<td>HL</td>
<td>standard</td>
<td>32,768 km</td>
</tr>
<tr>
<td>SFR16</td>
<td>M</td>
<td>Rain falls slowly</td>
<td>16,384 km</td>
</tr>
<tr>
<td>R5HNRE16</td>
<td>5H</td>
<td>No rain evaporation</td>
<td>16,384 km</td>
</tr>
</tbody>
</table>

6.2 Preferred scale of wave-CISK and the emergence of planetary scale concentration

Fig. 6.1 shows the temporal evolution of rainfall intensity in case R5H32. The structure of the convective activity is drastically different between the first and second halves of the experiment. In the first 30 days or so, it is characterized by a “mesh-like” pattern originating from a fairly homogeneously distributed organization of convective activity that propagates both eastward and westward and has a wavelength of about 3,000 km, which appears to be the preferred scale of wave-CISK in this setup. However, subsequently, the convective activity is gradually concentrated in one place, and finally it is almost exclusively in a stationary region with a width of about 2,000 km. Close examination of Fig. 6.1 reveals that the stationary region of concentrated cloud activity develops gradually from a wavenumber 1 stationary modulation of convective activity that appears at around t = 10 days and steadily develops with a time scale of about 20 days. In fact, as shown in Fig. 6.2, the total kinetic energy in this case grows almost exponentially during the development of the stationary planetary scale feature, suggesting that this process results from a kind of linear instability. A different set of random numbers was introduced into the initial conditions of each of 8 experiments. The results of the ensemble experiment show the development of similar features in each run except for the location, which shows that the development of a single, concentrated cloud activity in the large domain is a robust feature in this setup.

Fig. 6.3 shows the temporal evolution of the rainfall intensity in the case with low-level cooling. It is quite clear that no large-scale structure similar to that in the previous case is present. Weak modulation of cloud activity with a horizontal scale of several hundreds of kilometers exists, but the regions of stronger cloud activity are scattered in a fairly homogeneous manner. Each of the active regions of convection moves back and forth slowly, presumably advected by horizontal wind. Close examination of the moisture field indicates
that this slowly migrating feature results from weak positive feedback between the cloud activity and moisture field that functioned in the cases of sections 3 and 4.

Figs. 6.4, 6.5, and 6.6 show the temporal evolution of rainfall in cases R5HNRE16, RHL32V30, and SFR16, respectively. One should bear in mind that each of these setups resulted in the development of a propagating large-scale modulation of clouds, presumably through the operation of wave-CISK. In spite of the differing setups, the development of a planetary-scale stationary concentration occurs in all of the experiments.

Fig. 6.1 Temporal evolution of the rainfall intensity in case R5H32.

Fig. 6.2 Temporal evolution of the domain-integrated kinetic energy in case R5H32.
Section 6   Behavior of Wave-CISK on a Planetary Scale

Fig. 6.3 Temporal evolution of the rainfall intensity in case R5L32.

Fig. 6.4 Temporal evolution of the rainfall intensity in case R5HNRE16.
6.3 The mechanism of stationary concentration of cloud activity

In summary, the results show that the conditions for occurrence of a planetary-scale stationary concentration are the same as the conditions for activation of wave-CISK. This implies that the planetary-scale stationary feature is also a manifestation of wave-CISK. However, superficially this viewpoint is quite strange, because as noted in the beginning of section 5, the growth rate of a wave-CISK disturbance is larger at a smaller scale; a planetary-scale disturbance, whose growth rate is small, should not appear. Moreover, the complex phase speed of the wave-CISK unstable mode does not depend on the wavelength, so that the planetary-scale wave should move.

Reexamination of linear wave-CISK theory (subsection 5.2) suggests one possibility by which both the synoptic-scale and planetary-scale stationary disturbances can be explained. If
the coupling between cumulus heating and large-scale upward motion is scale dependent and is stronger for disturbances with longer wavelengths (Fig. 6.7), the different behaviors of the synoptic-scale and planetary-scale disturbances can be reproduced.

To explore this possibility, the correlation between the spatial Fourier components of vertical motion and those of rainfall, which is a proxy of heating, is examined. Figs. 6.8 and 6.9 are scatter diagrams of planetary-scale and synoptic-scale components, respectively. It is clear that the heating and vertical motion are more strongly related at the planetary scale than at the synoptic scale. As is shown in Fig. 6.10, the coefficient of proportionality varies by a factor of 5 from the synoptic scale (wavenumber 10) to the planetary scale (wavenumber 1). Although no quantitative examination has yet been done, the large difference in the heating parameter quite likely explains the difference in behavior between the synoptic and planetary scales.

**Fig. 6.7 Eigenvalue (complex phase velocity squared) of the two-level wave-CISK problem.** The imaginary part (left), real part of the first root (center), and real part of the second root (right) are shown by the contours. The abscissa is the strength of low-level heating, and the ordinate is the strength of high-level heating. The red lines show the results of top-heavy heating at various intensities. With weak heating (red circle near the bottom), two neutral propagating modes appear. With moderate heating (blue circle on the red line), a propagating growing mode and a propagating damping mode appear. With strong heating (green circle), a stationary growing mode and a neutral propagating mode appear.
Section 6   Behavior of Wave-CISK on a Planetary Scale

The coupling between cumulus heating and large-scale upward motion is scale dependent and is stronger for disturbances with longer wavelengths (Fig. 6.7), the different behaviors of the synoptic-scale and planetary-scale disturbances can be reproduced.

To explore this possibility, the correlation between the spatial Fourier components of vertical motion and those of rainfall, which is a proxy of heating, is examined. Figs. 6.8 and 6.9 are scatter diagrams of planetary-scale and synoptic-scale components, respectively. It is clear that the heating and vertical motion are more strongly related at the planetary scale than at the synoptic scale. As is shown in Fig. 6.10, the coefficient of proportionality varies by a factor of 5 from the synoptic scale (wavenumber 10) to the planetary scale (wavenumber 1). Although no quantitative examination has yet been done, the large difference in the heating parameter quite likely explains the difference in behavior between the synoptic and planetary scales.

Fig. 6.7 Eigenvalue (complex phase velocity squared) of the two-level wave-CISK problem. The imaginary part (left), real part of the first root (center), and real part of the second root (right) are shown by the contours. The abscissa is the strength of low-level heating, and the ordinate is the strength of high-level heating. The red lines show the results of top-heavy heating at various intensities. With weak heating (red circle near the bottom), two neutral propagating modes appear. With moderate heating (blue circle on the red line), a propagating growing mode and a propagating damping mode appear. With strong heating (green circle), a stationary growing mode and a neutral propagating mode appear.

Fig. 6.8 Scattering diagram showing the relationship between the low-wavenumber Fourier amplitudes of vertical velocity at z=1.42 km (abscissa) and the rain water mixing ratio at z=0.36 km (ordinate) in case R5H32.

Fig. 6.9 Scattering diagram showing the relationship between the high-wavenumber Fourier amplitudes of vertical velocity at z=1.42 km (abscissa) and rainwater mixing ratio at z=0.36 km (ordinate) in case R5H32.
Section 6   Behavior of Wave-CISK on a Planetary Scale

Fig. 6.10 Square of coefficient of proportionality of the Fourier amplitude of rainfall regressed to those of the vertical velocity at z=1.42 km in cases R5H32 (green) and case R5L32 (red) for various wavenumber (abscissa).

6.4  Sensitivity experiments on the concentration of cloud activity

In the experiments presented so far in this section, the stationary disturbance is wavenumber 1, i.e., the largest scale captured in the model, so the preferred scale of this feature remains to be revealed. To examine this issue, several additional experiments are performed with different combinations of troposphere cooling intensity $C_{\text{rad}}$ and wind speed for the surface flux calculation $V_{\text{sf}}$. Table 6.2 lists the specifications of the cases presented here. The model is integrated for 60 days in each experiment.

<table>
<thead>
<tr>
<th>case</th>
<th>domain</th>
<th>Shape of cooling profile</th>
<th>Maximum radiative cooling rate [K/day]</th>
<th>$V_{\text{sf}}$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R5H32C1V10</td>
<td>32,768 km</td>
<td>5H</td>
<td>1</td>
<td>10.0</td>
</tr>
<tr>
<td>R5H32C2V10</td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>R5H32C4V10</td>
<td></td>
<td></td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>R5H32C6V10</td>
<td></td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>R5H32C6V30</td>
<td></td>
<td></td>
<td>6</td>
<td>30.0</td>
</tr>
</tbody>
</table>

Fig. 6.11 shows the temporal evolution of the rainfall intensity in case R5H32C1V10, for which the intensity of the troposphere cooling is halved. A propagating, wave-CISK type structure is also notable in this case. However, stationary large-scale modulation as seen in the previous case does not seem to develop. Fig. 6.12 shows the temporal evolution of rainfall intensity in case R5H32C4V10, where the intensity of the troposphere cooling is doubled. In addition to the propagating, wave-CISK type structure, the development of stationary large-scale modulation of the cloud activity, although it is weak, can be noted and its wavenumber is 2.

- 46 -
6.4 Sensitivity experiments on the concentration of cloud activity

In the experiments presented so far in this section, the stationary disturbance is wavenumber 1, i.e., the largest scale captured in the model, so the preferred scale of this feature remains to be revealed. To examine this issue, several additional experiments are performed with different combinations of troposphere cooling intensity $C_{rad}$ and wind speed $V_{sfc}$ for the surface flux calculation.

Table 6.2 lists the specifications of the cases presented here. The model is integrated for 60 days in each experiment.

<table>
<thead>
<tr>
<th>Case</th>
<th>Domain Shape</th>
<th>Troposphere Cooling Profile</th>
<th>Maximum Radiative Cooling Rate [K/day]</th>
<th>Surface Flux $V_{sfc}$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R5H32C1V10</td>
<td>32,768 km</td>
<td>1</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>R5H32C2V10</td>
<td>32,768 km</td>
<td>2</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>R5H32C4V10</td>
<td>32,768 km</td>
<td>4</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>R5H32C6V10</td>
<td>32,768 km</td>
<td>6</td>
<td>30.0</td>
<td>10.0</td>
</tr>
<tr>
<td>R5H32C6V30</td>
<td>32,768 km</td>
<td>6</td>
<td>30.0</td>
<td>30.0</td>
</tr>
</tbody>
</table>

Fig. 6.11 shows the temporal evolution of the rainfall intensity in case R5H32C1V10, for which the intensity of the troposphere cooling is halved. A propagating, wave-CISK type structure is noted in this case. However, stationary large-scale modulation as seen in the previous case does not seem to develop. Fig. 6.12 shows the temporal evolution of rainfall intensity in case R5H32C4V10, in which the intensity of the troposphere cooling is doubled. In addition to the propagating, wave-CISK type structure, the development of stationary large-scale modulation of the cloud activity, although weak, can be noted and its wavenumber is 2.

Fig. 6.13 shows the temporal evolution of the rainfall intensity in case R5H32C6V10, where the intensity of the troposphere cooling is tripled. One might expect three regions of concentrated cloud activity to appear, but this is not the case; effectively no such modulation develops. If we increase the wind speed in the surface flux calculation the naïve expectation comes true. Fig. 6.14 shows the temporal evolution of the rainfall intensity in case R5H32C6V30. Three stationary regions of concentrated cloud activity clearly develop.

Figs. 6.15 and 6.16 show the temporal evolution of the total kinetic energy in experiments where different combinations of radiative cooling rate and $V_{sfc}$ are employed. In the case where exponential growth of kinetic energy is observed, conspicuous degree of stationary concentrated cloud activity develops as in case R5H32C6V30. However, even in cases where cloud organization into planetary-scale features is not discernible, a slow increase in kinetic energy is observed, implying that the stationary modulation could reach quite a large amplitude if the experiment were to be continued for a longer time.
Comparison of the behavior among the concentrations of cloud activities presented above suggests that a preferred spacing between cloud concentrations exists and that it is inversely proportional to the intensity of the troposphere cooling. In other words, the number of intense cloud activity regions is proportional to the strength of the troposphere cooling, which roughly determines the total amount of precipitation in the domain. This possible relationship between the total rainfall intensity and the number of rainfall regions can be understood if we assume that the total amount of rainfall in each such region is not sensitive to troposphere cooling. At the same time, comparison among cases R5HC4V10, R5HC6V10, and R5HC6V30 implies that for stationary concentrated cloud activity to fully develop, the coupling between the ocean and the atmospheric mixed layer must be strong. This relationship can be explained by considering a negative feedback from the concentration of rainfall to the moist static energy in the mixed layer, which will be weaker with a stronger surface wind.

Fig. 6.13 Temporal evolution of the rainfall intensity in case R5H32C6V10.

Fig. 6.14 Temporal evolution of the rainfall intensity in case R5H32C6V30.
Comparison of the behavior among the concentrations of cloud activities presented above suggests that a preferred spacing between cloud concentrations exists and that it is inversely proportional to the intensity of the troposphere cooling. In other words, the number of intense cloud activity regions is proportional to the strength of the troposphere cooling, which roughly determines the total amount of precipitation in the domain. This possible relationship between the total rainfall intensity and the number of rainfall regions can be understood if we assume that the total amount of rainfall in each such region is not sensitive to troposphere cooling. At the same time, comparison among cases R5HC4V10, R5HC6V10, and R5HC6V30 implies that for stationary concentrated cloud activity to fully develop, the coupling between the ocean and the atmospheric mixed layer must be strong. This relationship can be explained by considering a negative feedback from the concentration of rainfall to the moist static energy in the mixed layer, which will be weaker with a stronger surface wind.

Fig. 6.13 Temporal evolution of the rainfall intensity in case R5H32C6V10.

Fig. 6.14 Temporal evolution of the rainfall intensity in case R5H32C6V30.

Fig. 6.15 Temporal evolution of the domain-integrated kinetic energy in experiments similar to R5H32 with different radiative cooling strengths: 0.25 K/day (red), 0.5 K/day (green), 1.0 K/day (blue), 1.5 K/day (purple), 2 K/day (light blue), 3 K/day (yellow), 4 K/day (black), and 6 K/day (brown).

Fig. 6.16 Temporal evolution of the domain-integrated kinetic energy in experiments similar to R5H32 with different radiative cooling strengths and surface wind speeds used in the flux calculations: (0.5 K/day, 1.25 m/s) (red), (0.5 K/day, 2.5 m/s) (green), (0.5 K/day, 5 m/s) (blue), (2 K/day, 5 m/s) (purple), (2 K/day, 20 m/s) (light blue), (6 K/day, 15 m/s) (yellow), (6 K/day, 30 m/s) (black), and (6 K/day, 60 m/s) (brown).
6.5 Possible condition for the emergence of a large-scale stationary mode

One may suppose, in cases with bottom-heavy cooling, that stationary growth of large-scale modulation does not appear because the coupling is weaker for a larger scale disturbance. As is shown in Fig. 6.10, however, this is not true: the coupling is stronger at a larger scale also in cases with bottom-heavy cooling. Therefore, the enhancement of the coupling between clouds and vertical velocity at a larger scale is not a sufficient factor for the development of large-scale stationary modes.

A possible “missing link” may be the behavior of unstable modes at an “intermediate” scale. For cases preferable to wave-CISK, assuming that cumulus heating balances with cooling, wave-CISK analysis predicts the existence of propagating unstable modes for “intermediate” wavelengths for which the coupling is moderate. On the other hand, for cases with bottom-heavy cooling, wave-CISK analysis predicts stationary unstable modes for all wavelengths. It may be true that the development of propagating unstable modes acts to smooth cloud activity at a scale larger than the propagating disturbance, in which case it is effectively preparing a uniform environment for the wavenumber 1 stationary mode. This kind of “smoother” does not exist in cases with low-level enhanced cooling, and this may result in the absence of significant larger-scale stationary modes.

It requires explanation why propagating synoptic-scale disturbances do not grow, but allow the potential for stationary planetary-scale modulation to grow. This is especially puzzling when we compare the wave-CISK experiment with the lower-level cooling case. In the latter case, the small-scale component seems to consume the entire available energy source. One clue may be the difference in thermodynamic efficiency of the propagating and stationary disturbances. In Fig. 6.17, the contributions of various terms in the horizontally averaged heat budget equation are compared before and after the establishment of the planetary-scale stationary disturbance in case R5H32. Here, the center of mass of latent heating becomes lower, and vertical heat transport becomes more active, as the stationary feature develops. Because vertical heat transport is proportional to the conversion of potential energy to kinetic energy, an increase in vertical heat transport implies an increase in kinetic energy generation, i.e., an increase in the efficiency of the “heat engine” of the system as a whole. This higher efficiency might result in dominance of the stationary planetary-scale structure over the propagating synoptic-scale features. If we go one step further, we might say that the lower efficiency of the propagating mode as a heat engine results quite simply from its wave-like nature. To propagate, the phase of the temperature anomaly and the phase of the vertical motion should be shifted by about $\pi/2$, rendering correlation between the temperature and vertical motion nearly zero. Otherwise, from the viewpoint of small-scale dynamics, the propagating wave disturbances have to always create new convective areas. This takes the considerable “effort” of pumping up of the moisture and adiabatically cooling of the deep troposphere. Stationary disturbances can be free of both of these difficulties.
Section 6   Behavior of Wave-CISK on a Planetary Scale

6.5 Possible condition for the emergence of a large-scale stationary mode

One may suppose, in cases with bottom-heavy cooling, that stationary growth of large-scale modulation does not appear because the coupling is weaker for a larger scale disturbance. As is shown in Fig. 6.10, however, this is not true: the coupling is stronger at a larger scale also in cases with bottom-heavy cooling. Therefore, the enhancement of the coupling between clouds and vertical velocity at a larger scale is not a sufficient factor for the development of large-scale stationary modes.

A possible “missing link” may be the behavior of unstable modes at an “intermediate” scale. For cases preferable to wave-CISK, assuming that cumulus heating balances with cooling, wave-CISK analysis predicts the existence of propagating unstable modes for “intermediate” wavelengths for which the coupling is moderate. On the other hand, for cases with bottom-heavy cooling, wave-CISK analysis predicts stationary unstable modes for all wavelengths. It may be true that the development of propagating unstable modes acts to smooth cloud activity at a scale larger than the propagating disturbance, in which case it is effectively preparing a uniform environment for the wavenumber 1 stationary mode. This kind of “smoother” does not exist in cases with low-level enhanced cooling, and this may result in the absence of significant larger-scale stationary modes.

It requires explanation why propagating synoptic-scale disturbances do not grow, but allow the potential for stationary planetary-scale modulation to grow. This is especially puzzling when we compare the wave-CISK experiment with the lower-level cooling case. In the latter case, the small-scale component seems to consume the entire available energy source. One clue may be the difference in thermodynamic efficiency of the propagating and stationary disturbances. In Fig. 6.17, the contributions of various terms in the horizontally averaged heat budget equation are compared before and after the establishment of the planetary-scale stationary disturbance in case R5H32. Here, the center of mass of latent heating becomes lower, and vertical heat transport becomes more active, as the stationary feature develops. Because vertical heat transport is proportional to the conversion of potential energy to kinetic energy, an increase in vertical heat transport implies an increase in kinetic energy generation, i.e., an increase in the efficiency of the “heat engine” of the system as a whole. This higher efficiency might result in dominance of the stationary planetary-scale structure over the propagating synoptic-scale features. If we go one step further, we might say that the lower efficiency of the propagating mode as a heat engine results quite simply from its wave-like nature. To propagate, the phase of the temperature anomaly and the phase of the vertical motion should be shifted by about $\frac{\pi}{2}$, rendering correlation between the temperature and vertical motion nearly zero. Otherwise, from the viewpoint of small-scale dynamics, the propagating wave disturbances have to always create new convective areas. This takes the considerable “effort” of pumping up of the moisture and adiabatically cooling of the deep troposphere. Stationary disturbances can be free of both of these difficulties.

![Potential Temperature Tendencies](image)

Fig. 6.17 The vertical distribution of three important terms in the heat budget equation before and after the establishment of the planetary-scale stationary structure in case R5H32.
Section 7  Wind-Evaporation Feedback

7.1  Brief introduction to WISHE

In the last series of experiments, the possible realization of wind-induced surface heat exchange (WISHE; Yano and Emanuel, 1991) is examined. The content of WISHE feedback (Fig. 7.1) is a low-level wind anomaly associated with a large-scale disturbance induced by convective activity that enhances the surface flux anomaly, which in return modulates convective activity so as to amplify and translate the whole structure. In particular, in the presence of mean surface wind, the WISHE wave would propagate upwind. This concept was postulated by Emanuel (1986, 1987) and Neelin et al. (1987) as a mechanism of tropical intraseasonal oscillation. However, there is no reason to believe it does not work in the two-dimensional cumulus-resolving framework of this study.

Fig. 7.1 Schematic structure of the WISHE mechanism. Latent heating in a convective cloud drives the circulation, which, combined with the basic state wind from the right, strengthens the surface wind and enhances evaporation from the sea surface on the right. This helps the development of new cloud activity.

7.2  Specifications of the experiments

The specifications of the experiments that are presented are listed in Table 7.1. Details are explained below.

Table 7.1: Specifications of the experiments.

<table>
<thead>
<tr>
<th>case</th>
<th>domain</th>
<th>Cooling profile</th>
<th>Cloud physics</th>
<th>Initial condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>4,096 km</td>
<td>M</td>
<td>standard</td>
<td>standard Wavenumber 1 moisture</td>
</tr>
<tr>
<td>W32I1</td>
<td>32,768 km</td>
<td>H</td>
<td>standard</td>
<td>standard</td>
</tr>
<tr>
<td>WRH32</td>
<td></td>
<td>L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WRL32</td>
<td></td>
<td>M</td>
<td>No rain evaporation</td>
<td></td>
</tr>
<tr>
<td>W32NRE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7.3 Prototypes of WISHE disturbance

First, WISHE is demonstrated in its purest form. For this purpose, the surface wind used in the flux calculation is defined as

\[ V_{sf} = |u(z = 0) - U_g| \]

where \( U_g = 3 \) m/s.

Fig. 7.2 shows the x-t distribution of rainfall in case W. A pronounced generation of a wavenumber 1 propagating structure is evident. In contrast to the previous wave-CISK cases in which mesosystem and large-scale waves have similar propagation velocities, in this case the propagation of mesosystem and large-scale waves can easily be separated. The space–time spectrum of the rainfall distribution (Fig. 7.3) indicates significant power in wavenumber 1. In contrast to the spectra of precipitation in the wave-CISK cases (Figs. 5.6 and 5.9), the asymmetry in the strengths of the signals propagating upwind (positive phase velocity) and those propagating downwind is prominent. At the same time, it should be noted that the signals corresponding to cloud clusters, distributed at wavenumber 6 or larger and with small phase velocities, are similar to previous cases without WISHE, implying that WISHE is inherently large scale and does not affect the smaller scale structure directly. Note that the setup of case W is the same as that of case H0 except for the introduction of WISHE feedback. Thus, the critical importance of WISHE feedback in the generation of such a large-scale disturbance is evident. In fact, when WISHE feedback is turned off at a certain point in the time integration, the large-scale wave dispersed in a few tens of hours (not shown here).

![Fig. 7.2 Temporal evolution of the rainfall intensity in case W. Two cycles of the computational domain are shown.](image-url)
Fig. 7.3 Space–time spectrum of the rainfall intensity in case W. The abscissa indicates the characteristic phase velocity in units of [m/s], and the ordinate is the horizontal wave number measured by the domain scale (i.e., 4,096 km).

Fig. 7.4 shows the structure of the wavenumber 1 component of the disturbance propagating at a phase speed of 12 m/s. Although there is some degree of complexity in the middle troposphere, the disturbance is characterized mostly by an upright first baroclinic mode. This is in contrast to the structure of the wave-CISK disturbance (Figs. 5.10 and 5.12), which are rich in higher modes. Another notable difference is that the WISHE disturbance has a significant moisture anomaly in the lowermost level, which is absent in the wave-CISK disturbance. This exemplifies the important contribution of the anomalous water vapor flux associated with the wind anomaly in WISHE.

As in the disturbances in the wave-CISK experiments, the preferred scale is not determined in the 4,096 km model. Therefore, the setup used in case W is repeated as case W32I1, which uses a 32,768 km domain model, except that the low-level humidity is raised in half of the domain at the start of the experiment. The result of an experiment with a similar setup but with a much more localized initial moistened area is not notably different from the result of case W32I1. Fig. 7.5 shows the x-t distribution of rainfall in case W32I1. The propagation of wavenumber 1, i.e., the wave with a 32,768 km wavelength, is evident. Its amplitude is large enough to eliminate cloud activity in the “weak convection phase” completely. The separation between mesosystem and large-scale waves is also clearer. Sometimes two or three mesosystems exist in the active convection region at the same time. Thus, in the case W32I1, the hierarchy from cumulus convection to a large-scale wave is
reproduced. The establishment of the wavenumber 1 wave even in the extended model suggests that the “preferred scale” of the WISHE disturbance could be infinitely large.

Fig. 7.4 The structure of the wavenumber 1 disturbance in case W. The disturbance moves to the right.
7.4 Sensitivity to the vertical heating profile

The results of experiments presented in sections 5 and 6 show that the large-scale organization of cloud activity can be very sensitive to the vertical profile of cumulus heating. It is of interest to examine how WISHE responds to a difference in the vertical heating profile. As in the previous sections, the profile of the body cooling given to the model is changed with the expectation that the heating profile of cumulus convection would adjust to the cooling profile.

Fig. 7.6 shows the x-t distribution of rainfall in case WRH32, in which the upper troposphere is strongly cooled. As was noted in section 6, in the absence of WISHE, a propagating synoptic-scale waves and stationary planetary-scale modulation appear (Fig. 6.1). Here, as in the case with a standard cooling profile (Fig. 7.5), convective activity propagates generally upwind with wavenumber 1 modulation. However, unlike the previous case, the convective activity is more concentrated. With intermittent branching in the counter direction, convective activity continues just like a very long lived squall line. This could be interpreted as the result of a coincidence of inherent phase velocities of the wave-CISK mode.

Fig. 7.7 shows the x-t distribution of rainfall in case WRL32, where the lower troposphere is strongly cooled. Compared to cases with standard or upper enhanced heating, the intensity of the modulation of cloud activity is considerably reduced. However, there is an important common feature, i.e., the development of wavenumber 1. Still, there is an important difference; i.e., two dominant phase speeds of propagation exist in this case. One very slowly propagates upwind (~1 m/s) and the other propagates also upwind much faster (~20 m/s). The
latter phase speed is not very different from that of internal gravity waves that appear in many of the previous cases. It is notable that the intensity of the modulation of cloud activity is gradually growing. In short, WISHE is very robust and can develop in the upwind direction, propagating cloud modulation in a wide parameter range.

Fig. 7.6 Temporal evolution of the rainfall intensity in case WRH32. Two cycles of the computational domain are shown.

Fig. 7.7 Temporal evolution of the rainfall intensity in case WRL32. Two cycles of the computational domain are shown.
7.5 Vacillation of WISHE

By closely examining the WISHE experiments with a large-domain model, significant vacillation of cloud activity can be noted. Fig. 7.8 shows the x-t distribution of rainfall in the 32,768 km model with WISHE (case W32). Fig. 7.9 shows the temporal evolution of the integral properties in this experiment. All of the quantities vacillate at a time scale of 15 days. Maxima in the kinetic energy occur around t = 15, 30, 45, and 65 days. The amplitude of the vacillation relative to the average value is about 30% for evaporation and precipitation, and as large as 80% for total kinetic energy. The time sequence shows that the vacillation occurs by the following feedback loop. An increase of cloud activity results in strong surface wind (represented by an increase of kinetic energy), which causes an increase of surface flux from the ocean. This causes a further increase in convective clouds, after which the static stability of the troposphere increases and the convection reduces. The reduction of convection causes lowering of the air temperature and recovery of cloud activity.

![Temporal evolution of the rainfall intensity in case W32](image)

**Fig. 7.8** Temporal evolution of the rainfall intensity in case W32. Two cycles of the computational domain are shown.
Section 7  Wind-Evaporation Feedback

7.5 Vacillation of WISHE

By closely examining the WISHE experiments with a large-domain model, significant vacillation of cloud activity can be noted. Fig. 7.8 shows the x-t distribution of rainfall in the 32,768 km model with WISHE (case W32). Fig. 7.9 shows the temporal evolution of the integral properties in this experiment. All of the quantities vacillate at a time scale of 15 days. Maxima in the kinetic energy occur around t = 15, 30, 45, and 65 days. The amplitude of the vacillation relative to the average value is about 30% for evaporation and precipitation, and as large as 80% for total kinetic energy. The time sequence shows that the vacillation occurs by the following feedback loop. An increase of cloud activity results in strong surface wind (represented by an increase of kinetic energy), which causes an increase of surface flux from the ocean. This causes a further increase in convective clouds, after which the static stability of the troposphere increases and the convection reduces. The reduction of convection causes lowering of the air temperature and recovery of cloud activity.

By examining Fig. 7.8, it can be seen that the degree of cloud concentration varies in time with a temporal scale similar to that noted in Fig. 7.9. Around the times of maximum kinetic energy, convective activity concentrates into two persistent series of convection systems, one of which propagates eastward and the other propagates westward. The westward propagation

Fig. 7.9 Temporal evolution of various domain-integrated quantities in case W32. From top to bottom: average potential temperature deviation, surface layer moisture content, total kinetic energy, evaporation, and rainfall.
is counterintuitive because it is the reverse direction of that expected from WISHE theory. Such westward propagation of convective system is related to strong westerly surface (disturbance plus basic) wind that develops in those regions as the intense convection continues in the region to the east. Seven additional model runs were performed starting from slightly different initial conditions. In all of the runs (not shown here), similar vacillations in cloud activity occurred. This demonstrates that the 15–20 day scale vacillation of convective activity in the large-domain cloud model is a robust feature.

Fig. 7.10 compares the amplitudes of the vacillations realized in the runs with different domain sizes. The plot shows the normalized total kinetic energy, defined as the amount of kinetic energy per 32,768 km domain. It is evident that the volume-normalized kinetic energy is larger for the larger domain runs. Moreover, vacillation becomes more distinct for larger domains: the amplitude relative to the mean value is larger, and the characteristic time scale becomes longer.

Fig. 7.11 compares the amplitudes of the vacillations realized in the runs with different surface wind or cloud microphysics. In general, the vacillation is more prominent in cases with weaker basic state surface wind. It is also noted that the kinetic energy is reduced when the surface wind is very strong. This is because in that case the eastward propagating large-scale disturbances induced by WISHE are less active. In case W32NRE without rain water evaporation, the vacillation is much less active in spite of the generally large amplitude. This should be related to a difference in the mesoscale cloud organization between the runs with and without rain evaporation (Fig. 7.12), but the reasons remains unclear at present.

Fig. 7.10 Temporal evolution of the normalized total kinetic energy in models with different domain sizes: 65,536 km (red), 32,768 km (green), 16,384 km (blue), 8,192 km (purple), 4,096 km (dark olive green), and 2,048 km (orange).
Section 7  Wind-Evaporation Feedback

is counterintuitive because it is the reverse direction of that expected from WISHE theory. Such westward propagation of convective system is related to strong westerly surface (disturbance plus basic) wind that develops in those regions as the intense convection continues in the region to the east. Seven additional model runs were performed starting from slightly different initial conditions. In all of the runs (not shown here), similar vacillations in cloud activity occurred. This demonstrates that the 15–20 day scale vacillation of convective activity in the large-domain cloud model is a robust feature.

Fig. 7.10 compares the amplitudes of the vacillations realized in the runs with different domain sizes. The plot shows the normalized total kinetic energy, defined as the amount of kinetic energy per 32,768 km domain. It is evident that the volume-normalized kinetic energy is larger for the larger domain runs. Moreover, vacillation becomes more distinct for larger domains: the amplitude relative to the mean value is larger, and the characteristic time scale becomes longer.

Fig. 7.11 compares the amplitudes of the vacillations realized in the runs with different surface wind or cloud microphysics. In general, the vacillation is more prominent in cases with weaker basic state surface wind. It is also noted that the kinetic energy is reduced when the surface wind is very strong. This is because in that case the eastward propagating large-scale disturbances induced by WISHE are less active. In case W32NRE without rain water evaporation, the vacillation is much less active in spite of the generally large amplitude. This should be related to a difference in the mesoscale cloud organization between the runs with and without rain evaporation (Fig. 7.12), but the reasons remains unclear at present.

Fig. 7.10 Temporal evolution of the normalized total kinetic energy in models with different domain sizes: 65,536 km (red), 32,768 km (green), 16,384 km (blue), 8,192 km (purple), 4,096 km (dark olive green), and 2,048 km (orange).

Fig. 7.11 Temporal evolution of the normalized total kinetic energy in sensitivity experiments: standard case (black), case with rain evaporation switched off (red), case with 0.3 m/s basic state wind (blue), case with 7.5 m/s basic state wind (green), and case with 12 m/s basic state wind (purple).

Fig. 7.12 Temporal evolution of the rainfall intensity in case WNRE32. Two cycles of the computational domain are shown.
7.6 Remarks

The prototype WISHE experiments presented in the first half of this section show that WISHE can indeed have a notable effect. The amplitudes of the disturbances are large, and their wavelengths can be as large as the size of the Pacific. If the domain were to be extended, truly global disturbance could appear. On the contrary, disturbances in the wave-CISK experiments described in section 5 are much shorter. Some of the disturbances in section 6 have a planetary scale, but they are stationary. Thus, as an explanation of tropical intraseasonal oscillations, which has the planetary scale propagating character, WISHE seems to be more likely than wave-CISK.

The fact that amplification of WISHE waves also occurs at a smaller scale is also important, because, until now, WISHE was thought to be important only for scales larger than synoptic scale. Considering the results reported in this section, the effect of mean wind on mesoscale systems, especially larger classes of them, should be investigated not only in the context of vertical wind shear but also in the context of wind speed at the surface, which is important from the viewpoint of WISHE.

The enhanced vacillation in large-domain runs, especially in models with “planetary” domain size, suggests that the total amount of convective activity spontaneously vacillates at an “intra-seasonal” time scale. At present, the precise mechanism of the vacillation is unclear. One candidate, suggested by comparing the results with different basic state winds, is nonlinearity in WISHE feedback. That is, when the amplitude of the surface wind disturbance exceeds the basic state wind speed, the absolute value of the surface wind increases not only to the east of the convective area but also to the west, resulting in an increase in the total energy supply from the ocean. Further analysis of the results is necessary to resolve the issue. Sensitivity to cloud microphysics should also be investigated. Bantzer and Wallace (1996) show that various indices in the tropics as a whole, including net precipitation and average temperature, vacillate on an intra-seasonal time scale. The relationship between such vacillation in the real atmosphere and the behavior of the idealized two-dimensional model reported here should also be investigated.
Section 8  Concluding Remarks

I have described in section 3–7, the behavior of a large-domain, two-dimensional cumulus convection model in various setups. Briefly, the results from cloud and mesoscale systems are rather similar, whereas the results from large-scale systems diverge notably depending on the individual setup. Nevertheless, the behavior of cumulus convection seems to be within reach of understanding, at least in the simple setups that were investigated. Of course, various details of the model behavior remain to be analyzed. In this sense, rather than a final report on completed research, this monograph is a field guide to the “cloud-resolved” world, where one can find various seeds of research. As an appetizer for the reader, I add several color plates that show the rich features that appear in long-term integrations of large-domain cumulus-resolving models. As briefly touched upon in the captions, quite a large number of hierarchical structure phenomena of the tropical atmosphere are represented in the model. Of course, the two-dimensional nature of the model inevitably distorts various processes, so that some of them are not applicable to the real atmosphere. Still, we can say that the real tropical atmospheric field is rich in structure at various scales to the degree, at least, represented here.

I should also note that there is no clear distinction between the class of mesoscale system and the class of cloud cluster, which were listed as the two of the classes in the moist convection hierarchy in the Introduction. This may imply that these two classes are continuous: a mesoscale system in some preferred condition will grow to a size that should be called a cloud cluster. Another interpretation is that, based on the results of case IHM in section 4, if a large-scale moisture inhomogeneity exists, it will result in a rather long-lived group of mesosystems, and that group is a cloud cluster.

In any case, the ability of the model to reproduce a prototype of the moist convection hierarchy is proved, so there are many directions for future investigation. The most apparent is the analysis of results from the viewpoint of the interaction between convection and the large-scale environment. This is important, especially because the behavior of the large-domain cumulus convection model demonstrated in this monograph is free from “contamination” by the (possibly) inverted cause–result relationship that may be present in usual Cumulus Ensemble Modeling (CEM) studies where external forcing is prescribed. Inspection of the behavior of large-domain cumulus models in the setups similar to those in the present study from an observational viewpoint would also be interesting, because such experiment would contain the full dynamic range from individual clouds to large-scale waves. Such inspection should provide ample suggestions for the planning of future field observation programs in the real atmosphere such as GATE (International and Scientific Management Group for GATE, 1974).

Finally, I repeat that true calibration of moist convection in a GCM is possible within the framework of this study, but it is impossible with CEM. In the latter, causality may be broken, so that if one “tunes” some cumulus parameterization using CEM, the parameterization can also include seeds of false causality, which can manifest as serious problems in a GCM. In contrast, in the framework of this study, at least a subset of the natural interaction between convection and the larger-scale system is captured, so that an “active check” of the parameterization becomes possible. This is the first potential application of large-domain cumulus modeling to climate modeling.
Acknowledgements

The computations were mainly performed using the several generations of supercomputers at the Center for Global Environment Research, National Institute for Environmental Studies. The S-820 and S-3800 machines at the Computer Center, Tokyo University; the SX-3 at the Computer Center, Osaka University; and the SX-3 at the Computer Center, Tohoku University, were also used.

The first half of this monograph is based on the author’s Ph.D. thesis. He deeply thanks Taroh Matsuno for continuous advice and encouragement. Thanks are extended to Yoshi-Yuki Hayashi, Akimasa Sumi, and other members of the meteorological research lab, and to CCSR for numerous helpful discussions. Comments from Ryuji Kimura, Masanori Yamasaki, and other members of the thesis committee are also acknowledged. The later half of the thesis work was done when the author was affiliated with the Ocean Modeling Group of CCSR. Late Nobuo Suginohara is deeply appreciated for his generous encouragement.

The author appreciates Masaki Ishiwatari, Shin-ichi Takehiro, Masatsugu Odaka, Ko-ichiro Sugiyama, Tatsuya Yamashita, Yoshiyuki O. Takahashi, Masuo Nakano, and Yoshiyuki Tashima for their collaboration and helpful discussions in various stages of this study.

TISN, WIDE, SINET, and UTnet were used for the data transfers from these remote computers. The GFD-DENNOU library was used for some of the drawings.
Plates

Details of model fields
In the 60-day integration of 65,536 km model
Plates 1 and 2: Structure of cloud activity in the subdomain extending 2,800 km at two selected times. Each plate consists, from top to bottom, of the temperature anomaly, horizontal velocity, water vapor mixing ratio, vertical velocity, cloud water mixing ratio, and rain water mixing ratio. Warm coloring represents a positive or higher value, and cool coloring represents negative or lower values. Fine structure is present not only close to but far from convective clouds.
Plates 1 and 2: Structure of cloud activity in the subdomain extending 2,800 km at two selected times. Each plate consists, from top to bottom, of the temperature anomaly, horizontal velocity, water vapor mixing ratio, vertical velocity, cloud water mixing ratio, and rain water mixing ratio. Warm coloring represents a positive or higher value, and cool coloring represents negative or lower values. Fine structure is present not only close to but far from convective clouds.

Plate 3: Temporal evolution of cloud clusters in the subdomain extending 6,160 km at time intervals of 12 h. Time increases downward. In each panel, the water vapor mixing ratio (red), cloud water mixing ratio (blue), and rain water mixing ratio (green) are plotted.

Plate 4: Variables in the full 65,536 km domain. From top to bottom: horizontal velocity, temperature anomaly, water vapor mixing ratio, and cloud water mixing ratio.
Plates

Plate 5: Temporal evolution of the rainfall intensity.

Plate 6: Temporal evolution of evaporation from the sea surface. Structure of various scales, such as the wavenumber 1 propagating structure associated with WISHE, fast moving transient signals associated with mesoscale internal wave packets, and cold air pools below convective clouds, are observed.
Plate 7: Temporal evolution of low-level temperature. Other than intense cold air pools below each convective cloud, various larger scale signals are present.

Plate 8: Temporal evolution of low-level horizontal wind. Other than the wavenumber 1 signal associated with WISHE, various kinds of smaller scale structures are present.
Plate 9: Temporal evolution of the water vapor mixing ratio in the mixed layer. Other than the intense small-scale dry regions at the cold air pools generated by the downdraft from convective clouds, very dry air appears quite frequently, possibly resulting from the downward advection of dry air from above (see Plate 10).

Plate 10: Temporal evolution of the water vapor mixing ratio in the middle troposphere. Strong and persistent small-scale positive humidity anomalies are observed. The contrast is generated by the penetration of moist air by the convective activity into the generally dry air due to the large-scale downward motion, which is also the long-term large-scale result of cloud activity.
References


CGER'S SUPERCOMPUTER MONOGRAPH REPORT

Back Issues

Vol. 1  CGER-I021-'96 (Out of stock)
        Turbulence Structure and CO₂ Transfer at the Air-Sea Interface and Turbulent Diffusion in Thermally-Stratified Flows

Vol. 2  CGER-I022-'96
        A Transient CO₂ Experiment with the MRI CGCM - Annual Mean Response -

Vol. 3  CGER-I025-'97
        Study on the Climate System and Mass Transport by a Climate Model

Vol. 4  CGER-I028-'97 (Out of stock)
        Development of a Global 1-D Chemically Radiatively Coupled Model and an Introduction to the Development of a Chemically Coupled General Circulation Model

Vol. 5  CGER-I035-'99
        Three-Dimensional Circulation Model Driven by Wind, Density, and Tidal Force for Ecosystem Analysis of Coastal Seas

Vol. 6  CGER-I040-2000
        Tropical Precipitation Patterns in Response to a Local Warm SST Area Placed at the Equator of an Aqua Planet

Vol. 7  CGER-I045-2001
        New Meteorological Research Institute Coupled GCM (MRI-CGCM2)
        Transient Response to Greenhouse Gas and Aerosol Scenarios

Vol. 8  CGER-I055-2003 (Out of stock)
        Transient Climate Change Simulations in the 21st Century with the CCSR/NIES CGCM under a New Set of IPCC Scenarios

Vol. 9  CGER-I057-2004
        Vortices, Waves and Turbulence in a Rotating Stratified Fluid

Vol. 10 CGER-I060-2005
        Modeling of Daily Runoff in the Changjiang (Yangtze) River Basin and Its Application to Evaluating the Flood Control Effect of the Three Gorges Project

Vol. 11 CGER-I063-2006
        Development of Process-based NICE Model and Simulation of Ecosystem Dynamics in the Catchment of East Asia (Part I)

Vol. 12 CGER-I073-2007
        Climate Change Simulations with a Coupled Ocean-Atmosphere GCM Called the Model for Interdisciplinary Research on Climate: MIROC

Vol. 13 CGER-I080-2008
        Simulations of the Stratospheric Circulation and Ozone during the Recent Past (1980-2004) with the MRI Chemistry-Climate Model

Vol. 14 CGER-I083-2008
        Development of Process-based NICE Model and Simulation of Ecosystem Dynamics in the Catchment of East Asia (Part II)

Vol. 15 CGER-I092-2010 (Out of stock)
        Algorithms for Carbon Flux Estimation Using GOSAT Observational Data