# The Role of the Diurnal Cycle in Tropical Land-Ocean Contrasts, Convection, and the General Circulation

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## Contents

**Abstract**

The diurnal cycle of surface air temperature over land is something with which all humans are intuitively familiar, perhaps to the detriment of our scientific understanding of its role in the climate system. In this work, I propose examining the impacts of diurnal land-ocean contrasts on the tropical climate. I will focus on near-equatorial islands, due to the importance of the Maritime Continent (MC) region in the general circulation, the strong observed diurnal cycle of convection in the region, and the substantial deficiencies of GCM simulations of MC convection and precipitation. Additionally, several authors have suggested that the diurnal cycle may rectify into an enhancement of the time-mean precipitation and ascent over land in the MC through complex land-sea and mountain-valley breezes, yet mechanisms for such rectification are not well understood. A further motivation for focus on the MC is the provocative hypothesis that geologic changes in the region have driven climate changes since the early Pliocene. This confluence of factors strongly recommends the consideration of the MC as a test region for looking at the effects of the diurnal cycle on the mean climate.

In the proposed work, I will attempt to deconstruct the essential factors of the land-ocean boundary contrast that could lead to nonlinear interaction with the diurnal cycle, and consequent impacts on the tropical climate. Starting from radiative-convective equilibrium, and motivated by preliminary results with a cloud-resolving model, I hypothesize that the lower heat capacity of a land surface can, by itself, rectify the diurnal cycle and produce time-mean ascent, and enhanced convective activity, over islands near the equator. Key questions include exactly what the mechanism for such rectification is, how the enhanced convection depends on the surface properties of an island or island group, what controls the spatial extent and geometry of the compensating subsidence, and whether there is a threshold for island cover in the west Pacific beyond which the equatorial climate can be forced out of a "permanent El Niño" state and into one with a strong Walker Circulation. I plan to use a hierarchy of models, ranging from complex cloud-system resolving models (CRMs) and potentially a GCM, to simpler multiple-column radiative-convective models and analytic theory, with the goal of answering these questions, and building a better understanding of the role of the diurnal cycle in the climate system.

# 1 Introduction

As Geoff Vallis notes in the preface to Climate and the Oceans, "one of the most important questions to answer in the study of climate is to understand just what is a detail and what is essential." It is often implicitly assumed that the diurnal cycle of insolation is a detail, rather than an essential feature, in determining the time-mean atmospheric general circulation and surface climate. I propose to examine the notion that the diurnal cycle, primarily through its creation of, and interactions with, land-ocean contrasts, constitutes an essential feature of the climate system. I will look in particular at the possibility that the nonlinear behavior of convection and atmosphere-surface interactions in the tropics can rectify the diurnal cycle into a time-mean circulation with ascent and enhanced convection over land, especially islands, and subsidence elsewhere. I will thus explore the possibility that tropical landmasses, especially islands, are essential in breaking the zonal symmetry of the tropical climate, with significant impacts on the tropical precipitation distribution, global relative humidity and albedo, and teleconnections to the climate of the extratropics.

I am largely proposing a thesis based on idealized modeling and theory, with an emphasis on mechanistic understanding rather than realism, but there is a specific region that I will have in mind when thinking about the design of modeling experiments and the interpretation of results. This region is the Maritime Continent (MC), or zone of mountainous tropical islands and shallow seas that separates the Pacific and Indian oceans. It has long been known that the MC has a key role in the general circulation (Ramage, 1968), that there is substantial diurnal variability in precipitation and cloud cover over the MC (Holland and Keenan, 1980, Short and Wallace, 1980, Houze et al., 1981), and that land and ocean diurnal cycles of convective activity are very different (Gray and Jacobson, 1977). However, the possibility that the diurnal cycle plays a key role in establishing the MC as the dominant convective heat source to the tropical atmosphere has received less attention, perhaps because early studies such as Matsuno (1966) and Gill (1980) were able to broadly simulate the zonal asymmetry of the tropical climate by use of steady forcing (though this does not address the cause of the elevated time-mean convective heat source over the MC).

More recently, the tropics-wide diurnal cycle of convection has been observed by satellite (Yang and Slingo, 2001, Nesbitt and Zipser, 2003). Such studies have shown that the influence of land on the diurnal cycle of clouds extends well away from land regions, and is significant even in regions with as little as 1% land (Liberti et al., 2001). Such observations, together with deficiencies in GCM simulations of both the diurnal cycle and mean state of convective activity near the MC (Guichard et al., 2004, Slingo et al., 2003, Dai and Trenberth, 2004, Dai, 2006) have led some authors (Neale and Slingo, 2003, Qian, 2008, Robinson et al., 2008) to hypothesize that the diurnal cycle is critical to accurately capturing the time-mean convective heat source over the MC. However, the hypothesized mechanisms in these studies are somewhat divergent. Neale and Slingo (2003) conducted a GCM experiment, with a GCM that systematically underestimates precipitation over the MC, and found that even a threefold increase in resolution did not ameliorate the problem, while replacing islands in the MC with ocean improved the simulation, both locally and remotely – model physics and parameterizations are likely at least equal culprits with inadequate resolution. On the other hand, Qian (2008) performed a regional climate simulation (with parameterized convection) of Java and found that precipitation was substantially underestimated in model runs with flat topography, and was reduced even further in runs where the island was replaced with ocean, suggesting that resolution and topography are key to capturing the distribution of precipitation over the islands of the MC, and that the physics and parameterizations are adequate – quite a different conclusion than that of Neale and Slingo (2003)! The work by Robinson et al. (2008) is more theoretical, and is based on the idea that the heterogeneity of surface enthalpy fluxes introduced by islands in a domain that is largely ocean could enhance local convection; they further hypothesize that the diurnally oscillating sensible heat flux over islands could produce a resonance with the diurnal cycle for islands of a certain spatial scale, leading to enhanced convection. A core goal of the proposed work is to test the hypotheses of these authors, and attempt to clarify which mechanisms (if any) are most relevant for rectification of the diurnal cycle into enhancement of convective activity over tropical islands. All three of these studies, as well as other work on modeling of precipitation over tropical islands (Sato et al., 2009, Robinson et al., 2011), invoke the importance of convergence driven by land-sea and mountain-valley breezes in the diurnal cycle of precipitation. Whether or not this convergence is essential to rectification of the diurnal cycle is one subject that I plan to address. The proposed work also could ultimately help to improve the convective parameterizations used in global models, and improve our simulations of the current and future climate by reducing biases, both in the diurnal cycle and the mean climate.

Another motivation for focus on the MC lies in the potential for linkage between the climate changes of the past several million years, and the geologically recent emergence of a number of small islands in the MC, together with the steady northward motion of New Guinea and the Australian plate (Hall, 2002). The climate of the early Pliocene is thought to have resembled a "permanent El Niño" state, with much higher sea surface temperatures in the East and Central Pacific, warmer global-mean surface air temperatures, and much smaller global ice volume (Fedorov et al., 2006). Dayem et al. (2007) found that precipitation over the MC, rather than precipitation over the pacific warm pool, best correlates with variability in the strength of the Walker Circulation, and thus hypothesized that reorganization of the MC could have "provided a necessary condition for the onset of the Walker Circulation," contributing to a shift out of the "permanent El Niño" regime of the early Pliocene. A second core goal of the proposed work is to test the hypothesis of Dayem et al. (2007) in idealized models and theory. The existence (or non-existence) of threshold responses in idealized models as the fractional coverage, latitude, or elevation of islands is varied may provide additional support (or resistance) to the supposed importance of the MC in late Cenozoic climate change. Also of key interest to this problem is the examination of whether land/island convection may be more efficient than oceanic convection at producing available potential energy to fuel a large-scale overturning circulation.

This paper will outline an approach, based on idealized modeling and theory, to address the two core goals listed above. Extending the work of Neale and Slingo (2003) and Qian (2008), I hypothesize that the diurnal cycle can strongly rectify into time-mean ascent over lower-heat capacity land surfaces, and that this rectification plays a role in the observed enhancement of precipitation over islands in the tropics (Sobel et al., 2011). Furthermore, building on the work by Dayem et al. (2007), I hypothesize that deep convection and ascent over even small islands can be important for breaking the zonal symmetry of the tropical climate, by creating large-scale zonal overturning (e.g. Walker) circulations. As mentioned above, our modeling and theoretical assumptions and idealizations will tend towards a focus on tropical islands, and particular attention will be paid to investigation of mechanisms by which the diurnal cycle may rectify into time-mean atmospheric circulations.

## 2 Preliminary Methods and Results

A starting point for understanding the tropical climate is often taken to be the state of radiative-convective equilibrium (RCE). The level of sophistication of this simulated state has advanced from 1-dimensional models with simple convective closures and prescribed humidity and cloud cover (e.g. Manabe and Strickler (1964)), to 3-dimensional models that can resolve dynamics down to scales of hundreds of meters in the horizontal, and have explicit prognostic equations for clouds and multiple water phases, including hydrometeors (e.g. Romps and Kuang (2010)). Despite this long research record, and the limitations of the RCE state, there are still many open questions in climate, such as those posed here, that can be fruitfully addressed by using it as a jumping-off point. I worked with versions of a 1-D and 2-D radiative-convective model with mixed ocean/land domains for my generals project (using models described in Emanuel and Zivkovic-Rothman (1999) and Abbot and Emanuel (2007)), so starting from RCE substantially leverages my previous research.

I have simulated radiative-convective equilibrium using the SAM model (Khairoutdinov and Randall, 2003) in a doubly-periodic domain 384 by 384 km (with 3 km horizontal resolution and 64 levels in the vertical) and a slab ocean lower boundary with interactive surface temperature and no flux adjustment. Dynamics are nonrotating, but the solar flux has been reduced from equatorial values so as to give reasonable surface temperatures (runaway greenhouse regimes result if a tropical value of the time-mean solar flux is used). Most of the domain has a slab ocean 1 meter in depth, but a "swamp island" 1/16 of the domain size (square, 96 by 96 km) has a water surface only 5 cm deep. Other than the low heat capacity of the "island" surface, there are no differences between the "island" and the surrounding "ocean" surfaces (quotes will be dropped hereafter). The diurnal cycle of surface enthalpy fluxes over the island, together with the lack of large-scale forcing, produces a fairly regular diurnal cycle of convection and precipitation, with a precipitation maximum near 18 LST over land, and a weaker diurnal cycle over the ocean (Figure 1). The diurnal and subdiurnal variations in convection result in a marked time-mean precipitation maximum over the island: averaging over a 16-day period yields a precipitation rate of 6.0 mm/day over the island, but only 2.8 mm/day over the surrounding ocean (Figure 2).

These results are striking in the magnitude of the island-ocean contrast,

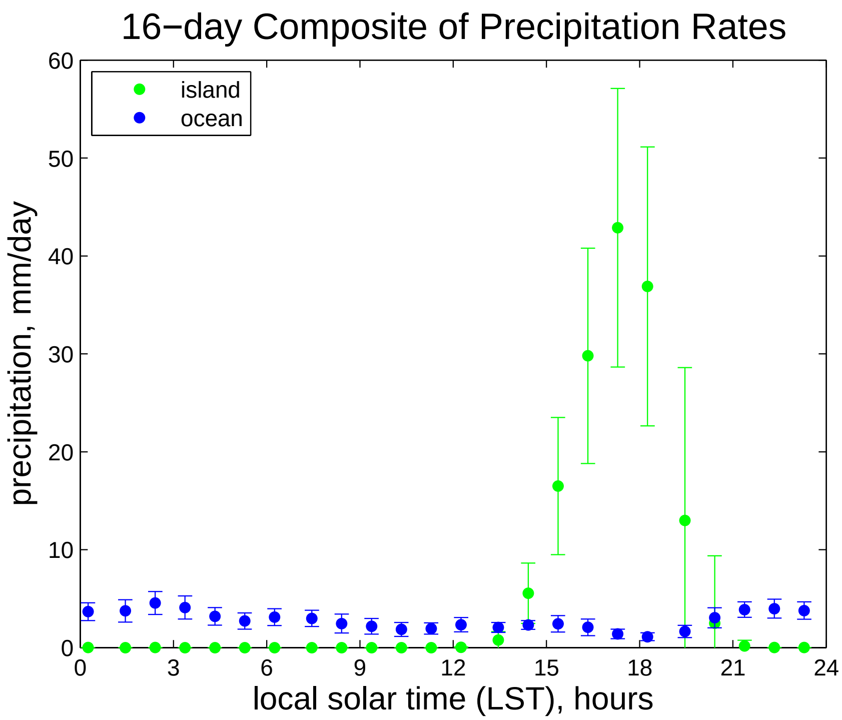


Figure 1: Diurnal composite of precipitation in RCE using the SAM model, over a 16-day period. Precipitation is strongly peaked over the island (green dots) in the late afternoon/early evening, while the diurnal cycle of oceanic precipitation is weaker, and has a nocturnal maximum (blue dots). Error bars represent day-to-day variability in the ocean or land spatially averaged precipitation at each hour (equal to the standard deviation of the 16 daily values for ocean- or land- precipitation).

especially given that the only difference between the two surfaces is their heat capacities. Even though the difference is smaller by over an order of magnitude than it would be in reality, it effectively filters out the diurnal cycle of surface enthalpy fluxes over ocean regions, while retaining a strong diurnal harmonic over the island. Why does the diurnal cycle rectify into time-mean ascent over the island? Initial exploration of the subject suggests that nonlinearities associated with both the time-mean surface temperature and the cloud radiative forcing could have substantial impacts on the column energy budget. Geometric asymmetry between convergence induced by land versus sea breezes could also be a factor, and the energetics of the overturning circulations still need to be explored in more detail. Further parametric and structural sensitivity experiments should clarify the mechanisms governing

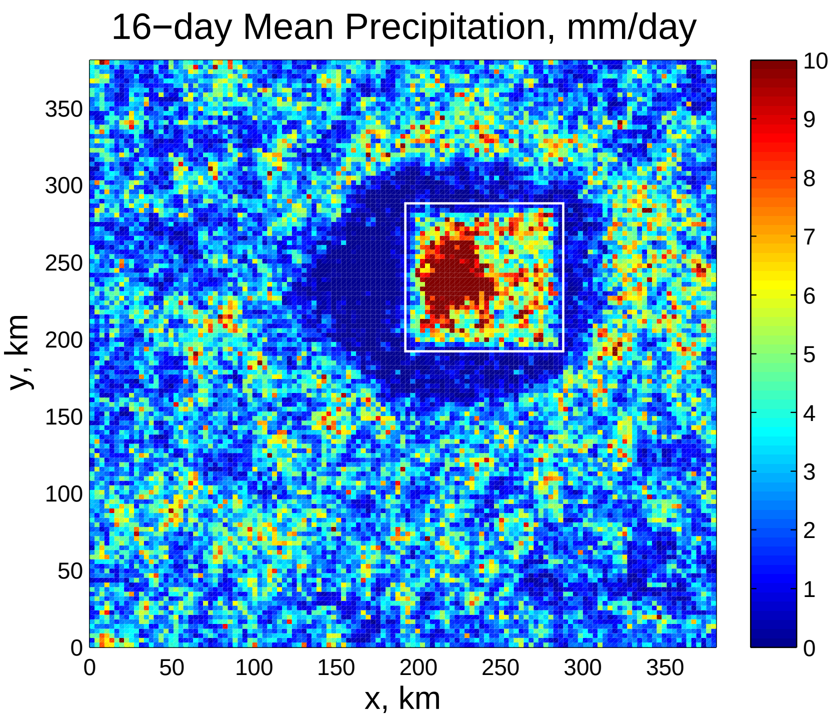


Figure 2: Map of time-mean precipitation in RCE using the SAM model, over a 16-day period. Precipitation is strongly peaked over the island (outlined by the white box in the upper right center), with a ring of minimum precipitation around the island. Strong mid-tropospheric ascent over the island is balanced by subsidence in the surrounding dry ring.

the sense of the mean circulation.

# 3 Research Plan

The following section presents a rough outline of the proposed research and a discussion of the new scientific contributions expected, as well as some potential barriers to progress. Due to interesting initial results, I plan on more near-term work with the SAM model, and potentially another cloud-system resolving model (CRM). This will be followed or accompanied by simulations with a two-dimensional radiative-convective model, as well as theoretical work.

## 3.1 Outline

1. Work with SAM extending current simulations to better understand the processes governing rectification of the diurnal cycle:

   (a) Comparison to control run with same forcing but all-ocean lower boundary (impacts of island existence on domain-average temperature and surface fluxes; knowledge of reference conditions)

   (b) Analysis of sea breeze dynamics in current simulations or extensions of them (importance of organization of convection by sea breeze-induced convergence)

   (c) Simulations with removal or homogenization of cloud-radiation interactions (importance of differential cloud radiative forcing over land and ocean)

   (d) Simulations with modified land-atmosphere enthalpy fluxes (exploration of importance of time-mean land-ocean surface flux contrast in current simulations)

   (e) Comparison to a "lake" instead of an island simulation (identification of intrinsic importance of land versus surface heterogeneity)

2. Work with SAM extending current simulations to more generally examine the precipitation distribution and atmospheric circulation in a mixed land/ocean domain (choice of parameters to explore will likely depend on above results):

   (a) Parametric sensitivity experiments with heat capacity asymmetry only (e.g. size of island and domain, resolution, absolute temperature, island heat capacity, Coriolis parameter, length of "day")

   (b) Sensitivity experiments exploring other land-ocean asymmetries (e.g. surface wetness, roughness, albedo, elevation)

   (c) Sensitivity to model structure and boundary conditions (e.g. Radiation and Microphysics schemes, large-scale ascent/subsidence, background flow/shear)

   (d) Exploration of threshold behavior in selected simulations

   (e) Study of selected sensitivities with another CRM

3. Work with simpler 2- or multiple-column RC model with parameterized convection

(a) Identification of a boundary conditions/forcings that mimic the setup of the SAM model (may require 2D runs with SAM)

(b) Test robustness of mechanisms for rectification suggested by SAM simulations

(c) Sensitivity to parameters in convective scheme, and/or convective parameterization

4. Work on extending smaller-scale results to the scale of the Tropical General Circulation

   (a) GCM (or SAM) simulation with parameterized convection tuned to mimic resolved convection in SAM (modification of quasi-equilibrium closure, entrainment parameterization, introduction of lag in cloud-top height?)

   (b) GCM simulation with superparameterized convection

   (c) SAM simulation with rescaled parameters to allow for resolution of equatorial waves

   (d) Equatorial wave response in linearized equations to diurnally oscillating convective heating, informed by SAM simulations (e.g. Silva Dias et al. (1987))

## 3.2 Discussion

Many studies have been conducted with cloud-resolving models, with a spectrum of realism of boundary conditions and forcing ranging from highly idealized (doubly-periodic RCE over fixed SST with temporally constant solar flux – e.g. Romps and Kuang (2010)) to fairly realistic (global model with prescribed SST, atmospheric initial conditions, realistic topography and soil moisture at 3.5-km – Satoh et al. (2008)). An increasing number of studies have used cloud-resolving models in idealized land-ocean domains, but most have focused on specific regions (e.g. Hector events over the Tiwi islands – Saito et al. (2001), Connolly et al. (2006)), or have used extremely idealized boundary forcing (Robinson et al., 2011), and no published studies that I am aware of have used a CRM to examine the RCE climate of a mixed land-ocean domain (though Back, personal communication, may be in press soon). Furthermore, most of these studies focus on the observed dynamical paradigms of sea-breeze fronts and cumulus merger (Simpson et al., 1993), but my preliminary work suggests that time-mean land-ocean energetic asymmetries may be key contributors to the time-mean atmospheric circulation, and may be just as important as these observed modes of convective aggregation. Thus, much of the proposed work in this study will be grounded in an extensive literature (observational, model, and theory) of island thunderstorm dynamics, but will seek to extend the relevance of these dynamics to climate, rather than weather, timescales.

I envision a few potential obstacles in the proposed line of study. One obstacle is that of computational power and the limits imposed on the domain size of a CRM. Ultimately, for purposes of climate study (outline item 4), it would be ideal to extend a cloud-resolving modeling study to the scale of an equatorial beta plane, which would be critical to capturing the effects of equatorial waves on the geometry of the compensating subsidence around very large islands or island groups. However, the brute-force approach of direct simulation will likely fail here due to excessive (for now) computational cost, especially if interactive surface temperatures are required (I believe they are) – Sato et al. (2009) simulate the global atmosphere at 3.5 km resolution with a CRM, but using significantly more computer power than I have access to, and only for a month of simulated time. Thus, attempting to answer the question of how equatorial islands may impact the general circulation will require some creativity – the points below outline item 4 above represent potential avenues towards progress on the issue.

A second obstacle is that of topography in the SAM model. I am not aware of past modeling experiments that have used topography in the SAM model, and it may be fairly difficult to modify the model so as to include reasonable (albeit simplified) topography, such as a pyramidal or gaussian mountain (it may also prove to be fairly straightforward, but assumption of difficulty is probably safer). Other models that can be run as CRMs (CM1, WRF) may include more flexibility with topography, and certainly the use of multiple CRMs would be a viable research avenue (outline item 2e), especially if general-circulation-scale simulations prove too unreliable or difficult.

A third, more nebulous problem, is that, even with major simplifications of boundary conditions, and choice of RCE as a jumping-off point, CRM simulations may be simultaneously both extremely complex and difficult to interpret, and far from convergence to the behavior of real-world moist convection. Even in the highly unlikely circumstance that all physical processes are adequately represented, there is still the nagging question of spatial resolution, which can be addressed to some extent, but only at significant computational cost. Thus, my simulations may stand uncomfortably far both from the theory underlying them, and the real world above them. Where possible, then, I will make efforts to suggest ways in which my findings could be tested by real-world observations, and I will attempt to construct clear model hierarchies that support the most important of my findings (much of the purpose of outline item 3). It is likely that the analysis of real-world observations for comparison with my simulations, or construction of simpler models to identify the robustness of underlying mechanisms, will compose a significant part of the work proposed here. Since this component of my research will emerge as a consequence of model results, rather than being specified at the outset of the study, it is somewhat underrepresented in the outline above.

# 4 Summary

I propose investigation of the role of diurnal-land ocean contrasts on the mean precipitation rate and atmospheric circulation near tropical islands, by use of sophisticated models with idealized boundary conditions, as well as simpler models and theory. There are several motivations for choosing tropical islands as a testing ground for the impacts of the diurnal cycle on the climate system, including the key role of convection over the Maritime Continent in the general circulation, the strong observed diurnal cycle of convection in the region, and the substantial deficiencies of GCM simulations of MC precipitation (and the diurnal cycle of land precipitation in general). I intend to test the hypothesis of Neale and Slingo (2003) and others that the diurnal cycle is climatically relevant, and clarify mechanisms by which the diurnal cycle may interact with land-ocean contrasts to produce time-mean atmospheric circulations. I also intend to test the hypothesis of Dayem et al. (2007) that geologically recent changes in the geography of the MC region have had an impact on moving the climate out of the "permanent El Niño" state of the early Pliocene, by looking for evidence of threshold behavior in model simulations, and by looking at differences between simulations with and without islands.

Successful work on testing the two hypotheses mentioned above may allow for:

1. A better physical understanding of the role of the diurnal cycle in the precipitation distribution of the tropics; specifically the enhancement

of precipitation and convective intensity over islands

2. A better understanding of the role (or lack thereof) of tropical islands of the MC in breaking the zonal symmetry of the climate of the tropical Pacific

3. A clarified mechanism for climate change in the late Cenozoic (or lack of support for the hypothesis that changes in the MC since the early Pliocene have contributed to changes in global climate)

4. Better parameterization of deep convection over mixed land/ocean and island/ocean regions, with potential for reduction of biases in GCM simulated climates, past, present, and future

This latter task is an ambitious and potentially high-impact goal, and may not be within the scope of the dissertation work, but could follow logically as a next step. This study represents novel ground in the use of CRMs over mixed land-ocean domains to simulate climate, as well as potentially novel ground in understanding scale interactions between the very small spatial and short temporal scale of diurnal convection, and the much larger and slower Walker circulation.

As this study involves mainly modeling and theoretical work, little to no additional funding is expected beyond the typical Research/Teaching Assistantship funding. I have a 1-semester Martin Fellowship which can be applied at any time, and I am also supported by NSF grant 1136466: "Collaborative Research: The Effect of Near-Equatorial Islands on Climate." I plan on using local computer clusters (elorenz, svante) for most model simulations, my laptop computer for analysis, and will apply for supercomputer time (e.g. Accelerated Scientific Discovery initiative) if necessary for some of the larger-scale simulations.

# References

Dorian S. Abbot and Kerry A. Emanuel. A Tropical and Subtropical Land–Sea–Atmosphere Drought Oscillation Mechanism. *Journal of the Atmospheric Sciences*, 64(12):4458–4468, December 2007.

P. J. Connolly, T. W. Choularton, M. W. Gallagher, K. N. Bower, M. J. Flynn, and J. A. Whiteway. Cloud-Resolving Simulations of Intense Tropical Hector Thunderstorms: Implications for AerosolCloud Interactions. *Quarterly Journal of the Royal Meteorological Society*, 132(621C):3079–3106, October 2006.

Aiguo Dai. Precipitation Characteristics in Eighteen Coupled Climate Models. *Journal of Climate*, 19:4605–4630, 2006.

Aiguo Dai and Kevin E. Trenberth. The Diurnal Cycle and Its Depiction in the Community Climate System Model. *Journal of Climate*, 17:930–951, 2004.

Katherine E. Dayem, David C. Noone, and Peter Molnar. Tropical Western Pacific Warm Pool and Maritime Continent Precipitation Rates and Their Contrasting Relationships with the Walker Circulation. *Journal of Geophysical Research*, 112(D6):1–12, March 2007.

Kerry A. Emanuel and Marina Zivkovic-Rothman. Development and Evaluation of a Convection Scheme for Use in Climate Models. *Journal of the Atmospheric Sciences*, 56:1766–1782, 1999.

A. V. Fedorov, P. S. Dekens, M. McCarthy, A. C. Ravelo, P. B. DeMenocal, M. Barreiro, R. C. Pacanowski, and S. G. Philander. The Pliocene Paradox (Mechanisms for a Permanent El Niño). *Science*, 312(5779):1485–1489, June 2006.

A. E. Gill. Some Simple Solutions for Heat-Induced Tropical Circulation. *Quarterly Journal of the Royal Meteorological Society*, 106(449):447–462, July 1980.

William M. Gray and Robert W. Jacobson. Diurnal Variation of Deep Cumulus Convection. *Monthly Weather Review*, 105:1171–1188, 1977.

F. Guichard, J.C. Petch, J.-L. Redelsperger, P. Bechtold, J.-P. Chaboureau, S. Cheinet, W. Grabowski, H. Grenier, C.G. Jones, M. Köhler, J.-M. Piriou, R. Tailleux, and M. Tomasini. Modelling the Diurnal Cycle of Deep Precipitating Convection over Land with Cloud-Resolving Models and Single-Column Models. *Quarterly Journal of the Royal Meteorological Society*, 130(604):3139–3172, October 2004.

Robert Hall. Cenozoic Geological and Plate Tectonic Evolution of SE Asia and the SW Pacific: Computer-Based Reconstructions, Model and Animations. *Journal of Asian Earth Sciences*, 20:353–431, 2002.

Greg J. Holland and Thomas D. Keenan. Diurnal Variations of Convection over the "Maritime Continent". *Monthly Weather Review*, 108:223–225, 1980.

Robert A. Houze, Spiros G. Geotis, Frank D. Marks, and Arthur K. West. Winter Monsoon Convection in the Vicinity of North Borneo. Part I: Structure and Time Variation of the Clouds and Precipitation. *Monthly Weather Review*, 109(8):1595–1614, 1981.

Marat F. Khairoutdinov and David A. Randall. Cloud Resolving Modeling of the ARM Summer 1997 IOP: Model Formulation, Results, Uncertainties, and Sensitivities. *Journal of the Atmospheric Sciences*, 60:607–625, 2003.

Gian Luigi Liberti, Frederique Cheruy, and Michel Desbois. Land Effect on the Diurnal Cycle of Clouds over the TOGA COARE Area, as Observed from GMS IR Data. *Monthly Weather Review*, 129:1500–1517, 2001.

Syukuro Manabe and Robert F. Strickler. Thermal Equilibrium of the Atmosphere with a Convective Adjustment. *Journal of the Atmospheric Sciences*, 21:361–385, 1964.

Taroh Matsuno. Quasi-Geostrophic Motions in the Equatorial Area. *Journal of the Meteorological Society of Japan*, 44(1):25–42, 1966.

Richard B. Neale and Julia Slingo. The Maritime Continent and Its Role in the Global Climate : A GCM Study. *Journal of Climate*, 16:834–848, 2003.

Stephen W. Nesbitt and Edward J. Zipser. The Diurnal Cycle of Rainfall and Convective Intensity according to Three Years of TRMM Measurements. *Journal of Climate*, 16: 1456–1475, 2003.

Jian-Hua Qian. Why Precipitation Is Mostly Concentrated over Islands in the Maritime Continent. *Journal of the Atmospheric Sciences*, 65(4):1428–1441, April 2008.

C. S. Ramage. Role of a Tropical "Maritime Continent" in the Atmospheric Circulation. *Monthly Weather Review*, 96(6):365–370, 1968.

F. J. Robinson, S. C. Sherwood, and Y. Li. Resonant Response of Deep Convection to Surface Hot Spots. *Journal of the Atmospheric Sciences*, 65(1):276–286, January 2008.

F. J. Robinson, S. C. Sherwood, D. Gerstle, C. Liu, and D. J. Kirshbaum. Exploring the LandOcean Contrast in Convective Vigor Using Islands. *Journal of the Atmospheric Sciences*, 68(3):602–618, March 2011.

David M. Romps and Zhiming Kuang. Do Undiluted Convective Plumes Exist in the Upper Tropical Troposphere? *Journal of the Atmospheric Sciences*, 67(2):468–484, February 2010.

Kazuo Saito, Tom Keenan, Greg Holland, and Kamal Puri. Numerical Simulation of the Diurnal Evolution of Tropical Island Convection over the Maritime Continent. *Monthly Weather Review*, 129:378–400, 2001.

Tomonori Sato, Hiroaki Miura, Masaki Satoh, Yukari N. Takayabu, and Yuqing Wang. Diurnal Cycle of Precipitation in the Tropics Simulated in a Global Cloud-Resolving Model. *Journal of Climate*, 22(18):4809–4826, September 2009.

M. Satoh, T. Matsuno, H. Tomita, H. Miura, T. Nasuno, and S. Iga. Nonhydrostatic icosahedral atmospheric model (NICAM) for global cloud resolving simulations. *Journal of Computational Physics*, 227(7):3486–3514, March 2008.

David A. Short and John M. Wallace. Satellite-Inferred Morning-to-Evening Cloudiness Changes. *Monthly Weather Review*, 108:1160–1169, 1980.

Pedro Leite Silva Dias, Jose Paulo Bonatti, and Vernon E. Kousky. Diurnally Forced Tropical Tropospheric Circulation over South America. *Monthly Weather Review*, 115: 1465–1478, 1987.

J. Simpson, Th. D. Keenan, B. Ferrier, R. H. Simpson, and G. J. Holland. Cumulus Mergers in the Maritime Continent Region. *Meteorology, and Atmospheric Physics*, 51: 73–99, 1993.

Julia Slingo, Peter Inness, Richard Neale, Steven Woolnough, and Gui-Ying Yang. Scale interactions on diurnal toseasonal timescales and their relevanceto model systematic errors. *Annals of Geophysics*, 46(February):139–155, 2003.

A. H. Sobel, C. D. Burleyson, and S. E. Yuter. Rain on small tropical islands. *Journal of Geophysical Research*, 116(D8):1–15, April 2011.

G.Y. Yang and Julia Slingo. The diurnal cycle in the tropics. *Monthly Weather Review*, 129:784–801, 2001.