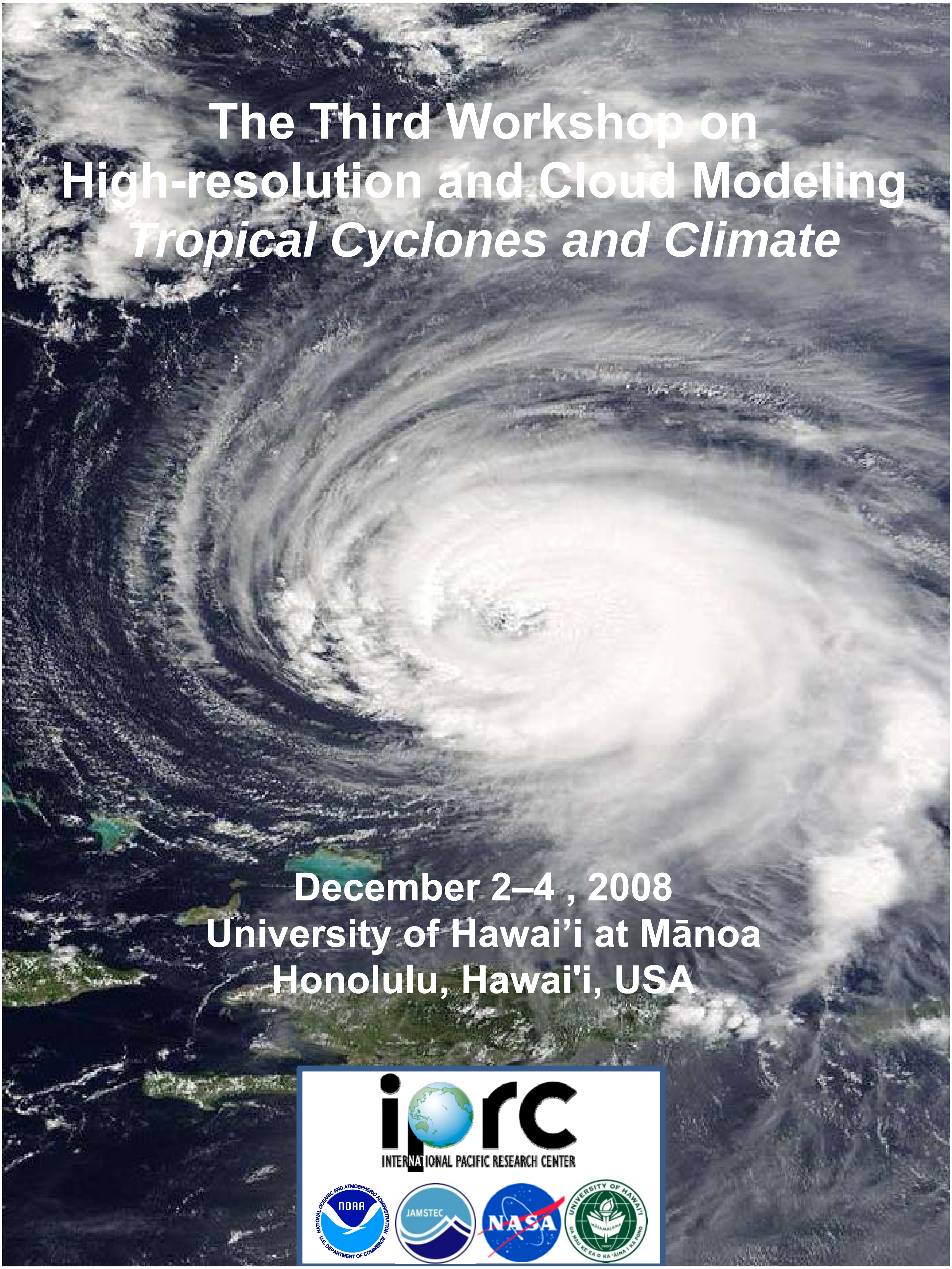
The Third Workshop on High-resolution and Cloud Modeling

Tropical Cyclones and Climate



December 2–4 , 2008
University of Hawai'i at Mānoa
Honolulu, Hawai'i, USA

INTERNATIONAL PACIFIC RESEARCH CENTER

The Third Workshop on High-resolution and Cloud Modeling – Tropical Cyclones and Climate

December 2-4, 2008
University of Hawaii at Manoa, Honolulu, Hawai'i, USA

This workshop follows the successful "First International Workshop on High-Resolution and Cloud Modeling – Fusion of Satellite Observations and High-Resolution Modeling" held in Kusatsu, Japan, and the "Second International Workshop on High-Resolution and Cloud Modeling – Tropical Convection and the Madden-Julian Oscillation" held in 2007 in Reading, UK. The aim of this workshop is to assess the current status of high-resolution atmospheric models, with a focus on the issue of simulation of tropical cyclones and the connection of tropical cyclones to climate variability and change. Key issues that are considered include the scale interactions related to tropical cyclone genesis, intensification, structure and intensity changes, and both large-scale control and large-scale impact of tropical cyclones, as well as dynamical downscaling of the impact of global warming on tropical cyclones. All oral presentations are presented by invited speakers. Other contributions are accommodated in poster sessions. The papers at the meeting also cover general issues in high-resolution modeling and satellite observations of cloud/mesoscale systems, and cloud-aerosol interactions.

Organizing Committee:

Co-Chairs

Yuqing Wang (IPRC)
Masaki Satoh (CCSR)

Members

Kevin Hamilton (IPRC)
Teruyuki Nakajima (CCSR)
David Randall (CSU)
Julia Slingo (Univ. Reading)
Graeme Stephens (CSU)
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Sponsors:

International Pacific Research Center (IPRC) and JAMSTEC. IPRC is supported by JAMSTEC, NASA, NOAA, and University of Hawai'i

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A historical review of the workshop series, **Masaki Satoh**, CCSR, University of Tokyo

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09:45-10:15 *Year of Tropical Convection (YOTC): A Joint WWRP and WCRP Activity to Address the Challenges of Tropical Cyclones and Multi-Scale Organized Convection*, **Duane Waliser**, JPL/Caltech

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11.45-12:15 *Tiling Domain Technique of the Cloud-Resolving Model and its Application to a High-Resolution Simulation of Typhoons*, **Kazuhisa Tsuboki**, Hydrospheric Atmospheric Research Center, Nagoya University

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09:30-10:00 *Tropical cyclogenesis within a tropical wave critical layer: Easterly waves, physical basis, and high resolution numerical simulations*, **Michael Montgomery**, NOAA/Hurricane Research Division, Miami, FL, and U.S. Naval Postgraduate School, Monterey, CA

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10:30-11:00 *Analysis and Modeling of Tropical Cyclones in Relation to Multi-scale Oscillations over the Northwest Pacific Ocean*, Chung-Hsiung Sui and **Ming-Ren Yang**, National Central University

11:00-11:30 *Case studies of tropical cyclone genesis using a global high-resolution model, NICAM*, **Wataru Yanase**, CCSR, University of Tokyo

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13:45-14:15 *The GFDL High-Resolution Atmosphere Model (HiRam) for Short-term forecasts and long-term simulations of tropical cyclones*, **Shian-Jiann Lin**, NOAA/GFDL, Princeton, NJ

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09:30-10:00 *Toward a better Understanding of Tropical Cyclone Predictability and Prediction*, **Shuyi Chen**, RSMAS/University of Miami, and Robert Houze, University of Washington, Seattle, WA

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10:30-11:00 *A Cloud-Resolving Simulation of Hurricane Wilma (2005)*, **Da-Lin Zhang**, Department of Atmospheric and Oceanic Science, University of Maryland, College Park, MD

11:00-11:30 *On the Distribution of Vertical Motion in Hurricanes*, **Wayne Schubert**, Colorado State University, Fort Collins, CO

11:30-12:00 *Performance of JMA Weekly Ensemble Forecast for Nargis*, **Tetsuo Nakazawa**, Meteorological Research Institute

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P2 *High-Resolution WRF Simulation of Hurricane Dennis (2005): Relating Vertical Velocity Distributions and Microphysical Processes to Rapid Intensity Change in the Context of TCSP Observations and NASA Satellite Retrievals*, **Eric Meyers**, University of Illinois at Urbana-Champaign

P3 *Simulation of the MJO-convection onset observed during MISMO*, **Kazuaki Yasunaga**, JAMSTEC

P4 *What determine tropical disturbances to develop or not?* **Lei Wang**[1], Alexis Kai-Hon Lau[2], Qing-Hong Zhang[3], [1]International Pacific Research Center, University of Hawaii at Manoa, Honolulu, HI, [2]Department of Mathematics, Hong Kong University of Science and Technology, [3]Department of Atmospheric Sciences, Peking University, Beijing

P5 *Genesis of Tropical Cyclone Nargis Revealed by multiple satellite observations*, **Kazuyoshi Kikuchi**, International Pacific Research Center, University of Hawaii at Manoa, Honolulu, HI

P6 *Informing statistical regressions of the decay rate of tropical cyclones after landfall using an enhanced event set of storms generated with a mesoscale model*, **A. Colette**[1], V. Daniel[1], N. Leith[1], E. Bellone[1], David S. Nolan[2], [1]Risk Management Solutions Ltd., 30 Monument Street, London EC3R 8NB, United Kingdom. [2]Division of Meteorology and Physical Oceanography, Rosenstiel School of Marine and Atmospheric Science, University of Miami

P7 *Assimilating Doppler Radar Data with a 3DVAR and Cloud Analysis System for the Prediction of Tropical Storm Erin (2007) over Land*, **Ming Xue**, University of Oklahoma, OK

P8 *A High-Resolution Simulation of Typhoon Rananim (2004) with MM5: Model Verification, Inner-Core Shear, and Asymmetric Convection*, **Qingqing Li**, Shanghai Typhoon Institute/CMA

P9 *A High-Resolution Simulation of Asymmetries in Severe Tropical Cyclone Larry (2006)*, **Hamish Ramsay**, Centre for Australian Weather and Climate Research, Australian Bureau of Meteorology

P10 *Typhoon formation and development experiment with a high resolution global model and a mesoscale model*, **Eiki Shindo**, Meteorological Research Institute (MRI)

P11 *Possible change of tropical cyclone intensity and frequency under a greenhouse-warmed climate condition in the global cloud resolving model, NICAM*, **Yohei Yamada**, FRCGC, JAMSTEC

P12 *The Landfalling Characteristics of Typhoon Nari (2001) over Taiwan*, **Ming-Jen Yang**, National Central University

P13 *Impacts of tropical cyclones over western Pacific Ocean on the climate in China*, **Zhong Zhong**, Department of Atmospheric Sciences, Nanjing University, Nanjing

P14 *High Resolution Prediction Tropical Cyclone 'Nargis' using the WRF*, **Raghavendra Ashrit**, National Centre for Medium range Weather Forecasting, Govt of India

P15 *A numerical study of the effect of Typhoon Songda (2004) on remote heavy rainfall in Japan*, **Yongqing Wang**, Pacific Typhoon Research Center, Nanjing University of Information Science and Technology, Nanjing, and International Pacific Research Center, University of Hawaii at Manoa, Honolulu, HI

P16 *Tropical cyclone activity over South China Sea*, **Le Thi Xuan Lan**, Southern Regional Hydrometeorological Center (SRHMC), Vietnam

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P20 *Dynamic and thermodynamic aspects of tropical cyclones in vertical shear and the 'stationary band complex'*, **Michael Riemer** and Michael T. Montgomery, Naval

Postgraduate School, Monterey, CA, Mel E. Nicholls, University of Colorado, Boulder, CO

P21 *Modulation of tropical cyclone activity by ENSO and MJO*, **Suzana Camargo**, Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, James Kossin, Kerry Emanuel, and Daniel Vimont

P22 *Dynamical Downscaling of Tropical Cyclones over the Northwest Pacific Using the IPRC Regional Atmospheric Model (IRAM),* **Yuqing Wang**[1,2], and Zhizhong Su[2], [1]International Pacific Research Center, University of Hawaii at Manoa, Honolulu, HI, [2]Pacific Typhoon Research Center, Nanjing University of Information Science and Technology, Nanjing

Abstracts

Overview of Cloud-Resolving-Model Development within CMMAP

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The Center for Multiscale Modeling of Atmospheric Processes is in the midst of a broad program of model development, with emphasis on cloud-resolving models. The models make use of new sets of governing equations, new discretization methods, and new multiscale approaches. Domain sizes range from mesoscale to global. A discussion of design issues will be interleaved with a presentation of selected results.

Year of Tropical Convection (YOTC): A Joint WWRP and WCRP Activity to Address the Challenges of Tropical Cyclones and Multi-Scale Organized Convection

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The realistic representation of tropical convection in our global atmospheric models is a long-standing grand challenge for numerical weather prediction and climate projection. To address this challenge, WCRP and WWRP/THORPEX have proposed a Year of coordinated observing, modeling and forecasting of organized tropical convection and its influences on predictability. This effort is intended to exploit the vast amounts of existing and emerging observations, the expanding computational resources and the development of new, high-resolution modeling frameworks, with the objective of advancing the characterization, diagnosis, modeling, parameterization and prediction of multi-scale convective/dynamic interactions, including the two-way interaction between tropical and extra-tropical weather/climate. This activity and its ultimate success will be based on the coordination of a wide range of ongoing and planned international programmatic activities (e.g., GEWEX/CEOP/GCSS, THORPEX, EOS, AMY), strong collaboration among the operational prediction, research laboratory and academic communities, and the construction of a comprehensive data base consisting of satellite data, in-situ data sets and global/high-resolution forecast and simulation model outputs relevant to tropical convection. The target time frame for scientific focus is May 2008 to October 2009, and was chosen as a period that would leverage the most benefit from recent investments in Earth Science infrastructure and overlapping programmatic activities (e.g., AMY, T-PARC). Specific areas of emphasis identified in YOTC are: 1) MJO and convectively coupled waves, 2) diurnal cycle, 3) easterly waves and tropical describe the development of this activity, its current status and planned programmatic framework and research agenda.

Mesoscale Organization of Maritime Tropical Convection: Large-Eddy Simulation

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Recently, the progress in supercomputers has allowed application of the grid resolutions previously characteristic of the Large-Eddy Simulation studies of shallow boundary layer clouds to modeling studies of deep clouds and mesoscale organization of convection. Some recent results of such high-resolution simulations using the System for Atmospheric Modeling (SAM) and 100 m horizontal grid-spacing over 200 km wide three-dimensional domain will be presented. The relative abundance of mid-level congestus convection with maximum local cloud amount near the freezing level is well simulated. It is shown that high vertical resolution of about 100 m throughout troposphere seems to be important for simulation of the congestus maximum. Tests of sensitivity to horizontal grid spacing show convergence of the results at 200 m spacing. The interplay of deep clouds, congestus clouds, and cold pools as well as the development of deep clouds as merging congestus clouds will be demonstrated in high-resolution visualization animations. The sensitivity experiment in which the cold pools were virtually eliminated by switching off evaporation of evaporation shows great reduction of the congestus convection. Challenges associated with the so-called 'data tsunami' of large-scale computing will be also discussed.

Multi-scale Structure of an MJO Event Simulated by a Global Cloud-System Resolving Model

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A global cloud-system resolving model (GCRM) is a useful tool to investigate interactions among various types of convective disturbances observed in the tropics. For this purpose outputs from the 7-km mesh simulation of an MJO event (mid December 2006 - mid January 2007) using a GCRM, NICAM is analyzed. The simulation suggests that squall-type convective systems can easily develop in the vertical wind shear associated with the MJO, under the effects of synoptic-scale wave disturbances passing through. The role of organized convection in large-scale dynamics associated with the MJO and the manner in which convection was coupled to tropical wave disturbances will be discussed.

Tiling Domain Technique of the Cloud-Resolving Model and its Application to a High-Resolution Simulation of Typhoons

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A computational domain of most regional models is usually rectangular. On the other hand, a region of interest is not always rectangular but often irregular shape. An arbitrary-shaped domain is more suitable for efficient computation of simulation. In the present study, we have developed a new technique to perform a parallel computation of the cloud-resolving model in an arbitrary-shaped region, which is named the "Tiling Domain Technique (TDT)" for the CReSS (the Cloud Resolving Storm Simulator) model. The arbitrary-shaped domain of parallel computation using the TDT is composed of many small rectangular domains named "domain tiles". If a side of a domain tile is connected to the neighbor domain tile, a halo region is set along the side and data exchange is performed with the neighbor domain tile by MPI. If no neighbor domain tile is present, the side is considered as a boundary of the computational domain. Each domain tile is, further, divided into sub-domains if necessary. Another parallel computation between the sub-domains within the domain tile is performed using MPI. The TDT performs these two types of data exchanges at different levels. We refer to this type of parallel computation as the "hierarchical parallel computations". Multiple computational domains consisting of different numbers of domain tiles in each domain are possible as well as an isolated domain. Using the TDT, we performed a simulation experiment of the typhoon 0418 (T0418) that caused severe damages all over Japan owing to strong wind. In the experiment, 64 domain tiles are used along the track of T0418 and one-week simulation was performed. The regional objective analysis data of the Japan Meteorological Agency (JMA) were used for initial and boundary conditions. The horizontal grid size is 2000 m and the experiment was started from the initial condition of 00UTC September 1, 2004. The central pressure of T0418 in the initial condition was about 60 hPa higher than that of the JMA best-track data. The central pressure of the simulated typhoon decreased rapidly and reached that of the best-track data after about 3 days from the initial time. The simulated typhoon almost follows the JMA best-track for the 7 days of the simulation period. When the simulated typhoon approaches the western Japan, it causes heavy rainfall over the land. The distribution and intensity of the simulated rainfall successfully corresponds to the observed rainfall. Since a typhoon moves along a long and curved track, the TDT is an efficient method for high-resolution simulation of the typhoon. Domain tiles are set along the typhoon track and total computational amount is reduced. The TDT increases flexibility and applicability of the cloud-resolving model for many different types of weather systems. For example, a computational domain is set along the Japanese Islands and isolated domain titles are set in the islands regions. Another possible application is convective activity in the tropical regions, where non-hydrostatic effect is essential. A nested simulation in GCM using the TDT will be also useful for dynamical downscaling of typhoons.

A Study of Aerosol Interaction with Cloud System Using Satellite Remote Sensing and High Resolution Modeling

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It is promising to make a better simulation of aerosol and cloud interaction by using a high resolution non-hydrostatic model. Simulation results can be compared with cloud microphysical characteristics retrieved from satellite remote sensing. It is also important to take account of the direct radiative forcing of aerosols which can generate a general circulation change and hence cloud field change. I like to discuss several important aspects of these aerosol climate effects.

Using Multi-scale Modeling Systems and Satellite Simulator to Study the Precipitation Processes

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In recent years, exponentially increasing computer power has extended Cloud Resolving Model (CRM) integrations from hours to months, the number of computational grid points from less than a thousand to close to ten million. Three-dimensional models are now more prevalent. Much attention is devoted to precipitating cloud systems where the crucial 1-km scales are resolved in horizontal domains as large as 10,000 km in two-dimensions, and 1,000 x 1,000 km2 in three-dimensions. Cloud resolving models now provide statistical information useful for developing more realistic physically based parameterizations for climate models and numerical weather prediction models. It is also expected that NWP and mesoscale model can be run in grid size similar to cloud resolving model through nesting technique. Recently, a multi-scale modeling system with unified physics was developed at NASA Goddard. It consists of (1) a cloud-resolving model (Goddard Cumulus Ensemble model, GCE model), (2) a regional scale model (a NASA unified weather research and forecast, WRF), (3) a coupled CRM and global model (Goddard Multi-scale Modeling Framework, MMF), and (4) a land modeling system. The same microphysical processes, long and short wave radiative transfer and land processes and the explicit cloud-radiation, and cloud-land surface interactive processes are applied in this multi-scale modeling system. This modeling system has been coupled with a multi-satellite simulator to use NASA high-resolution satellite data to identify the strengths and weaknesses of cloud and precipitation processes simulated by the model. In this talk, a review of developments and applications of the multi-scale modeling system will be presented. In particular, the results from using multi-scale modeling system to study the interactions between clouds, precipitation, and aerosols will be presented. Also how to use of the multi-satellite simulator to improve precipitation processes will be discussed.

Dynamical and Thermodynamic Controls on Tropical and Subtropical Convective Activity Inferred from Three Dimensional Latent Heating Distributions with TRMM SLH Beta-Version Data

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Tropical and subtropical latent heating associated with precipitation and its relationship with large-scale environments are studied. Three dimensional apparent heat source minus radiative heating (Q1-QR) data obtained with TRMM Spectral Latent Heating (SLH) algorithm, which evaluates the convective rain heating and the stratiform rain heating separately, are utilized for the analysis. The analysis region is 36N-36S and period is 1998-2007. There are three characteristic peaks in the average Q1-QR profiles, at ~2km, ~5km, and at ~8km. The former two attribute to the convective rain, while the last one is from the deep stratiform rain. 2km peak corresponds to the warm rain with the rain top height at ~4km and 8km peak well represents the organized deep precipitation. Warm rain heating is significant over oceans but not over land. We next compare the oceanic warm rain and deep rain heating with the large-scale environmental conditions. As a result, warm rain heating strongly correlates with the sea surface temperature (SST), while deep rain behaves like feeling SST as merely a threshold value. It is indicated that even for the same SST, deep convection is effectively suppressed with a large-scale subsidence represented by dp/dt at 500 hPa. It is quantitatively suggested that a reproduction of realistic large-scale circulation, especially subsidence, is essential for realistic distributions of tropical and subtropical precipitation.

An Application of TRMM and CloudSat Observations to Global Model Diagnosis

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A better representation of cloud and precipitation is crucial for further improving the performance of cloud resolving models (CRMs) and global circulation models (GCMs). Many efforts have been made to evaluate simulated clouds in comparison with observations. However, OLR and surface rain rate, popular parameters used for interfacing models with observations, do not tell us all that we need to know. Observational constraint on the detailed cloud structure and cloud microphysics is desired for better designing cumulus/cloud parameterizations implemented in the models. Fortunately, observational means suitable for this purpose are now provided by recent satellite capabilities including the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) and CloudSat Cloud Profiling Radar (CPR). This study explores ways to diagnose model-simulated clouds by use of TRMM and CloudSat measurements. The Non-hydrostatic Icosahedral Atmospheric Model (NICAM), a global CRM being developed jointly by JAMSTEC and University of Tokyo, is used as the testbed model. Radiative transfer calculations are applied to the outputs from the NICAM MJO experiment (Miura et al., Science, 2007). Different members of the tropical cloud family, ranging from shallow cumulus to deep convection, are clearly sorted out from each other in terms of cloud top height and precipitation top height. A contrast in shallow cloud population between the MJO wet and dry phases is well captured in the NICAM simulation, while snow in deep convective cores is found to be overly produced. A contoured frequency by altitude diagram (CFAD) is also informative particularly when the radars operated at separate frequencies are combined together. It is demonstrated that a bias in microphysical parameterization is detectable by joint analysis of TRMM PR and CloudSat CPR measurements.

Ice Initiation in Hurricane Convection and Dependencies on Insoluble Aerosol

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In July 2005, NASA's Tropical Cloud Systems and Processes (TCSP) experiment occurred near Costa Rica. The general mission of TCSP was to investigate how tropical cyclones are formed and their evolution. To improve the understanding of ice initiation in deep convective clouds, and of its effects, in a tropical cyclone has been a key goal of the TCSP program because such clouds produce much of the ice for its cirrus outflow aloft. Dust particles are ubiquitous in the troposphere and very effective at nucleating ice, if large enough (> 0.1 mm). Because large-scale subsidence in the sub-tropics can favor desert conditions on land, layers of dust at high concentrations are often advected near regions of hurricane genesis and intensification, such as in the tropical Atlantic. Dust concentrations in the layers can reach 1000 times higher than in the background free troposphere, causing active ice nucleus (IN) concentrations also to be higher. An empirical parameterization (EP) of heterogeneous ice nucleation has been created for cloud and large-scale atmospheric models. It represents dependencies on predicted loadings, sizes and chemistry of ice nucleus (IN) aerosols. The EP scheme includes condensation-, immersion- and two (inside-out and conventional) contact-freezing modes, and vapor deposition, as mechanisms for heterogeneous nucleation. These species of IN include mineral dust, black carbon and biogenic particles. The present study presents simulations with a cloud model of deep convection observed in Hurricane Dennis, during TCSP. The EP scheme has been implemented in the cloud model. Impacts of IN species, including dust, on the glaciation and of the outflow to cirrus are shown. Modification of precipitation production by altered IN loadings, as occur during a desert dust episode, are discussed. Relative roles of inside-out and conventional contact nucleation are shown. It is found that in-cloud scavenging of dust and/or soot has a major impact on the concentrations of heterogeneously nucleated crystals formed aloft in rapid convective updrafts.

Modulation of tropical cyclone activity by ENSO and MJO

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Tropical cyclone activity is modulated by on seasonal scales by ENSO (El Niño-Southern Oscillation) and on intra-seasonal scales by the Madden-Julian Oscillation (MJO). We examine how different environmental factors contribute to the modulation of ENSO and MJO, using a genesis potential index developed by Emanuel and Nolan. Composite anomalies of the genesis potential index are produced for El Niño and La Niña years separately. These composites qualitatively replicate the observed interannual variations of the observed frequency and location of genesis in several different basins. Specific factors that have more influence than others in different regions can be identified. A similar approach is used for the different phases of the MJO. Interestingly, the regional dependence is not strong in determining the environmental factors that are most important in the MJO composites.

A probabilistic clustering method, based on a regression mixture model, is used to describe tropical cyclone tracks in the western and eastern North Pacific. The association of specific track types with ENSO and MJO will be discussed.

Wave Accumulation, Tropical Cyclone Genesis and Climate Variability

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Climatological conditions suitable for tropical cyclone genesis have been known for several decades and are normally present during tropical cyclone seasons. However, the multitude of cloud clusters do not develop into tropical cyclones, which suggests these conditions are not sufficient. A hierarchical modeling approach is used to study the transient dynamical process in which interactions of easterly waves with the background flow can change their kinematic character to produce a regional accumulation of wave energy, a reduction in the longitudinal and vertical scale of the waves, and a local increase in relative vorticity, thereby increasing the likelihood of genesis. Interactions of waves and the background flow are first studied in the simplified framework of a shallow water model, with emphasis on identifying the important spatial (zonal and meridional) and temporal scales. The importance of the vertical shear of the zonal and meridional flow for wave modulation is then studied in idealized simulations using the Advanced Research WRF model. Finally, a high-resolution simulation (12km horizontal grid spacing) of the tropical North Atlantic region for the entire 2005 hurricane season using the NCAR Nested Regional Climate Model (NRCM) is used to study the importance of the wave accumulation process for tropical cyclone genesis in a full dynamical and physical model. We show by compositing that the dynamical environment leading up to genesis time for Atlantic cyclones differs significantly from the mean environment and in a fashion consistent with the theoretical and modeling requirements for enhanced wave accumulation. These findings will also be interpreted in the context of potential changes using preliminary results from the NCAR high resolution simulation of future Atlantic hurricane activity out to 2055 using the NRCM at 12km resolution.

Tropical cyclogenesis within a tropical wave critical layer: Easterly waves, physical basis, and high resolution numerical simulations

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Our recent work has hypothesized that tropical cyclones in the deep Atlantic and eastern Pacific basins develop from within tropical wave critical layers. We begin a systematic test of the so-called "marsupial theory" by revisiting the classical problem of the transformation of an idealized African easterly wave-like disturbance into a tropical storm vortex. An idealized configuration of the Weather Research and Forecasting (WRF) model is employed using an initial zonal flow consistent with NCEP analyses for the east Atlantic region. An analysis of the evolving winds, equivalent potential temperature, and relative vertical vorticity is presented from both intermediate and high resolution simulations. The results demonstrate the existence of a vorticity dominant region with minimal strain within the critical layer pouch that contains strong cyclonic vorticity and high saturation fraction and serves as the focal point for an upscale ³bottom up² development process while the wave and pouch move together.

Some implications of these results will be discussed as well as their relationship to a newly proposed field experiment that is planned to occur in 2010/2011 in collaboration with both NOAA and NSF.

Analysis and Modeling of Tropical Cyclones in Relation to Multi-scale Oscillations over the Northwest Pacific Ocean

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Tropical cyclones (TC) in the northwestern (NW) Pacific are known to be modulated by the tropical intraseasonal oscillation (ISO) in terms of genesis number, location, and tracks. These changes lead to significant modulations of TC landfalls in southern China, Korea, and Japan. To further look into the modulation of TCs by ISOs and the possible feedback of TCs to ISOs, the observed TC activity in the NW Pacific during the summer (June-September) of 2004 was analyzed in relation to low-frequency climate variability. The 46-yr climatology statistics from the Joint Typhoon Warning Center (JTWC) shows that the average number of TC genesis in June is 1.6. But in June 2004, five TCs were successively generated within a strong MJO convective episode. Two TCs made landfall over Japan. Such a MJO-TC relation is consistent with the observations that TCs tend to form in the large-scale confluent flow. Studies also showed that the five typhoons in June 2004 (Conson, Chanthu, Dianmu, Mindulle, and Tingting) are modulated by higher-frequency variations (HFV) including the equatorial Rossby waves, mixed-Rossby-gravity (MRG) waves, and tropical-depression-type disturbances. These HFV signals interact nonlinearly with the monsoon environment with larger spatial and longer temporal scales, contributing significantly to intra-seasonal convection activities in the northwestern Pacific Ocean. The interaction between these typhoon activities and the background MJO is being investigated.

Case Studies of Tropical Cyclone Genesis using a Global High-Resolution Model, NICAM

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A forecasting of tropical cyclone genesis is generally challenging partly because the high-resolution model is needed to represent the organization of convective clouds, and because large-domain model might be required if the origin of cyclogenesis came from a long distance. In order to solve these problems, high-resolution global simulations of cyclogeneses were performed using a Non-hydrostatic ICosahedral-grid Atmospheric Model (NICAM) developed in FRCGC, Japan. Among the recent typhoons, the genesis of 21st typhoon in 2006 (TY0621) was predicted with the initial time even more than three days before the genesis. The model reproduced the timing of genesis and intensification, tracks, and organization of cloud clusters into TY0621. The sensitivity experiments revealed that the tropical waves caused the genesis and part of the intensification of TY0621. We will also present other cyclogenesis cases, which are currently simulated by the NICAM.

Possible Control of Madden-Julian Oscillation over a Selection of Convective Regime and Tropical Cyclogenesis in the Boreal Summer Monsoon Period

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As a step toward achieving more comprehensive understanding of the relationship between tropical cyclogenesis, super cloud cluster, and MJO, results from global cloud-resolving model (NICAM) experiments are discussed. A strength of this study is explicit treatment of wide-ranging hierarchy of convections from synoptic-scale super cloud cluster down to mesoscale convections of O (10-100km) scale that are ubiquitous in the tropics. The experiments with 7- and 14-km grid spacing are performed for the boreal summer period of 2004 (June to October/August for 14km-/7km-mesh runs), with initialized by NCEP tropospheric analysis dataset at 1st June. The setup includes realistic topography and sea surface temperature (SST) interpolated from Reynolds weekly SST dataset. Tropical cyclogenesis influenced by an MJO-like event (MJO) is simulated quite reasonably in some cases. The typical genesis starts when signals of cyclonic vorticity propagate from the low-level anomalous equatorial westerly region associated with the eastward-propagating MJO. The process is enhanced occasionally by environmental disturbances including easterly wave. The anomalous westerly, resembling what they call "westerly wind burst," is followed by genesis of synoptic-scale ensemble of convection with 3000-5000 km scale (super cloud cluster; SCC) and tropical cyclone. It is found that the influence of MJO over the genesis of tropical cyclone and SCC is different between the Indian Ocean and the western Pacific. The difference originates from a difference, between the two regions, in the way of interaction between preferred convective regimes and climatological flow field in which MJO and these disturbances are embedded. Details will be discussed in the presentation.

Large Eddy Simulation of an Idealized Hurricane

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The present study is motivated by axisymmetric numerical models of hurricanes which find a significant sensitivity of hurricane intensity to the assumed turbulence mixing length. In this presentation, I report on work by myself and NCAR colleagues using the Weather Research and Forecasting model, run at resolution high enough to capture three-dimensional turbulent motions, to study an idealized hurricane. The present model uses initial conditions similar to those of the axisymmetric-modeling studies, but by virtue of its three dimensionality, it can and does develop energetic turbulent eddies. It is found that the ability of the model to produce turbulent eddies occurs when the grid interval falls below approximately 100m. The present results demonstrate that decreasing the grid interval from 1.67 to 185m produces hurricanes with increasing intensity because, without resolved turbulence, the horizontal diffusion is that given by a parameterization that essentially decreases the effects of diffusion with decreasing grid interval. With the appearance of turbulence for sub-100-m integrations, the resulting hurricane intensity begins to decrease. This study underlines the quantitative importance of internal turbulent diffusion for high-resolution numerical simulations and predictions of hurricane intensity.

The GFDL High-Resolution Atmosphere Model (HiRam) for Short-term Forecasts and Long-term Simulations of Tropical Cyclones

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A high-resolution version of NOAA/GFDL climate model has been developed with initial emphasis on the short-term predictions and long-term simulations of tropical cyclones. The model's dynamics is the non-hydrostatic extension of the vertically Lagrangian finite-volume dynamical core (Lin 2004) constructed on a quasi-uniform cubed-sphere grid (Putman and Lin 2007). Physical parameterizations are based on GFDL's IPCC-class climate models, except the deep convective parameterization is replaced by a non-intrusive shallow convection scheme, and the stratiform cloud scheme is replaced by a more sophisticated cloud-microphysics with 6 species of water substances. Both of these changes are more suitable for cloud-resolving applications. This High-Resolution Atmosphere Model (HiRam) was initially developed as a global "cloud-resolving" model. Due to severe limitation in computational resources, the focus has been shifted towards more attainable resolution of 12 to 50 km (C 720, C360, and C180 grids). Testing of the model at a near cloud-resolving resolution of C2000 (~ 5km) may begin at DOE's Argonne National Laboratory's Blue Gene system in late 2008. We will present preliminary results on the extended-range forecasts of recent land-fall hurricanes (2005 and 2008) and long-term simulation of the same model for the construction of the model's tropical cyclone climatology.

Multi-scale Interactions on the Lifecycle of a Tropical Cyclone Simulated by the Global Cloud-System-Resolving Model NICAM

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The NICAM simulation with a horizontal resolution of about 7 km reproduced the whole lifecycle of the real tropical cyclone, Isobel, formed in Indian Ocean in winter of 2006. This success results from the realistic simulations of not only the large-scale circulation, such as the MJO and the cross-equatorial flow, but also the embedded mesoscale convective systems, such as vortical hot towers, and their subsequent merging and axisymmetrization. Some mesoscale structures of the real TC were also captured by the model about 1-2 weeks in advance. This paper showed a mark for an unprecedented opportunity for advancing our understanding of multiscale interactions involved in TC genesis, intensification, and evolution in a global context.

A Very Fine-Resolution Tropical Cyclone Climate Model

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A very fine resolution (3km) tropical cyclone climate model is described. The model employs the CSIRO variable-resolution climate model CCAM, initially running at 60 km resolution, to generate incipient tropical cyclone vortices. Once detected, these are then simulated at fine resolution to improve the model's representation of tropical cyclone processes, including cyclone convection and intensity. Preliminary results from this model are presented, including an analysis of the cyclone structure and the sensitivity of formation rates to various representations of convective processes.

Tropical Cyclones in a Hierarchy of Climate Models of Increasing Resolution

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Tropical Cyclones are typically not properly represented in global climate models, as they are routinely deployed at low resolution, in order to enable sufficiently long integrations. A new class of GCMs is emerging, however, which is capable of simulating TC-type vortices by retaining a horizontal resolution similar to that of operational NWP GCMs, while permitting multi-decadal integrations. We present results from a 3-model, multi-resolution intercomparison including the UKMO-HC HadGEM1, ECHAM5 and MIROC models, integrated for the entirety of the AMIP2 period (25 years), using multiple mesh sizes, from 150 to 60km. Our simulation results indicate that the "weather-resolving" GCMs are capable of credibly representing the climatology (storm number and location) and TC storm tracks in all basins, as well as the preferential location of genesis and lysis. Storm intensity appears to be sensitive to resolution, with more violent storms emerging at the higher resolution end of the spectrum. Analysis of the TC climatology in idealized warm scenario simulations reveals a shift of the distribution towards a smaller number of moderate TCs and a larger proportion of the extremely intense storms.

The Impact of Vortex Asymmetries in Real-Time Tropical Cyclone Track and Intensity Prediction

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It is well-known that tropical cyclone (TC) vortex asymmetries play a major role in determining their motion and structure. In this study, the active 2004-2005 TC season over northwest Western Australia is chosen, as the operational models available to the forecasters performed poorly for many of the major storms of that season. The effects of these storms, several of which reached WMO Categories 4 or 5, can be linked to the massive economic losses in the off-shore and coastal industries of the region. It is shown in this presentation that the TC predictions were improved considerably by a combination of three factors: use of all available data, high model resolution with a grid spacing of 5km or less, and the use of an advanced 4-D data assimilation scheme over a 24 hour period proceeding the initial forecast period. Overall seasonal performance statistics for the 2004-2005 season and individual case studies of the structure of several of the more damaging TCs in that season, both will be presented to demonstrate the roles of these three factors. Finally, it is noted that in some cases the TC forecast failures clearly can be linked to other factors which varied from storm to storm. These intra-seasonal factors such as SST and vertical wind shear anomalies, and MJO phases.

Toward a better Understanding of Tropical Cyclone Predictability and Prediction

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Recent advancements in atmospheric and oceanic science and technology present an unprecedented opportunity to develop an integrated tropical cyclone prediction system that will provide forecasts with both longer and shorter lead times than are currently possible. The envisioned prediction system integrates a hierarchy of coupled atmosphere-wave-ocean-land models with a probabilistic ensemble-prediction framework, advanced data assimilation techniques that assimilate all available observations, adaptive strategies for optimally observing hurricanes and their environment, and innovative verification and validation. The very high-resolution (~1 km) coupled model ensemble forecasts will be used to drive impact models at and after landfall to gauge the likelihood of severe weather including extreme wind, rain, surge and flooding. A plan to better understand the tropical cyclone predictability across the broad timescales and to improve tropical cyclone prediction will be discussed.

A Cloud-Resolving Simulation of Hurricane Wilma (2005)

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In this study, a 60-h cloud-resolving simulation of Hurricane Wilma (2005) is performed using a two-way interactive, movable, nested grid version of the Weather Research and Forecast (WRF) model with the finest horizontal resolution of 1 km and 70 vertical layers. The WRF model is initialized with NCEP's analysis. A bogus vortex, generated by GFDL's vortex initialization scheme, is inserted into the initial conditions. In addition, time-varying sea-surface temperature (SST) is used in order to address the possible intensity change due to the SST factor. It will be shown that the WRF model reproduces reasonably well the track and intensity change, particularly the record-breaking deepening rate of 9 hPa h-1 and its subsequent steady state, as verified against the best track analysis. Moreover, the model simulates reasonably well the rapid eyewall contraction, different shapes of the eyewall structures, the eyewall replacement cycle, spiral rainband, and the evolution of storm size and radius of maximum winds. A series of sensitivity simulations to different horizontal and vertical resolutions and SST has been conducted. Results show that the reproduction of the record-breaking deepening rate depends critically on the use of high resolution in the horizontal and vertical. Any significant coarser resolution (e.g., 2 km grid size) would not be able to reproduce the observed intensity. It is found that the model simulation is less sensitive to the use of different cloud microphysics schemes. It will be shown that warm SST and weak vertical shear play an important role in determining the rapid intensification of the storm.

On the Distribution of Vertical Motion in Hurricanes

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Hurricanes are an interesting subject for application of GFD principles. Two hurricane eye features that require explanation are the clear-air moat that forms at the outer edge of the eye and the hub cloud that forms near the circulation center. To investigate whether these features can be explained by the spatial distribution of the subsidence field, we have derived an analytical solution of the Eliassen transverse circulation equation for a three-region approximation with an unforced central eye region of intermediate or high inertial stability, a diabatically-forced eyewall region of high inertial stability, and an unforced far-field of low inertial stability. This analytical solution isolates the conditions under which the subsidence is concentrated near the edge of the eye. Assuming the eye can be fairly accurately characterized by a single Rossby length, the following rules apply: (1) There is less than 10\% horizontal variation in the subsidence rate in the eye when the ratio of the eye radius to the Rossby length in the eye is less than 0.6. This tends to occur with small eyes and/or eyes with low inertial stability; (2) The subsidence rate at the edge of the eye is more than twice as strong as the subsidence rate in the center of the eye when the ratio of the eye radius to the Rossby length in the eye is greater than 1.8. This tends to occur with large eyes and/or eyes with high inertial stability. When subsidence is concentrated at the edge of the eye, the largest temperature anomalies occur there. This warm-ring structure, as opposed to a warm-core structure, is often observed in the lower troposphere of intense hurricanes.

Another hurricane phenomenon that requires explanation is the concentric eyewall cycle, a process in which an outer eyewall forms, the inner eyewall dies, and then the outer eyewall contracts. Such eyewall cycles are associated with dramatic changes in the radial distributions of inertial stability and diabatic heating, and hence with dramatic changes in the transverse circulation. To better understand the dynamics of such changes, we have derived an analytical solution of the transverse circulation equation for an idealized five-region model containing the eye, inner eyewall, moat, outer eyewall, and far-field. For a prototypical example, the model solutions illustrate how the diabatic heating in the inner eyewall, imbedded in a region of high inertial stability, induces larger temperature tendencies than the diabatic heating in the outer eyewall, which borders the far-field region of low inertial stability. Thus, as the inner eyewall dies, the storm temporarily loses its ability to produce an intense, localized warm region. This ability is restored during the contraction of the outer eyewall. These results provide a partial dynamical explanation of how a concentric eyewall cycle can act as a temporary brake on tropical cyclone intensification.

Performance of JMA Weekly Ensemble Forecast for Nargis

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We examined the performance of the JMA weekly ensemble forecast for Nargis over the North Indian Ocean in May 2008. Out of 51 ensemble members about 10 members could forecast the landfall on Myanmar in the 7-day forecast. The 7-day forecast in the Global model did not predict the landfall. As the initial time goes closer to the landfall date, May 2, the members to show landfalls increase, thus suggesting a capability of the JMA ensemble forecast.

Simulated Response of Atlantic Hurricane Activity to Projected 21st-Century Warming

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Atlantic hurricane activity has been reported to be strongly correlated to increasing sea surface temperatures in the tropical Atlantic Ocean since at least 1950. This has raised concerns that future greenhouse warming could lead to pronounced increases in Atlantic hurricane activity. However, Atlantic hurricane activity indices are also correlated with an index of tropical Atlantic SSTs relative to tropical mean SST, such that when the tropical Atlantic warms relative to tropical mean SST, hurricane activity increases in the Atlantic. This latter relationship implies a much smaller sensitivity of Atlantic hurricane activity to projected global warming during the 21st century than the relationship between Atlantic hurricanes and local Atlantic SST alone. Models that explicitly simulate hurricanes provide a useful tool, complementary to empirical approaches, for investigating which of these two relationships is more relevant for projecting future Atlantic hurricane activity under global warming. Our regional Atlantic basin climate model reproduces the observed rise in hurricane activity between 1980 and 2006, along with much of the interannual variability, when forced with observed sea surface temperatures and atmospheric conditions. Using this model, we investigate the influence on Atlantic hurricane activity of the large-scale climate changes projected for the late twenty-first century by a multi-model sample of global climate models. Downscaling first the ensemble mean climate change across the climate models, we find that Atlantic hurricane and tropical storm frequencies are reduced. In downscaling experiments for four of the individual climate models, the reduction in tropical storms and hurricane counts is robust for all four models. The reduction in storm counts is most pronounced for weaker storms in all models. In contrast, for major hurricane counts (central pressure below 965 HPa), the sign of the projected changes results is quite model-dependent, ranging from a 60% decrease to a 70% increase. A downscale of the multi-model average projection yields an 8% decrease. These results emphasize the importance of (still uncertain) regional details of future climate projections for Atlantic major hurricane activity. Conventional historical records of Atlantic tropical storm counts show a large increasing trend over 1878-2006. However, our analyses of tropical storm occurrence, which attempts to adjust for possible missing storms due to low levels of reporting ship track density in the late 1800s and early 1900s, shows no significant upward trend. In summary, neither our modeling results nor our observational analyses support the notion of large increasing trends in tropical storm or hurricane frequency driven by greenhouse gas-induced global warming. However, our model results, as well as earlier idealized simulations with higher resolution hurricane models, continue to suggest that the hurricanes will be more intense and have higher rainfall rates in the warmer climate.

Toward Improved Projection of the Future Tropical Cyclone Changes

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We conducted an experiment using a 20km resolution AGCM to make a detailed projection of future climate change. In the experiment, tropical cyclones have been simulated much more realistically than lower resolution models. By the experiment we could show that the global number of tropical cyclones will decrease but the number of intense tropical cyclones will increase. We have noted, however, there remains a considerable uncertainty in the projection of the future tropical cyclone change, particularly in the future regional changes. To reduce the statistical uncertainties, we need a large number of ensemble experiments with longer period using a lower resolution models. On the other hand, we have also noted some major deficiencies in the model. We have much less number of typhoons in the western Pacific in the model than reality. The average intensity of simulated tropical cyclones is considerably weaker than that of the observed tropical cyclones even with the 20km resolution model. To further improve the simulation of tropical cyclones, we need to improve the model, particularly the cumulus parameterization scheme. We also need to improve our understanding of the mechanism of tropical cyclogenesis, and improve the interpretation of the GCM experiment results based on the understanding.

Simulation of Intense Atlantic Hurricane Activity in a Twenty-first Century Warmed Climate, using the GFDL High-Resolution, Coupled Hurricane Model

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Observed increases in sea surface temperature (SST) and hurricane activity in the tropical Atlantic over the past two decades has heightened concerns that anthropogenic greenhouse warming may significantly impact hurricane activity in the future climate. The greatest concern is the possibility of a sharp increase in the number of devastating intense hurricanes that could impact the US coast. Knutson et al. (2008) recently attempted to address some of the issues of hurricane actively in a globally warmed earth, using a non-hydrostatic 18-km grid regional climate model. In their climate change simulations, they altered the mean atmosphere state and SSTs in the Atlantic by the late twenty-first century changes projected by a multi-member ensemble of global climate models. Although the average Atlantic SSTs were warmed by 1.72 degrees C, other components of the large-scale environment became less favorable for hurricane activity (e.g. increased vertical wind shear and reduced relative humidity). This resulted in substantially fewer tropical storms and hurricanes in the warm-climate runs than in their current climate runs. A small positive shift in the frequency of the more intense hurricanes was also found, but these results were inconclusive due to the model's inablility to simulate major hurricanes (wind speeds exceeding 50 m/s) in general. To rectify this shortcoming, a new downscaling study was undertaken, using the latest version of the GFDL hurricane prediction system. This model, with an inner nest having double the finest resolution of the regional climate model, has been run operationally by the National Weather Service for the past decade, providing guidance on track and intensity for forecasters at the Tropical Prediction Center. Unlike the GFDL regional climate model, the GFDL hurricane model simulates a more realistic distribution of storm intensities, including storms of category 3, 4 and 5 (50 m/s and greater). In the new study, the output of the regional climate model served as the initial condition for the hurricane model, for all of the storms in both the current and warmed climate. The hurricane model was then run for five days, with each forecast initiated 72h hours before the storms in the regional model reached their maximum intensity. The distribution of storm intensity reproduced by the GFDL hurricane model matched the observed storm intensity distribution surprisingly well, for the current climate runs. The model shows some skill (r=0.4) at reproducing interannual variability of category 4 and 5 storms over 1980-2006 due mainly to skill at simulating tropical cyclone numbers in general. In the warmed climate simulations, the number of category 4 and 5 hurricanes (winds >= 59 m/s) increased by about 33% with the number of higher intensity hurricanes (winds >= 65 m/s) increasing by an even larger percentage. However, the number and frequency of intense hurricanes in the Gulf of Mexico and Caribbean were not significantly impacted, with the majority of the increased frequency of intense hurricanes occurring in the main development region of the central Atlantic.

NOAA Hurricane Forecast Improvement Project (HFIP)

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Tropical cyclones continue to be a serious concern for the Nation, causing significant risk to life, property, and economic vitality. While NOAA has made steady improvements in forecasting track since 1990, intensity has lagged behind, primarily because a good track forecast is essential before addressing any intensity changes. However, over the last 5 years NOAA's track forecasts improved enough for us to now focus on intensity forecast improvements. The National Oceanic and Atmospheric Administration (NOAA) in cooperation with other government and university entities has met on several occasions since the devastating 2005 Hurricane Season to discuss issues and develop a plan to improve hurricane intensity

NOAA launched the Hurricane Forecasting Improvement Project (HFIP), a 10-year project designed to accelerate improvements in one to five day forecasts for hurricane track, intensity, and storm surge and to reduce forecast uncertainty, with an emphasis on rapid intensity change because of its importance to emergency management amongst others. The HFIP Plan has been widely distributed and reviewed, with an alliance of the hurricane research and forecasting communities agreeing to move forward with its implementation. The Plan's strategy is to perform basic research into hurricane genesis and rapid intensification mechanisms, exploit new observing systems, expand computing capacity, build higher resolution coupled control models and ensembles, improve infrastructure for transitioning research to operations (R2O) and support operations-like systems to the research community (O2R), and broaden NOAA expertise and expand interaction with the external community. In this paper we describe the goals and framework of the HFIP plan. Using limited initial resources and leveraging high performance computing capabilities outside of NOAA, work has begun on higher resolution models and radar data assimilation. We intend to give an update on current research activities and provide insight on where work is needed to carry the plan forward.

High-Resolution WRF Simulation of Hurricane Dennis (2005): Relating Vertical Velocity Distributions and Microphysical Processes to Rapid Intensity Change in the Context of TCSP Observations and NASA Satellite Retrievals

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Recent field projects, such as NASA's Tropical Cloud Systems and Processes (TCSP, 2005), have provided the observations necessary to supplement satellite retrievals and spearhead research of tropical cyclone (TC) microphysics. These in-situ observations and satellite retrievals, in combination with a high-resolution Weather Research and Forecasting (WRF) simulation of Hurricane Dennis (2005), are used to investigate microphysics, the feedbacks between these processes and distributions of localized, penetrative updrafts (i.e., convective bursts) and downdrafts, and ultimately the distributions of latent heat (LH) that modulate dramatic and often unexpected changes in TC intensity and rainfall. This research attempts to quantify statistically the impact of these convective vertical motions and associated microphysics on Dennis's RI. The WRF simulation consists of a 4-domain nested configuration with 1-km grid spacing on the innermost domain, 62 vertical levels, and cloud microphysical processes parameterized with an updated, multi-ice scheme. Microphysical observations from a joint NASA ER-2/NOAA P-3 mission, in addition to Tropical Rainfall Measuring Mission (TRMM) precipitation retrievals, form the framework for evaluating the simulation. The analysis period of the simulation is coincident with TCSP observations during Dennis's transition from a tropical storm to a category 1 (CAT1) hurricane and thereafter RI (-31 hPa, +50 kts. in 24 hr) before striking southeastern Cuba as a CAT4 hurricane. Robust statistical comparison within the framework of generically observed structure is used to evaluate the WRF simulation. Contoured frequency by altitude diagrams (CFADs) provides insight into the physical processes that affect the distributions of updrafts, downdrafts, and LH. CFADs of vertical velocity, reflectivity, and hydrometeor (e.g., graupel, rain, snow) mixing ratio for the eyewall, rainband, convective, and stratiform regions of the simulated TC illustrate unique evolution before, during, and after RI. Particular attention is given to CFAD tails (e.g., > 99th percentile) because the isolated, yet intense, vertical motions represented therein suggest large impact on microphysics, LH distributions, and ultimately TC intensity. The vertical distributions evident from CFADs are analyzed more closely in terms of azimuthal variation, evolution, and duration. Distributions of Doppler velocity and reflectivity derived from the WRF simulation are then compared with observations from the ER-2 Doppler radar (EDOP) and the TRMM Precipitation Radar (PR). EDOP, although restricted to approximately 20-km swath coverage by the ER-2, is used to supplement analysis of TRMM PR retrievals by providing increased resolution of inner-core precipitation structure. These comparisons highlight the importance of inner-core vertical velocity structure and microphysical processes in modulating Dennis's intensity. It is found that the proximity of convective bursts to the existing vortex center, as well as their magnitudes, vertical extents, durations, and associated microphysics contribute to Dennis's RI.

Simulation of the MJO-Convection Onset observed during MISMO

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The Mirai Indian Ocean cruise for the Study of the MJO-convection Onset (MISMO) was a field experiment that took place in the central equatorial Indian Ocean during October - December 2006, using the research vessel Mirai, a moored buoy array, and land-based sites at the Maldives Islands. By late November and early December, deep convection developed over the central Indian Ocean and eastward movement of large-scale cloud systems were observed. A global cloud-system resolving model (NICAM) succeeded in reproducing the convection onset, and the simulated internal structures are similar to observed ones. The simulation results indicate synoptic-scale wave disturbances play an important role to organize the convection.

What Determine Tropical Disturbances to Develop or not?

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Tropical disturbances are often the precursors of tropical cyclones. Comparing with the number of tropical disturbances, the formed tropical cyclones are much less due to the high percentage of the non-developing tropical disturbances. The relative rareness of tropical cyclone formation has not been easily explained by existing theories and not been well understood. In this study, 30 non-developing and 13 developing tropical disturbances over the SCS in 2000 and 2001 are compared using satellite and reanalysis data sets, in order to understand why some tropical disturbances developed into tropical cyclones, while others did not. It is shown that persistent large amount of latent heat release is the critical condition for tropical cyclogenesis, which determines one tropical disturbance to develop or not. Environmental parameters which are statistically relevant to latent heat release are determined and the importance of each parameter is assessed quantitatively. The large amount of latent heat release during tropical cyclogenesis is induced by the Coupling of Lower-Upper Troposphere (CLUT). The reasons why non-developing disturbances can not develop into tropical cyclones are due to the deficiency of lower-upper tropospheric coupling in dynamic conditions and/or in thermal conditions. The statistics reveal threshold values useful to forecasters in the tropical cyclone formation forecast.

Genesis of Tropical Cyclone Nargis revealed by Multiple Satellite Observations

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Tropical cyclone (TC) Nargis recently battered Myanmar on May 2 2008 is one of the most deadly tropical storms. Its initiation and formation processes are investigated by using multiple satellite observations. TC Nargis was initiated as a Rossby wave-induced vortex by northeastward shift of Madden-Julian oscillation convection in the eastern Indian Ocean. The collocation between well-built surface winds and active convection makes it possible to create a central warm core structure, forming the tropical depression (TD) on April 26. The TC formation is characterized by two distinctive stages: a radial contraction followed by a rapid intensification. The middle tropospheric warming near the TD center lowers surface pressure, resulting in contraction of the band of maximum winds and convection. Continuous northward migration of pre-TD disturbance and TD may help that process by increasing boundary layer convergence due to increase of the Coriolis parameter. During the contraction, both surface vortex and convection compact in a corporative way. When the contraction reaches a certain threshold, rapid intensification occurred as a result of deep convection development followed by axisymmetrization process. This new scenario is instrumental for understanding how a major TC develops in the northern Indian Ocean.

Informing Statistical Regressions of the Decay Rate of Tropical Cyclones after Landfall using an Enhanced Event Set of Storms Generated with a Mesoscale Model

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The decay of tropical cyclones after their landfall is a key factor in the total losses induced by such events. However, our understanding of the intensity change after landfall is inhibited by the low frequency of past events and the scarce coverage by surface observation networks. The limited number of past events makes difficult the investigation of driving processes. Understanding the geographical variability of the decay rate (for instance in the North East US where transitioning storms are not exposed to the classic tropical decay processes) is challenged by the uneven geographical density of historical landfalls. In addition, state of the art reanalysis datasets provide intensity time series with 6 hourly timesteps; hence offering a coarse coverage of the intensity change in the first hours after landfall where much of the damage occurs. We propose to complement the historical record by means of numerical modeling. Using a bogus technique in conjunction with a mescoscale model we simulated a large number of landfalling hurricanes in the mainland US. Meteorological situations that could potentially steer tropical cyclones towards land were targeted using kinematic trajectory modeling in a sample of 10 historical years. A synthetic bogus was embedded in the initial condition. Several thousand of such events where then simulated with the WRF model to document the intensity change of tropical cyclones after their landfall. We will present a thorough evaluation of the event set generated with this technique and illustrate how it can help us to better understand how tropical cyclones decay after their landfall. The large size of the dataset compared to historical records allows for the inclusion of more predictors in statistical regressions of the decay rate. We will show how we can achieve this by quantitative testing of these models against historical data. Past studies such as Vickery 2006 (*J. Appl. Met.*, Vol 44) have highlighted the sensitivity to the intensity, size and translational speed. This enhanced dataset makes it possible to revisit this approach and to conclude on the role of external factors such as landuse or extratropical transition.

Assimilating Doppler Radar Data with a 3DVAR and Cloud Analysis System for the Prediction of Tropical Storm Erin (2007) over Land

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A rare event occurred over Oklahoma in August 2007 when Atlantic tropical storm Erin (2007) re-intensified over western Oklahoma three days after making a landfall. The storm re-developed an eye, an eye wall structure and spiral rain bands after weakening significantly over western Texas, producing strong winds and heavy flooding that claimed several lives and caused extensive property damage. Being over land and covered by the operational WSR-88D radar network and in a region with extensive surface observing networks, this event provides an excellent opportunity to test the assimilation and impact of operational weather radar data for the prediction of such a tropical storm, including the prediction of track, intensity, structure and precipitation. In this study, the NCEP GSI (Grid-point Statistics Interpolation) 3DVAR system is enhanced to assimilate level-II WSR-88D radial velocity data, and the mosaic reflectivity data derived from the level-II reflectivity. The radial velocity data are variationally analyzed directly with GSI and the reflectivity data are assimilated within the GSI framework using a complex cloud analysis package based on that of the ARPS (Advanced Regional Prediction System) Data Analysis System (ADAS). Frequent assimilation cycles of 10 to 30 minute long are performed over up to 6 hour assimilation window, and the subsequent prediction is made using the WRF-ARW model at 3 and 1 km resolutions. The forecasts are compared against that starting from the operational NAM analysis directly. Significant improvement is found with the radar data assimilation in terms of both overall vortex structure and propagation, and the embedded rainbands. The impacts of assimilating radar radial data or reflectivity data alone or in combination are examined through direct verification of the forecasts against radar and other observations. The scale of the background error covariance in the 3DVAR is tuned for optimal results when analyzing radial velocity data. The sensitivity of the prediction to model microphysics will also be examined. Detailed results will be reported at the conference.

A High-Resolution Simulation of Typhoon Rananim (2004) with MM5: Model Verification, Inner-Core Shear, and Asymmetric Convection

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In this study, the fifth-generation Pennsylvania State University-National Center for Atmospheric Research (PSU-NCAR) Mesoscale Model (MM5) is used to simulate Typhoon Rananim (2004) at high resolution (2-km grid size). The simulation agrees well with a variety of observations, especially for intensification, maintenance, landfall, and inner-core structures, including the echo-free eye, the asymmetry in eyewall convection, and the slope of the eyewall during landfall. The asymmetric feature of surface winds is also captured reasonably well by the model, as well as changes in surface winds and pressure near the storm center. The shear-induced vortex tilt and storm-relative asymmetric winds are examined to investigate how vertical shear affects the asymmetric convection in the inner-core region. The inner-core vertical shear is found to be nonunidirectional, and to induce a nonunidirectional vortex tilt. The distribution of asymmetric convection is, however, inconsistent with the typical downshear-left pattern for a deep-layer shear. Qualitative agreement is found between the divergence pattern and the storm-relative flow, with convergence (divergence) generally associated with asymmetric inflow (outflow) in the eyewall. The collocation of the inflow-induced lower-level convergence in the boundary layer and the lower troposphere and the midlevel divergence causes shallow updrafts in the western and southern parts of the eyewall, while the deep and strong upward motion in the southeastern portion of the eyewall is due to the collocation of the net convergence associated with the strong asymmetric flow in the midtroposphere and the inflow near 400 hPa and its associated divergence in the outflow layer above 400 hPa.

A High-Resolution Simulation of Asymmetries in Severe Tropical Cyclone Larry (2006)

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Advances in observations, theory and modeling have revealed that inner-core asymmetries are a common feature of tropical cyclones (TCs) in all TC ocean basins. In this study, we investigate the inner-core asymmetries of a severe Southern Hemisphere tropical cyclone, TC Larry (2006), using the fifth-generation Pennsylvania State University- National Center for Atmospheric Research (PSU-NCAR) Mesoscale Model (MM5). The simulated TC exhibited significant asymmetries in the inner-core region, including rainfall distribution, surface convergence and low-level vertical motion. The near-core environment was characterized by very low vertical shear and consequently the TC vortex had almost no vertical tilt. It was found that, prior to landfall, the rainfall asymmetry was very pronounced with maxima consistently to the right of the direction of TC motion. Persistent maxima in low-level convergence and vertical motion formed ahead of the translating TC, resulting in deep convection and mid-level precipitation. The spatial discrepancy of roughly 90 degrees between the surface and mid-level precipitation maxima is explained by the rapid cyclonic advection of hydrometeors by the tangential winds in the TC core. Our results for TC Larry support earlier studies that show enhanced translation-induced frictional convergence in the boundary layer plays a major role in determining the asymmetrical structures.

Typhoon Formation and Development Experiment with a High Resolution Global Model and a Mesoscale Model

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We use the JMA high resolution global model (GSM) and the JMA nonhydrostatic model (NHM) to investigate the typhoon formation and development process. Horizontal resolutions of GSM and NHM are both 20km. For initial and boundary conditions, we use the JMA's operational global analysis (GANAL) and JMA's reanalysis data (JRA25) and investigated important factors in the typhoon formation and development process. Typhoon 200422 (Ma-on) is selected for the case study and the target is 08 October 2004, when the typhoon intensity reached its maximum. Both GSM and NHM can simulate the formation and development of the typhoon when GANAL is used for the initial condition, while when JRA25 is used the formation and development are delayed. There is a large difference in equivalent potential temperatures in the lower atmosphere between the two initial data. An absolute vorticity analysis was conducted. In the case that the typhoon successfully develops, a weak cyclonic circulation continues in the initial stage with a gradual increase of the horizontal convergence at lower levels and the vertical advection term effectively enhances the positive vorticity of the typhoon. Above dynamical processes don't work in the case that the model fails to reproduce the typhoon development. In the presentation, dependency of the typhoon formation and development process on model physics and the influence of lateral boundary conditions will also be shown.

Possible Change of Tropical Cyclone Intensity and Frequency under a Greenhouse-warmed Climate Condition in the Global Cloud Resolving Model, NICAM

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Using the global cloud resolving model, NICAM (Nonhydrostatic ICosahedral Atmospheric Model), we conducted a greenhouse-warmed climate experiment with horizontal 14km-mesh on the Earth Simulator. Although most of the conventional GCM studies suggested a significant reduction of frequency and increased intensity for the intense tropical cyclones, the reliability of the findings and mechanisms of the change remain to be completely understood. The results from the 20-km mesh climate model (Oouchi et all.,2006) are generally in consistent with the findings, but they also indicated that the model underestimated the intensity, and suggested that improvement of the cumulus parameterization is necessary for more reliable investigation into the problem of cumulus parameterization. Our experiment is expected to provide some important insight into the problem and contribute to IPCC 5th Assessment Report. A present-day climate experiment is conducted for 5 months (June to October) in 2004, and a greenhouse-warmed climate experiment is conducted under the greenhouse gas concentrations, sea surface temperature and sea ice coverage at the end of 21st century, based on the estimate of SERSA1B scenario. Compared between the present-day experiment and the greenhouse-warmed experiment, we will discuss whether our consequence is in consistent with the previous results with the conventional climate models. In addition, our study will give new insight into the change in structure in the greenhouse-warmed condition, by making use of the merit of the global cloud resolving framework.

The Landfalling Characteristics of Typhoon Nari (2001) over Taiwan

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Although there have been many observational and modeling studies of tropical cyclones, our understanding of their landfalling characteristics is still rather limited. In this study, six 84-h cloud-resolving simulations of Typhoon Nari (2001), that produced torrential rainfall of more than 1400 mm over Taiwan, are carried out using the quadruply nested-grid MM5 model with the finest grid size of 2 km. It is shown that the model reproduces reasonably well the kinematic and precipitation features as well as the structural changes of Nari, as verified against radar and rain-gauge observations. These include the storm track, contraction and sizes of the eye and eyewall, the spiral rainbands, the rapid pressure rise during landfall, and the nearly constant intensity after landfall. In addition, the model captures the horizontal rainfall distribution and some local rainfall maxima associated with Taiwan's orography. The storm structures prior to, right at, and after landfall on Taiwan are compared in great details to examine Nari's landfall characteristics. A series of terrain sensitivity experiments are performed to examine the topographic effects on Nari's track, intensity, rainfall, and landfalling attributes. Results show that changing Taiwan's terrain heights produces nonlinear tracks, with circled shapes and variable movements due to different degrees of blocking effects. The nonlinear track dependence on terrain heights results from the complex interactions between the environmental steering flow, Nari's intensity, and Taiwan's topography, whereas the terrain-induced damping effects balance with the intensifying effects of latent heat release associated with the torrential rainfall in maintaining the near-constant storm intensity after landfall.

Impacts of Tropical Cyclones over Western Pacific Ocean on the Climate in China

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The contribution of tropical cyclones (TCs) over the Western Pacific Ocean (WPO) and China to the formation of the regional climate over East Asia is investigated by the use of a regional climate model. Our results show that the regional climate is significantly affected by the frequency of TC activity in terms of weakening the Western Pacific subtropical high when TCs are over the WPO and interrupting the summer monsoon when TCs make landfall over China. If there were no TCs, the atmosphere over southeast China and northeast China would become drier while that over southwest China and north China would become wetter.

High Resolution Prediction Tropical Cyclone 'Nargis' using the WRF

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Cyclone Nargis (JTWC designation: 01B, also known as Very Severe Cyclonic Storm Nargis) was a strong tropical cyclone that made landfall on Myanmar (also known as Burma) in May 2008, causing catastrophic destruction and at least 22,000 fatalities. It was the first tropical cyclone to strike the country since Cyclone Mala made landfall in 2006. It developed on April 27 in the central Bay of Bengal. Initially it tracked slowly northwestward, and encountering favorable conditions it quickly strengthened. Dry air weakened the cyclone on April 29, though after beginning a steady eastward motion Nargis rapidly intensified to attain peak winds of at least 165 km/h (105 mph) on May 2; the Joint Typhoon Warning Center assessed peak winds of 215 km/h (135 mph). The cyclone moved ashore in the Ayeyarwady Division of Myanmar near peak intensity, and after passing near the major city of Yangon (Rangoon), the storm gradually weakened until dissipating near the border of Myanmar and Thailand. In this paper the cyclone 'Nargis' is studied using the Weather Research and Forecasting (WRF) Model forecasts. The operational WRF2.2 model forecasts are used to study the predicted track and intensity of the cyclone vis-à-vis the operational global model predictions of NCMRWF the T254L64 model. This is followed by experiments with enhanced horizontal resolution using a nested domain of 9 km grid increment for a detailed study of the cyclone structure. The T254L64 model captures the broad circulation and genesis in the initial analysis (though intensification is poor compared to observations) and develops the system into a well organized cyclone and takes it close to the Myanmar coast in the Day-5 and Day-3 forecasts. The WRF model predicts strong intensification despite poor initialization. Experiments with WRF 9km nested runs with two-way interaction given strong intensification at the time when cyclone is close to the observed landfall point. The 9km WRF runs show that the cyclone featured a moderate diameter eye wall, with diameter increasing with height. The cyclone is characterized by warm core as seen by the temperature cross section. The mean vertical circulation consists of inflow below 900 hPa and out flow between 700 - 100 hPa. The strong updrafts occur in the eye walls, which is also region of strong convection and rainfall. The theta-e in the eye wall is relatively high; this is due to convection, which transports high theta-e in the boundary layer upward. The eye region features warm, dry downdrafts of moderate strength typical of strong cyclones.

A Numerical Study of the Effect of Typhoon Songda (2004) on Remote Heavy Rainfall in Japan

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When Typhoon Songda (2004) was located southeast of Okinawa over the western North Pacific during 2 to 4 September 2004, a heavy rainfall event occurred in the southern central Japan and its adjacent seas, more than 1,200 km from the typhoon center. The Advanced Weather Research and Forecast (WRF, also ARW) model was used to investigate the possible effect of Typhoon Songda on the remote precipitation in Japan. The National Centers for Environmental Prediction (NCEP) global final (FNL) analysis was used to provide both the initial and lateral boundary conditions for the WRF model. The model was initialized at 18 UTC 2 September and integrated until 18 UTC 6 September 2004 during which Songda was a super typhoon. Two primary numerical experiments were performed. In the control experiment, a bogus vortex was inserted into the FNL analysis to enhance the initial storm intensity such that the model typhoon had an intensity similar to the observed at the initial time. In the no-typhoon experiment, the vortex associated with Typhoon Songda in the FNL analysis was removed by a smoothing algorithm such that the typhoon signal did not appear at the initial time. As verified against various observations, the control experiment captured reasonably well the evolution of the storm and the spatial distribution and evolution of precipitation, while the remote precipitation in Japan was largely suppressed in the no-typhoon experiment, indicting a significant far-reaching effect of Typhoon Songda. It is found that Songda enhanced the remote precipitation in Japan through two major processes. Its outer cyclonic circulation, on one hand, enhanced the northward moisture transport into the precipitation region, and on the other hand, it contributed to a strong moist frontogenesis of the original precipitation system through enhancing the deformation fields in the middle-lower troposphere. Both effects are crucial to the observed heavy rainfall in Japan. It is also shown that the orographic forcing of the central mountains in Japan played a secondary role compared with Typhoon Songda in the extreme precipitation event studied.

Tropical Cyclone Activity over South China Sea

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From analysis of tropical cyclone data from 1952 to 2007, tropical cyclone season starts in June and ends in late November, and some years, the tropical cyclone season last until early December. In average, every year there are 6 typhoons land over Vietnam from June to December. The trend of tropical storm activity increased from decade to decade. Especially in decade 1987-1996 the number of cyclones was 23, this was period of La-Nina condition very strong. In the other hand, the global warming played a role of interaction between atmosphere and ocean increase, leaded the increasing of tropical cyclone over Pacific Ocean. Because of the disaster from tropical cyclone is large as well as hundreds kilometer from the cyclone center, very severe marine condition. Analyze the high-resolution satellite productions for simulation of tropical cyclones, using in tropical cyclones prediction as well as tropical cyclone genesis, structure, intensity and movement change. That is the aim of this study.

Hurricane Satellite (HURSAT) data

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The Hurricane Satellite (HURSAT) data set provides tropical-cyclone-centric data from numerous satellite platforms. The variety of sensors and platforms lends the wide utility of data. All HURSAT files are stored in netCDF following the Climate and Forecasting (CF) netCDF convention, to facilitate intercomparisons with other data sets. Geostationary data (HURSAT-B1) is made available at 3-hour intervals and at 8-km spatial resolution. The infrared window and water vapor channels (11 um and 6.7 um, respectively) have undergone long-term intercalibration with other satellites. Data from the AVHRR is also available at 4 km resolution but at more sporadic temporal resolution (depending on the number of NOAA polar orbiters operating at the time). Information from all AVHRR channels is provided. SSMI data is also used to derive a HURSAT-microwave. All HURSAT data are centered over the present location of the cyclone and follow it through its lifetime. The variety of sensors available in HURSAT provides a unique set of data for analyzing cloud structure, precipitation rates, winds, and column water vapor for comparison when modeling historical tropical storms. http://www.ncdc.noaa.gov/oa/rsad/hursat/

Isotope Ratios of Precipitation and Water Vapor observed in Typhoon Shanshan

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Isotope ratios of precipitation and water vapor were observed during the passage of Typhoon Shanshan at Ishigaki Island, southwestern Japan, on 15-16 September 2006. Such high-resolution isotopic observations allow for qualitative understanding of atmospheric moisture cycling; they revealed that isotope ratios decreased radially inward in the cyclone's outer region; anomalously high isotope ratios appeared in the cyclone's inner region; and d-excess tended to decrease in the cyclone's inner region. In the cyclone's outer region, the converging water vapor is isotopically depleted due to the rainout effect. In contrast, water vapor in the cyclone's inner region was isotopically enriched by weak rainout effect and recharge from water vapor evaporated from the sea surface and sea spray with heavy isotope ratios. A unique circumstance is very intensive evaporation even with almost saturated surface air, causing anomalously high isotope ratios and low d-excess values of water vapor in the cyclone's inner region.

Interannual Variations in Mixed Rossby-Gravity Waves and their Impacts on Tropical Cyclogenesis over the Western North Pacific

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The present study investigates the transition from mixed Rossby-gravity (MRG) waves to tropical depression (TD) type disturbances and its interannual variations over the western North Pacific (WNP), using ECMWF high resolution data for the years 1980-2001. As the equatorially trapped MRG waves propagate westwards into the WNP, the MRG waves transit to TD-type disturbances due to background flow change. Interannual variations in the transition of MRG waves are related to monsoon circulation change in response to tropical convective heating over the warm pool (WP) region. When the WP is in a warm state, convective heating is enhanced in the western part of the WNP and the monsoon trough retreats westwards, which induces a westward shift of wave transition zone. In contrast, when the WP is in a relatively cold state, the eastward penetration of convection and monsoon trough shifts the wave transition to the eastern part of the WNP. The zonal wind convergence and shear in the monsoon trough region provide a favorable condition for MRG waves to asymptote to Rossby waves. The asymmetric basic flow contributes to MRG waves moving off the equator towards northwest. The northeast-southwest oriented axis of TD-type disturbances in collaboration with the monsoonal environment is favorable for the conversion of eddy kinetic energy from mean flow. The intensification of the amplitude and shortening of the wavelength during wave transition, to a certain extent, is associated with tropical cyclogenesis over the WNP. Therefore, interannual variations in the longitudinal location of tropical cyclone formation may be interpreted partly by displacement of the wave transition zone. Moreover, this phenomenon of cyclogenesis induced by the wave transition is more common during the cold years in which the monsoon trough penetrates eastward and equatorward.

Dynamic and thermodynamic aspects of tropical cyclones in vertical shear and the 'stationary band complex'

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The processes leading to intensity change of a tropical cyclone in vertical wind shear in an idealized numerical experiment are revisited. Previous work has hypothesized that interaction of environmental air with the storm core at mid- to upper levels leads to intensity modification. We propose a new hypothesis and show that downdraft-driven flushing of the boundary layer with cooler and dryer air governs the intensity evolution in our experiment. The downdrafts are linked to a quasi-stationary convective asymmetry outside of the eyewall. The formation of the convective asymmetry is driven by the balanced dynamical response of the tropical cyclone vortex to the vertical shear forcing. This convective asymmetry is compared to the stationary band complex forming at the Lagrangian boundary between the swirling winds dominating the near core region and the low-level storm relative flow. We present some observational support that the processes identified in the idealized experiment apply to the real atmosphere.

Modulation of North Atlantic tracks and genesis by the Atlantic Meridional Mode

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The modulation of Atlantic tropical cyclone activity by the Atlantic Meridional Mode (AMM) and El Nino-Southern Oscillation (ENSO) is examined. We use cluster analysis and to separate the track types and analyze the environmental composites associated with each track type, and their relationship to AMM and ENSO phases. Composites of the genesis potential index in different phases of AMM and ENSO are also constructed and the influences of AMM and ENSO on the genesis index and compared. Synthetic tracks obtained in different phases of the AMM and ENSO are also compared with these results.

Dynamical Downscaling of Tropical Cyclones over the Northwest Pacific Using the IPRC Regional Atmospheric Model (IRAM)

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Dynamical downscaling approach has been widely used in recent years to provide more details of the regional climate systems, such as tropical cyclones in an individual ocean basin. By this approach, a high-resolution limited area model is driven by relatively coarse resolution reanalysis or output of a coarse resolution global model to produce more detailed regional features. In this study, the performance of the regional atmospheric model (IRAM) developed at the International Pacific Research Center (IPRC) in reproducing the tropical cyclone activity over the Northwest Pacific has been evaluated. The NCEP/NCAR reanalysis is used to provide both initial and lateral boundary conditions to the IRAM, which was run at a horizontal resolution of 0.3^o lat/lon. The weekly mean Reynolds SST was used as the lower boundary conditions for the model over the ocean. Simulations for 17 years from 1990 to 2006 are analyzed in the study. The model was initialized at June 1 and integrated continuously through November 30 for each year. The model TCs are located and tracked using an objective algorithm previously developed by Stowasser et al. (2007) for the IRAM.

The results show that the model reproduced not only the mean seasonal cycle but also the interannual variability of tropical cyclones in the Northwest Pacific realistically. The correlation coefficients between the modeled and observed annual tropical cyclone counts and the power dissipation index reach 0.82 and 0.74, respectively. The correlation coefficient between the modeled and observed seasonal cycle reaches 0.92. Further, the model also reproduced the spatial distributions of genesis locations and frequency occurrence reasonably well. Therefore, our results demonstrate that given accurate large-scale circulations by a coupled global model, the IRAM can be used to provide skillful seasonal prediction of tropical cyclone activity over the Northwest Pacific.

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