BIRS-Workshop report: Multiscale process in the tropics, April 26-May 1, 2009.

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The BIRS workshop on “multiscale processes in the tropics” brought together about 41 participants among applied mathematicians, physicists, observational experts, and government lab modelers with a considerable number of students and postdocs. The students and postdocs were constantly encouraged to ask questions during the lectures and to talk to the more senior scientists during the meal breaks. Some of the students and postdocs were given the opportunity to give a lecture on their research. Although many people didn’t know each other before the workshop, there was a lot of interaction and discussion during the lectures and during the meal breaks that were very stimulating. The lecture room was always full until the last day.

1) Overview

A general overview of the tropical multiscale processes and the inherent complex wave dynamics and their interactions with convection, was given by Andrew Majda from Courant Institute (New York University) to open the workshop and set the basis for discussion. Majda emphasized why and how the tropics are both fascinating and important, for applied mathematicians and scientists to study. Most the earth’s solar-energy intake is absorbed in the tropical region and redistributed to the rest of the globe through various atmospheric and oceanic flow patterns. However, because of the vanishing Coriolis force at the equator, simplified balanced dynamics that are useful for climate modelling in midlatitudes fail at the equator. The equatorial fluid-dynamic equations harbor a large spectrum of waves that travel along the equator and interact with moist convection (i.e. clouds), with each other, and with midlatitude waves at various time and spatial scales. The dominant signal that is believed to regulate tropical mid-to-long term range weather and climate is a planetary-scale/intraseasonal oscillation known as the Madden-Julian oscillation (MJO). However, many questions surrounding the MJO and its interaction with meso- to synoptic scales, tropical cloud clusters, and superclusters remain open, and current general circulation models (GCM) used for climate predictionson the global scale representthe MJO poorly if at all. Tropical cyclones and hurricanes are other examples of the complexity of the multiscale processes in the tropics. Majda concluded his overview by setting up five key milestones to be discussed during the workshop.

1. The MJO propagation and initiation. The MJO is observed to start by its inactive phase in the western Indian Ocean. It becomes active and organizes convection on the planetary scale as it slowly propagates over the Indian-ocean and the Indonesian maritime-continent toward the western Pacific. The MJO speeds up and finally dies when it reaches the eastern Pacific. The driving mechanisms behind its propagation and its initiation are not known. Are they due to interactions with extra-tropical (external) dynamics such as Rossby waves or is

the MJO a purely self-sustained tropical (internal) signal.

2. Interactions of the MJO and convectively coupled waves with the extra-tropics. What is the role of the base state in these interactions? How much of the interaction is due to shears and how much is due to moist thermodynamics?
3. Convective momentum transport. There is a chicken-egg question related to the interaction of large-scale shears and organized convection. The shear provides a favorable base state for convective organization and organized convection feeds back onto the shear through upscale and downscale convective momentum transport.
4. Diurnal cycle. The effect of diurnal cycle on the MJO and organized convection in general is not understood.
5. Hurricane initiation and intensification. There are many theories for this but there is still no consensus among the specialists. State-of-art hurricane forecasting tools are still unable to predict accurately hurricane embryos and their intensification or make good predictions about their intensity once initiated.

2) Cloud processes, the mixed layer, and diurnal cycle

Basic cloud-processes and their relationship with the dynamics of the subcloud mixed layer at both the convective-cell (local) and the MJO (global) scale were covered in lectures by Philip Austin from the University of British Columbia (entrainment and detrainment in trade winds) and Richard Johnson from Colorado State University (diurnal cycle and the MJO).

Johnson provided observation evidence linking the diurnal cycle and large-scale organized convection. He observed that the diurnal warming of the ocean surface induces a gradual increase in precipitating cumulus and congestus cloud populations. The transition to large-scale organization starts with the appearance of a meso-scale circulation on the form of the Benard cells, familiar from laboratory convection. The shallow and congestus cloud activity phase moistens the air above the mixed-layer, which allows the mixed-layer to deepen over scales of 100 km. Johnson noticed that the moistening process between 600-800 hPa, which is in phase with the wind anomalies in the wake of the MJO (the westerly wind burst, WWB), induces a deepening of the mixed-layer during the WWB phase and remoistening the mid-troposphere after the WWB episode. The diurnal cycle is believed to help the moistening-processes by allowing an afternoon drying of the mixed-layer and moistening above the mixed-layer according to the sequence of mechanisms listed above. The mixed layer is found to be the warmest and driest in the afternoon.

Austin explained that clouds act like fish in the sense that small clouds feed big clouds through vertical turbulent fluxes or various tracers. Based on the mass flux formulation used in cumulus parametrizations, he computed the area fractions of shallow cumulus clouds from large-eddy-simulation (LES) data. He used a steady state plume model to determine the rates of entrainment of environment air into the cloud and detrainment of cloudy air to the environment. He pointed out that there is a linear relationship between the total water content (vapor, liquid, and ice) and the liquid-water potential temperature, a feature that he took advantage of to compute the buoyancy of convective parcels. The LES results demonstrated that shallow cumulus clouds are positively buoyant below and negatively buoyant above with associated entrainment at low levels and detrainment above. These are the two main mechanisms through which environmental air mixes into the cloud and cloudy air mixes with the environment. Above a certain critical mixing fraction the cloudy parcel becomes negatively buoyant and detrains. In a typical LES simulation most of the shallow cumulus clouds are negatively buoyant on average. Moreover, convective available potential energy (CAPE)—the potential energy of an adiabatically raised parcel, a measure that is believed to play and important role in moist convection turns out to be very misleading as CAPE doesn't seem to determine the top of the clouds but the background moisture does because of the crucial importance of mixing processes.

3) Observations of large-scale tropical waves

One of the most intriguing features of tropical convection is its organization into a hierarchy of cloud clusters and superclusters ranging from hundreds to thousands of km that are associated with waves propagating in both directions along the equator. Although it is now well established that these waves are the moist—convectively coupled analogues of a wide spectrum of equatorially trapped waves(the linear solutions to the equatorial-beta plane shallow water equations), the mechanisms that set up their energy sourcesfrom organized convection, their initiation, the way they modulate convection, their vertical structure, and their interactions with each other and with extra-tropical waves, all remain uncertain. These issues were the focus of lectures by George Kiladis from the USA National Oceanic and Atmospheric Administration (NOAA), Yukari Takayabu from the University of Tokyo, Duane Waliser from the California Institute of Technology, Chidong Zhang from the University of Miami, Paul Roundy from the University at Albany, and Gui-Ying Yang from Reading University.

Kiladis talked about the relationships between convectively coupled Kelvin waves and extra-tropical wave activity, based on recent satellite (CLAUS[1]) and analysis (NCAR) datasets. He revealed some interesting "non-Kelvin aspects'' of convectively coupled Kelvin waves in sheared environments consistent with theoretical models. Differential advection leads to straining and deformation that affects the shape and group velocity of the wave. Rossby-wave energy is trapped along extra-tropical jets resulting in a wave-guide. However, changes in climatology due to the seasonal westerly wind burst (WWB) open a "wide channel" over the western Pacific ocean within a region where equatorial easterlies from the jet are balanced by the WWB, allowing extra-tropical Rossby waves to propagate across the equator. These Rossby waves were believed to help initiate convectively coupled waves that then propagate eastward along the equator. Among the non-Kelvin aspects that were observed were an anti-cyclonic Rossby gyre in the Northernhemisphere for the winter Kelvin wave and a cyclonic gyre in the

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1 *Cloud Archive User Services*

Southernhemisphere for the summer Kelvin waves that are believed to be part of extra-tropical Rossby waves tied to the Kelvin waves. For the mechanisms that helped the initiation of the Kelvin waves, Kiladis suggested local changes in dynamical and thermodynamical fields due to the propagation of extra-tropical Rossby waves.

Takayabu's talk was on shallow and deep modes of tropical precipitation heating and their relationship to large-scale environment. She used precipitation data from the TRMM[2] mission to infer estimates of latent heating. She relied on global precipitation data coverage that is relevant to the MJO dynamics. It is argued that suppression of deep convection in subsidence regions is one of the major inconsistencies between observations and models. Earlier works suggested that congestus clouds are prominent in the suppressed phase of the MJO. A universal trimodality of tropical clouds is observed in almost all data sets over the Indian ocean/Western Pacific. Shallow cumulus clouds give rise to cumulus congestus, which then transit to deep convection. Takayabu observed that shallow heating as opposed to deep is more effective for moisture convergence. However, congestus clouds, of intermediate depth, are found to act only over the ocean. Over land there is a more direct transition from shallow-trade-wind cumulus to deep convection. The overall distribution of clouds over the globe shows a clear dominance of congestus cloud decks in the subtropics that are not associated with deep convection. It is observed that in general a dry middle troposphere is not favorable for deep convection, thus the transition from shallow to deep through moistening. This last result is believed to have a significant implication on the MJO dynamics.

Duane Waliser gave a talk on vertical structure and processes revealed with recent satellite data. Combining data from various sources (CMAP, TRMM, AIRS, HZOV, QuickScat, etc.), he found that large-scale rainfall patterns were consistent among different instruments with the well known MJO and hydrological cycles. Among other features, Waliser noticed a high correlation of rainfall and moisture convergence, with the latter leading near the equator. There is a significant vertical tilt in water vapor (BOUALEM – what kind of a tilt?). Rainfall anomalies of about 3 mm/day are balanced by moisture convergence column average. Upper troposphere temperature anomalies of about +0.5 K always lead moisture anomalies. There is also a non-negligible residual between moisture convergence and rainfall. This subtle difference between moistening and rainfall implies significant moistening and drying and provides some clues about the mechanism of the preconditioning process.

Chidong Zhang delivered his lecture on the vertical mode structure of tropical heating. He used both sounding and radar data to infer latent heating in the tropical atmosphere following two different methodologies: A bulk budget equations of large scale fields following Yanai (1973) and localized cloud variables such as liquid and ice water content and cloud area fractions. Some of the questions Zhang wanted to address included the shape of the tropical heating profile, how the large-scale circulation responds to this profile, and what is the implication and role of MJO regarding the heating profile. The

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[2] *Tropical Rainfall Measurement Mission*

radar data in particular, confirmed the trimodal nature of the tropical cloudiness consisting of deep, stratiform, and congestus clouds with some of the congestus clouds contributing a significant amount to the total. Thus, Zhang concluded that two heating modes are important for the large-scale circulation: a deep heating mode, associated with deep convection, and a shallow heating mode associated with congestus clouds. The shallow heating mode is suggested to have a bottom heavy profile with very little heating in the upper troposphere. Stratiform heating is found to be very weak but a stratiform heating mode should still be used in cumulus parametrization because it is believed to play an important dynamical role.

Gui-Ying Yang gave a talk on her observational work of convectively coupled waves in ECMWF reanalysis data. Based on intuition gained from earlier work, her main approach was to project the data on the equatorial shallow water modes of Matsuno, a.k.a equatorially trapped waves, associated with the first baroclinic mode of vertical structure. The results are overall in agreement with in situ data and provided some important new insight into the subject because of the wider coverage. It is found in particular that there are interesting discrepancies between convectively coupled Kelvin waves (CCKW) in the Western hemisphere (WH) and those in the Eastern hemisphere (EH). For instance, CCKW's propagate faster in the WH. WH CCWK's have a vertical tilt while those in the EW do not. There was a particular focus on westward-propagating mixed Rossby-Gravity (WMRG) waves. It was suggested that WMRG's are basically forced internal modes that emerge from barotropic Rossby waves propagating toward the equator.

Paul Roundy gave a talk on convectively coupled waves of the free troposphere. Roundy started by an overview of the observations of convectively coupled waves (CCW). Relying on the fact that some CCW's propagate upward to the stratosphere as internal waves, he introduced an alternative to the "two-baroclinic modes" representation of CCW's. Noticing that smaller scale CCW's are more tilted than larger scale ones, e.g, synoptic versus planetary, the representation of CCW's by interval modes yields upward propagation of plane waves that tilted backward in the troposphere layer and forward aloft--in the stratosphere due to the sudden jump in stratification thus associating the boom-rang shape of CCW's to the discrepancy in the effective-buoyancy between the troposphere and the stratosphere. This theory assumes that, due to latent heating, the effective buoyancy in the troposphere is much smaller than what is normally measured or computed in clear-sky conditions. This is in disagreement with the more-or-less widely accepted twobaroclinic modes theory in which 1) the slow propagation is interpreted as a combination of the projection of waves on both the fast (deep) and slow (shallow) baroclinic modes and the change in the background stratification due to moisture (not heating), 2) the front-to-rear backward tilt is believed to result from the progressive deepening of convection, and 3) the boomerang shape is due to the forward-up propagation of stratospheric waves in response to the moving heat source.

4) Mathematical models for large-scale tropical dynamics

Highly filtered and idealized mathematical models, often guided by intuition gained from observations or numerical simulations, are important tools to gain theoretical insight into the complex dynamics of the large-scale tropical waves. Two types of such models were presented at the workshop: Phenomenon driven ad hoc models that are designed to mimic the physics that is believed to reproduce an observed feature or features (here convectively coupled waves and the MJO) and rigorously derived models using asymptotic analysis based on some distinguished limits that are chosen according to some intuition gained from observation. The first category of models was covered in the talks by Majda and Pauluis, from Courant Institute (NYU), Waite and Khouider, from Victoria, and Stechmann, from UCLA while the second category is covered in the talks of Biello, from UC Davis, Klein, Dolaptchiev, and Owinoh, from Free University of Berlin, and Shaw from the University of Toronto.

4.1) Simple models for organized tropical convection

Andrew Majda presented a model skeleton of the tropical intra-seasonal oscillation. Motivated by a desire to design simple models with very few parameters to showcase the dynamics and the physics that are believed to characterize the MJO, Majda constructed an idealized harmonic oscillator-like model where the large scale low level moisture interacts with the latent heating and precipitation to form a planetary-scale/intra-seasonal, neutrally stable oscillating mode—a skeleton for the MJO. This is the first model for the MJO that predicts main features of the observational record: a roughly 5 m/s propagation speed, a quadruple Rossby gyre, and a peculiar dispersion relation with a zero group velocity. It is argued that the "skeleton'' gets its muscle from synoptic scale waves through mechanisms such as convective momentum transport that breaks the symmetry between east/west vortices and produce a strong WWB and thus provides a self-sustained multi-scale system.

Michael Waite gave a talk on boundary layer dynamics in a simple model for convectively coupled gravity waves. Waite was interested in synoptic scale convectively coupled waves that are produced in the multicloud model of Khouider and Majda and that have dynamical and physical features resembling those of observed convectively coupled Kelvin waves in the Western Pacific, including their slow phase speeds, horizontal and vertical scales, and the famous front-to-rear vertical tilt. The multicloud model uses the first two baroclinic mode equations forced and coupled by parametrized heating and cooling terms, based on the three cloud types inferred from observations, congestus, deep, and stratiform and is coupled to the sea-surface through a slab boundary layer reduced to one equation for the equivalent potential temperature. The goal was to incorporate the fluid dynamics of the boundary layer into the multicloud model, using turbulent closures to derive detrainment and entrainment rates of boundary layer air into the free troposphere and vice-versa. An important feature of the new boundary-layer model is that it implies a barotropic flow with a non-zero divergence in the free-troposphere that feeds back with environmental downdrafts that cool and dry the boundary layer. Among many other interesting features, it is found that the environmental downdrafts enhance the instability of the gravity waves and that overall the boundary layer dynamical picture is in phase with the rest of the wave pattern in a way that is consistent with observations.

Boualem Khouider presented a stochastic multicloud model for tropical convection. The stochastic model uses a lattice of sites that are either occupied by a cloud of a certain type: congestus, deep, or stratiform, or it is a clear-sky site. The lattice sites transition from one cloud type to another or to clear sky according to probability laws based on intuition gained from observations and numerical simulations of organized tropical convection. For example, a site that has a high CAPE and low mid-troposphere moisture transitions from clear sky to congestus with high probability and a transition to a deep site is allowed only if the environment is sufficiently moist, as suggested by observations. Coarse-graining of the microscopic lattice model to the level of the GCM grid yields a Markov chain birth-death process for the evolution of the area cloud-type fractions on each grid box. The conditioning of the stochastic/microscopic dynamics by the large thermodynamics resulted in a self-organization of the large scale heating into leading shallow or congestus, deep, and trailing stratiform, as in observations.

Samuel Stechmann talked about gravity waves in shear based on linear analysis and numerical simulations using the multicloud model of Khouider and Majda also used by Waite. The idea is to introduce a vertical shear profile that can interact with the wave dynamics through non-linear advection. The shear providing large scale advection to the waves and the waves feed back through convective momentum transport in the way mimicking the interaction of the MJO winds in the background and the embedded convectively coupled two-day and Kelvin waves. These interactions result in interesting consequences. Linear theory reveals that the profile of the large-scale shear is crucial. Not only does it set a preferential direction for the synoptic scale waves but it also introduces a small-scale instability of squall line-like modes that propagate in the opposite direction. In the non-linear simulations, the convectively coupled gravity waves feed back to the mean shear through CMT and trigger their own demise while the mean shear undergoes important oscillations on the intra-seasonal scale. The transition periods are characterized by squall line-like meso-scale waves modulated by synoptic scale waves moving in the opposite direction, thus providing some interesting clues for the dynamical interactions between the MJO, synoptic scale convectively coupled waves, and squall lines.

The talk of Olivier Pauluis was titled “Impacts of the global distribution of precipitation on the propagation of convectively coupled waves”. Pauluis used an idealized tropical climate model, based on a simple parametrization of convection and precipitation to study the dynamics and propagation properties of convectively coupled Kelvin waves in a non-homogeneous environment consisting of a narrow moist region located along (but somewhat off of) the equator, mimicking the intertropical convergence zone (ITCZ).; This model supports simple exact solutions, consisting of moving and/or stationary precipitation fronts separating moist/precipitating and dry/non-precipitating regionsIt is found that such an environment can reduce the propagation speed of the waves and at the same time modify significantly their horizontal structure. It induces a meridional velocity for the Kelvin wave, which is otherwise zero, in a way that is more consistent with observation providing some hints about the impact of the ITCZ on convectively coupled waves. Also due to the lower speeds of wave propagation in the moist regions, small perturbation analysis showed that precipitation fronts lead to interesting reflection and deflection of incident tropical Kelvin and Rossby waves.

4.2) Multiscale asymptotic analysis

Joseph Biello's talk was on synoptic/planetary multi-scale theory for the tropics. By making some judicious choices of time and spatial scales of interest, he derived balanced equations to address the issues of tropical and extra-tropical interactions, through resonant interaction of Rossby waves, and interactions across scales of the MJO and synoptic scale organized convective systems. The MJO model in particular is based on the Majda and Klein IPESD framework and consists of weakly non-linear PDEs at the planetary/intraseasonal scale forced by synoptic scale dynamics through momentum and energy turbulent-like fluxes (convective momentum and energy transport). The synoptic scale variables solve a linear PDE system forced by a prescribed synoptic scale heating with the three cloud-types profile, mimicking observations. Biello insisted on the important role of tilts in the synoptic-scale heating profile for convective momentum transport to work. This resulted in a planetary scale/intraseasonal oscillation in the large-scale equations with dynamical features and flow structure resembling the MJO.

Rupert Klein introduced an asymptotic model for columnar clouds and internal waves. Klein extended the asymptotic analysis to the cloud physics scales and made a rigorous derivation of a linear model for internal waves coupled to a pressure-less cloud column model somewhat within the framework of mass flux cumulus parametrizations. Two different cloud closures were proposed: one with a steady-state area fraction as in traditional cumulus parametrization and one with a varying area fraction. One of the interesting findings is that in dry environments mountain waves radiate away except for the very high-frequency waves. But in moist environment both high frequency and low frequency mountain waves become evanescent. It is also demonstrated that clouds may narrow the spectrum of lee waves and can cause critical layers.

Steman Dolaptchiev discussed asymptotic models for the planetary and synoptic scales in the atmosphere. He generalized the Majda-Klein IPESD equations, that apply only for the beta-plane equatorial dynamics, for the case of the primitive equations on a sphere and conducted some numerical experiments to demonstrate the validity of the distinguished limits on the whole globe. His main interests were in planetary scale atmospheric motions such as thermally and geostrophically-driven quasi-stationary Rossby waves, teleconnection patterns, and large scale zonal winds.

Anthony Owinoh chose his distinguished limits to address the issue of multiscale modeling of stratocumulus clouds. By assuming two horizontal scales of 500 m and 100 km and two time scales of one minute and 5 hours, representing respectively a cumulus scale and a boundary-layer dynamical scale, he derived bulk (vertically averaged) boundary layer equations coupled to cumulus dynamics. He used closure assumptions for entrainment and detrainment for cumulus clouds based on radiation and strength of the inversion layer above the boundary layer. One important finding resulting from the balanced equations is that liquid water content is proportional to the cloud depth constraining a universal horizontal scale for cumulus clouds.

Tiffany Shaw's talk was "on using wave-activity conservation laws to understand the generation of subgrid-scale energy and momentum". The goal is to derive wave activity conservation laws to use as sub-grid scale parametrizations. Shaw's strategy is based on a Hamiltonian formulation using conserved quantities through multiscale asymptotics. She was interested in the generation of gravity waves in a flow over convective complexes, thought to be occurring in a manner similar to mountain waves. This is especially important for the cumulus-parametrization problem in the context of CMT.

5) Numerical simulations and large scale models

Given the complexity of the atmospheric flows, except for some specific balanced dynamics, the governing equations are intractable analytically in general. To get a more complete picture of the atmospheric flow, in particular for applications to weather and/or climate predictions, computer simulations are unavoidable. However, because of limitations in computational resources, the equations of motion cannot be fully resolved on the whole planet and for long integration times(e.g. climate timescales). In a typical climate simulation, the equations are approximated on a coarse grid, on the order of 100 km to 200 km, and the small scale processes associated with clouds, gravity waves, chemistry, vegetation, and interaction with boundaries/topography, are parameterized according to various recipes motivated by physical intuition and in situ measurements. Because of the complex interactions between clouds and the large-scale flow, the so-called cumulus parametrizations used to represent the unresolved cloud processes in general circulation models (GCM) are not perfect. In fact, they are often blamed for the poor performance of GCMs in representing convectively coupled tropical waves and the MJO.

To gain insight into those small-scale processes, scientists and mathematicians often rely on detailed numerical simulations, localized in both time and space. "Cloud resolving modeling" denotes a type of numerical simulations that specializes in cloud processes. At this workshop many speakers addressed the issues of tropical convection and waves in GCMs and provided various insights into the subject using cloud resolving modeling.

Talks on GCMs and simulations of large scale tropical circulation were given by Jia-Lin Lin, from Ohio State University, Dargan Frierson, from the University of Washington, Patrick Haertel, from the University of North Dakota, Norman McFarlane, Hai Lin, and Ajaya Mohan, from Environment Canada, and Brian Mapes, from the University of Miami while Stefan Tulich, from NOAA and Jahanshah Davoudi, from the University of Toronto delivered lectures on cloud resolving modeling.

5.1) Cumulus parametrizations and GCMs

Jia-Lin Lin's lecture was titled "understanding the tropical biases in GCMs". GCM-based climate simulations are notorious for having several biases when compared to observations. Lin and his collaborators have conducted an intercomparison study of climate simulations using 27 different operational climate models and compared their results to satellite OLR data, NCEP reanalysis products, and buoy data. They found that in the tropics, GCMs often exhibit a double ITCZ instead of one, an El-Nino/Southern Oscillation (ENSO) with too short or too long periods, and a poorly represented MJO(if represented at all). Their study revealed that the MJO problem is directly connected to cumulus parametrization. Lin suggested during his lecture a methodology for constantly improving GCMs through a feedback loop between theory, observations, and models.

Dargan Frierson presented some numerical experiments with a hierarchy of simplified GCMs to study the response of convective activity and the ITCZ on midlatide climate. An important question he wanted to address is why the ITCZ in CGMs moves southward towards the equator as in paleoclimate data. He noticed that the location of the ITCZ depends on midlatitute processes, such as the crossing line between heating in NH and cooling in SH ("the energy flux equator"), the gross moist stability (GMS), and the cloud radiative forcing. Eddies in midlatitudes affect the Hadley circulation. He also noted that the Kelvin-wave speed in the models depends on GMS, which therefore can have a big impact on tropical climatology.

Norman McFarlane's talk was on parametrization of CMT and energy conservation in GCMs. According to McFarlane, parametrization schemes of all kinds, from boundary-layer turbulence to cumulus convection, should preserve integral constraints of the basic equations, e.g. conservation of momentum and energy. Although viscous forces are small in the atmosphere, heating effects due momentum friction could be important. However traditional cumulus paramerization formulations have ignored the momentum effects of convection while introducing the top hat approximation for cumulus properties. McFarlane suggested a new way of looking at parametrization of CMT in cumulus parameterization, under the above constraints, by relying on the first and second moments of turbulent kinetic energy.

Ajaya Mohan discussed the role of mean state and SST in MJO simulation. Mohan used numerical simulations to investigate the role of boundary layer and surface processes in the northward propagation of the MJO. Existing theories suggest that the poleward propagation of convection is associated with boundary layer convergence, the summer mean flow, and asymmetries in the distribution of humidity. He performed several studies using the German climate model (ECAHM4) coupled to the ocean. In his control simulation the sea-surface-temperature (SST) anomalies propagated northward and were followed by precipitation. But a test with a fixed SST showed the same northward propagation of convection and concluded that lead SST is not necessary for the northward propagation.

Brian Mapes' talk was titled "toward understanding the MJO through the MERRA data assimilating model". Mapes introduced a framework for parameter assimilation in the cumulus parametrization of Takioka--one of the early parameterizations used in GCMs, using the MERRA data. The model in particular produces a slow Kelvin wave but has no MJO. Large convergence errors were found in the assimilation algorithm. It is argued that those errors were essentially due to inconsistencies in the model physics compared to nature. For example, the model is characterized by a rapid transition to deep convection without a congestus preconditioning phase. There is too much deep convection. Convection is too deep too soon.

Patrick Haertel's talked was entitled "LO and behold convectively coupled Kelvin waves". Haertel introduced a new parametrization of cumulus convection based the Lagrangian overturning (LO) method. Rising and sinking parcels of fluid within the convecting cloud are represented by Lagrangian particles that are allowed to exchange mass and energy with the environment when necessary. He performed some aqua-planet (a planet with an ocean everywhere) simulations and obtained perpetual Kelvin waves (circulating the globe forever) that have realistic dynamical and physical structures. According to the lecturer, evaporation of precipitation is believed to be an important process to include in a cumulus parametrization in order to establish a realistic moisture profile, which is crucial for organized convection and convectively coupled waves. It is argued that mixing of clouds with environmental air and evaporation of precipitation play an important dual role in the simulations.

Hai Lin lectured on the interaction between MJO and north Atlantic oscillation (NAO), which regulates the northern hemisphere climate in the North Atlantic section, Observations suggested the existence of two-way interactions between the NAO and the MJO. It is observed that NOA amplitudes increase 5 to 15 days after the MJO convection reaches the western pacific and some MJO's are preceded by strong NAO's. Hai Lin performed a dry GCM simulation (i.e. without convection) and generated an intraseasonal signal in the tropics that was directly linked to the extra-tropics, thus suggesting a possible mechanism for MJO initiation through tropical-extra tropical interactions.

5.2) Cloud resolving modeling

Stefan Tulich lectured on tropical squall lines as convectively coupled gravity waves. Satellite observations suggested that tropical squall line are in fact convectively coupled gravity waves as their spectral peaks lie on the gravity wave branches of the dispersion relation. However, it is not clear why most of these waves move westward. Westward gravity waves (WGW) are found to dominate over Africa and there is a striking similarity between WGW in Africa and over the western-Pacific ocean. To investigate these issues, Tulich conducted detailed numerical experiments using cloud resolving modeling (CRM) both with and without a mean zonal wind vertical shear. He used a grid-nesting strategy to achieve simulations on sufficiently large domains. It turns out only the simulations with easterlies at low-level exhibited solutions with westward propagating gravity waves.

Jahanshah Davoudi was interested in mass flux fluctuations in a cloud resolving simulation with diurnal forcing. His goal was to assess a theory by Craig and Cohen that predicts the mass flux in clouds as the equilibrium Boltzman distribution of statistical mechanics, under the quasi-equilibrium theory of moist convection. One major assumption of this theory is that external forcing such as solar radiation affects the number of clouds but not the mass flux of individual clouds, allowing these clouds to play the role of "fundamental particles". Davoudi analyzed CRM simulation data in the presence of a diurnal variation of the solar forcing. Thirty day long time series revealed that the diurnal cycle is observed in the liquid water and temperature but not in water vapor, an indication that water vapor has in fact a longer memory. He found that the stat-mech theory is approximately valid in the lower troposphere and for shallow clouds but not aloft, for deep convection. He suggested that this discrepancy is essentially due to the fact that deep convection is often organized into cloud clusters and therefore not in agreement with the "ideal gas" non-interacting assumption for the clouds.

6) Tropical cyclones and the hurricane embryo

Hurricanes and typhoons are among the most devastating extreme weather events characteristic of the tropics . Although they form over the warm waters of the tropical oceansfar from land, they often move to the shores and over land and affect human populations in many ways—by massive floods and titanic winds that can destroy cities miles away from the ocean shore and immense costs for the shipping industry. Although, in typical situations, today's weather-forecasters are able to track the speed and path of hurricanes and typhoons with some precision a few days in advance-once they are localized and recognized as such- the physical processes that lead to their genesis and intensification remain two of the major research areas in tropical meteorology. The BIRS workshop on "multiscale process in the tropics" brought three world experts to lecture on this research topic. Timothy Dunkerton, from Northwest Research Associates and Michael Montgomery, from Naval Research Institute both lectured on theories for tropical cyclogenesis while Roger Smith, from L-M University of Munich, delivered a lecture on hurricane intensification.

Dunkerton's talk was entitled "Tropical waves, tropical cyclo-genesis, and more tropical waves". Dunkerton first give a brief survey of the importance of organized convection on the synoptic and planetary scale and how the MJO in particular affects the intensification of tropical cyclones. Data suggest a close relationship between hurricane intensity and the global warming of ocean waters—a hot topic of climate change. He then discussed the pathology of traditional theories for MJO and organized tropical convection of wave-CISK and WISHE and hinted on possible links between the synoptic scale convectively coupled waves and hurricanes, through "direct and indirect'' Ekman effects that are claimed to be relevant for the cyclo-genesis. In essence, this perspective shifts the problem of predicting the genesis of hurricanes to that of "getting the waves right". He introduced a new theory for cyclo-genesis, metaphorically called "the marsupial theory" (after those mammals that hide their young inside their pouches until they mature) , according to which tropical cyclones build up inside the large cyclonic gyres associated with easterly waves when this latter hit the critical line where the wave propagation speed matches the mean flow velocity. This new theory introduces a controversy for the scientific community who long believed that tropical cyclogenesis can be triggered by Rossby gyres of all kinds and not necessarily easterly waves.

Montgomery followed up on the marsupial theory for genesis of hurricanes in a talk titled "Multiscale aspects of tropical cyclogenesis'' by performing some case-study numerical simulations. In addition to the critical layer, the "marsupial theory" requires large scale convergence of moisture and diabatically amplified eddies, providing two distinct stages for hurricane intensification: (1) preconditioning of the synoptic scale environment by the wave and (2) the mesoscale organization and construction of tropical cyclone-scale potential vorticity (PV). Montgomery concluded his talk by giving a few recommendations for the forecasting community of guidance provided by the marsupial theory when looking for signs for cyclo-genesis.

As mentioned earlier Roger Smith's lecture was on tropical cyclone intensification. Smith conducted a basic thought experiment for TC intensification focusing on the important physical principles, using detailed numerical simulations. His set up consists of an axisymmetric vortex, over a 28 ^{o}C sea surface, and prescribed vertical profiles of temperature and moisture. According to Smith, surface friction over a "friction layer'' is very important for TC intensification. Accordingly, three viewpoints were considered: 1) mass convergence and conservation of angular momentum, 2) wind induced surface heat exchange (WISHE), and 3) reduction of angular momentum in BL due to friction—the so-called M-theory or the asymmetric viewpoint. The latter was believed to be the mechanism at work during Smith's experiment, which automatically invalidates theory 1). Moreover, apparently, the WISHE theory assumes a gradient wind-balance, which is not realistic and makes the validity of WISHE theory for hurricane intensification questionable. In Smith's experiments the resulting flow asymmetry is believed to be due to convective towers that are sensitive to low-level moisture convergence. Reduced centrifugal and Coriolis forces in BL cause an imbalance with respect to pressure gradient and cause lifting, which result in a secondary circulation. However, there are still many open questions regarding this new theory, such as the limits of predictability of hurricane intensity and rapid intensification, a better understanding of the flow field inside and outside the eye-walls, and more importantly an analytic representation of the boundary layer dynamics to use in climate models, is still missing.

7) Connection to sea surface and to global dynamics

Many other processes that are traditionally thought of as being characteristic to midlatidute or so-called dry dynamics are also relevant to and must be understood in the context of the tropics; these were also part of the workshop on "multiscale processes in the tropics''. In fact some of the talks classified under the present category are of more general interest, therefore directly relevant to the tropics as well. Getting people who do not traditionally go to conferences on the tropics is important to foster new interactions and have the different communities learn from each other. Such interactions are essential giving the aforementioned connections between tropical circulation and midlatitude weather and climate.

Adam Monahan from the University of Victoria lectured on the distribution of sea surface winds. Surface fluxes that are relevant to tropical convection and hurricanes depend strongly on surface winds, and more precisely, on their high order moments—their variability. Surface winds are also important for power generation as offshore wind turbines are becoming popular nowadays. Observations revealed that surface wind skewness is negative in the tropics and positive along the midlatidude jet-stream peak—it is anti-correlated with its mean. Rather than assuming a Weibull distribution for surface wind speed, Monahan used BL momentum budget equations, where horizontal advection is neglected and the drag coefficient is a stochastic process that is conditionally distributed on SSTto propose a theory for surface wind distribution that is in good agreement with observations. He noticed that the ocean stratification is unimportant but dynamical variation of the BL depth improves the model results.

Leslie Smith from the University of Wisconsin-Madison gave a talk on wave interactions in stratified flows. According to observations (SPARC data), there is a significant accumulation of energy at the equator, which is believed to be due to wave-wave interaction. To address this question, Smith studied wave interactions in a dry-model on an f-plane. Apparently, there are two competing theories: 1) two waves interacting through a vortical mode and 2) a three-wave interaction. Instead, the lecturer derived a reduced model where the two theories can work together. This is done by introducing a stream function and velocity potential in the physical space and arriving at a reduced PDE-system that conserves energy. In Fourier space, the model has a vortical mode and a sequence of wave modes that interact with the vortical mode and with each other. The vortical mode recovers the QG limit when the Rossby and Froude numbers are small and the gravity modes are forced only through the vortical mode. An important issue that was believed to prevent the three-wave interactions to occur in numerical simulations is believed to be under-resolution as confirmed with the new model.

David Muraki of Simon Fraser University discussed PV dynamics for rotating shallow water on the sphere. An important balanced model that is traditionally used to study Rossby waves in midlatitudes is the celebrated quasi-geostrophic (QG) model derived from a beta-plane approximation. The QG equations develop a singularity in Rossby number when we approach the equator. Nonetheless, Rossby waves are often observed to cross the equator in well-behaved packets. Because of the aforementioned singularity deriving balanced equations for Rossby waves that are valid near the equator becomes an interesting research question. Such a balanced model could help understand the mechanisms behind the propagation of Rossby waves across the equator and possibly consolidate the theories for Rossby waves in midlatitudes and in the tropics. Toward this end Muraki decided to work with rotating shallow water equations in spherical geometry instead of a beta-plane model. However, the singular Rossby number limit at the equator remains intact. Nevertheless, asymptotic expansion in a small parameter epsilon using Ray theory from geometric optics was possible. The result was a Hamilton-Jacobi equation for short waves and balanced dynamics with zero geopotential hight (barotropic fow) at large scales.

8) Discussion

The last session of the workshop was devoted to an open discussion between the participants to discuss some open issues and summarize things that could be done better as an outcome of the workshop.

Some of the important issues were related to data. Enormous data sets have been collected by satellites over the years. However, these data are generally sparse and often measured in quantities that are not directly the physical variables considered in mechanistic models. Therefore, intensive analysis and cooperation between different institutions and countries are necessary to make these data useful. Duane Waliser brought up the year-of-tropical-convection (YOTC) experience, which is a multi-institutional and multi-national project directed to this end during the period of 2008-2009. With the ultimate common goal of improving cumulus parametrizations in GCMs, the YOTC scientists combined their own resources to make available the following items

- Atmospheric analysis and forecast products
- Satellite data sets
- Periods of interests
- Modeling resources
- Resolved data sets to use for boundary conditions for CRMs
- Comprehensive number of variables such as horizontal velocity, temperature, and water mixing ratios.

Chidong Zhang mentioned an upcoming international effort to conduct a series of field campaigns in the Maldives and in the Island of Diego Garcia to provide detailed radar data from this region of the globe. Philip Austin recalled the existence of the Radar-Sat data set that permits for congestus clouds vertical profiling. An important issue that the assistance had agreed upon is related to cloud distribution in GCMs: It has become clear that stratiform clouds are under-represented in climate simulations and especially the associated mesoscale circulation which is believed to play a major role in upscale transport of momentum. Also the diurnal cycle seems to be poorly represented in GCMs despite its importance for convectively coupled waves and the MJO. Moreover, there is a need for accurate representation of atmosphere-ocean coupling. Paul Roundy reported two examples (1985 and 2002) of oceanic Kelvin waves that were initiated by the MJO and traveled slowly within the Pacific Ocean.