Banff International Research Station Workshop Report: Organized tropical convection and large-scale circulation: Theory, modelling, and observations, 11w5047

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Overview

The tropical circulation workshop brought together 33 specialists in the field of tropical convection and large-scale circulation from North America and Australia, with various backgrounds, including mathematicians, physicists, and meteorologists. It brought together a spectrum of scientists and mathematicians with a good balance between early career faculty/scientists and very senior researchers. There were five students and post docs.

Each morning started with a session of two to three 30-minute-long focussed talks, to give an overview on the state-of-the-art a specific topic. This was followed by a panel discussion on that specific topic to elaborate further and initiate a brain-storming of the topic of the day. The afternoon started with a session of 5 to 6 15-minute talks of more traditional research-type. It was then followed by and interactive open discussion session. The discussion often revolved around one or more the topics related during the 15-minute talks. The panels consisted of a chair (one of the organizers, who will present the topic and direct the discussion) and up to 5 expert panellists. The audience and especially the young students and postdocs were encouraged to participate by asking questions and making comments. The interactive sessions were free-format open discussion to stimulate spontaneous interventions.

Workshop Objectives

Despite the recent advancement in theory, observation, and modeling to improve our ability of understanding, simulating, and predicting tropical organized convective systems, many fundamental issues need to be fully addressed: (1) Given the observed self-similarity in convective development, what mechanisms distinguish the generation of tropical perturbations of different scales and propagating speeds (e.g., the MJO vs. convectively coupled Kelvin wave)? (2) How does the convective multiscale interaction occur in conjunction with convective interaction with the environment (e.g., moisture)? (3) What is the untapped potential and limitation of cumulus parameterization in weather and climate models in representing tropical organized multiscale convective systems and their interaction with the large-scale dynamics and thermodynamics? (4) How can new theoretical insights guide innovative data analysis on tropical organized multiscale convective systems and their interaction with the large scales, especially in the context of the new generation of satellite observations (e.g., TRMM, A-Train) and field campaigns in the near future? (5) How can new observations and numerical simulations inspire more theoretical ideas? (6) How should innovative numerical experiments be designed to test new ideas from theories and observations?

The dynamics of organized multiscale convective systems in the tropics presents one of the most challenging problems in contemporary dynamical meteorology. Its expedited progress requires new developments in applied mathematics, fluid mechanics, scientific computing, observations, statistical physics, and cross-fertilizing between all these fields.

Tropical meteorology has experienced some fundamental advances in recent years, both theoretical and observational (due in large measure to significant improvements in satellite databases). However the sparseness of in situ data, in both space and time, limits their applicability and calls for the development of new statistical and applied math tools and expertise from cross disciplines for their analysis. Higher resolution coverage with radars, balloons and ship-borne data is still not feasible to the extent of the tropics. Thus, targeted field campaigns motivated by theoretical work are highly desirable. The improvement of operational models in the tropics passes both through theories and intuitions gained from the effective analysis of the observational records. There is an immediate need for new developments in the theoretical and modeling aspects of tropical meteorology. The workshop has focued on the following topics:

- Vertical structure and self-similarity of large scale tropical convective systems
- Effects of the MJO on monsoon dynamics and rainfall
- MJO initiation and tropical extra-tropical teleconnections
- Atmosphere-Ocean coupling and the MJO
- Climate predictability and data assimilation in the tropics.

Workshop Sessions and Discussions

Day 1, Morning: Tropical convection, Synergy between theory and observations

The meeting was opened by a presentation by Mitch Moncrieff of NCAR on convective organization and intersection of weather and climate. Moncrieff argued for the multiscale representation of convection in climate and weather forecast models. He demonstrated that the intersection between weather and climate spans a wide range of time scales involving processes such as the diurnal and the seasonal cycles of solar heating. The diurnal cycle forces mesoscale convective systems that in turn influence synoptic and planetary scale waves such as the Madden Julian oscillation while the seasonal cycle which triggers monsoons has a direct impact on synoptic scale convectively coupled waves and the MJO. The known two-way interactions between the synoptic and planetary scale waves and mesoscale convective systems are well represented in neither weather-forecast nor climate models. According to Moncrieff, mesoscale systems are absent in present climate models but they are well represented in cloud resolving modeling (CRM) and, to some extent, numerical weather prediction (NWP) models. He argued for the representation of the upscale energy transport by organized convection as well as for the control of convection by the large scales. Through various examples of numerically simulated mesoscale convective systems, he showed as an example how the large-scale shear can influence the organization of convection at such scales. He argued against the old paradigm of convection being interpreted as one small scale isolated phenomenon and for a multi-type convection phenomena occurring on wide spectrum of scales that interact with each other.

Sam Stechmann of U. of Wisconsin followed by a talk on multiscale theories and models for the MJO. He introduced the concept of multiscale cloud which refers to clusters and superclusters of cloudy cells that are observed to propagate in the tropics and are responsible for the largest portion of rainfall in the tropics. Starting with the more general theory of equatorial wave dynamics, he introduced a new theoretical model for the MJO as an oscillatory and neutrally stable mode that is best represented by the interaction between the planetary scale low-level moisture and precipitation. Because of its neutral stability, it is called the MJO skeleton. The MJO mode is sustained by synoptic and meso-scale convective systems that provide the necessary upscale transport of energy, reminiscent of the multi-type convection paradigm seen in Moncrieff's talk.

Katherine Staub from Susquehanna University then reported on the outstanding notion of MJO initiation. She begin by asking some fundamental questions as why the MJO is often initiated in the Indian Ocean and how MJO events can be identified accurately in observational data. For the latter, two main tools exist, namely, the space-time filtering introduced by Wheeler and Kiladis and real-time multivariate MJO (RMM) index of Wheeler and Hendon. She gave some pros and cons for both methods. She argued that RMM is dominated by wind anomalies and ORL (which is a surrogate of precipitation) doesn't seem to contribute. As such it may lead to false alerts as she demonstrated through various examples. She concludes that since MJO is primary driven by convection this latter issue should be always taken into account when making MJO diagnostics.

Panel Discussion #1: The upcoming CINDY/DYNAMO field program.

The panel consisting of Zhang (chair), Johnson, Jakob, Schumacker, and Stechmann were asked the following question. How can theory help set up observation goals and how can observation best help feedback to the theory?

Johnson: Should target the diurnal cycle. Hovmuller diagrams of the MJO already demonstrated the influence of diurnal cycle variability of convection. This is indeed consistent with Moncrieff's earlier talk.

Schumacher: Need radars with different wavelengths to measure various cloud types (precipitating and non-precipitating) and polarimetry (or dual polarization) to get cloud microphysics measurements.

Jakob: Convective parametrization problem should be addressed. New observations are needed to build new stochastic paramtrizations.

Stechmann: How background state affects CCWs and mesoscale CS's needs to be addressed. Theories exist but observations are very diffuse when it comes to this matter. Moisture convergence and shear are both important for the selection of cloud types.

The audience more or less agreed that congestus cloud preconditions the environment for deep convection and stratiform clouds are a follow up of deep convection. But the fundamental question about what triggers congestus clouds still remained.

It has been suggested that traditional statistical data analysis could not address this questions. Majda warned about the use of EOF's that can be very misleading. It was then agreed that DYNAMO could address key dynamical triggers that EOF's maybe missing. Jakob then added that existing reanalysis products are bad for wind convergence, especially, for vertical structure of the divergence field. It was mentioned that according to some work done by Rossow and co-workers, the MJO is basically present at all time in terms of the moisture field but the question as when it intensifies and precipitates remains This is in some sense consistent with the neutrally stable (moisture-precipitation) mode presented by Stechmann.

It was argued that moisture tendency is mostly controlled by vertical advection while congestus detrainment plays a secondary role. Can new observations be used to address this issue?

Day 1, Afternoon:

The afternoon of Day 1 started by two 15-minute talks by Courtney Schumacher (Texas A&M) and Christian Jakob (Monash, Australia). Jacob reported on the convection parameterization problem and on how new observations could help design or calibre existing stochastic multicloud parametrization. It was suggested that existing notion of cloud regimes observed at various scales could be used as guidelines. There should be a distinction between small and large scale parametrization. What variable should be measured for the design of future stochastic parameterizations? Does large vertical velocity control the mean and standard deviation of the stochastic convection or rather their ratio does? Is convection a Poisson process as it was suggested previously? Schumacher's talk was on stratiform rain formation and co-existence of various cloud types. She noticed however some geographical variations in the intensity of the various types of convection. Congestus heating is very weak over land and over the Atlantic Ocean it is very shallow. Stratiform rain is higher over the ocean than over land. Using a TWP-ICE radar network, she demonstrated the existence of three regimes of convection: Strong convection, suppressed convection, and easterly convection.

This was then followed by two 15-minute talks by George Kiladis and Juliana Dias of NOAA. Kiladis lectured on principal modes of tropical variability and Juliana Dias exposed a new method for identifying convectively coupled waves. Kiladis showed through a judicious use of EOF analysis the spectrum of tropical waves, which can effectively capture the continium nature of the MRG and n=0 EIG branch near k=0, where eastward and westward moving MRG waves are divided. He showed examples of MRG waves that are meridionally tilted, which first move westward then progressively northward. Dias started by relating some problems with traditional Hovemuller diagrams of Tb, for example, in capturing spectrally filtered Kelvin waves. Instead, she suggests using contiguous cloudy regions (CCRs, which are traditionally used for mesoscale systems) in order to capture well the tails of the distribution. She used Radon transformation to separate zonally propagating CCRs whose peaks are associated with propagating waves.

Open Discussion #1: MJO initiation versus MJO intensification

The main driving question is weather initiation of convection, on a large enough scale (in the Dynamo experiment for example), implies the initiation of an MJO event? Perhaps, it is necessary but not sufficient. Also what mechanisms allow such triggering of large scale convection in first place?

Possibilities:

1. Dry MJO mode: Is there an extra-tropical mode that excites and intensifies a moisture mode (as in the Majda-Stechmann skeleton MJO model).
2. Stochastic initiation.
3. Successive versus primary MJO events. It is argued that some MJO events are triggered by the remains of previous MJO events while sometimes MJO seem to start independently of others.
4. Formation of wave packets of mesoscale systems favoured by a sheared environment or by the succession of cold pools.
5. Persistence of dry pre-onset region, which in some sense related to the existence of a moisture mode, mentioned earlier in the day.

Day 2, Morning: Models

The second day was dedicated to models and modeling issues related to the general circulation and clouds. The morning session consisted of three 30-minute talks delivered by Dargan Frierson (U. Washington), David Randall (U. Colorado), and Philip Austin (U. British Columbia).

Frierson is interested in the use of idealized climate models to study specific climatic processes. He described the northward shifting of the ITCZ (the region of intensive convection in the tropical belt) due to global warming and the compensating effect of cooling by aerosols. He suggested that the ITCZ shifting is due to the balanced structure of the forcing by solar heating and longwave cooling. Frierson noted that humans actually contribute to both effects through namely the release to the atmosphere of greenhouse gases and aerosols, respectively. He suggested that the likely shifting of the ITCZ would cause a dramatic change in the climate system. He pointed out that the very complex-traditional climate models as opposed to his simplified model (which is carefully tuned to the problem) fail to capture accurately the ITCZ. So such change in our climate would not be predicted accurately by current operational GCMs.

David Randall's talk was on "qualifying the limits of convection parameterization''. He started by saying that the main issue with the conventional cumulus parameterization is the lack of scale separation between the convective scales and the large scale circulation that we aim to represent by these models. He argued that with current climate models, higher resolution doesn't necessarily mean better forecast because the sample size (of clouds) becomes smaller and the quasi-equilibrium assumption breaks down. Instead, one should consider non-equilibrium or stochastic closure assumptions. He then demonstrated through direct numerical simulations using a 256x256 km domain that the lag between the forcing and precipitation response depends on the period of the forcing and the standard deviation depends on the domain size and argued that these are good metric for stochastic parameterization of convection though he questioned whether such a stochastic behaviour can be also seen in observation. He concluded by suggesting that super-parameterization (clouds are represented by numerical model that is run in parallel within each grid-cell of the GCM) is some kind of stochastic parameterization after all, which in some sense explains its own success.

Austin described a new methodology for statistical analysis of large-eddy simulation of shallow cumulus clouds. He motivated his study by the uncertainties in entrainment and detrainment of the mass flux in GCMs. His algorithmic approach tracks cloudy parcels as they ascend and descend and uses various interpolation techniques to measure mixing of dynamics and thermodynamics quantities. He demonstrated the methodology for two case studies of shallow cumulus over land (ARM) and over the ocean (BOMEX). His findings suggested that cloud area controls future properties of the parcels and provides core protection, cloud entrainment is proportional to area and is controlled by large eddies while detrainment is driven by mixing of dry air.

Panel discussion #2: Climate Models

The models panel consisted of 4 panellists (Austin, Frierson, Kiladis, and Randall) and a chair (Khouider). First the following issues were identified to be important:

-New generation of climate models highly advanced in terms of scientific computing;

- Tendency for unified frameworks: Seamless modeling, etc.
- Super-parameterization v.s. global CRMs and the future of coarse resolution GCMs.
- Convection parametrization problem is still open.
- How to use observations in the parameterization process?
- Phenomenological/process driven models.
- Quantitative validation of statistical features.
- Data driven parameterizations. Is it possible to gather enough data from obs? What kind of data should one use? What data are available and waht data are good enough? Could numerical simulations help? What is the equivalent of DNS in the climate community? LES? What are the key issues/processes that can be quantified by such models?
- Convection parameterization v.s. organized convection parametrization: The multicloud/self-similarity paradigm.
- Representation of mesoscale systems.
- Stratiform anvils and associated downdrafts.
- Congestus clouds: what role do they play? How are they different from deep clouds? Are they represented in current GCMs? Are they parametrizable? (Are they functions of the large scale variable/variables?) Is moisture convergence the cause or the effect? Is there a connection with the 0_oC layer?
- Role of shallow cumulus? Do we understand its associated turbulence?
- Stochastic models
- Uncorrelated random noise v.s. multi-scale correlated (both in time and space) Markov chain type models.
- What calls for stochastic modelling? Grid resolution v.s. separation/non-separation of scales? Nature of the problem?
- What kind of processes is intrinsically stochastic? Turbulent entrainment v.s. triggering? Conceived as add-ons to preexisting (deterministic) parametrizations. Can we do better?
- How about stochastic super-parametrization?
- If the future is for global CRMs and superparameterization: Aren't we to some extent shifting the problem to smaller scales ... to cloud microphysics? (Another buzzword). More so for LES. Are the interactions between cloud physics and small scale eddies understood? How complex is this problem? Can stochastic models help at such small scales?

The panel noted that current GCMs do not capture well the vertical structure of C.C.Ws. Kiladis showed some slides relating of some of his earlier work where various models were compared against observation that confirmed this statement. It then argued that simple models that take into account the morphology of tropical clouds capture well the vertical structure and Khouider gave a brief explanation on the board of the Khouider-Majda multicloud model. It is also noted that there are more complex models that capture the vertical structure such as the Lagragian-Overturning Model of Haertel (presented later in the afternoon).

Day 2, Afternoon:

The Tuesday afternoon session started with five 15-minute talks by Khairtoudinov (CUNY), G. Zhang (SCRIPT), Y. Frenkel (NYU), M. Waite (Waterloo), and W. Boos (Yale).

Haertel presented a new global circulation model based on the Lagrangian tracking of fluid parcels. The fluid parcels are advected by the ambient velocity and allowed to switch vertical position whenever there is an instability. The method which is originally designed for the ocean circulation and is called a Lagrangian overturning model. Despite the crudeness of the model, which uses a limited number of parcels (of a 500 km) to represent the whole atmosphere, it captures well some surrogate of the Madden Julian Oscillation with many realistic features.

Khairtoudinov gave a lecture on his new results using the multiscale modeling framework (MMF) model. He used both 2d and 3d simulations to address the issue of the transition from shallow to deep convection. He first recalled that the super-parametrization framework already demonstrated a huge success by being the first model to simulate a realistic MJO and when the model (SPCAM) is coupled to the ocean it produced the full sprectrum of convectively coupled waves. He then looked at the sensitivity of MJO simulations to external and internal factors. He demonstrated that moisture is key and when stratiform heating is shut off the MJO becomes a Kelvin wave. A key question remains unanswered however. Why is ocean coupling so important for the full spectrum of convective coupled waves?

Zhang's talk was on "convection parameterization and tropical climate''. His main contribution is to address differences between ealrier so-called CAPE closure parameterizations and recent CAPE-tendency parameterization. He demonstrated that the new closure improves the Hadley and Walker circulations. Zhang noted that some other feature are also improved with the CAPE tendency closure such as the atmospheric response to ENSO and the MJO in terms of Hovmuller diagram representation. Curiously, when the shallow convection is turned off the MJO disappears in the model.

Frenkel discussed some numerical simulations using the stochastic multicoud model of Khouider et al. as a paradigm example to improve the variability of organized tropical convection. He showed that the "stochasticization" of convection in the model not only improves the variability of the waves but it also improves their physical and dynamical structure. Intriguingly, he showed an example of simulation results that looked impressively similar to those shown by detailed cloud resolving simulations (which is thousands if not millions of times more expansive in terms of computational complexity) obtained by Grabowski and co-worker with the same episodic bursts of convective events.

M. Waite presented CRM simulations of the transition from shallow to deep convection through moistening by congestus detrainment. He showed that prior to the transition to deep convection congestus clouds from sporadically and detrain in the middle troposphere depositing a substantial among of moisture that help precondition the environment for deep convection. It is demonstrated through various sensitivity tests that three dimensional turbulent mixing of moisture plays a major role in delaying the transition to deep convection and in moistening the environment through congestus detrainment. It is also established that while temperature mixing is also important it plays a secondary role.

Boos's talk was about the investigation of the monsoon variability through an axisymmetric modeling framework. His framework is based on a model Hadley circulation using the one baroclinic mode-QTCM model. He conjectured that a second baroclinic mode is not necessary for monsoon dynamics unlike convectively coupled waves.

Open discussion session #2: Super-parameterization and MJO super-rotation.

The discussion was led by Majda who described his recent work in Xing et al. 2009 where they showed the success of super-parameterization strategies, in two different shear regimes: A strong shear that allows organized convection and a weak shear where chaotic convection persists. They particularly demonstrated the feasibility of sparse space-time super-parameterization. The discussed that reported on how a hierarchy of models could be put in synergy and help understand better various aspects of the climate modeling problem, including global CRMs, super-parameterization GCMs, Coarse resolution GCMs, idealized GCMs, and analytical/asymptotic models.]

The discussion then followed on the MJO super-rotation, which has been noticed in various idealized simulations and demonstrated in asymptotic models. It has been asked whether global warming will lead to stronger MJO and thus to supper-rotating, i.e, equatorial westerly, mean wind. At the present times the mean wind in the tropics is very weak and is mainly easterly. Various research directions to address this issue have been suggested regarding the MJO: change in frequency of the propagation signal, sensitivity to seasonal variability, and evidence of super-rotation in observations.

Day 3: Data assimilation and predictability.

There were three talks in this session: M. Wheeler (Australian Weather Bureau), W. W. Tung (Perdue), and J. Harlim (NC State). Wheeler reported on the "MJO prediction for improving weather forecast skill" over Australia. Using the RRM index in a T47 ocean-coupled model, he showed that compared to a statistical benchmark model, the numerical model that is conditioned to the MJO phases had a better skill overall and the skill of the ensemble mean is better than the mean skill of each individual member. She particularly demonstrated the sensitivity of the skill to the initial MJO phase. He also showed that strong MJO's resulted in better forecast-skill than weak MJO cases.

Tung's talk was on "intrinsic predictability of the MJO''. The main issue she was interested in is how to separate chaotic dynamics from observational noise. She started by recalling that in current state-of-the-art, the MJO predictability doesn't exceed 30 days. She then presented and adaptive "denoising" algorithm based on spline interpolation. She used the Lorenz 63 model with an artificial noise added as an example to illustrate her methodology. She then applied it to the case of the MJO index EOF 1. The chaotic dynamics were captured by the adaptive denoising algorithm and the MJO skill was improved to 50 days.

Harlim presented some “applied math tools for tropical data assimilation’’. He started by giving a short tutorial on the theory of data assimilation. The main difficulty in the tropical weather prediction problem, according to Harlim, is due to the lack of scale separation and balanced dynamics for the large scales. He was interested in the general problem of model error quantification in complex dynamical systems for which is he presented an “online model error estimation strategy”. His strategy is based on a “mock’’ dynamical equation for parameter “evolution’’ consisting of a stochastic differential equation. He tested his model in a two-layer QG model (Smith et al.) in two distinct regimes: open jet and blocked circulations.

Panel discussion #3: Predictability and data assimilation for the tropics

Panellists: Tung, Wheeler, Harlim, Chair: Majda.
The hardcore problem that’s been largely discussed is the design of radical strategies for stiff-turbulent systems. There was also discussion about the use of a benchmark model for various climate models. The Canadian climate model (CCCma) in particular has been identified as one with a large ensemble spread, which is apparently a good thing for data assimilation.

Day 4, Morning: Theory

The Thursday morning session started with a series of short talks by J. Biello (UC Davis), J. Frederikson (CSIRO, Australia), L. Smith (U Wisconsin), and W. Shubert (Colorado State). Biello presented a multiscale asymptotic model for the “meso/planetary scale interactions through gravity waves in the deep tropics’’. His model is based on the Majda-Klein IPESD theory and on the new findings by Dolaptchiv of a planetary scale pressure balance. He is interested in the modulation of the ITCZ convection by planetary scale gravity waves and to develop a tropical wave theory with matching condition to mid-latitudes. He started by deriving the MEWTG equations and then showed some numerical simulation using the asymptotic model of large –scale gravity waves that tend to homogenize the zonal wind.

Frederikson’s talk was about “extra-tropical initiation of the MJO”. He started with the barotropic-baroclinic vorticity equations and the thermodynamic equations in a mean shear and mean potential temperature basic state. The tropical-extratropical model exhibits wave solutions consistent of all the classical equatorially trapped wave-modes and an “MJO’’ mode but no WIG waves. Stronger basic states seem to lead to a stronger MJO mode and extra-tropical disturbances result in an MJO mode response but no Kelvin wave response. Consistently, the MJO mode has a significant barotropic component. He suggested that the MJO mode is related to the classical barotropic-baroclinic instability, which seems to move to the tropics and reduces the moist static stability.

Smith presented a 3D Bousinesq model for the hurricane embryo. To emphasize the role of hot towers in cyclogenesis, she considered a Boussinesq fluid with a small Froude number with a condensational heating. The gaol is to compare numerical simulation of the full Bousinesq system that support gravity waves with a simplified model obtained earlier by Majda et al. She also studied the sensitivity of the hot tower to the low-level shear.

Shubert's talk was on the derivation of new long wave approximations that does not distort the Rossby waves. His strategy consists of rewriting the linearized equatorial beta-plane primitive equations in Riemann invariants and then partitioning the solution into a Kelvin and a non-Kelvin parts. He then introduced a new functional that he called the Ripa-Moura potential for the non-Kelvin part which satisfies a certain master equation. A new long-wave model was then obtained by neglecting second order derivative terms in the Ripa-Moura potential. The new model filter out the inertio-gravity waves just like the classical long-wave equations but they retain an accurate Rossby spectrum.

Panel Discussion #4: Theory

The panel on theory consisted of three panellists (Moncrieff, Frederiksen, Biello) and a chair (Majda). Frederikson commented on the possibility that extra-tropical modes such as the PNA and AO may play some major role in the extra-tropical initiation of the MJO. Smith explained the importance of parallel v.s. perpendicular shear in the transport of momentum from convective to larger scales. She also commented on the possible role of gravity waves in dynamics of hot towers, so important for the hurricane embryo. According to Moncrieff, some aquaplanet inter-comparison studies are necessary in order to understand how climate person (??) with respect to some specific physical mechanisms. He also pointed out that there are some studies done for the case of momentum transport in parallel shears.

Thursday Afternoon:

There were three talks by R. Johnson (Colorado), S. Sessions (New Mexico), and S. Tulich (NOAA). Jonhson's talk was on various aspects of observed MJO events. He pointed out over the Indian Ocean the role of atmospheric humidity is key and should be addressed by the DYNAMO program. He suggested that an SST--surface wind map should be very informative as air generally flows from cold to warm water. In YOTC MJO, however, he noticed an eastward extension of the MJO. He also noted that the mixed layer variability may play a role in MJO dynamics. The stratiform/deep convection ratio seems to be another important variable; MISMO reported 26-27% of stratiform rain while it is a bout 40% in TOGA CORE. Sometimes stratiform rain doesn't lag deep convection (in MISMO). However, a major issue is that the MISMO result is mostly a reanalysis product and some of these discrepancies maybe an artifect of the underlying models.

This session was interested in incorporating some observational data into WTG simulations of tropical convection while Tulich reported on convectively coupled gravity waves and their interaction with the diurnal cycle. Later in the day there was an informal discussion on satellite observations. There is huge flux of data arriving from the sky and people are wondering what is the best way to extract the maximum out of it. The data mining problem has arrived.

A concluding discussion was held on Friday morning. The following points were mentioned as additional points to what were covered earlier in the workshop.

1. Mechanisms for initiation of deep convection. Importance of low-level moisture as a

necessary condition for deep convection under normal conditions. Low-level moistening by detrainment is not sufficient. Low-level heating maybe key but need to be addressed by observations.

2. Concept of gross-moist static stability: there is no observation evidence for it.
3. Modeling studies to address scale interaction issue. Wave and convection interaction.
4. Convective momentum transport.
5. Extra-tropical influence although somehow covered in the MJO initiation.
6. Surface evaporation.
7. Cloud radiation.