TROPICAL MULTISCALE CONVECTIVE SYSTEMS

Theory, Modeling, and Observations

BY BOUALEM KHOUIDER, ADAM H. MONAHAN, NORMAN MCFARLANE, JOHN SCINOCCA, AND KNUT VON SALZEN

A fundamental advance in the field of tropical meteorology was the discovery by Madden and Julian (1972) that the dominant component of intraseasonal variability in the tropics is a 40–50-day oscillation of enhanced and suppressed rainfall, now known as the Madden–Julian oscillation (MJO). Nakazawa (1988) suggested that these tropical intraseasonal oscillations are actually space–time envelopes of multiple organized clusters and superclusters of convective clouds occurring on shorter scales than the longwave oscillation. While the MJO envelope propagates eastward, the embedded clusters and superclusters move at faster speeds in both directions. Recent studies (e.g., Wheeler and Kiladis 1999), using outgoing longwave radiation (OLR) spectrum power to produce empirical estimates of the frequency–wavenumber structure of propagating features, have identified these clusters and superclusters as the moist equivalents of linear shallow-water equatorially trapped waves, whereas the MJO signal appears on the bottom of the empirical dispersion diagram, separate from the dispersion relation curves of the linear waves. Organized convection and convectively coupled waves in the tropics have a significant impact on midlatitude weather and climate through atmospheric and oceanic teleconnection patterns (e.g., Zhang 2005). While a broad range of mechanisms has been proposed to explain the MJO, it is typically only poorly represented in contemporary general circulation models (GCMs), apparently due to the inadequate treatment across multiple spatial scales of the interaction of the associated hierarchy of organized structures.

TROPICAL MULTISCALE CONVECTIVE SYSTEMS: THEORY, MODELING, AND OBSERVATIONS

WHAT: Graduate students, postdoctoral fellows, and senior researchers from universities and operational climate modeling centers met to discuss multiscale convective systems in the tropics.
WHEN: 30 July–3 August 2007
WHERE: Victoria, British Columbia, Canada

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To address this important topic, a 5-day meeting[1] was held at the University of Victoria in British Columbia, Canada, which brought together 25 graduate students and postdoctoral fellows from across North America with senior observationalists, theorists, and climate modelers in applied math, physics, or meteorology from Canadian and American universities and operational modeling centers for discussion. To emphasize the multiscale nature of the problem, lecture topics from the 3-day short course and 2-day workshop ranged from cloud microphysics through convective organization to global-scale dynamics. (The lecture notes and the abstract volume are available to download at www.pims.math.ca/science/2007/07sstmcs/index.html.)

SHORT-COURSE PRESENTATIONS. At the start of the first day, Andrew Majda from the Courant Institute (New York University) spoke on the theory of equatorially trapped waves, starting with a discussion of the importance and complexity of tropical meteorology. Drawing on chapter 9 of Majda (2003), he derived from the linear hydrostatic primitive equations the spectrum of equatorial waves with different equivalent depths, corresponding to the different baroclinic modes, thus connecting the standard shallow-water wave theory of Matsuno (1966) with the full 3D equations. Particular emphasis was placed on the role of the first two baroclinic waves in the explanation of dynamical features of convectively coupled waves, following from the trimodal nature of tropical convection (involving deep convective, stratiform, and congestus clouds).

Philip Austin from the University of British Columbia gave the second lecture, an overview of dynamic and thermodynamic aspects of atmospheric convection in the tropics. Austin began by showing observational evidence of the impact of convection on local- and large-scale circulations in the tropics, and he discussed characteristic features of tropical clouds (e.g., morphology, location, and radiative impact). In his subsequent detailed description of moist thermodynamics, he explained that the role of convection is to release the vertical instability through redistribution of heat and moisture into the large scales but that many of the associated (mixing) processes are very complex and remain poorly understood.

In the afternoon, George Kiladis from the National Oceanic and Atmospheric Administration (NOAA) gave an overview of observations of convectively coupled waves starting from the power spectra of Wheeler and Kiladis (1999). Satellite data were used to illustrate organized convective clusters and superclusters, including the MJO. He emphasized the fact that the MJO can be an envelope of either higher-frequency, westward-moving cloud clusters (2-day waves) or eastward-moving superclusters (Kelvin waves), or both. Kiladis then illustrated the spatial structure of the waves, linking them with the linear theory and demonstrating that most of these waves present a self-similar structure in the zonal/vertical plane that is characterized by a progressive deepening of shallow convection into deep convection with a trailing stratiform wake, resulting in a front-to-rear vertical tilt of the velocity, temperature, moisture, and heating fields.

At the end of the day, John Scinocca from the Canadian Centre for Climate Modelling and Analysis (CCCma) presented an introduction to GCMs. Scinocca began his lecture with a historical survey of GCMs and numerical weather forecasting, starting with Richardson and Charney. He then discussed in detail today's state-of-the-art general circulation modeling, emphasizing that only planetary- and synoptic-scale disturbances are explicitly represented in contemporary GCMs. These models are subject to considerable uncertainties because of the need to parameterize many important physical processes, including convection and cloud physics. He also explored many numerical issues, such as the danger of using spectral methods to advect nonsmooth fields (e.g., with sharp corners), and the possible errors induced by the averaging on the GCM grid of nonsmooth processes like large-scale/stratiform precipitation.

The second day of the school began with a lecture by Norm McFarlane from CCCma on the complex subject of convective parameterizations, covering both mass flux–and adjustment-based schemes. McFarlane presented an overview of the widely used Zhang–McFarlane scheme, using the fundamental conservation laws of mass and momentum to carefully illustrate some of the steps and approximations involved (many of which remain poorly understood). For instance, equations for the updrafts and downdrafts were contained in a convective plume-based model, depending on cloud entrainment and detrainment rates and base mass fluxes, which remain the major uncertainties in mass flux schemes. He then gave a general survey of the different alternative schemes used in contemporary GCMs, such as buoyancy sorting and adjustment schemes; according

[1] Consisting of a 3-day summer school followed by a 2-day workshop, the meeting was sponsored by the Pacific Institute for the Mathematical Sciences (PIMS) as the first event in a 3-yr period of concentration on "Multiscale processes in the tropics."

to McFarlane, the performance of neither scheme is obviously superior.

Wojtek Grabowski from the National Center for Atmospheric Research (NCAR) introduced the exciting topic of the cloud-resolving modeling (CRM), which is becoming very popular as computational power increases. Many research groups around the world are working on global cloud-resolving and superparameterization models as alternatives to represent organized convective features. Even CRMs with grids of 1–3 km do not actually resolve cloud processes but rather are directed to organize cloud systems. The parameterization problem is simply shifted to smaller scales, with the cloud microphysical processes, turbulent mixing, and atmospheric chemistry still being parameterized. After giving a short survey of the current state-of-the-art models, Grabowski concluded that the physics of these microscale processes remain among the most challenging problems (and active research areas) in the atmospheric sciences.

In the afternoon of the second day, Mitchell Moncrieff from NCAR gave a lecture on organized mesoscale convection, making the analogy between organized convective systems and coherent structures in a turbulent flow (both involving upscale transport). He emphasized the fact that single column-based convective parameterizations currently in use in GCMs are inadequate for meso-organized convection. He pointed out how the explicit representation of cloud systems in CRMs captures the important features of organized convection, and he demonstrated that meso-organized convection involves some multibranched flows resulting from an upscale transport of momentum and associated with downdraft cooling in the wake of deep convection. He proposed a conceptual model with regimes based on a Richardson-like nondimensional number supporting prototype multibranched flow configurations, and he noted that the implementation of these concepts in global models is the subject of ongoing research.

Knut von Salzen from CCCma covered in detail the subject of cloud microphysics, following up on Grabowski's lecture on CRMs. In his lecture, von Salzen emphasized the role of aerosols for the formation of cloud droplets, presenting observations to illustrate effects of aerosol/cloud interactions on climate, including interactions of microphysical and cloud dynamical processes, which remain in general poorly understood. These are just some of the exciting opportunities for future research regarding the role of clouds for climate.

On the morning of the third day, Cecile Penland from NOAA then discussed "The multiple scales of El Niño." Starting with an overview of ENSO phenomenology, she developed a theory of ENSO prediction based on the theory of linear inverse modeling. By using a linear stochastic differential equation as a model for tropical SSTs, the spatial patterns of initial conditions that develop into mature ENSO episodes can be computed and incorporated into operational forecast systems. Calculations that include the extratropical North Pacific lead to the Pacific decadal oscillation (PDO) structure on seasonal time scales, suggesting a low-frequency manifestation of ENSO.

Finally, Boualem Khouider from the University of Victoria discussed waves and instabilities in idealized model convective parameterizations, with the aim of assessing some different parameterization closures currently in use. He showed that a moisture convergence closure leads to a catastrophic instability of a standing gravity wave with growth rates increasing with the wavenumber, while an adjustment scheme leads to propagating but stable waves, unless wind-induced surface heat exchange (WISHE) is added. Using models based on two vertical modes instead, a stratiform instability can be generated. Better yet, Khouider suggested using models with three cloud types, including cumulus congestus, where convective instability arises from middle-tropospheric moistening and low-level moisture convergence, consistent with observations.

THE WORKSHOP. The 2-day workshop following the short course involved 20 half-hour presentations of new research by meeting participants. The scope of material was broader than that of the short course, reflecting the meeting participants' diverse backgrounds. The subjects of these presentations can be broken down into three broad categories.

Cloud physics. The upscale effects of organized convection were considered by Mitch Moncrieff—in particular, the parameterization of vertical momentum transport. He advocated a "predictor–corrector" parameterization scheme for convective momentum and heat flux tendencies for mesoscale simulations in which the organized convection is coarsely resolved. Expanding on his previous lecture, Wojtek Grabowski considered the implementation of superparameterization and global CRM as alternatives to the explicit representation of cloud systems, for synoptic- and large-scale organization of convection, to capture adequately and get a better understanding of the mutual interactions between convective cells and the large-scale circulation. He briefly described some of his recent large-scale CRM and superparameterization results and hinted at some nontrivial dynamical interactions involved in organized convective systems, which are not adequately represented in cumulus parameterizations. These range from the formation of squall lines in a sheared environment to the importance of convective momentum transport in the MJO dynamics.

Jahanshah Davoudi (University of Toronto) used cloud-resolving simulations to investigate the height dependence of the probability distribution of convective mass fluxes. These simulations demonstrated characteristic structures of this distribution from which stochastic subgrid-scale parameterizations could, in principle, be developed and assessed. Large-eddy simulations used by Phil Austin to critically assess the realism of the entraining plume model for trade cumulus clouds demonstrated that such models perform better than might be expected from first principles. Norm McFarlane addressed the role of buoyancy sorting in a new formulation of lateral entrainment and detrainment in a parameterization of shallow cumulus clouds. This new parameterization was shown to be consistent with recent large-eddy simulations of such clouds.

The size spectrum of cloud droplets is an important determinant of the interaction stratiform clouds have with incoming shortwave radiation, and these size spectra are strongly affected by aerosol distributions. New parameterizations of cloud-droplet formation were presented by Yiran Peng and Xioyan Ma (Canadian Centre for Climate Modelling and Analysis). In particular, the total indirect forcing of sea salt aerosols was demonstrated to be amplified if climate feedbacks are accounted for. The relationship between large-scale circulations and the distribution of subtropical marine stratocumulus clouds (MSC) was addressed by Yanping He (University of Victoria). A newly developed scheme, in which local cloud cover is determined explicitly, was shown to produce an improved simulation of the seasonal and interannual variability of subtropical MSC.

Large-scale dynamics. George Kiladis discussed new observations of the mesoscale organization of equatorial waves, showing evidence of the dominance of westward-propagating mesoscale features greater than can be explained by simple advection. These mesoscale features are associated with westward-propagating gravity waves and display pronounced diurnal and semidiurnal cycles. Cecile Penland presented evidence of the influence of boreal autumnal SST in the south tropical Atlantic on the American Midwest precipitation three seasons later, as modulated by extratropical forcing of ENSO—a potential improvement for seasonal forecasting in the continental United States.

Convective parameterizations incorporating the characteristic three-cloud structure of organized convective systems were considered by Boualem Khouider and Samuel Stechmann (Courant Institute, New York University). These parameterizations are very successful in reproducing many qualitative features of the observed structure of synoptic-scale convectively coupled waves. Using rescaling arguments, the instability is extended toward the mesoscale, showing a potential application of these models to squall lines. Andrew Majda discussed a hierarchy of models obtained from systematic multiscale asymptotics appropriate for the study of interactions across multiple time and spatial scales in organized convective systems. A new systematic strategy for superparameterization was presented that exploits self-similarity properties of organized convective systems. MJO analog waves with realistic phase speeds and high-frequency variability are shown to persist when such ideas were implemented into the multicloud models. William Boos [Massachusetts Institute of Technology (MIT)] presented observational characterization of the rapid seasonal intensification of the Somali jet, which is much greater than that expected as a direct linear response to seasonal forcing. An idealized mechanistic model demonstrates the importance of WISHE feedback in producing this rapid intensification.

Tiffany Shaw (University of Toronto) addressed the importance of ensuring that subgrid-scale parameterizations respect fundamental conservation laws. As a result of wave dynamics, many conservation laws are nonlocal. She presented strategies to implement conservative parameterizations through the development of wave-activity conservation laws appropriate for mesoscale dynamics. Thomas Birner (University of Toronto) addressed the heat budget of the tropical tropopause layer, providing evidence that cooling in this region can arise as a remote response to lower- through midtropospheric convective heating, mediated by convectively coupled waves.

Internal waves, gravity currents, and instabilities. Bruce Sutherland (University of Alberta) demonstrated that internal waves of even moderate amplitudes generate mean flows analogous to Stokes drift. These nonlinear effects influence wave propagation as well as the process of tunneling. Sabine Decamp (University of

Alberta) presented laboratory simulations of internal waves generated from density currents and collapsing density fronts, allowing estimates to be made of the role of internal waves in energy transport. A theory for the dynamics of a plume incident on the interface of a two-layer stratified fluid was presented by Joseph Ansong (University of Alberta). This theory characterizes distinct regimes and predicts scaling relations for the subsequent radial propagation of currents that agree well with laboratory observations. While increased stratification is typically thought to increase stability of a flow, Michael Waite (NCAR) discussed the zigzag instabilities that occur in strongly stratified flow. He showed that a transition to turbulence is associated with gravitational overturning.

OUTCOME. The accurate simulation of atmospheric convective processes remains one of the most challenging problems of dynamical meteorology. The coupling of dynamics and thermodynamics across multiple spatial scales motivates the development of new observational, diagnostic, modeling, and theoretical techniques. The material presented at this meeting represents a snapshot of the current state-of-the-art modeling multiscale convective processes. While much has been accomplished, much more remains to be done.

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