Collaborative research at the intersection of weather and climate

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Introduction

Fundamental barriers to advancing weather and climate diagnosis and prediction on time-scales from days to years are partly attributable to gaps in knowledge and the limited capability of contemporary operational and research numerical prediction systems to represent precipitating convection and its multi-scale organization, particularly in the tropics. In this regard improvements in convective parameterization have not kept pace with improvements in knowledge gained from process studies of convective organization. As convective organization is not represented by contemporary parameterizations, the large-scale effects of convective organization have, therefore, yet to be properly assessed. Examples of tropical phenomena in which the multi-scale organization of convection is a key process are:

- The Madden-Julian Oscillation (MJO; Madden and Julian, 1972; Figure 1) and other types of convectively coupled disturbances involving Kelvin waves and Rossby-gravity waves;
- High-impact weather events, such as tropical cyclones;
- Easterly-wave disturbances within the Inter-Tropical Convergence Zone (ITCZ).

Common to these examples is the multiplicity of interacting scales associated with precipitating systems and the accompanying distinctive three-dimensional transports of mass, momentum and energy. The ubiquity of organized phenomena underscores the necessity for representing dynamical coherence, upscale evolution, and regime-dependent transport in global models, since these aspects are not captured by contemporary parameterizations.

The effects of phase changes of water within organized convective systems are manifested on various temporal scales: from convective turnover and diurnal time-scales (hours to a day), to the time-scale of meso-convective organization (~days), to the residence time of water in the atmosphere (~2 weeks). Thus, the behaviour and effect of phase changes of water and their association with convective organization is a fundamental research challenge affecting weather and also longer-

Weather and climate research at WMO

THe Observing System Research and Predictability Experiment (THORPEX) is a part of the WMO World Weather Research Programme (WWRP). It was established by Fourteenth World Meteorological Congress (2003) as a 10-year international global atmospheric research and development programme under the auspices of the WMO Commission for Atmospheric Sciences (CAS). The aim of THORPEX is to accelerate improvements in the accuracy of one-day to two-week high-impact weather forecasts for the benefit of society, economy and the environment.

The World Climate Research Programme is co-sponsored by WMO, the Intergovernmental Oceanographic Commission of UNESCO and the International Council for Science. WCRP identifies knowledge gaps, prioritizes needs and leads world-class research into climate variability and climate change to meet end-user requirements and policy needs.

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term climate processes through the effects of humidity and clouds on cloud-radiation interaction.

Although the MJO is not the only manifestation of tropical multi-scale convective organization, it represents a critical mode of atmospheric variability that straddles the intersection of weather and climate (Shapiro and Thorpe 2004; THORPEX/ICSC 2005). The MJO dominates tropical variability on subseasonal time-scales. It has global influences through tropical/extra-tropical interactions and is directly involved with breaks in the Asian, Australian and African monsoons. The MJO is increasingly recognized as influencing high-impact weather events and climate variability on seasonal-to-interannual time-scales. Yet, adequate knowledge of the processes contributing to the initiation and maintenance of the MJO and realistic simulations and predictions remain major scientific challenges for the weather/climate community.

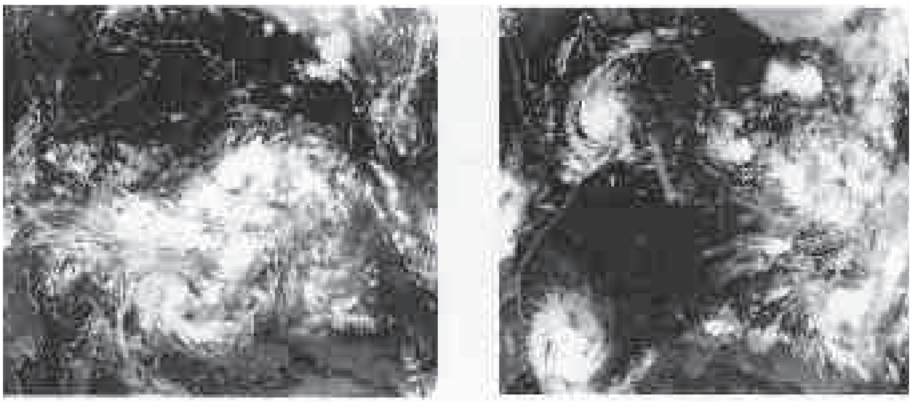

Figure 1 — Multi-scale convective organization and the Madden-Julian Oscillation (MJO): an MJO over the Indian Ocean on 2 May 2002 (left); a week later, the MJO has moved eastwards over Indonesia, spawning tropical cyclones in its wake (right). The multi-scale organization of convection is clearly visible within the MJO. The twin cyclones illustrate that high-impact organized weather events are directly associated with large-scale convective organization and equatorial waves.

Observations, parameterized and explicit representation of convection, theoretical and idealized models

Precipitating tropical convection is organized across a wide range of spatial-temporal scales, specifically, four key categories of multi-scale organization:

- Cumulonimbus (~1-10 km, hour);
- Meso-convective clusters (~100-500 km, day);
- Synoptic-scale superclusters (~1 000-3 000 km, week);
- The MJO envelope (~10 000 km, weeks-months).

A crucial unknown is how the smaller scales interact to form self-reinforcing larger-scale organized systems, e.g. MJO, monsoons. It is recognized that tropical synoptic/meso-convective activity is often coupled to meridionally trapped modes of atmospheric variability idealized as Rossby gravity waves and Kelvin waves. Issues have been raised regarding:

- How convective activity is modulated by wave modes and vice versa;
- Feedback between convection and synoptic-scale to planetary-scale processes;
- Thermodynamic processes and momentum transport as an upscale effect of meso-convective organization;
- The effects of extra-tropical disturbances propagating into equatorial regions on MJO genesis, such as cold surges originating in Siberia, and extra-tropical to tropical Rossby-wave propagation (Kiladis, 1998).

Observations

Field campaigns document regional to mesoscale structures and associated physical processes, e.g. coupled atmosphere-ocean boundary layer processes. Two regional campaigns of direct relevance to MJO genesis in the western Indian Ocean were conducted recently:

- The VASCO-CIRENE Experiment coordinated the CIRENE ship and the VASCO observing system (aeroclippers and pressurized balloons launched from the Seychelles). The objective was to measure the effect of physical processes (e.g. warm layer formation, Ekman pumping, sub-surface cooling due to vertical mixing and surface fluxes) on sea-surface temperature (SST) perturbations, ranging from diurnal to subseasonal time-scales in order to quantify the mechanisms affecting the sub-seasonal SST variability, and the feedback of SST variations to the atmosphere (http://www.lmd.ens.fr/vascocirene);
- The MIRAI Indian Ocean cruise for the Study of the MJO-convective Onset (MISMO) examined atmosphere-ocean characteristics of the eastern-to-central Indian Ocean with emphasis on the vertical structure of the atmosphere, e.g. water vapour, cloud regimes, moisture convergence, air-sea interaction, including diurnal variability and

the oceanic response to MJO onset (http://www.jamstec.go.jp/iorgc/mismo/docs/MISMOplanE_6-1.pdf). The potential for future Indian Ocean field campaigns taking advantage of proposed enhancements of long-term measurements is summarized in *CLIVAR Exchanges* (2006).

The fact that the MJO spans a large range of spatial and temporal scales, from convective to planetary, means that traditional regional campaigns *per se* are no longer sufficient to fully document and/or predict the scope of MJO episodes. It is necessary to engage the full global observation and prediction systems along with the traditional regional campaigns such as the those described above. This observational prediction requirement was the basis of a recommendation of the THORPEX-WCRP international workshop reported on below; namely, to "develop an internationally coordinated, virtual computational-observational laboratory". This concept has developed into a WCRP-THORPEX initiative: "Year of tropical convection (YOTC)". It is summarized in Waliser and Moncrieff (2007). A draft of the details of the concept is described in http://hydro.jpl.nasa.gov/imp/WCRP.THORPEX.YOTC.pdf.

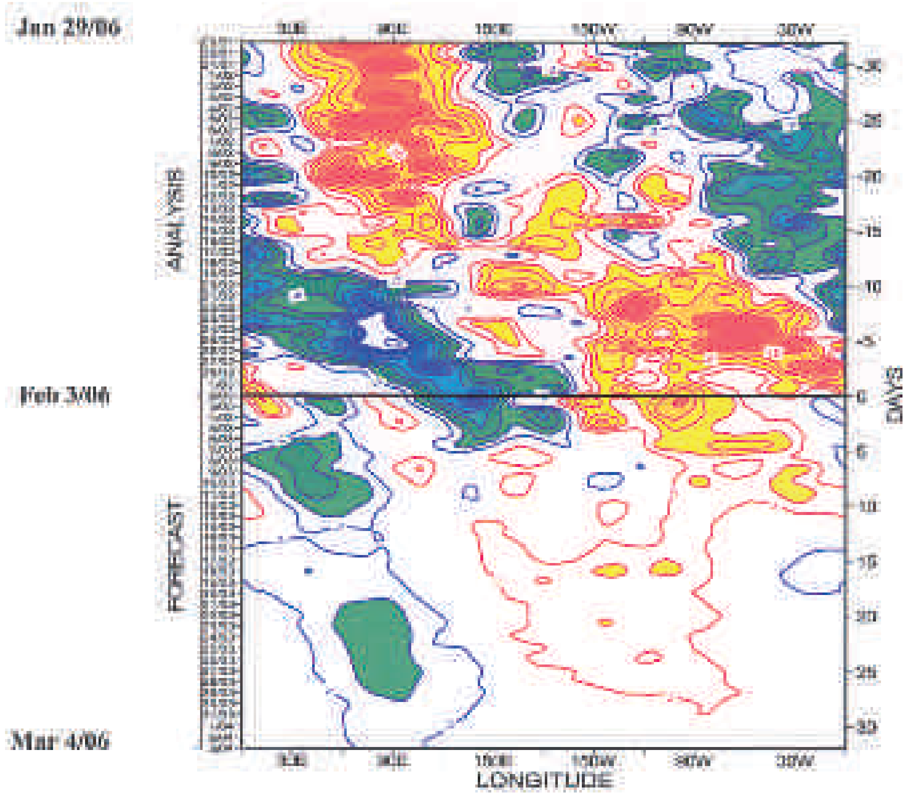

Figure 2 — MJO within the ECMWF forecast system for an event in February 2006. The eastward propagating MJO is prominent in the analysis as a velocity potential at 200 hPa, but the signal is lost after about five days in the forecast from 3 February (courtesy Adrian Tompkins, ECMWF).

Parameterized and explicit representation of convection

A long-standing shortcoming of weather forecast and climate prediction systems is their inadequate representation of subgrid-scale physics and the MJO is no exception. Figure 2 shows an example where an MJO disintegrates from a robust system in the analysis to a nonentity in the forecast in ~5 days. This issue is widely thought to be due to deficiencies in convective parameterization, although there is no fundamental proof of this conjecture. Simulations with Aqua-Planet models experience similar difficulties. Figure 3 shows the minimal consistency of simulated convective organization in Aqua-Planet climate models having different convective parameterizations. Simulated systems propagate eastward, others westward and, most likely, none is truly an MJO. Moreover, the disparate spatial scales of the simulated convective organization shows that the simulations do not provide a correct scale selection.

Modern computers enable cloud-system resolving models (CRM; presently, non-hydrostatic models operating with a grid spacing of order 1 km originally developed for process studies and idealizations) to have progressively larger computational domains and be run for progressively longer times. At a grid-spacing of a few kilometres, CRMs may represent mesoscale circulations explicitly but imperfectly represent cumulonimbus convection. In other words, CRMs incompletely capture the spatial hierarchy identified in the opening paragraph of the section "Observations, parameterized and explicit representation of convection, theoretical and idealized models", specifically, the first of four key categories of convective organization. The effects of this truncation are not fully known and constitute an important research area.

The state-of-the-art is the global CRM, e.g. Tomita (2005). CRMs are applied in place of contemporary convective parameterization in an approach called cloud-system resolving convection parameterization or superparameterization, originally developed in an Aqua-Planet model (Grabowski, 2001) and recently applied in full climate models (e.g. Khairoutdinov *et al.*, 2005). Interestingly, MJOs in superparameterized models are usually too intense and persistent—the opposite from MJOs in conventional parameterized models. This exaggerated behaviour poses new questions that are, arguably,

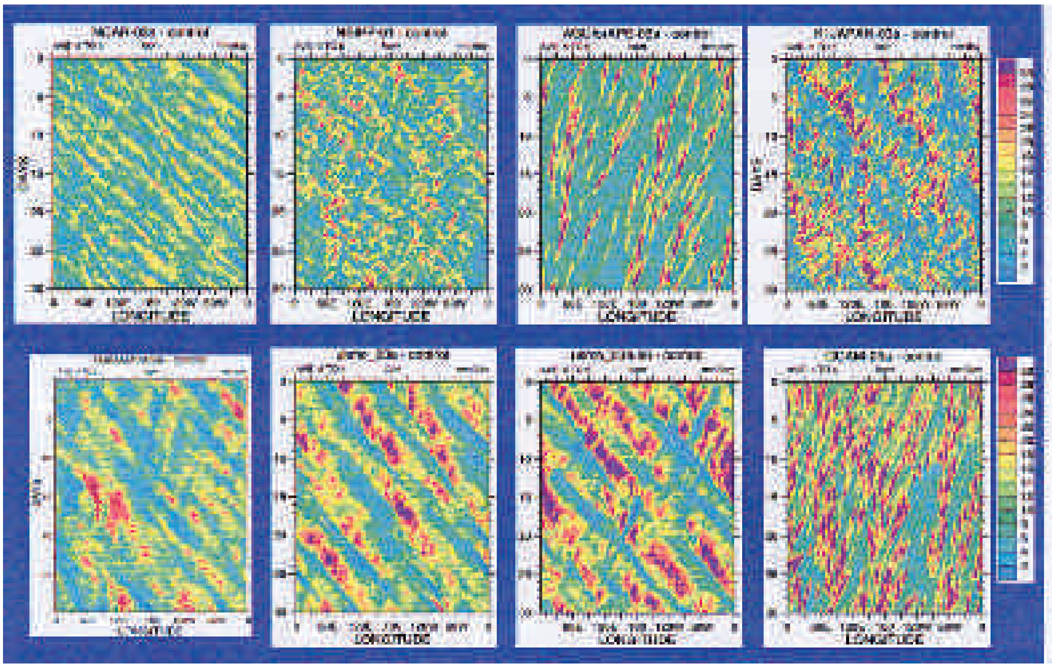

Figure 3 — Large-scale organization of tropical convection (precipitation) occurring in some of the climate models participating in the Aqua-Planet Model Inter-comparison Project (http://www-pcmdi.llnl.gov/projects/amip/ape/). (courtesy Mike Blackburn, University of Reading, and Dave Williamson, NCAR.)

more amenable to solution than those associated with contemporary parameterization.

Theoretical and idealized models

The parameterization problem is unlikely to be solved through enhanced-resolution simulation alone. Idealized dynamical models quantify important issues, such as upscale energy transport associated with meso-convective organization and mechanisms at work in numerically simulated systems. For example, the non-linear mechanistic model of Moncrieff (2004) in which meso-convective organization interlocks with Rossby-gyre dynamics quantifies upscale transport and super-rotation properties of MJO-like systems generated by the Grabowski (2001) superparameterized simulation. The quasi-linear multi-scale model of Biello *et al.* (2006), based on the asymptotic perturbation theory of Majda and Klein (2003) and representing three categories of heating (deep convection, stratiform and congestus (Jonnson *et al.*, 1999), shows that MJO-like systems can be generated by organized upscale momentum flux and heating. Figure 4 shows characteristic signatures of MJOs in this model:

- Westward-tilted meso-synoptic eddies;
- Vertically and horizontally coupled cyclonic and anticyclonic gyres;
- A westerly wind burst in the lower troposphere.

Another idealized approach to quantifying large-scale convective organization involves models with a dynamically active troposphere, a passive planetary boundary layer, and analogue parameterizations of deep convection, surface heat exchange, and radiative cooling, and crude vertical resolution, i.e. the first and second baroclinic velocities proportional to sin πz and sin $2\pi z$, respectively. Multi-scale convective organization occurs in the presence of the first baroclinic mode but not MJO-like coherence (Yano *et al.*, 1995). More realistic MJO-like systems occur when the second baroclinic mode is introduced (Khouider and Majda, 2006).

MJO interactions

MJO and ENSO

The El Niño-Southern Oscillation (ENSO) is mostly driven by large-scale atmosphere-ocean coupling in the Pacific region. Convective organization strongly affects atmosphere-ocean coupling by modifying the surface radiation budget, evaporation and wind stress and hence slow-manifold interaction between oceanic and atmospheric boundary layers. Strong surface eastward-travelling equatorial westerly wind bursts associated with the MJO excite oceanic Kelvin waves that affect the onset of El Niño by reducing the equatorial zonal gradient of sea-surface temperature. This interaction involves three distinct mechanisms:

- Cooling the western Pacific warm pool as a direct result of enhanced surface evaporation by the wind burst, convective-scale and mesoscale downdrafts, and precipitation;
- Eastward expansion of the warm pool through induced westerly currents in the oceanic mixed-layer;
- Warming of the equatorial eastern Pacific by oceanic Kelvin waves that deepen the thermocline and reduce the upwelling of cold water.

Observational studies of anomalously strong MJO activity prior to the onset of El Niño suggest a plausible relationship between the MJO and El Niño.

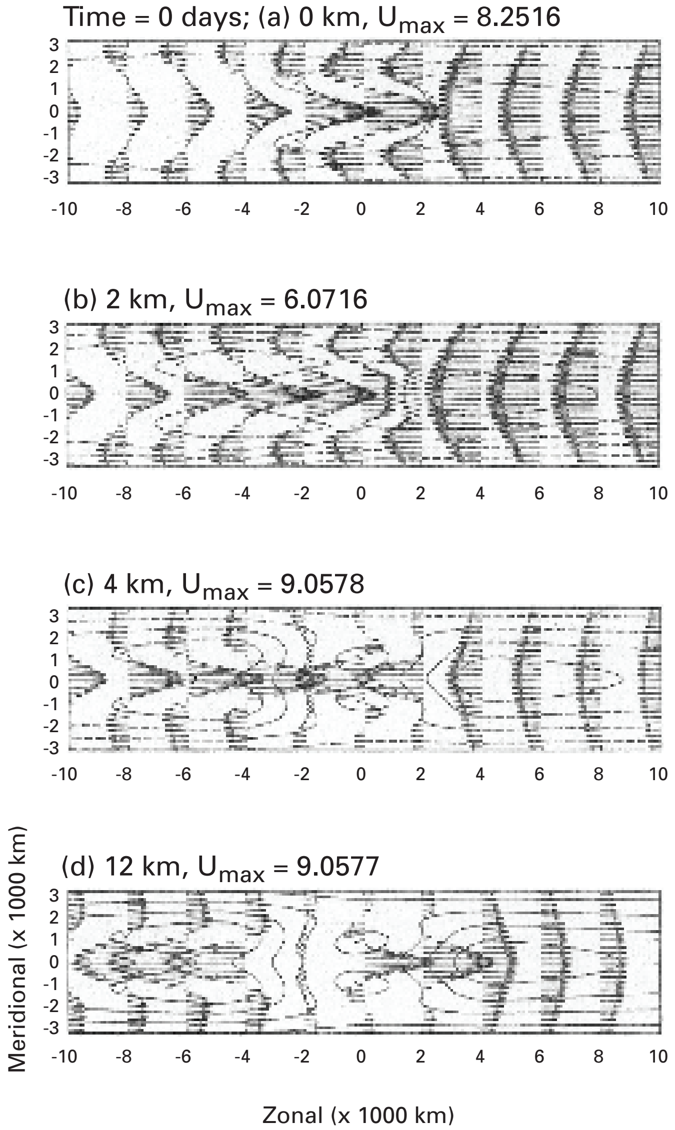

Figure 4 — Horizontal velocity at selected heights in the troposphere, along with contours of the perturbation pressure in a multiscale dynamical model forced by vertical fluxes of synoptic-scale heating and zonal momentum. (courtesy Biello, Majda and Moncrieff (2007))

Improved predictive skill for the MJO will ultimately need to be incorporated into next-generation ENSO prediction models. The fact that large-scale convective organization is significantly different in coupled atmosphere-ocean models compared to atmosphere-only models suggests that incomplete formulations of how boundary layers of the ocean and atmosphere interact lie at the heart of the MJO-ENSO interaction issue.

MJO and the extra-tropics

The influence of multi-scale convective organization is distinctly non-local. The subseasonal to interannual variability of tropical convection has a profound influence on synoptic-scale Rossby-wave dispersion into the extra-tropics and on planetary-scale circulation anomalies such as the Pacific North-American oscillation (PNA), the Arctic Oscillation (AO) and North Atlantic Oscillation (NAO). Studies such as Ferranti *et al*. (1990) suggest that a successful representation of tropical convection in weather and climate models will lead to improved mid-latitude predictive skill at week-2 and beyond. Global CRMs and superparameterization can address a primary objective of THORPEX/WCRP: the two-way interaction between the tropics and the higher-latitudes sketched in Figure 5.

The initiation and maintenance of planetary waves by organized convection, as a two-way interaction between tropical and extra-tropical circulation, are crucial to more skilful prediction in the week-2 timeframe. For example, tropical cyclones influence the extra-tropics through their direct migration polewards into the mid-latitude storm tracks and/or poleward Rossby-wave dispersion. Similarly, Kiladis (1998) has shown that Rossby waves propagating from higher latitudes can excite tropical convection. The challenge of improving the representation of convection, its organization and interaction with the regional-to-global scale circulations for weather and climate prediction systems cannot be over-emphasized.

THORPEX-WCRP workshop

THORPEX and WCRP convened an international workshop on the organization and maintenance of tropical convection and the Madden Julian Oscillation at the International Centre for Theoretical Physics in Trieste, Italy, 13-17 March 2006. The objective was to assess the current state of knowledge and predictive skill of multi-scale organized tropical convection, and set priorities for collaborative research leading to advanced knowledge and predictive skill of organized tropical convection and the MJO. The workshop brought together experts in tropical convection and two-way interaction between the tropics and higher latitudes. The participants were charged with formulating recommendations and fostering opportunities that address key challenges to advancing knowledge and predictive skill of tropical convection and its large-scale organization and two-way interaction with the extra-tropics, that would emerge from:

- Recent and additional diagnostic studies and observations;
- Increased computing capacity that enables CRMs;
- Present and forthcoming space-based remote-sensing measurements and *in situ* observations of clouds and precipitation. The workshop

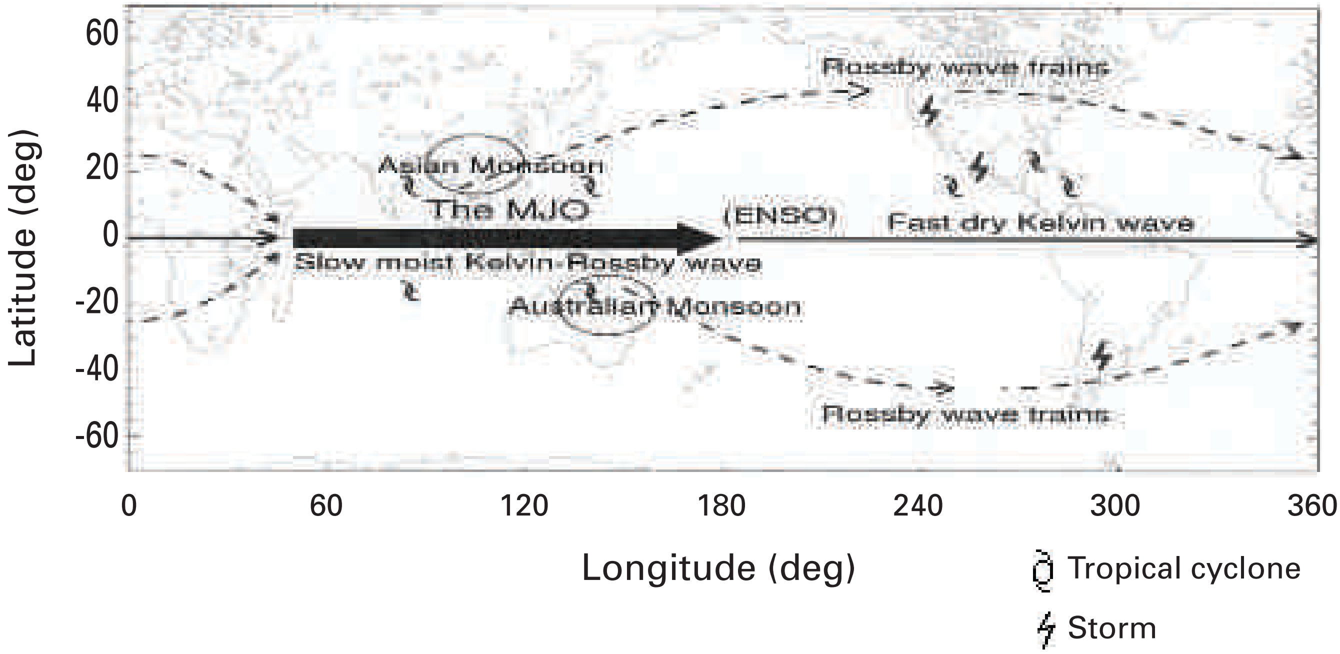

Figure 5 — Schematic diagram of the relationship between MJO, planetary wave teleconnection and high-impact weather at higher latitudes (courtesy J. Lin, NOAA/CERES)

agenda and presentations are available at http://cdsagenda5.ictp.trieste.it/full_display.php?ida=a04205.

The workshop reviewed current knowledge of organized tropical convection, with a specific focus on the MJO. This included the identification of issues to be addressed as a collaborative THORPEX/WCRP effort to improve knowledge, numerical simulation and prediction of tropical organized convection and the MJO, as well as socio-economic research and applications. An important issue was the two-way interaction between the tropics and the higher latitudes. Specifically, how are extra-tropical synoptic and planetary waves modulated by organized tropical convection and vice versa? Knowledge of the diagnosis, genesis and maintenance of organized tropical convection were discussed, e.g.:

- Its influence on high-impact tropical weather systems and their prediction;
- Two-way interaction with extra-tropical weather systems e.g. Rossby-wave initiation, propagation and dispersion;
- Improvement of weather and climate prediction systems. A second important issue was the role of upscale energy transport in weather and climate (Figure 6).

Strategic objectives

The workshop break-out groups identified the following two major objectives as a basis for advancing observing, modelling and predicting the MJO and its socio-economic implications, and the design of forecast demonstration projects:

- Develop an internationally coordinated "virtual computational-observational laboratory" to facilitate:
  - Access to observational, experimental and operational global weather/climate databases commensurate with the highest resolution achievable, given the near-term computational constraints;
  - New diagnostic analysis packages and visualization methods. This effort will provide the infrastructure to exploit the observations, operational prediction and high-resolution simulations of tropical convection, its two-way interaction with extra-tropical weather and climate, and socio-economic impacts and their assessment.
- Prepare a strategy for a coordinated observing, modelling and forecasting activity/ programme with emphasis on organized tropical convection and its influence on predictive skill in the western Pacific and Indian Ocean area, achieved through leveraging recent and near-term gains in modelling, observations, computer capabilities and other programmatic activities.

Recommendations for collaborative research

The following items were identified as collaborative THORPEX/WCRP activities:

- Develop metrics/descriptions of the daily, subseasonal, seasonal, and interannual characteristics of the MJO and organized convection that encapsulate our knowledge, enable model/forecast validation and guide future research;

- Promote collaboration on the use experiments of the numerical weather prediction type for exploring error growth in simulations of organized convection and the MJO and two-way interactions of tropical and extra-tropical weather and climate systems;

- Promote international collaboration on high-resolution CRM studies for exploring the upscale effects of organized convection in order to optimize use of computing resources and to share the development of data-analysis tools;

- Integrate process studies of observed organized convection based on satellite and ground-based remote-sensing (including 3D Doppler radar), with *in situ* measurements to provide improvements and validation of high-resolution models;

- Promote collaboration on forecast demonstration experiments coupling statistically based systems (e.g. Newman *et al.*, 2003) and dynamically based systems to assess the value of improved MJO/organized convection simulations for deterministic and ensemble prediction on time-scales up to four weeks;

- Consider the feasibility and strategy for the design and implementation of field campaigns on organized convection (e.g. over the Indian Ocean) guided by high-resolution modelling studies;

- Endorse the need to maintain and enhance existing and planned satellite missions that measure tropical cloud and precipitation systems in order to provide a long-term capability for process studies, data assimilation, and prediction;

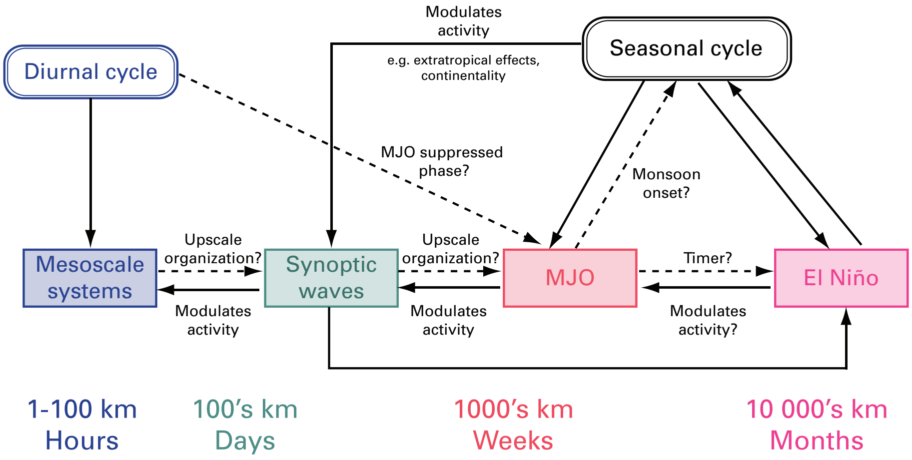

Figure 6 — The continuum character of tropical convection and scale-interaction in weather and climate. Interactions of space- and time-scales of tropical convection: linking THORPEX and WCRP.

- Develop the concept of seamless prediction within the context of the MJO;

- Promote the transfer of advanced knowledge and predictive skill of organized convection into improvements for operational numerical weather prediction and climate models through links with key groups within GEWEX/CLIVAR/THORPEX and the operational prediction centres;

- Develop a strategy for demonstration and assessment of socio-economic benefits and applications arising from advanced knowledge and predictive skill of multi-scale tropical weather/climate events on time-scales of days to seasons.

Post-workshop activities

There has been considerable activity since the THORPEX-WCRP workshop, as follows:

- The Second THORPEX International Science Symposium (STISS) convened in Landshut, Germany, 4-8 December 2006, was attended by over 200 participants from five continents and 32 countries. Organized tropical convection was identified as a potential collaborative effort and integrative objective embracing all four components (predictability and dynamical processes, observing systems, data assimilation, observing strategies, and societal and economic research and applications) of the THORPEX International Science Plan;

- A workshop on the intersection of weather and climate was hosted by the Institute for Integrative and Multidisciplinary Earth Studies, of the US National Center for Atmospheric Research (NCAR). The workshop brought together researchers from the US university community, the US Department of Defense, the US National Aeronautics and Space Administration, NCAR and Environment Canada tasked with providing objectives relevant to tropical convection as a contribution to THORPEX. The report can be seen at http://www.tiimes.ucar.edu/events/documents/wc-WhitePaper-draft.pdf;

- A consortium based in the United Kingdom at the University of Reading (called Cascade) focuses on cloud-system resolving modelling of the tropical atmosphere. Cascade is sponsored by the Natural Environment Research Council and is collaborative with universities and institutions, notably the UK MetOffice;

- The Center for Multi-Scale Modeling of Atmospheric

Processes (CMMAP) at Colorado State University, Fort Collins, Colorado is a Science & Technology Center sponsored by the National Science Foundation (NSF). The objective of CMMAP is to improve the representation of cloud processes in climate models addressed through a multi-scale modelling framework (MMF). In MMFs convective systems are represented explicitly using CRMs: superparameterization. The MJO is one of the focal research themes of CMMAP;

- The Climate Variability and Predictability (CLIVAR) Subseasonal MJO Working Group develops metrics for assessing performance in climate and extended-range/ subseasonal forecast models, designs and coordinates multi-model and cloud-resolving model experimentation and analysis to diagnose and improve predictability and prediction of the MJO. It also helps coordinate MJO-related activities and workshops among various WWRP-WCRP programmes (e.g. the Global Energy and Water Cycle Experiment (GEWEX), CLIVAR, THORPEX). Additional information is available at www.usclivar.org/Organization/MJO_WG.html.

Position papers under development

Two position papers have been commissioned by THORPEX and WCRP to address the broader aspects of collaborative research of weather/ climate and its intersection with the Earth system. The first paper, referred to as THORPEX/WCRP White Paper 1, is directed toward the weather/climate/ socio-economic communities and their supporting agencies. This effort will propose specific collaboration between THORPEX and WCRP involving high-priority issues on numerical prediction and modelling, data assimilation, observations from weeks to seasons and socio-economic assessments and applications.

A second paper being prepared to inform policy-makers, national academies of science and users of weather, climate and environmental information of the urgent necessity for establishing an international multidisciplinary research agenda to accelerate advances in predicting high-impact weather and climate events, knowledge of complex interactions in the biological-chemical Earth System, and hence improved decision-making.

Conclusions

This paper summarizes the challenge of advancing the knowledge of tropical convection, multi-scale convective organization and mechanisms of two-way interaction with the extra-tropics, within the framework of a THORPEX/ WCRP collaborative research initiative. Meeting this challenge is a critical step toward improving present medium-range numerical prediction skill and its extension into subseasonal time-scales and beyond. The activities described show timely progress towards this lofty goal.

Acknowledgements

We thank Gilbert Brunet, Duane Waliser and Huw Davies for their helpful comments.

References

Biello, J.A., A.J. Majda and M.W. Moncrieff, 2007: Meridional momentum flux and superrotation in the multiscale IPESD MJO model. *J. Atmos. Sci.* (in press).

CLIVAR Exchanges 2006: Special edition on Indian Ocean climate, 39, Vol. 11, 31 pp.

Ferranti, L., T.N. Palmer, F. Molteni and E. Klinker, 1990: Tropical-extra-tropical interaction associated with the 30-60 day oscillation and its impact on medium and extended range prediction. *J. Atmos. Sci.*, 47, 2177-2199.

Grabowski, W.W., 2001: Coupling cloud processes with large-scale dynamics using the Cloud-Resolving Convection parameterization (CRCP). *J. Atmos. Sci.*, 58, 978-997.

Johnson, R.H., T.M. Rickenbach, S.A. Rutledge, P.E. Ciesielski and W.H. Schubert, 1999: Trimodal characteristics of tropical convection. *J. Climate*, 2397-2407.

Khairoutdinov, M. and D. Randall, 2007: Evaluation of the simulated interannual and subseasonal variability in an AMIP-style simulation using the CSU Multiscale Modeling Framework. *J. Climate,* submitted.

Khouider, B. and A.J. Majda, 2006: Multicloud convective parameterizations with crude vertical resolution. *Theoretical and Computational Fluid Dynamics.* Special issue: Theoretical Developments in Tropical Meteorology, 20, 351-375.

Kiladis, G.N., 1998: Observations of Rossby waves linked to convection over the eastern tropical Pacific. *J. Atmos. Sci.*, 55, 2321-339.

Madden, R.A. and P.R. Julian, 1972: Description of global-scale circulation cells in the Tropics with a 40–50 day period. *J. Atmos. Sci.*, 29, 1109–1123.

Majda, A.J. and R. Klein, 2003: Systematic multiscale models for the tropics. *J. Atmos. Sci.*, 60, 393-408.

Moncrieff, M.W., 2004: Analytic representation of the large-scale organization of tropical convection. *J. Atmos. Sci.*, 61, 1521-1538.

Newman M., P.D. Sardeshmukh, C.R. Winkler and J.S. Whitaker, 2003: A study of subseasonal predictability. *Mon. Wea. Rev.*, 131, 1715–1732.

Shapiro, M.A.. and A.J. Thorpe, 2004: THORPEX International Science Plan. WMO/TD-No.1246, WWRP/ THORPEX, No.2, 51 pp.

THORPEX/International Core Steering Committee (ICSC), 2005: THORPEX International Research Implementation Plan, WMO/TD-No.1258, WWRP/ THORPEX, No.4, 95 pp.

Yano, J.-I., J.C. McWilliams, M.W. Moncrieff and K.A. Emanuel, 1995: Hierarchical tropical cloud systems in an analog shallow-water model. *J. Atmos. Sci.,* 52, 1723-1742.