Introduction

The topic of this workshop was "Intraseasonal Variability with a focus on the Madden-Julian Oscillation". There are a number of reasons why this topic is particularly timely. First of all, ECMWF has recently begun routinely producing ensemble forecasts to 30 days. An important component of the flow which is believed to have predictability beyond the conventional 10-day timescale, is the Madden-Julian Oscillation (MJO). Although the MJO is principally a tropical mode of variability, it can certainly influence the development of the extratropical flow, even over Europe, on intraseasonal timescales. Secondly, the MJO continues to be a difficult phenomenon to simulate well in numerical models. As such, simulating the MJO well is a fairly stringent test of such models, specifically of the moist physical parametrisations and their coupling to the resolved dynamics. Related to this, understanding the basic physical mechanisms that account for the formation, propagation and decay of the MJO, is a key priority. Amongst these basic mechanisms is the role of coupling to the oceans. The ECMWF intraseasonal forecasts are made with a coupled ocean-atmosphere model, but how well should mixed-layer processes be resolved in such models? Finally, there is some evidence (though not unambiguous evidence) that the MJO plays a role in the development of El Nino. Hence there is a fundamental question: how important is it for seasonal forecast models of El Nino to have a good representation of the MJO. These topics and more are discussed in the papers presented in this proceedings.

The workshop followed the usual format of invited lecturers followed by discussions in working groups and it concluded with a plenary session. Groups were set up to consider the subjects of: "observations, mechanisms and theories", "modelling and predictability", and "role of the Madden-Julian Oscillation in climate". The discussions and recommendations of the three working groups are summarized in the following three reports. The contributions to the workshop can also be found on the ECMWF web site (http://www.ecmwf.int/publications/)

The workshop organisers thank CLIVAR for their support.

David Anderson, Martin Miller and Tim Palmer (co-organisers)

1. Working Group 1: Observations, mechanisms and theories

Present: Mitch Moncrieff (chair), Mark Rodwell (rapporteur), Andy Majda, Dave Raymond, Glenn Shutts, Adrian Tompkins, Bin Wang, Steve Woolnough, Jun-Ichi Yano, Chidong Zhang

1.1. Overview

The MJO is a dominant component of tropical intraseasonal variability and needs to be better represented in GCMs. The MJO involves numerous physical processes and scale interactions. Achieving a better representation of the MJO in models will therefore generally benefit the simulation of weather and climate.

The most basic characteristics of the MJO are its intraseasonal timescale (30 – 60 days), planetary circulation scale, and slow eastward propagation (5 ms-1). These are the zeroth order features that any MJO simulation should capture. However, MJO simulations need to be evaluated against observations on a higher standard. The structure (both vertical and horizontal), location and seasonal cycle of the simulated MJO should be consistent with the observations.

Presently, a common approach to identify and diagnose the MJO is the use of the first two modes from a (linear) EOF analysis of the complete tropical band. However, the complexity of the MJO suggests inherent non-linearity and fine scales in its structure. One basic question that arises is whether a diagnosis based on a large-scale linear EOF analysis can discriminate between the conceptual models for the structure of the MJO.

Conceptual models of the MJO are presently based on observations, numerical simulations, and theories (see Chidong Zhang's talk). These models, which describe the relative phases of the convective centre, surface winds, and SST perturbations, may be improved by including the vertically tilted baroclinic structure in wind and moisture and the surface pressure field of the MJO. Statistical properties and significance of the different configurations also need to be quantified.

Regional and fine-scale (non-hydrostatic) modelling studies, possibly forced with boundary conditions associated with well-observed MJO events during TOGA-COARE could be used to validate the fine-scale structure of the modelled MJO and investigate the apparent sensitivity to the relative contributions of grid-scale and parameterized convection.

The European Centre has access, through its DEMETER seasonal forecasting program, to many other coupled models. Continued in-house comparison of the simulation of the MJO in these models is clearly beneficial.

1.2. Theories

There are several theories for the MJO. The approach taken here is to identify the key processes and physics involved in each of these theories and to recommend methods by which these processes can be validated in the ECMWF model. While the theories usually invoke multiple processes, most can be classified into one of five categories depending on the dominant mechanism of interaction between convection and the larger-scale flow.

i) *Convection forced by low-level convergence*: Numerous theories fall into this category, with variations including frictionally produced and wave produced convergence.

ii) *Wind-induced surface heat exchange (WISHE)*: In this class of theory, spatial variability of surface heat fluxes associated with variations in surface wind speeds control the structure of convection. The linearised version of such theories probably cannot explain MJO, but nonlinear versions may be viable.

iii) *Water-vapour feedback*: In such theories the humidity of the free troposphere is thought to primarily control the production of precipitation.

iv) *Radiative-convective instability*: Large-scale convective overturning given by a combination of latent heat release and radiative heating anomalies induced by cloud-radiation interactions are thought to be the primary driving mechanism of the MJO in such theories.

v) *Coupled modes*: The general feature of these theories is that the organization of convection is controlled by SST anomalies, which are generated by flux anomalies associated with the convection. The process by which the SST anomalies organize convection are not understood but may include destabilization of neutral low-frequency modes of the atmosphere or local adjustment to the SST

1.3. Mechanisms

In midlatitudes baroclinic instability is the dominant mechanism and numerical models have been extensively developed with this key point in mind. In the tropics we lack understanding of the mechanisms behind the dominant source of intraseasonal variability, namely the MJO. We cannot expect to make progress on the numerical prediction of tropical weather unless these mechanisms are fully understood.

Existing theories/hypotheses that attempt to explain MJO present a broad range of possible feedback mechanisms or critical processes. Experiments that establish the sensitivity of the MJO to these processes or that validate these processes with observations are likely to be key to an improved representation of the MJO.

i) *Frictional convergence and convection*: This mechanism can be tested by computing the frictional convergence of the surface wind field resulting from gradient wind balance and comparing with deep convection and/or rainfall.

ii) *Wave-convection interaction*: This is the forcing of convection by convergence associated with large-scale waves. Computing surface convergence and deep convection/rainfall yields interesting diagnostics. (Deep-layer convergence is associated with convection by mass continuity but surface convergence may not always be in conjunction with deep-layer convergence).

iii) *WISHE (Wind-induced surface heat exchange)*: The effect of the variability of surface heat fluxes with wind speed can be tested in models by performing sensitivity experiments in which convection is artificially suppressed.

iv) *Water vapour feedback*: This is the sensitivity of deep convection/precipitation to free-tropospheric water vapour. The precipitation rate should be compared to column-integrated water vapour.

v) *Radiative-convective instability*: Large-scale radiative-convective instability is measured by the quantity $\Gamma_{eff}(z) = d\theta / dz - dS_\theta / dw$ where θ is the potential temperature, w the vertical velocity and $S_\theta = d\theta / dt$. Some simple models only produce an MJO when $\Gamma_{eff} < 0$ for a certain range of heights.

vi) *Ocean mixed layer feedback*: The effects of the horizontal gradient of SST on the evolution and mature state of the MJO are poorly understood and require examination.

vii) *Momentum transport and upscale dynamical influences*: The effects of parameterized convective momentum transport and momentum transport by resolved scales need to be understood. A small fraction of the kinetic energy generated by deep convection may cascade to large scales and help to excite low frequency variability.

viii) *Mid-latitude forcing of MJO*: The influence of Northern Hemisphere wintertime East Asian cold surges and their association with tropical convection activity should be revisited. Mid-latitude Rossby waves, possibly associated with the Himalayan plateau, may modulate or trigger deep convection as they propagate into the tropics. Wave propagation may be diagnosed using Eliassen-Palm fluxes or Hoskins E-vectors.

1.4. Issues

The MJO is a multi-scale, low frequency mode of tropical atmospheric motion. A fundamental challenge is to understand the role of scale interaction in sustaining the MJO. It is best documented by using temporal-spatial filtered data. The planetary scale MJO does not directly organize convection and the convective heat source is largely consumed by mesoscale or synoptic scale disturbances. Understanding this complex scale interaction and upscale cascade of energy released in convective scales may be key for understanding the failure of AGCM simulations. Convective and mesoscale momentum transport mechanisms and systematic multi-scale models are likely to provide a more complete understanding of MJO dynamics.

1.4.1. Resolved-scale circulations and parametrized convection

In high-resolution prediction models there is a tendency for grid-scale circulations to develop and even dominate the parameterized convection. Clearly, having grid-scale convection in a model using a resolution of 100 km is unphysical. Among other problems, this surrogate behaviour alters the rainfall distribution as well as the vertical structure of the latent heating and the relationship between the vertical circulation and the heating. Understanding this surrogate behaviour will be illuminating because grid-scale circulations, which crudely approximate the mesoscale organization of convection, tend to induce MJO-like activity (but can have detrimental effects on the large-scale tropical circulations). One of the issues is therefore why parameterized convection apparently damps low wavenumber eastward propagating signals relative to explicit heating. One obvious contrast is that explicit latent heating is constrained to take place in regions of upward vertical motion, and thus low level convergence. It should be emphasized that the presence of fractional cloud scheme permit significant latent heating to occur well before grid-scale saturation is achieved. It is interesting that earlier Kuo-type convective parameterization schemes utilized to investigate CISK-type mechanisms used convergence for their closure. Most mass flux schemes now close on CAPE and are thus highly sensitive on low-level moist static energy, and may provide heating out of phase with wave activity, damping rather than amplifying the signal (Emanuel et al. 1994).

1.4.2. Multi-scale interaction and upscale transfer

This issue relates in some way to the previous one. While high-resolution prediction models may represent upscale transport associated with mesoscale organization and the relationship between heating and large-scale vertical velocity explicitly, the physical basis of this representation is questionable. A particular issue is the (mesoscale) transport of horizontal momentum by organized convection in the vertical direction and its parameterization (e.g., Moncrieff 1992; Wu and Yanai 1994). A full understanding of the upscale effects associated with organized convection may explain why some prediction models better represent the MJO than others. A basic issue is how much upscale transfer of kinetic and potential energy across scales affects the structure of the MJO. Observations show slowly moving westward mesoscale squall clusters and equatorial synoptic scale (O(1,000 km)) super-clusters in an MJO. The MJO-like structures in the Grabowski (2001) simulations with "super-parameterization" feature such upscale interaction. However, this explicit approach has a pronounced scale-gap between the cloud-resolving scale (200 km) and the large-scales with a mesh of 1,200 km so interactions with the equatorial synoptic scales are omitted completely (the simulations have no convectively-coupled Kelvin waves). These simulations and nonlinear momentum transport theory (Moncrieff 1992) highlight such upscale interactions in an idealized context.

There are new balanced models, which explicitly involve interaction across scales on intraseasonal time scales, namely the IPESD models in Majda and Klein (2003) that are potentially useful diagnostic and prognostic models to quantify multiscale interactions in the MJO.

1.4.3. Fine-scale simulation of MJO systems

While global models can generate MJOs, their grid-increment is too coarse to explicitly represent mesoscale structure and important components such as super-clusters and westerly wind bursts. These sub-structures likely involve scale interactions and upscale transport within the MJO. Interactively nested numerical prediction models (e.g., MM5/WRF) can simulate these multi-scale substructures, if not the MJO itself. Better understanding of scale interaction may result from simulations wherein global analyses provide the "first-guess" and also the lateral boundary conditions for limited-area simulations. This approach may lead to improved convective parameterizations and better knowledge of the ratio of grid-scale precipitation and parameterization tendencies. (Moncrieff and Klinker 1997 have documented some major uncertainties associated with the treatment of TOGA COARE super-clusters at T213 spectral resolution).

1.4.4. MJO-related Bay of Bengal disturbances

The MJO in the Indian Ocean during the summer monsoon can bifurcate into two large-scale cyclonic systems. The one that travels into the Bay of Bengal is of particular interest since it is associated with severe weather, strong winds, and heavy rainfall, all of which are poorly forecasted.

1.4.5. Observations

More definitive diagnostics of the MJO are needed to better describe its characteristics, understand its mechanisms, and validate fine-scale numerical simulations. Based on currently available observations and global model (re)analyses, fundamental and robust features of the MJO are discernable in terms of its dynamic field (e.g., the vertically tilted baroclinic structure and Kelvin-Rossby wave complex) relative to the large-scale centre of deep convection and precipitation. The heating profile associated with the MJO, however, is not well understood. Satellite retrievals (e.g., TRMM radar and microwave profiling) in combination with derived quantities (e.g., TRMM diabatic heating profiles) provide useful new datasets.

Statistics can extract the most common features of the MJO and evaluate model simulations. Case studies, from e.g. the TOGA COARE experiments, are essential to describe the more detailed evolution and multi-scale structure of the MJO and to evaluate in detail model errors in forecasting the MJO. Diagnostics need to be available from the real world and from model output.

1.5. Recommendations

- Construct a more complete diagnostic description of the observed MJO (e.g., the heating profile) making use of the reanalysis and new observational datasets (e.g., TRMM and field experiments such as TOGA COARE).

- Conduct non-hydrostatic simulations (e.g., the interactively nested MM5/WRF prediction model or cloud-resolving models) of the MJO using the a) TOGA-COARE datasets, b) ERA40 reanalysis; c) IFS forecasts.

- Identify the dominant processes active in the MJO in order to inform the development of numerical models of the tropics (e.g., relationships between frictional convergence and convection). It is important that diagnostic methods should be useable on both observations and model output. A "catch-all" approach may be to validate the representation of all the possible mechanisms identified in section 3.

- Understand the sensitivity of the simulated MJO to the ratio of grid-scale to parametrized convection.

- Inter-compare models (e.g., multi-model ensemble) in order to identify common strengths and weaknesses and notable differences in simulations of the MJO.

1.6. References

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2. Working Group 2: Modelling and predictability·

Present: Peter Webster (Chairman), Thomas Jung (Secretary), Wanqui Wang, Matt Wheeler, Ken Sperber, Carlos Hoyos, Wojtek Grabowski, Peter Bechthold, Iracema Calvacanti, and Normand Gagnon.

2.1. General Statement

This group stresses the fact that it is difficult to improve MJO simulations if no generally accepted theory for MJO exists (envelope of eastward and westward propagating waves?). Although some elements of existing theories can be tested in existing models (using both idealized and realistic setup), theoretical developments in this area seem critical.

2.2. Introductory statement

Diagnostic studies have shown that the Madden-Julian Oscillation (MJO) of the boreal summer and winter is a large scale and robust feature of the tropics with strong signals in the equatorial regions which may extend to, or be linked with, the mid-latitudes. Recent empirical prediction efforts of both the summer and winter MJOs have been relatively successful in predicting the evolution of intraseasonal variability. Thus empirical studies have shown that the MJO is a resilient large-scale feature of the tropical system and that there is strong predictability in the system. Currently, numerical models have been less successful in simulating and predicting the MJO. However, the establishment of predictability by empirical techniques is heartening and sets an achievable goal for numerical models.

2.3. The suppressed phase of the MJO

Prior to the generation of an MJO episode, and associated with the propagating mature MJO is a region of suppressed convection. Prior to the formation of an MJO, suppressed convection under the action of broad scale and strong subsidence exists over large regions of the tropics. During this time, it is thought that high insolation heats the surface of the ocean and the boundary layer becomes successively more moist with vertical mixing occurring through cumulus humilus below the inversion. Similar conditions appear to exist in the boundary layer ahead of the propagating MJO. Through such processes, the boundary layer is "pre-conditioned". However, it is uncertain whether these processes are replicated in numerical models. For example, it is uncertain whether or not deep convection is produced by the models as distinct from the sub-inversion cumulus which is observed. It is recommended that model output is examined carefully to see that the suppressed phase is indeed a true replication of nature.

2.4. The diurnal variation

Observations from field experiments as JASMINE in the Bay of Bengal and TOGA COARE in the western Pacific have shown that in the generally low wind/high insolation suppressed phase of intraseasonal variability there is a diurnal variation of SST of order 2-3C. Furthermore, serial ascents have shown that these increases in SST are accompanied by plumes of moist air rising through the boundary layer through the actions of sub-inversion cumulus clouds. It is thought that these boundary layer moistening processes may be important in "preconditioning" the boundary layer. However, it is uncertain how well models replicate these diurnal processes.

Stand-alone atmospheric models (e.g., the ECMWF operational model) does not include diurnal SST variability but rather the 5-day running Reynold's SST product. Also, it is unclear how well the coupled operational climate model produces a realistic SST variation. What is known is that both models produce cloud systems that are not in phase with observations often producing a mid-morning maximum as distinct from a mid-afternoon maximum. Given the possible importance of diurnal variability to the evolving state of the boundary layer it is suggested that the diurnal variability of the models is assessed critically. For stand-alone atmospheric models, it is suggested that a simple diurnal variability parameterization be added to the SST which would depend on surface wind and insolation as has been established from simple mixed layer models and field studies. It is suggested that test studies be run to see if the atmospheric model produces a better suppressed boundary layer, on the one hand, and a better MJO simulation on the other. The diurnal variability of the coupled model should also be scrutinized and whether vertical resolution of the model allows the observed diurnal heating of the surface layer of the ocean.

2.5. Tropical-extratropical interactions

There is some evidence from observational studies that there is considerable intraseasonal variance in the mid-latitudes as well as the equatorial regions. It is unclear whether or not these signals are transmitted from the tropics or are produced in situ. It is thought that the nature of this variability be determined because it may add to the predictability of the extratropics. Furthermore, most concentration has been on the MJO in the tropics. If a mid-latitude source of intraseasonal power can be determined it will be important to determine its physical nature and what role (if any) it has on the tropical MJO.

2.6. Data availability and collaborative efforts

The suggested tasks and recommendations describe a considerable amount of work for ECMWF. We recommend that ECMWF consider seriously the added value that collaborative efforts with other centers and university groups will bring to research on intraseasonal variability. Specifically, we recommend that ECMWF makes available in a much easier manner specific data from experiments such as the recommended DERF experiments, and also other data that ECMWF produces including the reanalysis and the extended 30 day predictions.

2.7. Coupled versus uncoupled modelling

For the purpose of parametrization sensitivity testing the working group concludes that the use of uncoupled AGCM integrations is appropriate initially. Subsequent to demonstrate improvements of MJO variability testing with coupled ocean is recommended.

2.8. Comparison of the MJO in different models

The workshop has shown that model-to-model differences of the MJO are significant. The working group has concluded that it is useful to carry out further diagnostic studies on different model runs. Further, it has been concluded that the DEMETER models would be ideal for this purpose. This is particularly true as the ECHAM4 model, with its apparent realistic MJO, is part of the multi-model ensemble.

Further, Ken Sperber has offered to include ECMWF model integrations based on the latest model cycle in future MJO model intercomparison studies. This undertaking should help to clarify whether the ECMWF model has a realistic MJO.

2.9. Diagnosis of different phases of the MJO

It is strongly suggested to study the MJO in all its different stages (generation, propagation, decay). It is felt that to this end DERF-like (Dynamical Extended-Range Forecasts) daily integrations should be carried out with the Monthly Forecasting system for specific periods of strong MJO activity. It is crucial that these integrations start well in advance of the observed MJO generation. Possible periods encompass the TOGA period and the pre-96/97 El Nino onset period. Peter Webster offered to provide a detailed list of dates.

2.10. Seasonality

The MJO is present in all seasons, albeit with varying characteristics. Diagnostics should reflect this, paying just as much attention to the northern summer mode as its southern summer counterpart.

2.11. Resolution

Little experience exists in diagnosing and evaluating statistics of MJO/ISO at high horizontal resolution. ECMWF is encouraged to compare MJO/ISO diagnostics at deterministic forecast resolution with lower resolution versions of the model (T255, T159, T95). This will shed light on the importance of scale interactions in representing intraseasonal variability. If the results indicate an insensitivity to horizontal resolution, then detailed analyses of low-resolution (climate-type) integrations will provide a framework for evaluating improvements in the development cycle of the forecast model.

2.12. Diagnostics

ECMWF should adopt a more comprehensive suite of diagnostics to better explore the phenomenon of MJO/ISO in their model. Examples of established benchmarks presented at the workshop include the vertical structure and the phase relationship between the boundary layer and the middle and upper troposphere.

Observations show the predominant occurrence of a full spectrum of convectively-coupled equatorial waves (e.g., Wheeler and Kiladis, 1999). These waves invoke simpler explanations than the MJO, yet presumably require many of the same essential physical and dynamical processes. Diagnostics of models should thus include their analysis, e.g., identifying their apparent moist equivalent depth from wave-number frequency spectra.

2.13. Sensitivity to parametrization

Analysis of existing model simulations (e.g., those presented at the workshop) to relate the strength of the MJO signal to the type of convection scheme and/or scheme closure might indicate the importance of various processes in MJO (convection initiation, sensitivity to free-tropospheric moisture - concerning both the growth of convective clouds in a dry environment, and the moistening of this environment by convective clouds, boundary layer physics, etc.). Would such results be consistent with a picture emerging from ECMWF simulations where artificially suppressing convection and aliasing latent heating into large scales improves MJO? Is this the case for the role of organized convection (Moncrieff and Klinker)? The influence of other model parameters like numerical diffusion should also be investigated.

2.14. Superparametrization

Results from climate simulations applying superparameterization (e.g., CSU group) suggest that tropical variability, including MJO, is much improved in such models. This issue needs to be quantified using analysis techniques applied to traditional models, along the lines of results presented at the workshop. This would be an important test for the superparameterization and it might help to quantify physical processes that are essential for MJO simulations that are poorly treated by traditional parameterizations (e.g., sensitivity to free tropospheric moisture).

3. Working Group 3: Role of the MJO in climate

Present: Jean-Philippe Boulanger (Chair), Paco Doblas-Reyes (Raporteur), David Anderson, Magdalena Balmaseda, Anton Beljaars, Silvio Gualdi, Peter Inness, Andrew Marshall, Gill Martin, Geert Jan van Oldenborgh, Anna Pirani, Jean-François Royer, Chidong Zhang.

3.1. Introduction

The working group considered that the discussion should be broadened from the role of the MJO in climate to the role of intra-seasonal (IS) variability in climate. It was agreed that IS variability interacts with regional variability as well as large-scale climate modes, depending on the phenomenon under study. In general, further investigation is required to demonstrate an obviously coupled feedback interaction. Examples of climate modes for which the intra-seasonal variability is (or may be) important, are the monsoon systems (Indian, Australian, South American, North American, West African), ENSO and the Indian zonal mode. In order to synthesize the discussions, the key issues raised by the working group and summarized here are presented in two sections:

i) Role of MJO as part of the intra-seasonal variability

ii) Role of the intra-seasonal variability in climate.

3.2. Role of MJO as Part of the Intra-seasonal Variability

The assessment of the importance of the MJO in regional IS variability can be achieved through the use of surface variables relevant to either ocean-atmosphere or land-atmosphere exchanges as well as to society. To analyze interannual-to-interdecadal variability of the MJO requires a regional definition over long periods of time. Most of the working group participants expressed the need for new MJO indices that can represent the local variance of the MJO and can be used to trace it back to its region of formation, with the final aim of assessing its potential for predictability. Therefore, there is an urgent need for a refined definition of what the MJO is, especially outside the Indian and western Pacific regions. It transpired later that this issue was raised independently in the other two working groups.

It is expected that indices of a regional MJO and IS variability would allow the development of more pertinent statistical analyses, crucial for assessing the potential impacts on climate and for evaluating climate models. Although there is overall agreement that there is a need for regionalized MJO indices, it was not clear how best to do it. Various approaches were considered:

- Design "storm-track" maps of MJO activity using both Eulerian and Lagrangian approaches and taking into account the seasonality of the phenomenon. Such a diagnostic would help in analysing the sensitivity (at seasonal, interannual, and longer time scales) of MJO paths to the large-scale mean conditions. However, it must be completed locally by a more detailed analysis of the atmospheric column and surface variability.

- Determine local/regional indices of MJO activity based upon these activity maps to identify local effects and the sensitivity to both local and large-scale climate conditions. This is important for studying the remote or indirect effects on climate modes

- Promote new statistical approaches (e.g. local mode analysis, wavelets, etc) to obtain regionalized MJO and IS variability indices appropriate for the study of the link with climate. In addition, this should allow for the evaluation of model performance.

3.3. Role of Intra-seasonal Variability in Climate

Much of the discussion focused on the relationship between intra-seasonal activity (ISA) and ENSO although other topics (interaction with the Indian zonal mode, convergence zones and monsoon systems) were also covered.

3.3.1. Effect of the mean state on intra-seasonal variability

The influence of the atmosphere and ocean mean state on the characteristics of the ISA was discussed. A comparison between the observed and simulated MJO features suggests that errors in the model mean state are likely to be a major impediment to the simulation of a realistic MJO. Both observational and model results indicate that natural climate variability (e.g., ENSO) impacts the nature of the ISA. This suggests that the characteristics of the oscillations might be altered in climate change scenarios. Another important point raised is the extent to which ISA determines the mean state, in such a way that the analysis of the MJO and the mean state in isolation becomes difficult.

Recommendations:

- Analysis of the ISA in model inter-comparison studies should include information about mean state errors as well as about the structure, geographical distribution, and seasonal evolution of climate variability on different time scales, setting up higher standards in model validation.

- The sensitivity of the MJO to the characteristics of interannual variability should be considered in coupled model studies.

- The advantages of ensemble methods should be exploited by trying to discriminate the dynamical behaviour and the feedback onto the mean state, of the different ensemble members.

3.3.2. ENSO

There is evidence that the seasonal activity of IS Kelvin waves forced by the MJO are statistically related to tropical Pacific SST anomalies, with ISA leading SST variability by 9 to 12 months. However, this relationship has been found only for the period starting in 1980 (Zhang and Gottschalck, 2002). It is important to recognize that IS phenomena other than the MJO, e.g., westerly wind events (WWE), can also generate the above mentioned Kelvin waves. In other words, the MJO is but one mechanism for WWEs. Other mechanisms include extratropical cold surges and tropical cyclones. It was agreed that small-scale, short-lived, weak WWEs are unlikely to significantly affect ENSO, although some uncertainties remain in the following aspects:

i) Linear versus nonlinear effect of the ISA: The linear effect refers to the modification of the mean winds in the western tropical Pacific and the thermocline structure in the eastern Pacific. These changes require pulse-like winds in one direction not compensated by similar wind events in the opposite direction. The nonlinear effect concerns the rectification of high-frequency surface wind events to the lower-frequency variability, even if the mean wind remains unchanged.

ii) Local versus remote effects: The local effect includes cooling of the western Pacific warm pool (by the enhancement of latent heat flux and the reduction of solar radiation flux) and eastward extension of the warm pool (by thermal advection). The remote forcing includes Kelvin waves forced in the western Pacific propagating into the eastern Pacific and deepening the thermocline there. Both local and remote effects may reduce the zonal SST gradient and help to create the trade wind relaxation linked to warm ENSO events.

iii) Single versus ensemble IS events: It is still unclear whether the major impact is due to the timing, amplitude, duration, and structure of individual events or to the seasonal activity of a group of events. This question is relevant because, even if individual IS events are not predictable, their seasonally averaged impact might be predictable.

iv) The importance of the mean state: The ISA effect on ENSO is likely to depend on the season and the phase of the ENSO cycle. The size of the warm pool and the depth of the thermocline, for instance, would influence the strength of the ISA and the Kelvin waves generated (See also section 3.3.1).

Recommendations:

- Analyze observations and the DEMETER database in order to identify recurrent patterns prior to an ENSO event. The model results will only be indicative, as they may depend on the skill of the individual model to simulate WWEs and correctly represent the Indo-Pacific mean state.

- Assess the impact of the main modes of IS variability on ENSO in long integrations. Possibilities are for annual forecasts such as those proposed by ECMWF, or the multi-annual integrations to be carried out in the framework of the EU-funded projects ENACT and ENSEMBLES.

- Promote the analysis of specific case studies by comparing the simulations from various coupled models.

- Systematically investigate uncertainties using both observations and models.

3.3.3. Decadal Variability

Observations have allowed the identification of a clear shift in ENSO dynamics since the 1982-83 warm ENSO event. This change is potentially linked to the so-called 1976 climate shift, clearly detected as a warming of the Indo-Pacific Warm Pool). In a climate change context, it seems important to evaluate the possibility of a warmer Indo-Pacific warm-pool favouring a more westerly wind mean state in the western Pacific, stronger individual WWEs and/or more frequent occurrence of WWEs during specific seasons. Such studies could be linked to the issue of a potential relationship between WWE (latitudinal) location and maximum SST in the warm pool.

Recommendations:

- Analyze the DEMETER database for the periods pre- and post-1976 with those models simulating a similar-to-observed warm-pool evolution. Also diagnose the location of WWEs relative to the maximum SST.

- Identify, distribute and analyze alternative local datasets such as tropical station data, tide gauges, etc.

- Recommend daily storage of certain variables in IPCC simulations to allow the study of the ISA features.

3.3.4. Indian Zonal Mode

Observations and forced/coupled model studies indicate that a potential interaction between tropical westerly winds and the development of the Indian zonal mode exists. Such preliminary results should be investigated using several independent models to evaluate the robustness of this result. If confirmed, a key issue consists in understanding whether the occurrence of such MJO-related events is purely stochastic (and thus unpredictable) or, instead, depends on external large-scale conditions (pointing to some potential for predictability).

Recommendations:

- Carry out a more thorough examination of observations and undertake the analysis of case studies such as the 1961 event.
- Analyze the Indian zonal mode events using the DEMETER database and promote specific case study inter-comparisons.

3.3.5. Teleconnections and Regional Studies

The working group highlighted the need for a more thorough documentation of IS variability features over several regions of the globe (e.g. monsoon regions). Specifically, the major requirements are the documentation of the changes over time (at the interannual and interdecadal time scales) of the ISA, the identification of the active and break phases of the different monsoons, and the teleconnections of the MJO in the extratropics.

Recommendations:

- Support the construction of daily historical data sets containing both surface and upper air variables, especially in regions so far poorly documented (Africa, Indian Ocean, etc.).
- Encourage the archiving of daily outputs of centennial runs (e.g. IPCC, CMIP) to study changes in statistical distributions and probability of extreme events over both local and remote areas.

3.4. Summary

The importance of the use of ERA-40 to assess the multi-annual changes in the tropical IS variability has been emphasized, although the need for a set of reliable observational data sets independent from the analyses has also been mentioned. These two sources of data should be considered as complementary and allow for the production of a comprehensive catalogue of ISA features.

The requirement of an index to characterize tropical IS variability has been stressed. A clear definition of the ISA and, in particular, of the MJO is needed to best characterize the tropical IS events. A suggestion consisted in tracking individual MJO events to create a catalogue of features. In particular, given that different phenomena seem to show different impacts at the IS time scale, indices able to characterize different aspects of the IS variability will be strongly appreciated. The lack of a unified index points towards a lack of understanding of the phenomena, as was also concluded by other working groups. For instance, the validation of the MJO features in climate models would require the use of upper level variables and radiation at the top of the atmosphere to detect the large-scale signals, while the analysis of the forcing in ocean models will demand the use of low level winds and surface radiation to study the influence of WWEs. In this framework, it was recognized that the features of the ISA identified using low-level winds or OLR are different from those obtained with the use of upper-level zonal wind or velocity potential, the first set of variables showing more regional characteristics. Narrowing the uncertainties in the structure (both horizontal and vertical) of the ISA was also mentioned as a primary requisite. This kind of information would be required to design efficient tracking algorithms as well as large-scale or regional indices. The algorithms would be based upon the use of both low and upper-level variables to better discriminate the events.

In addition, a clear methodology to perform experiments with global models needs to be designed, although the availability of a great deal of recent experiments (IPCC, DEMETER, ENACT, etc.) suggests that an initial phase of analysis should be undertaken first. These simulations could be used to identify model drawbacks and to target specific mechanisms to be analysed in sensitivity experiments.