Introduction

On 13 to 15th November 2006, ECMWF held a workshop on the parametrization of clouds in large-scale models. Experts were invited to give overview lectures relating to this task, which occupied the first day and a half of the workshop. This was followed by break-out sessions during which participants formed three working groups, covering the topics of *validation*, *subgrid variability*, and *cloud parametrization priorities*, respectively. The last afternoon consisted of a plenary session to summarize the workshop findings and recommendations for future research directions both at ECMWF and more widely within the research community. Even by ECMWF standards, the workshop was a popular and oversubscribed event, with many more applicants than available spaces, and was considered a success by all who attended.

The three working groups provided a wealth of recommendations, pertinent to the research plan of ECMWF. The parametrization priorities group emphasized the importance of representing subgrid-variability, and thus recommended that further use of cloud resolving models be made to this end. They stated that particular attention should be paid to representation of mixed phased clouds, and that in general the wider research community needs to continue efforts to investigate ice and mixed phased processes in controlled environments such as cloud chambers. Interestingly, they considered aerosol-cloud microphysics interactions currently too uncertain for inclusion into a NWP framework.

The subgrid-scale variability group agreed with the need to represent subgrid-scale variability in large-scale models. However, they struck a cautionary note and recommended investigating for which processes variability could be neglected. The working group noted that statistical cloud schemes permitted one to work towards an unified approach for all cloud types, but recognised that each regime has specific difficulties to tackle (such as the need for representing the joint probability density function, or PDF, of temperature, water and vertical velocity, or more complex bi-modal PDFs) and therefore an ultimate unified approach may not be achievable. To this end they highlighted the need for further observations that reveal the nature of observed joint PDFs.

The final working group on "validation" highlighted the need for improved observations of the following: near surface winds for evaporation, better resolved boundary layer temperature and moisture structures, soil moisture, aerosol types and their vertical profiles and lastly of microphysical processes. They stated that further efforts needed to be made to combine multiple sensors to achieve this aim, and used the example of the NASA 'A'-train to illustrate this. It was maintained that the development of new sensors should not be at the expense of maintaining existing platforms, as long-term continuous observations from platforms such as CERES and MODIS were critical. The development of ground-based networks such as the ARM and Cloudnet structures was also recommended. They noted that observations could be usefully supplemented with high resolution modelling studies. The working group paid special attention to data assimilation needs, as often the parametrization developments are made without regard to the linearization demands of variational assimilation systems. Improved integration and communication between the cloud parametrization and data assimilation communities could greatly facilitate the data assimilation mission. Data assimilation requirements also necessarily demand further efforts towards real-time access to future remotely sensed information.

ECMWF would like to thank all participants for their contribution to the success of the workshop and providing new ideas and guidelines for further research in cloud parametrization.

The contributions are available from the ECMWF website (http://www.ecmwf.int/publications/).

Working group on the representation of sub-grid scale cloud variability in large-scale models

The working group considered four subjects. These subjects are (a) the importance of sub-grid scale variability in cloud, (b) the desirability of using probability distribution functions (PDFs) to represent this variability, (c) the use of observations and cloud-resolving model to inform the parametrizations of sub-grid scale variability, and (d) the dependence of parameterizations of sub-grid scale variability on model resolution and their convergence in the limit of very high resolution.

1. The importance of sub-grid scale parameterization of clouds

The working group considered the question of how important it is to account for sub-grid scale variability of cloud occurrence, cloud condensate and water vapour and temperature. This was considered from the perspective that combining the complexity of cloud macrophysics with cloud microphysics may be difficult. Another perspective is that as the horizontal and vertical resolution of the ECMWF model increases, less sub-grid scale parameterization of cloud macrophysical effects may be necessary.

Despite these considerations, the consensus of the working group was that consideration of subgrid scale cloud variability is too important to neglect. For example, while mesoscale models may not include a parameterization of cloud fraction (i.e. there condensation is ‘all-or-nothing’), the microphysical parameterizations in these models may be modified to account for unresolved variability in cloud condensate and relative humidity. One prominent example is the precipitation formation process which is non-linear and very sensitive to the unresolved variability. Having an explicit treatment of sub-grid scale variability permits consistent treatment across many physical processes such as cloud microphysics, radiation, turbulence, and convection.

Recommendations:

The working group recommends that it is better to explicitly consider the sub-grid scale variability than to neglect it. Nonetheless, tests should be made to understand where and when sub-grid scale variability is needed. As a first step, a test whereby the cloud fraction is forced to be ‘all-or-nothing’ for purposes of radiation and cloud microphysics should be performed to ascertain what remains sensitive and thus needs parameterization.

2. The desirability of PDF approaches for cloud parameterizations

2.1. Current consensus

It was noted that the prognostic PDF approach, where the evolution of shape of the PDF describing total water and/or velocity/temperature fluctuations is explicitly modelled, allows greater consistency between model processes. For example processes such as radiation, dynamics and microphysics can use the estimate of sub-grid variability of water and clouds to consistently correct biases due to nonlinearity. The PDFs can also be used consistently in the convective triggering for example. Therefore the move towards the prognostic PDF approach is encouraged.

2.2. Towards a unified approach

A unified approach for PDF modelling for all cloud types is still pending. Most approaches to date have considered a single regime (e.g. PBL clouds or cirrus). Other schemes such as that in ECHAM5 needed many ad hoc assumptions and simplifications for the process influences on the PDF, especially for the microphysics.

There is a lack of knowledge concerning the PDF shape for some specific cloud regimes. Additionally the influence of some processes such as microphysics is difficult to specify. Last but not least there are some processes that may be key for certain cloud processes such as gravity or orographic wave driven vertical velocity fluctuations in the generation of cirrus that are not considered.

2.3. Development strategies

There are two general approaches that are not mutually exclusive to consider and model the sub-grid scale PDF. One could explicitly model the moments that define the PDF, or one can choose to diagnostically fit a PDF to other prognostic variables, such as cloud cover in the Tiedtke scheme. A choice is also required for the variables for which the sub-grid-scale fluctuations require representation. If more than one variable is required, (for example, temperature, total water and perhaps also vertical velocity) it is also necessary to consider whether each variable can be considered separately with a univariate PDF, or whether their correlations are significant, in which case a joint-PDF approach is mandatory. Again this choice is regime dependent, with PBL clouds likely to require a joint PDF approach, while univariate considerations may be adequate in the free troposphere.

Once these decisions are reached, it is also necessary to decide on the required complexity of the PDF shape for each variable. While it is evident that bimodal distributions may be more appropriate to describe convective situations, the aim should be to keep the PDF schemes as simple as possible. Complicated PDFs require more defining parameters significantly complicating the development and implementation task. Observations and high resolution models also indicated that simple unimodal PDFs may also be widely applicable. It may be the case that certain cloud regimes would be better treated by separate PDFs for the in-cloud and environmental regions, but this is currently unclear and deserves further attention.

2.4. Recommendations:

ECMWF should continue work towards implementing a prognostic statistical scheme to represent the subgrid-scale variability of total water (and by inference cloud water). Unification of the treatment of various cloud regimes should be striven for as far as possible, and if achievable, beneficial..

Further work should also be completed to ascertain whether representation of temperature and velocity fluctuations is necessary.

In addition to using this information to diagnose cloud cover, efforts should be made to move the ECMWF parametrizations towards greater self-consistency. This requires that all parametrizations use the same PDF information to assess sub-grid fluctuations for e.g. radiation and microphysics bias correction or convective triggering for example.

3. The use of observations and cloud-resolving models to inform parameterizations of sub-grid scale cloud variability

The working group considered the use of observations and fine-scale models in the development of a PDF-based cloud scheme. Observations will find additional use as a means of verifying the parameterization and this process will be iterative. The literature contains a wide range of examples in which in-situ, satellite, and ground-based observations have been used to examine the PDFs of clouds and water in the atmosphere. Such information has been useful in guiding assumptions such as the choice of PDF to be used in a cloud scheme and in determining the values of empirical parameters. Such studies should certainly be continued, and new observational capabilities (especially the A-train and ground-based sensors such as ARM and Cloudnet) will no doubt prove useful in these further assessments. Observations have not, to date, been used to elucidate the processes responsible for changing the PDF over time. It might be possible to use observations in this way, however, given clever sampling strategies, such as examining the PDF of cloud ice as a function of distance from a convective tower.

3.1. Recommendations regarding observations:

That the Centre support observational efforts, especially in remote sensing, to make collocated measurements of relevant dynamic and thermodynamic quantities at fine time and space scales.

That the Centre consider a range of ways to use existing observations to help assess rates at which processes in the atmosphere affect the PDF of total water and other quantities.

The working group noted that cloud-resolving models have been used in the development of PDF cloud schemes and will likely become more important with time. The models are useful both as a way of testing assumptions in the scheme (such as the shape of the PDF) and, more importantly, as a way of assess the rates at which other processes (such as convection) influence the PDF over time. Fine-scale models may be more useful than direct observations in this context because they contain much more of the information needed by a PDF cloud scheme, particularly regarding the time evolution of the PDF.

3.2. Recommendations regarding fine-scale models:

That the Centre continue to support the efforts of groups such as GCSS that aim to develop cloud-resolving and large-eddy models, and to evaluate their performance against observations.

That the Centre make active efforts to use analysis of cloud-resolving and large-eddy model simulations to aid in the development of PDF cloud schemes. Such simulations might come from existing case studies (i.e. GCSS), from global simulations (such as super-parameterizations or global cloud resolving models), or from simulations done within the Centre itself.

4. Dependence of sub-grid variability parameterizations on model resolution and their convergence in the limit of very high resolution

There was quite a bit of discussion regarding resolution, both horizontal and vertical. The major issue is whether there is convergence of various model physical schemes across horizontal resolutions. This is very important for cloud parametrizations, including boundary layer and shallow clouds as well as for microphysical parametrizations. It is not clear that the present cloud schemes are convergent in this way. Sub-grid variability is a method to attempt to ensure this convergence by representing important variability at sub-grid scales for larger resolutions.

Statistical approaches for cloud schemes are beneficial since they potentially converge smoothly at small scales. As more and more of the variance is resolved, the sub-grid variance shrinks with increasing resolution to something approaching a binary cloud at resolved scales. This convergence is less obvious for the current prognostic cloud fraction parametrization.

There was less discussion of vertical resolution. There was a general consensus that vertical resolution at ECMWF (91 levels or nearly 250m in the free troposphere) is sufficient to ignore sub-grid variability of cloud in the vertical for large scale condensation. This is not necessarily true for the boundary layer. It would be wise to verify this statement at least in a single column model framework (through varying vertical resolution). Note that this is not to state that the vertical resolution is sufficient *per se*, merely that it is felt to be sufficient to ignore this specific issue of representing vertical subgrid variability.

4.1. Recommendations:

The major recommendation is that parametrizations for subgrid variability should be developed across vertical and horizontal resolutions, and tested for convergence across this range of resolutions.

Working group on Validation

1. Measurement Gaps and Future Priorities

Remote sensing methods for observing key cloud properties keep improving. This advance has occurred partly through the intelligent blending of surface, in situ and satellite observations and partly through the recent arrival of new capabilities in observing clouds and precipitation globally. However, a more direct pathway between the essential processes that shape global cloud and precipitation, the modeling parameterization of these processes and both these new observations and existing observations is required.

Despite these advances, important gaps still exist in our ability to provide observations that will critically test current and evolving parameterization schemes;

1.1. Cloud and precipitation observational gaps

- The measurement of solid precipitation
- The microphysical properties (profiles) of (solid and liquid) precipitation (all intensities)
- The microphysical properties (profiles) of clouds
- In cloud vertical motions
- The sampling of these properties over the diurnal cycle

Although current global observations are now beginning to provide information about the mass of water and ice in clouds (or proxies for this information), it is clear that other moments of the particle size distributions will be required to validate new generation parameterization schemes. It can be anticipated that observational approaches that provide at least measures of two moments (such as concentration and mass) will be a minimum requirement. Also important in this context, as well as for other applications, such as cloud and convection dynamics, is the need for in-cloud vertical motion observations. The cloud parameterization community should offer a guiding voice in defining requirements on the spatial and magnitude resolutions of such observations.

1.2. Related environmental observational Gaps

Other areas of need include;

- Near surface winds for evaporation
- Better resolved boundary layer temperature and moisture structure
- Soil moisture
- Aerosol types/profiles/microphysics

1.3. Observing Strategies

While the need for global observations of the critical cloud and precipitation parameters is obvious, the observing strategy has to involve (i) the integration of these observational types with other types, such as those provided from advanced surface observatories (e.g., ARM sites), (ii) the use of multiple types of remote sensing observations of the same and complementary parameters such as is now available from the TRMM and the A-Train. Furthermore, future global observing systems designed to make probing measurements of critical processes do not need to provide these observations everywhere all the time. For many properties, perhaps notably microphysical properties, it is most likely that providing highly relevant, globally sampled measurements will more critically advance parameterization than observations obtained from broader-scale measurements of poorly resolved cloud parameters.

2. Continuity of Existing Data Sets

For the purposes of validating cloud representation in models, it is crucial to maintain continuity of a number of existing data sets as well as perform specialized field experiments. Their continuity is important to address the needs associated with the following four areas:

1) *Process studies, cloud modeling (e.g., CRM), and parameterization development* – derived from intensive observing campaigns as well as strategic use of super sites and satellite data in order to target specific processes (e.g., convection, marine stratocumulus). Such activities are also vital to develop and validate remote retrievals that in turn are used for model development and validation.
2) *Long-term and global validation* – in order to thoroughly evaluate cloud models and parameterizations under a full range of synoptic and regional climate conditions.
3) *Data assimilation* – due to the effort required in assimilating new types of observations, it is important to establish continuity of quantities that have proven impact. Continuity of such measurements is also important in order to best represent long-term variability and trends in re-analysis products.
4) *Climate Trends* – proper representation of climate trends and associated cloud feedbacks provide a stringent test for cloud models and parameterization. This goal will only be met by having consistent calibration between satellites measuring the same quantities.

2.1. Recommendations:

In order to meet the above requirements, we recommend that a high priority be placed on continuing the following data sets (not in priority order):

2.1.1. Global/Satellite

- Cloud frequency/cover characteristics, including cloud top, optical thickness and effective radius (e.g., ISCCP and MODIS)
- Cloud Ice and Liquid Water profiles (e.g., CloudSat, MLS)
- Total water vapor and total liquid water (e.g., SSMI, AMSR-E, TRMM/TMI)
- Temperature and water vapor profiles (e.g., AIRS, IASI, AMSU-A/B, MHS)
- Surface Precipitation Estimates (e.g., TRMM/TMI, SSM/I, GPM, AMSR-E, CloudSat)
- Precipitation profile (e.g,. TRMM/PR, CloudSat)
- Aerosol optical depth (e.g., TOMS, MODIS, CALIPSO)
- Top of the Atmosphere and Surface Radiation Budget (e.g., CERES, ISCCP, MODIS)

2.1.2. Local/In-Situ

- High temporal resolution broadband surface radiation (e.g., BSRN) and surface turbulent fluxes.
- High temporal/vertical resolution liquid and ice water content, particle size, rain profiling (e.g,. ARM/CloudNet – continuous cloud radar, cloud lidar, microwave radiometer)
- Intensive observation campaigns for cloud process studies, including aircraft and dynamical forcing (e.g., ARM IOPs, TWPIce, weather radar)

3. Use of Cloud Simulators

The forward modelling of satellite measurements is an established component of the data assimilation process. Since the early 90's, ECMWF has pioneered the use of forward modelling to make use of multi-spectral satellite measurements not only for data assimilation, but for validation clouds, water vapour and other atmospheric constituents. (e.g. Morcrette 1991, Chevalier et al 2002.) This approach allows maximum use information from satellites, but requires an understanding of the radiative transfer on the part of analysts. This can be contrasted with the alternative approach of comparing retrieval products with model variables. The latter comparisons are often not quantitatively useful because the retrieval process uses different assumptions to those made in the models (e.g. cloud radiative properties) and the retrievals may be limited in terms of the viewing geometry from above (e.g. low clouds not visible when obscured by high clouds.)

Klein & Jakob (1999) and Webb et al (2001) developed an ISCCP simulator, which lies between the two approaches outlined above, running a simple forward model on the GCM's clouds and applying a simplified version of the ISCCP cloud retrieval to the results. The ISCCP simulator also samples the overlaps in GCMs to give information on the subgrid cloud distribution. This simulator is openly available and has now been applied to a range of models, for example as part of the Cloud Feedback Model Inter-comparison Project. It has helped to improve cloud simulations in a range of models by identifying problems that are not detectable using ERB data alone (e.g. Webb et al 2001, Zhang et al 2004). As part if the CFMIP Phase II, a combined ISCCP/CloudSat/CALIPSO simulator is under development in collaboration with a number of groups including CSU. Simulators could also be applied in the context of ground based radar/lidar comparisons.

In climate mode, it is also necessary to have well designed statistical summaries of these products (e.g. the tau/Pc diagrams of the ISCCP D1 product.) Methodologies for compositing cloud observations (e.g. the clustering technique of Jakob and Tselioudis 2003) are also required to present cloud data in a process oriented/parametrization focused framework (e.g. by separating deep convective/low cloud statistics). These should be applicable to a range of timescales (e.g. diurnal, seasonal, interannual).

3.1. Recommendation

We recommend that modelling groups run these simulators routinely in their climate and NWP models, to gain maximum benefit from satellite cloud observations as part of the model validation/development process.

4. Data Assimilation

Operational forecasting systems have greatly evolved over the last decade and provide forecasts of atmospheric temperature and wind fields with unprecedented accuracy. The forecast skill of moisture fields as well as clouds and precipitation is less accurate, largely because of the lack of detailed knowledge of moist physical processes (cloud statistical properties, sub grid-scale variability, convection), the crude approximation of moist physical processes by model parameterizations due to limitations in computer memory and time, and the inadequacies of data assimilation systems to handle cloud and rain affected observations (observation operators, non-linear processes, wide range of scales). At present, this results in model analyses that are dominated by clear-sky observations. This produces inadequate data coverage and constrains moist processes only with observations that are only indirectly related to moist processes.

Despite these problems, several studies have demonstrated the feasibility of cloud and precipitation data assimilation in global (NCEP, ECMWF) and regional systems (JMA, CSU, NCAR, FSU) only few of which succeeded to produce operational systems (NCEP, ECMWF, JMA). Improvements in moist physics parameterizations, data assimilation systems (e.g. observation operators, observation operator error definition, model background error definition in clouds/precipitation), and the rather vast amount of satellite observations sensitive to clouds/precipitation (passive and active microwave on both operational [DMSP, NOAA, EPS, NPOESS] and experimental [TRMM, Cloudsat, EarthCare] satellite systems) promise large improvements of NWP systems related to cloud and precipitation data assimilation in the future.

The assimilation of cloud/precipitation observations in cloud-resolving models (CRMs) greatly emphasizes issues related to model non-linearity and under-constrained analyses that will be difficult to overcome in operational applications. New systems may have to approach the data assimilation problem in a statistical way such that the cloud/precipitation pdf's are constrained by related pdf-type information from satellites.

4.1. Recommendations

- Improve description of sub grid-scale variability of cloud statistics and convection.
- Improve linearized schemes.
- Develop new methods for model error estimation in clouds/precipitation.
- Perform sensitivity and simplified assimilation studies where well-defined/comprehensive datasets are available (ARM-type sites) to improve understanding of system performance and areas of largest potential for future developments.
- Perform extensive monitoring of cloud and precipitation affected observations against model simulations (see Simulators above).
- Include available operational datasets from ground-based networks (radar); however this requires availability in near real-time (US vs. Europe) and strict data quality control.
- Improve communication between observation, data assimilation and physical parameterization experts.
- Observational datasets to be used in operational data assimilation must be available in *near real-time* (NRT). The NRT requirements depend on application and usually range from 3 hours (global NWP) to minutes (regional NWP, NWC) (see WMO summary of operational NWP requirements).

4.2. Further information

JCSDA workshop on 'Assimilation of Satellite-Observed Cloud and Precipitation',

2-4 May 2005; http://www.jcsda.noaa.gov/CloudPrecipWkShop/index.html with special issue of JAS in press.

5. Utilization of CRMs

CRMs and LES predict clouds explicitly and thus do not use any parameterisations for cloud fraction or cloud overlap and thus represent the cloudiness with less tunable parameters than GCMs. On the other hand, they need to use microphysical parameterisations which are somewhat uncertain. Note however that the resolution of CRMs does not allow to simulate turbulent processes explicitly (contrary to LES) and therefore the simulation of boundary-layer clouds might be deficient in CRMs. They are also able to reproduce convective circulations and the different diabatic heating terms at the scale of the cloud systems. They are able to simulate better than GCMs the transition between shallow and deep convection, the interaction between orography and convection, or the triggering of new convective cells by gravity currents generated by the evaporation of the falling precipitation.

For these different reasons, CRMs can play a key role in providing guidance on how physical processes control the subgrid-scale variability of water (for instance) and how this may be represented in GCMs' cloud parameterisations (e.g shape of PDFs for statistical cloud schemes, diagnostics of statistical moments).

On the other hand, owing to uncertainties in their representation of cloud microphysics, their prediction of the cloud cover, cloud optical properties and radiative processes are not good enough to be used for the evaluation of similar quantities in GCMs.

We note a growing use of CRMs for cloud-in-climate studies (climate sensitivity studies performed by global CRMs, MJO simulations performed by super-parametrizations, etc).

5.1. Recommendations :

- encourage CRMs/LES intercomparisons and comparisons to observations to clarify what the robust aspects of these simulations are that may be used by the GCM community to develop parameterisations. For instance, it would be very valuable to use high-resolution satellite data to assess the subgrid-scale variability of moisture simulated in CRMs/LES.
- encourage CRMs/LES studies that help to determine the level of complexity required for cloud parametrizations (e.g. the number of cloud species in microphysical parametrizations)
- encourage comparisons between CRMs/LES and single-column models or GCMs focused on particular physical processes or phenomena (e.g. the sensitivity of convection to moisture in the free troposphere, the diurnal cycle of convection, the transition between stratocumulus and cumulus clouds, the simulation of shallow convective clouds, etc).
- encourage the analysis of climate simulations performed by CRMs (e.g. MJO, monsoons, climate sensitivity, etc) to better understand why the results from these models might be better (e.g. for MJO) or different (e.g. for climate sensitivity) than the corresponding simulations from GCMs.

As a more general point, the working group felt strongly that models should be validated/tested in both NWP and Climate Simulation modes.

Working group on Cloud Parameterization Priorities

This working group focused on the following four questions: i) How to determine the weaknesses of cloud parameterizations, ii) what degree of microphysics is needed in NWP/climate models, and iii) what should be the focus for future cloud parameterizations. It might not be possible to answer these questions generally as different regimes might require different approaches, eg. deep convection and anvil clouds, mid-level (altostratus, altocumulus, frontal clouds) and PBL clouds (fog, stratocumulus, shallow cumulus). Nevertheless some general guidelines are proposed below.

1. How to determine weaknesses

The first question to be answered is how to determine weaknesses in cloud parameterizations. This is not always easy as clouds are strongly linked to the model dynamics and moisture fields. However existing and future observations from space like geostationary satellites (using e.g. brightness temperatures), lidar/radar profiles of clouds from the A-train including Cloudsat and Calipso, and ground-based retrievals of cloud profiles (Cloudnet: 6 ARM, 4 EU sites) provide solid independent information. Furthermore, the temporal and spatial variability of the clouds and convection should be examined including the diurnal cycle of clouds/convection over land and water, the Sc/Cu transition problem, the wintertime Sc over land, as well as the ability of the schemes to produce a tri-modal cloud distribution in the Tropics. Also, the GCSS (GEWEX Cloud System Study) regional modelling activities such as performed by the deep convection, and mid-latitude groups, as well as by the "Pacific cross-section Intercomparison" groups deliver benchmark simulations, and allow to reveal the first-order errors in a controlled environment. This controlled environment could be short-range forecasts where the model is close to the analysis.

2. Microphysical processes key for NWP and climate models

From experience in modelling/observations a few general statements can be made about key microphysical processes in NWP. Generally one can say that the smaller the horizontal scale, the more details in terms of processes and species are required for the microphysical scheme in order to model the storm dynamics. The microphysical parameters that are not well-constrained and leave room for tuning are the autoconversion rates and the collection efficiencies (the latter affecting also the drizzle production). Furthermore, the evaporation of precipitation, a process that affects the subcloud-layer dynamics and the evaporation from the oceans, is difficult to model as it requires the subgrid-scale distribution of the moisture field. Finally, processes like ice nucleation, impacting the precipitation and radiation, supercooled water, impacting aircraft icing, and size distributions of cloud species, are thought to be presently of secondary importance for NWP and climate models.

3. Focus for future cloud parameterization development

It is thought that further progress in the representation of clouds and in NWP in general will be made by including some form of subgrid variability in microphysics and radiation, and maybe even convection. Ideally one can imagine an approach like McICA for all cloud parameterizations and one could have one information stream (subgrid variability in total water and/or vertical velocity) that links the radiation, the PBL, the stratiform cloud, and the convective cloud parameterizations. However, so far no statistical cloud scheme has been developed that outperforms a prognostic deterministic large-scale cloud scheme; probably because the representation of long-lived mid-level clouds and upper-tropospheric cirrus is difficult in a statistical approach.

Nevertheless, further improvement with the prognostic large-scale cloud scheme seems feasible through the increase from 1 to say 4 hydrometeor classes (including the precipitating phases). Some groups reported improved orographic precipitation with such an approach. Finally, developers of microphysical schemes should always keep the data assimilation aspect in mind, and in particular to limit the numbers of free parameters that cannot be controlled by observations, and to develop schemes that are quasi-linear.

4. Recommendations

The general recommendations that emerged from this working group concern the use of CRMs and LES in order to study i) the importance of subgrid-scale variability by gradually degrading the 4D resolution of the simulations and then evaluate their impact against observations and the reference simulations, and ii) the degree of complexity needed for microphysics by systematically degrading the complexity of the microphysical schemes. It is believed that going the longer way (learning curve) through CRMs is preferable to directly manipulating the GCMs parameterizations, as CRMs resolve more processes. Furthermore, it is suggested to investigate deficiencies of the simple microphysics used in convective parameterizations, and to further develop the numerical aspects (implicit solvers, accurate advection schemes) of the microphysical schemes. Concerning the aerosol-cloud interactions, these could certainly help to improve systematic errors in the long integrations, but are still too uncertain, and too difficult to control, and probably cannot be implemented in NWP in the short-term. However, the direct aerosol effect on the radiation is a priority in NWP and might be possible to implement in the coming years.

Finally, on the more specific side we think that further attention has to be given to processes in mixed phase clouds, the evaporation of rain in multi-layered clouds and clouds in strongly-sheared environments, the link of vertical velocity to subgrid-scale processes in 2-moment microphysical schemes, and, not surprisingly, more laboratory studies are needed for EVERY microphysical process.