1. WORKING GROUP 1: OBSERVATIONS AND DATA SETS

1.1 INTRODUCTION

1.1.1 CTBL clouds and data sets

The group discussed briefly the range of BL clouds from fog to Cu and SCu over land, sea and ice. It was agreed that the diurnal cycle of Cu and SCu over land presented the most critical problems at present in NWP models (because of their impact on the surface energy budget). BL clouds over the ocean, while they do not impact the surface temperature in these models, are also important because they affect the surface fluxes and atmospheric radiation field (and may of course be advected over land).

The majority of data sets that have been collected address oceanic BL clouds; for example, FIRE and ASTEX addressed the SCu regimes and the transition through mixed Cu and SCu BL's to broken cumulus. ARKTIS studied the BL growth off the Arctic ice; KONTUR frontal clouds in the North Sea; FATE the cloud fields near Ascension Is.; while ACE and SOCEX are in progress near Tasmania. There is a large body of MRF research flights which study marine cloud fields around the UK.

There is a lack of data sets for the study of the diurnal cycle of CTBL over land. BLX83 over central Oklahoma is probably still the most important data set. Also HAPEX in the south of France has a few days with broken clouds. FIFE studied the surface and BL interaction over grassland in Kansas, but paid little attention to the cloud fields. BOREAS, over the Boreal forest in Canada during 1994, will provide some data on this problem, since BL clouds are a characteristic feature of this forested area full of lakes. However, this is again not the primary focus of the experiment.

Besides the issue of winter and summer clouds over land, we were concerned that the momentum transports by shallow convection have not been adequately studied. These may contribute to the backing of wind with height in cold air outbreaks. The formation of SCu, and mid-latitude SCu also need further study.

We were agreed on the importance of drizzle processes, but the close coupling to aerosol history and chemistry makes this a more distant topic for inclusion in NWP models; to be deferred until we have successfully modelled the bulk thermodynamics of the CTBL, using assumed drop spectra.

We suggest that the cloud climatologies, such as ISCCP and the Warren cloud atlas, be supplemented at ECMWF by the routine archiving and processing of synoptic cloud reports as an ongoing climatology.

We suggest that efforts be made to add surface radiation data to the GTS, so that validation of the model surface radiation budget can be done operationally.

1.1.2 Mechanisms seen in the marine data sets

Results of analysis of these data sets have shown that certain processes dominate the mechanisms occurring in the stratocumulus capped boundary layer. Detailed below are the processes that are considered to be the most important:

a) Decoupling of the boundary layer

Throughout these data sets decoupling of the cloud layer from a well mixed surface layer is pervasive, both as a feature of the diurnal cycle and on a quasi-permanent basis in deeper boundary layers. In boundary layers where mixing is driven by longwave radiative cooling from cloud top, short wave absorption in the cloud during the day can limit the production of turbulent kinetic energy and restrict the depth of the mixing, cutting off the cloud layer from the surface moisture supply. Entrainment of dry air from free troposphere into the cloud layer can then cause the cloud layer to thin or even break up. This change in cloud liquid water path and fractional cover can have significant consequences on the cloud reflectivity and thus the surface energy budget. Moisture build up in the well mixed surface layer can lead to conditional instability which produces cumulus clouds that can penetrate the stratocumulus layer. These can either act to thicken the stratocumulus by recoupling it to the surface moisture source or aid in breaking it up through enhanced entrainment of dry air from above the inversion.

The data shows us that large scale numerical models currently are treating the boundary layer in too simplistic a manner and that there is a need to simulate its layered structure. This has significant implications on the vertical resolution of predictive boundary layer schemes where it is considered that the resolution should be at least 100m.

b) Microphysics and drizzle processes

It is abundantly clear from the data that the aerosol characteristics of the boundary layer affect the microphysics and radiative transfer properties of the cloud layer. To correctly simulate the surface energy budget, account must be taken of the cloud condensation nuclei (CCN) concentration which govern the size and number of cloud drops. Drizzle production, which can be an effective decoupling mechanism through evaporative cooling and can also limit the cloud liquid water, can be turned off in stratocumulus if CCN concentrations are high enough in the boundary layer.

The treatment of cloud microphysics and drizzle processes is a very difficult problem for large scale numerical model parametrizations but at some time in the future the sources, sinks and advection of CCN need to be considered and included in such models.

c) Mesoscale organisation

Satellite observations and field experiments show that boundary layer clouds do on occasion have mesoscale organisation. It is thought that these features do not have a large effect on the transition from extensive stratocumulus to no stratocumulus, rather they smooth out the transition. At present our understanding of the physical mechanisms underlying these organisations is very poor and it is not known how to handle the parametrization of the processes in larger models.

d) Cloud Top Entrainment Instability (CTEI)

The ASTEX data indicates that the transition from solid stratocumulus to trade wind cumulus is not a sudden event. The aircraft measurements and radiosonde profiles can be used to investigate if CTEI is an important mechanism in the transition. It can certainly be seen from aircraft measurements of penetrations of cumulus clouds that CTEI is playing an important role in producing downdraughts and eddies in cumuli.

e) The Evolution and Break up of Stratocumulus

The ASTEX data set probably contains enough high quality data to study the important processes involved in maintaining and breaking up stratocumulus layers. The break up is observed to be a gradual process, happening on time scales much longer than the circulation timescales of the stratocumulus eddies.

During ASTEX multifarious mechanisms were observed to be occurring in the cloud topped boundary layer. Decoupling of the cloud layer from the well mixed layer was seen for the majority of the time. Dramatic changes in air mass were encountered, when north easterly winds brought highly polluted air from Europe, allowing extensive measurements of the sensitivity of the cloud microphysics to boundary layer aerosol to be made. Cumulus clouds, often seen rising from the well mixed surface layer into the stratocumulus layer and their effects on maintaining and breaking up the layer, could be monitored. Drizzle production was observed on several occasions and two intensive-measurement Lagrangian experiments were carried out to look at the evolution of the cloud topped boundary layer over a 48 hour period.

1.1.3 The Use of Data in Developing Parametrizations

Routine and climatological data are very important for validating parametrizations and pointing out model deficiencies. Integrated field experiments are better suited to the development of better and more physically based parametrizations. In the ASTEX Lagrangian IFO's, for instance, almost continuous aircraft sampling of turbulence, microphysics and radiation in the same air mass for 36 hours was combined with remote sensing, chemical measurements, and shipboard measurements of sea-surface temperature. This should permit a comparison of cloud and turbulence properties with both large-eddy simulations and bulk and other parameterized models of CTBL evolution. The insights gained by comparing different types of models on the same well-observed case are very important. LES models are beginning to show substantial skill in reproducing some features of marine stratocumulus-capped boundary layers (decoupling, for instance) and can help suggest and calibrate physical frameworks for parametrizations. Nonetheless, they are no substitute for data; for instance current LES's do not resolve the entrainment zone at a trade inversion, and may produce incorrect entrainment rates. Furthermore, mesoscale variations in cloudiness have yet to be accurately simulated with any model. Good parametrizations, good highly resolved models,and good observations (including laboratory fluid flows!) all feed back on each other through improvements in scientific understanding.

In this context it is important that integrated data sets suitable for either column or regional intercomparisons of data with parametrizations, LES's, mesoscale and global models are easily available. Such data sets have already been compiled for modelling (1) A quasi-steady trade cumulus regime (BOMEX) and (2) the coastal stratocumulus diurnal cycle (FIRE, see presentation of P. Duynkerke at this workshop). The ASTEX Lagrangian IFO's are being documented currently by C. Bretherton, providing case studies on stratocumulus to cumulus transition, diurnal variability and drizzle. In addition, a well-documented example of changes in cloud organization and optical properties due partially to aerosol variations has been compiled by D Johnson (see workshop proceedings). During the FIRE and ASTEX experiments, Pat Minnis and coworkers at NASA performed regional satellite retrievals of cloud fraction and cloud-top temperature on a daily basis. These are important in defining the overall cloud properties for comparison with cloudiness parametrizations. We also hope that a cold-air outbreak data set will be compiled from the ARKTIS experiments off the Greenland sea-ice edge. A good data set integrating dual-Doppler radar and aircraft observations of precipitating shallow cumuli was also compiled during HaRP but has not been integrated into a form easily comparable to cloud-scale models. An integrated data set (including surface flux and cloudiness measurements) in continental stratocumulus is still sorely needed.

1.1.4 Validation of CTBL in GCM's

The validation of Boundary Layer clouds in GCM's involves not only the basic cloud validation (cloud cover, liquid water content and optical properties) but also the verification of different parameters that affect or are affected by the presence of clouds. The parameters we should validate are mainly:

- cloud cover
- integrated liquid water content (liquid water path)
- surface fluxes (radiative, latent and sensible heat)
- radiation fluxes at the top of the atmosphere
- 2m temperature

- inversion height and mixing ratio at the inversion and in the boundary layer
- large scale subsidence

Some very useful observations of the 3 dimensional distribution of cloud parameters are available from measurement campaigns. They can be used to validate the satellite products that do not describe the vertical distribution (eg for the liquid water content):

- 3-d radiation fluxes
- turbulent fluxes at the cloud base and turbulent fluxes in clouds
- vertical profiles of cloud liquid water

There are different types of measurements available for direct cloud verification. For a global validation of cloud cover satellite products like those produced for ISCCP can be used in a non simultaneous way. However, the 3-dimensional model cloud cover should be post processed in a similar way as the satellite derived clouds to achieve comparable results in situations of higher clouds overlapping lower clouds.

SYNOP observations are useful for direct point observations of model clouds. With additional use of satellite imageries one can select situations in which exclusively low clouds occur.

Another aspect of the validation of the Cloud Topped Boundary Layer in GCM's concerns the diurnal variation of surface fluxes, inversion level, cloud emissivity, that are strongly coupled with the diurnal cycle of insolation. This aspect addresses the need of a regular temporal sampling of the observations (at least 3 hours).

The general lack of observational data for a direct verification of cloud related processes can at least partially be overcome by investigating the internal balance of all relevant processes in the model. In areas where the large scale analysis is sufficiently supported by radiosonde data, budget residuals calculated form initial model tendencies can give a good indication of problems in the parametrization scheme.

2. WORKING GROUP 2: LARGE EDDY SIMULATION (LES), CLOUD RADIATION AND MICROPHYSICS

2.1 INTRODUCTION

In this working group we assessed the current state of knowledge, examined how LES can be used to improve cloud parametrizations in large-scale models and identified some major research needs.

2.2 CURRENT STATE OF KNOWLEDGE

We addressed the question of what is the current state of knowledge by constructing a chart that shows the location of various boundary layer flow regimes in relationship to the difficulty of simulating them with LES and the current level of understanding. Not surprisingly, there is a strong correlation between ease of simulation and level of understanding.

The clear convective boundary layer is easiest to simulate and best understood. The shallow cumulus BL is not difficult to simulate, but is less well understood. The stratus-topped boundary layer is significantly more difficult to simulate and less understood due to the strong interactions between turbulence, cloudiness and radiation, and the dynamical importance of small-scale mixing, including explicit microphysics, further adds to the complexity. The stratus-to-cumulus transitional BL is more complex than the stratus-topped BL, and is more difficult to simulate due to the longer time scales involved (several days). These four regimes are considered sufficiently easy to simulate that LES data sets can be reliably used to increase understanding, improve and validate parametrizations. Less attention has been paid to boundary layers affected by deep, precipitating convection. These are more difficult to simulate due to the greater range of scales of motion involved.

The BL in a baroclinic flow is also not well understood, and is still not easy to simulate. Additional scaling parameters add complexity to parametrizing this flow regime.

The boundary layer regime that is poorly understood is the stably-stratified BL. This is also difficult to simulate due to the nature of intermittence, the quasi-two-dimensionality of turbulence, the smaller scales involved and the greater importance of wave motions in this situation.

These regimes are considered feasible for LES in the next few years.

The remaining three regimes shown on the chart are on the limits of feasibility for some time. These regimes are the BL over heterogeneous surface or in a mesoscale-organized environment, the precipitating cloud-topped BL, and the cloudy BL with 3-D interactive radiation.

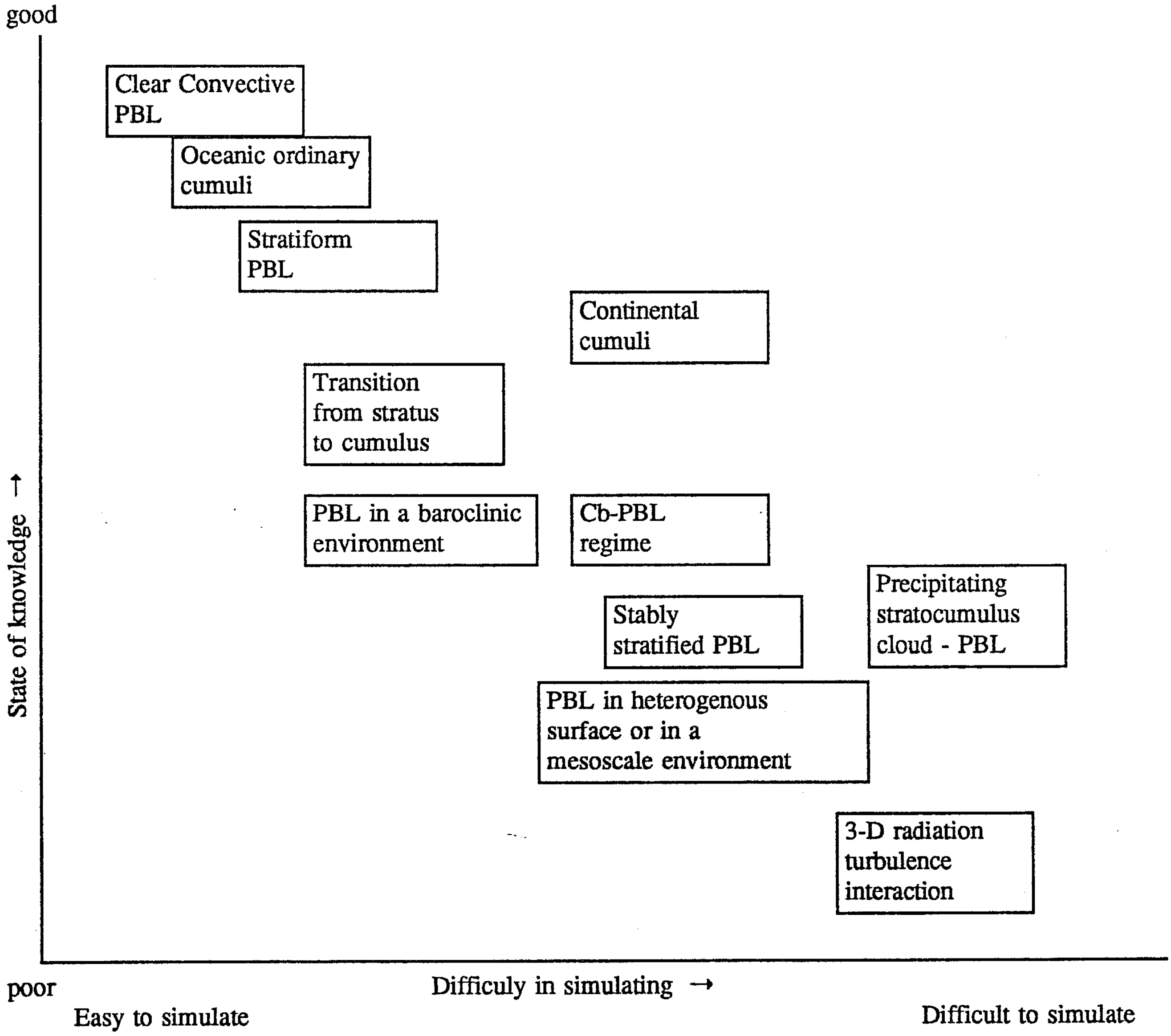

Table 1: Schematic diagram of the state of knowledge of BL clouds and level of difficulty for LES

2.3 HOW CAN LES BE USED TO IMPROVE CLOUD PARAMETRIZATIONS IN LARGE-SCALE MODELS?

- LES can contribute to understanding of the physical processes which control heat, moisture and momentum fluxes that determine the thermal and dynamical state of the cloud layer.

- Statistical profiles obtained from LES can be used to calibrate closure assumptions and coefficients used on existing and newly-developed schemes and verify predictions with those schemes.

- The performance of boundary layer cloud parametrization schemes (eg in predicting turbulent fluxes, cloud depth, liquid water, cloud coverage) can be evaluated over a broad range of large-scale conditions simulated by LES.

- LES with detailed microphysics can simulate drizzle formation and the vertical and horizontal variability of cloud microstructure, that can be useful for parametrizing drizzle and radiances.

- Application of a three-dimensional radiation scheme to LES-generated cloud fields can provide a data base for developing simpler radiation schemes for GCMs.

2.4 RESEARCH NEEDS

LES models have been used to study only a limited range of boundary layer structures and the total number of simulations is small. The use of LES models to develop parametrizations, either using statistical techniques or through improved physical understanding, will require LES models to be applied to a variety of situations as well as further model verification and development.

A major problem in parametrizing the boundary layer is the role of mesoscale organization due to changes in the underlying surface or to the mesoscale atmospheric circulation. In order to quantify the impact of such forcing it will be necessary to undertake LES model runs as well as further field experiments. The aim of the studies would be to determine the impact of organization on the flux profiles and on the cloud cover.

LES model runs in which cloud fields have been predicted, have not included simulations of cold boundary layer clouds. In such clouds the presence of the ice phase will influence the microphysical processes which control the evolution of the cloud layer through precipitation formation and through radiative effects. Numerical simulations of such clouds should determine the impacts of the ice phase.

The development of parametrization of the boundary layer cloud fields will require detailed analyses of the LES model dynamical and microphysical fields. It appears that coarse resolution models under-estimate cloud formation because they cannot represent that region of high vertical velocity in which cloud forms preferentially. Research is necessary to develop techniques for statistical analysis of LES model-output fields.

A variety of microphysical schemes has been used in LES models, some highly parametrized schemes and some explicit schemes. Comparisons are needed to evaluate the performance of the parametrization schemes since these are often based on schemes developed for convective clouds and may not be applicable to clouds in which the turbulent vertical velocities are comparable with the fall speeds of the droplets and, as a result, droplet lifetimes may be very long. It is known that the radiative properties of cloud fields are sensitive to the structure of the cloud field although the radiation schemes employed in LES cloud simulations are currently based on the plane parallel assumption. The extent to which the 3-D radiation field affects the eddy structure of the cloud should be investigated using more complex (eg 6-stream) radiative transfer codes.

Although inaccuracies in the prediction of cloud water content and cloud coverage dominate the calculation of radiative heating and cooling profiles in large-scale models, this may not be true of climate models where the results are sensitive to the assumed droplet sizes and hence the CCN concentration. Research is needed, using LES and other models, to determine the impact of CCN on parametrized cloud microphysical properties.

Further data sets are required in order to evaluate LES models and the radiative and microphysical parametrizations. Over land, observations are required which particularly relate the structures of the boundary layer to the nature of the forcing by the underlying surface.

The problem of the transition layer requires more detailed flux profiles to be obtained, with high vertical resolution.

One of the most difficult problems in evaluating LES models is that of verifying entrainment rates for which good observations are not available. Also, large-scale vertical velocity fields are seldom known to a sufficient accuracy. Field experiments are required in which such information is obtained in addition to measurements of the fluxes.

While there are several observational data sets relating to the properties of the stratocumulus capped boundary layer, there is presently only limited information on the cumulus cloud layer and on the transition from cumulus to stratocumulus. Further detailed observational studies are required in these areas to assist in the verification of the LES models.

Recommendations

The current state-of-the-art in LES modelling is such that we recommend the application of LES models to assist in developing, refining and testing PBL parametrization schemes for large-scale models of:

- the cloud-free PBL
- non-precipitating stratocumulus-topped PBL
- ordinary or trade-wind oceanic cumuli
- transition from stratus to cumulus.

The other cloud regimes listed in Table 1 are also suitable to LES but the current level of understanding and the difficulty in simulating those clouds is such that we do not have confidence that LES will make a major impact upon their parametrization at this time.

There is a need for closer coordination between those parametrizing clouds and LES modules. There is a nucleus of such efforts currently at ECMWF, NCAR, UKMO, KNMI and NCAR/ECMWF but this should be done more extensively. Perhaps GCSS can assist in fostering such coordination.

3. WORKING GROUP 3: PARAMETRIZATION IN FORECAST AND CLIMATE MODELS

3.1 INTRODUCTION

3.1.1 Importance of boundary-layer parametrization

Accurate representations of boundary-layer processes in weather prediction and climate models are important for several reasons. The relative importance of these depends on the type of application.

For weather prediction, especially in the short and early medium range, there is a key requirement for accurate forecasts of the weather parameters of particular relevance to users. Surface temperature, winds and cloud cover are traditional products for the general user, but there is interest also in newer products such as air-quality indicators. Additional products are provided for specialized users, for example, cloud-base height for aviation. Also data assimilation requires accurate boundary layer parameters in the short range as a first guess.

The treatment of the surface fluxes of momentum, heat and moisture assumes increasing importance as one moves from short to medium and longer forecast ranges, principally because of the influence of these fluxes on the evolution of atmospheric circulations. Requirements for seasonal forecasting and climate modelling are more stringent still, not least because of the need for a reliable prediction or simulation of the evolution of oceanic surface temperatures and circulations. Correct handling of cloud/climate feedback processes is a major issue in the study of global change.

3.1.2 Current model deficiencies

It is beyond the scope of this report to give a comprehensive review of deficiencies in the treatment of the cloudy boundary layer in atmospheric models. A few general remarks and specific examples are nevertheless given, and further examples can be found in some of the accompanying lecture texts.

There are problems in the treatment of all types of boundary-layer cloud. A particular difficulty is knowing how to represent thin stratus and fog. Significant errors are found in predictions and simulations of the amount of stratocumulus and fair-weather cumulus. Underprediction of these cloud types results in surface land temperatures that are too cold in winter and too warm in summer, a particular current problem of the ECMWF model and some others. In atmospheric climate models, errors in the simulation of marine stratocumulus can cause serious errors in coupled ocean models unless surface fluxes are artificially corrected.

Difficulties are found also in predicting other cloud characteristics such as cloud-base and cloud-top. A specific example recently encountered at ECMWF concerns the height and strength of inversions. A tendency for inversions that are too strong and too high has been found to depend on vertical resolution and the numerical scheme chosen for vertical advection, as well as on the parametrizations of shallow convection, turbulent diffusion, clouds and radiation.

3.2 EVALUATION OF CURRENT BOUNDARY LAYER CLOUD PARAMETRIZATION

Current GCM models treat separately the deep/shallow convection and boundary layer (BL) turbulence. For boundary layer clouds both are important. Shallow convection deals mainly with cumulus (small cloud cover) type clouds whereas the BL parametrization should treat the layered stratus clouds.

3.2.1 Boundary layer turbulence

Turbulence parametrization has to mix the momentum, heat and moisture in the boundary layer. An important aspect of the turbulence model is the entrainment across the inversion at the top of the boundary layer. Current turbulent parametrizations used in GCM's are (see C Moeng paper in this proceedings): diffusion coefficients that depend on gradient Richardson number, higher-order turbulence closure models, non-local closure models, eddy-exchange profile methods and mixed-layer models. Transilient turbulence closure may be adequate, but has not been used yet in a GCM.

The turbulence parametrization will have to describe properly the cloud/subcloud coupling and give the proper interaction with the convective parametrization. Vertical resolution currently used by GCM's is coarser than the thickness of most BL clouds. Increasing vertical resolution, although desirable from the physical point of view, creates numerical problems associated with representation of vertical advection in the presence of sharp gradients and/or numerical instability. For fast time-varying clouds, the typical timestep for radiation computations used by current GCM's (~ 3 hours) might be too large.

3.2.2 Representation of clouds

GCM's predict properties of BL clouds such as : cloud fraction, cloud water, precipitation, etc. These properties can either be calculated diagnostically (eg the cloud cover is often made dependent of relative humidity or characteristics of the large scale flow such as subsidence) or prognostically.

The advantages of one scheme over another have not yet been fully demonstrated in terms of better cloud fraction or cloud liquid water. Diagnostic schemes have the attractive advantages of low numerical costs, and avoid the difficulties of advection/diffusion of non-conserved variables. However they rely on the specification of constants whose magnitude often depends on the host model and must be calibrated every time the physics or numerics of the host model change. Prognostic schemes can provide a more natural basis for coupling with radiation and convective processes and, in principle, can be calibrated using data from field experiments.

It is desirable to have a scheme that treats BL cumulus and stratiform clouds and turbulence in a consistent manner. A physically based definition of entrainment rate for the cloud-topped BL is needed.

3.3 NEW APPROACHES

3.3.1 Resolution issues

3.3.1.1 *Vertical*

Cloud processes operate over length scales which often are smaller than the vertical resolution in most numerical weather prediction and climate models eg radiative cooling and cloud top entrainment. For accurate cloud prediction some way of dealing with this will be needed. An obvious approach is to use a finer mesh in the boundary layer, but this may be too expensive, particularly if the dynamics have to be computed on this grid as well. Alternative ways of overcoming this problem are:

* To design a sub vertical cloud parametrization.
This is the least expensive but maybe the most difficult from a parametrization point of view.

* To vertically nest a 1-D PBL representation with high vertical resolution for PBL and cloud calculations only.

* To construct an adaptive grid in the vertical so that the highest resolution is placed where it is needed.

3.3.1.2 *Horizontal*

Mesoscale variations significantly affect the cloud characteristics and distribution. Causes include natural variability and surface inhomogeneities. Examples of the latter are: land/water contrast, mountains, soil and vegetation variability and CCN emissions. An obvious approach is to use a finer mesh in the horizontal, but this may be too expensive. Alternative ways of overcoming this problem are:

* A nested (two-way) grid approach

* A surface mosaic approach where a grid box is divided into a number of subclasses each with their characteristic values of surface parameters.

- The use of aggregation results derived from mesoscale model simulations that have been run for single grid boxes of larger scale models.

The last two techniques will work only if the dynamics on the unresolved scales are not dominant.

3.3.2 Cloud analysis and assimilation

Spin up time for clouds and cloud condensates are longer than the typical assimilation cycle interval. This means that cloud cover and cloud condensates have to be analyzed and assimilated. Cloud observations should be used to obtain a consistent humidity temperature and dynamical structure of the atmosphere.

3.3.3 Aerosols and CCN

Cloud microphysical and radiative processes depend strongly on the type, size spectrum and concentration of aerosols and CCNs. Present models could carry these quantities as prognostic variables. To do this we need a source inventory and accurate transport schemes as well as parametrizations of the atmospheric processes that alter spectra and concentrations.

3.4 MODEL AND PARAMETRIZATION VALIDATION

3.4.1 Methods

In order to improve the performance of the models in the prediction and representation of the cloud topped boundary layer, both the skill of the overall model and the accuracy of the individual parametrizations need to be assessed.

The overall skill of forecast models can be assessed through routine verification against the synoptic observing system and satellite data. Climate models can be validated against longer term climatologies. However, to improve the performance of the models more detailed validation and diagnostic studies are required.

Study of the timestep increments from the various schemes (ie convection, boundary layer mixing, radiation, cloud and precipitation) to the updating of the model's prognostic variables identifies the processes that dominate in the areas where errors occur and can therefore give insight into the cause of errors.

Sensitivity of performance to numerical aspects such as model resolution (horizontal and vertical), timestep, frequency of calling the parametrization schemes (eg radiation is only updated 3-hourly in many large scale models and physics increments can be calculated on a reduced grid) will indicate whether problems are fundamental to the parametrizations or just to limited resolution.

Co-ordinated investigations linked with observational field studies are vital since many parameters predicted by the models are not routinely observed or are not observed at sufficient resolution. The field observations can be used in a variety of ways. One is by direct comparison with the full 3D model forecasts and single column information extracted from them. This has been used successfully by ECMWF to improve their soil hydrology and boundary layer scheme. However, errors in the 3D models may come from other sources such as initial conditions and dynamics. Consequently, simplified single column models containing the parametrization schemes and vertical advection, initialized with observed profiles and possibly forced with observed subsidence, geostrophic winds or surface fluxes can isolate the performance of the parametrization.

Investigations of sensitivity to different parametrization schemes within the 1D and 3D models can also be investigated. The development of plug compatible schemes will facilitate this. Comparisons of different schemes within one model are easier to interpret than comparisons of different models. Exchange of schemes and standardised coding methods should be encouraged.

An understanding of the physical processes involved in the cloud topped boundary layer as a result of field programmes will also indicate the limitations of current parametrizations and indicate whether additional processes need to be parametrized.

Increasingly, LES models can be used to validate parametrization schemes. Ideally they should be used to reproduce, as closely as possible, a detailed observational data set that then can be used repeatedly for simulations with a wider range of mean flow parameters. In this way 'constants' needed for parametrizations can be calibrated accordingly, and assumptions tested. Examples of this are dependencies on shear, gravity waves and the properties of the lower boundary such as orography. Such synthetic data sets can also be processed in a similar manner to high resolution aircraft and remote sensed data to provide suitable comparisons with output from the parametrization schemes. However, these results must be treated with caution and may eventually need to be calibrated against further observations. Also the possibility of nesting a LES model domain within a mesoscale model will soon be a practical proposition.

3.4.2 Required Observations

There are now a number of data sets available for verification of marine stratocumulus prediction and development of new schemes. However, for NWP models, there are three types of situations for which good observational data sets are lacking. These are

- Continental cloud (fog, stratus, stratocumulus and fair weather cumulus)
- Mid-latitude oceanic cyclones
- Cold-air outbreaks

Observations of vertical structure of the clouds, in particular thickness, cloud condensate (amount and phase), radiation and turbulent fluxes are required. However, observations of the basic atmospheric structure are also required eg subsidence, geostrophic winds, shear, stratification and humidity profiles as errors in the models may be due to errors in the basic state rather than the parametrizations. The modellers should be involved with the planning of observational programmes in order to specify precise requirements not detailed above. Time series, particularly those describing the diurnal cycle are especially important.