· Science Plan for Clouds Water Vapour and Climate (CWVC)

The overall aim of the programme is to improve our understanding of the physical processes responsible for the distribution of humidity and clouds and of their influences on climate. The major role played by clouds and water vapour in controlling and moderating the Earth's energy balance, through their effects on both incoming shortwave and outgoing long wave radiation streams represents one of the largest uncertainties in climate modelling. Our poor understanding of how the distribution and microphysical properties of different cloud types affect the radiative balance and in particular how clouds and water vapour respond to climate change cause these uncertainties. This is a major obstacle to our ability to predict climate change with confidence.

The main beneficiaries of the CWVC programme will thus be the global climate modelling community (e.g. the Hadley Centre of the UK Meteorological Office - running the unified model UM, or the UK Universities Global Atmospheric Modelling Programme UGAMP). Benefits will also accrue to the Department of Environment, Transport and the Regions (DETR) and to the wider scientific community as a whole e.g. through The Intergovernmental Panel on Climate Change (IPCC)

The main elements of the programme will be:

1. The Microphysics and Radiative Properties of Ice and Mixed Phase Cloud

The main aim of this element is to increase the understanding of the microphysics and then radiative properties of mixed phase and ice clouds so that parameterisations of cloud in global climate models can be improved to much better quantify the effects of these clouds on climate and climate change.

Key objectives are:

a) To understand the mechanisms responsible for the initiation, multiplication and propagation of the ice phase in these clouds, and the underlying physics of the ice particle generation mechanisms.

b) To identify the concentration, shape and size distributions of ice crystals in a range of cloud types.

c) To understand the radiative properties of ice and mixed phase clouds, throughout the visible, IR and far IR.

d) To quantify the vertical transport of water vapour into the upper troposphere by these clouds. To investigate the role of clouds in determining the distribution of water vapour in the free troposphere.

e) To understand and model the conversion of cloud water to precipitation in these cloud types

f) To undertake laboratory measurements of the scattering and absorption properties of ice crystals and mixed phase water.

g) To derive new parameterisations of the cloud microphysics and cloud radiative properties for use in single column, cloud resolving, and general circulation models.

The programme will require laboratory measurements of ice crystal formation and multiplication processes. New field studies will be required to investigate detailed microphysical processes and the cloud radiative properties. These will make use of aircraft and other platforms, including the UK Met Office C-130 aircraft and its successor. There is a need for new instrument development particularly for measuring ice particle size distribution and the ice water and liquid water contents in clouds, and for spatially resolving the radiative properties of clouds. New developments in cloud radar potentially enable remotely retrieved cloud ice water contents and ice crystal effective radius to be made over much larger scales than is possible by aircraft. It is envisaged that major field campaigns bringing together insitu measurements of microphysics and radiation together with remote sensing studies by radar and lidar will be undertaken. Detailed cloud microphysical modelling will be an essential part of the interpretation of the data from these projects. Cloud Resolving Models (CRMs) will be used to link the cloud microphysics and radiation fields to the cloud dynamical structure. Proposers are encouraged to take full advantage of available cloud and radiation budget data sets.

2. Understanding the structure of inhomogeneous clouds and their impact on radiation

The main objective of this section is to understand the effects of inhomogeneous cloud structure on cloud radiative properties. The transfer of solar and longwave radiation through cloud is a complex function of the distribution of condensed water and of the cloud particle size and shape. Cloud structure is typically very inhomogeneous, with variations on a wide range of horizontal and vertical scales. Recent work has shown that these inhomogeneities can significantly affect the bulk radiative properties of the cloud. The problem remains, however, of how to incorporate satisfactorily the impact of these inhomogeneities in the representation of clouds in climate models. A further complexity may arise when a cloud layer becomes broken and dynamical processes need to be taken into account. Finally, the problems of making meaningful experimental observations of the properties of an inhomogeneous cloud field are very considerable, and need to be carefully taken into account by proposers.

Key Objectives are::

a) To develop novel approaches to modelling radiative transfer in inhomogeneous cloud fields combined with campaigns of focused field observations.

b) To make multi-spectral observations over a wide range of time and length scales. Measurements of radiances above and below cloud, together with detailed cloud microphysical observations, especially for cirrus clouds are required.

c) To exploit the large-eddy simulation technique for modelling of cloud structure, as an integral part of this work.

3. Understanding and parameterisation of deep convection

Deep convection is especially important for the transfer of water substance to upper parts of the troposphere. Deep convective clouds also produce large extensive anvils in the upper troposphere and are a major source of tropical cirrus. In addition, these clouds play a key role in the transport of air and water vapour across the tropical tropopause. Hence, the understanding of the dynamics and microphysics of these clouds leading to improved parameterisations is a priority.

Global Climate Models (GCMs) represent atmospheric physical processes within arrays of grid boxes that have much coarser scales than those of clouds, and so clouds have to be represented statistically in terms of sub-models, known as single-column-model (SCM) parameterisations, which describe the net effect of many small-scale processes such as cloud microphysics, turbulence and radiation. The underlying assumptions of SCMs are based on observed cloud characteristics, but simplifications need to be made and improved parameterisations are needed.

Large-eddy-simulation (LES) models have become particularly successful in simulating turbulent processes within the atmospheric boundary layer, and may be used to extend CRMs by including representations of cloud microphysics, rainfall, radiative exchanges

The CRMs can be used to derive physically based estimates of bulk properties that are difficult to observe, such as mass flux or net radiative heating profiles, against which to evaluate SCMs. These CRMs are potentially very powerful tools because of their ability to supply much more extensive information about the coupled physical processes involved and of the large-scale effects of these processes, than can be obtained from observations. However, the CRMs themselves do have to be evaluated observationally using data obtained for a variety of different cloud types.

Key Objectives are:

a) To apply Cloud Resolving Models to deep convection.

b) To verify these models by comparison with observations including Doppler radar, lidar and insitu aircraft borne cloud microphysical measurements. Case studies of deep tropical convection over the oceans and the continents are required in a wide range of meteorological conditions. Data from recent field campaigns may be used. New campaigns involving international collaboration may be needed.

c) The development and testing of improved parameterisations in CRMs and SCMs.

4. **Understanding the distribution and transport of water vapour throughout -the atmosphere**.

The main aim is to assess the extent to which the water vapour distribution is treated realistically in GCMs, and the importance that this treatment has in assessing the radiative feedback of water vapour.

Water vapour measurements have been made by a variety of techniques for many years, but substantial uncertainties still remain (e.g. poor geographical coverage of radiosondes; poor vertical resolution of satellite observations). However, because water vapour plays such a dominant role in tropospheric thermodynamic and radiative processes, especially in the middle and upper troposphere, that a good knowledge of its distribution is essential. For example, a major uncertainty lies in the precise nature of the water vapour feedback which occurs as the climate system seeks to respond to radiative forcing. Improved analysis and interpretation of existing measurements, and particularly new data from NASA and ESA programmes, in order to improve our knowledge of water vapour distributions, is a priority.

Output from various re-analysis projects around the world (e.g. the Re-Analysis Projects of the European Centre for Medium Range Weather Forecasts (ECMWF), ERA, or from the National Science Foundation (NSF) in the US) is now available. Work needs to be undertaken to fully understand the limitations of the reanalysis data sets for scientific problems. We need to systematically compare the historic re-analyses with coincident satellite data, including from the NOAA operational sounding system, the United States Air Force Special Scientific Sounder microwave sounders, and the Upper Atmosphere Research Satellite (UARS). The new satellite measurements mentioned above will provide new ways to validate the reanalysis fields. The products may prove to be directly superior for certain height ranges.

Key Objectives are:

a) To analyse and interpret existing and new satellite measurements of humidity, with a view to improving accuracies, and vertical and horizontal resolution, especially in the middle and upper troposphere

b) Measurement campaigns using aircraft, balloons and ground based instruments to obtain water vapour fields especially in the upper troposphere at different locations. These will make use of national and international flight facilities, and international collaboration may be appropriate.

c) To validate UK and US re-analysis water vapour fields using independent satellite and in-situ measurements.

5. Understanding the Radiative Properties of Water Vapour relevant to climate

Water vapour has by far the greatest impact of any gaseous constituent on the radiation balance of the atmosphere with absorption features from visible wavelengths to the far infrared. It is thus of fundamental importance to our understanding of climate and climate change, that the radiative effects of water vapour are understood in theoretical terms and also are quantitatively established. Nevertheless, there are several important areas in which uncertainties in its radiative properties are still large. One such problem is that of the water vapour continuum. Despite many laboratory and atmospheric studies, the fundamental theoretical basis for its existence is not firmly established, and its representation in line-by-line radiative transfer codes is based on empirical extrapolation of laboratory measurements and tuning of high resolution atmospheric observations. Improved data on continuum absorption, especially at low temperatures, and an improved theoretical understanding, remain high priorities. Another problem requiring more accurate measurement is our understanding of water vapour absorption in the far-infrared region, which dominates infrared cooling rates in the mid and upper troposphere. A further issue is that of short wave water vapour absorption. Most GCMs significantly underestimate atmospheric absorption of solar radiation even under clear-sky conditions. This implies that the models do not satisfactorily represent atmospheric heating by solar radiation. The reasons for this are not clear but possibilities include an inadequate knowledge of: the near-infrared absorption by weak water vapour lines and continuum

To improve current understanding of the radiative properties of water vapour and cloud a combination of focused observations and modelling is required. Multi-spectral observations over a wide range of time and length scales are needed to assess critically the performance and utility of detailed radiative transfer models and of those utilised in GCMs. Clear sky measurements of spectral radiance in both the near and far-infrared, both at the ground and throughout the troposphere, together with accompanying data on temperature, humidity and aerosol loading, would provide a strong constraint on water vapour calculations. Improved high resolution laboratory measurements of the water vapour absorption spectrum are also required.

Key Objectives are:

a) To improve knowledge of clear sky spectral radiance, temperature, and humidity profiles, through coordinated measurement campaigns from the ground and airborne platforms.

b) Improved knowledge of water vapour spectroscopy over a complete range of temperatures and pressures.

c) Improved understanding of water vapour feedback, and the radiative effects of changing vertical distributions of water vapour.

d) Improvement and validation of radiative parameterisations used in GCMs.

· **Important notes for Applicants:**

In order to achieve the stated aims of the CWVC programme, it is important that all potential researchers within the programme should demonstrate the applicability of their work to understanding important climate processes and to the development and evaluation of climate models. Projects should therefore aim to provide products that will be of benefit to the development of global climate models GCMs (such as the Unified Model, UM, of the UK Meteorological Office, or to the UGAMP). Researchers are encouraged to use a wide variety of tools, such as Cloud Resolving Models, observational field studies (both insitu and remote sensing), reanalysis, laboratory measurements etc, as discussed above, in an integrated manner. In order to support such interdisciplinary research, proposals from consortia will be encouraged.

Training is considered an important element of the CWVC programme and therefore, both tied and stand-alone studentships will be encouraged. However, Fellowships are unlikely to be part of this programme.