Evaluation of Projects funded by the Climate Change Action Fund (CCAF)
In response to a Call for Proposals for work on the topic of
Climate Model Improvements

Background:

Nine projects were funded by the CCAF on the topic of "climate model improvements" in response to a call for proposals issued in early 1999. Funding for most of the projects commenced in the summer of 1999 and ended 31 March 2001. All of the funded projects were chosen on the basis, amongst other criteria, of how well they purported to address the scientific focus for this segment, "key climate processes of importance to Canada in order to improve our global and regional atmospheric/ocean models".

The titles of the nine projects were:

1. Improvements in the parameterisation of ice cloud radiation processes in GCMs
2. Sulphate aerosol forcing in GCMs
3. Improving the representation of the interaction between clouds and radiation in Canadian climate models
4. Northern oceans dimethylsulphide emission models (NODEM)
5. Parameterising sloping bottom boundary layers for incorporation into Ocean GCMs
6. Scaling of cold season land surface processes and application to improving land surface parameterisation in Canadian climate models
7. Improved parameterisation of land surface snow processes for Canadian climate models
8. Improved representation of sea-ice in the CCCma global CGCM
9. Generalised aerosol optical properties generator for the Canadian GCM

Relevance to the objectives of the Kyoto Protocol:

Under the Kyoto Protocol, Canada is committed to a number of actions, one of which is to contribute to climate science and to the improvement of climate change prediction. Canada has a record of exceptional contribution to the development of climate models over the past two decades. Canadian scientists have been active in the international climate science community, have made substantial contributions to the Intergovernmental Panel on Climate Change (IPCC) and Canada's climate models are recognised as being among the best in the world. Although the core of this work has been carried out in government labs it is not possible for a country of Canada's small population to maintain such a high level of accomplishment without the full engagement of the university community. The specific objectives for this segment of CCAF funding were designed to fill known gaps in the government in-house expertise and to foster co-operation between government and university scientists for urgently needed work to improve Canada's suite of climate models. All of the selected projects were relevant to the Kyoto objectives. Many of them have and will contribute to reducing the uncertainty of the sensitivity of the climate system to changes in greenhouse gas levels.

Achievement of specific project objectives:

Each of the project leaders provided a list of specific objectives for their project. Nearly all of these objectives were achieved. Specifics are discussed in more detail in the individual project evaluations. In some cases not all of the objectives were accomplished, but this was mostly because of a late start to the funding and some misunderstanding about the ability to carry over funds beyond the end of the fiscal year for which they were awarded. In most of these cases the work continued after the formal end of the CCAF funding using resources from other sources. In one case an objective was not achieved because of the premature departure of the student involved in developing an algorithm, delaying its implementation. This implementation work also will continue under other auspices.

Overall quality and breadth of science funded:

The evaluation team was impressed by the overall quality of the science produced under these projects. New approaches were developed for the treatment of several aspects of clouds and aerosols, their interactions with solar and terrestrial radiation and their feedbacks to climate. This work is of fundamental importance to understanding the sensitivity of climate to anthropogenic emissions of greenhouse gases. Several advances were made in the field of parameterising these and other effects in GCMs, notably the treatment of cloud inhomogeneity and the treatment of fluxes between the air and snow-covered ground. New work on the contribution of the oceans to the production of sulphate aerosols will ultimately lead to more accurate estimates of aerosols and their effects on climate sensitivity. Fundamental work on better defining the location and magnitude of turbulent energy generation in the oceans will ultimately lead to better estimates of the sensitivity of the large-scale ocean thermohaline circulation to climate change. The quality of the science is reflected in the fact that the projects have already resulted in a few published papers, another score or so have been submitted and several more are in preparation.

Relation to other funding

Much of the work funded by CCAF was an add-on to larger projects funded from other sources. These sources include the Natural Sciences and Engineering Research Council (NSERC) that funds solely on the basis of scientific excellence and the Climate Research Network (CRN) that, like this segment of CCAF, has a strategic focus on improving climate modelling. The CCAF funding provided the opportunity to fill significant knowledge gaps, carry out algorithm development and testing and/or implement previously developed algorithms in climate models. The CCAF funds were mainly used to allow the principal investigators to engage graduate students, post-doctoral fellows and research assistants to work on the projects. In all cases the leverage of the CCAF funding was substantial and the impact almost immediate.

In other cases the CCAF funding permitted a start on new work that was not getting funded from other sources, even though such work was clearly of high priority for fulfilling Canada's science commitments under the Kyoto Protocol. These projects, by producing promising early results, subsequently attracted first funding from the other agencies, especially NSERC and the recently established Canadian Foundation for Climate and Atmospheric Sciences (CFCAS).

Clearly the CCAF funds have been used strategically to foster additional work related to the CCAF objectives and to lever funds from other sources. With the advent of new and more substantial funding from CFCAS for university-based research on similar strategic objectives, one might expect the CCAF resources to be redirected to filling gaps in the government lab programs. Many of these programs have yet to attract new sources of funding to make up for years of cuts suffered under recent program reviews.

Capacity building

The additional funding made available by this segment of CCAF resulted in the training of several students at the masters and doctoral level. The projects also leave behind a number of unique and important datasets that will continue to be useful for further research as well as FORTRAN codes for improved physical processes for incorporation into the Canadian GCM and regional climate models. Another important legacy, mentioned by several of the proponents, is the collaboration that was fostered between atmospheric and oceanographic scientists on the one hand and between process scientists and modellers on the other. The projects encouraged a notable degree of cooperation between university and government scientists and several included international components as well.

Follow-on research

It is suggested that the following areas of follow-on work to address climate model improvement should be a priority for future funding:

- Tests in full climate simulations of improved ice-cloud parameterisations to determine their impact on the surface radiation budget and on albedo-cloud-radiation feedbacks.
- Specification of the parameters for the distribution of unresolved horizontal inhomogeneity of cloud fields.
- Determination of the effect of sub-grid-scale cloud inhomogeneity on solar radiation.
- Coupling of NODEM to an ocean turbulence model, then to a column version of NARCM, followed by development and implementation of a computationally viable scheme in a global coupled 3-D GCM.
- Further development of a parameterisation scheme for deep ocean turbulent diffusivities based upon the breaking of internal tides forced by stratified flow over topography.
- Focussed research on the development of a bottom boundary representation to prevent the loss of negative buoyancy in regions of deep water formation over the flanks of steep topography like that of the North Atlantic
- Implementation of improvements to the formulation of heat flux over snow-covered land in CLASS.
- Implementation of a blowing snow module in CLASS.
- Improvement of the representation of sea-ice in the Canadian GCM.

- Tests of whether the bulk approach or some other relatively simple approach to modelling aerosols could be adequate for climate models, rather than the much more computationally expensive size-segregated method.
- Further studies of the impact of various assumptions about aerosol mixing on short and long wave radiation and ultimately on climate change sensitivity.

CCAF Project Evaluation

Project S99-14-01: Improvements in the parameterisation of ice cloud radiation processes

The specific objectives identified by the project leaders were:

- parameterisation of ice particle mean effective size
- parameterisation of particle asymmetry
- parameterisation of multiple scattering in the infrared
- parameterisation of cirrus cloud inhomogeneity

All of the specific objectives seem to have been met and they represent an important contribution to the overall issues. Methods to include scattering processes in the infrared and the effects of particle asymmetry and cloud inhomogeneity were developed. The mean effective particle size of cirrus clouds was parameterised as a function of temperature, at least for high latitude clouds. The new parameterisation gives values that are lower and with less temperature dependence than those generally used today. Some questions remain about the treatment of clouds at lower latitudes.

Most climate models show a bias in outgoing long wave radiation (OLR) compared to observation. This project showed that the effect of cloud inhomogeneity on the calculated OLR could be large, especially for high thin cirrus. The inclusion of all of the above factors should produce changes in the right direction but the effect on a full climate simulation remains to be determined.

Another problem that remains to be resolved is the proper treatment of the radiative properties of mixed water and ice clouds.

The impact of these improved parameterisations should be tested in full climate simulations. The impact on the surface radiation budget and on albedo-cloud-radiation feedbacks needs to be determined.

CCAF Project Evaluation

Project S99-14-02: Sulphate aerosol forcing in GCMs

The specific objectives identified by the project leaders were:

- implementation and testing of a shallow convection scheme
- introduction of aerosols other than sulphate
- introduction of a prognostic equation for cloud droplet number concentration
- introduction of a correlated-k distribution scheme
- introduction and testing of a prognostic cloud scheme

All of these were achieved except for prognostic cloud droplet number. The shallow convection scheme was developed elsewhere, as were the prognostic cloud scheme and the correlated-k radiation scheme, but this project brought them together and tested their interaction in a full climate model. Although the project title mentions only sulphate aerosols, work was done on the inclusion as well of sea-salt, dust, black carbon and organic carbon aerosols in this bulk formulation. For sulphur, the prognostic species are SO_2 and DMS. In-cloud oxidation produces $S0_4$ and some is produced as well by clear air reactions with OH and NO_3. The model-calculated total column sulphate burden agreed well with observations. The model showed high sensitivity to the shallow convection parameterisation.

This work raises the question of whether the bulk approach used here or some other relatively simple approach could be adequate for climate models, rather than the much more expensive size-segregated approach currently under development. Given the sensitivity to the treatment of clouds it will be important to get the interaction with cloud microphysics right in climate models.

CCAF Project Evaluation

Project S99-14-03: Improving the representation of the interaction between clouds and radiation in climate models

The specific objectives identified by the project leaders were:

- Implementation of new solar radiation code in the GCM
- Construction and testing of new LW code
- Estimation of the forcing due to plane-parallel homogeneous (PPH) radiative transfer

The first two objectives were met, but the third was not because of lack of time. However the unused funding was returned and the third objective has since been accomplished under other auspices. Both the short wave and long wave codes have been implemented in the Canadian GCM. The effects of sub-grid-scale cloud variability on the short and long wave outgoing radiation received considerable attention and were found to be important.

In these studies, the unresolved cloud variability was described by a gamma distribution for which a width parameter needs to be specified. It is to be hoped that a more physical specification of the variability will result from the MOC2 project, recently funded by the CFCAS. How does the variability of clouds and of water vapour and their effect on radiation depend on turbulence, for example?

CCAF Project Evaluation

Project S99-14-04: Northern Oceans Dimethylsulphide Emission Models (NODEM)

The specific objectives identified by the project leaders were:

- Determination of the key mechanisms responsible for DMS production in the North Atlantic and North Pacific Oceans
- Development of models for DMS production and emission to interface with the Northern Aerosols Regional Climate Model (NARCM)
- Provision of better estimates of biogenic sulphur fluxes to climate models

All of the objectives were met except the first for the North Pacific, although DMS measurements for this region were obtained. Biogenic oceanic fluxes of DMS account for about 25% of global sulphur emissions to the atmosphere, hence it is important to model them realistically. The variability with space and time of DMS fluxes has been documented by data gathered for this project. The NODEM model builds on previous models. A first simulation of the full seasonal cycle of DMS production was performed with a column version of the model and it shows reasonable agreement with the observed cycle. The sensitivity to various parameters was explored.

The next steps will be to couple NODEM to an ocean turbulence model, then to a column version of NARCM. Implementation in a global coupled 3-D GCM is still some time off and it will be important to devise a minimum complexity version for that purpose.

CCAF Project Evaluation

Project S99-14-05: Parameterising sloping bottom boundary layers for incorporation into OGCMs

The specific objectives identified by the project leaders were:

- Improvement of understanding of vertical mixing processes in the deep ocean
- Improvement of the mixing parameterisation in OGCMs

Both of the objectives were achieved. In particular, the work makes it clear that a significant fraction of the turbulent mixing in the ocean is associated with the conversion of barotropic tidal energy to turbulent energy through the generation of internal tides and waves by tidal flows over rough bathymetry and subsequent wave breaking. The linear theory was extended to realistic three-dimensional flows and a parameterisation of these effects for OGCMs was developed which uses a large enhancement of the diffusivity over rough bottom topography. This results in a much better ocean climate than that produced with the usual uniform diffusivity.

Since the ocean thermohaline circulation is sensitive to the specification of diffusivity it is clearly desirable to implement in GCMs a dissipation scheme such as this one that is as physically realistic as possible. It will be important to determine the effect of such schemes on deep ocean mixing, the formation of bottom water on sloping bottom topography and on the large-scale thermohaline circulation. The theoretical paper accompanying this work seems to rely upon the approximation that the direct effect of the Coriolis force on the breaking of internal waves is negligible. It would be worthwhile to examine the impact on the parameterisation scheme of relaxing this assumption.

CCAF Project Evaluation

Project S99-14-06: Scaling of cold season land surface processes and application to improving parameterisations in Canadian climate models

The specific objectives identified by the project leaders were:

- Investigation of the of cold season land surface processes through a hierarchy of regional climate simulations over the Mackenzie basin
- Improvement of the parameterisation of these processes in Canadian climate models

These objectives were mostly achieved through the development of a high-resolution surface data set needed for the simulation of surface fluxes over snow-covered terrain, the carrying out of model runs at various resolutions and the development of improved scaling strategies.

Model comparison experiments had shown that the Canadian Land Surface Scheme (CLASS) produces insufficient downward sensible heat flux and upward latent heat flux in stable conditions over snow and hence too much mid-season snow accumulation and too-long a snow covered period. The recommendations to overcome this deficiency, based on this project work, are to relax the stability criterion for turbulent fluxes in the model, to implement an ad hoc windless exchange coefficient or a physically-based sub-grid velocity scale to account for turbulent exchange by the mesoscale circulations and to calculate fluxes for a mosaic of patchy snow covered ground. In addition, the implementation of physically-based parameterisation modules that account for the interception of snowfall by canopy and its subsequent transport and sublimation, as well as the sublimational loss of surface snow by blowing snow should also improve the accumulation and ablation problems in the current snow model in CLASS. It was difficult to evaluate fully the validity of these recommendations from the material presented, although they seem reasonable enough. One wonders as well how these conclusions mesh with those from project SS99-14-07.

CCAF Project Evaluation

Project S99-14-07: Improved parameterisation of land surface snow processes for Canadian climate models

The specific objectives identified by the project leaders were:

- Validation of CLASS algorithms
- Fractional snow cover calculations
- Incorporation of blowing snow

The objectives were met with the exception of the implementation of the blowing snow algorithm, although the algorithm was fully developed and tested. A number of improvements were made in the CLASS algorithms as a result of testing against validation data sets developed for this project. These improvements include a new snow-ageing scheme, the incorporation of variable snowfall density, investigation of liquid water storage in snowpack, allowance for mixed precipitation and improvement to the albedo calculation for snow covered forest. Evaluations using WATFLOOD coupled to CLASS showed improved runoff from mixed snow-covered and snow-free areas.

The improvements to CLASS, which has only a single snow layer, make it competitive in terms of results with computationally more expensive multi-layer schemes. This is desirable from the point of view of implementation in a full climate model. The PIEKTUK blowing snow algorithm shows promise, but it remains to be implemented into the CLASS code structure.

It is not clear how well coordinated this work is or should be with that of project S99-14-06, especially the conclusions regarding the treatment of fractional snow cover.

CCAF Project Evaluation

Project S99-14-08: Improved representation of sea-ice processes in Canadian climate models

The specific objectives identified by the project leaders were:

- Implementation of a multi-category, dynamic-thermodynamic sea-ice model in the CCCma CGCM
- Development of diagnostic programs to analyse the results
- Evaluation and assessment of impact on modelled climate and climate sensitivity

All of these objectives were achieved. The model was implemented and a suite of diagnostic programs devised. A series of model experiments was performed in order to isolate the effect of the inclusion of more sophisticated thermodynamics and the inclusion of ice dynamics. It was found that the volume response of sea ice to climate perturbations was enhanced by the multi-layer multi-category thermodynamics but the ice area response was decreased. The introduction of ice dynamics reduced the climate sensitivity of the sea-ice compared to a thermodynamic only model, in agreement with other results.

The Coupled Model Intercomparison Project (CMIP) has shown a large inter-model variability over the Arctic of predicted temperature change, associated with variability in the predictions of sea-ice. It is to be hoped that inter-model variability will be sharply reduced once models of sea-ice formation and dispersal reach a higher level of sophistication. The calculation of ice cover in the control runs with this model is in better agreement with observation than that for the simple thermodynamics-only model that it replaces.

CCAF Project Evaluation

Project S99-14-09: Generalised aerosol optical properties generator for the Canadian GCM

The specific objectives identified by the project leaders were:

- Development of a generalised optical properties generator
- Quantification of the effect of the aerosol mixing assumption
- Determination of geographic variations of aerosol properties
- Determination of the role of black carbon and anthropogenic aerosols in mixtures

All the objectives were met. The computer code was developed. Calculations of extinction coefficients and single-scattering albedo for various mixing assumptions under various conditions of relative humidity showed a larger than expected effect on calculated direct radiative forcing due to aerosols. Generally external mixtures produce more radiative cooling than homogenous internal mixtures. Most models currently assume external mixing of aerosols. The optical properties are particularly sensitive to the assumed aerosol distribution.

Studies are needed using predicted aerosol concentrations from general circulation models in order to quantify the influence of mixing assumptions on global radiative forcing.