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Arctic Atmospheric and System Modeling: A Survey of IARC-related Activities (Extended Abstract)

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1. Introduction

Modeling activities at the University of Alaska Fairbanks International Arctic Research Center have focused on several primary objectives:

- To produce demonstrable improvements in simulations of Arctic climate by coupled earth system and climate models.
- To support the Arctic Climate Impact Assessment (ACIA) project by supplying information on likely scenarios for the Arctic climate through the 21st century.
- To test the robustness of modifications made to such earth system/climate models for application to the Arctic regions.

Motivation for such objectives can be seen through reference to Figures 1 and 2. Figure 1 shows four different climate system model realizations of annual mean precipitation over the Northern Hemisphere for the period 1961-1990. The models shown are those from the Geophysical Fluid Dynamics Laboratory (GFDL), Canadian Climate Centre (CCC), National Centre for Atmospheric Research (NCAR) and the Commonwealth Scientific and Industrial Research Organization (CSIRO). Examination of Figure 1 clearly shows that even in simulations of the recent climate, current state-of-the-art models produce annual mean precipitation amounts that differ by as much as a factor of three over the Arctic Basin. Furthermore, substantial differences in precipitation also occur over the mid-latitude storm track regions of the North Pacific and North Atlantic oceans as well as the northern continents. Clearly there is a need to better understand and depict (in numerical models) the behavior and interactions of the various components of the climate system in order to reduce the uncertainty in predictions of future climate.

Figure 2 provides a visual depiction of such uncertainty, albeit with respect to a

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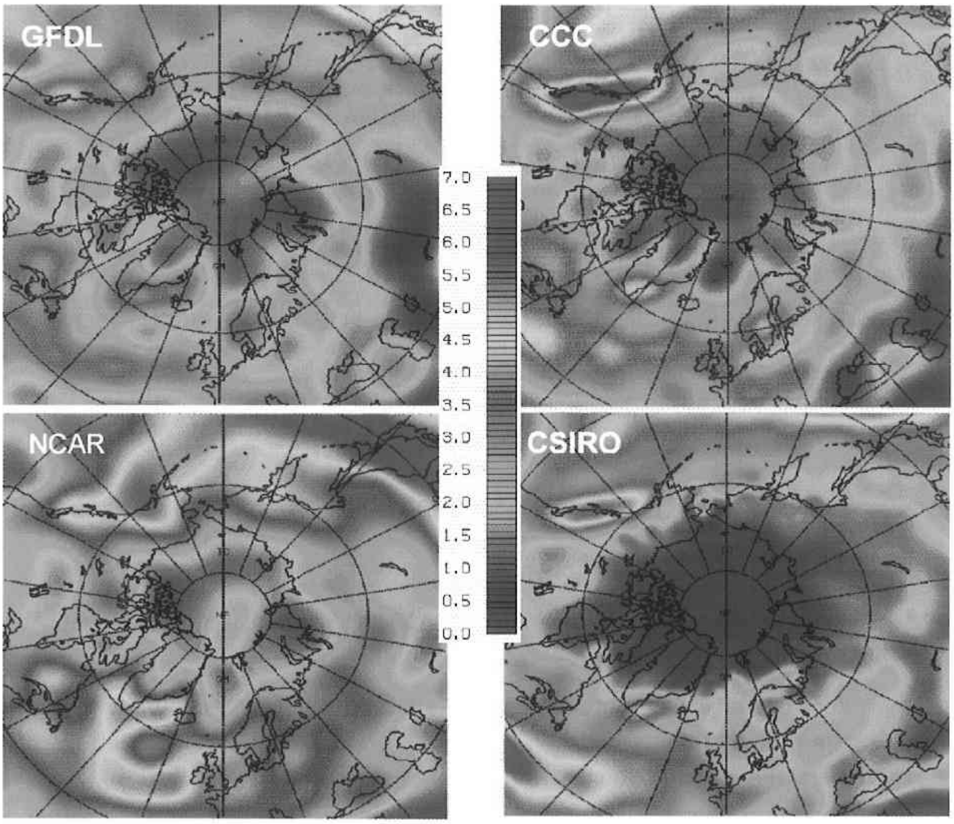


Fig. 1. Annual Mean (1961 1990) Transient Simulated Precipitation (mm/day) from several climate/earth system models: GFDL (upper left), Canadian Climate Centre (upper right), NCAR (lower left), and CSIRO (lower right).

different variable, air temperature. Specifically, the figure illustrates projected changes in mean circumpolar surface air temperature over the next century relative to the corresponding mean temperature during the 1990-1999 period. Five different climate system model projections are shown. Examination of the plots indicates that the relative degree of warming associated with the warmest model projection as opposed to the coldest model projection differs by approximately a factor of two throughout the entire century. While these absolute differences are small early in the century, they reach 3°C during the lattermost decade, a difference which is on the order of IPCC projected mean warming for the entire globe. Such uncertainty in warming can, for example, translate into projected lengths of the growing season that differ by 1-1.5 months in a given region (figures not shown). It is clear that such uncertainty makes production of credible impacts scenarios and planning difficult, and work is needed to reduce these uncertainties in understanding and prediction.

In the remainder of this paper we will present an overview of current modeling studies performed at or funded by the International Arctic Research Center in support of

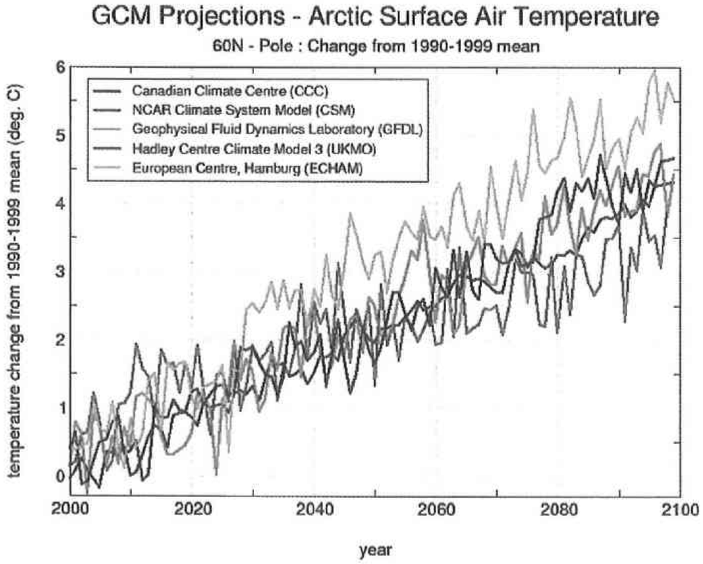


Fig. 2. Projections of mean Arctic (60°-90°N) surface air temperature change (°C) relative to the observed 1990-1999 mean, produced from five climate system models as indicated in the key.

the aforementioned objectives. This work includes model intercomparison efforts, parameterization development and studies examining climate system feedbacks. These efforts will be presented in turn in the following sections.

2. Model intercomparison efforts

2.1. The Arctic Ocean Model Intercomparison Project (AOMIP)

The Arctic Ocean Model Intercomparison Project (AOMIP) is a coordinated international effort to examine the ability of current state-of-the-art Arctic Ocean models to simulate variability on seasonal to interannual scales, and to improve our qualitative and quantitative understanding of Arctic Ocean model behavior.

Participating models and associated institutions within the AOMIP effort are briefly described in Table 1, which is derived from the AOMIP website maintained at New York University by Dr. David Holland. On this website (URL provided in the table caption) there are links to other webpages with detailed information on the models being used in the intercomparison, the principal investigators and their AOMIP-related efforts. It is clear from Table 1 that many of the AOMIP models can trace their roots to either the Princeton Ocean Model (POM) or the GFDL Modular Ocean Model. All the model simulations are being conducted over a common Arctic domain with a common grid, shown in Figures 3a and 3b, respectively.

While various investigators are performing some individual experiments as part of AOMIP, three general coordinated experimentation efforts are under the AOMIP

Table 1. Participating ocean models and associated institutions within the Arctic Ocean Model Intercomparison project. An online version of this table, with links to more detailed information on each of the models, can be found at http://fish.cims.nyu.edu/project aomip/.

AOMIP Model	AW1	GSFC	IARC	IOS	NPS	NYU	RAS	UW
Home Institute	Alfred Wegener Institute	Goddard Space Flight Center	International Arctic Research Center	Institute Of Ocean Science	Naval Postgrad. School	New York University	Russian Academy Of Science	Univ. Of Washington
Ocean Model Pedigree	MOM	MOM	POM	POM	MOM	MICOM	Finite Element	MOM
Coupled Sea ice Model?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

umbrella:

- Experiments examining the seasonal cycle of the Arctic Ocean's temperature and salinity structure as well as sea ice thickness and concentration;
- 30 year simulations covering the 1948-1978 period utilizing a coordinated spin-up procedure, including common forcing fields derived from the NCAR/NCEP reanalysis;
- A 20 year experiment using a coordinated analysis data set derived from Arctic buoy data.

The most recent workshop to discuss AOMIP results and coordinate future work was held in May 2002 in Washington, D.C. Downloadable presentation slides documenting specific efforts are available on the world wide web at http://fish.cims.nyu.edu/project_aomip/workshops/workshop_5/overview.html.

2.2. The Arctic Regional Climate Modeling Intercomparison Project (ARCMIP)

This effort differs from the previous intercomparison project in that regional coupled system models of the Arctic are considered. The effort is organized out of the University of Color-

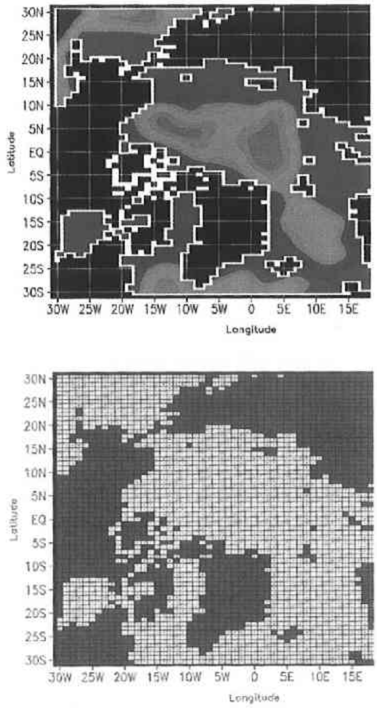


Fig. 3. a) Domain used in the AOMIP experiments. b) Representation of the grid mesh used for the AOMIP simulations. Grid coordinates are spherical with a 1°lat x 1°lon. resolution.

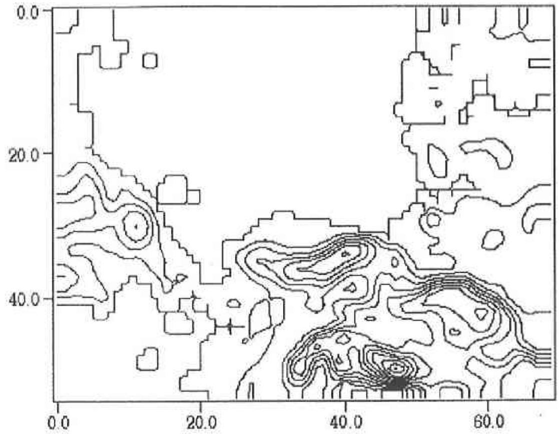


Fig. 4. Domain utilized in the initial ARCMIP experiments (1a and 1b) described in the text. Contoured field is terrain in meters.

ado (CU) but has participation from other Arctic modeling groups at U.S. and European institutions. As of this writing, participating models include the CU ARCSyM model, German REMO and HIRHAM models, Canadian NARCM model and Norwegian RegCLIM. The initial experiments involve a period of time covering the "SHEBA year" from 1 Sept. 1997-31 Sept. 1998, during which extensive observations were obtained over the Beaufort and Chukchi Seas in association with the Surface Heat Balance of the Arctic program. The initial domain chosen is illustrated in Figure 4.

Two initial experiments have been conducted as of this writing:

- 1a: Simulations where the sea surface temperature (SST) and sea ice temperatures, as well as sea ice concentration over the domain of interest, are specified over the period via a bootstrapping technique. This technique utilizes both AVHRR satellite retrievals and in-situ measurements;
- 1b: Simulations where SST and the other variables are initialized, but then allowed to vary interactively during the yearlong period.

Preliminary results of these initial experiments are summarized as follows:

- The current domain is the most useful for evaluating process parameterizations for situations where the large-scale dynamics are constrained. In other situations, the lateral boundary forcing can often be too dominant of an influence on the simulation.
- By contrast, Pan-Arctic simulations with the HIRHAM model tend to illustrate stronger influences of feedback mechanisms, ice/ocean interactions and how the initial conditions are specified.
- Simulations with both the RegCLIM and the NARCM models indicate that current GCM stratocumulus parameterizations produce too much cloud cover, especially in winter. The Xu-Randall cloud scheme, which utilizes relative humidity as well as cloud water and ice mixing ratios shows some promise.
- The inclusion of aerosols in the simulation has significant impacts on the cloud

depictions.

- Simulated interactions between cloud systems and the atmospheric boundary layer interactions continue to need improvement.
- The land snow parameterization in the REMO model has proved inadequate for simulating the spring snowmelt period.
- Evaluations of mass/water conservation, the surface energy budget, and vertical structure are in progress.

3. Parameterization development

A recent project in parameterization development is related to the general area of land-atmosphere interactions in the Polar Regions. This focus is related to recent work that suggests that climate may not only affect the permafrost distribution, but there may be feedbacks from a changed permafrost distribution back to the climate as a whole.

The project described here involves modifications to the Hydro-Thermodynamic Soil Vegetation Scheme (HTSVS) as described in Molders *et al.* (1999). This scheme contains a canopy plus multiple snow and soil layers, coupled heat and moisture transfer equations, and a vertically variable root distribution dependant on vegetation type. The modifications to HTSVS that have occurred within the context of this project fall into the areas of snow metamorphism and permafrost dynamics. Specifically, the new version of HTSVS developed contains:

- Prognostic equations for the temperature, snow water equivalent, snow density and snow depth including metamorphic changes to the snowpack from snowfall, sublimation, melting, compaction, settling, percolation and freezing of meltwater;
- Soil freezing/thawing along with the associated latent heat exchanges and impacts on the vertical fluxes;
- Temporally varying snow albedo and emissivity.

We present a set of experiments using HTSVS coupled to the Penn State/MM5 Mesoscale model (hereafter denoted MM5) to demonstrate the impact of the modified scheme on medium range simulations. Figure 5 shows the domain of the numerical experiments. The case study period selected is March 1-10, 2001, covering a period where varying degrees of snow cover are present over the state and additional snowfall occurred at some locations due to progressive synoptic cyclonic systems. Atmospheric, SST and snow cover data for the simulations were obtained from NCAR/NCEP analyses, while United States Geological Survey and satellite sources were used to derive vegetation data, including fractional coverage of vegetation in a grid cell.

Figures 6 and 7 show a sample of results from coupled MM5-HTSVS simulations both with and without the improvements noted above. Such comparisons allow us to infer the impact of the changes to the parameterization schemes that are incorporated.

It is clear from comparing Figures 6a and b that inclusion of the new physical process treatments has significant impacts upon the simulated surface temperatures.

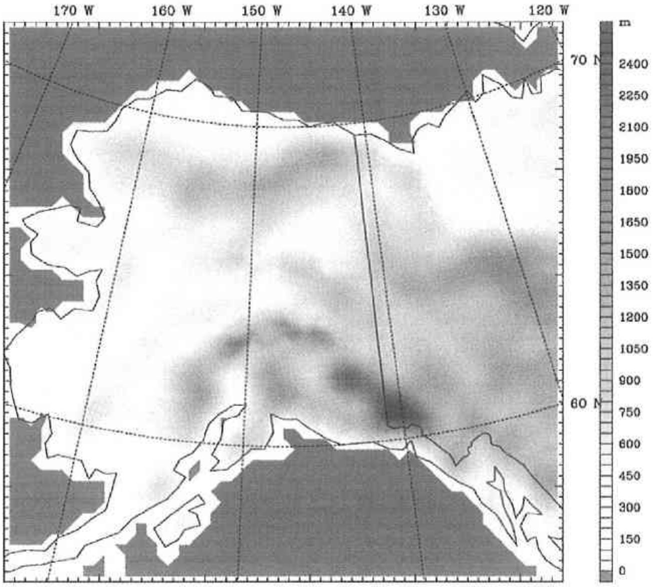


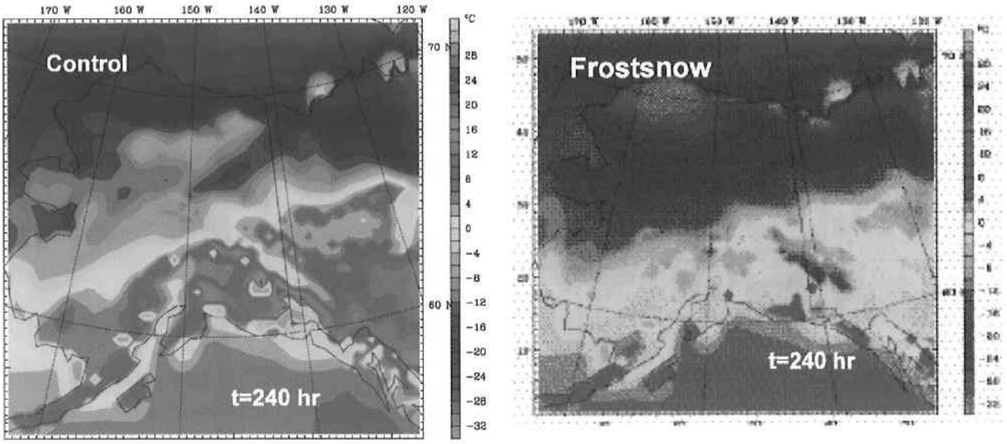
Fig. 5. Domain and terrain field (brown shades) used in coupled HTSVS-MM5 experiments.

The simulation with the improved physics indicates colder surface temperatures than the Control along the Alaskan North Slope where there is continuous permafrost and warmer temperatures in the southern half of the state where both permafrost and snow cover are discontinuous. The pattern in Figure 6b also reflects to a much lesser extent the mean atmospheric temperature through the simulation period, suggesting a slower, more realistic response to atmospheric forcing.

Figure 7a indicates that the bulk of the precipitation accumulated during the first 48 hours in the Control simulation occurs in southcentral and southeastern Alaska, a not uncommon pattern. There is a secondary precipitation area over the east-central Interior sections of the state which extends into the Yukon Territory. Figure 7b, the difference between the Control Simulation and the simulation with the enhanced permafrost and snow treatment (denoted "Frostsnow"), shows that the new physical treatments lead to small increases in accumulated precipitation over much of the precipitation area, but especially over the areas with highest terrain. In addition, the new scheme leads to the formation of a small amount of accumulated precipitation (likely as snowfall) during the period over parts of northern and western Alaska which are dry in the Control simulation, indicating the importance of including the snow and permafrost processes to even short-range weather prediction.

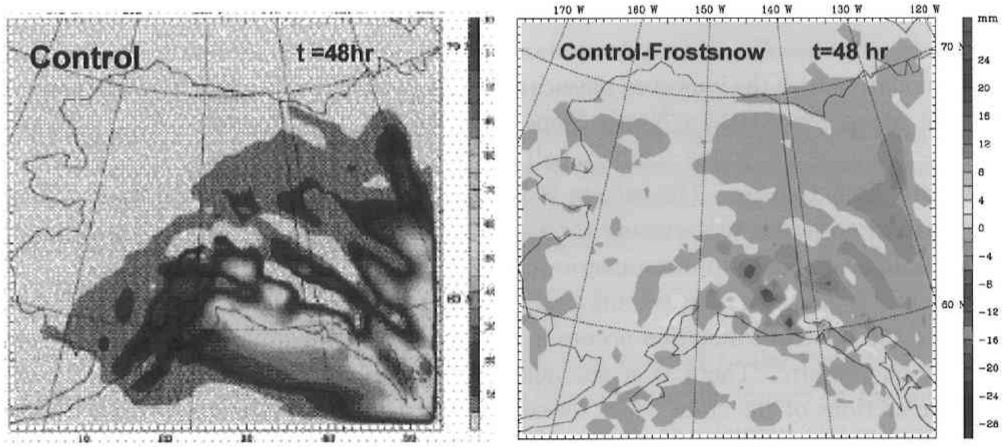
4. Climate feedback studies

In this section, we will briefly examine two studies examining different feedback



(a) (b)

Fig. 6. Simulated surface temperature (°C) at $t=240$ hours for two coupled MM5-HTSVS system experiments. a) Control experiment without enhanced snow or permafrost properties; b) Experiment with enhanced snow and permafrost treatment.



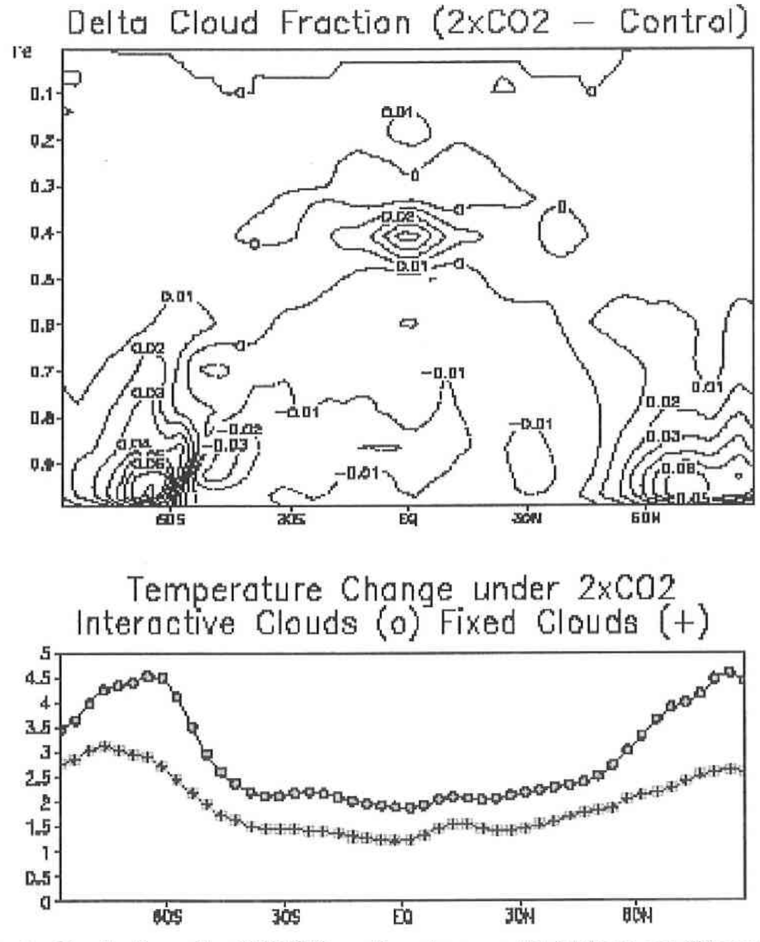
(a) (b)

Fig. 7. Simulated fields at $t=48$ hours for two coupled MM5-HTSVS experiments. a) Control simulation accumulated precipitation (mm); b) Difference field of accumulated precipitation, (Control simulation-simulation with enhanced snow/permafrost treatment (mm)).

mechanisms within the Arctic climate system: feedbacks between clouds and the climate, and feedbacks between the sea ice, ocean and atmosphere. We will examine each of these in turn.

4.1. *Cloud-Climate Feedbacks*

While the effect of clouds on the climate system has been studied through a variety of means over the past decade, there are still numerous outstanding gaps in our understanding of the role cloud processes will play in scenarios of global climate change related to greenhouse gas or other forcing mechanisms. A recent study using the GENESIS earth systems model (e.g., Pollard and Thompson 1995) provides new insights which are of interest since this model has shown a superior ability to reproduce the current annual cycle cloud climatology in the Arctic regions. In particular, GENESIS produces realistic winter cloud fractions compared to other GCMs, which tend to predict too much cloudiness over the Arctic Basin.


Delta Cloud Fraction (2xCO2 − Control)

Temperature Change under 2xCO2
Interactive Clouds (o) Fixed Clouds (+)

Fig. 8. Results from the GENESIS earth systems model (Pollard and Thompson, 1994) for cloud-climate feedback experiments.
Top panel: Vertical cross section of zonally averaged cloud fraction changes between a simulation containing doubled CO_2 forcing plus interactive clouds and a control climate simulation. Vertical scale corresponds to sigma coordinate levels between the surface and the top of the atmosphere (approximately 1 hPa).
Lower panel: Zonally averaged surface temperature changes (K) for doubled CO_2 simulations with and without interactive clouds. Fixed cloud simulations used a prescribed, constant cloud climatology derived from a long control simulation.

Figure 8 shows a sample of results from these simulations. The top panel indicates that under a global warming scenario there are general increases in the mean annual cloud fraction in the higher latitude troposphere, especially the lower troposphere. Spatially, the maxima in the fractional increases appear to occur over the latitudes which under the current climate exhibit the greatest sea ice concentration fluctuations during the annual cycle. This result would appear to argue for a prominent role for the so-called sea ice-boundary layer-cloud feedbacks which were a focus of the recent Surface Heat Balance of the Arctic experiment (e.g., Uttal *et al.*, 2002).

Another interesting result can be seen in the lower panel of Figure 8, showing resultant surface temperature changes under doubled CO_2 scenario simulations. Simulations with interactive cloud processes show a much more pronounced high latitude warming, consistent with the increase in low cloud fraction, than simulations where cloud cover is fixed using a climatology from a long control (no CO_2 forcing) simulation. Clearly the full incorporation of cloud processes (including aerosols, which the GENESIS model incorporates) has a significant (and amplifying) effect on the system, and raises some concern about the fidelity of GCM greenhouse gas simulations using model cloud climatologies.

4.2. *Sea Ice-Atmosphere Feedbacks*

A somewhat more focused study on sea ice feedbacks to the atmosphere has been recently conducted by a group of IARC, UI and NOAA investigators. This study specifically sets out to address the question: What is the atmospheric response to observed sea ice extent anomalies during summer?

The approach chosen was to undertake ensemble simulations with the NCAR Community Climate Model 3 (CCM3) where the simulations are forced with climatologically observed SSTs but with varying sea ice extents or concentrations. Table 2 lists the various experiments conducted. Note that in the ensemble approach utilized here,

Table 2. Characteristics of CCM3 ensemble experiments described in text. (min) designates a reduction of sea ice extent while (future avg.) denotes a mean of the various scenarios incorporated.

Experiment	Boundary Conditions & Integration Period	# in each ensemble
Control	1979-99 mean SST & ice extent	55 years
SUM95e (min)	Apr 1996-Oct 1996 extent	51
SUM95c (min)	Apr 1996-Oct 1996 concentration	51
SUM21ste (future avg.)	Apr-Oct ice extent, based on multi-model avg. of future scenario simulations	51

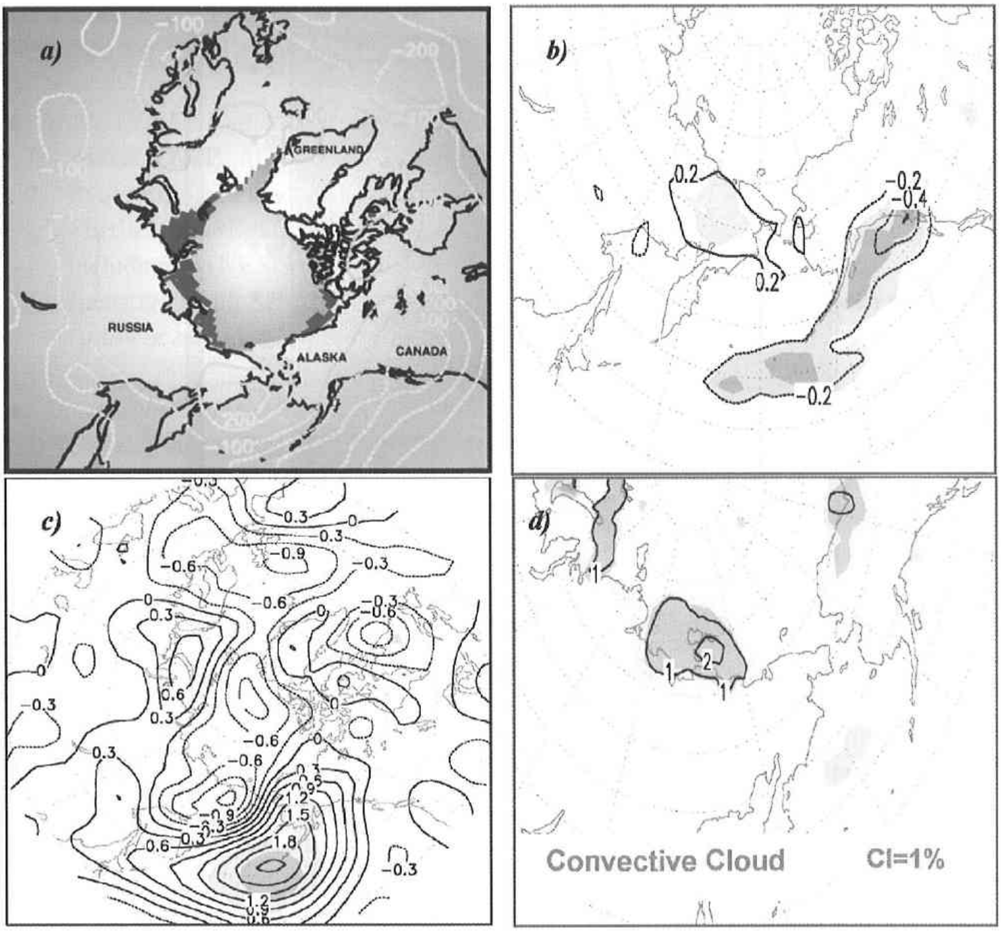


Fig. 9. Ice extent change and ensemble mean field responses to this change in the CCM3 SUM95e simulations. a): Ice extent change (red areas) and 500 hPa geopotential height variance anomalies (m^2). b) stratiform precipitation rate (mm/d); c) sea level pressure (hPa); d) convective cloudcover (%). Contours labeled in b)–d); contour interval 100 m^2 in a).

the last 51 years of the 55-year Control simulation with climatological SSTs and ice extents are used to provide the atmospheric and land initial conditions for the 51 ensemble members comprising each experiment listed in Table 2.

Figure 9 shows, for Experiment SUM95e, the August ice extent and the ensemble mean response in the convective cloud, precipitation, sea level pressure and 2–7 day band passed 500 hPa height variance fields. It is clear that there are not only local responses to the sea ice coverage decrease (indicated by the red area on Figure 9d) but also larger scale and hemispheric responses, as seen in the sea level pressure and 500 hPa height variance fields, which indicate a poleward shift of the surface Aleutian–Bering trough/subtropical high pattern often present in August and a corresponding shift of the main

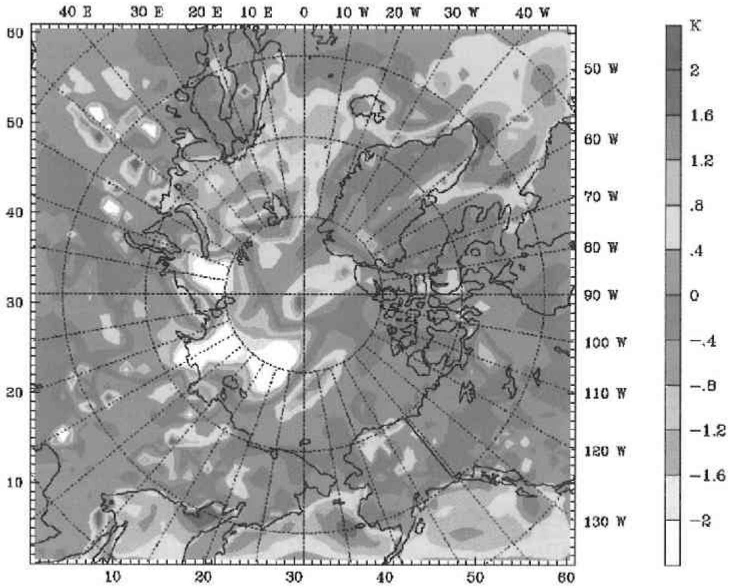


Fig. 10. Forecast time $t=360$ hour air temperature difference (K) with respect to coupled MM5-sea ice simulations for May 2001 with and without treatment of the ocean mixed layer. From Zhang and Tilley (2002).

mid-tropospheric jet/storm track.

It is interesting to note that a similar pattern of responses occurs in August for Experiment SUM21ste, which looks at the impact of projected sea ice decreases associated with 21st century global warming (figures not shown). This would tend to suggest a very clear relationship between sea ice extent and accompanying atmospheric changes. However, it is important to note that such a strong signal is only apparent upon examination of the ensemble mean fields. There is considerable scatter (not shown) among the individual realizations, suggesting that the linkages here may, for a given situation, be influenced by other factors that require further investigation.

Local responses to sea ice change are also apparent in recent work by Zhang and Tilley (2002) using an Arctic regional system model based upon MM5 and including sea ice and mixed layer ocean processes. Figure 10 illustrates the difference in surface air temperature that results over a 15-day period through the incorporation of an ocean mixed layer model. There are corresponding local responses in the cloud and precipitation fields, all of which can be tied to changes in the surface fluxes of heat and moisture over the Arctic ice pack. Such changes in the surface flux regime are apparent in the CCM3 simulations.

5. Future activities

During the coming year several projects are planned which build upon the recent work that has been summarized here. There are four primary areas of emphasis. Below we list these areas and highlight specific efforts planned to occur :

- *Arctic Clouds, Radiation and Feedbacks*
  1. Assess CMIP, ACIA, ERA-40, NARR analyses with field data
  2. Evaluation of cloud-radiative schemes in the ECHAM model
  3. Further investigate the ice-albedo and cloud-radiative feedbacks with models including GENESIS
  4. Investigate the Xu-Randall type cloud fraction scheme and circulation sensitivity to lower boundary conditions

- *Downscaling of GCMs to Regional Scale*
  1. Develop an optimal strategy for embedding high resolution grids within a GCM grid, utilizing ARPEGE & ALADIN models
  2. Examine the validity of parameterizations at differing scales

- *Towards a new Arctic Reanalysis*
  1. Enhancement of the under-development Weather Research/Forecasting model for Arctic applications
  2. Preliminary satellite data assimilation experiments over the Arctic

- *Extreme Events*
  1. An exploratory effort evaluating the simulation of extreme events by the models used in the ACIA project.

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