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Report on the SCAR - CliC – IASC – ICPM Workshop on

Recent High Latitude Climate Change

NOAA/PMEL, Seattle, 22-24 October 2007

The meeting was held to advance our understanding of the mechanisms behind recent climate change in the Arctic and Antarctic. It consisted of invited presentations, discussion periods and breakout sessions to address particular questions. The following is a summary of the various presentations organized into Arctic, Antarctic and bipolar issues. It is followed by summaries of the breakout sessions.

The Arctic

Jim Overland (NOAA PMEL) provided an introduction to recent climate change in the Arctic. He began by noting that the extent of Arctic sea ice had reached a new minimum in September 2007, which was some 25% below the previous minimum in 2005. The age of the ice had decreased in recent years as a result of the ‘flushing’ of much of the ice in the early 1990s. The loss of ice has frequently been linked to the positive nature of the Arctic Oscillation (AO) in recent years, but the AO peaked around 1990, yet the ice extent has continued to decrease. The ice minimum in 2007 was attributed to the pre-conditioning of the region by the flushing of the old ice, coupled with favourable synoptic conditions in 2007. This consisted of a persistent anticyclone north of Alaska that resulted in less cloud over the area and a feed of warm air into the central Arctic through the Bering Strait. Throughout the meeting there was discussion of whether the ice minimum was a result of anthropogenic factors or whether it could have occurred because of natural climate variability. Jim pointed out that some of the ensemble members of the IPCC AR4 models when run through the late 20th century DID have sea ice extent decreases of the magnitude observed in recent years. In summary, it was felt that the sequence of hemispheric and local atmosphere-ocean-ice processes and feedbacks led to the current conditions.

Many other aspects of the arctic climate system are also changing, including permafrost, where the active layer is increasing in depth in some areas and areas of permafrost are being lost. The Greenland ice sheet is now receiving more precipitation and there has been a well-publicized increase of surface melt, resulting in a possible lubrication at the lower boundary of the ice sheet.

Arctic sea ice

Ignatius Rigor also dealt with the loss of Arctic sea ice and the preconditioning for the summer ice minima. The importance of the AO was discussed and ice conditions during the low AO period of the 1980s and the high AO period of the 1990s contrasted. Sea ice may reside in the Arctic for over 5 years, with increased ice advection away from the Russian coast during high AO and faster export of sea ice from the pole to Fram Strait. During high AO summers (JJA) ice motion increases concentration of sea ice and temperature advection increases ice concentration in Chukchi Sea, but decreases ice concentration in the Canadian Beaufort Sea. Warmer temperatures during the 1930s did not decrease sea ice. It was suggested that the correlation between the AO and Arctic climate may now be broken. There is a continued decrease in the area of older ice. This seems to occur in episodic, wind driven events.

The question was asked as to whether there were possible brakes on the system. Polar amplification of global warming may slow poleward transport of sensible heat, but transport of latent heat may increase. Arctic cloud cover is increasing during winter and decreasing during other seasons. However, over the Arctic Ocean the “shading effect” will be small due to low contrast between clouds and ice/snow. Increased P-E may slow the THC, but model results imply a constant or even increasing flow of warm Atlantic water into the Arctic Ocean.

In summary, it was stated that most of the older, thicker sea ice was lost during the extreme high AO conditions of the early 1990s. The area of perennial sea ice over the Arctic Ocean has decreased from over 5.6 million km^2 to 2.7 million km^2 as sea ice drifted at twice the speed. Preconditioning and positive feedbacks (ice-albedo, & ice mechanics) may help explain the record minima in summer sea ice extent. Spring and summer winds may enhance the summer minima. Prolonged low AO conditions may sequester sea ice, and may promote the recovery of sea ice. Decadal “memory” of sea ice implies continued record/near-record minima in summer sea ice extent.

Cecilia Bitz presented work on atmosphere/ocean forcing and the uncertainty in predicting sea ice change. Arctic sea ice is declining faster than forecast by climate models. The goal has to be to develop a framework for describing climate model uncertainty in sea ice retreat. It was stressed that the mean state matters. A feedback analysis has been applied to the Earth’s temperature and a climate sensitivity parameter computed. In summary, sea ice albedo feedback causes sea ice thickness to decrease about 50% faster. Although positive, the feedback is not enough to cause much uncertainty in thickness prediction. Instead errors are probably more a function of error in the mean state.

Jennifer Francis looked at atmospheric drivers of Arctic sea ice variability. Understanding sea ice variability is very important, but most models do not lose ice rapidly enough when run over recent decades. New satellite products can provide insight and allow investigation into the relationships between sea ice anomalies and subsetted time series (1979 to 2004) of anomalies in other satellite-derived parameters, such as downward longwave flux (DLF), downward shortwave flux, zonal wind, meridional wind and advective heating. The variance in maximum ice retreat is explained by integrated forcing parameters. In most areas and seasons, the downward longwave flux has increased since 1979.

In conclusion, until 2004, anomalies in DLF explained about half of the variability in perennial ice extent (this conclusion may now be obsolete in a new ice albedo-feedback-ruled world). Two IPCC models are reasonably successful in reproducing observed perennial ice drivers; causes of differences are not known yet. Observed trends in DLF are driven primarily by increasing cloud fraction and water vapor, offset by lowering cloud bases (except in the Barents Sea). Cloud-base heights are the major uncertainty in DLF trend attribution. Winter ice extent is driven mainly by ocean heating in the Barents Sea, and by easterly wind anomalies in the Bering. Summers with extreme ice area predict the following winter's NAO index and precipitation anomalies in Europe and N. America.

Jim Overland presented the work of Muyin Wang who looked at IPCC sea ice projections. The AR4 models have a very wide range of projects for sea ice evolution over the next century. Options were to develop super ensembles. It would also be possible to remove outliers. There was no single best model.

Oceanic change

Michael Steele dealt with Arctic Ocean warming: Atlantic, Pacific, & local sources. Subsurface layers within the Arctic Ocean are sensitive to the penetration of heat from Atlantic Water (AW) and Pacific Water (PW) via the Fram Strait and Bering Strait. Expeditions such as SCICEX during the 1990s and NPEO during the 2000s measured variations in the heat content of AW, indicating a peak warming near the North Pole in 1995, a minimum in 2005, and a new warming pulse thereafter. With respect to the surface layer of the Arctic Ocean, an analysis of the past 80 years of summer-mean sea surface and upper 100 m temperatures indicates control by both ocean and sea ice advection. During 1965-1995 as the Arctic Oscillation index rose, warming was observed from AW advection into the Barents/Kara Seas and from PW advection into the Chukchi and western Beaufort Seas. Also during this time, winter sea ice transport away from the Eastern Siberian shelves created thin ice that melted quickly during summer, leading to a longer summer open water period during which solar energy warmed the ocean. Recent ocean surface warming in the Beaufort/Chukchi/East Siberian Seas since 2002 seems forced more by shortwave energy absorption than by northward-flowing ocean advection, although more in-situ data are needed to confirm this.

Koji Shimada considered further the ocean contribution to the recent catastrophic reduction of sea ice in the western Arctic Ocean. The importance of warm Pacific Water entering the Arctic Ocean via the Chukchi sea was once again stressed. Data on outflow through the Barrow Canyon was presented. Northward advection of Pacific Summer Water (PSW) along the Northwind Ridge was described as an Arctic Kuroshio. Pacific Summer Water reaches the Northwind Ridge in mid winter. Recently observed reduction in sea ice cover in the Arctic Ocean is not spatially uniform but rather is disproportionately large in the Pacific sector of the Arctic Ocean. The spatial pattern of ice reduction is similar to the spatial distribution of warm Pacific Summer Water that interflows the upper portion of the halocline in the southern Canada Basin north of the Chukchi Sea. The upper ocean is not directly driven by wind forcing, but by sea ice motion. Less ice near the coast enhances the sea ice motion and the upper ocean circulation. As a result, heat transportation into the basin is increased. Ocean warming results in less ice formation and further activation of ice motion leading to outflow of sea ice through the Fram Strait. A positive feedback mechanism was described that involved oceanic warming, activation of sea ice motion and ice extent decrease.

The processes of Arctic climate change

Alex Hall looked at causes and consequences of the spread in snow albedo feedback. The strength of snow albedo feedback exhibits a three-fold spread in the current generation of climate models. This is a major source of spread in projections of future climate in the region. Variations in snow albedo feedback strength account for a significant portion of the intermodel variations in temperature response over northern hemisphere landmasses. Signals are particularly large in spring and summer. The intermodel standard deviation of the change in temperature and soil moisture occurring by the end of the 21st century in AR4 models was shown. There was a large spread in model response of both variables in a band stretching across the United States. Models with strong snow albedo feedback lead to large reductions in summertime soil moisture over the continental U.S. This occurs because strong snow albedo feedback leads to earlier springtime snowmelt, so that the summertime evaporation season lasts longer. Summer drying leads to increased warming through reduced evaporative damping of surface temperature, linking feedback strength with temperature response. Snow albedo feedback is also a controlling factor on the annular-mode-like response of the northern hemisphere circulation to anthropogenic forcing. We can break down snow albedo feedback strength into a contribution from the reduction in albedo of the snowpack due to snow metamorphosis, and a contribution from the reduction in albedo due to the snow cover retreat. It turns out that the snow cover component is overwhelmingly responsible not only for the overall strength of snow albedo feedback in any particular model, but also the intermodel divergence of the feedback. Snow albedo feedback strength is highly correlated with a nearly three-fold spread in simulated effective snow albedo, defined as the albedo of 100% snow-covered areas. Improving the realism of effective snow albedo in models will lead directly to reductions in the divergence of snow albedo feedback.

Conclusions were, snow albedo feedback is a significant cause of intermodel spread in temperature, particularly during spring in the lands of the pan-Arctic, and during summer in mid-latitudes. The summer response is also associated with large intermodel spread in the change in soil moisture. The feedback also leads to intermodel spread in the midlatitude atmospheric circulation in an annular-mode-like pattern. The spread in the feedback is linked to the optical properties of the model land surface, an element of the climate system that is observable in principle.

Thorsten Mauritsen gave a talk on ‘Some thoughts on the Arctic boundary layer’. Changes in the boundary layer parameterization can have a major impact on the output of operational NWP models, as seen in fields such as 2 m air temperature as well as the life-cycle of cyclones. The impact of different parameterisations on simulated climate and climate change is not well known. It was concluded that the Arctic surface is trapped between the two Arctic inversions, both in the atmosphere and the ocean. Ocean currents and atmospheric winds transport heat from lower latitudes into the Arctic. However, the transfer of heat towards the Arctic surface is strongly inhibited by the presence of stable stratification. There is currently no consensus on how to treat transfer under stable stratification amongst boundary layer modellers involved with micro-meteorology and operational forecasts.

Rune G Graversen discussed the vertical structure of the Arctic amplification. In recent decades large temperature trends have been observed in the Arctic troposphere well above the boundary-layer. The Arctic amplification is apparent not only near the surface. During the 1980s and 1990s, the vertical structure of the amplification cannot be explained by snow- and ice-albedo feedbacks as well as other processes leading to the largest temperature response near the surface. In the summer half year, the Arctic temperature amplification is largest well above the surface. At this time of year, increase of meridional energy transport across 60 N can explain a considerable part of the Arctic amplification.

Arctic hydroclimatology

Jessica Cherry discussed variability and trends in Arctic hydroclimatology. There are still many problems in measuring solid precipitation at high latitudes and gauge undercatch is a significant problem, especially in winter. There is also a marked downturn in the number of stations operating and delays in accessing data. Determining the changes in precipitation over recent decades is difficult, and there are differences between the different data sets available. However, overall there does seem to have been a recent increase in precipitation in certain locations like central Siberia These trends are more evident from snow depth records than from precipitation records. There are large biases between the ECMWF 40 year reanalysis (ERA-40), the NCEP reanalysis and the Global Precipitation Climatology Project data. All 21 IPCC Four Assessment (AR4) models have increasing trend in ensemble mean precipitation. Winter trends are similar to annual means, but summer shows no systematic changes. Most General Circulation Models (GCMs) tend to overestimate precipitation. A pan-Arctic snowfall reconstruction is being created for the period 1940-1999. Precipitation can be summarized as poorly constrained by observations, even over land and highly variable in time and space. Detecting trends is difficult and an extremely thorough analysis of biases and sophisticated statistics is required. Attribution studies should take biases into account.

There has been an increase in river discharge in northern Eurasia since the mid-1930s. This has happened in parallel with rising air temperatures. But there has been decreasing river discharge in eastern Canada over 1964-2003, probably tied to trends in the Arctic Oscillation. The Mackenzie River in Western Canada shows no long-term trend. Discharge trends are greatest in the north where permafrost is most extensive. Summarizing runoff, it is better constrained by observations, though gauge numbers have decreased. Detecting trends is difficult, as it doesn't typically take autocorrelation into account, which can be caused by subsurface storage, the NAO, etc. Attribution studies require land surface model with major processes or at least proxies and they should take land use and regulation into account.

Modelling and predicting the Arctic climate

Klaus Dethloff discussed modelling and predicting Arctic climate and weather. We have a long record of Arctic temperatures that show that the Arctic has warmed twice as much as the global mean warming. There is also large decadal temperature variability. Climate variations occur because of external forcing and internal nonlinear dynamics. Temperature changes are linked to natural modes of atmospheric variability - Eurasian warming: positive AO/NAO, and Alaska warming: positive PDO. The AO and PDO are connected with trends in Arctic cyclones and variations influence sea ice cover. Cyclone simulation requires high resolution modelling in the form of Regional Climate Models

(RCMs). The Arctic climate responds to regional and global forcing factors. The goals of IPY-THORPEX were described along with the Thorpex Arctic Weather and Environmental Prediction Initiative (TAWEPI). An important goal of TAWEPI is to develop a regional Numerical Weather Prediction (NWP) system (10-15km horizontal resolution) over the Arctic in support of the IPY projects, like THORPEX and field measurement campaigns. Meso-scale spatial scale features developed in RCMs are attributed to four types of sources - the surface forcing, the nonlinearities presented in the atmospheric dynamical equations, hydrodynamic instabilities - shear and buoyancy in the flow can also, through hydrodynamic instabilities, produce mesoscale features without the help of surface forcings and the noise generated at the lateral boundaries and model errors. The Arctic Regional Climate Model Intercomparison Project (ARCMIP) was described.

In summary, the Arctic climate system involves complex atmosphere-ice-ocean interactions and numerous feedbacks (e.g., ice-albedo, PBL, aerosol-radiation-circulation). Arctic changes are neither spatially nor temporally uniform. Much better data are needed over the Arctic Ocean. Arctic processes and changes can trigger changes of global atmospheric circulation via modified teleconnection patterns leading to a shift to negative AO phase. For further research (IPY) there must be improved understanding of Arctic key processes and their global links, synthesis of observations and regional & global climate model simulations, study of key processes, such as sea ice-atmosphere-ocean coupling, permafrost-soil, aerosol-clouds, boundary layer processes and regional feedbacks, stratospheric ozone. Ther was a call for suggestions for coordinated AOGCM runs with a special Arctic focus during IPY.

An Arctic reanalysis

An Arctic system reanalysis is to be carried out. The aim is to integrate all available observations into a consistent framework, providing a vehicle for monitoring and diagnosing environmental change in the Arctic. The large variations of the past decade can then be placed into a broader perspective. It will be a “system reanalysis” of the atmosphere, sea ice, upper ocean and land hydrology. A regional reanalysis for the Arctic (Arctic System Reanalysis, ASR) was developed under NOAA funding; now funded by NSF A prototype (proof of concept) was based on the Polar MM5 model. The final system is to be based on the Weather Research and Forecasting (WRF) system. Lateral boundary forcing will be provided by a global reanalysis, ERA-40.

Primary activities to date have been parameterization experiments targeting Arctic processes, evaluation of global reanalyses (ERA-40, NCEP) over the Arctic and tests of different data assimilation strategies.

Planned activities are three-dimensional, multi-component Arctic regional reanalyses spanning the satellite/buoy era (1979-present) and a longer (half-century) period of global reanalyses. There will also be diagnostic emphasis on poorly observed quantities (surface fluxes, hydrology, cloud/radiative fields) and observing system experiments to guide priorities of (sustained) Arctic Observing Network.

The Antarctic

John Turner presented the introductory talk into recent climate change in the Antarctic. The Southern Annular Mode (SAM) was felt to be very important in driving many of the climatic changes observed across the continent and Southern Ocean in recent decades. The SAM has shifted into positive phase over recent decades as a result of the ozone hole, increasing greenhouse gases and natural factors, such as volcanic aerosols. The greatest change in the SAM has been in the summer and autumn, with the least in the spring. Studies have suggested that the largest contributing factor to the shift in the SAM has been the ozone hole, followed by increasing greenhouse gases and then natural forcing. The resulting drop in pressure over the Antarctic and increase in mid-latitudes has increased the surface winds over the Southern Ocean by about 15%.

In terms of surface temperature changes across the continent in recent decades, there has been a warming of the Antarctic Peninsula and a small cooling around the coast of East Antarctica. The peninsula warming has been largest on the western side in winter and on the east during summer. The eastern warming has occurred largely because of more maritime airmasses crossing the peninsula, as a result of the stronger westerlies through changes in the SAM. The warming is therefore, at least in part, a result of anthropogenic activity. The winter warming is believed to have occurred as a result of a decrease in sea ice extent since the 1950s. This may be because of greater cyclonicity over the Bellingshausen Sea in recent decades, although lack of data make confirming this difficult. At present it is not known whether the western peninsula warming is a result of natural climate variability or has an anthropogenic origin or component. The small cooling around the coast of East Antarctica is thought to be a result of changes in the SAM, which give a warming across the peninsula and cooling around East Antarctica. It was also noted that a new ice core from the southwest corner of the Antarctic Peninsula has shown that there has been a doubling of the accumulation since about 1850. Across the rest of the continent there had been no significant change in accumulation since the late 1950s.

At upper levels a major change has been the warming of the mid-troposphere during winter, which is the largest temperature increase at this level on Earth. Current research to understand this warming has focused on the increase in Polar Stratospheric Clouds (PSCs). These have increased above the continent as stratospheric temperatures have dropped in recent decades. PSCs are not included in most climate models, but initial experiments including a layer of PSCs in an atmosphere-only model have suggested that they can result in a mid-tropospheric warming if they have an optical depth of around 0.4-0.5. It was suggested that the SPARC project may be able to help with this work since some of their models included PSCs. Prof. Fu gave a short presentation on the value of data from the CALIPSO cloud lidar. It may be able to provide insight into the nature and occurrence of PSCs above the Antarctic.

It was reported that a new sea ice extent retrieval algorithm had shown that the Southern Hemisphere sea ice extent had increased at a statistically significant rate since the late 1970s. The greatest increase was in the Ross Sea sector in the autumn. The change in this area had been linked to a stronger cyclonic flow over West Antarctica giving greater southerly flow off the Ross Ice Shelf. This change in circulation was reflected in the ECMWF 40 year reanalysis (ERA-40) and the AR4 models run through the late 20th century. Atmosphere-only model experiments had suggested that the change in circulation was a result of Rossby wave generation from East Antarctica in the stronger westerly flow that had occurred as a result of the change in the SAM. Experiments had therefore suggested that the increase in sea ice had occurred because of the ozone hole and was therefore anthropogenic.

The ozone hole

Nathan Gillett discussed the role of ozone depletion in high latitude climate change. Until about 10 years ago, stratospheric ozone depletion was thought to play little role in forcing tropospheric trends. However, Sexton et al. (2001) and Kindem and Christiansen (2001) both simulated a positive SAM response to Antarctic ozone depletion. Thompson and Solomon (2002) showed observed geopotential height and temperature trends were largest in the stratosphere at the time of maximum ozone depletion, and appeared to propagate downwards 1-2 months later. Gillett and Thompson (2003), Arblaster et al. (2006) and Shindell and Schmidt (2004) have simulated similar trends in response to observed ozone trends. SAM trends have not been exclusively forced by ozone, but likely by greenhouse gases as well. Shindell and Schmidt (2004) and Arblaster and Meehl (2006) find that approximately half of the December-May SAM index trend between 1958 and 2000 was due to ozone depletion, and half due to greenhouse gas increases. Since the 1970s the fraction of trends attributable to ozone depletion is likely to be larger.

It has been suggested that the Antarctic tropospheric response may be driven mainly by ozone depletion in the lowermost stratosphere, which is at a maximum 1-2 months after maximum depletion in the core of the ozone layer. However, Keeley et al. (2007) find that the Antarctic tropospheric response is driven mainly be ozone depletion above the lowermost stratosphere. Recent results suggest that zonal asymmetries in the distribution of ozone may strongly influence stratospheric temperature and circulation in the Southern Hemisphere.

While Volodin and Galin (2000) found a link between ozone depletion and Northern Annular Mode trends, this finding has not been reproduced in other models, and simulations of HadSM3-L64 forced by Randel and Wu (1999) ozone trends did not show a significant Northern Hemisphere circulation response, suggesting that the much weaker ozone depletion observed in the Northern Hemisphere has not been an important driver of circulation changes there.

Antarctic sea ice

Marika Holland looked at Antarctic sea ice variability and change. In contrast to the north, Antarctic sea ice in both winter and in the annual average have a small increasing trend in both area and extent. What is happening in the Antarctic is perhaps not what would be expected from a straightforward global warming scenario, but instead results from a complicated set of events involving ice-ocean-atmosphere interactions and change. Around the continent we are seeing compensating regional trends. Ice cover is reducing along Antarctic Peninsula, extending into the Atlantic, but increasing in the central Pacific sector. There is a high correlation between this general pattern of ice extent and the SAM. Additionally, long control climate model integrations suggest that the Antarctic dipole in ice cover, which is the leading mode of sea ice variability, is correlated with the SAM. In the future, models show reduced warming across 40-60S, but little SH polar amplification in the near term (next 50-100 years). It has long been recognized that increasing ocean heat uptake is in part responsible for this reduced simulated surface response and that a small observed Antarctic surface change is broadly consistent with model results. The concluding question was asked ‘why does Antarctic have little ice change?’. As with Arctic change, probably multiple factors are involved. A positive trend in the SAM leads to compensating sea ice anomalies. Ice dynamics/thermodynamics and ocean changes are all important in this SAM driven response. The Southern Ocean buffers surface change by heat uptake and reduced surface heat loss. Model simulations suggest that changing sea ice freshwater flux in a warming climate plays an important stabilizing role for the Antarctic sea ice. These changes in the SAM and ocean conditions, which promote a relatively stable Antarctic ice pack, are consistent (and indeed expected) from anthropogenic climate change.

Antarctic glaciers

Andrew Fountain gave a presentation on glaciers, with a particular focus on the meteorology and glaciers of the McMurdo Dry Valleys. Globally there has been a loss of mass from glaciers giving a positive contribution to sea level rise. Melt across Greenland is increasing with greater ice flow to the ocean. Data was presented on the mass balance over various glaciers in the Dry Valleys that have been measured over a decade or more. Photographs from the early part of the Twentieth Century showed that lake levels had risen since that time. There had been a well publicized cooling of the Dry Valleys since the mid-1980s.

The Southern Ocean

Mike Meredith (BAS) considered climate change in the Southern Ocean: observations and mechanisms. The Southern Ocean is changing, in some places very rapidly, but the pattern and physical nature of the changes are complex, and a number of mechanisms and feedbacks are implicated. At the circumpolar level, it is now well-established that the waters of the Antarctic Circumpolar Current (ACC) are warming more rapidly than the global ocean as a whole. Gille (2002, 2003) compared data from the 1990s with data from earlier decades, and deduced a large-scale warming of around 0.2°C in the ACC waters at around 700-1100 m depth. More recently, this work was extended to show that this warming is surface intensified, reaching as much as 1°C at the surface, and that a large jump in temperature of the upper ocean occurred during the 1960s (Gille, 2007).

The reasons for this warming of the circumpolar Southern Ocean are not known unambiguously, and it is likely that one or more processes will be contributing. Some of these processes have, as their root cause, the increase in eastward wind stress over the Southern Ocean associated with the shifting of the SAM into its positive phase (Thompson and Solomon 2002). As well as affecting the magnitude of the wind stress, this change in the SAM has also affected the location of the Southern Hemisphere winds, with the band of maximum wind stress moving southwards as a result. This has led to theories, supported by coarse-resolution climate modelling studies, that the ACC may have moved southward in response (e.g. Oke and England; Fyfe and Saenko, 2006), effectively bringing warmer water further south, and leading to an apparent warming. Observational evidence to support this process has been somewhat scant, however there are some recent indications based on *in situ* data that this may be a contributor (Gille, 2007).

It has also been suggested, based on climate modelling studies, that the strengthening of the winds over the Southern Ocean may be leading to an acceleration of the ACC (Hall and Visbeck; Fyfe and Saenko, 2006). While there is good observational evidence that the strength of the ACC does indeed depend on the SAM on timescales from days and weeks (Aoki, 2002; Hughes et al., 2003) to years (Meredith et al., 2004), there is, at present, no evidence for a sustained, long-term increase in transport. Partly this is due to the lack of a suitable monitoring system, but available indications do suggest that any change in transport over the past few decades will have been small (order of just a few Sv). This lends weight to the theory that the ACC is “eddy saturated”, whereby excess energy from the accelerating winds is cascaded from the large (circumpolar) scales to smaller (eddy) scales on interannual and longer timescales (e.g. Hallberg and Gnanadesikan). Satellite altimeter measurements of Southern Ocean eddy activity support this theory (Meredith and Hogg, 2006), and it has been demonstrated in both parameterized and eddy-resolving models that the poleward eddy heat flux associated with this process can be a significant contributor to the observed Southern Ocean warming (Fyfe et al., 2007; Hogg et al., 2007).

A further process very likely to be a contributor to the warming is increased atmosphere-to-ocean heat flux associated with raised levels of radiative greenhouse gases in the atmosphere, and modelling studies have indicated that the rate of Southern Ocean would even higher but for the masking effects of volcanic and other aerosols (Fyfe, 2006).

South of the ACC, the subpolar gyres are also undergoing very significant change (e.g. Boyer et al., 2005). A large sector of the fringes of Antarctica between the Amundsen Sea and the Adelie coast has undergone a very significant freshening in recent decades (Jacobs et al., 2006), of a magnitude comparable (and possibly exceeding) the remarkable freshening observed in the North Atlantic (Dickson et al., 2002). This is evidence of a change in the hydrological cycle affecting both northern and southern limbs of the global overturning circulation. The Southern Ocean freshening is not confined to the upper layers of the ocean; these regions include some active areas of Antarctic Bottom Water (AABW) formation, most notably the Ross Sea, and this water mass has been shown to be getting progressively fresher in recent years as a consequence (Rintoul, 2007; Aoki et al., 2005). The cause of the freshening is believed to involve increase melt of glacial ice from adjacent regions of Antarctica (Jacobs et al., 2002), and it has been theorized that the excess heat to cause this melt has come from the increasing ocean temperatures.

In the other major site of AABW formation, the Weddell Sea, there have also been very significant changes, but of a different nature. Robertson et al. (2002) found that the Warm Deep Water (WDW) layer here warmed by around 0.3°C since the 1970s, and it was hypothesized that this is related to a recovery from the years of the Weddell Polynya, when the deep layers of the Weddell Sea were directly ventilated. WDW is the deep ocean precursor of AABW, so the changes in its properties are likely to influence AABW formation. Possibly consistent with this, Weddell Sea Bottom Water (WSBW, the densest form of AABW in the Weddell Sea) has recently been observed to be warming (Fahrbach et al.). WSBW is too dense to be directly exported to the global overturning circulation, and is topographically constrained to lie within the Weddell Sea. However, the component of AABW that can readily escape the Weddell Sea (Weddell Sea Deep Water; WSDW) has been observed to be warming downstream in the South Atlantic, with the warming signal reaching as far north as the equator (Zenk and Morozov, 2007; Hogg et al.; Coles et al.).

It is unlikely that the WDW warming in the Weddell Sea can explain all of the WSDW warming observed at lower latitude. Current research is focusing on determining the processes that control the export of this dense water mass from the Weddell Sea, as well as its properties (e.g. Meredith et al., 2007). This is pertinent since a reduction in the export of the very densest WSDW would be manifest as a warming of WSDW, with potential long-term impacts on the meridional overturning circulation in the ocean. Current lines of investigation relate the export of WSDW from the Weddell Sea to cyclonicity of the wind stress over the Weddell Gyre, with a link to El Nino having been mooted (Martinson and Iannuzzi; Meredith et al., 2007).

In addition to the above changes in globally important water masses that participate in the oceanic overturning circulation, there are also some very strong regional changes in the surface and near-surface layers of the Southern Ocean that warrant mention. These include a very strong warming on the west side of the Antarctic Peninsula where the summertime surface ocean has warmed by more than 1ºC since the 1950s, with an accompanying increase in salinity (Meredith and King, 2005). These changes reflect the well-known increase in atmospheric temperature and reduction in sea ice at this location. However, the ocean is not purely a receptor of the climate change signal; instead the oceanographic changes are positive feedbacks, acting to promote further decrease in ice production and further atmospheric warming. A strong warming is also seen downstream of the Antarctic Peninsula, close to South Georgia in the Scotia Sea. Here, data exist back to the Discovery Investigations in the 1920s, and recent analyses indicate a strong summertime warming (>1ºC) and an even stronger wintertime warming (>2ºC) (Whitehouse et al., in prep). The causes of this warming are being investigated; certainly the location of South Georgia within the ACC implies that the general circumpolar warming of the Southern Ocean will be playing a role. Added to this, the Scotia Sea is a region where positive changes in the SAM (positive wind anomalies) induce instantaneous warming rather than cooling, therefore the rising trend of the SAM may have an anomalously exacerbating effect on ocean warming here.

These upper-layer regional changes are interesting physically, and may be extremely biologically important. Benthic species on the Antarctic Peninsula shelf are know to be very well evolved to cope with low temperatures, but very poorly evolved to cope with changes in temperature. A rise in temperature of just 2ºC could have major deleterious effects on populations and species here (Peck et al.). The observed summertime warming of >1ºC occurred in just a few decades, and the continued warming that is observed must be seen to be a major threat to the present biota on these timescales. In the South Atlantic, populations of Antarctic krill have been in steep decline in recent decades (Atkinson et al.). Krill is a key species in Antarctic foodwebs, with many higher trophic levels relying on it as a primary food source, and is also economically important due to its commercial exploitation. Krill is ostensibly a cold-water species, and the rising ocean temperatures here could well be a major contributor in its decline. The predicted continued warming of the Southern Ocean could well have profound consequences for Antarctic krill, and other species that depend on it.

Predicting the Antarctic climate

JohnTurner presented the work of Tom Bracegirdle on high latitude climate projections from the IPCC AR4 models. The IPCC AR4 is based on 23 of the world's best models, but the output of the models is simply averaged regardless of their ability to reproduce recent high latitude climate variability. The output of the models had therefore been compared for the last couple of decades against the observations. Quantities assessed were sea ice extent, mean sea level pressure, temperatures at upper levels, precipitation – evaporation (P-E) and SSTs. Surface temperature and surface wind speed/direction would not be good quantities to assess because of the many local factors that influence them in the Antarctic. The models handled SH sea ice very poorly. A model output weighting scheme had been developed based on a comparison with observations. The scheme used rms errors of modelled mean climate for the period 1979-1998. Both global and Antarctic errors were taken into account. The weighted model output suggests that we can expect a warming of around 0.33 +/- 0.1 deg C/dec (land) and 0.26 +/- 0.1 deg C/dec (ocean/sea ice zone) by the end of the century. Where sea ice is lost around East Antarctica the warming is about 0.5 deg C per decade. There will be a reduction of Antarctic sea ice area by about 33% over the year as a whole, and 25% of sea ice extent. We expect an increase of snowfall across the continent of 25-50%. We can expect a switch of 10% of snowfall to rain in summer. Winter warming of the peninsula will continue due to reduced sea-ice extent ans similar warming will spread to many other coastal regions. A widespread increase of the circumpolar westerlies is expected, leading to a decrease of coastal easterlies, particularly in summer and autumn. The models suggest westerlies over the Southern Ocean will increase by 10-20%. There will be little change in winds over the continent. The good news is that most of Antarctica will remain well below freezing so there will be no large-scale melting of the ice sheet.

Bipolar issues

The role of tropical forcing on recent change in the Arctic and Antarctic was dealt with by Ryan Fogt. We see opposite responses in the polar regions to Indian Ocean warming. The Indian Ocean warming is coincident with and perhaps drives the winter positive NAO /NAM trend in the CCM3, NSIPP-1, and GFS ensemble mean. A model was run for 25 years with a progressive 1K increase in Indian Ocean SSTs prescribed, which shows that the Indian Ocean warming projects onto positive NAM, but a negative SAM. The NH response is primarily eddy-driven, while SH response can also be modulated by stratosphere-troposphere dynamic coupling. Indian Ocean warming weakens the polar vortex through an increase of planetary wave activity from the troposphere into the stratosphere. These anomalies migrate downward into the troposphere. Previous research on ENSO decadal variability in West Antarctic snow accumulation has shown decadal time scale variability in the relationship between precipitation and the SOI. Upper air observations From the Drake Passage region also show decadal ENSO variability. In terms of ENSO / SAM interactions, there were large changes between the 1980s and 1990s in the September-November data. For ENSO / SAM zonal wind interactions, earlier work finds strong interaction with the zonal-mean zonal wind and the CTI [cold tongue index, the SST anomalies in the $6^oN – 6^oS$, 180^o – 90^oW region] in NDJF. The SAM fit accounts for virtually all of the structure and amplitude of the SH zonal mean circulation response to variations in the ENSO cycle. The residual is an expected pattern due to variations in tropical heating, mostly marked in the subtropics. The interaction mechanisms are thought to be (1) convergence of meridional momentum associated with ENSO leads to [u] increases at 60^oS, and vice-versa at 40^oS and (2) ENSO and SAM both show poleward momentum flux at 50^oS, but the causes for this latter interaction are still not well understood. Similar SAM / ENSO interactions occurred in the past. During DJF 1959-1968 the response was similar to that in 1980-1990s. In MAM 1976-1985, very weak ENSO and SAM patterns are seen. Therefore, in order to have strong high latitude response, not only is coupling with SAM important, but there also needs to be a strong ENSO response locally (i.e., the tropics/ subtropics), as noted in a recent study by Lachlan-Cope and Connelley (2006). To examine the interaction before the IGY, longer reliable SAM indices are needed. Here reconstructed SAM indices are obtained similar to Jones and Widmann (2004) for all seasons using pressure observations across the SH. Two different reconstructions were conducted for each season, using different calibration data. Each reconstruction correlates with its calibrated index > 0.75 over fitting period; differences are largest in winter. Together, the reconstructions indicate that decadally varying periods of SAM / ENSO interactions have occurred in the past, but none as persistent or as marked as the recent interactions during the last 50 years.

In summary, Indian Ocean warming projects onto a positive trend in the NAO / NAM, but a negative trend in the SAM. ENSO decadal variability is marked in the SH, and helped to force strong circulation patterns in the 1990s. There is growing evidence for interaction between ENSO and SAM, especially in austral summer, but no connections are observed between ENSO / NAM. Examining periods before the 1980s reveals that ENSO and SAM interactions continue to dictate the high southern latitude response to ENSO; therefore this may help in predicting the strength of future high southern latitude ENSO responses. Using SAM reconstructions, it is likely that periods of SAM / ENSO interactions have occurred in the past, but none as persistent or as marked as the recent interactions during the last 50 years.

John Fyfe talked on ‘Two Examples of High Latitude Anthropogenic Change’. There has been a shift to stronger and more poleward Southern Hemisphere winds in recent decades, which has been linked to changes in the SAM, which have a strong anthropogenic influence. There has also been a strengthening of the ACC over the same period. Models suggest that over the coming century Ekman Transport will increase slightly, with the peak moving further south. Ocean carbon uptake is predicted to increase over the next 100 years. In-situ observations show a warming of the Southern Ocean at the 700-1100 m layer over 1930-1990. Models can do a reasonable job of simulating this, though more research is needed to further elucidate the relative roles of the different mechanisms involved (air-sea flux changes, ACC shifts, poleward eddy heat flux changes etc).

John Fyfe described some results concerning anthropogenic change in the Aleutian Low, which is one of the main features of atmospheric circulation in the Northern Hemisphere winter with a controlling influence on North Pacific Ocean circulation, Bering Sea ice extent, and Western North American surface climate. He identify a statistically significant 20th century shift to a deeper and more poleward winter Aleutian Low, which can be attributed to anthropogenic greenhouse gases and sulphate aerosols. The 15 climate models used in the study project continued anthropogenic deepening and poleward shifting in the coming decades, along with increasing interannual depth variability. He suggested that these changes in the North Pacific atmospheric circulation will likely have a profound impact on the marine ecosystems of the North Pacific. He also showed that the anthropogenic intensification of the Aleutian Low will, in the coming decades, likely be associated with a significant reduction in interannual surface temperature variability over Western North America, which in turn may have wide-ranging societal and economic effects in the region.

The final morning was devoted to breakout sessions addressing six questions. Summaries of the deliberations were:

Qustion 1. Why do we have contrasting changes taking place in the Arctic and Antarctic.

- Common conditions are
  - Very similar annual shortwave radiation forcing
  - Similar greenhouse gas levels - slight lag
  - Water vapour amounts very important in both polar regions
  - The annular modes play an extremely important role
  - Ice-albedo feedback very important, although more effective in the north due to greater solar radiation in summer
  - Fresh water injection into the ocean – more river runoff in north; more glacial ice melt in south

- Differences
  - Hugely different orography/topography – very different Rossby wave propagation – non-linear feedbacks with the storm tracks
  - Strat ozone depletion very much more important in south
  - Very different oceanographic conditions – more stratified in north – denser water formed in south (but comparable amounts of Antarctic Bottom Water and North Atlantic Deep Water are thought to be formed in the two high-latitude regions)
  - Stronger westerly atmospheric flow in the south – transient eddies play a greater role
  - More variable teleconnection from the tropics to the south than in north
  - More teleconnection patterns in north
  - More zonal ocean flow in south - Antarctic Circumpolar Current
  - Greenland is melting, but little mass balance change across Antarctica
  - Strong semi-annual oscillation in the south, but not the north
  - Increasing aerosols more important in the north

- Contrasting changes
  - Sea ice loss in north, gain in south. Ozone depletion = isolation through stronger SAM + off pole orography giving generation of Rossby waves
  - Temperature change . Linked to ice loss in north. In south driven largely by SAM change
  - WEST PENINSULA WARMING NOT UNDERSTOOD
  - Large loss of permafrost in north. Some lost in peninsula
  - Mid-trop warming in both polar regions. Larger in south due to PSCs.

- CONCLUSIONS
  - Topographic/orographic difference main factor
  - Very different ocean conditions

  - Without the Antarctic ozone hole we might have already seen some warming and sea ice loss
- Future work
  - Need interactive ozone chemistry in coupled climate models
  - Improve sea ice representation in coupled regional and global climate models
  - Better Antarctic orography
  - Improve the ocean in models – circulation and water masses, deep convection – need bottom water. Improved representation of eddies and subgridscale processes of importance to THC.

Question 2 – What is causing Arctic Sea Ice to decrease so rapidly

Ice minimum is 50% below pre-1989 average, and 23% below 2005 record. This new record minimum was a 4 SD drop below the trend in Summer SIE. At no point in the longer term record has this minimum been 125 year observational record.

What is causing the Arctic sea ice to decrease so rapidly.

1.1. Decadal conditioning is important, i.e. flushing of sea ice during high-AO early 1990's.

1.2. This summer's weather conditions aligned to produce large retreat, i.e.

- 1.2.1. The SLP field and winds aligned to flush more ice out of the Arctic, i.e. high-AO conditions during winter, and higher/lower pressures than normal in the Beaufort/Siberia.
- 1.2.2. Downwelling longwave may play a role, however, shortwave forcing from clouds does not appear to play a large role in these changes, e.g. decrease in clouds does not overly large decreases in SIE trends.
- 1.2.3. Ocean advection of heat in the Arctic (especially Pacific water) has increased, but does not quite underlie the areas of largest retreat. However, some of the ice does drift over these areas of warm water in the Beaufort and Chukchi area, and may have been advected into the areas of larger retreat.
- 1.2.4. Ice –mechanics feedback, the thinner sea ice is more responsive to the winds and drifts out quicker, leaving more younger, thinner sea ice behind.
- 1.2.5. Enhanced SW absorption by sea ice increases melt ponding, and bottom melt by transmission into the sea ice.

How much may be attributed to anthropogenic vs. natural variability?

1.3. It is hard to attribute 1 event to anthropogenic climate change. 4 SD drop (1 in 100) below the trend!

1.4. Pillars supporting anthropogenic climate change:

- 1.4.1. Preponderance of evidence of Arctic change.
- 1.4.2. None of these rapid changes that have been observed occurs in the model control runs without GHG.
- 1.4.3. These changes have not been observed in the 125 year observational record.

1.4.4. Without preconditioning (due to winds and temperature) we have not had a similar loss of sea ice as we observed this year, i.e. similar SLP field was observed in 1978 and 1988, i.e. happen every 10-20 years but a similar loss of sea ice was not observed.

Question 3. What is causing the Antarctic sea ice increase?

- Marked longitudinal and seasonal differences: primarily occurring in Ross Sea sector in austral autumn (MAM). This is the season of greatest coincident increase in the SAM (circumpolar westerlies).
- Increase in southerly winds off the continent due to lower pressure in Amundsen Sea. This is a regional component of the enhanced wave number 3 pattern.
- Increased winds are consistent with a rise in wind stress curl over the Ross Gyre. This would likely accelerate the Gyre, enhancing the sea ice export.
- Freshwater increase in near-surface layers of Ross Sea will reduce vertical heat flux from deeper ocean layers.
- This pattern is reproduced by the (mean) AR4 models.
- Atmospheric model forced by ozone depletion – which drives the positive SAM change - also shows the enhanced trough in the Amundsen Sea.
- Therefore increase in sea ice has an anthropogenic component: possibly due to enhanced Rossby waves from East Antarctica from stronger westerlies (SAM).
- In the future, AR4 models suggest a decrease so likely to be an ephemeral effect.

Question 4. What evidence is there of anthropogenic change?

Arctic

- Sea ice - Decrease in summer sea ice extent, inconsistent with simulated internal variability. All models predict some decrease in sea ice, but large differences.
- Temperature - Strong warming in Arctic, and warming predicted by models. No formal D&A studies, but we think there is a likely anthropogenic influence.

Other variables showing possible anthrogenic influence:

- NH snow extent in spring has decreased.
- Permafrost decreases.
- Greenland surface melting.
- Water vapour increase.
- Increased Arctic river flow/N. Atlantic freshening.
- NAM trend likely partly anthropogenic
- Aerosols.

Antarctic

- Southern Ocean warming – models reproduce observed S. Ocean warming.

- SAM trend inconsistent with simulated internal variability in summer and autumn. Models indicate contributions from greenhouse gases and ozone.
- Temperature - East Coast Peninsula summer warming likely anthropogenic due to increased SAM.
- Models suggest upward trend sea ice in autumn may be linked to ozone depletion.
- Stratospheric cooling dominated by ozone and very likely anthropogenic.
- Carbon - Likely decrease in S. Ocean carbon uptake in part due to change in winds – likely anthropogenic.

Question 5 How are the models simulating the changes?

- Southern Ocean warming – models reproduce observed S. Ocean warming, but more work needed to better elucidate relative roles of mechanisms.
- SAM trend inconsistent with simulated internal variability in summer and autumn. Models indicate contributions from greenhouse gases and ozone.
- Temperature - East Coast Peninsula summer warming likely anthropogenic due to increased SAM.
- Models suggest upward trend sea ice in autumn may be linked to ozone depletion.
- Stratospheric cooling dominated by ozone and very likely anthropogenic.
- Carbon - Likely decrease in S. Ocean carbon uptake in part due to change in winds – likely anthropogenic.

Question 6 - How well can we model recent change?

Difficult question to answer -
need more specifics/ what metrics;
do we have the metrics to answer this;
is it possible to answer given large natural variability and short records, etc.
Can make probablistic statements from models;
allow us to address questions of attribution;
attribution of anthropogenic signal is easier on large spatial scales

Obstacles in model improvements: computation power (resolution); for foreseeable future will need to parameterize sub-gridscale processes; requires better understanding of processes
Better understanding requires close interaction with observational community; modeling should not be done in isolation
Arctic improvements should not have adverse effects elsewhere; cannot allow regionally dependent parameterizations
Organized activities (like IPCC) important for understanding what we do/don’t understand (
Some consistent large-scale changes present among the models (polar amplification, Arctic ice loss);
Modeling benefits from a healthy competition

Attendees were:

From out of town

- John Turner (BAS)
- Mike Meredith (BAS)
- Gareth Marshall (BAS)
- Nathan Gillett (UEA)
- John Fyfe (Victoria)
- Marika Holland (NCAR)
- John Walsh (UAF)
- Andrew Fountain (Portland)
- Jennifer Francis (Rutgers)
- Koji Shimada (JAMSTEC)
- Greg Flato (Canadian Climate Centre, Victoria)
- Alex Hall (UCLA)
- Klaus Dethloff (AWI)
- Michael Tjernström (Univ of Stockholm)
- Thorsten Mauritsen (Univ of Stockholm)
- Rune Grand Graversen (Univ of Stockholm)
- Yonghua Chen (Rutgers University)
- Jessica Cherry (IARC, Fairbanks)
- Jinro Ukita (Niigata Univ)
- Ryan Fogt (NOAA)

Local

- Jim Overland (NOAA)
- Mike Steele (University of Washington, APL)
- Cecilia Bitz (Univ Washington)
- Mike Wallace (Univ. of Washington)
- Ignatius Rigor, U. Wash