of heat is the CDW, the core of which is isolated from the atmosphere by a layer of cold water hundreds of metres thick.

The near coastal winds that drive ice production on both warm and cold shelves are dictated largely by the ice sheet geometry, so should remain relatively robust features in a warming climate. However, changes in the mean westerly airflow around Antarctica could influence the water masses coming onto the continental shelf. Stronger westerly winds over the ACC could conceivably raise CDW higher in the water column (Hall and Visbeck, 2002) allowing it more widespread access to the shelves. Although this is an attractive hypothesis, more vigorous upwelling of CDW could also promote more rapid oceanic heat loss to the atmosphere and overall a lower heat flux onto the shelves. The links between the westerly wind regime and the shelf waters of the Amundsen Sea are thus only speculative at present, but they are high priorities for research as they could hold the key to the attribution of the causes of change and improved prediction of the future mass balance of the ice sheet.

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Predicting the Fate of Ice Shelves

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Ice shelves are an important part of the cryosphere that can affect the sea-level rise and salt balance of the oceans. Most of the snow falling on inland Antarctica drains via large ice streams to the sea where it floats seaward of the grounding line, forming ice shelves. Much of the Antarctic coastline is composed of large ice shelves in coastal embayments (such as the Filchner, Ronne, Ross and Amery) and fringing shelves on the periphery of the ice sheet (such as the Shackleton, Fimbulisen, West, and Larsen shelves).

The state of ice shelves depends on the flow of the glaciers that feed them, snowfall and ablation on the upper surface, melting and freezing on the lower surface as well as the calving of icebergs. The estimated effect of basal melt is a significant proportion of the total mass loss on most ice shelves. In most cases, the major forcing on ice shelf evolution is the basal melt/freeze rate, which, in turn, is determined by the oceanographic conditions on the continental shelf.

Since ice shelves are floating on ocean water at the freezing point, even a small rise in ocean temperature can significantly affect the basal melt rate and cause them to thin quickly. Increased ocean temperatures and melting have been implicated in the thinning of a number of ice shelves in West Antarctica and in the collapse of ice shelves on the Antarctic Peninsula. The presence of ice shelves are now well understood to buttress the ice sheets. Ice shelves that collapse and break up cause an increase in the rate at which the ice sheet drains into the oceans, thereby increasing sea level. For example, a significant increase in the discharge of the glaciers that previously fed Larsen A and B has been observed, leading to a corresponding increase in the rate of sea level rise (e.g., Rignot, *et al.*, 2004). Furthermore, the increased melting of ice shelves was stated as being the most likely cause of the observed freshening of Antarctic Bottom Water (Rintoul, 2007).

Ice shelves largely isolate the ocean below from the effects of the atmosphere – the interaction between the ice shelves and the ocean being mainly thermodynamic – with heat and freshwater fluxes occurring across the ice/ocean interface. The local nature of these fluxes is largely understood and can be reasonably well characterised (Holland and Jenkins, 1999). However, despite the importance of basal processes in the Antarctic ice sheet mass balance, the dominant forces behind the melting and freezing – such as the effects of changing ocean temperatures, frazil ice and tidal mixing processes – are poorly understood.

Numerical modelling studies are crucial to improve our understanding of the impact of climate change on floating ice shelves. For example, any ice-shelf-cavity model should include the processes which affect marine ice accretion. Observations suggest that the ice forms as frazil ice crystals, which are initially suspended in the water column. As the ice crystals grow, they rise faster and eventually turn into slushy layers deposited at the base of the ice shelf. Consolidation of the slush then leads to layers of marine ice. This slush is also thought to be partly responsible for the *mélange* observed in rifts, which can affect the fracture and rifting processes that can cause the ice shelves to break up.

Process-orientated studies of simplified (e.g., rectangular) cavities are important for investigating the sensitivity of the simulations to cavity geometry and to the various parameterisations which describe the internal physics of the models (e.g., Determann and Gerdes, 1994). Three-dimensional numerical ocean models have been successfully applied to ice shelves, such as the Filchner-Ronne Ice Shelf (e.g., Holland *et al.,* 2007), the Ross Ice Shelf (e.g., Dinniman *et al.,* 2007) and the Amery Ice Shelf (e.g., Williams *et al.,* 2002; figure below).

Unfortunately, accurate measurements of bathymetry in polar regions are often not available. Both the sub-ice-shelf bathymetry and the shape of the ice-shelf base must be known, in order to infer the total thickness of the water column. Numerical studies of simplified ice-shelf cavities show the strong effect of cavity shape on basal melt rates (Holland *et al.,* 2008). As such, the shape of the ocean cavity beneath ice shelves is an important parameter for the numerical models used to simulate the sub-ice circulation patterns and melt/freeze rates.

The figure below shows the results of three models used to simulate the ocean cavity beneath the Amery Ice Shelf.

The results indicate that the response of ice shelves to increased ocean temperatures is enhanced by tides. The resultant higher basal melting rates have significant implications for the stability of ice shelves. The most up-to-date model is based on the Regional Ocean Modeling System and uses the latest cavity geometry developed by Galton-Fenzi *et al.,* (2008) and a comprehensive treatment of ice-ocean boundary conditions (red lines). When tides are included in this model, it yields total melt rates and spatial patterns of melting and freezing, which are in reasonable agreement with glaciological observations. The results suggest that a warming of 1ºC can potentially remove the ice shelf in 350 years, solely due to increased basal melting. Dynamical processes could lead to a collapse of the ice shelf before this time.

It is clear that a warmer ocean will cause increased melting of ice shelves and may lead to their collapse. Predictions of the evolution of ice shelves under climate change scenarios is key to providing robust projections of the ice sheet and its impact on sea level and freshwater budgets. To the authors' knowledge, there is currently only one global climate model which includes the effects of glacial ice-ocean interaction (Losch, 2008). There are many processes at the the ice-ocean boundary that need further examination before climate predictions can become more reliable.

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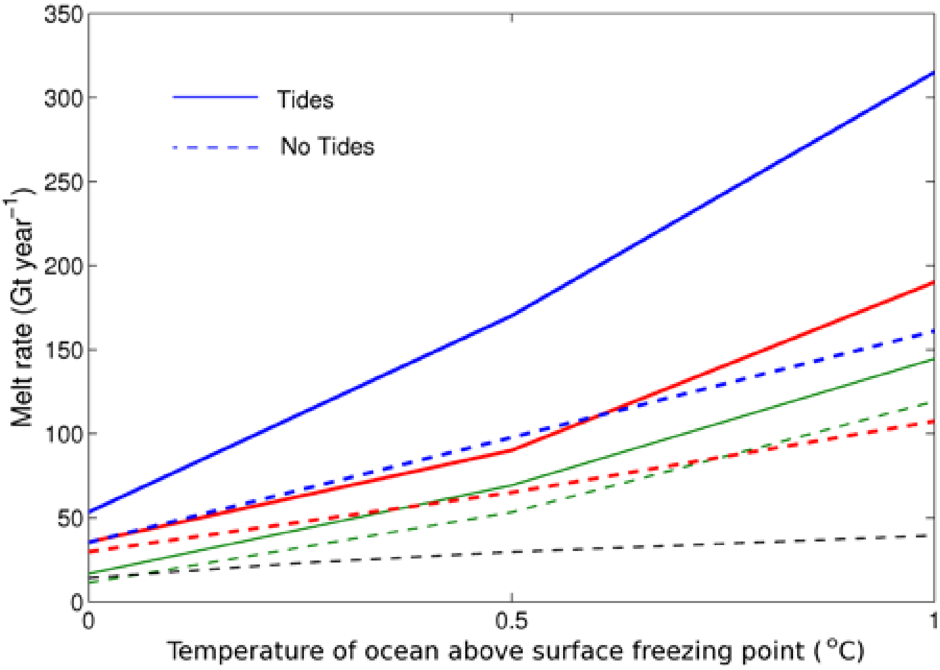

Results from three different hydrodynamic ocean models used to simulate the cavity beneath the Amery Ice Shelf. The response of the total basal melt rate per year due to an increase in ocean temperature and tides, using: The Regional Ocean Modeling System with linear (blue) and non-linear (red) ice-ocean boundary conditions; the Princeton Ocean Model (Green; Hunter *et al.*, 2004); and the Gerdes model (Black; Williams *et al.,* 2002). The solid lines are models with tidal forcing, and the dashed lines are models without tidal forcing.

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Monitoring Arctic Coastal Dynamics

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Arctic coastal processes differ from those in more temperate regions due to the presence of ice, which may be in the form of sea ice or permafrost (either along the shorelines or under the sea bed). It is this ice that renders the Arctic coastline vulnerable to changes in the global climate system, because small shifts combined with positive feedbacks between climate system components can mean a transition to an ice-free state. This vulnerability is augmented by the marginal nature of the coastal zone. Marginal environments react most rapidly to changes in environmental forcing, and in this case on three fronts: oceanic, atmospheric, and terrestrial.

Coastal dynamics, particularly in the Arctic, are influenced by a number of variables. Exposure to wind and waves strongly determines the shoreline's vulnerability to erosion, and this again depends on the extent of open water, the presence of sea ice, as well as on storminess. How a shoreline responds to incoming waves depends on coastal morphology and composition, and on environmental factors such as air and water temperature (Figure 1). Changes in these forcing factors can result in rates of erosion that are three to four times higher in the Arctic than along similar coasts in temperate regions (Are, 1998). Changes in a number of environmental conditions due to climate warming will likely intensify coastal processes, resulting in increased erosion of the shoreline at many sites.

The Arctic Ocean's seasonal ice cover means that wind fetch is often limited for a large part of the year. However, dramatic decreases in annual sea-ice extent in recent years (Stroeve *et al*., 2008) have resulted in increased fetch in most Arctic coastal regions, producing larger waves and increased wave power at the coast. In the next century, climate warming is expected to be twice as high in the Arctic as in other parts of the world. Projections call for increases of up to 6.4ºC by 2099 (IPCC, 2007). A number of climate modeling scenarios project an increase in storminess for the Arctic in the 21st century (Cassano *et al.,* 2006). On shore, as warmer air temperatures propagate into the soil, the ground temperature, ground ice melt, and the depth of the seasonally thawed layer will increase, thereby reducing the strength of coastal permafrost and making it more susceptible to mass wasting and mechanical and thermal abrasion (Are, 1998). Globally, sea-surface temperatures have increased by approximately 0.8°C in the last century, and recent surveys have shown a distinctly warmer layer in the Arctic Ocean (IPCC, 2007). Warmer water will further contribute to thermal erosion of bluffs (Nairn *et al.,* 1998). In addition, an increase in water temperature will result in accelerated thaw of subsea permafrost (Dyke, 1991) and a readjustment of the near-shore profile (Are, 1998; Dallimore *et al.,* 1996). Sea-level rise due to thermal expansion of the ocean and the addition of water from melting glaciers and icecaps is predicted to be 0.59 m by 2090 (IPCC, 2007). Areas that are undergoing isostatic submergence, or where ground ice is melting onshore, will be subjected to even greater relative sea-level rise in the coming century. Although the implications for coastal dynamics will be site specific and depend on backshore morphology, changes to the coastline can be expected as low coastal bluffs will be