

David Ainley, Joellen Russell, Stephanie Jenouvrier, Eric Woehler, Philip O'B. Lyver, William R. Fraser, and Gerald L. Kooyman. 2010. Antarctic penguin response to habitat change as Earth's troposphere reaches 2°C above preindustrial levels. *Ecological Monographs* 80:49–66.

Appendix A. The derivation of a model ensemble useful for predicting changes in penguin habitat.

Russell et al. (2006b) evaluated 18 of the coupled IPCC models by comparing the relationship between the pre-industrial westerly winds and the strength of the ACC, and we use this as our starting point. We compared the wind stress and ACC strength for the last 20 years of the 20th century for each model run (Fig. A1). Several of the models clustered close to the observations: these include the GFDL-CM2.1, GFDL-CM2.0, MIROC3.2(hires), MRI-CGCM2.3.2a, IAP-FGOALS1.0g, INM-CM3.0, and CCCMA3.1-T47 simulations, and as a first cut, these models seemed to be producing a Southern Ocean that is reasonably true: they have winds and an ACC that is relatively close to the observations.

As Russell et al. (2006b) noted, most climate models have a maximum wind stress equator-ward of the observations, some by more than 10° latitude. The models singled-out in Fig. A2 all have a relatively accurate wind profile: neither too weak nor too strong and a maximum within 6° latitude of the observed. [As we eventually eliminated the CCCMA47, IAP, and INM models from our ENSEMBLE, their wind stress curves are not separated from the remainder.]

Continuing the winnowing process, we examined the seasonal cycle of sea ice around Antarctica (Fig. A3a). Most of the models had a reasonable range of total ice area, between 0 and 20 million km². In modern observations, sea ice still exists around Antarctica in February (month of the yearly minimum), but some models had no sea ice at all for one or more months of the year. We chose to use a root-mean-squared error calculation so that problems with too little ice in the austral summer would not be weighted as strongly as a significant error in winter. One of the models, IAP, which has nearly perpetual ice cover out to almost 40°S, was excluded from further consideration. Fig. A3b provides a clear view of why care must be taken when looking at ensembles of different models. The RMS error in June for the collection of models is significantly lower than that for any individual model!

The next step in the winnowing of models involved comparing their simulations of the boundaries of the ACC to the observational record (Fig. A4). Orsi et al. (1995) defined the northern boundary of the ACC as the subtropical front (the location of salinities between 34.9 and 35.0 ppt at 100 m) and defined the Southern Boundary of the ACC as the surface transition from Upper Circumpolar Deep Water to the denser Lower Circumpolar Deep Water (the location of the 27.6 ppt isopycnal at 200 m). Of the models not eliminated in the first pass or due to serious flaws in the sea-ice simulations (GFDL-CM2.1, GFDL-CM2.0, MIROC3.2(hires), MRI-CGCM2.3.2a, INM-CM3.0, and CCCMA3.1-T47), the CCCMA47 simulation was eliminated due to its extremely poor frontal structure. There were no ocean data for the INM model for the 20th century run, so although it seemed to be a reasonable simulation, we felt we could not include it in our ENSEMBLE either. Therefore, as a result of the above steps in winnowing, our ENSEMBLE was composed of the GFDL-CM2.1, GFDL-CM2.0, MIROC3.2(hires), and MRI-CGCM2.3.2a models.

As a final check on the appropriateness of our model choices, we then compared the simulated annual mean ice thickness from our collection to the observational record (Fig. A5). In fact, the models chosen did a reasonable job of simulating that variable. The thickest ice is in the western Weddell Sea along the eastern shore of the Antarctic Peninsula and in the eastern Ross Sea. The southwestern Ross Sea has less ice cover in both the data and the models owing to the Ross Sea Polynya, the largest coastal polynya in the Antarctic.

PENGUINS' RESPONSE TO HABITAT VARIABILITY: A REVIEW

A view at the large-/centennial- to millennial- spatio-/temporal-scales

In the case of both species, at the large spatial and temporal scales, there can be too much sea ice. It almost goes without saying that if the coast is comprised of a glacier or an ice shelf, without a polynya and without any persistent fast ice also being present in the case of the Emperor, neither species will be found nesting. Using 14C -datable remains found in extinct and existing Adélie Penguin colonies, well documented for the last 45,000 years, i.e. the last glaciation and inter-glacial periods on either side, is the colonization of the coast as ice shelves retreated to expose nesting habitat or, conversely, extinction of colonies as ice sheets and shelves advanced (Emslie et al. 2007).

Because Emperors nest on annual sea (fast) ice, they have left no remains to chronicle their breeding history at geologic (millennial) time scales. Therefore, we have no idea about how this species fared during glacial periods. With the Ross and Weddell seas covered by glacial ice sheets, and glacial ice extending farther out than now in general, obviously Emperors could only nest at low latitudes. During these periods, penguins would likely have experienced an ocean significantly reduced in primary productivity owing to persistent and concentrated sea ice; any local foodwebs, as well as Emperor Penguins, would be restricted to where ever polynyas occurred adjacent to ice shelves (Thatje et al. 2008). As these authors note, overall conditions were more severe than currently, with some data indicating more but others indicating fewer polynyas.

Currently, Emperor Penguins at the two largest colonies, Coulman Island and Cape Washington in the Ross Sea (Woehler 1993), experience a 20-30 km walk over fast ice to reach a flaw lead at the fast ice edge, with the looser pack ice there being part of the marginal ice zone of the Ross Sea Polynya (see Marshall and Turner 1997). Emperor Penguins at other colonies require walks of up to 100 km (Kirkwood and Robertson 1997). Massom et al. (2009) showed that variation in the distance between 10 and 70 km can have inverse effects on breeding success at Pointe Géologie.

In the case of Adélie Penguins, if faced with a commute of more than a couple of kilometers during the chick-provisioning portion of the annual cycle (when chicks need to be fed almost daily), its colonies will disappear. This is well documented along the Victoria Land coast, where extensive fast ice that is about 20 km wide precludes Adélie Penguins from nesting (Ainley 2002, Emslie et al. 2003). However, when the fast ice disappeared during a brief, mid-Holocene warm period, the penguins colonized this area but then deserted it when the fast ice returned. Recent, short-term 'natural experiments' support this: 1) unusually compacted pack ice off colonies on the west coast of the Antarctic Peninsula during one spring (owing to anomalously persistent on shore winds) resulted in the temporary skipping of breeding and thus a one-year dramatic decrease in nesting numbers (Massom et al. 2006); and 2) in a scenario still unfolding, unusually concentrated sea ice in the Southwest Ross Sea for several years (owing to blockage by immense, grounded ice bergs; Arrigo et al. 2002) is resulting in substantial but different rates of population decrease and emigration among four widely-spread colonies whose demography is being studied simultaneously (Ainley, Ballard, Dugger, Lyver, unpublished data; but see Shepherd et al. 2005). Before the latter scenario began to unfold, Adélie Penguins were beginning to re-colonize an area (Cape Barne) that required a 2-3 km walk over fast ice during the incubation period, but which was fast ice free during the chick period (Ainley, pers. obs.)

The other extreme, that of no sea ice at all, has also been investigated at the geologic time scale, again using datable Adélie Penguin remains in conjunction with sediment cores to indicate the presence/absence of ice (cf. Smith et al. 1999, Emslie 2001). Adélie Penguins colonized the northwestern coast of the Antarctic Peninsula when sea ice extended increasingly northward with the Little Ice Age. In recent decades, as the sea ice cover has receded (Stammerjohn et al. 2008), Adélie Penguins have been disappearing and ice-avoiding penguin species have been replacing them (Ducklow et al. 2007, Hinke et al. 2007). The advance of the latter species is unprecedented in the existing, 600 yr sub-fossil record (Emslie et al. 1998).

This scenario can be inferred for Emperor Penguins from the modeling of Jenouvrier et al. (2009a). Using IPCC model output for the generalized sea-ice coverage and extending to the 22nd century, the colony at Pointe Géologie was projected to decrease from 2600 pairs at present to 400 pairs as sea ice disappears. In a scenario similar to that of Cheung et al. (2008) for Antarctic fish, the authors note that if the model is extended farther in time, there is no sea ice and no Emperor Penguins. This scenario, in fact, is apparent in real time at Dion Islets (67° 52'S, 68° 43'W). The colony disappeared in accord with the dramatic decrease in sea ice along the west coast of the Antarctic Peninsula (cf. Ainley et al. 2005, Ducklow et al. 2007). Sea ice has yet to retreat significantly from the colder east coast of the Peninsula and, thus, Emperor colonies there are currently doing fine, even a few latitude degrees farther north than Dion Islets (Fig. 1).

A view at the meso-/decadal- spatio-temporal scales

Emperor Penguin response to habitat change. – Three investigations have discussed the demography and population dynamics of the Emperor Penguin with respect to variability in ice and other habitat characteristics at the meso-/decadal- spatio-temporal scale (Barbraud and Weimerskirch 2001, Ainley et al. 2005, Jenouvrier et al. 2005a). All dealt with the data derived from studies at Pointe Géologie (66° 40'S, 140° 01'E), which is one of the most northerly located of all colonies of this species (Figs. 2, EA6).

The findings of these studies were as follows:

- Barbraud and Weimerskirch (2001) found that survival, decreased when SST north of the pack ice was higher and SIE was reduced (see also Jenouvrier et al. 2005a: male correlation to SIE even more sensitive than females). Their data also showed a marked, 50% decrease in colony size during a few years in the mid-1970s and one from which the colony has not yet recovered. They showed that the population crash coincided with a period of low adult survival and that after the

population crash, breeding success became far more variable than before, due especially to an increasing frequency of years in which the fast ice blew out prematurely and along with it eggs and chicks (zero reproductive success).

- Ainley et al. (2005), using the same data set but several different covariates and a different analysis, found that the population increased with less positive SAM, and decreased with greater wind, SIE and thinner ice. They also noted that average breeding success was much lower after the mid-1970s, corresponding to the time when SAM switched from negative to positive.
- Jenouvrier et al. (2005a) showed that population size is positively related to SIC and SIE during autumn, and to the Southern Oscillation Index (SOI). Adult survival varied inversely with air temperature during summer and winter months for both genders, and was positively related to SIC for males. Using population models, they showed that annual survival and breeding success contributed equally to explain population variation.

The basic findings of these analyses in regard to how Emperor Penguins have responded to *past* but relatively recent sea-ice variability are compatible with one another and *together* they show how this species responds to habitat change. The most difficult covariate to deal with is SST (as perceived by satellite) north of the sea ice (see Barbraud and Weimerskirch 2001), as many factors can alter SST with likely different ecological consequences. Certainly, elevated SST could directly reduce SIE (melting at its outer edge) as in the case of the coincidence of the pack ice edge with SBACC (see above). The warmer ocean extends to depth. However, as will be discussed in climate model projections, reduced wind also causes SIE to decrease, but at the same time reduced wind would also lead to greater stratification of surface waters. The latter would lead to higher SSTs, owing to heat absorption from solar insolation, in the thin, surface layer sampled by satellites. Underlying waters would remain cool. Finally, the upwelling of Circumpolar Deep Water, which is warmer than Antarctic Surface Water, can also be involved and, in fact, this is the factor that would be most important to the penguins on the basis of our climate modeling. In fact, sensible heat polynyas are the result of this upwelling.

The findings of Ainley et al. (2005) that the Pointe Géologie Emperor colony increased with less positive SAM (see also Massom et al. 2009), and decreased with higher wind and thinner ice may seem contradictory to the findings of Jenouvrier et al. (2005a) that population increases with greater SIE. However, as noted by Ainley et al. (2005), greater wind at Pointe Géologie leads not just to greater SIE (pack ice), but also to thinner and more unstable fast ice (see Jacobs and Comiso 1989), and hence greater chance of premature fast-ice blow-out. On the other hand, greater wind (as long as it is not too strong) would lead to a persistently open polynya, more easy access to food, and thus an increase to survival and breeding success. The fact that Jenouvrier et al. (2005a) found higher adult survival with lower air temperatures is consistent with effects of the hurricane force katabatic winds (which consist of cold air draining off the Antarctic plateau towards the coast) on maintaining the adjacent coastal polynya, ice formation and greater SIE (see Barber and Massom 2007). The katabatic winds of the Adélie Land coast reduce air temperature or at least they did during the negative SAM (Wendler et al. 1997). The fact that male emperor penguin survival decreases when SIE decreases during winter is consistent with less wind that would also reduce or negate the development of the Mertz Glacier Polynya, thus increasing the time and energy needed for the emaciated males to reach open water and food (see Massom et al. 2009). Obviously, more work is needed to understand the effect of local, polynya-favorable vs -unfavorable winds, polynya size, ice thickness, and ice stability in regard to the Pointe Géologie Emperor colony's growth through direct effects on vital rates.

The Emperor Penguin population at Pointe Géologie, as noted by all authors, has not been able to recover from a major decrease in the mid-1970s (see especially Jenouvrier et al. 2009 b). This is similar to the pattern exhibited by seabirds elsewhere that have suffered a catastrophic adult mortality unrelated but occurring after a regime shift. It is well known that for long-lived species, such as the Emperor Penguin (and many other seabirds), adult survival is a key driver in population trends, but that breeding success also contributes (e.g., Jenouvrier et al. 2005a). Indeed, it has been shown that in certain states of climate oscillations, the capacity of a population to recover appears to be limited by breeding success. For example, the capacity to breed successfully became reduced in new regimes for the endemic Galapagos penguins (*Spheniscus mendiculus*) in the Peru Current and Common Murres (*Uria aalge*) in the California Current (Ainley and Divoky 2001) and, therefore, these populations could not easily recover from single-event mortalities: an intense El Niño and/or a large oil spill, respectively.

The factors likely responsible for reduced breeding success of the Emperor Penguins during more recent years are prolonged katabatic blizzards (and deepening low temperatures), which increase chick mortality (Jouventin 1974); and especially in recent years premature ice break-out, which causes total loss of eggs, or chicks, depending on timing (Budd 1962; see also Barbraud and Weimerskirch 2001). Finally, with dramatically lower breeding success, and especially total breeding failure, subadults resulting from previous years' breeding likely would be discouraged from recruiting into the Pointe Géologie colony, especially if the extent of recruitment is affected by a performance-based assessment of a colony's vitality, as has been shown in other

seabird species (e.g. Danchin et al. 1997, 1998). That is, in years when the colony was blown out to sea, upon arriving later in the breeding period (as young seabirds do), these potential recruits would find neither adults nor chicks present and, therefore, may look elsewhere for a more viable colony.

The Taylor Glacier Emperor Penguin colony (67° 28'S, 60° 53'E), also in East Antarctica, is one of only two, so far known, that exist on land. [The other, at Dion Islets, has decreased by > 90% since the 1940s, but it is in an area where sea ice is completely disappearing (Ainley et al. 2005; see main text).] Therefore, the Taylor Glacier colony would not be directly affected either by sea-ice thickness or stability of fast ice for breeding. This colony during the past 20 years has remained at about the same size that it was during the 1950s and 1960s (cf. Horne 1983, SCAR 2002; B. Wienecke, pers. comm.); there was a hiatus in censusing during the 1970s. Thus, either it never saw a decrease or, unlike, Pointe Géologie, it has recovered. If the latter scenario is a possibility, the fact that it is fairly close to other colonies, in contrast to the relative isolation of Pointe Géologie (see Fig. 1), then this might further encourage the recruitment of returning subadults and emigrants. On the other hand, by no means is Pointe Géologie completely isolated (Fig. 1).

Also indirectly contributing to this discussion is the record in the western Ross Sea: Emperor Penguin colonies at Cape Crozier (Ross Island) and Beaufort Island (Kooyman et al. 2007; Fig. A7). The extent of variability in fast ice stability is quite instructive, although the cause is not thinning sea ice and katabatic winds. At Cape Crozier, the colony is situated at the north face of the Ross Ice Shelf where it squeezes by Ross Island in its constant northward growth, and becomes fractured in the process. As a result, this corner breaks back after several years of growth, calving lots of small icebergs and bergy bits. When the Shelf front has retreated well back from of its maximum position (2-3 km), the colony is vulnerable to rafting sea ice, insurmountable pressure ridges 10s of meters high, and early sea-ice break-out as no features lock it in place. In these conditions, breeding success has been low and the colony has remained small or decreased further. This was especially the case from the late 1960s through the 1980s. Then, as the Shelf front progressively moved forward, without breaking off, it provided a 'bay' between Shelf and shore, as its growth caused it to veer slightly offshore from the island as well. With a persistent, fast-ice covered bay providing reliable, stable and protected habitat year after year, the colony experienced rapid growth in the 1990s, owing at the least to high breeding success. The bay was destroyed when crashing large icebergs broke back the ice front in 2001, and the colony decreased severely in size.

At nearby Beaufort Island, the fast ice on which the colony exists is locked in place by icebergs that ground on other parts of the submerged caldera (of which Beaufort Island is part) and offer protection, and stable fast ice on which to breed successfully. The colony's growth pattern has been similar to that at nearby Cape Crozier; whether the two adjacent colonies may be part of a metapopulation, with the well-being of one contributing directly to the other through emigration/immigration, is not presently known.

The growth and variability of other Ross Sea colonies were investigated by Barber-Meyer et al. (2008), but with a record beginning only in 1983. As with the Kooyman et al. (2007) study, these authors analyzed chick counts, which act as a crude proxy of actual colony size because the number of chicks is a function of adult population size, proportion of adults breeding (i.e., effort), and breeding success. Nevertheless, they do indicate trends in relative colony size as indicated in the studies at Pointe Géologie. As with Barbraud and Weimerskirch (2001) and Jenouvrier et al. (2005a), Barber-Meyer et al. (2008) for some colonies found the same growth relationships with SIE (positive) and SST (negative). They found a relationship to SAM similar to that described by Ainley et al. (2005) and Massom et al. (2009), and concluded, consistent with the story that emerges from the various other studies of this species, mesoscale rather than large-scale sea-ice patterns are the most important.

Adélie Penguin response to habitat change.— Several studies have related population trends of Adélie Penguins to sea-ice variability at a spatio-temporal meso-/decadal-scale consistent with the habitat optimum model (Fraser et al. 1992, Trathan et al. 1996; Wilson et al. 2001; Jenouvrier et al. 2005c). Three studies conducted in the Antarctic Peninsula region confirm one side of the bell-shaped curve of the Fraser-Trivelpiece model (see explanation above; Fig. A8), showing that colonies of this species decrease as sea ice disappears. Long-term studies at Arthur Harbor (Ducklow et al. 2007), Admiralty Bay (Hinke et al. 2007), and Signy Island (Forcada et al. 2006) described fluctuating penguin numbers around a mean until the early to late 1970s, when all then began to decrease in accord with decreasing sea-ice season/persistence and extent (cf. Parkinson 2002). According to Stammerjohn et al. (2008), in 1979 the sea ice season off the western Antarctic Peninsula was 365 d long, but by the early years of the 21st century it was at most 270 days including some years when it was zero. In their study area of 182 x 105 km² (Ducklow et al. 2007), maximum ice decreased an order of magnitude from it being almost entirely covered to one-third covered, at most. All this time Adélie Penguin numbers decreased.

In East Antarctica and the Ross Sea, the situation has been more complex, because there the pattern for some colonies has been steady growth over decades, while for large colonies there has been a subsequent leveling of numbers (e.g., Cape Bird, Cape

Crozier; [Fig. A9](#)). The leveling occurred at about the same time that colonies in the Antarctic Peninsula region began to decrease (late 1980s). Smaller colonies at Cape Royds, Pointe Géologie and the Windmill Islands (Whitney Point) continued to grow ([Fig. A10](#)). Thus, besides the response to ice conditions at a broader scale some sort of regional-scale density dependence must be involved in these responses to physical conditions.

Three studies have related the demography and population dynamics of the Adélie Penguin to sea-ice characteristics in the Ross Sea-East Antarctica sector. The findings of these studies were as follows:

- Wilson et al. (2001) found that for colonies on Ross Island, greater SIE during the winter months reduced colony growth five years later ([Fig. A9](#)). These authors surmised that when extensive ice moved the penguins' wintering area north of the southern boundary of the Antarctic Circumpolar Current subadults, in particular, had more difficulty in coping with reduced food availability in those waters and/or were subjected to higher predation. Waters north of the SBACC are depleted in prey compared to those to the south (Tynan 1998, Nicol et al. 2000). The fact that the response did not show up until five years later is related to the average age of recruitment, ~5 years (Ainley 2002).
- Jenouvrier et al. (2005c) found similar results for the colony at Pointe Géologie ([Fig. A10](#)): population size increased six years after a year of reduced SIE (and SIC). As with Wilson et al. (2001), these authors also found a relation to the SOI, the wind patterns associated with which affect SIE and SIC (Stammerjohn et al. 2008).
- Ainley et al. (2005), investigating trends at several colonies in East Antarctica and the Ross Sea, found that, in general, colony size decreased with increasing ice thickness and increased with increasing SAM and winter air temperature.

As with the Emperor Penguin, these results are not incompatible with one another and *together* tell the story of how Adélie Penguins have been responding to climate and sea-ice variation in areas where there is still plenty of sea ice (i.e., everywhere surrounding the Antarctic continent except the west coast of the Antarctic Peninsula). These results complete the "habitat optimum model" showing growth in colonies as local SIC, in the form of growing polynyas, lessens. When SAM entered its positive mode and the AOH began to grow in the mid-1970s, circumpolar and katabatic winds began to increase in strength, leading to larger, more persistent coastal polynyas and, thus, lower SIC and thinner sea ice itself in coastal areas (see Parkinson 2002, Russell et al. 2006a, Stammerjohn et al. 2008). The importance of polynyas, as well as the spatial scale at which they are assessed, is particularly evident by the somewhat counter results of a growing, large-scale sea-ice season and SIE in the Ross Sea sector (Zwally et al. 2002, Parkinson 2002, Stammerjohn et al. 2008), but nevertheless, at the same time, growing coastal polynyas at the regional scale.

These results also may show that once a colony reaches a certain size that further growth in polynya persistence or size is not beneficial, and that other factors come into play. These factors are likely biological in nature, stemming from density-dependent relationships among the number of penguins foraging at any one time and the availability of food within their foraging range (Ballance et al. 2009).

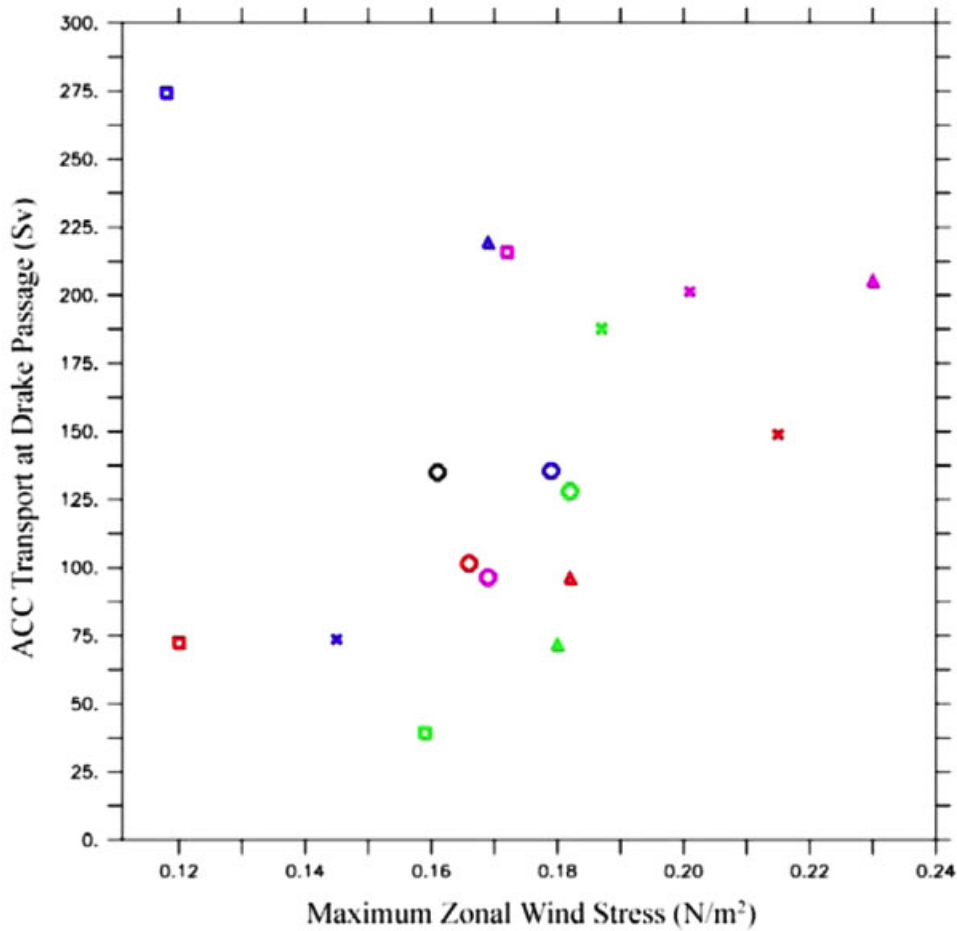


FIG. A1. The maximum zonally-averaged annual-mean wind stress between 70°S and 30°S (N/m^2) plotted against the ACC transport at Drake Passage (69°W) for the 20th century. Observed (black circle), GFDL-CM2.1 (blue circle), GFDL-CM2.0 (red circle), CCCMA3.1-T47 (red triangle), CNRM-CM3 (red square), CSIRO-Mk3.5 (red cross), GISS-AOM (blue triangle), GISS-ER (blue square), IAP-FGOALS1.0g (blue cross), INM-CM3.0 (green triangle), IPSL-CM4 (green square), MIROC3.2 (hires) (green circle), MIROC3.2 (medres) (green cross), MRI-CGCM2.3.2a (purple circle), NCAR-CCSM-3.0 (purple triangle), UKMO-HadCM3 (purple square), and UKMO-HadGEM1 (purple cross). The 20th century annual mean for the model runs is defined as the average of all months between January 1981 and December 2000.

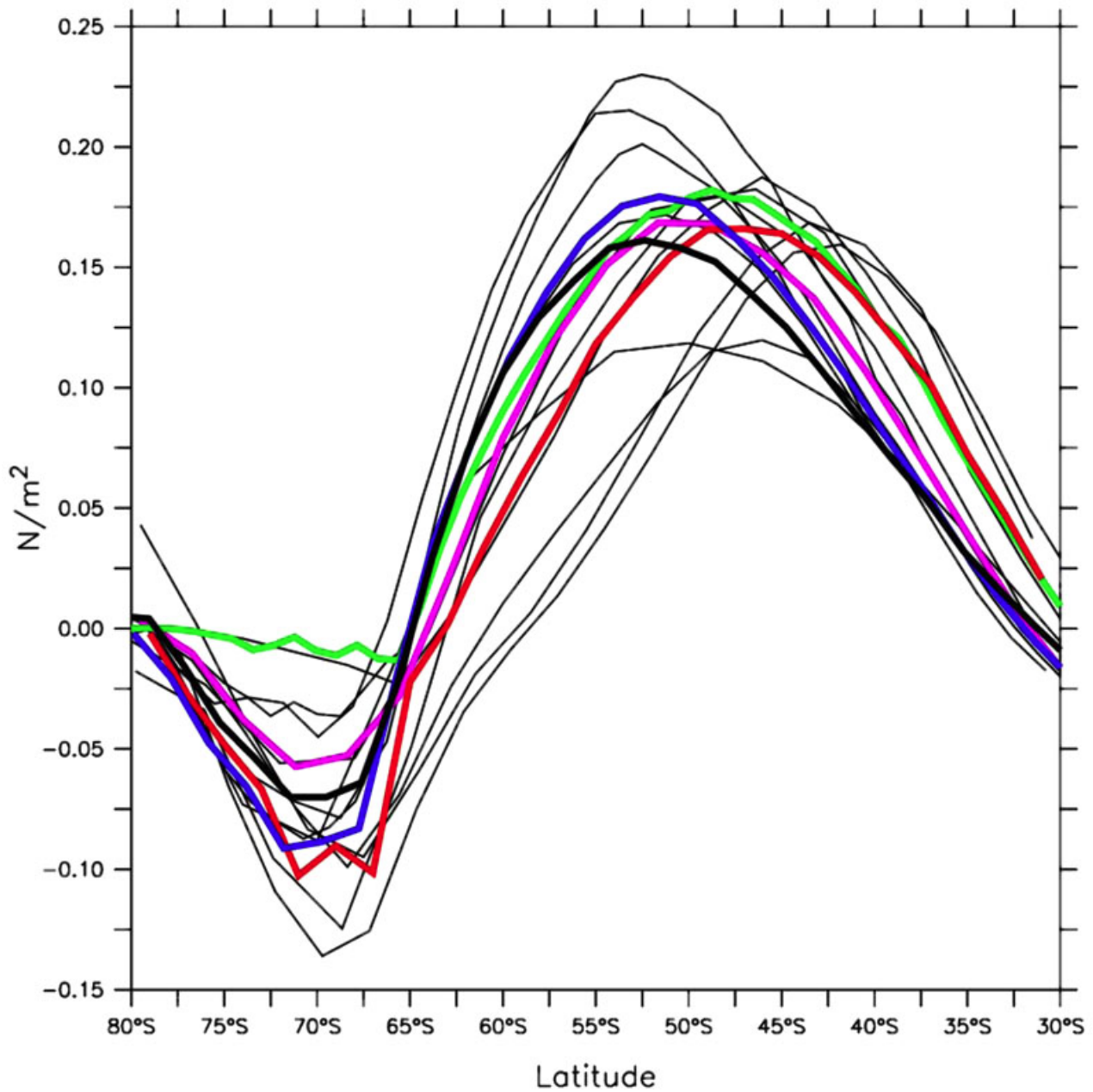


FIG. A2. Zonally-averaged annual mean wind stress (N/m^2) for the 20th century. The 20th century annual mean for the model runs is defined as the average of all months between January 1981 and December 2000; wind stress is defined as positive toward the east, so when winds blow from east to west as they do near the Antarctic coast (polar easterlies), the wind stress is negative. Observed long-term mean from National Center for Environmental Prediction (thick black), GFDL-CM2.1 (blue), GFDL-CM2.0 (red), MIROC3.2 (hires) (green), and MRI-CGCM2.3.2a (purple). Models included in the original analysis but eventually omitted from our ENSEMBLE are indicated with thin black lines and include CCCMA3.1-T47, CNRM-CM3, CSIRO-Mk3.5, GISS-AOM, GISS-ER, INM-CM3.0, IPSL-CM4, MIROC3.2 (medres), UKMO-HadCM3, and UKMO-HadGEM1.

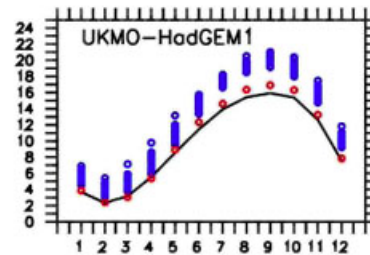
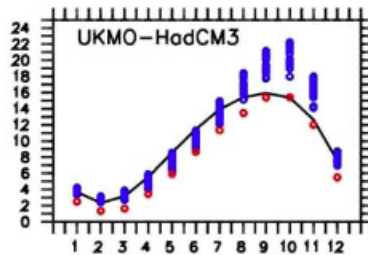
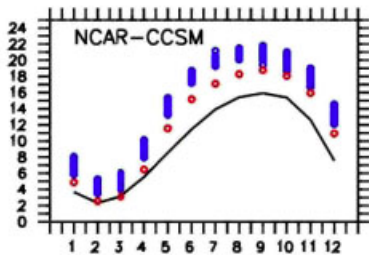
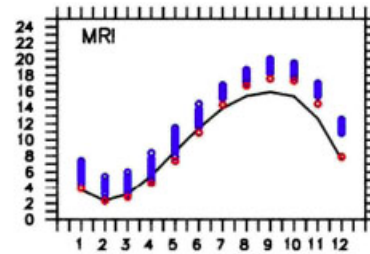
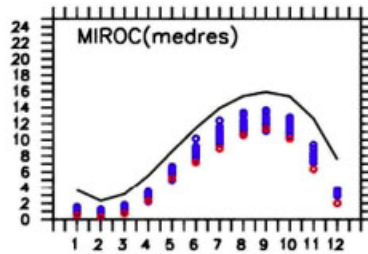
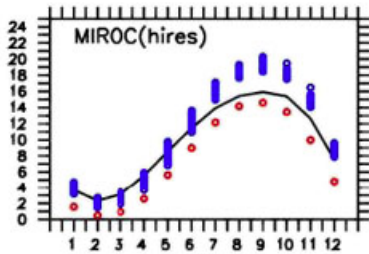
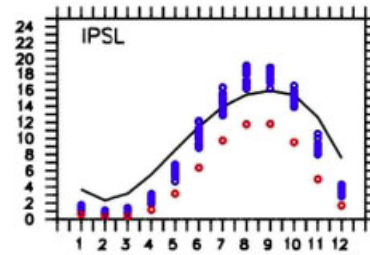
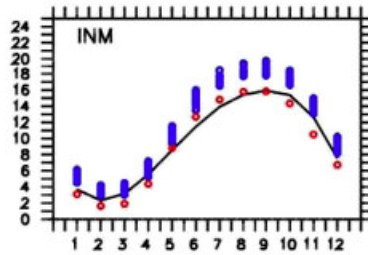
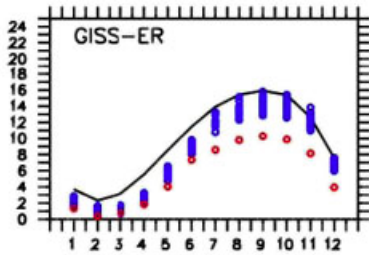
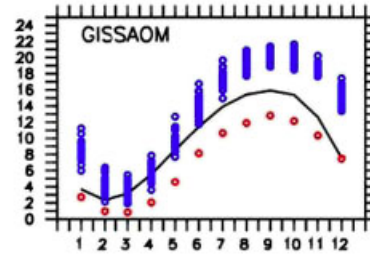
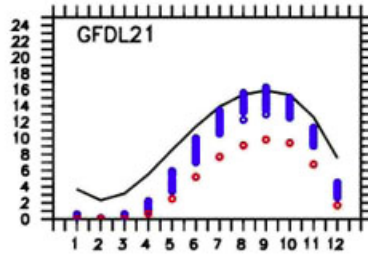
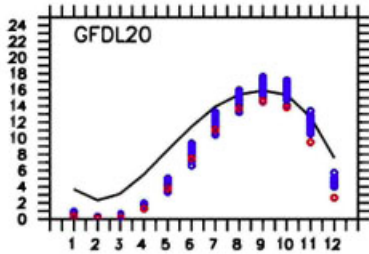
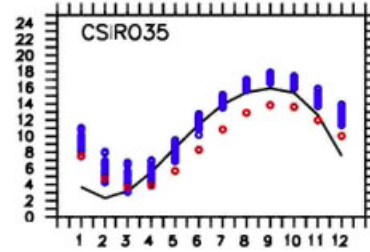
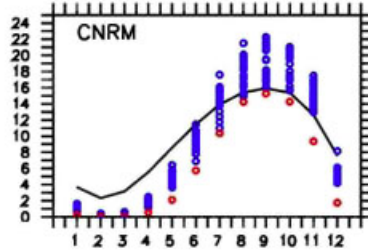
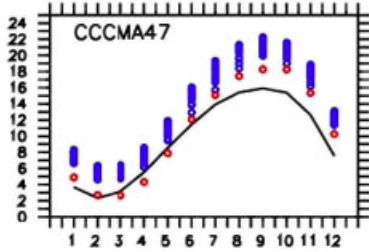
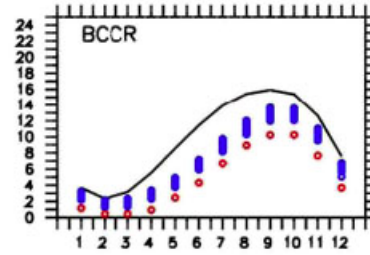
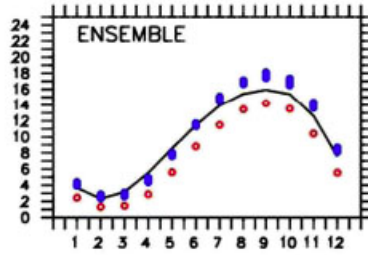
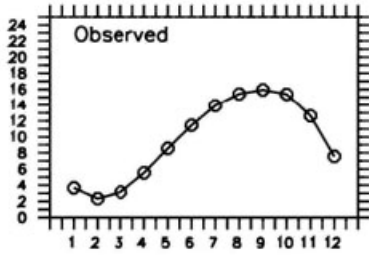


FIG. A3a. The interannual variability for each month of the total Antarctic sea-ice coverage for the pre-industrial control (blue) and at the year of 2°C warming (red).

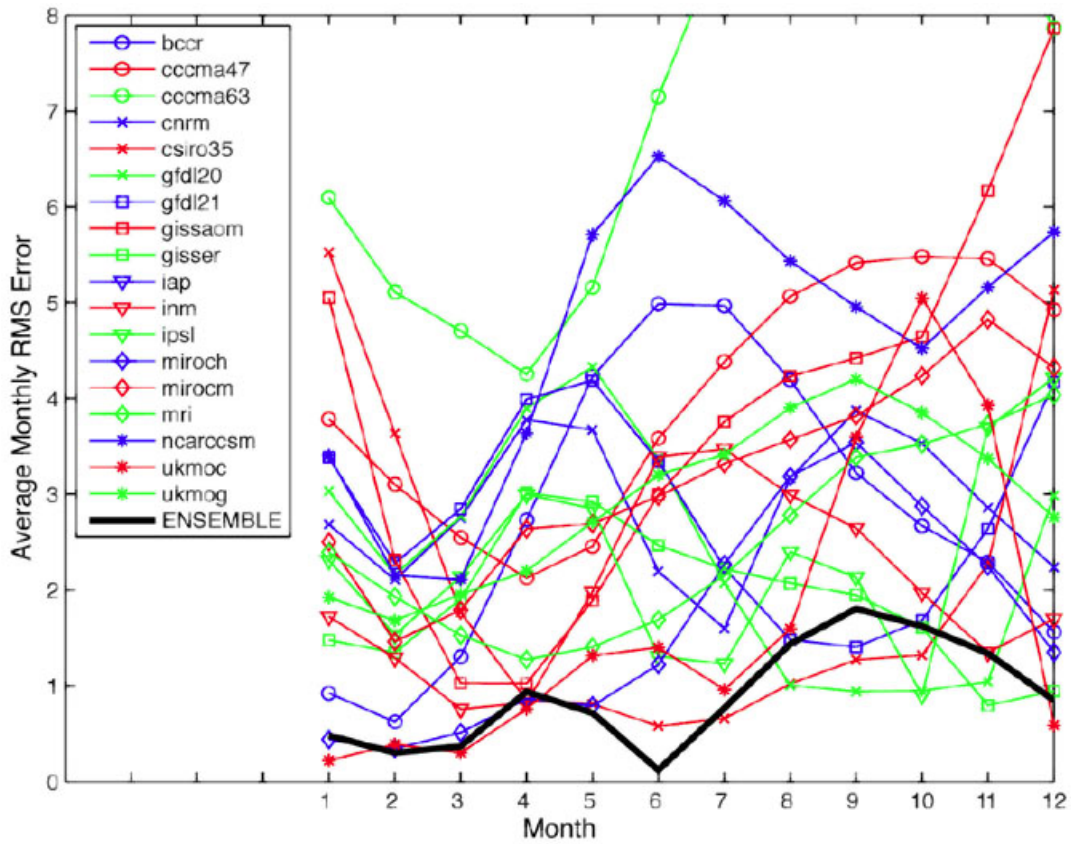


FIG. A3b. the mean RMS error for each month for the total area of Antarctic sea ice for the 20 years of the pre-industrial control experiment, relative to the modern observations. SIC coverage is the percent of grid cells having ice, as function also of time (season) in units of 10^6 km^2 . The thick black line is the RMS error of the 16-member ensemble. The table indicates the annual mean of the monthly RMS error for each model.

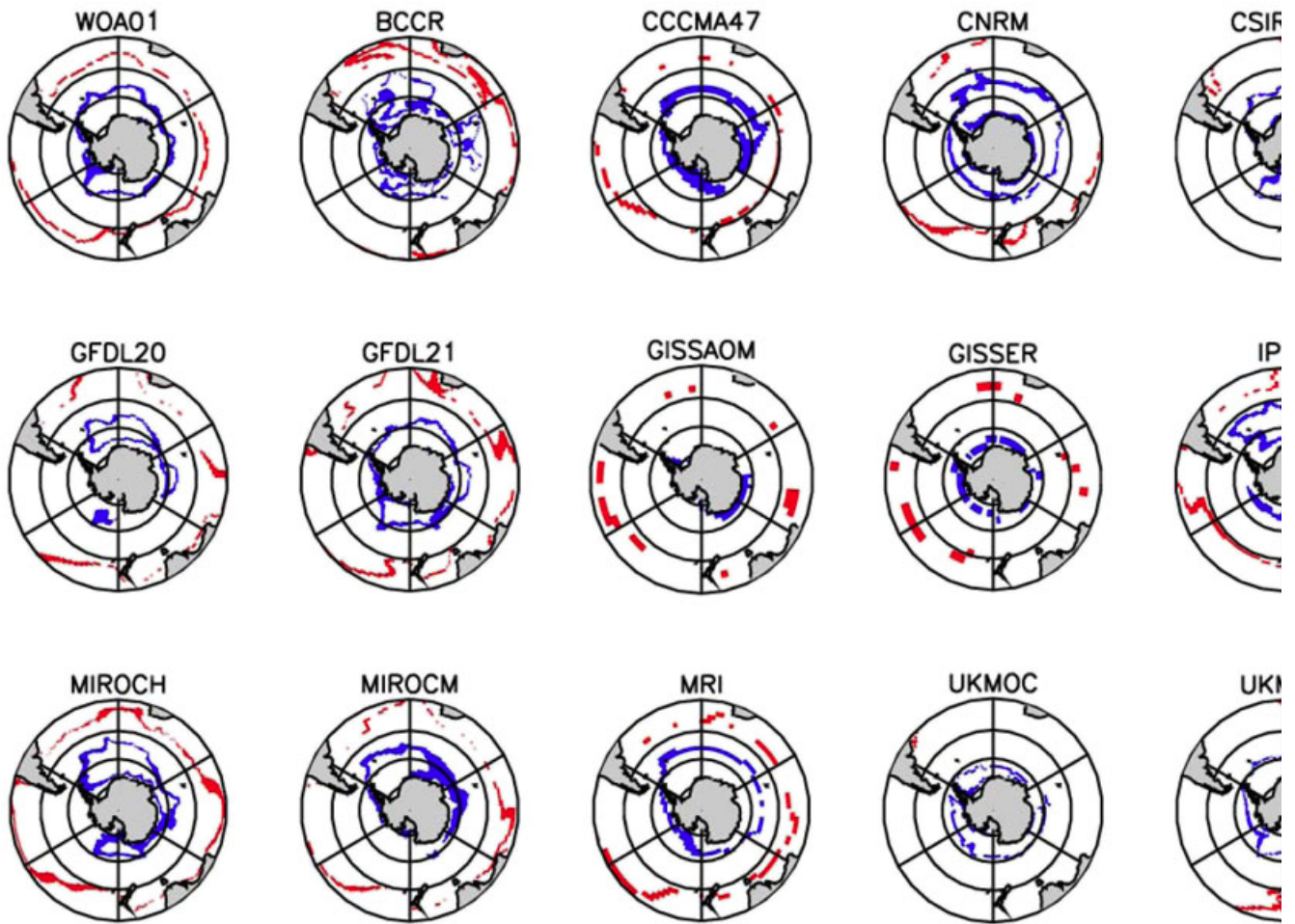


FIG. A4. The ACC in each of the models considered. It is demarcated by the subtropical front to the north (red) and by the south boundary close to the continent (blue); boundary definitions taken from Orsi et al. (1995). WOA01 refers to the existing ocean, the World Ocean Atlas (Conkwright et al. 2002); latitude lines are 75°, 60° and 45° S.

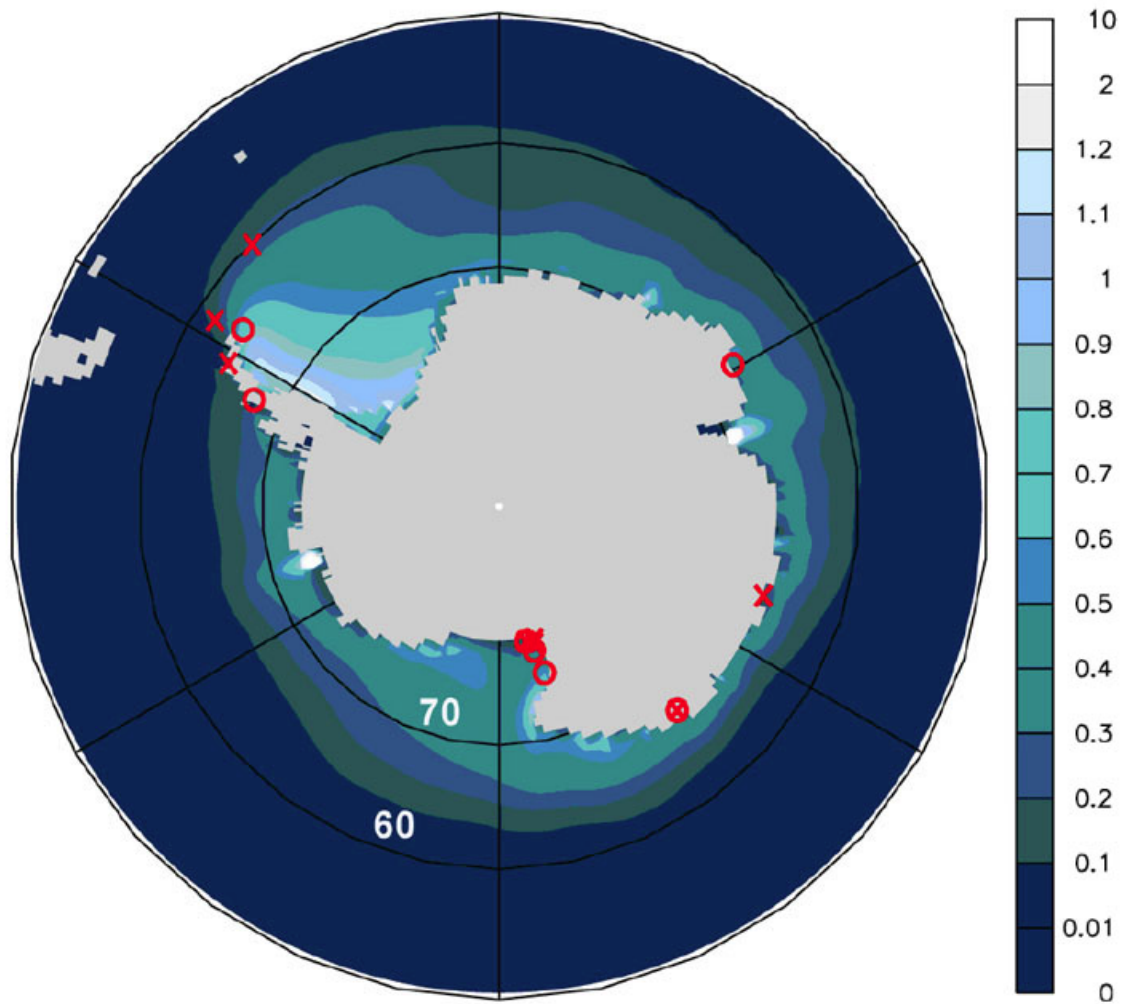


FIG. A5. ENSEMBLE: annual mean sea-ice thickness (m) during the satellite era (1982-2007; compare to Timmermann et al. 2004). Also shown are colonies of Adélie Penguin (X), Emperor Penguin (open O), and locations where both occur, and which are mentioned in the text (see text Figs. 1, 2).

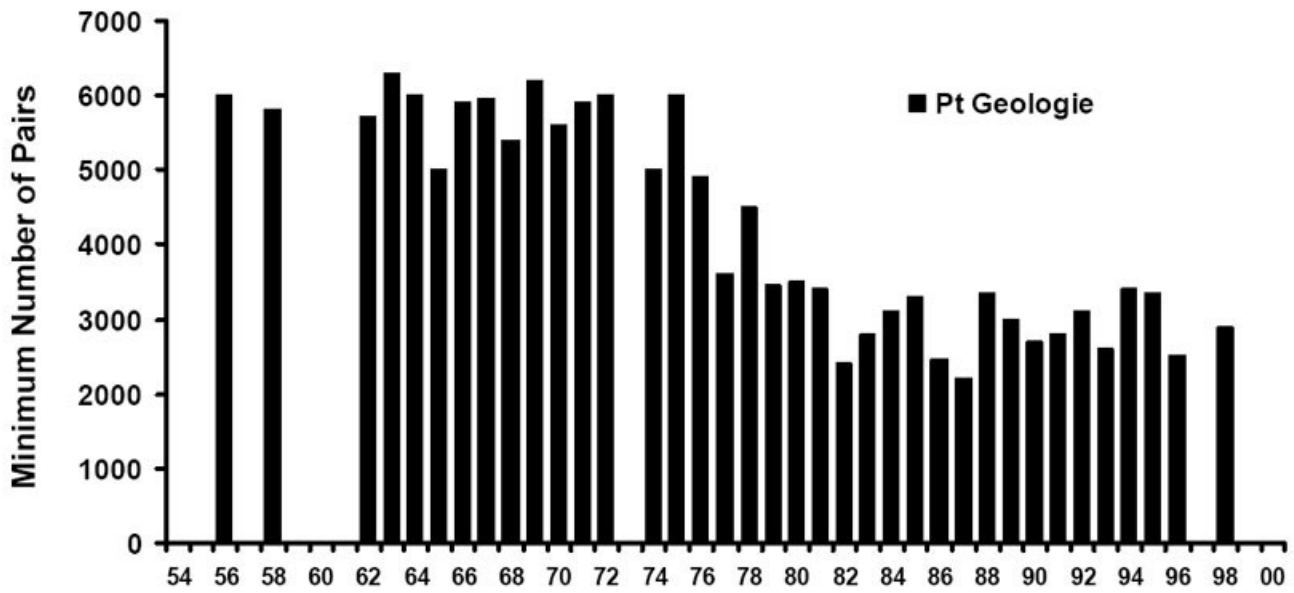


FIG. A6. Minimum numbers of breeding pairs of Emperor Penguins at Pointe Géologie, 1956–1998 (data from Barbraud and Weimerskirch (2001)).

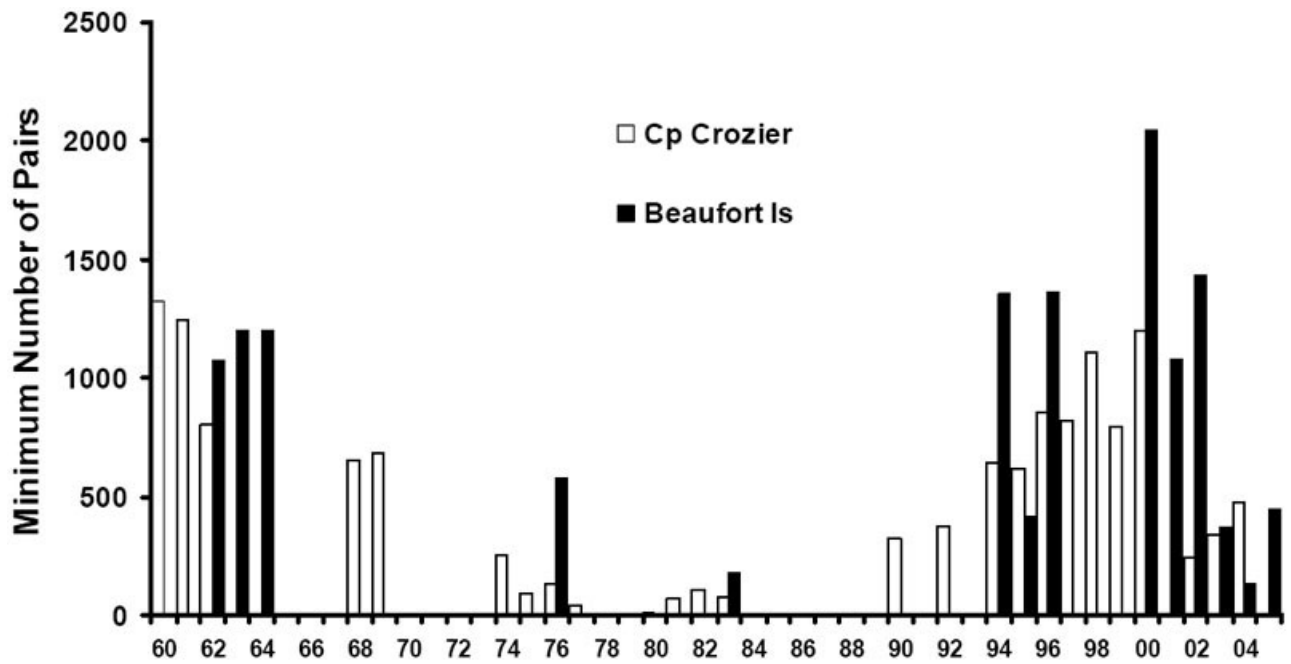


FIG. A7. Numbers of breeding pairs of Emperor Penguins at two colonies in the southern Ross Sea, 1960–2005 - numbers are from chick counts and, therefore, constitute a minimum estimate of breeding population size (from Kooyman et al. 2007).

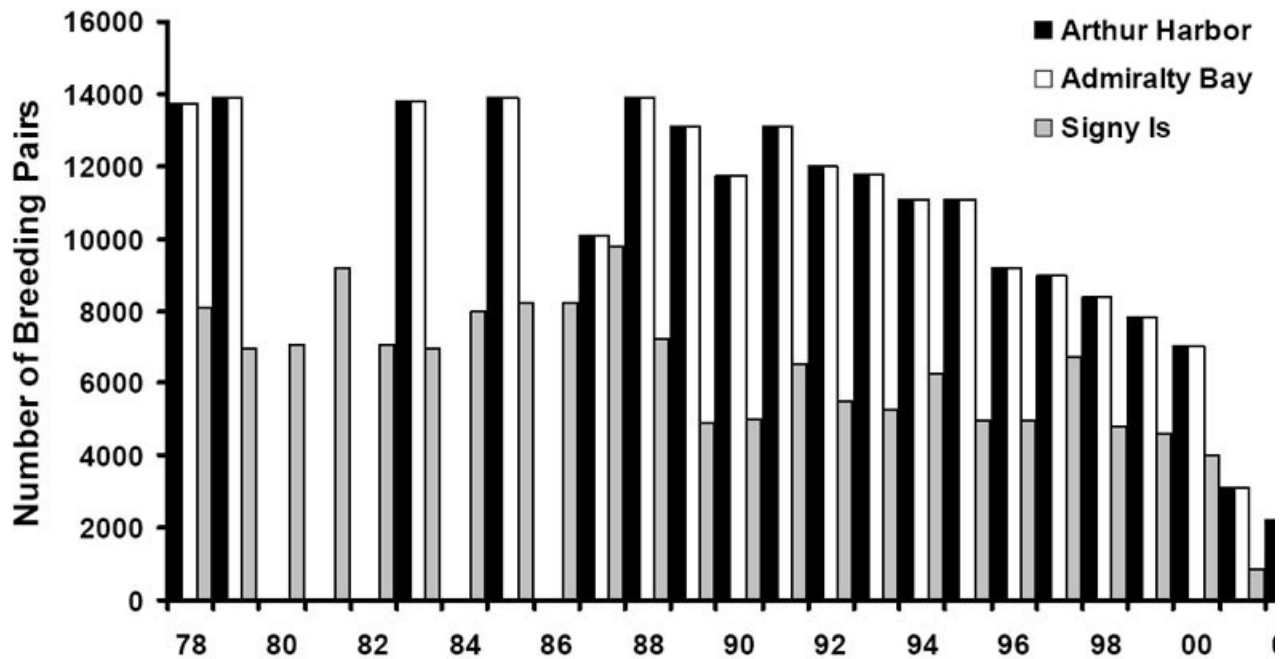


FIG. A8. Numbers of breeding pairs of Adélie Penguin at three colonies along the north and northwest coast of the Antarctic Peninsula: Arthur Harbor (Ducklow et al. 2007), Admiralty Bay (Hinke et al. 2007), and Signy Island (Forcada et al. 2006).

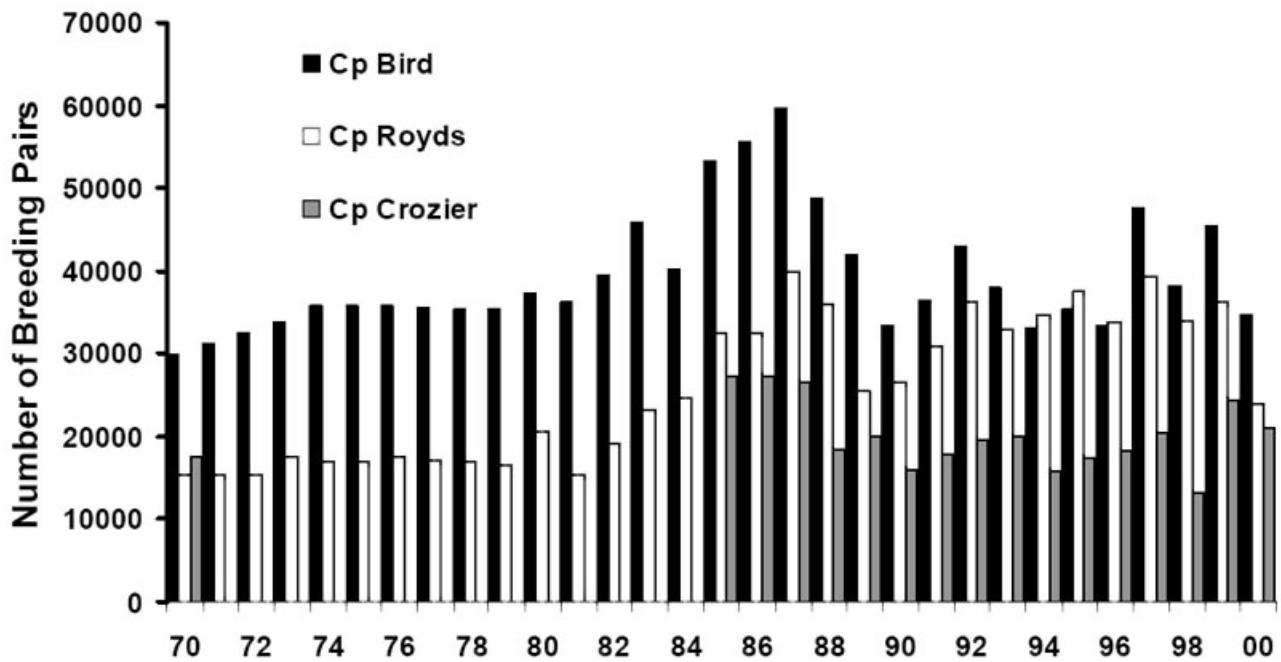


FIG. A9. Numbers of breeding pairs of Adélie Penguins at three colonies in the Ross Sea (Cape Bird, Cape Royds, Cape Crozier East), 1970–2000. Data are from Wilson et al. (2001).

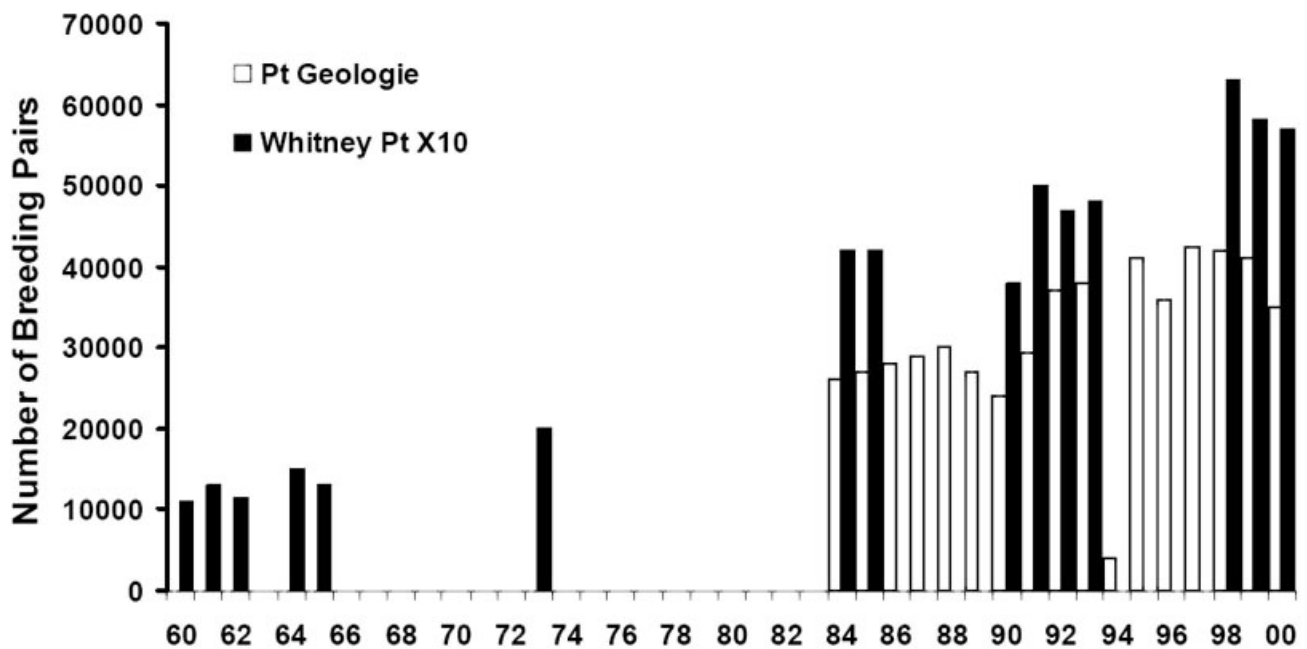


FIG. A10. Numbers of breeding pairs of Adélie Penguins at two colonies in East Antarctica, 1960–2000. Data for Whitney Point are from Woehler et al. (2001), and for Pointe Géologie from Jenouvrier et al. (2005c). Those from Whitney Point were multiplied by 10 in order that the trend would show up next to the Pointe Géologie data.

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