Background Document for Development of a Circumpolar Ringed Seal (*Phoca hispida*) Monitoring Plan

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I. Ecology of the species

A. Brief review of biology and natural history

1. Basic biology

Ringed seals are in many respects the “classic” arctic ice-seal. This species uses ice exclusively as its breeding, molting, and resting (haul-out) habitat, rarely if ever coming onto land. Their unique ability to create and maintain breathing holes in sea ice using the well-developed claws on their fore-flippers allows them to thrive in areas where even other ice-associated seals cannot reside (Fig. 1). Although ringed seals are quite small they deal with the thermal challenges posed by the arctic winter by having a very thick blubber layer, and by building lairs (small caves) in the snow on top of sea ice during the winter, that are particularly important for neonatal survival (Fig. 2). Each seal builds several lairs so that they can escape if a predator attacks one of their structures; ringed seals have co-evolved with their principle predator, the polar bear (*Ursus maritimus*) over the last 10s of thousands of years.

a

b

Fig. 1. Breathing holes of ringed seals a) a haul-out hole currently being used only for breathing (total hole diameter ~60 cm) b) a ringed seal breathing hole (approximately 10 cm in length) along a natural crack in the land-fast ice.

Ringed seals are a phocid seal (Family Phocidae, Subfamily Phocinae) that is in the Tribe Phocini. They are alternatively classified in the genus *Phoca* or the genus *Pusa* (see Rice 1998), with recent genetic evidence leaning towards the former classification (see Davis et al. 2004). Based on distribution and morphometry, the species has been divided into several subspecies. *P. h. hispida* inhabits all of the circumpolar Arctic Ocean (Frost and Lowry 1981) and is the subspecies that will be the primary focus of this brief review. No intensive research related to stock or population identity has been conducted within the huge distributional area for this sub-species, but it is assumed that such units might well exist.

Ringed seals are usually silver-grey in color. Their bellies are light, while their backs are darker and bear a conspicuous pattern of small rings that gives them their common name, though some individuals can be quite brown-black and have few discernable rings. There is little sexual dimorphism within the sub-species *P. h. hispida*, and adult animals normally reach lengths between 1.1-1.6 m and weights of 50-100 kg (Smith 1987, McLaren 1993) with averages being around 130 cm and 66 kg. Like all of the northern seals, their body mass varies markedly on a seasonal basis. Ringed seals are fattest in the autumn and thinnest in the late spring/early summer following the breeding period and the annual molt. Breeding males are easily discernable in the spring because of an oily secretion from glands in the facial region, which causes their faces to appear much darker than those of females or juvenile seals (Hardy et al. 1991, Ryg et al. 1992). At other times of the year the sexes are difficult to distinguish. At birth pups are about 60 cm in length and weigh about 4.5 kg. They have a white fuzzy lanugo coat that is shed when they are about two months old. Their juvenile fur is silver on the belly and dark grey on the back – animals with this coat are called silver-jars. They acquire rings on their pelage gradually with age. Ringed seals are long lived, with a life span of up to 45 years of age (Lydersen and Gjertz 1987), although 25-30 is probably a more normal longevity (e.g. Lydersen and Gjertz 1987, Krafft et al. 2006a).

2. General Distribution and Abundance Patterns of Arctic Ringed Seals

Ringed seals (*P. h. hispida*) inhabit the Arctic Ocean and adjacent waters such as the Bering Sea, Sea of Okhotsk, Barents Sea, White Sea, and Kara Sea and extend into some lake and river systems in Northern Canada (see Heide-Jørgensen and Lydersen 1989). Extralimital records for ringed seals extend south on both sides of the Atlantic, to Sable Island in the west and Portugal in the east (Bree 1996, Lucas and McAlpine 2002) and Bree (1997) suggests that this species' occurrence is sufficiently frequent on the European coast that it should be considered a regular visitor. Ringed seals are the most abundant high arctic seal and although no accurate global estimate is available, the species is thought to number at least a few million animals (Reeves 1998). Ringed seals occur throughout the Arctic, north to the pole. They are the only northern seal that can maintain breathing holes in thick sea ice and this special ability allows them to have an extensive distribution in the Arctic and sub-Arctic.

Ringed seals occupy fast-ice areas in the late fall/early winter in preparation for early spring breeding (Smith and Stirling 1975, 1978, Smith and Hammill 1981, Smith and Lydersen 1991). Their principal pupping habitat is land-fast ice (McLaren 1958, Lukin and Potelov 1978). But, they are also known to breed in at least three regions on free-floating pack ice, in the Okhotsk Sea, the Barents Sea and Davis Strait (Fedoseev and Yablokov 1964, Fedoseev 1975, Finley et al.1983, Wiig et al. 1999). During the fast-ice season ringed seals show preferences for areas with stable ice, over medium-depths (10-35 m) of water (e.g. Smith and Lydersen 1991, Lunn et al. 1997, Moulton et al. 2002, 2005, Simpkins et al. 2003). Significant snow cover is required for lair construction; these structures are usually constructed in snow drifts that form downwind of ice ridging or behind glacier ice pieces frozen into annual ice (Lydersen and Gjertz 1986, Smith 1987, Hammill and Smith 1989, Furgal et al. 1996). Prime habitat is occupied by breeding adults, while reproductively inactive animals including immature individuals are usually found in peripheral areas (Stirling et al. 1981, Krafft et al. in press).

In the summer and fall, when land-fast ice is not available, ringed seals show considerable diversity in their distribution patterns. Some animals remain in the general vicinity of their breeding sites while others disperse along coastlines where ice from glaciers is available. Some spend time pelagically, and yet others move north to the southern edge of the permanent ice (Heide-Jørgensen et al. 1992, Teilmann et al. 1999, Gjertz et al. 2000, Born et al. 2002, Freitas et al. ms, also see – movement patterns below). During the summer and early fall ringed seals seem to maintain their preference for annual ice (as opposed to multiyear ice), and are usually found at highest densities over shallow-mid-depths (100-200 m) of water (Smith and Hammill 1980a,b, Stirling et al. 1982, Kingsley et al. 1985). Despite the variable patterns of space use, ringed seals consistently are more mobile and have larger "home ranges" during the open water season (e.g. Born et al. 2004; see below for more details in Section 4 - Movements). In a detailed study of space use during the post-molting period, ringed seals on the east coast of Svalbard showed two distinct distribution patterns during the open-water season, that were independent of sex and maturity status of the seals (Freitas et al. ms). Approximately half of the individuals moved northward to offshore areas containing 40-80% ice coverage (maximum preference), while others spread along the coasts of Svalbard, concentrating their time near glacier fronts. Both strategies lead ringed seals to highly productive areas where they had access to ice-platforms for resting. When offshore, sea ice concentration and season (time in the year) were the variables that influenced habitat selection most markedly. Late in the autumn, increased probabilities of leaving an area were identified for the offshore seals, even when ice conditions were still favorable, which reflects their need to return to over-wintering/breeding areas before the fjords of the archipelago become frozen. The seals that traveled offshore returned to the coast of Svalbard during August-November. For ringed seals that remained inshore, habitat selection was influenced mainly by distance to glacier fronts and season. These animals were already close to their over-wintering habitat and hence their probabilities of leaving a given area decreased significantly as winter approached.

Abundance of ringed seals has been estimated using a variety of methods including aerial surveys of various types, surveys of holes and lairs using trained dogs, remote sensing of ice conditions, ship-based surveys, inferences from the size of resident polar bear populations, as well as extrapolations from pup production estimates (e.g. Mansfield 1970, Digby 1984, Kingsley et al. 1990, Smith and Lydersen 1991, Stirling and Øritsland 1995, Lunn et al. 1997). However, the method of choice in recent years for relatively large areas is clearly aerial surveys (Moulton et al. 2002, 2005, Frost et al. 2004, Bengtson et al. 2005, Krafft et al. 2006b). Surveys must be timed to coincide with peak haul-out season which occurs just prior to the ice break-up (that for most regions occurs in the first week of June), and ideally flying should be done around mid-day in clear, relatively warm, calm weather (see Burns and Harbo 1972, Smith and Hammill 1981, Born et al. 2002, Carlens et al. 2006). However, correction factors are still required to account for the number of animals that are not visible to be counted at the time of the survey because they are either in the water, or in some cases still in their snow lairs. A variety of methods have been employed to attempt to take counts to population estimates; these are reviewed in Reeves (1998). More recently Bengtson et al. (2005) and Krafft et al. (2006b) have performed flying surveys with correction factors modeled upon data from haul-out behavior of ringed seals under different environmental conditions, times, etc.

However, it is clear from intensive, hourly counts performed simultaneously with VHF studies done in compliment to flying surveys that calibration issues remain (Carlens et al. 2006, Krafft et al. 2006a), and that most if not all abundance surveys to date should probably be considered indexes of abundance. Use of digital photographic methods during surveys flown at quite high altitudes reduces many sources of error inherent in visual surveys and, given that it is quite cost-effective, it is likely to be the method of choice in the future for ringed seal surveys (see Heide-Jørgensen 2004, Krafft et al. 2006b).

Average densities of ringed seals hauled out on the ice during surveys are quite variable, even within areas known to be good ringed seal habitat where aggregations are known to occur (e.g. Stirling et al. 1977, Lunn et al. 1997, also see Reeves 1998 for a review), but generally averages within individual studies of "good" ringed seal areas fall between 1-2 seals km^{-2} (Eastern Baffin Island, 1.7 seals per km^{-2}, Finley et al. (1983); Kong Oscars Fjord Greenland, 1.0 seals per km^{-2} Born et al. (1998); Scoresby Sund, 2.0 seals per km^{-2} Born et al. (1998); 1.62 /- 1.91 seals km^{-2}, in the eastern Chukchi Sea, Bengtson et al. 2005; Svalbard fjords, 1.4 seals km^{-2}, Krafft et al. 2006b). Late summer surveys in the southeastern Beaufort Sea where aggregations of ringed seals were known to occur produced densities of 0.08 – 0.42 overall with 1.21-3.26 seals km^{-2} within the immediate areas of aggregations (Harwood and Stirling 1992).

Lair surveys have also been used to produce crude estimates of the numbers of ringed seals occupying areas, or to produce pup production estimates (number of birthing lairs), that are then extrapolated to population sizes. For these sorts of surveys trained dogs are often used to find the sites of lairs and it is assumed that each seal has several lairs (e.g. Smith and Stirling 1975, 1978, Lydersen et al. 1990, Lydersen and Ryg 1991). This method is labor intensive, but it is the only direct means to determine pup productivity given that pups are not readily visible for other types of surveying (see reproduction below). Vocalization rates have been explored as a means of assessing the suitability of pupping habitats, but results have been ambiguous (Calvert and Stirling 1985). Production can of course be crudely estimated with a time-lag from back-calculating production from age-structure if age-specific mortality and overall abundance are known with some precision.

3. Reproductive biology

The preferred breeding habitat of ringed seals is stable land-fast ice, where ringed seal densities are usually higher inshore than offshore prior to and during peak breeding (e.g. Smith and Stirling 1975, Lydersen and Gjertz 1986, see above for exceptions). Ringed seals of both sexes build subnivean lairs (Fig. 2) excavated out of snow drifts that occasionally form on top of breathing holes in the ice; seals use these lairs to haul out and rest during the inclement winter months (e.g. Smith and Stirling 1975, 1978), and females give birth in these small snow caves in the early spring (March/April).

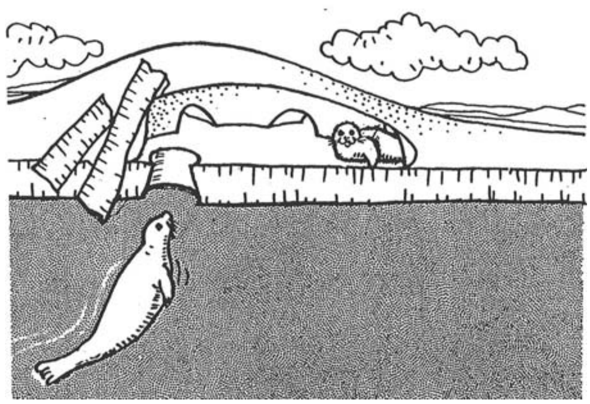

Fig. 2. Ringed seal pupping lair, with the pup in the lair and the female approaching the haul-out hole from the water (From Gjertz and Lydersen 1983). Pups excavate the side tunnels.

Individual lairs are often part of a complex of lairs and breathing holes used by the same animal in an area; the distance between lairs or breathing holes with a complex can be up to several hundred meters (Smith and Hammill 1981, Lydersen and Gjertz 1986, Kelly and Quakenbush 1990). The sizes of the areas females occupy are probably determined to some degree by the availability of structures in the ice around which snow accumulates for lair construction, and by the density of available prey organisms in the area (Smith et al. 1991, Smith and Lydersen 1991, Lydersen 1995). Lairs provide protection from harsh environmental conditions and predation (Smith 1976, 1980, Smith and Stirling 1975, Lydersen and Gjertz 1986, Lydersen and Smith 1989, Smith et al. 1991, Furgal et al. 1996). A female will move a young pup between lairs within her complex if one lair is attacked by polar bears (*Ursus maritimus*) or arctic foxes (*Alopex lagopus*); older pups are able to shift between structures independently (Lydersen and Hammill 1993a).

Breeding males also use several lairs, spread through an area that contains the lairs of several females (Kelly and Quakenbush 1990). This fact in addition to sex ratios and general spatial patterns of adult males and females observed in prime breeding areas, and wounds seen on males in the spring suggests at least a low level of polygyny in this species with territorial fighting among males (Stirling 1983, Smith and Hammill 1981, Krafft et al. 2007). During the breeding period, adult ringed seal males secrete a very strong-smelling oily substance produced by facial sebaceous glands (Ryg et al. 1992). The function of this “tiggak” secretion is thought to be related to marking of territories (Ognev 1935, Capskii 1940Smith 1987), and the most logical places to mark would be the breathing holes or lairs, since the seals are unlikely to be able to smell under water where mating is thought to occur. Based on direct observations of haul-out behavior of a few recognizable individual ringed seals, Smith and Hammill (1981) suggested that breeding units were made up of several adult females that occupied an area defended by a territorial male. Sex ratios, spacing patterns and movements of individuals under the ice all support the concept that male ringed seals (at least) are territorial (Hammill and Smith 1991, Kelly and Quakenbush 1990, Kelly and Wartzok 1996). A detailed study of the spatial relationships among adults during the breeding period also supports this suggestion and found that adult males with the most adult female neighbors were not necessarily the largest individuals, but were significantly older than those with few female neighbors (Krafft et al. 2007). This suggests that experience plays a role in achieving reproductive success for male ringed seals.

Ringed seal neonates weigh 4-5 kg (Lydersen et al. 1992) when they are born; at this time they bear a white lanugo coat that insulates well enough to keep the pups thermoneutral without the shelter of the lair as long as the lanugo stays dry (Smith et al. 1991). However, wet pups require the shelter of lairs in order to regain thermoneutrality (Smith et al. 1991). In addition, pups born on the surface of the ice in years with poor snow conditions suffer very high mortality rates (Lydersen and Smith 1989). Thus, both the physical and thermal protection provided by these lairs is particularly important for the survival of young pups. Ringed seals have the longest nursing period of the ice-breeding northern phocids with an average lactation duration of 39 days (Hammill et al. 1991). The pups are able to swim and dive shortly after birth and they develop foraging skills prior to weaning (Lydersen and Hammill 1993a). During the nursing period pups gain around 375 g per day (Lydersen et al. 1992). Weaning is less abrupt than for most phocid pups, which are abandoned by their mothers before they have entered the water for the first time (Bowen 1991, Lydersen and Kovacs 1999). Many of the larger phocid species are so-called “capital breeders”, which means that they cover the energetic costs of lactation entirely from stored energy reserves. This is not the case for ringed seals, which rely heavily on energy obtained from foraging during lactation (Lydersen and Hammill 1993b, Lydersen 1995, Lydersen and Kovacs 1999). Pups are weaned when they weigh approximately 20 kg and although this is quite small for an arctic mammal, they are already quite capable swimmers and divers (Lydersen and Kovacs 1999).

Information on growth and reproduction has been collected for ringed seals from many areas (see McLaren 1993, Holst and Stirling 2002 for reviews). Both males and females generally reach sexual maturity around the age of 4-7 years, with some variation between different geographic areas and over time (McLaren 1958, Nazarenko 1965, Johnson et al. 1966, Smith 1973, 1987, Fedoseev 1975, Frost and Lowry 1981, Lydersen and Gjertz 1987, Holst and Stirling 2002). In most studies females show a tendency to achieve sexual maturity earlier than males and they undoubtedly breed successfully at earlier ages than most males. Reported mean age at sexual maturity (MAM) for ringed seals females varies in the literature from 3.5 – 7.1 years (Holst and Stirling 2002, Krafft et al. 2006a). Reproductive rates of female ringed seals usually vary between 0.45-0.86 (see Reeves, 1998), with extremes as high as .91 pups per year (Lydersen and Gjertz 1987). Regional production rates are variable; reproductive success depends on many factors including prey availability, the relative stability of the ice, sufficient snow accumulation prior to the commencement of breeding etc. (e.g. Lukin 1980, Kelly 1988, Smith 1987, Lydersen 1995).

Growth rates and population parameters are not static characteristics of populations. For example, MAM is known to be a flexible characteristic of populations that can change rapidly. Generally, variations in MAM for pinnipeds over time are explained by factors causing changes in food availability, either via overall changes in ecosystem productivity or via density-dependent responses of a variety of types, including intra- and inter-specific competition, predation and harvest levels, and physical changes to the environment that impact productivity (Laws 1953, Carrick et al. 1962; Eberhardt and Siniff 1977, Bengtson and Siniff 1981, Bowen et al. 1981, Capstick and Ronald 1982, Lydersen and Gjertz 1987, Kjellquist et al. 1995, Sjare et al. 1996). In the extreme, female ringed seals up to age 9 that had never been pregnant were reported from the Amundsen Gulf, NWT in the mid to late 1980s when food was scare in this area and animals were in poor condition (Kingsley and Byers 1998). Time series that enable studies of trends in population parameters are therefore important for understanding the dynamics of the ecosystem a given population inhabits.

4. Movements/migrations

Small scale movement patterns by ringed seals have been studied using radio telemetry or acoustic tracking under water during the fast-ice season. Such studies have provided information regarding how ringed seals locate their holes during the arctic winter, what sorts of search patterns and diving behaviors are employed during prey searches within their home ranges, as well as basic time-budget information and space use patterns (Kelly and Quakenbush 1990, Lydersen 1991, Lydersen and Hammill 1993a, Lydersen et al. 1993, Wartzok et al. 1992, Kelly and Wartzok 1996, Simpkins et al. 2001a,b,c). Each ringed seal uses several haul-out lairs and additional breathing holes within its home range and travels between them quite regularly. A seal's lairs are usually only a few hundred meters apart, but a record 3, 438 m between haul-out liars has been recorded for an individual radio-tagged seal (Kelly and Quakenbush 1990). Male's lairs are spread over greater distances on average than those of females. The use of individual lairs appears to be quite exclusive, although seals do occasionally use lairs that are primarily used by another seal. During the reproductive season females spend more time on average out of the water than males and both sexes shift from hauling out during the night in early spring to hauling out during day-time hours in late spring, with more time spent on the surface during the latter period (Kelly and Quakenbush 1990, Carlens et al. 2006)

It is not known whether ringed seals show fidelity to natal sites, or if they are faithful to breeding sites as adults. In some areas, very predictable ice stability, sufficient snow to construct lairs, and good food availability create prime habitat for ringed seals that is used over long periods of time, and there are a few mark-recapture events that support the concept of site fidelity by adult animals. Both adult males and females have been marked and then recaptured in the next year or after several years, some observed only a few 100 m from where they were marked in Kongsfjorden, Svalbard (Lydersen and Kovacs, unpublished data). Small amounts of other data also suggest both intra-annual and inter-annual site fidelity for breeding ringed seals in other studies (see McLaren 1958, Smith and Hammill 1981, Kelly and Quakenbush 1990). However, there are also reports that strongly suggest that there is considerable mobility among ringed seals in some areas. For example, it appears that harvests of ringed seals by humans or polar bears well above levels that could be supported by a local population are sustained in some locales for long periods of time via recolonization from the broader range of the population (Smith 1973, Hammill and Smith 1991).

Information regarding seasonal and inter-annual movement patterns of ringed seals is somewhat limited. There are references in the literature to ringed seal migrations including an annual migration that apparently takes place through Bering Strait as the seals follow the receding pack-ice northward in spring, then southward again just ahead of the advancing sea ice in autumn (Kelly 1988). Stirling et al. (1982) refer to "large and predictable" annual westward migrations by sub-adult ringed seals along the north coast of Alaska during late summer and autumn, and some movement of individual seals from the eastern Beaufort Sea westward to the Chukotka Peninsula has been demonstrated by tagging and recapture (Smith 1987). Additionally, variable densities of ringed seals seem to follow seasonal patterns in some areas. For example, near Baffin Bay ringed seals seem to leave some coastal areas in summer, while in other, generally more northerly areas, large influxes of ringed seals occur during the open water period, suggesting substantial migrations, either north-south or inshore-offshore (Miller et al. 1982).

Traditional tagging studies have shown that ringed seals can travel significant distances (e.g. 1,400 km - Knutsen and Born 1989, >1000 km Kapel et al. 1998); the record distance recorded for this species was a ringed seal tagged by Kelly and Wartzok (1996) in Resolute in the Canadian High Arctic in the spring moving to Narsalik SW Greenland by the following March (2,272 km; Kapel et al. 1998). The record round trip by a ringed seal must go to the juvenile that swam to France, where it was rehabilitated, tagged and released, prior to its return to the Arctic, where it was recovered from the stomach of a Greenland shark on the coast of Iceland (Ridoux et al. 1998). But, the number of ringed seals tagged and recovered is quite small throughout their geographic distribution and most tags are recovered within 100 km of the tagging site.

The development of satellite tags in recent years has expanded our knowledge of movement patterns of many marine mammal species including ringed seals. However, the number of tags deployed in any given study is usually quite small, and large-scale, inter-annual, or geographic patterns are as yet far from clear. The one consistent pattern among satellite tracking studies of this species to date seems to be that individuals tagged at any one location display variable dispersal patterns. Some individuals remain local throughout the open-water season, traveling along coastlines, while others move offshore or northward to the permanent pack-ice (Heide-Jørgensen et al. 1992, Gjertz et al. 2000, Teilmann et al. 1999, Born et al. 2004). It is also clear that distances traveled are greater during the open water season compared to the months when ringed seals occupy fast-ice areas. During a study that deployed a relatively large number of tags (N= 23) in Svalbard over a three year period, animals tagged on the east coast remained on that side of Svalbard, with approximately half of the animals remaining coastal during the late summer and fall, while the other half all went NE to the nearest edge of the northern pack-ice (Freitas et al. ms). Offshore trips started between 22 July and 15 September, and lasted between 18 and 90 days. The trips reached maximum distances of 231 to 593 km away from the tagging location. The directions of these trips were not random, all animals traveled in a NE direction (at angles between 19°- 84° from the tagging location). The offshore trips always started in an ice-free area and had their northernmost locations in areas with ice concentrations between 40-80%. Twenty one of the 23 animals returned to the general area of tagging the following over-wintering period, while two individuals moved over to the west coast as the fast-ice season approached.

5. Seasonal/regional variation

Although a significant number of publications involving ringed seals have been produced in the scientific literature (see Appendix I), time-series are virtually non-existent for even very basic population parameters for ringed seals, such as production rates, abundance trends, mortality rates etc., for most regions in the Arctic. This makes it difficult to separate inter-annual variation from regional or seasonal variation. It is clear that inter-annual is naturally high with respect to condition of the animals and reproductive success, with both varying markedly from year to year, in response to physical and biotic conditions that animals experience in a given year in a given area. Natural patterns of seasonal variation in all arctic seals, including ringed seals are also high with respect to body condition, with fattening and thinning periods accompanying different biological “seasons”. Some seasonal patterns can be pieced together (e.g. see diet below), but even these analyses involve a range of locations, a variety of years etc. A general paucity of recent, accurate abundance data means that even quite dramatic changes in population trends will be very difficult to assess in a meaningful way in the near future because of the lack of comparative data and statistical power.

6. Foraging

Many studies of ringed seal diet have been conducted across the species’ range, and, although this seal feeds on a variety of fishes and invertebrates, several strong tendencies with respect to prey selection are found among ringed seals across the Arctic (McLaren 1958, Johnson et al. 1966, Lowry et al. 1980, Popov 1982, Gjertz and Lydersen 1986a, Smith 1987, Lydersen et al. 1989, Weslawski et al. 1994, Belikov and Boltunov 1998, Siegstad et al. 1998, Wathne et al. 2000, Holst et al. 2001, Labansen et al. 2007). Most ringed seal prey is small, and preferred prey tends to be schooling species that form dense aggregations. Fishes are usually in the 5-10 cm range and crustacean prey in the 2-6 cm range. Typically, a variety of 10-15 prey species are found with no more than 2 - 4 dominant prey species for any given area. Fishes are generally preferred over invertebrate prey, but diet is regionally determined to some extent by availability of various types of prey during particular seasons as well as preference, which in part is guided by energy content of various available prey (Reeves 1998, Wathne et al. 2000). Prey availability is dictated to some extent by oceanographic conditions, such as water depth, which water mass dominates a specific area, and general productivity level.

Spatial and temporal variations are apparent in the diet of ringed seals, but gadid fishes tend to dominate the diet of ringed seals at least from late autumn through the spring in many areas. Polar cod[11] (*Boreogadus saida*) is often reported to be the most important prey species for ringed seals (McLaren 1958, Lowry et al. 1980, Gjertz and Lydersen 1986a, Smith 1987, Belikov and Boltunov 1998, Lydersen et al. 1989, Welch et al. 1993, Weslawski et al. 1994, Siegstad et al. 1998, Holst et al. 2001, Labansen et al. 2007). This small fish occurs in both ice-free and ice-covered waters and especially at ice edges (Ponomarenko 1968). Young polar cod (≤2 yrs) are often found tightly associated with sea ice, living under and even in spaces within sea ice, while larger polar cod tend to reside in deeper, more offshore waters (Falk-Petersen et al. 1986). It is an important prey species not only for ringed seals but also for a wide range of other marine mammals, sea birds, and fishes in arctic waters (Bradstreet and Cross 1982, Haug and Gulliksen 1982, Gabrielsen and Lønne 1992, Hjelset et al. 1999, Andersen et al. 2004). In Svalbard and the broader Barents Sea region, ringed seals consume a high fraction of young polar cod which suggests that at least in this area ringed seals forage primarily in the upper parts of the water column or in association with ice (Gjertz and Lydersen 1986a, Gjertz et al. 2000, Wathne et al. 2000, Labansen et al. 2007 - also see oceanography and prey below). The seasonal prevalence of polar cod in the diet during winter in many areas also suggests that this prey species is targeted by ringed seals in ice-covered waters (e.g. Lowry et al. 1980). Ringed seals

[1] Please note that the common names for polar cod and arctic cod are not internationally consistent. In Europe, and in this document, polar cod refers to B. saida and arctic cod to *A. glacialis*. But in the United States these common names are reversed.

also eat a variety of other members of the cod family, including arctic cod (*Arctogadus glacialis*; Holst et al. 2001), and saffron cod, with the latter being particularly important during the summer months in Alaskan waters (*Eleginus navaga;* Lowry et al. 1980). Redfish (*Sebastes* spp. (Weslawski et al. 1994, Siegstad et al. 1998), capelin (*Mallotus villosus;* Siegstad et al.1998), and herring (*Clupea harengus;* Popov 1982) are also important in the diet of ringed seals in some regions. Greenland halibut (*Reinhardtius hippolglosssoides*), *Liparis* sp. and a variety of other fish species also contribute to the diet of ringed seals, but represent small amounts of the total diet (e.g. Siegstad et al. 1998, Labansen et al. 2007). Some studies also suggest sex-related differences in prey composition for ringed seals (e.g. Holst et al. 2001).

Invertebrate prey seems to become more important to ringed seals in most areas during the open-water season in areas where sampling across seasons has been performed and is often found to dominate the diet of young animals (Lowry et al. 1980, Bradstreet and Cross 1982, Weslawski et al. 1994, Siegstad et al. 1998, Holst et al. 2001). Large amphipods (e.g. *Themisto libellula*), "krill" (e.g. *Thysanoessa inermis*) mysids (e.g. *Mysis oculata*), shrimps (e.g. *Pandalus* spp., *Eualus* spp., *Lebbeus polaris*, *Crangon septemspinosa*) and cephalopods (e.g. *Gonatus* spp.) are all eaten by ringed seals and can be very important in some regions at least seasonally.

Identification of pinniped prey by recovered hard parts from fecal or gastrointestinal tract (GIT) sampling are the most commonly used method for studying diet in pinnipeds, and otoliths in particular are an important means to analyze diet (e.g. Härkönen 1986). However, these types of analyses have a number of inherent potential biases that must be kept in mind including: partial or complete digestion of otoliths of some species; a larger possibility of identifying species with otoliths with distinctive morphological characteristics or larger size; and the fact that fish heads of larger fish may not always be ingested (see Pierce and Boyle 1991, Browne et al. 2002). Otolith digestion can also be affected by prey species and size, meal size and composition, and predator behavior (Marcus et al. 1998, Bowen 2000, Christiansen et al. 2005). Species with fragile otoliths (e.g. clupeids, salmonids (e.g. *Salvelinus alpinus*), pleuronectids (dabs, flounders)) can be underestimated. A recent study makes the point strongly that it is important to sample whole GITs when studying pinniped diets (Labansen et al. 2007) because stomach clearance rates are fast in pinnipeds (e.g. Murie and Lavigne 1986), and even some hours after feeding most hard-parts are recovered from the intestines (Labansen et al. 2007). Stable isotopes and fatty acid analyses have also been used to augment conventional dietary studies in recent years (see Hobson et al. 1997, Iverson et al. 2004, Dehn et al. 2007).

Ringed seals go through a marked annual cycle in weight that is related to their activity and food intake levels (Ryg et al. 1990, Ryg and Øritsland 1991). During the spring (April, May and into June) all age and sex groups (except pups of the year) are in a period of negative energy balance (e.g. Ryg et al., 1990). Most adult female ringed seals give birth during late March or early April (e.g. Lydersen 1995) and then go through an energically demanding lactation period (Hammill et al. 1991, Lydersen and Hammill 1993). During this period the adult males are also in a negative energy balance (Ryg and Øritsland 1991); they are busy defending underwater territories (see above – reproductive section) and interacting with the adult females as they become available for copulation. Following the breeding season all animals one year of age and older go through their annual molt; during this time their energy intake is low (Ryg et al. 1990). Being in negative energy balance implies that the seals are relying on energy stored in their blubber layer (Ryg and Øritsland, 1991), but these stores are not sufficient in this small pinniped species to cover all of the energetic costs of this part of the ringed seals annual cycle, so they do continue to feed at some level during the reproductive and molting periods (e.g. Ryg and Øritsland 1991, Lydersen 1995, Lydersen and Kovacs 1999). Most of the annual "fattening" of ringed seals takes place during the late summer, fall and winter.

7. Competition for prey

Dietary overlaps among carnivorous fish, seabirds, and arctic marine mammals are common, and ringed seals almost certainly face significant competition for food from other fish-predators. For example, the polar cod is a preferred prey species for most fish-eating high arctic predators. The fact that ringed seals are able to exploit this resource under the ice as well as at edges likely gives them a competitive advantage at least with young age classes of polar cod. But, there are few studies exploring the degree to which arctic marine mammals compete for prey. Dietary studies of harbor, bearded, and ringed seals in a small area on the west coast of Svalbard near Forlandsundet suggest that both primary (polar cod) and secondary prey species (Stichaeidae and Cottidae) are eaten by all three seal species coastally in this region. It would be difficult to conceive how these species would not be competing for these resources in this small geographic area.

A study in the Barents Sea by Wathne et al. (2000) explored the potential for competition between ringed and harp seals in the Barents Sea and found an almost 100% overlap in diet between the two species. However, harp seals were found to prey on significantly larger polar cod than ringed seals, which they take at deeper depth than the small cod consumed by ringed seals. These results suggest that there is some niche separation achieved and that these two species, in this area, exploit different fractions of the same resource.

8. Predators

It is unquestionable that the most important predator of ringed seals through most of the Arctic is the polar bear (e.g. Smith 1980, Davis et al. 1980, Stirling 1988). The majority of the polar bear's diet is ice-dependent seals, and ringed seals are the most numerous species consumed (e.g. Derocher et al. 2002). There are approximately 26,000 polar bears in the Arctic and each adult bear kills a seal every few days when it is hunting on the sea ice, resulting in 100s of thousands of ringed seals taken each year by bears (Stirling 1974, Stirling and Latour 1978, Stirling and Øritsland 1995, Stirling and Lunn 1997). Polar bears are specialists in hunting ringed seals on the spring fast-ice, taking both pups and older animals either from their lairs or breathing holes (Fig. 1a,b) (Stirling and McEwan 1975, Stirling and Archibald 1977, Lydersen and Gjertz 1986, Gjertz and Lydersen 1987b, Hammill and Smith 1991). Polar bear detect the presence of lairs under the snow easily, and either through smell or sound, know if the lair is occupied. If a seal is detected by a hunting bear in its lair, the polar bear will crash through the roof using its full weight delivered via the front paws and attempt to trap the seal before it gets into the water. Spring hunting of ringed seals in lairs is particularly important to female polar bears coming out of the den after many months of fasting. Polar bears also use a sit-and-wait strategy at holes, waiting for a seal to surface to breathe. Bears also hunt ringed seals from the water during the summer and autumn when the seals are hauled out on ice floes (personal obs.), and even when seals are swimming on rare occasions (Furnell and Oolooyuk 1980). Estimates of actual mortality rates of ringed seals due to polar bear predation are scarce, but bears seem to be successful in predation attempts on ringed seal lairs about 10% of the time (e.g. Gjertz and Lydersen 1986b, Lydersen and Gjertz 1986, Hammill and Smith 1991), and Hammill and Smith (1991) estimated that polar bears killed up to 44% of the estimated annual pup production in areas within Barrow Strait. The physical structure of the lair has some influence on predation success rate, with lairs that have thicker snow roofs being somewhat more protected (e.g. Furgal et al. 1996). Presumably the thicker roofs are harder to crash through so the seals get a bit of time to attempt to escape down the hole.

Walruses also eat ringed seals, though predation events by this predator are only rarely observed (Lowry and Fay 1984, Fay et al. 1990), presumably because most attacks occur in the water. Although it is not possible to quantify predation pressure by walruses on ringed seals, Muir et al. (1995) found that walruses in the Hudson Bay area showed organochlorine (OC) patterns that suggested "a regular seal-eating habit". Data from Svalbard for fatty acid signatures and contaminants in combination suggest that walruses in this area also eat ringed seals (Wolkers et al. 2006). Additionally, the facts that ringed seals seem to avoid walruses generally, and show fright responses in their presence, has been interpreted as predator avoidance (Kingsley et al. 1985, Gjertz 1990, Stirling 1997). A tour group traveling on Svalbard photographed a walrus consuming a freshly-killed ringed seal (and an attack on a bearded seal by a walrus was photographed during the event; other reports and incidents involving walruses eating seal carcasses are also reported; kmk).

Arctic foxes (*Alopex lagopus*) are also significant and effective predators of ringed seal pups early in the reproductive season in some areas (e.g. Smith 1976, Lydersen and Gjertz 1986). Foxes also scavenge ringed-seal kills made by polar bears both inshore and offshore, with some individuals specializing in this behavior and traveling long distances off-shore (Stirling 1988, Roth 2003, pers. obs.). Other canid predators include red foxes (*Vulpes vulpes*) and wolves (*Canis lupus*), which can be regionally important, particularly in years when there is little snow or very early melting (Lukin 1980 Andriashek et al. 1985, Andriashek and Spencer 1989). Burns (1970) also notes the domestic dog (*Canis familiaris*) as a predator of ringed seals, in addition to wolverines (*Gulo gulo*). In poor ice and snow years even avian predators such as ravens (*Vorvus corax*) and glaucous gulls (*Larus hyperboreus*) will take young ringed seal pups (Burns 1970, Lydersen and Smith 1989).

Killer whales (*Orcinus or*ca) are also frequently cited as being ringed seal predators (e.g. Stirling and Calvert 1979, Kovacs and Lydersen 2006), but the intensity of predation is difficult to assess. Presumably, ringed seals receive some protection from this predator via their natural tendency to be in heavily ice-filled waters. But, ringed seal parts have been found in killer whale stomachs, so they do take them on occasion (see MacLaren Marex Inc. 1979). Another aquatic predator, the Greenland shark, is also known to ingest ringed seals, and given the fresh character of one ringed seal reported in the stomach of a shark it appears that it was killed rather than scavenged (Ridoux et al. 1998). Furthermore, Fisk et al. (2002) suggest that high OC levels suggest that seals are a common food item for some Greenland sharks.

9. Human harvests

Humans have hunted ringed seals in the Arctic since the arrival of people to the region millennia ago (e.g. Murdoch 1893, Riewe and Amsden 1979). They are a fundamental subsistence food item for most coastally dwelling northern peoples. Their hides have been an important item for making clothing and other household items and have at various times been an important source of cash income for people in the Far North. Ringed seals have never been the subject of large-scale commercial hunting at the levels of harp or hooded seals because of their dispersed distribution and inaccessibility to hunters. But, many 10s of thousands of ringed seals are harvested annually by Inuit and other peoples of the Arctic Basin.

Harvesting pressure on ringed seals across the Arctic is highly variable. In Svalbard, Norway, licensed hunters can shoot ringed seals from 20 May – 20 March. The seals are protected during their breeding season. Additionally, ringed seals, like all other species, are totally protected in the national parks and nature reserves in Svalbard throughout the year. Sport hunting is permitted on the Norwegian mainland based on quotas for ringed seals and licensing of individual hunters. The numbers of ringed seals taken within Norwegian waters annually are quite low (a few hundred animals total). In Canada the ringed seal is an important resource in coastal communities and is taken in subsistence harvests in Labrador and throughout the Canadian Arctic. Reeves et al. (1998) reviewed the catch history for ringed seals in Canada. These authors suggested that annual removals were probably highest in the 1960s and 1970s when price for seal pelts were high, with catches might have exceeded 100,000 annually. Exact figures are not available, but recent catch levels in the 1980s and 1990s are believed to 50,000 – 65,000 animals per year. (*The Nunavut Wildlife Management Board did conduct a wildlife harvest study from 1998-2002 that included all northern seal species of seals.)* Ringed seals are also important in the diet of Native Alaskan people and are harvested in significant numbers. There are no restrictions to hunting, other than the general principle that human harvest should not induce declines in abundance of wildlife.

In Greenland, about 170,000 seals are taken annually (mainly harp and ringed seals). They are an important source of traditional food, and about 100,000 skins are sold for tanning (Jessen 2001). There are few national regulations in Greenland regarding seal hunting; there are four Executive Orders, two related to catch reporting, one banning importation of skins from pups, and a fourth that is specific to harbor seal hunting in spring. Overall for Greenland, the catch of ringed seals was about 43,000 in the 1950s, it peaked in the 1970s similar to the Canadian harvest at about 100,000 animals, and more recently has decreased somewhat to about 70,000 per year in the 1990s (Teilmann and Kapel 1998)

Seal harvesting in Russia operates on the basis of Total Allowable Catches (TACs) that are assigned by species and geographic region. Ringed seal TACs in 2002 by area were: Western Bering Sea 5, 900; Eastern Kamchatka 600; Sea of Okhotsk 28,000; Barents Sea 1,500 and; White Sea 1,100 (according to Government of the Russian Federation Decree 20 - November 2001 # 1551). Harvest statistics reported for Western Russia by Belikov and Boltunov (1998) suggest that maximum catches earlier in this century exceeded these TACs significantly, with maximum harvests of 8,900 in the White Sea (1912), 13,200 in the Barents Sea (1962), and 13,200 in the Kara Sea (1933). These harvests are thought to have dropped considerably in recent decades, though there are no available data. Reporting of harvest statistics and enforcement of TACs is difficult to manage in outlying areas, and the harvest of ringed seals in Eastern Russia is largely unknown.

10. Health (disease, parasites, contaminants)

Information on disease and health parameters is generally scarce for ringed seals (Tryland et al. 2006). To date, arctic phocids do not seem to have experienced any of the epizootic events that have caused massive declines in some species in recent decades along the European coast. No antibodies for the pathogen causing these events – a phocine distemper virus – have been reported in arctic seals (Dietz et al. 1989). Rabies has been reported in ringed seals, with the source of the infection likely being the arctic fox (Ødegaard and Krogsrud 1981). The patterns of antibody prevalence for *Brucella* spp. bacteria in ringed seals suggests that they are exposed to this pathogen at low prevalence, but over a wide area with sporadic infection taking place probably from enzootically infected animals such as the arctic fox (Nielsen et al. 1996, 2001, Tryland et al. 1999). Pneumonia, fungal dermatitis and focal necrosis of the liver, and eye disorders have also been reported in ringed seals (see Frost and Lowry 1981).

Trichinella has been documented in ringed seals from the Canadian arctic (Forbes 2000), although it is either rare or nonexistent in ringed seals at Svalbard (Larsen and Kjos-Hansen 1983). The lungworm *Otostongylus circumlitus* also occurs in ringed seals (Bergeron et al. 1997, Gosselin et al. 1998). Severe infections of this parasite could impact diving performance or even lead to death, but no detrimental effects on body condition have been associated with infection in the studies performed to date. Ringed seals can also be infected with the heartworm *Acanthocheilonema spirocauda*, particularly when they are young (Measures et al. 1997). Protozoan parasites that can cause severe diarrheal disease in mammals have been detected in ringed seal faces (*Cryptosporidium* spp. and *Giardia* spp) (Hughes-Hanks et al. 2005). Additionally, antibodies for the protozoans *Toxoplasma gondii* and *Neospora caninum* have been found in ringed seals; these protozoans have been recognized as a cause of marine mammal encephalitis (Dubey et al. 2003). The most abundant parasites of ringed seals are helminths of the gut tract. Nematodes, acanthocephalans, and cestodes are common, sometimes in significant numbers (Measures and Gosselin 1994, Hoberg and Measures 1995, Johansen et al. ms). Trematodes have also been reported from the liver and gall bladder (see Lydersen 1998). Sucking lice are common ectoparasites of ringed seals (pers. obs.). Although parasite burdens can be quite high in ringed seals, parasite infestations alone seldom debilitate otherwise healthy pinnipeds, though they may cause harm if the animals are weakened by other health conditions (Geraci and Lounsbury 1993).

Until the late 1970s or early 1980s the Arctic was perceived to be one of the last pristine wilderness areas in the world. It was thus a surprise when the presence of persistent organic pollutants (POPs) and other contaminants were documented in the arctic ecosystem. The most abundant contaminant residues detected in marine mammal tissues in the Arctic were polychlorinated biphenyls (PCBs), toxaphene, and chlordane (Wagemann and Muir 1984, Jensen 1991). The main sources of these pollutants were agriculture and industrial activities that occurred far from the Arctic (Tomy et al. 2000). Freshwater drainage followed by ocean current transport and global air-flow patterns from southern locales moving north are the major transport pathways for contaminants to come into the Arctic; contaminants are "dropped" from air currents when temperatures cool toward the Pole and they are also delivered from air masses via precipitation (see Barrie et al. 1992, Mackay and Wania 1995, Bard 1999, MacDonald et al. 2000, Kallenborn 2006). Another contaminant source that is important in some arctic regions is sea ice formed in the south and then transported north by ocean currents (e.g. Nies et al. 1999, Borga et al. 2002).

The organochlorine contaminants (OCs) were of particular concern because they are lipophilic ("lipid-loving") compounds that have potential detrimental effects on the health and reproductive performance of animals. Pathological changes in uterine physiology were documented in Baltic Sea ringed seals during the 1960s and 1970s that were attributed to high concentrations of chlorinated hydrocarbons (Helle et al. 1976, Helle 1980). Although contaminant levels in the Arctic are generally relatively low (see Holden 1972, Wolkers et al. 1998a), contaminant induced effects on physiological processes related to reproduction have been shown for top trophic animals in the Arctic. For example, ringed seals from the west coast of Svalbard show a clear negative relationship between the hepatic cytochrome P450 (CYP) enzymes involved in steroid breakdown (CYP 3A) and PCB burdens, illustrating that even at the observed low contaminant loads the metabolism of hormones may be influenced (Wolkers et al. 1998a,b). During years with poor feeding, the biological effects of even the relatively low levels of contaminants found in the Arctic may have increased significance (e.g., Muir et al. 1999), and high interannual variability in food resources is a common feature of the Arctic.

Given the findings for ringed seals, in addition to the high contaminant burdens documented for their primary predator the polar bear (e.g. Zhu and Norstrom 1993, Wolkers et al. 2004) in various arctic locales, it is not surprising that most health-related work with ringed seals in recent decades has been performed in relation to contaminant burdens. Additionally, ringed seals are a significant component of the diet of many coastal aboriginal communities in the Arctic, which puts human arctic residents at risk of exposure to lipophilic organochlorine contaminants because these compounds are persistent and they bioaccumulate through the food chain (Jensen 1991, Cameron and Weis 1993, Kuhnlein and Chan 2000). Contaminants have been detected in human breast milk and other body tissues in several arctic locales at levels that may warrant some concern (Kuhnlein et al. 1995, Polder et al. 2003). The developing fetus and breast-fed infants are likely to be more sensitive to the effects of OCs (and metals) than adults and are the age groups at greatest risk in the Arctic (Van Oostdam et al. 1999). The levels of POPs, mercury, and radionuclides are particularly high in communities that have traditional dietary habits, consuming a lot of marine mammal meat and blubber (Polder et al. 2003, Bonefeld-Jorgensen 1994).

The Arctic Monitoring and Assessment Program (AMAP) was established in the 1990s to address the risks and trends in contaminants in the Arctic. AMAP's top priorities include the following contaminant groups and issues:

- Persistent organic contaminants
- Heavy metals (in particular mercury, cadmium, and lead)
- Radioactivity
- Acidification and Arctic haze (in a sub regional context)
- Petroleum hydrocarbon pollution (in a sub regional context)
- Climate change (environmental consequences and biological effects in the Arctic resulting from global climate change)
- Stratospheric ozone depletion (biological effects due to increased UV-B, etc)
- Effects of pollution on the health of humans living in the Arctic (including effects of increased UV radiation as a result of ozone depletion, and climate change) as well as the combined effects of pollutants and other stressors on both ecosystems and humans

Ringed seals have been repeatedly recommended as an important species to use in the study of global patterns of dispersal of compounds and for documenting the general "health" of the Arctic (e.g. CAFF 1999, Luckas et al. 1990, Muir and Norstrom 1991, Hickie et al. 2005). Age and sex of animals sampled should be recorded because contaminant burdens are often higher in adult animals than in juveniles, and males tend to have higher toxic loads than females for many substances (e.g., Cameron et al. 1997, Hickie et al. 2005, Kucklick et al. 2006). Ringed seals have been selected as a key monitoring species in AMAP because of their broad circumpolar distribution, high abundance, high trophic status and their frequency in the diet of coastal peoples (AMAP 1998).

Some contaminants taken up by ringed seals, for example some oil components, can be metabolized and excreted without apparent deleterious effects (see Geraci and St. Aubin 1990). Ringed seals exposed to crude oil directly through immersion show irritation and transient damage to the eyes and also show petroleum residues in tissues, presumably via transfer across respiratory epithelium cells. Direct exposure for modestly protracted periods can be fatal, but it is hard to envisage this situation occurring at a large scale in the Arctic when animals are free to move out of oiled waters. Ingestion of oil-contaminated fish does not cause immediate deleterious effects, but residues accumulated in the blubber and other tissues may challenge liver and kidney function when the stored, tainted blubber is metabolized (Geraci and Smith 1976, Engelhardt 1983). Studies of ringed seals and oil pollution have not been particularly conclusive, but it is likely that the seriousness of oil contamination would most likely be mediated by the volume of oil involved in a spill, the type of crude, and the timing of the spill (McLaren 1990). Oil would likely have the greatest harmful impacts to ringed seals if it spread into breeding habitat where pups could become oiled and locally important food could be contaminated (Smith 1987).

Other compounds such as some PCBs and pesticides are known to be quite resistant to degradation, and are accumulated in fatty- tissues of animals. Seals occupy a high trophic level and hence are exposed to substantial amounts of these sorts of contaminants when they are present in the food chain (Muir et al. 1988, 1992, 1999). Most data are available for PCBs and DDT in ringed seals across the Arctic, and, although local variations certainly exist, the patterns of many accumulative substances are quite similar across relatively large regions (see Becker 2000, but also see Weis and Muir 1997, Aguilar et al. 2002, Hoekstra et al. 2003). Concentrations of most "legacy" OCs (PCBs, DDT, etc.) have declined significantly in biota at most locales in the Arctic and are generally less than half the levels they were in the 1970s in areas where time series exist for both seabirds and ringed seals (Addison et al. 1986, Addison 1992, Muir et al. 1988, 1999, Addison and Smith 1998, Riget et al. 2004, Braune et al. 2005). These trends are expected to continue with major decreases expected (filtering through to human populations) in the Arctic by 2030 in areas where values are currently high (Odland et al. 2003). A few exceptions in the declining trends seen in Canada and elsewhere include hexachlorocyclohexanes (HCH, THCH), chlordane, and toxaphene which have remained relatively constant, and chlorobenzenes and endosulfan, which are OCs that have shown increases over the last few decades in the Canadian Arctic (Muir et al. 1999, Braune et al. 2005). For most OCs, marine mammal tissues from the European Arctic are more contaminated than those from the Canadian and US Arctic, but this is likely a legacy of a more polluted European Arctic in the past because contaminant levels at low trophic levels do not differ across these regions currently (Borga et al. 2005). Generally speaking the Western North American Arctic has been less contaminated than the Eastern areas (e.g. Kucklick et al. 2006). High levels of DDTs and PCBS in the Western Russian Arctic suggest the presence of recent significant local sources in the Kara Sea region (Nakata et al. 1998; PCBs are still used in the production of electrical equipment and other application in Russia – Muir et al. 2000). However, OCs seem to be declining in the White Sea to the west of the Kara, though marine food webs in the White Sea region are still more contaminated than adjacent open ocean because of the proximity of urban/industrial areas (Muir et al. 2003).

Similar concerns to those above for POPs have also arisen regarding the health of ringed seals and humans and other animals that consume ringed seals because of heavy metal burdens in seals' tissues. The most commonly reported heavy metals in Arctic marine mammals include mercury, cadmium, lead, selenium, arsenic, and nickel (e.g. Wagemann and Muir 1984, Dietz et al. 1990, Skaare et al. 1994, Riget and Dietz 2000). The effects of these compounds are not specifically known, and toxic and mutagenic effects have not been unequivocally demonstrated in marine mammals (Melnikov 1991), but mercury poisoning is possible at high concentrations (see Tillander et al. 1972). High mercury levels in ringed seals in Lake Saimaa in Finland were reported as the probable cause of reduced pup production (Hyvärinen et al. 1997, also see Sipilä and Hyvärinen 1998). Ringed seals living in Strathcona Sound, Canada, near a lead-zinc mine have higher levels of lead in the liver and selenium in their muscles than seals from adjacent areas (Wagemann 1989), and cadmium levels are high in the liver of ringed seals from the eastern Canadian Arctic compared to ringed seals from elsewhere (Wagemann et al. 1996). Some regional differences in heavy metal concentrations in ringed seals are likely due to differences in natural background concentration (Wagemann et al. 1995, 1996, Riget et al. 2005). However, studies in the Canadian Arctic have found higher mean concentrations of mercury in recent ringed seal samples, compared to earlier collections (Muir et al. 1999, MacDonald et al. 2000). Rates of accumulation of mercury are also higher in present day animals compared to 10-20 years ago. Cadmium concentrations have shown no change over the last decade (Muir et al. 1999).

A suite of new-use chemicals previously unreported in arctic biota (e.g. polybrominated diphenyl ethers (PBDEs), short chain chlorinated paraffins (SCCPs), polychlorinated naphthalenes (PCNs), perfluoro-octane sulfonic acid (PFOS), and perfluorocarboxylic acids (PFCAs)) has recently been documented in arctic biota including ringed seals, but little information exists for these compounds in terms of spatial patterns, food web dynamics, or species differences in levels (e.g. Martin et al. 2004, Wolkers et al. 2004, Vorkamp et al. 2004, Bossi et al. 2005, Braune et al. 2005). Some of the PFC compounds appearance in Arctic fauna will be transitional, because of the 2001 ban on perfluoroocatane sulfonyl fluoride based compounds by 3M; levels in ringed seals are already showing rapid declines (Butt et al. 2007). Hexabromo-cyclododecane (HBCD) has reached measurable concentrations in even the lower trophic species and, not surprisingly, is found at higher levels in ringed seals and polar bears (Sørmo et al. 2006). Although levels of these compounds are currently low, there is concern because some are increasing rapidly in concentration in some areas (e.g., PBDEs, also see Riget et al. 2006), and some have unique toxicological properties (Braune et al. 2005). Some of these compounds were presumed to have low potential for long-range transport, so were not expected to make their way into arctic biota.

Some concern has been expressed regarding radionuclide exposures and concentrations in arctic marine species because of a number of accidents in arctic regions involving nuclear vessels and the presence of potential radioactive contamination sources in some arctic areas (see Brown et al. 2006). However, dose-rates associated with the presence of anthropogenically derived radionuclides for ringed seals measured in Svalbard, an area at risk because of its proximity to and location in the path of currents from the Russian coast, fall many orders of magnitude below the dose-rates at which any biological effects would be expected (Gwynn et al. 2006). Additionally, it has been clearly established that the levels of anthropogenic radiocnuclides in the Arctic are declining; most fallout was derived from nuclear weapons testing from 1945-1980 (AMAP 2003). Residents in the Arctic that are consumers of traditional food, however, are exposed to an approximately seven-fold higher radiation dose than non-consumers of traditional foods due predominantly to the bioaccumulation of natural radionuclides in the food chain (Van Oostdam et al. 1999).

Although concern is clearly warranted regarding contaminants in the Arctic in relation to ringed seals, it must be noted that concentrations of OCs and metals are generally below effects thresholds through much of the Arctic and there is little evidence that contaminants are having widespread effects on the health on artic organisms, with the possible exception of polar bears (Fisk et al. 2005). However, it is expected that the Arctic will become a major sink for organochlorines in the future; this process may already be significant for some compounds such as HCB and HCHs (Aguilar et al. 2002). Given the risk of exposure to "new" organohalogen contaminants, the fact that some regions are contaminated, and the risks of climate change stresses (see below), a better understanding of the effects of contaminant exposure is needed (Fisk et al. 2005).

B. Climate change in the Arctic and its impacts on ringed seals

1. Physical conditions

Cold temperatures, extensive seasonal variation in light and heat regimes, low overall levels of primary production (and solar radiation), extensive snow cover, permanent sea ice cover over large areas of the Arctic Ocean, and extensive formation of annual sea ice are defining characteristics of the Arctic (Stonehouse 1989). However, it has become clear that climate change is occurring and that the Arctic has already undergone significant physical environmental change due to global warming. Both multiyear and annually formed sea ice play important roles in the climate and ecology of the Arctic, but numerous studies have now documented a reduction in arctic sea ice cover over the past several decades (e.g. Francis et al. 2005, Moore 2006, also see ACIA 2005). This pattern is consistent with statistically significant surface warming that is particularly pronounced in fall and early winter, which is predicted to continue into the future based on climate models (e.g., Keup-Thiel et al. 2006). Both the seasonal and spatial extent of the Arctic's sea ice cover has been reduced, in addition to the ice thinning. Future predictions suggest that the Arctic will be subject to warming at a rate that is 1.5 to 2 times the global average and that the current climate trends are in general expected to accelerate during the coming century (Drinkwater 2005, Corell 2006, Kaplan and New 2006, Teng et al. 2006). Changes to atmospheric sea-level pressure, wind fields, sea-ice drift, and precipitation patterns are also suggested to have already occurred (see MacDonald et al. 2005). These changes will in turn lead to alterations in the hydrographic properties of the ocean, as well as the vertical stratification and circulation patterns (e.g. MacDonald et al. 2005, Drinkwater 2005). Ocean temperatures are likely to increase, with the arctic ice–ocean system changing faster than the global average (Zhang 2005). The changes that take place in the Arctic will impact the global climate system (e.g., Sewall 2005).

Sea ice extent, thickness, and seasonal duration are expected to continue to decrease, and many models predict an ice-free Arctic in summer by the year 2100 (Arzel et al. 2006, Dumas et al. 2006, Meehl et al. 2006, Parkinson 2006, Serreze and Francis 2006, Zhang and Walsh 2006). Change will not take place at identical rates across the Arctic; there will be considerable geographical variation in changing patterns of sea ice distribution, thickness, etc. (see Parkinson and Cavalieri 2002). The regional patterns that will occur in environmental change, in combination with potential variation in responses to particular stressors in individual sub-populations or stocks makes Pan-Arctic predictions difficult for a species (Tynan and DeMaster). However, the general, longer-term predictions for changes in sea ice will have consequences for all arctic animals that depend on sea ice as their breeding or foraging habitats (e.g., Stirling and Derocher 1993, Tynan and DeMaster 1997, Loeng et al. 2005).

2. Direct impacts of climate change on ringed seals

All ice-associated seals are vulnerable to changes in the extent, concentration, and quality of sea ice in the Arctic because they depend on the ice as a pupping, molting, and resting platform, and some seal species also do much of their foraging on ice-associated prey species (see Tynan and Demaster 1997, Barber and Iacozza 2004). Ringed seals are perhaps the most vulnerable of the high Arctic pinnipeds because so many aspects of their life-history and distribution are tied to sea ice. Ringed seals also require sufficient snow cover to construct lairs in which they rest, give birth, and care for their young; both ice and snow must be stable enough in the spring season to successfully rear young (Lydersen and Kovacs 1999). Premature break-up of the land-fast ice can result in premature separation of mother-pup pairs and hence high neonatal mortality (e.g. Smith and Harwood 2001, Ferguson et al. 2005). Spring rains or high temperatures in spring can cause the roofs of lairs to prematurely collapse leaving ringed seals subject to increased predation and exposure risks (Stirling and Smith 2004). Years in which insufficient snow fall takes place prior to breeding results in a similar phenomenon. Ringed seals in some areas are already showing relatively long-term downward trends in reproductive rates and survival of young that are thought to be linked to changes in sea ice conditions and other major ecosystems shifts, the pathways of which are poorly understood (Stirling 2005).

If the extremes predicted do indeed occur, and there is no summer sea ice in the Arctic, it is difficult to envisage how ringed seals will survive. Ringed seals do not normally haul out on land and performing this behavior would be a rather dramatic change to the species behavioral repertoire. Land-breeding would expose the ringed seals' small neonates to much higher predation rates, even in a best case scenario.

3. Indirect effects of climate change on ringed seals

Climate change poses risks to ringed seals beyond the changes that alterations to the physical environment will cause directly to their habitat. These include: changes to their forage base (species shifts, density shifts, and distributional shifts of prey species, etc.); increased competition from temperate species (ACIA 2005); increased predation rates from polar bears (Rosing-Asvid 2006) and arctic foxes (at least initially) as well as killer whales; increased disease and parasite risks (Harvell et al. 1999); greater potential for exposure to increased pollution loads (AMAP 2003, MacDonald et al. 2005); and impacts via increased human traffic and development in previously inaccessible, ice-covered areas.

i) Changes at lower trophic levels

Most pinniped species are relatively high trophic predators that live in regions with high productivity at least seasonally (see Bowen and Siniff 1999). They target oceanographic "hot-spots" such as ice-edges, shelf breaks, canyons, ridges, and plateaus where prey are attracted because nutrient mixing in the water column via up-welling or ice melt promote primary production. In Polar Regions the thermocline is usually weak early in the year, if one exists at all, and is not an effective barrier to upward mixing of nutrients from deeper waters. Although there is little direct information on specific locales where ringed seals forage, they are not expected to deviate greatly from the general pinniped pattern (i.e. targeting oceanographic hot spots). Some oceanographic measurements have been collected via temperature tags carried by ringed seals (Lydersen et al. 2004), and post-molting distribution data suggest that they target areas that contain 20-80% ice cover, whether these are coastal (near glacier fronts) or farther offshore in the free-floating pack (Freitas et al. MS). But, relatively little is known about key oceanographic features of importance to ringed seals, beyond the presence of sea ice. Ringed seals consume most of their annual energy in a period from late summer through to early winter (Ryg and Øritsland 1991), focusing on lipid rich, large, zooplankton and polar cod in their diet (see "Foraging" above).

A warmer climate and less extensive ice cover in the Arctic should result in an increase in primary production, on the order of 30-40 % greater overall production (Wassmann et al. 2006a), with a relatively greater contribution from pelagic plankton at the expense of ice algae (see Wassmann et al. 2006b). These climate-induced changes are likely to have profound impacts on the trophic structure and energy flow of the ice-pelagic-benthic systems in some arctic areas and will generally bolster the pelagic system at the expense of the benthic system (Carroll and Carroll 2003). An analysis of the fate increased production as a result of climate change in the central Arctic Ocean, suggests that the system has the capacity to capture this increased production via grazing capacity of expatriated mesozooplankton and hence produce increased food for higher trophic levels (Olli et al. 2007).

This positive picture of production increase in the Arctic is not universally shared, as there is a risk that reduced sea ice cover, warmer water, and a shorter sea ice season might promote stratification of the water column earlier in the season, which could disrupt the connection between phytoplankton production and consumption by grazing zooplankton (ACIA 2005). This sort of de-coupling, as well as other temporal mismatches, could have cascading effects through the food web. Additionally, there are concerns that a warmer climate with reduced ice cover will cause shifts in zooplankton community structure towards a smaller zooplankton size spectrum (e.g., favouring *Calanus finmarchicus* over *C. glacialis*), which may have cascading effects for arctic top predators (Falk-Petersen et al. 2006). There will be considerable geographic variability in what transpires under conditions of climate change across the different Arctic Seas, and hence variable impacts on food webs (see Wassmann 2006 for reviews). However, declines in overall production or changes to the abundance of traditional "arctic" adapted zooplankton and fish that carry large lipid stores could have negative impacts on ringed seals.

ii) Competition from temperate species expansions northward

Relatively little scientific work has specifically addressed competition among marine mammal species, but it is virtually certain that at least indirect competition takes place. Dietary overlaps among various species of seals (and whales) sharing a geographic range are quite common (see “Competition for prey” above). Wathne et al. (2000) documented niche separation between ringed seals and harp seals in the Barents Sea that fed on different size spectrums of prey, found at different depths, while targeting the same principle prey species. Further niche separation, as well as more direct competition would be expected within the marine mammal community in the Arctic as north-temperate species expand their ranges northward as the climate warms (ACIA 2005). Reduced ice cover will promote the rapid expansion of migratory routes for cetaceans that traditionally have avoided areas with summer sea ice cover. Some of these species are likely to consume small, pelagic schooling fish, overlapping with ringed seals. Competition would be expected to have heavier impacts on specialists, such as many of the arctic endemics, as opposed to species that tend to be more flexible generalists. It is difficult to evaluate how ringed seals would fare facing increased competition from other pinniped and cetacean species in an altered environment given our current level of uncertainty regarding future primary production levels in the Arctic and possible changes to the forage base in terms of species composition.

iii) Increased predation rates

During initial phases of reduction of sea ice during the spring season, it is likely that ringed seals will experience increased levels of predation from polar bears and arctic foxes. This has been documented to be the case with respect to polar bears during mild springs in the past (Rosing-Asvid 2006). Fox predation may also initially be high if ringed seals are more densely packed in a reduced area of breeding habitat along coastlines. However, this is dependent to some degree on snow cover; precipitation levels are predicted to increase with climate warming in the Arctic, but whether the precipitation falls as snow or rain is all-important to ringed seal mortality levels to these predators. During this transitory phase, polar bears and perhaps also foxes, might likely exhibit population growth, at least until the ringed seal population has been depleted. However, there is also the risk of a negative feedback system if predation is particularly strong in early spring in regions where ringed seals are the majority of the polar bears’ diet. This could occur because the overall energy intake of the bears could be reduced if too many ringed seals pup were taken very early in the nursing period; ringed seals pups are 7-8 times more energy-rich at the end of lactation compared to when they are newborn. So, a spring feeding boom could actually result in an increase in starving bears late in the season (Rosing-Asvid 2006). Arctic foxes also could be affected, but they are less likely to be heavily impacted by ringed seal population reductions, because they probably would shift to eating coastal birds and other terrestrial prey (Roth 2003).

Killer whales are known to prey on ringed seals, but it is uncertain how much mortality is attributable to this marine predator. The ringed seals’ tight association with sea ice likely affords it considerable protection. However, when the seasonal sea ice retracts, it is likely that killer whales will expand their range northward and increase in abundance in arctic waters. Killer whales have been shown to be capable of having large impacts on marine mammal populations (Williams et al. 2004), and were likely the cause of recent, severe reduction in sea otter (*Enhydra lutris*) populations in Alaska (Estes et al. 1998), and perhaps some pinniped populations as well (Bhargava 2005).

iv) Increased risk – disease, parasites, contaminants and human activities

Warmer water temperatures in combination with increased frequencies of contact with potential hosts of pathogens and parasites via range shifts of other marine species will put ringed seals at risk (see Harvell et al. 1999). Climate-mediated physiological stress may also contribute to the problem, compromising host resistance and increasing the possibility of contracting disease or experiencing damage via parasite infections.

Changes in contaminant pathways to, within, and from the Arctic are almost certain to occur under the influence of global climate change. Additionally, it is likely that there will be increased local releases of contaminants with increases in human populations in northern regions. Agriculture and silviculture will likely spread northward, influencing the arctic drainage basin. Climate change may promote the spread of insect pests globally, forcing some countries to re-introduce or increase the use of pesticides. The significance of contaminants as added stressors to predators already suffering from habitat and ecosystem change, while widely suspected, is not confidently understood (AMAP 2003). Key species and study areas in this latter context include marine mammal populations (particularly seals and bears) from the Kara Sea, Franz Josef Land, Svalbard and Hudson Bay (AMAP 2003).

Other human activities are also likely to change in the Arctic as climate change proceeds (see AMAP 2003 for a review) that pose variable risks to ringed seals. Commercial fisheries will expand northward into the Arctic, potentially altering food web structure in the oceans. Shipping will be enhanced, increasing the risks of oil contamination, habitat disruption, and ocean noise. Marginal seas clear of ice for a large portion of the year will also encourage increases in tourism, oil exploration, and other industrial activities – each of which brings with it associated contaminants and potential for disruption of wildlife behavior. Oil development activities have been shown to reduce the densities of ringed seals somewhat at a local scale in some areas and create noise that is audible to ringed seals over distances of up to 10 km, but current levels of activities are judged to be unlikely to have large-scale population effects (Kelly et al. 1988, Davis et al. 1991, Moulton et al. 2002, 2003, 2005, Blackwell et al. 2004).

II. Developing an international ringed seal monitoring program

A. Reason for selection of ringed seals

Ringed seals (*Phoca hispida*) occupy a key ecological role in Arctic ecosystems. They are the most numerous and widely distributed high Arctic pinniped species, with a world population that currently probably numbers in the millions. Ringed seals are found in virtually all seas and oceans encircling the North Pole. These seals are a major trophic link in arctic and sub arctic ecosystems (Lowry et al. 1980). They are the main prey species of polar bears (*Ursus maritimus*), and the most important natural resource for many indigenous people in coastal areas of the circumpolar Arctic. Despite the ecological and subsistence importance of this species, knowledge of stock identities, trends in population sizes, production rates, population parameters, and population condition status ("health") is generally sparse. Knowledge of such trends, over a significant time scale, is essential in order to understand the dynamics of the Arctic ecosystem. Marine mammals such as ringed seals that are totally dependent on the sea ice environment have, not surprisingly, been identified as being sensitive to the likely impacts of climate change (Stirling & Derocher 1993; Tynan and DeMaster 1997).

The potential effects of climate change on polar ecosystems is becoming of paramount concern. Scenarios have been put forward, predicting declines in virtually all ice-dependent arctic marine mammal populations. At a time when human activity is believed to be having exponentially increasing negative impact on populations within the Arctic, it is essential that we conduct basic monitoring activities of key ecosystem components. Because of their ubiquitous occurrence, availability for sampling, sensitivity to ice conditions, and importance within the arctic ecosystem, ringed seals have repeatedly been recommended as ideal subjects for circumpolar monitoring of arctic marine systems. Both the international programs CAFF (Conservation of Arctic Flora and Fauna) and AMAP (Arctic Monitoring and Assessment Programme) have specifically requested that all of the Arctic countries launch scientific monitoring program on ringed seal population structure, trends in abundance, vital rates and age structures because of this species value as an "indicator species" for monitoring global climate change and contaminant patterns.

B. Current status of ringed seal monitoring in the Arctic

The only arctic country that currently has a national program for ringed seal monitoring is Norway. This programs first active field work commenced in 2002 in Svalbard. Ringed seals in this region have been the subject of a series of research projects over the last 15-20 years. Studies conducted in the 1980s included work on demographic population parameters, diet, habitat use, reproductive and general ecology, as well as abundance determinations for local sub-populations within several fjords. More recently, in the 1990s, ringed seal research in Svalbard has focused on reproductive energetics, diving behavior and physiology, and contaminant burdens. This body of research provides a basis on which to build a meaningful data time series that will permit assessment of population and ecological trends, but the data collected prior to 2002 did not have monitoring of this population as its primary purpose. Similar "sets" of research data exist from the Alaskan, Canadian and Greenlandic Arctic that will be useful in a time-series context when monitoring is established (see Section I).

The Norwegian Polar Institute (NPI) began its simple monitoring program for ringed seals as part of MOSJ (Monitoring of Svalbard and Jan Mayen; http://mosj.npolar.no) in 2002. It includes the following parameters for this species:

- density and abundance of ringed seals in selected fjords in Svalbard;
- population parameters determined in 1981-82 and 2002 and beyond (age structure and vital rates);
- diet on a local basis;
- condition and "health" status (blubber-reserves, serum chemistry) of the ringed seal population; and

- contaminant burdens (POPs, heavy metals, toxaphenes) and exploration of (less expensive) biomarker methods for long term monitoring of contaminants.

Among pinnipeds, harp seals, hooded seals, walrus, and the red-listed population of arctic harbor seals on Svalbard are also included in MOSJ. Cetacean monitoring in MOSJ currently includes only NPIs cetacean sightings program for bowhead whales, white whales, and narwhal. It must be noted however, that financial backing for this monitoring system is not currently secure.

Canada has meetings planned in 2007 to develop an arctic monitoring plan, which might include ringed seals. The other arctic nations do not currently have plans with respect to monitoring ringed seals despite CAFF's specific request to develop such plans in each nation in 2000.

The lack of focused, long-term monitoring of ringed seals among the arctic countries is surprising, given the ecological and subsistence importance of this species and the fact that they have repeatedly been recommended as high priority subjects for circumpolar monitoring of arctic marine systems. However, ringed seals have never been a species of large-scale commercial interest because of their dispersed, high arctic distribution; hence it is not easy to finance research programs for this species in many arctic countries. Additionally, their basic biology makes them a logistical challenge as they are inaccessible in many ways for much of the year, and their wary nature makes them quite difficult to capture for live studies of ecology and in-the-wild physiology, etc. However, research teams around the Arctic have overcome many of the challenges in working with this species, and it is timely to begin comprehensive monitoring. A focused (financed) international plan with simultaneous data collection according to standard protocols across the Arctic is required to monitor ringed seals effectively. It is important to commence monitoring as soon as is possible, given that the Arctic is already clearly showing signs of experiencing climate change.

C. Candidates for parameters to monitor

1. Ringed seal parameters

Abundance of ringed seals (and trends in abundance)
Lair densities and pup production rates (including phenology of reproduction)
Population parameters (age structure and age specific mortality/survivorship)
Pup production
Pup growth and first-year survival rates
Seasonal movement patterns
Ringed seal diet (seasonal, inter-annual, and comparative geographic basis)
Predation rates (seasonally (spring, summer))
Body condition and "health status" (nutrition, disease, parasites)
Contaminant exposure and contaminant-induced biological effects (follow AMAP)

2. Affiliated biological parameters

Predator abundances, densities, distributions
Prey abundance (particularly polar cod abundance and distribution)
Competitor surveys (assessment of competition)

3. Desired physical/environmental parameters

Sea ice phenology
- Time of formation
- Time of break-up

Sea ice characteristics
- Maximum depth
- Seasonal extent

Snow cover on sea ice
- Seasonal snow depth (critical pre-breeding period especially important)

General meteorological monitoring
Frequency and timing of extreme weather events – particularly winter/spring rain
Oceanographic features important to ringed seals (ocean color (spring, summer and fall), others?)

4. Human activities

Harvest rates
Industrial development (oil and gas exploration, extraction)
Tourism
Commercial fishing

D. Issues to be discussed at the workshop with respect to parameters

Localities to be monitored (intensively – at intervals)
Intervals for sampling
- Annual collection (tissue collections – contaminants, health etc.)
- 3 – year intervals – analyses of age structure in hunts etc.
- 3- year intervals – diet analyses
- 5 year intervals – surveys

Methods to be used internationally to collect data on selected parameters

E. Possible additional issues to develop or discuss at the workshop

Limitations in the methods
Analyses of the data
Annual costs
Quality assurance
Desired length of time series
Originating institutions (responsible for delivery to CAFF, IUCN?)
Data availability
Form of reporting
Relevant links (to Web pages)

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