Supplementary Material

# Supplementary Tables

***Table 1****: Reports of range shifts as climate-change footprints in Arctic marine ecosystems. \* indicates that the criteria for a ‘footprint’ in a strict sense are not fully matched but the report is still noteworthy. “New” indicates a first-time observation. “Continuing” indicates that a reported footprint has been confirmed, albeit not necessarily in a time series study.*

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| --- | --- | --- | --- | --- | --- | --- |
| **Biota** | **Parameter** | **Region** | **Driver** | **Footprint** | **Timespan** | **Source** |
| **Phytoplankton** | General | Arctic Ocean | Earlier sea-ice retreat | Northward shift of spring bloom location | 2003-2013 | Renaut et al. (2018) |
| *Emiliania huxleyi* | European Arctic | Stronger surface currents | Northwards shift | 1993 - 2016 | Oziel et al. (2020) |
| *Emiliania huxleyi* | Barents Sea | Warming and shift of Polar Front | Northward shift | 1998 - 2007 | Neukermans et al. (2018)\* |
|  | Phytoplankton | Barents Sea | Reduced sea-ice extent | North- and eastward shift | 1998 - 2014 | Oziel et al. (2017) |
| **Zooplankton** | *Themisto compressa* (Amphipoda) | Central Arctic Ocean to Eastern Fram Strait | Warming | New arrival and reproductive success | 2000-2012 | Kraft et al. (2013) |
| *Calanus glacialis* (Copepoda) | Chukchi Sea | Several, e.g., prolonged growth season and shorted development cycle | Northward range shift | 1980-2014 | Feng et al. (2018) |
| *Pandalus borealis* | Northeast  Greenland | Advection | Northward range shift | 2001-2017 | Andrews et al. (2019) |
| *Thysanoessa raschii* | Kongsfjorden | Probably climate change | Northward range shift | New | Buchholz et al. (2012) |
| *Gammarus oceanicus* | Svalbard Waters | Advection and expansion of existing colonies | Northward range shift | 1980 – 1994 and 2008 till 2016 | Weslawski et al. (2018)\* |
| *Periphylla periphylla* (jellyfish) | Barents Sea | Increased Atlantic inflow | Northward range shift | News | Geoffroy et al. (2018) |
| Benthos | *Mytilus* spp. | Svalbard Waters | Changed environmental conditions | Continung northward trend and reproductiv sucess | Continuing | Leopold et al. (2019) |
| **Fish** | Fish community | Barents Sea | Warming | Northward range shift | 2004-2012 | Fossheim et al. (2015)\* |
| Several fish species | Bering Sea | Possibly climate change | Northward range shift | First since the 70s | Rand & Logerwell (2011) |
| Atlantic mackerel | Isfjorden | Warming | Northward range shift | New | Berge et al. (2015b) |
| Atlantic cod, snake pipefish & haddock | Svalbard | Warming | Continuing northward range shift | New | Renaud et al. (2012) |
| Atlantic cod, beaked redfish, capelin | Northeast Greenland | Advection | Northward range shift | 2001-2017 | Andrews et al. (2019) |
| Pacific sand lance | Beaufort Sea | Warming | Northward range shift | New | (Falardeau et al., 2014; Suzuki et al., 2015) |
| Pacific sand lance | Canadian Arctic Archipelago | Warming and sea ice change | Continuing north- and eastward range shift | Continuing | Falardeau et al. (2017) |
| Bluefin tuna | East Greenland | Warming | Northward range shift | New | MacKenzie et al. (2014) |
| **Benthos** | Benthic biomass | Transect from Bering to Chukchi Sea | Warming and sea ice retreat | Northward range shift | 1998-2018 | Grebmeier et al. (2018) |
| **Birds** | Short tailed albatross, northern gannet & rhinoceros auklet | Eastern Chukchi Sea and Beaufort Sea | Reduced sea ice | Northward range shift | New | Day et al. (2013) |
| **Mammals** | Polar bear | Baffin Bay | Reduced Sea ice | Northward range shift and range concentration | 90s and 2000s | Laidre et al. (2018b) |
| Bowhead whale | North-West Passage | Reduced Sea Ice | First recorded whale passage | New | Heide-Jørgensen et al. (2012) |
| Blue whale, mink whale, fin whale humpback whale | Svalbard | Warming | Northward range shift | 2002-2014 | Storrie et al. (2018) |
| Cetacean community | Iceland | Changing environmental parameters and feeding response | Northward shift | 1987 - 2009 | Víkingsson et al. (2015) |

***Table 2****: Reports of changes in production and stock size as climate-change footprints in Arctic marine ecosystems. “\*” indicates that the criteria for a footprint are not fully matched, too short time period, but still noteworthy. “New” indicates a first-time observation.*

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| **Biota** | **Parameter** | **Region** | **Driver** | **Footprint** | **Timespan** | **Source** |
| **Phytoplankton** | Primary production | Arctic Ocean | Longer open water season | Increased primary production | 1998-2009 | Arrigo & van Dijken (2011) |
| Primary production | Arctic Ocean | Increased light availability due to sea ice loss | Increased primary production | 1998-2010 | Bélanger et al. (2013) |
| Primary production | Arctic Ocean | Changed Cloud Cover | Damping the rate of increasing PP | 1998-2010 | Bélanger et al. (2013) |
| Primary production | Arctic Ocean | Longer growing season/ reduced sea Ice extent | Increased net primary production | 1998-2012 | Arrigo & van Dijken (2015) |
| Primary production | Pacific Arctic | Possibly warming | Increased net primary production | 1950-2012 | Hill et al. (2018) |
| Primary production | Sub-Sectors of pan-Arctic | Earlier ice break-up | Increased Primary Production of spring bloom | 2003-2013 | Renaut et al. (2018) |
| Phytoplankton | Chukchi Sea | Thinning pack ice | Increased under ice phytoplankton bloom | New | Arrigo et al. (2012) |
| Phytoplankton | North of Svalbard | Most likely Thinning ice | Pack-ice associated red tide | New | Olsen et al. (2019) |
| **Zooplankton** | Zooplankton biomass | Chukchi Sea | Increased inflow of Pacific waters | Increase, mainly *Calanus glacialis* | 1946-2012 | Ershova et al. (2015) |
| Biomass of *Calanus glacialis* | White Sea | Increased Temperature and changed salinity | Increasing | 1964-present | Persson et al. (2012) |
| *T. libellula, Calanus finmarchicus,* euphausiids | Barents Sea | Changing water masses | Species specific in- or decrease of biomass | 1981-2010 | Dalpadado et al. (2012) |
| Euphausiid and Shrimp | Barents Sea | Increased Atlantic Water masses | Increased abundance | 1970-2009 | Johannesen et al. (2012) |
| Euphausiids | Barents Sea | Warming | Increased Biomass | 1980-2009 | Eriksen & Dalpadado (2011) |
| Euphausiids | Barents Sea | Warming | Increasing autumn biomass | 2000-2012 | Eriksen et al. (2016) |
| Ice-associated Amphipods | Pan-Arctic | Sea Ice Decline | Decreased ice-amphipods, mainly Gammarus wilkitzikii | 1977-2012 | Hop et al. (2021) |
| **Fish** | Species with northern affinity | Barents Sea | Warming and sea ice change | Decrease of cold adapted species | 2004-2012 | Fossheim et al. (2015)\* |
| Pacific sand lance | Central Canadian Arctic | Warming and sea ice change | First record and increasing abundance | 2011-2016 | Falardeau et al. (2017) |
|  | Deep-water fish | Eastern Greenland | Warming and changed species interaction | Stock decline for several species | 1998 - 2016 | Emblemsvåg et al. (2020) |
| **Benthos** | Changing in benthic species abundances | Chukchi Sea | Multifactorial influence | Changing Abundance | 2004-2012 | Grebmeier et al. (2015)\* |
| **Sea Birds** | Bird population | Hornsund | Glacier melt | Stabil bird population |  | Stempniewicz et al. (2017)\* |
| Bird populations | Arctic Alaska Gyre | earlier marine prey peak | No change, declining and increasing abundance, species specific | 1996-2011 | Thompson et al. (2012) |
| **Mammals** | Polar bear | Davis Strait | Seal population | Stable/  increasing abundance | Data analysis 35 years | Peacock et al. (2013) |
| Harp seal | White Sea | Sea ice decline | Increased pup mortality | 1993-2010 | Johnston et al. (2012) |
| Harp seal | White Sea | Increased seal pup mortality | Declining population | 1993-2010 | Johnston et al. (2012) |
| Harp seal | Northwest Atlantic | Likely declining sea ice | Increased abortion rate | 1954-2014 | Stenson et al. (2016) |
| Ringed seal | Hudson Bay | Multiple Stressors | Declining population | 1995 - 2013 | Ferguson et al. (2017) |
| Polar bear | Hudson Bay | Changed sea ice conditions | Declining population | 1984-2011 | Lunn et al. (2016) |
| Polar bear | Beaufort Sea | Changed sea ice conditions | Declining population | 2001-2010 | Bromaghin et al. (2015) |

***Table 3****: Changes in community composition as climate-change footprints in Arctic marine. \* indicates that the criteria for a footprint are not fully matched, too short time period, but still noteworthy*

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| **Biota** | **Parameter** | **Region** | **Driver** | **Footprint** | **Timespan** | **Source** |
| **Phytoplankton** | *Phaeocytis pouchetii* | Fram Strait | Warming (mostly not exclusively) | Shift to *P. pouchetii* dominated community | 1998-2011 | Nöthig et al. (2015) |
| Phytoplankton | Barents Sea | Multiple Drivers | Phytoplankton community shift | 2002 - 2018 | Orkney et al. (2020) |
| Sea ice protist | Arctic Ocean | Multiple Drivers | Declining diversity | 80s till 2010s | Hop et al. (2020) |
| **Zooplankton** | Copepods | West Spitsbergen Current | Warming | Shift to more boreal community | 2001-2009 | Weydmann et al. (2014)\* |
| Copepods | Fram Strait and Barents Sea brunch | Warming | Gradual change towards more boreal community | 2001-2014 | Gluchowska et al. (2017) |
|  | *Pseudocalanus* spp. | Northeastern Greenland | Changed sea-ice cover and freshwater content | Decreasing Pseudocalanus spp. | 2003-2015 | Middelbo et al. (2019) |
| **Benthos** | Benthic community changes | Two Arctic Fjords Svalbard | Reduced Sea Ice and Warming | Several community changes | 1980-2010 | Kortsch et al. (2012)\* |
| Benthic invertebrate community | Northern Bering Sea & Southern Chukchi Sea | Possibly higher water temperatures | Change to polychaete-dominated community | 2004-2012 & 1998-2015 | J. Grebmeier et al. (2018); J. Grebmeier & Cooper (2016) |
| Fish | Deep-water fish | Eastern Greenland | Warming and changed species interaction | Borealisation of deep-water fish community | 1998 - 2016 | Emblemsvåg et al. (2020) |
| Bird | Bird community | Eastern Chukchi Sea | Changed ice phenology | Change towards planktivorous bird community | 1975-2012 | Gall et al. (2017) |

***Table 4****: Changes in phenology as climate-change footprints in Arctic marine. \* indicates that the criteria for a footprint are not fully matched, too short time period, but still noteworthy*

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| **Biota** | **Parameter** | **Region** | **Driver** | **Footprint** | **Timespan** | **Source** |
| **Phytoplankton** | Phytoplankton | Arctic Ocean | Ice retreat | Earlier bloom offset | 1997-2009 | Kahru et al. (2011) |
| Phytoplankton | Arctic Ocean | Ice retreat | Earlier bloom offset resulting in increased PP | 1997-2015 | Kahru et al. (2016) |
| Phytoplankton | Arctic Ocean | Reduced Sea ice extent | New fall bloom | 1998-2012 | Ardyna et al. (2014) |
| Phytoplankton | Pacific Arctic | Interannual variation in phytoplankton size structure | New fall bloom | 2003 - 2017 | (Waga & Hirawake, 2020)\* |
| **Mammals** | Beluga Whale | Eastern Chukchi Sea | Sea ice freeze up | Delayed migration | 1993-2002 & 2004-2012 | Hauser et al. (2017) |

***Table 5****: Changes in physiology and body condition as climate-change footprints in Arctic marine ecosystems. \* indicates that the criteria for a footprint are not fully matched, too short time period, but still noteworthy*

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| --- | --- | --- | --- | --- | --- | --- |
| **Biota** | **Parameter** | **Region** | **Driver** | **Footprint** | **Timespan** | **Source** |
| **Zooplankton** | Calanus | West Spitsbergen Current | Prolonged growth season and warming | Faster development | 1980-2014 & 2001-2011 | Feng et al. (2018a)\*; Weydmann et al. (2018) |
| *Aglantha digitale* | West Spitsbergen Current | Warming and increased Salinity | Faster development | 2003-2014 | Mańko et al., (2022) |
| **Fish** | Saffron Cod | Bering and Northern Chukchi Sea | Changing temperature or sea ice retreat | Higher instantaneous growth rate and smaller body size | Data from 2012 and ´76 &´79 | Helser et al. (2017)\* |
| **Birds** | Little auk | East Greenland | Decreasing sea ice | Decreasing body conditions | 12 years | Amélineau et al. (2019) |
| Red-legged kittiwakes | St. Georg Island | warming | Decreased nutritional stress | ~100 years | (Will et al. (2018) |
| **Mammals** | Polar bear | Hopen Island/ Svalbard | Changed sea ice regime | Lower body conditions and reduced reproductive success | 1979 - 2010 | Derocher et al. (2011) |
| Polar Bear | Hudson Bay | Changes sea ice phenology | Declining body conditions | 1980-2012 | Obbard et al. (2016) |
| Ringed seal | Hudson Bay | Changed prey and increased competition | Declining body conditions | Min. 2003-2013 | Chambellant et al. (2012); Ferguson et al. (2017) |
| Ringed seal | Masoyak | Increased predation pressure | Declining body conditions | 1992-2011 | Harwood et al. (2012) |
| Harp seal | Barents Sea | Increased resource competition | Declining body conditions | 1992-2011 | Øigård et al. (2013) |
| Bowhead whale | Pacific Arctic | Multiple climate change related factors | Increasing body conditions | Two decades | George et al. (2015) |
| Polar Bears | Western Hudson Bay | Earlier ice break-up and longer open water period | Decreased energy content | Three decades | Johnson et al. (2020) |

***Table******6****: Changes in behaviour as climate-change footprints in Arctic marine. \* indicates that the criteria for a footprint are not fully matched, due to a too short time period, but still noteworthy.*

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| --- | --- | --- | --- | --- | --- | --- |
| **Biota** | **Parameter** | **Region** | **Driver** | **Footprint** | **Timespan** | **Source** |
| **Birds** | Little Auk | Atlantic Arctic | Increased temperature and reduces sea ice | Changed forage behaviour | 2004-2015 | Amélineau et al. (2019) |
| **Mammals** | Polar bear | Eastern Greenland and Baffin Bay | Changed ice regime | Change in territory use | From the 90s and 2000s | (Laidre, Born, et al., 2018a; Laidre et al., 2015; Laidre, Stern, et al., 2018b) |
| Polar bear | Hudson Bay, Chukchi Sea and Southern Beaufort Sea | Changed sea ice regime | Increased land use | 1986-2014 | Atwood et al. (2016); Cherry et al. (2013); Rode et al. (2015) |
| Polar bear | Baffin Bay& Kane Basin | Changed snow and sea ice conditions | Changes in dents location and timing | 1991-1997 and 2009-2015 | Escajeda et al. (2018) |
| Polar bear | Svalbard | Changed Sea ice | Increased bird nest predation | 70s 80s and now (2002-2004 & 2010-2013) | Hamilton et al. (2017); Prop et al. (2015) |
| Polar bear | Spitsbergen | Decreased seal availability | New hunting behaviour | First report | Stempniewicz et al. (2014) |
| Polar bear | Beaufort and Chukchi Sea | Increased ice drift | Increased activity time or faster movement | 1987-2013 | Durner et al. (2017) |
| Ringed seal | Svalbard | Changed ice regime | Multiple behaviour effects | 2002-2003 and 2010-2012 | Hamilton et al. (2015)\* |
| Ringed seal | Svalbard | Changed ice regime | More time at tide glacier fronts | 1995-2016 | Hamilton et al. (2019) |
| Beluga Whale | Svalbard | Changed Ice regime and changed Atlantic water influx | Less time a tide glacier fronts | 1995-2016 | Hamilton et al. (2019); Vacquié-Garcia et al. (2018) |
| Bowhead whale | Pacific Arctic | Reduced sea ice extent | More time in open water away from coast | 1982 - 2014 | Druckenmiller et al. (2018) |

**Table 7**: Reports of changes in diets as climate-change footprints in Arctic marine ecosystems. *\* indicates that the criteria for a footprint are not fully matched, too short time period, but still noteworthy*

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| --- | --- | --- | --- | --- | --- | --- |
| **Biota** | **Parameter** | **Region** | **Driver** | **Footprint** | **Timespan** | **Source** |
| **Fish** | Greenland halibut | Cumberland Sound | Multiple factors | Towards forage fish | (1990-2002 & 2005-2012 | Yurkowski et al. (2018) |
| **Birds** | Thick-billed murres | Transect between Akpatok Island and Prince Leopold Island | Multiple factors | Reduced polar cod | Data from 70s and 80s and present | Provencher et al. (2012) |
| Black-legged kittiwake and Thick-belled murres | Pribilog Islands | Multiple factors | Shift towards pollock | 35 years | Renner et al. (2012) |
| Black-legged kittiwake | Kongsfjorden | Immigrating boreal fish | Increased Atlantic Fish | 1982-1987 & 1997-2016 | Vihtakari et al. (2018) |
| **Mammals** | Polar bear | Eastern Greenland | Lower Northern Atlantic oscillation | Change | 1984-2011 | McKinney et al. (2013) |
| Beluga whale | Cumberland Sound | Multiple factors | Towards non-endemic species | 22 years | Yurkowski et al. (2018) |
|  | Narwhale | Baffin Bay & northern Hudson Bay | Sea Ice and migratory changes | Reduction of Capelin & increase of Greenland Halibutt | 1982 - 2011 | (Watt & Ferguson, 2015)\* |

***Table 8****: Changes in competition structure and pathogen load as climate-change footprints in Arctic marine ecosystems. “New” indicates a first-time observation*

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| **Biota** | **Parameter** | **Region** | **Driver** | **Footprint** | **Timespan** | **Source** |
| **Fish** | Polar and Atlantic cod | Svalbard | Competition | Partly diet overlap | New | Renaud et al. (2012) |
| Capelin and Polar cod | Western Canada | Competition | Pronounced diet overlap | New | McNicholl et al. (2018) |
| **Birds** | Thick-billed murre | Hudson Bay | Warming | Increased parasitism | 1970/80 to present | Gaston & Elliott (2013) |
| **Polar Bear** | Polar bear | Southern Beaufort Sea | Increased land time | New and increased pathogen exposure | New | Atwood et al. (2017) |