

Are cruise ship trips to Antarctica still acceptable? A careful consideration

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Reports, discussions, opinions

Abstract

Background: Cruise tourism to Antarctica has increased extensively in recent years. It can be assumed that this has had an impact on the environment.

Methods: Searches were conducted in international specialist databases (e.g. Medline, Web of Science) and electronic media using various combinations of the keywords 'Antarctica', 'tourism', 'cruise ships', 'environment', 'damage' and 'pollutants' (January 1990 to January 2026). Only electronic media that met standard scientific requirements (authorship, source references, etc.) were included. The search results are summarised and evaluated.

Results: There is a significant impact of tourism on the region. This includes, among other things, the disruption of breeding grounds, the release of various types of pollutants, the introduction of non-native species, soil compaction and other factors. The extent of the damage increases with the number of visitors.

Conclusion: Due to its extreme ecological sensitivity, Antarctica is not suitable for large-scale tourism. The continent should be reserved for scientific research and otherwise strictly protected. Practically everything that tourists can see and experience there can also be seen in less sensitive locations. At the very least, tourism should be much more strictly regulated and monitored than it has been to date, and the number of visitors should be drastically reduced.

Keywords

- tourism
- impact
- nature conservation
- pollution
- cruise ships

Contribution

- A – Preparation of the research project
- B – Assembly of data
- C – Conducting of statistical analysis
- D – Interpretation of results
- E – Manuscript preparation
- F – Literature review
- G – Revising the manuscript

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Introduction

Ecologically Antarctica is a highly sensitive region and some specific climate factors which only occur here make the situation even more critical.^{1,2} The simple presence of humans may have a long lasting impact here. A footprint in Antarctic moss may need 100 years to recover and a lost piece of plastic may need 1,000 years or more for decomposition. Small volumes of discharged oil may kill rare plants or animals,³⁻⁵ and this takes place in a region where 60% of all land living creatures and 70% of all marine diversity is endemic.⁴ Plants, animals and tourists struggle about the 2% of ice free land mass.^{4,6} Numerous species are already struggling to survive without the influence of tourism.⁷ It is expected that the number of king penguins will decline by 90% by the end of the century due to global warming and the associated melting of ice.^{6,8} The more tourists visit the region, the higher the probability will be that the region visited will be damaged by some means or others.³ Considering the geographical and meteorological special features we try to make a careful consideration whether tourism to Antarctica is acceptable or not. Public data about cruise ships will be taken into account.

We have the following personal preconditions: We do not intend to present an alarmist perspective. We also do not believe without proof anything which has been published by the different pressure groups or science. Numerous ecological crises have been solved in the past through technology, science and political will: The European wood died by acid rain in the 60's and 70's—the problem was solved surprisingly fast by obligatory filter systems, catalysators, and desulfurisers which became industrial standard.⁹ In the 70's the Club of Rome feared the end of several resources like copper and lead.^{10,11} Nobody talks about that now: Today we are recycling more than 90% of the copper and nearly 100% of the lead. By this we'll have enough for centuries. Unfortunately it must be stated that the knowledge of technology and science will be used not before it is virtually too late. And this is becoming increasingly critical since denial of global warming is becoming more and more widespread and measures to protect the climate are being delayed, restricted or even reversed. The paper aims to encourage the reader to carefully consider about cruise ship tourism in highly sensitive regions. It should be taken into account that based on international contracts it is necessary, that in and around Antarctica “no activity shall be done which includes an inherent tendency to change the environment in any way until activities are fixed which are able to estimate such changes before

and effective procedures are established to control it” (Antarctic Treaty Consultative Meeting, ATCM VIII-13 und ACTM IX.5).

Special conditions of the Antarctic environment

Meteorology

In the northern as well in the southern polar region a quite constant high pressure system exists. At moderate latitude there is an adjacent low-pressure region. The winds flowing off the high-pressure system are deviated by Coriolis forces. This causes quite stable southeast and east winds around Antarctica (“circumpolar winds”) which are limited more northward by western winds. On the northern hemisphere this is principally the same, but here big land masses (Greenland, Canadian Arctic, northern Russia) are disturbing the system. By this a stable rotating wind system as it is the case around Antarctica does not exist. This stable system makes Antarctica an “enclosed environment” (Figure 1) while in the North there is a regular exchange of air masses with lower latitudes by large-scale turbulences. Already at the time of the clippers these windy southern regions were called the “roaring forties” and captains who mastered their ship around Cape Horn were highly respected. A very good drawing of these wind systems for January and July may be found at <https://www.blauwasser.de/globale-windsysteme>. Details about the system, its dynamics and stability may be found at the information provided by the Australian Government (Australian Antarctic Program, <https://www.antarctica.gov.au/about-antarctica/ice-and-atmosphere/atmosphere/winds-waves-and-temperatures/from-the-katabatic-to-the-polar-vortex/>). An impressive visualization has been published by NASA (2024) at <https://svs.gsfc.nasa.gov/31329/>. It shows that Antarctica is literally isolated from the rest of earth's atmosphere and that there is a low exchange of air masses only.

The situation at Antarctica's coast becomes even more critical by the continental Antarctic wind system. The winds coming down from the ice shield and its high elevation blow to the coast. Therefore any emission cannot escape (and be diluted), neither to the north because of the circumpolar winds which block the exchange of air masses with lower latitudes nor to the south by the winds coming from this direction (Figure 1). In consequence emissions concentrate at the ecologically critical coastal region with its numerous but small breeding grounds.

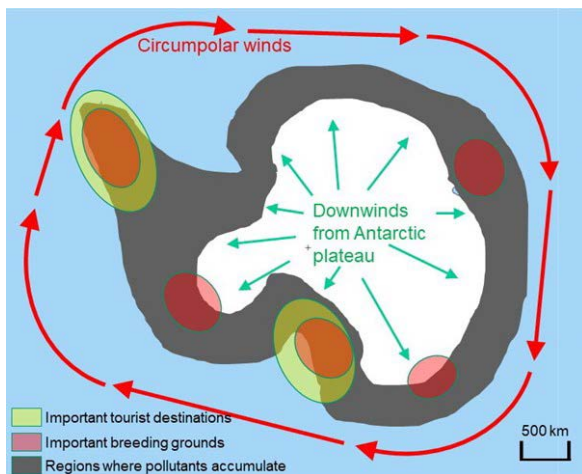


Figure 1. Antarctic wind systems, pollution and breeding grounds (drawn by T. Küpper)

A valid risk assessment for this narrow environment is almost impossible. We simply do not know enough about Antarctica's nature. This is also true for the region called "Amundsen Sea Low", a stormy region southwest of Antarctic Peninsula. But these storms do not significantly support the dilution of contaminants. Summarising the atmospheric conditions cause that any pollution will be locked within a narrow region along the coast.

Temperatures and UV-light

Because of several environmental factors (permanent low temperatures, low UV radiation etc.) there is only minimal degradation of contaminants in Antarctica. As a first approximation the effect of contaminant discharge may be called "permanent" there.¹²

Cruise ships—some facts

It is indisputable that most cruise ships still use toxic heavy oil. Recent research showed only a few ships are propelled by LNG (Liquified Natural Gas), even if their number increases: While there was only one ship in 2018, the Aida Nova, there are 23 reported in January 2026 (<https://www.cruisemummy.co.uk/lng-cruise-ships/>). However, this corresponds to about 5.4% of all cruise ships only (end of 2024, see <https://www.cruise-tricks.de/wie-viele-kreuzfahrtschiffe-gibt-es-weltweit/>).

Heavy oil is a residuum from the processing of mineral oil and contains several impurities, also sand and ashes. When burned several toxic substances are set free, e.g. carbon dioxide, carbon monoxide, nitrogen oxides (NO_x), sulfur dioxide, particulates, volatile organic compounds

(VOCs) and many others.¹³ All these substances significantly impair the biogeochemical cycles.¹⁴ C. Busseau, a shipping expert of Greenpeace, has summarized it as follows: "Principally ships (also freight, author's comment) are floating garbage incineration plants".¹⁵

Larger vessels which are favored by the operators for commercial reasons principally cause higher risk for the environment, not only by direct discharge of several substances.¹⁵ In the case of an accident, a crash into an uncharted rock under water or damages by ice enormous amounts of contaminants may be released.¹⁵ They cannot be degraded in the Antarctic climate. In spite of all progress in nautical technology half of all hip accidents have happened from 2000 to 2012.¹⁵ Although more recent data could not be found there is also no indicator for a decrease of this problem.

However, ships also discharge such substances via leakages in generators and hydraulic systems or various types of engines. Furthermore, there are several other chemicals which are needed for a routine operation or to clean a ship.¹⁶ It is difficult to get reliable data, but careful estimations show that a medium size cruise ship needs about 150 metric tons of heavy oil. The use of such fuel is regulated and restricted in Antarctica by the international ban of heavy fuel oil (HFOs) in Antarctic waters in 2011 (<https://www.asoc.org/campaign/heavy-fuel-oil-ban-in-antarctic-waters/>). However, there is still skepticism concerning severe environmental damage.¹⁵

Less discussion can be found about the "black sheep": A ship with 2,700 passengers produces several metric tons of garbage every day¹⁶ and there are several proven cases where such garbage has been disposed illegally. Royal Caribbean was convicted to be guilty for at least 21 cases of illegal discharge of oil and chemicals from their cruise ships.¹⁵

How is the impact of cruise ships compared to other sources of pollution?

In the last 15 years several papers were published—often in internet publications, but with the authors or institutions and references listed—which compared the discharge of pollutants by cruise ships with other sources, e.g. traffic. When reading this one has to be careful since sometimes authors compare apples with oranges, e.g. one comparison included the worst possible ship fuel with the best one for cars. That is, of course, scientifically unacceptable. A reliable overview for a standard cruise ship which needs 150 tonnes of fuel per day is given in Table 1.

Table 1. Emissions of a standard cruise ship [t/day]¹⁷

	Cruise ship	Car	Factor: 1 cruise ship equals passenger cars:
Fuel consumption/day	150 t	0.002 t	-
Sulfur content	25 kg/t	0.005 kg/t	
SO ₂ emission/day	7,500 kg	0.00002 kg	376,030,220
NO _x emission factor	35 kg/t	0.35 g/km	
NO _x emissions/day	5,250 kg	0.0124 kg	421,135
Particle emission factor	3 kg/t	0.012 g/km	
Particle emissions/day	450 kg	0.0004 kg	1,052,885
CO ₂ emission factor	3,179 kg/kg	160 g/km	
CO ₂ emissions/day	476,850 kg	5.698 kg	83678

If a cruise ship needs 150 metric tons of heavy oil per day,¹⁸ it releases more sulfur oxides and NO_x into the air than millions of cars or “the total traffic of a medium sized town”. The respirable dust exceeds the bus traffic of London (UK). This correlates to five metric tons of NO_x and 450 kg respirable dust per day according to the German expert for exhaust fumes Axel Friedrich, a former employee of the German Federal Environmental Agency (<https://www.deutschlandfunk.de/umweltverschmutzer-schiffahrt-unge-loeste-abgasprobleme-100.html>).¹⁸ And the amount of exhaust emissions are substantial: According to the owner the “Harmony of the Seas” needs 1,377 gallons (more than 6,000 liters) of diesel for its three engines per hour, correlating to 32,000 US gallons (about 145 m³, about 150 metric tons) per day. And without the microbubble technology this would be 10% to 20% more.¹⁸ Even without scientific data available one can easily conclude that several hundred metric tons of pollutants are produced per ship per day—even when it is in a harbor! In contrast to a car where the engine is shut-off when it is at a parking or in a garage the engines of a ship have to run continuously to keep the systems onboard operating since shore power in such enormous quantities (11,000 volts, 400 amps!) can only be provided at a few ports. This includes to heat the big tanks for the heavy oil which would harden when

temperature should go lower than 60°C. About 40% of their operation cruise ships are fixed in a harbor or in the case of a cruise to Antarctica in front of its ecologically sensitive coastline.

The amount of pollutants is not the only argument, but also the composition of the main contents: Heavy oil may contain up to 3.5% sulfur. This is 3,500 times more than gasoline or diesel may have for urban traffic. The sulfur content has been reduced significantly in European and North American seas to 0.1%, but this is still 100 times more than in European urban traffic. A cruise ship discharges about 7 metric tons of SO₂ (sulfur dioxide) per day which is similar to 376 million of cars with usual daily driving distances (about 40 km). Their respirable dust is also far above all limits of urban traffic: The “Harmony of the Seas” discharges as much fine dust as 21.45 million VW Passat cars would do. The calculation was based on a Variant 2.0 TDI with 190 PS and mixed traffic (data from VW). But: In whole of Germany there are 45.8 million cars only which means that this ship alone discharges as much respirable dust as half of the German traffic. The comparison per person is also impressive: Compared to an Audi Q5 2.0 quattro, a car which would not be called “environmentally friendly”, the person would discharge 11.5 mg fine dust per day. The “Harmony of the Seas” creates 5,146 mg per day and person which is about 500 times the amount of the person driving the Audi Q5! The CO₂-footprint per person joining a 7-days cruise is between 1,300 and 3,300 kg, depending on the ship and the calculation model. NO_x and VOC emissions differ significantly depending on the technology and burning temperature. The variability exceeds the limitations of a reliable general estimation. However, these substances contribute to the ground-level ozone.

The list of potentially dangerous substances could be continued. An increased concentration of various aromatic hydrocarbons has been found in the ground near touristic destinations in Antarctica.¹⁹ The dominant PAH congeners are naphthalene, phenanthrene and anthracene.²⁰ Black carbon content in snow surrounding research facilities and popular shore tourist-landing sites is considerably increased.²¹ This darkens the snow and makes it melt sooner. By this radiative forcing snow melting accelerates and the snowpack shrinks by up to 23 mm water equivalent (w.e.) every summer.²¹ The energy input into Antarctica through tourism can be estimated quite accurately: each cruise tourist melts 83 tons of ice.²¹ That is 1,000 times their own weight, and with 107,270 tourists (2024/25),²² this adds up to 8,904,310 tons, or almost 9 megatons of ice melt.

Impact of humans on the ecology of Antarctica

Tourism in Antarctica disrupts this sensitive, complex and dynamic ecosystem via at least five direct and indirect factors.¹⁵ This includes local and temporary elements, e.g. seasonal tourism.^{23,24} It is difficult to estimate the importance of the factors in such a complex and dynamic system, but in Antarctica any impact is for sure higher than in other destinations.^{15,23,25} Principally the problem was realized a long time ago. But constructive management is limited because tourism to Antarctica is not subject to governmental control and mainly not regulated. Therefore it is a real danger for Antarctica.^{4,26} Tourism operates in a legal vacuum here.⁴

Tourism and contamination concentrates seasonally and regionally on those regions where many animals live and which are picturesque. This happens during the mating season of the local fauna and causes significant ecological pressure.^{4,15,27-29} Studies showed tourism to be the most important factor among others and its management needs the highest priority.^{30,31}

As explained above all discharged contaminants concentrate along a quite narrow strip along the coastline and this is where most cruise ships aim to, e.g. Antarctic Peninsula and the islands around it.^{15,24,28} Unfortunately this is a very critically endangered region with a high number of species and individuals, among them many critically endangered species. A special problem is the increasing number of visitors: From 1958 to 1987 the annual number of tourists was less than 1,000. In the 1980s the number increased to 2,500 to 3,000, in the season 2011/12 there were 26,000 and in 2013/14 about 35,000 were recorded here.^{4,24,32,33} McCarthy et al. estimated in their study that in 2019 there were more than 500 tours with 180 ships³⁴ and a total number of 74,401 tourists visited the continent in the 2019–2020 season [35]. The highest number of tourists ever was in the 2023–2024 season with 122,072 visitors.²² This was only slightly less in 2024–2025 with 107,270 tourists of which 69,059 were “traditional expedition tourists” (with landings) and 28,360 “cruise-only tourists” (without landings).²² 98% of all tourists visit the Antarctic Peninsula region,²² a concentration of humans which has a significant impact on the environment there.

Another factor which has not been investigated accordingly so far is the introduction of potentially invasive species by ships, a phenomenon which has caused problems at other locations worldwide but in ecosystems which are more „robust” than Antarctica.^{15,36} The carry-over of angiosperms, bryophytes, microinvertebrates, nematodes, fungi, bacteria and some seeds was

found at Antarctic Peninsula.^{37,38} At Deception Island¹⁷ introduced species of fungi were found (*Aspergillus*, *Penicillium*, *Pseudogymnoascus*, *Purpureocillium*, *Mortierella*).³⁹ The ecological risk varies here significantly because of the local situation. Whalers Bay Historic Site at Deception Island is assumed to be at highest risk. Because of the small scale ecological variability and the intense geothermal activity potentially invasive species may find perfect conditions here. Among others the introduction of the highly invasive algae *Caulerpa webbiana* is well documented.⁴⁰ The fly *Trichocera maculipennis* was introduced here from the northern hemisphere in 2005 and has spread rapidly here since then.⁴¹ The consequences for the ecosystem are still not clear.⁴¹ Recent data suggest that the establishment potential of nonnative species, in number and geographical range, is considerably greater than currently indicated by species distribution modelling approaches.⁴²

The effect of substances used by tourists for care, protection, therapy or misuse (drugs, hormones, sun protection, pyrethroids, perfluorinated materials etc.) is also unclear. Olalla et al.⁴³ estimated the risk of these substances by using the Hazard Quotient of the European Union. They found a high ecological risk by acetaminophen, diclofenac and ibuprofen.⁴³ They obtained similar results for hormones (contraceptives), pyrethroids (especially biphenin and cyhalothrin) and sun protection.

Even the transport of tourists (disembarking, embarking) impairs the breeding habits of penguins. By this the number of Adélie penguins at Cape Royds decreased by half during six years only.^{44,45} Tourism may also cause acute catastrophic local impact if the visitors do not behave properly: in June 1990, during a stampede at Macquarie Island, 6,000 king penguins died after a group of visitors approached “offensively” to the colony.⁴ And even if the animals do not die tourists put a massive stress on the colony.⁴⁴

Medical risks associated with Antarctic ecology

Exposure to cold, UV radiation, and specific risks like hypothermia especially in the case of a fall into the water is standard of advice by travel medicine. But more and more elderly people, several of them with one or more health risks, visit Deception Island with its geothermal activities. Some of these visitors have an impaired immune system. A mean age of the tourists here of 60 years has been reported.⁴ Geothermal activities at Deception Island provide good environment

for germs which are less cold tolerant. Persons with impaired immune system may be at risk by thermoresistant aspergillus species, but also by pseudomonas and other germs.^{39,46} More recent data also show that there is a potentially increasing risk of antibiotic-resistant and multi-resistant germs, which would increase the risk to people who are not fully immunocompetent and, of course, to native fauna.⁴⁷

Some regions of interest for tourists were investigated for soil contamination by parasites potentially pathogenic for humans. In 10% of the specimens from three of the five regions investigated there were Cryptosporidia, Toxoplasma gondii, Diphyllbothriidae spp. eggs, helminths (cestodes and nematodes) and other species were identified.⁴⁸ Travelers should be advised to follow standard hygiene procedures.

Conclusions

The comparisons mentioned above are based on some assumptions and should not be interpreted as „scientifically hard data“. But they show in an impressive way the scale of impact by tourism in Antarctica. This needs consequences. Polar world is fascinating and it is comprehensible that people want to see it. However, with regard to a business which ignores since years the possibilities of modern technology to operate with ecologically friendly vessels and which pushes this strategy by perfect lobbying, Antarctica should not be an option. Concerning the emissions and their effects and also the significant ecological pressure by the large number of visitors there are remarkable differences between Antarctica and the Arctic. Growth and diversification of tourism activities in Antarctica have not been matched with proactive strategies for planning or management although an adaptive management approach has been effectively implemented in managing tourism in protected areas.³⁵

What should a person do who is fascinated by polar regions? With the information given above the authors recommend to prefer the Arctic. By more intensive and large-scale exchange of air masses the local impact is lower than in Antarctica. Whatever one wants to see in Antarctica may be seen in other, less sensitive regions, too. In contrast to a common opinion this is also true for king penguins which have a big breeding colony at Tierra del Fuego.

However, there are even more possibilities to protect polar regions. Don't underestimate the power of consumers! If they book environmentally friendly cruises only at ships with modern technology (efficient filters

for respirable dust, SCR catalysators which reduce NOx emission by 90% and modern fuel (LNG or in future “green” hydrogen)) this will change the mentality of those operators which ignore such necessities for years and which discharge thousands of tons of emissions every year into a critical environment. However, also LNG is so far not always the golden path. Actually LNG is available in a few harbors only. There are cruises where the vessel itself burns LNG, but another one which burns heavy oil pilots to the harbor to transport LNG there when the cruise ship should need it.

There are several tasks to be done! Unfortunately history teaches us that action will be taken only when salary is going down. Let us travelers increase the pressure on the operator's bank accounts by careful booking. We have the technology—we just have to want! Then guests may enjoy their cruise without bad conscience, but please not to Antarctica! However, to be realistic: It may be impossible to shut down tourism to Antarctica completely but then a strict management which includes a limitation of visitors at “critical” or most visited locations is a must.^{20,35}

References

- [1] Alekseev I, Abakumov E. The content and distribution of trace elements and polycyclic aromatic hydrocarbons in soils of Maritime Antarctica. *Environ Monit Assess.* 2020;192(11):670. doi: 10.1007/s10661-020-08618-2.
- [2] Alekseev I, Abakumov E. Content of trace elements in soils of Eastern Antarctica: Variability across landscapes. *Arch Environ Contam Toxicol.* 2021;80(2):368-388. doi: 10.1007/s00244-021-00808-4.
- [3] Masson D. Holidays to help the planet. *The Australian Magazine.* 1990;3-4:56.
- [4] Hall CM. Tourism in Antarctica: Activities, impacts, and management. *J Travel Res.* 1992;30(4):2-9. doi: 10.1177/004728759203000401.
- [5] Codling RJ. Sea-borne tourism in the Antarctic: An evaluation. *Polar Record.* 1982;21(130):3-9. doi: 10.1017/S0032247400004186.
- [6] ntv Tausende Küken ertrunken – Eisschmelze ist Todesfalle für junge Pinguine [Thousands of chicks drowned – melting ice is a death trap for young penguins]. ntv Wissen. <https://www.n-tv.de/wissen/Eisschmelze-ist-Todesfalle-fuer-junge-Pinguine-article24902477.html>. Published April 26, 2024. Accessed January 29, 2026.
- [7] Gallagher KL, Cimino MA, Dinniman MS, Lynch HJ. Quantifying potential marine debris sources and potential threats to penguins on the West Antarctic Peninsula. *Environ Pollut.* 2024;347:123714. doi: 10.1016/j.envpol.2024.123714.

- [8] Fretwell P. A 6 year assessment of low sea-ice impacts on emperor penguins [Short Note]. *Antarctic Sci.* 2024;36(1): 1-3. doi: 10.1017/S0954102024000130.
- [9] Wohlleben P. *Der lange Atem der Bäume [The long breath of trees]*. Munich: Ludwig Verlag; 2021.
- [10] Meadows DH, Meadows DL, Randers J, Behrens WW. *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*. New York: Universe Books; 1972. <https://ia600907.us.archive.org/30/items/TheLimitsToGrowth/TheLimitsToGrowth.pdf>.
- [11] Forrester JW. *Der teuflische Regelkreis. Kann die Menschheit überleben? [The vicious circle: Can humanity survive?]*. Munich: Deutsche Verlags-Anstalt; 1972.
- [12] Lozoya JP, González-Pleiter M, Lacerot G, et al. Plastic debris on the shores of Bahía Esperanza/Hope Bay: Stranded testimony of the historical occupation in the northern Antarctic Peninsula. *Sci Total Environ.* 2026;1015:181410. doi: 10.1016/j.scitotenv.2026.181410.
- [13] Biesiot W, Noorman KJ. Energy requirements of household consumption: A case study of the Netherlands. *Ecol Econ.* 1999;28(3):367-383. doi: 10.1016/S0921-8009(98)00113-X.
- [14] Babbar R, Agarwal S. A new approach to hypobaric hypoxia induced cognitive impairment. *Indian J Med Res.* 2012;136(3):365-367.
- [15] Kariminia S, Ahmad SS, Hashim R, Ismail Z. Environmental consequences of Antarctic tourism from a global perspective. *Procedia: Soc Behavioral Sci.* 2013;105:781-791. doi: 10.1016/j.sbspro.2013.11.081.
- [16] Davies T, Cahill S. *Environmental Implications of the Tourism Industry*. AgEcon Search. Washington, DC: Researches for the Future; 2000. doi: 10.22004/ag.econ.10824.
- [17] Friedrich, A. *Vergleich Luftschadstoff-Emissionen bei Kreuzfahrtschiff und Pkw [Comparison of air pollutant emissions from cruise ships and cars]*. NABU – Naturschutzbund Deutschland. https://www.nabu.de/imperia/md/content/nabude/verkehr/tabellevergleichkreuzfahrtschiff_pkw.pdf. Published 2012. Accessed January 29, 2026.
- [18] *Harmony of the Seas*. 2023. Wikipedia. https://de.wikipedia.org/wiki/Harmony_of_the_Seas. Accessed January 29, 2026.
- [19] Dauner ALL, Hernández EA, MacCormack WP, Martins CC. Molecular characterisation of anthropogenic sources of sedimentary organic matter from Potter Cove, King George Island, Antarctica. *Sci Total Environ.* 2015;502:408-416. doi: 10.1016/j.scitotenv.2014.09.043.
- [20] Potapowicz J, Szopińska M, Szumińska D, Bialik RJ, Polkowska Ż. Sources and composition of chemical pollution in Maritime Antarctica (King George Island), part 1: Sediment and water analysis for PAH sources evaluation in the vicinity of Arctowski station. *Chemosphere.* 2022; 288(Pt 3):132637. doi: 10.1016/j.chemosphere.2021.132637.
- [21] Cordero RR, Sepúlveda E, Feron S, et al. Black carbon footprint of human presence in Antarctica. *Nat Commun.* 2022;13(1):984. doi: 10.1038/s41467-022-28560-w.
- [22] *Antarctica Tourism Numbers 2024–2025: The Real Data Behind the Headlines*. Unsold Antarctica. <https://unsoldantarctica.com/latest/antarctica-tourism-numbers-2024-2025-the-real-data-behind-the-headlines#:~:text=The%20IAATO%20data%20shows%20that%2098%25%20of%20all,presence%20at%20any%20given%20location%20is%20remarkably%20small>. Published July 14, 2025. Accessed January 26, 2026.
- [23] Kariminia S, Ahmad SS, Hashim R. Assessment of Antarctic tourism waste disposal and management strategies towards a sustainable ecosystem. *Procedia: Soc Behavioral Sci.* 2012;68:723-734. doi: 10.1016/j.sbspro.2012.12.262.
- [24] Lamers MAJ, Eijgelaar E, Amelung B. Last chance tourism in Antarctica – Cruising for change? In: Lemelin H, Dawson J, Stewart EJ, eds. *Last-Chance Tourism: Adapting Tourism Opportunities in a Changing World*. London: Routledge, 2011:25-41.
- [25] Gössling S. Global environmental consequences of tourism. *Global Environ Change.* 2002;12(4):283-302. doi: 10.1016/S0959-3780(02)00044-4.
- [26] O'Sullivan D. Antarctic tourism: Problems for management. In: Wells M, ed. *Parks, Recreation and Tourism*. Launceston: Royal Australian Institute of Parks and Recreation: Launceston; 1984:155-163.
- [27] Bertellotti M, D'Amico V, Cejuela E. Tourist activities focusing on Antarctic penguins. *Ann Tourism Res.* 2013;42:428-431. doi: 10.1016/j.annals.2013.02.017.
- [28] Cajiao D, Albertos B, Tejado B, et al. Assessing the conservation values and tourism threats in Barrientos Island, Antarctic Peninsula. *J Environ Manage.* 2020;266:110593. doi: 10.1016/j.jenvman.2020.110593.
- [29] Pertierra LR, Hughes KA, Vega GC, Olalla-Tárraga MÁ. High resolution spatial mapping of human footprint across Antarctica and its implications for the strategic conservation of avifauna. *PLoS One.* 2017;12(1):e0168280. doi: 10.1371/journal.pone.0168280.
- [30] Gao Y, Li R, Gao H, et al., Spatial distribution of cumulative impact on terrestrial ecosystem of the Fildes Peninsula, Antarctica. *J Environ Manage.* 2021;279:111735. doi: 10.1016/j.jenvman.2020.111735.
- [31] Sutilli, M., et al., Depositional input of hydrocarbons recorded in sedimentary cores from Deception and Penguin Islands (South Shetland Archipelago, Antarctica). *Environ Pollut.* 2019;253:981-991. doi: 10.1016/j.envpol.2019.07.057.
- [32] Bargagli R. Environmental contamination in Antarctic ecosystems. *Sci Total Environ.* 2008;400(1-3):212-226. doi: 10.1016/j.scitotenv.2008.06.062.

- [33] IAATO Overview of Antarctic Tourism: 2012-13 Season and Preliminary Estimates for 2013-14 Season. In: 34. Antarctic Treaty Consultative Meeting. Brussels 2013. https://iaato.org/system/files/2025-01/ATCM36_ip103_e.pdf. Accessed January 26, 2026.
- [34] McCarthy AH, Peck LS, Hughes KA, Aldridge DC. Antarctica: The final frontier for marine biological invasions. *Glob Change Biol*. 2019;25(7):2221-2241. doi: 10.1111/gcb.14600.
- [35] Cajiao D, Benayas J, Tejedó P, Leung Y-F. Adaptive management of sustainable tourism in Antarctica: A rhetoric or working progress? *Sustainability*. 2021;13(14):7649. doi: 10.3390/su13147649.
- [36] Hughes KA, Hughes KA, Convey P, Pertierra LR, Vega GC, Aragón P, Olalla-Tárraga MÁ. Human-mediated dispersal of terrestrial species between Antarctic biogeographic regions: A preliminary risk assessment. *J Environ Manage*. 2019;232:73-89. doi: 10.1016/j.jenvman.2018.10.095.
- [37] Hughes KA, Convey P, Maslen NR, Smith RIL. Accidental transfer of non-native soil organisms into Antarctica on construction vehicles. *Biological Invasions*. 2010;12(4):875-891. doi: 10.1007/s10530-009-9508-2.
- [38] Bonnedahl J, Broman T, Waldenström J, Palmgren H, Niskanen T, Olsen B. In search of human-associated bacterial pathogens in Antarctic wildlife: Report from six penguin colonies regularly visited by tourists. *Ambio*. 2005;34(6):430-432.
- [39] Figueredo HM, Gonçalves VN, Godinho VM, Lopes DV, Oliveira FS, Rosa LH. Diversity and ecology of cultivable fungi isolated from the thermal soil gradients in Deception Island, Antarctica. *Extremophiles*. 2020;24(2):219-225. doi: 10.1007/s00792-019-01146-z.
- [40] Câmara PEAS, Carvalho-Silva M, Pinto OHB, et al. Diversity and ecology of Chlorophyta (Viridiplantae) assemblages in protected and non-protected sites in Deception Island (Antarctica, South Shetland Islands) assessed using an NGS approach. *Microb Ecol*. 2021;81(2):323-334. doi: 10.1007/s00248-020-01584-9.
- [41] León MR, Hughes KA, Morelli E, Convey P. International response under the Antarctic Treaty System to the establishment of a non-native fly in Antarctica. *Environ Manage*. 2021;67(6):1043-1059. doi: 10.1007/s00267-021-01464-z.
- [42] Bokhorst S, Convey P, Casanova-Katny A, Aerts R. Warming impacts potential germination of non-native plants on the Antarctic Peninsula. *Commun Biol*. 2021;4(1):403. doi: 10.1038/s42003-021-01951-3.
- [43] Olalla AL, Moreno L, Valcárcel Y. Prioritisation of emerging contaminants in the northern Antarctic Peninsula based on their environmental risk. *Sci Total Environ*. 2020;742:140417. doi: 10.1016/j.scitotenv.2020.140417.
- [44] Thompson RB. Effects of human disturbance on an Adélie penguin rookery and measures of control. In: Llano GA, ed. *Adaptations within Antarctic Ecosystems*. Washington, DC: Smithsonian Institution; 1977:1177-1180.
- [45] Bond CR, Siegfried R, Johnson P. *Antarctica: No Single Country No Single Sea*. London: New Holland Publishers; 1988.
- [46] Rosa LH, da Silva TH, Ogaki MB, et al. DNA metabarcoding uncovers fungal diversity in soils of protected and non-protected areas on Deception Island, Antarctica. *Sci Rep*. 2020;10(1):21986. doi: 10.1038/s41598-020-78934-7.
- [47] Gugliandolo E, Mghili B, Fabrizi F, et al. Antibiotic and heavy metal resistance in marine bacteria from Terra Nova Bay (Ross Sea): Insights from wild fish and environmental samples. *Animals*. 2025;16(1):51. doi: 10.3390/ani16010051.
- [48] Lim PKC, Mohd Nazimi NMA, Tang YY, et al. Parasites in soil samples from Signy Island, Antarctica. *Trop Biomed*. 2018;35(4):1007-1016.