Climate Change and Seabirds: Insights from Ecological Monitoring of Snow Petrels in the Indian Antarctic Program

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Abstract Climate driven changes in the Southern Ocean impact biological communities and processes. Monitoring these changes requires systematic and periodic data collection on indicator taxa such as seabirds, which act as ecosystem sentinels. Understanding their breeding behaviour and phenology helps assess the impacts of anthropogenic pressure and environmental variations on seabird populations. Antarctic Wildlife Monitoring Program of Wildlife Institute of India is currently evaluating the population status, distribution and genetic structure of key seabird species (Adelie penguin, snow petrel, south polar skua, Wilson's storm petrel) breeding around Indian research stations. This chapter discusses the results of work being conducted on snow petrel, a climate-dependent seabird found in the ice-free coastal areas and inland mountains in Antarctica. Monitoring snow petrel populations in east Antarctica is critical to understanding their populations' response to climate change and predicting future impacts.

Keywords Climate change · Biological communities · Breeding behavior · Phenology · Antarctic Wildlife Monitoring Program

1 Introduction

Climate change is considered a significant driver of change across ecosystems as geographically diverse as tropical (Barlow et al. 2018), temperate (Schlaepfer et al. 2017) and polar (Hansen 2005; Du Pontavice et al. 2020). These changes amplify further in areas highly vulnerable to its impacts, exceptionally high mountain glaciers (Banerjee and Shankar 2013) and polar ice caps in the Arctic (Box et al. 2019) and Antarctica (Lee et al. 2017a, b). These regions comprise some of the planet's remotest parts, making scientific measurements challenging to undertake, limiting our understanding of physical, chemical, geological and biological processes driving or impacted by climate change.

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Antarctic continent, the fifth-largest continent in the world (larger than Australia and Europe) recognised globally as the last wilderness (Sanderson et al. 2002), has been under severe pressure from the rapidly shifting global climate (Shaw et al. 2014; Lee et al. 2017a, b). Though highly remote, with year-round harsh weather patterns, the continent and its surrounding Southern Ocean regulate global ocean circulations and atmospheric processes. An internationally controlled Antarctic Treaty System prohibits commercial activities (except tourism) and restricts human activities in Antarctica; its polar ecosystem and biodiversity are considered to be under serious threat (Croxall et al. 2002; Barbraud and Weimerskirch 2006; Chown et al. 2012; Constable et al. 2014; Shaw et al. 2014; Cimino et al. 2016). Thus, despite a global treaty protecting Antarctica from globally mounting environmental change pressure, the white continent designated as a natural reserve, devoted to peace and science (NRC 1993), is at the receiving end of the Anthropocene. The rapid changes in the physical environment of the Southern Ocean affect marine life at all trophic levels, primary prey species (zooplankton including Antarctic Krill), to mesopredators (like squids) to top predators such as marine mammals and seabirds (Atkinson et al. 2004). It is expected that modifications in the Southern Ocean's cold climate will impact the community composition of primary producers, thereby affecting the higher trophic levels (Croxall et al. 2002; Agusti et al. 2010; Constable et al. 2014), which includes seabirds.

1.1 Seabirds as Indicators of Environmental Change

Seabird populations across the globe are threatened with human-induced changes. Long-term monitoring programs have highlighted these threats and the declining status of seabirds worldwide (Croxall et al. 2012; Thiebot et al. 2016; Pertierra et al. 2017); Antarctica is no exception. In the Southern Ocean, where seabird populations have declined substantially over the last few decades (Paleczny et al. 2015), interdisciplinary approaches are being utilised to aid their conservation and management (Friesen 2007; Croxall et al. 2012; Taylor and Friesen 2012). Current knowledge on seabird distribution in Antarctica has been known through the efforts of long-term datasets generated by National Antarctic Programs. With Antarctic researchers' efforts working in megafauna ecology, a Biogeographic Atlas of the Southern Ocean documents the distribution of seabirds and marine mammals in the Southern Ocean and Antarctica (Ropert-Coudert et al. 2014). The atlas gives large spatial scale distribution maps from the data on the species sighted at sea or using the tracking data available from multiple studies on seabirds and marine mammals. It came out as a product of the discussion during the International Polar Year 2007–2009 (www.ipy.org) and later from the Census of Marine Life 2000–2010 (www.coml.org), provided by the SCAR Marine Biodiversity Information Network (www.scarmarbin.be) and Census of Antarctic Marine Life (www.caml.aq) (De Broyer et al. 2014). Seabird species distribution has also been extensively studied utilising data from ground surveys and through remotely sensed data along several portions of the Antarctic coast (Mehlum et al. 1988; Schwaller et al. 1989, 2018; Fretwell and Trathan 2009; Lynch et al. 2010; LaRue et al. 2014; Lynch and LaRue 2014).

Marine top predators such as seabirds serve as indicators of environmental changes in the Antarctic environment (Woehler 1990; Croxall et al. 2012). Seabirds, being top predators, maintain the structure of marine food webs, regulate island and marine ecosystem processes and act as indicators of aquatic ecosystem health (Lascelles et al. 2012; Paleczny et al. 2015). Monitoring their populations thus acts as a potent tool to assess the Antarctic environment's anthropogenic impact (Croxall et al. 2002; Micol and Jouventin 2001) and understand the variability of the climatic effect on the Antarctic biota. Scanty information exists from very few long-term population studies on pelagic seabird populations in Antarctica (Jouventin and Viot 1985; Chastel et al. 1993; Lorentsen 1996; van Franeker et al. 1999; Barbraud 1999, 2000; Barbraud and Weimerskirch 2001, 2006; Jenouvrier et al. 2005; Barbraud et al. 2015; Descamps et al. 2016a, b). Limited quantitative knowledge on dynamics of interactions between top predators, their prey, and their environment hinders the understanding of complex processes occurring in Antarctica (Croxall et al. 2002), including anthropogenic activities and climate change (Kennicutt et al. 2014; Rodríguez et al. 2019).

Several studies focusing on seabird population monitoring have highlighted the threatened status of seabirds across the globe (Croxall et al. 2012; Thiebot et al. 2016; Pertierra et al. 2017), especially in the Southern Ocean, where seabird populations have declined substantially over the last few decades (Paleczny et al. 2015). This has led to efforts focusing on understanding seabird population dynamics using interdisciplinary approaches to aid conservation and management across their distribution range (Friesen 2007; Croxall et al. 2012; Taylor and Friesen 2012). Focused studies on Antarctic seabird populations have been carried out on the Antarctic peninsula, especially on penguins (Lynch et al. 2012a, b; Clucas et al. 2014), skuas (Borghello et al. 2019; Phillips et al. 2019) etc. Besides, site-specific monitoring of pelagic species has been carried out at sub-Antarctic islands (Brown et al. 2015; Quillfeldt et al. 2017) and multiple sites along the Antarctic coast (Barbraud and Weimerskirch 2001, 2006; Techow et al. 2010; Brown et al. 2015).

Seabirds, a numerically significant group in the Southern Ocean fauna (Warham 1996; Olivier 2006), exert control over the marine trophic web and are affected by the same environmental variations as their prey. Preventing the further decline of their populations is essential as these species have broad ecological impacts (Welch et al. 2012) in the Southern Ocean. The baseline data necessary to study seabird population changes over time are scarce and are challenging to obtain given remoteness and inaccessibility of seabird habitats in Antarctica. Monitoring breeding success and temporal variations in seabird populations have been successfully validated as a potent tool to assess the anthropogenic impact and effects of environmental variations (Croxall et al. 2002; Micol and Jouventin 2001). However, seabirds' data collection is often hindered by the extreme climatic conditions in the Antarctic continent. Accurate forecasting of any environmental or anthropogenic impacts would require a thorough understanding of drivers of change in the seabird population demographics (Barbraud et al. 2011) or breeding phenology (Lynch et al. 2012a, b).

1.2 Long-Term Monitoring of Antarctic Seabirds in Indian Antarctic Program

Antarctic Wildlife Monitoring Program of the Indian Antarctic Program has been monitoring seabirds and marine mammals since the early 1990s (Sathyakumar 1995; Bhatnagar and Sathyakumar 1999; Hussain and Saxena 2008; Sivakumar and Sathyakumar 2012; Kumar and Johnson 2014; Pande et al. 2017, 2018, 2020). The Phase-I of this program was conducted to ascertain the feasibility of conducting long-term research on Antarctica wildlife species. Later, as the Phase-II of the program, in two successive expeditions, extensive spatial scale surveys were carried out in the Indian sector of operation in Antarctica and the Southern Ocean to assess penguins' distribution and abundance seals (Sivakumar and Sathyakumar 2012; Kumar and Johnson 2014). With knowledge of existing species around the Indian research station and logistical capabilities, the Phase-III of the program was launched in 2013–14 to undertake detailed long-term monitoring work on selected indicator species of the polar ecosystem. The Phase-III of the program was conducted during three successive expeditions (33rd, 34th and 35th Indian Scientific Expeditions to Antarctica) and resulted in a critical understanding of species' distribution and breeding biology as pelagic seabirds, penguins and seals (Pande et al. 2017, 2018). The program's Phase-IV is in progress, ascertaining the population status, distribution and genetic structure of select seabird species (Adelie penguin, snow petrel, south polar skua, Wilson's storm petrel) breeding around Indian research stations (Pande et al. 2020). It aims to understand two significant aspects of seabird biology in east Antarctica, viz. nesting ecology and population genetics, with a long-term objective of looking at changes concerning climatic variations in the environment. This chapter discusses the work being conducted on snow petrel, a climate-dependent seabird found in the ice-free coastal areas and inland mountains in Antarctica.

*1.3 Nesting Ecology of Snow Petrel (*Pagodroma nivea*)*

The snow petrel (*Pagodroma nivea*) is endemic to Antarctica, being the most southerly breeding bird species of the world (Loy 1962; Harrison 1983). It is the only member of the genus *Pagodroma* (Bonaparte 1856) in the family Procellariidae. It spends its entire life in the Southern Ocean waters surrounding the continent while breeding during the austral summer ice-free areas on the Antarctic coast, rarely found breeding inland (Ryan and Watkins 1989). Snow Petrels breed colonially at ice-free islands along the Antarctic coast and on exposed rocky mountain areas over 300–400 km inland from the open sea during the austral summers (Løvenskiold 1960). Some earlier reports on breeding locations of snow petrels include Maher (1962) near Cape Hallet, Pryor (1968) at Haswell Island, Ryan and Watkins (1989) in Dronning Maud Land and Chastel et al. (1993) at Terre Adélie. Several other authors have reported snow petrel breeding in locations in the vicinities of Australian stations, Davis and Mawson (Brown 1966; Johnstone et al. 1973; Bonner and Lewis-Smith 1985; Woehler and Johnstone 1991). Detailed studies on the distribution and abundance of snow petrels on the Ardery and Odbert Islands were conducted in the 1980s–90s by Bonner and Lewis-Smith (1985) and van Franeker et al. (1990). A comprehensive review of the existing literature and unpublished records reported breeding at 298 localities in a circumpolar distribution (Croxall et al. 1995). However, several reports have documented this species' presence and breeding sites from different parts of the continent; the environmental factors influencing its breeding distribution are relatively unknown in Antarctica (Olivier and Wotherspoon 2008). Despite comprehensive knowledge of their breeding distribution, only two long-term studies have been conducted on snow petrels. These include a ~60 year long study on snow petrel breeding biology by French Antarctic researchers at Pointe Géologie Archipelago, Terre Adélie, Antarctica, site of the French station Dumont d'Urville (Jouventin and Viot 1985; Viot et al. 1993; Barbraud 1999; Barbraud 2000; Barbraud and Weimerskirch 2001; Barbraud et al. 2015) and; at the Australian Antarctic Territory encompassing Australian Antarctic stations of Mawson, Davis and Casey (Woehler 1990; Olivier 2006; Olivier and Wotherspoon 2008; Einoder et al. 2014).

Snow petrel nesting behaviour and reproductive success might differ with nest site location (Pierotti 1982; Gaston and Elliot 1996), where reproductive success is influenced by behavioural factors such as breeding synchronisation, incubation scheduling, etc., predator defence (Coulson 2002; Hamer et al. 2002). It has been positively demonstrated that nesting behaviour and reproductive success can differ with nest site location in a seabird colony (Pierotti 1982; Gaston and Elliot 1996), where reproductive success is influenced by behavioural factors such as breeding synchronisation, incubation scheduling and predator defence (Coulson 2002; Hamer et al. 2002). Apart from location, the physical characteristics of a nest site can influence intensities of disturbance from conspecifics (Kim and Monaghan 2005a), predation events (Gaston and Elliot 1996; Gilchrist and Gaston 1997) and nest microclimate (Kim and Monaghan 2005a, b) and thereby influence parental behaviour at the nest. Moreover, nest sites with high visibility may cause the parents to spend more time in vigilance or defending their nest against conspecific intruders or patrolling predators (Drent 1975; Hatch and Nettleship 1998) with drastic impacts on both energy stores and the time spent in parenting.

Snow petrels form colonies of variable sizes and suitable nesting locations in ice-free areas, cliffs and rock faces in Antarctica. They are highly mobile and have few apparent physical barriers to dispersal like other colonially nesting seabird species. Thus, they are capable of flying vast distances in search of epipelagic prey (Avise et al. 2000). However, many seabird species exhibit strong philopatry and can become genetically distinct over short geographical distances (Milot et al. 2008). The birds' movement between breeding sites influences their population dynamics, gene flow and individual fitness, with subsequent significant consequences for population persistence and viability (Hanski 2001; Bowler and Benton 2005). Though several studies have focused on investigating dispersal mechanisms in individual animals using capture-recapture (Lebreton et al. 2003) or bio-telemetry (Shaffer et al. 2006), these approaches are relatively difficult to implement in Antarctica due to extreme weather conditions and inaccessible terrain supplemented by limited logistics. Alternatively, molecular techniques have been effectively used for explaining colonisation patterns, population genetic structure, gene flow and individual immigrants (Rousset 2001) across a varied range of taxa (Knight et al. 1999; Jehle et al. 2005; Welch et al. 2012).

Nest site selection, protecting both adults and young from environmental conditions and predation, is a substantial factor in bird survival and reproduction, particularly for order Procellariiformes (Warham 1996; Thompson et al. 1993) species nest in cavities or burrows. Processes of nest site formation and selection in snow petrels were suggested in the early work of Brown (1966). Other studies also have proposed topography as the significant determining factors explaining snow petrel colonies' distribution (Ryan and Watkins 1989). More recently, detailed habitat selection models were established for the snow petrel at Casey in East Antarctica (Olivier and Wotherspoon 2006). However, the specific process of spatiotemporal selection of nest sites by snow petrel has not yet been entirely clarified (Olivier et al. 2004; Olivier 2006; Olivier and Wotherspoon 2008; Einoder et al. 2014).

Isotopic records of stomach oil spits deposited at the nest cavities of snow petrels suggest that they might be continuously occupied for over 14,000 years (Hiller et al. 1995). Philopatry has been demonstrated in snow petrels though there are studies that indicate otherwise, too (Chastel et al. 1993). Morphological studies in snow petrels have shown two forms of different size (*P. N. Nivea* and *P. N. Major*) which are sympatric at some breeding sites (Isenmann 1970; Cowan 1981; van Franeker et al. 1990; Marchant and Higgins 1990). The origin, status and significance of these two forms remains controversial (Jouventin and Viot 1985) and demands the need to clarify the issue using molecular techniques.

CCAMLR Ecosystem Monitoring Program (CEMP) has overlooked snow petrel in their program to understand population size changes, breeding success, body mass, and foraging behaviour in select indicator species (https://www.ccamlr.org). An in-depth understanding of these dynamics is vital as colonies of seabirds sometimes contain a disproportionately large population at a small number of sites. Seabirds are some of the most threatened groups of birds globally. It becomes imperative to understand gene flow between snow petrel colonies as an essential prerequisite for their successful conservation and management. Their wide distribution across the Antarctica coast makes them an important indicator species for monitoring the Antarctic marine ecosystem's health.

Snow Petrels are long-lived, upper-trophic-level predators greatly dependent on the Southern Ocean's seasonal ice system, which increases their vulnerability to climate change (Olivier 2006). They are specialist foragers near pack ice areas (Griffiths 1983; Ainley et al. 1986), usually occurring abundantly at latitudes south of 60°S (Griffiths 1983; Hunt and Veit 1983; Ainley et al. 1986; Bretagnolle and Thomas 1990). Dietary studies have reported Antarctic Krill *Euphausia superb* to be the significant component of the snow petrel diet during the breeding season, apart from fish and squids (Brown 1966; Griffiths 1983; Ainley et al. 1992). Commercial krill harvesting has raised concerns about its potential damage to the dependent predators, highlighting the need to generate accurate information on the distribution and abundance of Snow Petrels. Climate-dependent variables such as sea ice extent have been shown to affect their breeding success by affecting nesting rates and chick body condition (Barbraud and Weimerskirch 2001). Long-term datasets on these birds link climate change to variations in phenological events in the species' life history (Barbraud and Weimerskirch 2006).

2 Methods

2.1 Study Areas

This work was carried out around the Indian sector of operations at two significant sites in east Antarctica viz. Larsemann Hills and Schirmacher Oasis. Larsemann Hills (69° 20′S to 69° 30′S Latitude; 75° 55′E to 76° 30′E Longitude), is a group of islands at Prydz Bay (Fig. 1a). It is an ice-free oasis on the Ingrid Christensen Coast, Princess Elizabeth Land, located approximately midway between the eastern end of the Amery Ice Shelf and the Vestfold Hills (Kiernan et al. 2009). Together the islands form the second largest group of four major ice-free oases found along East Antarctica's 5000 km long coastline spread over an area of about 50 km^2 (Hodgson et al. 2005). The region is bordered on both sides by two large peninsulas, the western

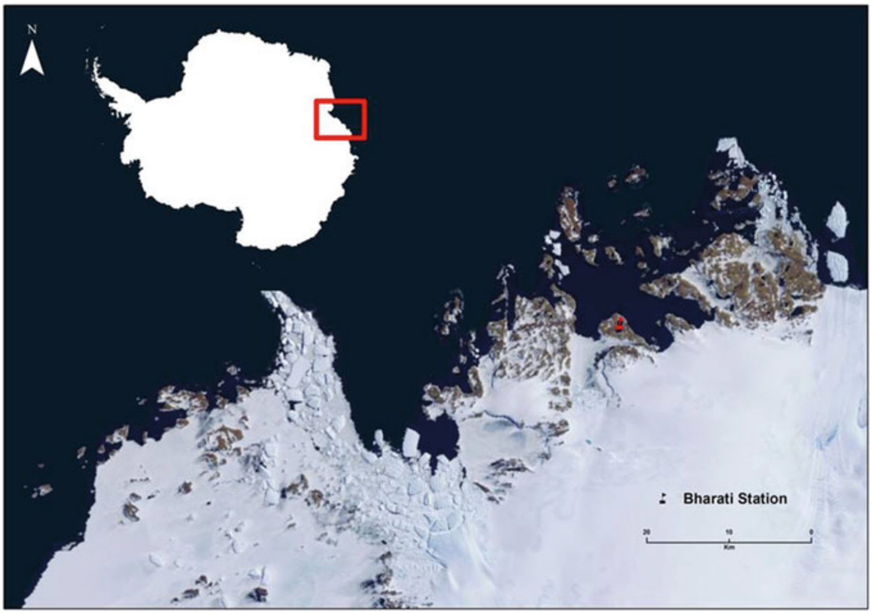

Fig. 1 Larsemann Hills, East Antarctica, site of Bharati, Indian Antarctic research station

Stornes and the eastern Broken, which enclose a group of variously sized islands and peninsulas. India's 2nd permanent research station in Antarctica, *BHARATI*, is located on the North Groves peninsula (Fig. 1). Four other Antarctic stations, viz. the progress I and Progress II (Russia), Law-Racovita (Australia-Romania) and Zhongshan (China), are located along the edge of the Broken peninsula.

Weather at Larsemann hills is influenced by persistent, intense katabatic winds that blow from east to south-east during austral summer. Daytime ambient average air temperatures range from a maximum of 4 °C (Dec–Feb) to a minimum of –40 °C (May–July) (Turner and Pendlebury 2004). Precipitation occurs as snow not exceeding 250 mm of water equivalent annually (Hogdson et al. 2001). Pack ice is extensive in the north-eastern side throughout the austral summer, and the fjords and bays are hardly ice-free even during peak summer. Snow cover is generally higher and persistent on Stornes Peninsula compared to Broken Peninsula. The sea ice grows slowly during March–September, reaching its peak in April–June (NCAOR 2006). Since this study also incorporated the phylogeographic assessment of snow petrel, part of the sampling was conducted at Schirmacher Oasis, Central Dronning Maudland. Schirmacher Oasis is situated on the Princess Astrid Coast of Dronning Maud Land, Antarctica, between the Fimbul ice shelf and continental icecap (Fig. 1). This ice-free land is spread across 34 km^2 between the coordinates 70° 44′–46′ S and 11° 26′–49′ E (Singh et al. 2014). Indian research station *MAITRI* is located on the south-eastern part of the oasis (Fig. 2).

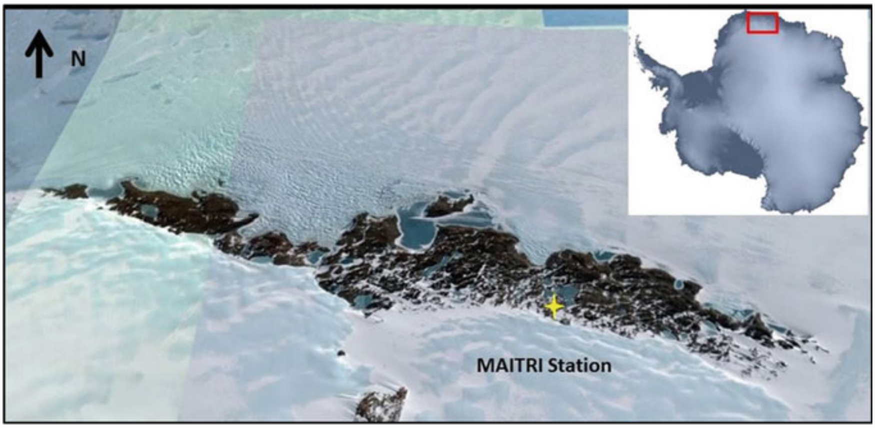

Fig. 2 Schirmacher Oasis, central Dronning Maudland, site of Maitri, Indian Antarctic research station

2.2 Field Sampling

Field surveys were conducted to locate snow petrel nests over several Larsemann hills' islands under the "Antarctic Wildlife Monitoring Program" of Indian Scientific Expeditions to Antarctica (ISEA). These surveys were spread over three austral summers (November–March) of 2013–14, 2014–15 and 2015–16, coinciding with the Antarctic seabird species' breeding season. At Larsemann hills, all the named islands/peninsulas and their adjoining rocky outcrops were surveyed for the presence of snow petrel nesting sites (Pande et al. 2020). Snow petrel nests were physically located using a hand-held flashlight (300 lumens) using the area search method. Snow petrels' nest in rock cavities or crevices formed within natural boulders in steep rocky slopes (Olivier and Wotherspoon 2008; Tveraa and Christensen 2002). Cavities large enough to hold snow petrel breeding pairs were marked as an occupied nest (OCN) based on the presence of one or more adult bird or an unhatched egg or a live chick or a potential unoccupied or potential nest (UPN) based on the fact of dead egg/s or broken eggshells or hatched eggshells or dead chick or quiet adult or guano marks or mumiyo deposits. Once a snow petrel nest was detected, an extensive search was conducted in a 50 × 50 m area around it to locate all occupied and unoccupied or potential nest cavities. Each OCN and UPN nest cavity was marked using non-toxic, odourless paint (red or yellow), and its geographic coordinates were recorded on a hand-held GPS unit (GARMIN eTrex 30xTM). The periphery of the colony was mapped on the GPS device by walking around the outermost detected nests. Once a rough estimate of the colony perimeter was ascertained, 3 × 3 m plots were placed at fixed intervals along lines running diagonally from the bottom to the colony's top (Mehlum et al. 1988). Random nests were then chosen from these intensive study plots (3 × 3 m) within snow petrel colonies to study nest cavity characteristics (Figs. 3 and 4).

The nest cavities' physical characteristics were manually profiled into rock type, nest bowl metrics, nest orientation, etc. Nest cavity metrics were obtained using a measuring tape, i.e. nest entrance measurements and nest bowl measurements. In cases where the access to nest bowl was not possible, an extension mechanical arm tool was used to reach deeper cavities. Nest orientation and aspect was measured using a hand-held clinometer and compass verified using a digital compass on the GPS unit. Each potential nest cavity within the study plot was marked using non-toxic paint, and its geographic coordinates were recorded on a hand-held GPS unit. The nest locations were also observed on Google Earth Pro v.7.1.8 and then later extracted as KML files for visualisation and planning for monitoring visits over the expedition duration (Figs. 5 and 6). The monitoring planned to cover all phases of nesting of the species, starting from November (egg-laying) and ending in February–March (fledging).

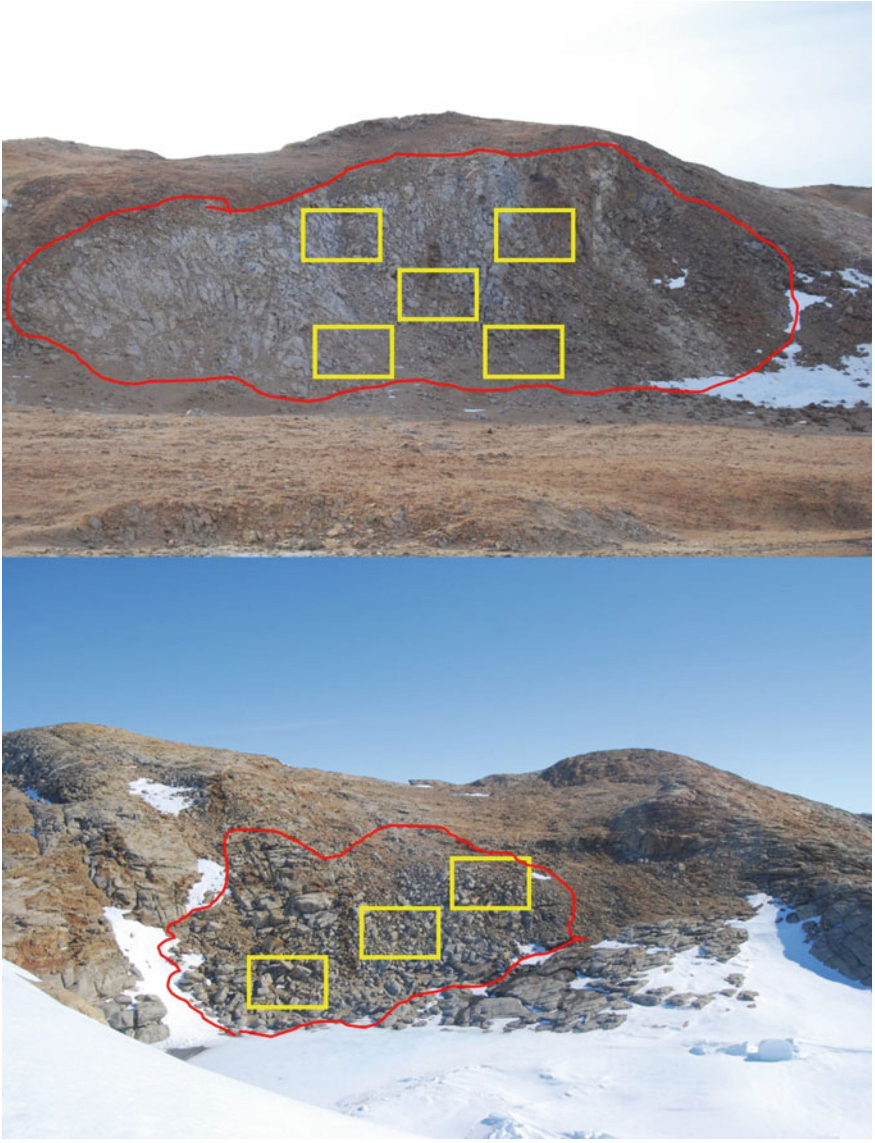

Fig. 3 Typical cliff habitats where snow petrels nest in Larsemann hills. Yellow boxes represent plots where nests were marked over these cliffs, while red polygon is the colony's approximate periphery

Fig. 4 Top: Slab type of snow petrel nest cavity; the snow petrels occupy narrow spaces under these flat rocks. Bottom (left): Boulder type of snow petrel nest cavity; the snow petrels occupy spaces created within two or more boulders. Bottom (right): Crack or Crevice type of snow petrel nest cavity; the snow petrels occupy spaces created within a crack in a rock

2.3 Nest Monitoring

Due to logistical constraints and limitations in visiting each marked nest site regularly or in a planned manner over the fieldwork period, it was decided to maximise the nest visits by visiting all substantial nests opportunistically. These visits were conducted in conjunction with sampling for genetic samples to look at the species' breeding success in the study area. Further, few nest sites were chosen for automatic camera

Fig. 5 Snow petrels occupy natural rock cavities at Grovnes peninsula, Larsemann Hills, East Antarctica

Fig. 6 Snow petrel nest cavities were measured physically, and nest occupancy was determined at Larsemann Hills, East Antarctica

operated monitoring to understand nest attendance and parental care strategies in snow petrels.

In association with Indraprastha Institute of Information Technology—Delhi, we designed motion-sensing cameras for monitoring breeding pairs of snow petrels. Being cryptic cavity-nesting species, manual observation methods do not work with snow petrel. Moreover, inclement weather conditions in the study area make it difficult to collect continuous observation data on the species. We decided to experiment with automated modes of image collection using motion-sensing cameras after due discussion with engineers and technicians working in wildlife biology. The camera design needed to be small enough to be fitted inside the nest cavities and sustain the study area's sub-zero temperatures (Fig. 7).

The main idea behind developing an automated camera system was to ensure:

(i) An inexpensive device that can be quickly recovered. The camera system's cost needed to be less as the chances of losing a device is inaccessible, extreme climate prone, remote areas is very high.
(ii) The camera system needed to be durable for the harsh climatic conditions of Antarctica. Larsemann hills change very frequently and receive precipitation from the katabatic winds blowing from the south-east.
(iii) The camera system needed to be insulated from external temperatures and snow precipitation to conserve battery power and provide output for a longer duration.

Fig. 7 Snow petrel individuals at nest cavities, Larsemann Hills, East Antarctica

With these constraints in mind, we designed a camera system with an optimised power consumption profile to prolong battery life. Therefore, the system consisted of two standard USB cameras connected to a Raspberry Pi A+, the smallest and most power-efficient board of the Raspberry family. Both cameras were programmed to take an image every second and compile them into short videos after every 10 min. If there is a change due to, e.g., a movement, the current incarnation was recorded along with a time stamp on a connected USB pen drive. The timestamp was provided by a custom PCB equipped with a DS3231 Real-Time-Clock (RTC). Since the system is self-sufficient, the PCB also provided a user interface to replace the USB pen drive and a depleted power supply on the fly without shutting down the system. The device itself recognised these events and acted accordingly by, e.g., turning off the cameras in case the pen drive has been removed. In case a fault is detected, the system shut down to a saved state, preserving the battery and preventing any further damages. Given the harsh environment of Larsemann Hills, where temperatures around −20 °C to −30 °C are recorded regularly, maintaining a power supply remained a challenge. We fitted one Lithium-ion battery with a rated capacity of 13,000 mAh to supply each operating system for approximately 24 h before it needed to be replaced. This was achieved by insulating both the Raspberry Pi and the Li-Ion battery against the sub-zero temperatures and using the electronic components' heat to warm the battery (Fig. 8).

A total of five camera systems were deployed, each nest camera system comprising of USB cameras (n = 2), Raspberry Pi microcomputers (n = 2), 16 GB USB storage

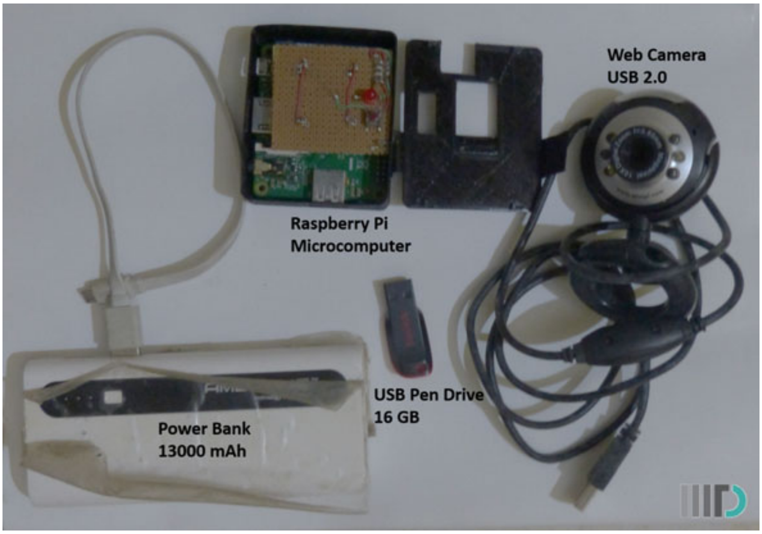

Fig. 8 Nest camera system designed with the support of Indraprastha Institute of Information Technology–Delhi. The images were recorded by a USB Web Camera connected to a pre-programmed Raspberry Pi microcomputer powered by a 13,000 mAh power bank battery. The images were recorded on a 16 G.B. data storage pen drive

devices (n = 2) powered by Li-ion battery (1) at nest sites adjacent to each other. The nest sites chosen to be monitored using the camera system were selected from pre-marked nest sites from field surveys conducted earlier (Pande et al. 2017; see Chap. 1 for details). The nest sites were selected based on their accessibility in inclement weather conditions and ease of replacement of batteries every 24 h. Nest sites on the north Grovnes peninsula, the Bharati research station site, were selected for undertaking this camera-operated continuous monitoring due to accessibility and feasibility in visiting throughout the study period.

3 Results

A total of 9 islands were covered to establish long-term plots for nest monitoring of snow petrels. Over 250 cavities/crevices large enough to contain snow petrel breeding pairs were paint-marked during the breeding season of 2014–15 and 2015–16 for long-term monitoring. Being alternate year breeders (Chastel et al. 1993; Olivier et al. 2005), it is imperative to monitor snow petrel nests for a minimum of two seasons to understand breeding success. In the first season of 2014–15, 95 nest sites (including OCN and UPN nests) were visited and marked for monitoring. In the second season (2015–16), 159 more nests were drawn and observed in the previous year. However, due to various logistical constraints during the fieldwork, an equal number of visits could not be made to all the nest sites in both seasons. Only 198 nests out of the total 254 (78%) could be visited in 2015–16. Moreover, only a subset of these marked nests (n = 66) could be seen more than twice in the next season to check for any nesting activity. A total of 238 nests were visited throughout two austral summer seasons (Table 1).

3.1 Nest Cavity Characteristics

Snow petrel nest cavities were classified into three types, viz. crack or crevice, boulder and slab, based on Einoder et al. (2014). A crack or crevice type of nest cavities are formed by glacial or cold weathering of rocks; boulder type of nest cavities are spaces available in between two or more stones, whereas; slab type of holes are rooms open between the ground and large flat boulders.

Out of the 192 cavities classified for rock type (Fig. 9), the boulder and slab type were equally occupied for nesting (40.6% and 40.2%, respectively). In contrast, lesser cavities of crack or crevice type were occupied (19.2%). The niches occupied by snow petrels had about 16% smaller entrance area (Fig. 10) and were about 18% lower in volume (Fig. 11) compared to the unoccupied ones. An independent-sample t-test of cavity volumes showed no significant difference between unoccupied and occupied nest cavities (t-stat = 0.94, $p > 0.05$).

Table 1 Nest occupancy, laying success and hatching success of snow petrel nests monitored over two breeding periods 2014–15 and 2015–16, Larsemann Hills, East Antarctica. Numbers in parentheses (n) indicate several nests, (–) represents sites not visited to ascertain the status of snow petrel nesting, (DNA—Data Not Available)—means places that could not be visited later in the season for confirming nest status

Island	2014–15			2015–16		
	Occupied nests	Laying success%	Hatching success%	Occupied nests	Laying success%	Hatching success%
Betts	–	–	–	6	63.6 (4)	DNA
Bharati	31	90.3 (28)	87.1 (27)	55	63.6 (35)	16.4 (9)
Breadloaf	–	–	–	5	100 (5)	100 (5)
Broknes	34	91.1 (31)	85.3 (29)	41	87.8 (36)	4.8 (2)
Cook	–	–	–	5	20 (1)	120 (6)
Easther	26	50.0 (13)	42.3 (11)	15	93.3 (14)	73.3 (11)
Fisher	–	–	–	24	100 (24)	54.2 (13)
Manning	–	–	–	1	100 (1)	100 (1)
McLeod	4	100 (4)	100 (4)	6	66.6 (4)	DNA
Total nest monitored	95	76	71	152	105	47

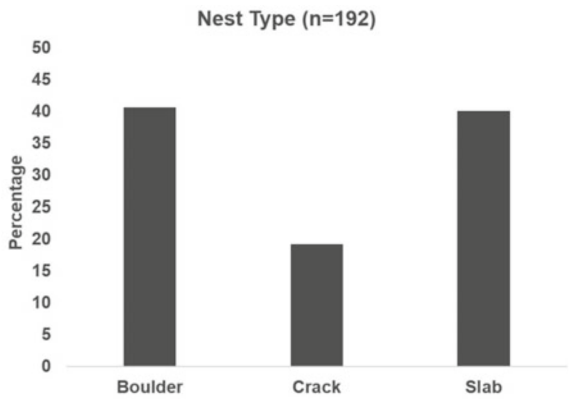

Fig. 9 Rock type of nest cavities occupied by snow petrels at Larsemann Hills, East Antarctica

Nest cavities were mostly oriented towards the east direction (~39%) in the study area (mean Vector 61.749°). Wind direction data (weekly average for December 2015, incubation period) was acquired from a weather station deployed by India Meteorological Department at *Bharati* station about 1.5 km away. The wind in the area was predominantly from the north direction (mean Vector 12.379°). Rose plots plotted using software Oriana v.4.0 for nest orientation and wind direction exhibit complete exclusion of north-facing cavities by the snow petrels (Fig. 12). Rayleigh's test performed on the circular data of nest orientation was significant (Rayleigh's $z_{7.298}$, $p < 0.001$; see Table 2 for circular statistics), which means that nest cavities

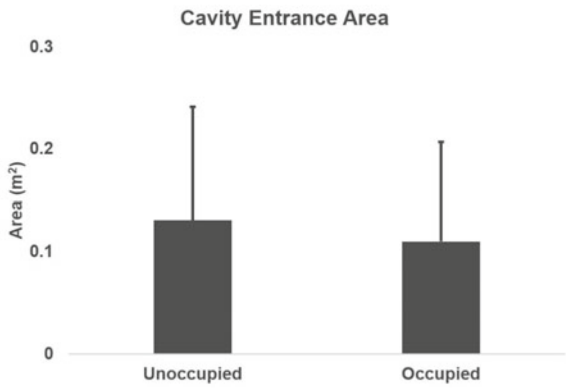

Fig. 10 Nest cavity entrance areas of occupied and unoccupied nests of snow petrels at Larsemann Hills, East Antarctica

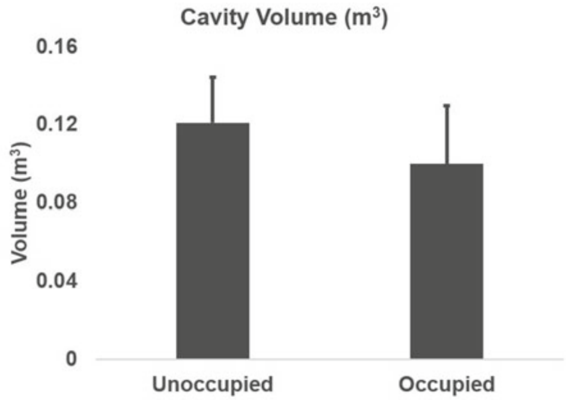

Fig. 11 Nest cavity volumes of occupied and unoccupied nests of snow petrels at Larsemann Hills, East Antarctica

were clustered towards specific directions, in this case towards east-northeast and north-northwest.

3.2 Breeding Success

Breeding success was classified into (i) laying success calculated as the number of eggs laid in the occupied nests and (ii) hatching success as the number of eggs hatched of eggs laid. The fledging success could not be determined as the fieldwork could not be done post-late-February (last dates for visiting nests in 2014–15 and 2015–16 was 19-Feb 2015 and 12-Feb 2016, respectively). For each year, the percentage of

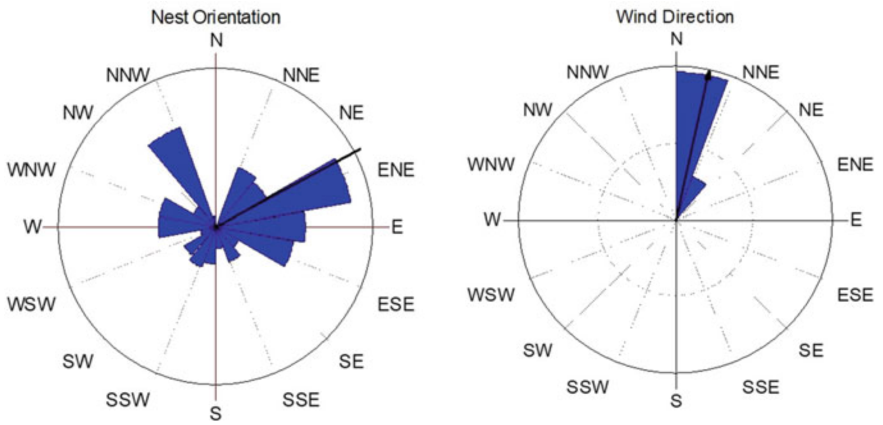

Fig. 12 Snow petrel nest orientation and wind direction rose plots of Larsemann Hills, East Antarctica. The blue triangles represent the wind direction and nest orientation clustering concerning the movement, and the black arrow represents the mean direction

Table 2 Summary circular statistics of nest orientation and wind direction measurements at Larsemann hills using Oriana v.4.0

Variable	Nest orientation	Wind direction
Data type	Angles	Angles
Number of observations	171	10,134
Mean vector (μ)	61.749°	12.379°
Length of mean vector (r)	0.207	0.995
Concentration	0.422	100.1
Circular variance	0.793	0.005
Circular standard deviation	101.755°	5.741°
One-sample tests		
Rayleigh test (Z)	7.298	10,032.76
Rayleigh test (p)	6.77E-04	<1E-12
Rao's spacing test (U)	275.211	348.028
Rao's spacing test (p)	<0.01	<0.01

occupied nests was calculated as the number of nests in which laying was observed divided by the total number of nests monitored. In 2014–15, the mean laying and hatching success for the first season 2014–15 was higher than that of the second season 2015–16 (82.8% for 2014–15 and 77.2% for 2015–16; 74.7% for 2014–15 and 58.6% for 2015–16 respectively; Fig. 13).

To account for non-parametric and unequal variances, Mann–Whitney U tests (two-tailed) were performed to test the effect of cavity characteristics concerning nest occupancy and laying success, respectively. Sample sizes were not sufficient to test for differences in the distribution of values in the nests with successful hatching. The rock cavity volume did not have any effect on occupancy or laying success. Nest

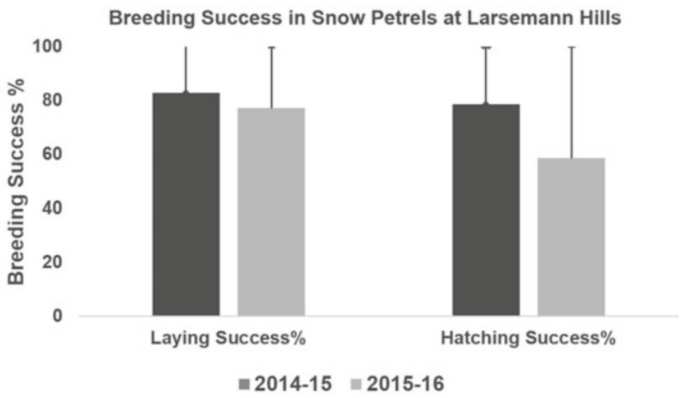

Fig. 13 Breeding snow petrel success derived from monitored nests during the austral summers of 2014–15 and 2015–16 at Larsemann Hills, East Antarctica

Table 3 Mann–Whitney U test (two-tailed) statistics for nesting success comparison between cavity volume and nest bowl volumes

	Nest occupancy		Nest with egg (successful laying)	
	Cavity volume	Nest volume	Cavity volume	Nest volume
Samples	$N_1 = 137, N_2 = 33$	$N_1 = 137, N_2 = 33$	$N_1 = 59, N_2 = 66$	$N_1 = 66, N_2 = 71$
U-value	1778.5	1670	1697	1820
z-score	−1.89702	−1.89702	−1.23389	2.2508
p-value	0.06	0.06	0.21	0.02*

*Indicate significant value, $p < 0.05$, 2-tailed

bowl volumes did not affect occupancy but significantly affected spreading success (see Table 3).

3.3 *Breeding Phenology*

A total of 12 nests were monitored using the automated motion-sensing camera systems deployed at North Grovnes peninsula. Cameras were moved if the breeding pair deserted the nest cavity or the laying did not happen. Out of 12 cavities occupied, 4 teams failed to lay an egg, while two out of those later could not hatch. Hatching was successful in only 6 of the nests monitored. Over 3 million images from the automated nest camera systems obtaining crucial insights into the breeding biology of snow petrels in the study area. Nest attendance patterns of snow petrels were ascertained during the breeding period using these images.

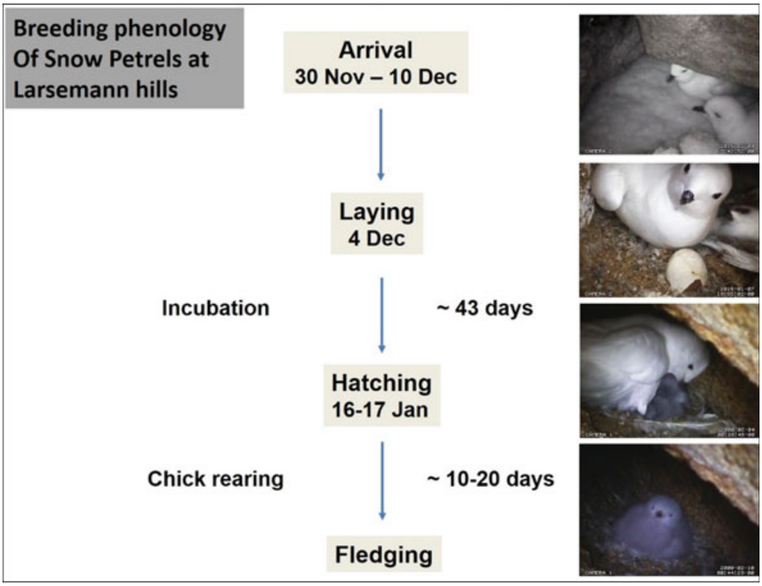

Fig. 14 Breeding phenology of snow petrels revealed through automated motion-sensing cameras deployed at North Grovnes peninsula, Larsemann Hills, East Antarctica

Snow petrels arrived in the last week of November in the area after the pre-laying exodus and occupied rock cavities for nesting. Nesting began by the first week of December, though individuals kept coming till Dec 10. Seven snow petrel breeding individuals were documented laying a single egg during the intervening night of 4th and 5th December 2015. One of the nests could not be assessed for the egg's presence as the bird moved very little to give away any hint. After an incubation period of 43 days, the eggs hatched on 16th or 17th January ($n = 6$). Later, the chick-rearing period varied between 10 and 20 days in different breeding pairs. The monitoring could not go 26–27 days beyond the hatching date due to the expedition vessel's departure from Larsemann hills on Feb 12 2016. This first-time automated monitoring of an Antarctic cavity-nesting seabird provided crucial insights into its breeding phenology and serves as the first baseline information on the species from Larsemann hills (see Fig. 14).

4 Discussion

Multiple environmental factors affect the nest-site selection and breeding success (Bourgeois and Vidal 2007; Catry et al. 2003; Drummond and Leonard 2010; Einoder et al. 2014). Various physical factors such as cavity depth, volume, rock type, substrate, slope, aspect and environmental parameters like wind, temperature, precipitation etc. are critical for selecting a nesting site to avoid inclement weather conditions and provide protection from predators (Ramos et al. 1997; Bourgeois and Vidal 2007). However, collecting data on these variables needs repeated systematic surveys over several years to assess each variable's role in nest-site selection studies significantly. This study forms the first attempt under the Indian Antarctic Program to gather systematic data on Antarctica's single species. After several years of field surveys under limited logistics (Sathyakumar 1995; Bhatnagar and Sathyakumar 1999; Hussain and Saxena 2008; Sivakumar and Sathyakumar 2012), snow petrel colonies were mapped and marked for long-term monitoring around Indian research station Bharati (Pande et al. 2017, 2018).

In the Indian Antarctic Expeditions, the field visits are limited by the availability of travel support to Larsemann Hills islands. When the sea ice is thick around the station area (roughly >1 m thickness), the travel to various nearby islands or peninsulas is supported by snowmobiles. However, due to the thinning of sea ice in the Quilty bay and Thala fjord area, the use of snowmobiles is curtailed for safety reasons, somewhere around mid-December every year. Later, after the arrival of the expedition vessel near the station area, the field visits are supported by single-engine light utility helicopters that facilitate the visit to far-flung islands. Considering these logistical limitations, the effort to visit and mark colonies of snow petrels varied over the two seasons of 2014–15 and 2015–16. In the 2014–15 season (34th Indian Antarctic Expedition), the support to visit field sites was significantly reduced due to the helicopter's technical glitch. Only 95 nest sites could be seen and marked in 10 days (Jan 29 and Feb 19 2015). On the other hand, the duration spent at Larsemann hills was more in the second season (2015–16; 35th Indian Antarctic Expedition). Thus, more field visits could be made (24 days between Nov 30, 2015, and Feb 11 2016). Consequently, 62.5% more nests were monitored in the second season.

The laying as well hatching success was higher for the second season compared to the first season. However, this difference in breeding success could be attributed to various factors, including differences in sample sizes and local weather pattern, as excessive snow accumulation is known to negatively impact snow petrel breeding success (Einoder et al. 2014). At Larsemann hills, snow petrels established nests between boulders and under flat slab-like rocks and preferred fewer crevices or cracks within stones. However, a detailed study on the availability of these spaces suitable for snow petrel nesting versus actual use could be done in the future to look at the nesting habitat preference of the species.

Snow petrels breed in naturally formed rock cavities (Einoder et al. 2014; Olivier et al. 2004). At Larsemann hills, snow petrels selected cavities with smaller entrances and lower overall volume for breeding. Narrower gates presumably reduce airflow (Einoder et al. 2014) and subsequently lead to lesser ice accumulation during precipitation or snowdrifts. This aspect of nest-site selection could be studied in detail in future monitoring studies. The wind direction in the study area is mainly from a north direction, and snow petrels select sites which are towards mostly east-northeast and north-northwest directions. However, the wind direction data was taken from the weekly average for December 2015. Long-term weather data is needed to look for prevailing wind conditions during late November and early December, the months when the snow petrels arrive for occupying nest cavities.

Research on breeding biology of seabirds has been conducted chiefly from direct observations or repeated site visits or with the use of hand-held camera devices (Bourgeois and Vidal 2007; Einoder et al. 2014; Lacey 2018; Mallory 2009; Mejías et al. 2017; Olivier and Wotherspoon 2008). However, in recent times and with the advent of advanced remotely operated camera technology, many cryptic cavity-nesting species have been monitored worldwide (Landers 2011; Prinz et al. 2016; Sabine et al. 2005). The camera monitoring system designed by us at Wildlife Institute of India and Indraprastha Institute of Information Technology- Delhi were the first attempt to study a cavity-nesting Antarctic seabird species. It gave helpful information on the breeding phenology of snow petrels at Larsemann hills, specifically about the dates of laying, hatching and nest attendance by parents. The image dataset obtained from nest monitoring requires quantification for detailed analysis of snow petrels' intra-season breeding behaviour pattern at Larsemann Hills. More data on the breeding of the only predator in the area, the south polar skua, on long-term weather patterns and sea ice conditions should also be collected simultaneously to investigate the impacts of climate change on the breeding success of snow petrel and other co-habiting seabird species (Barbraud et al. 2015; Barbraud and Weimerskirch 2001; Constable et al. 2014). Species-specific monitoring work with a systematic long-term approach would yield crucial data on species' biological responses to climate change in the continent.

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