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Summary

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Pilot study on monitoring climate-induced changes in penguin colonies in the Antarctic using satellite images

Summary

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The effects of **global climate change** can also be seen in the Antarctic, particularly on the western Antarctic Peninsula in winter. Meteorological data from the Faraday/Vernadsky station show that the temperature in June has risen by 6°C over the last 50 years. This rising temperature trend has far-reaching effects on the marine ecosystem and triggers a cascade of changes. Satellite images taken over the past two decades show that the extent of sea ice cover is shrinking. Sea ice plays a key role in the life cycle of Antarctic krill (*Euphausia superba*), which is at the centre of the food web of the Antarctic ecosystem. The distribution and density of krill have an effect on the survival and reproduction rate of its predators, and thus also on penguin populations.

Population change and relocations of penguin breeding areas, in particular those of gentoo (*Pygoscelis papua*), chinstrap (*Pygoscelis antarctica*) and Adélie penguins (*Pygoscelis adeliae*) in the Antarctic Peninsula region, are the result of such climate change and have been observed in diverse areas of the Antarctic. These studies show that populations of Adélie penguins and, to some extent, also chinstrap penguins are decreasing in the northern parts of the Antarctic Peninsula. In contrast, evidence has been found of positive population trends in southern Antarctic areas.

So far, investigations into population developments of penguin colonies have usually involved population counts and mapping on the ground or using selective aerial photographs taken from aeroplanes and helicopters. These methods are comparatively laborious and very costly. The population details thus obtained for small areas are mostly used in maintaining valuable long-term data sets. The number of colonies is large (it can be assumed that many are as yet undiscovered) and access to them is generally very difficult. It would thus appear that, objectively speaking, very comprehensive monitoring is only possible using remote sensing data from satellites. **The objective of the present project** was to investigate the **possibility of creating a penguin monitoring system** that is as comprehensive and representative as possible.

In order to assess the feasibility of a monitoring programme, the satellite-based remote sensing systems available were assessed as to their ability to detect particular features (e.g. colony area, number of individuals, changes over time, separation of species). In addition, the possibilities of automation were explored and preliminary proposals made as to the course of action to be taken internationally to create a comprehensive monitoring project.

The project involved selecting **six test sites** which cover the required range of species (target: all five Antarctic penguin species) as well as the diversity of the landscapes, and where population counts were carried out during the 2011/2012 season. Two of the test sites (Cape Bird and Kopaitic) have two colonies, while another has five (Adélie Land). In five of the test sites there are count data from previous years, which were used for multitemporal analyses.

The next stage of the study was to analyse the images and to draw up proposals for a monitoring programme. Separately, counts of emperor penguins will be carried out during the 2011/2012 Antarctic winter, when this species breeds, and the relevant satellite images obtained and analysed.

Test sites

In preparation for the project both the contractor and the Federal Environment Agency contacted a large number of scientists, scientific institutions and Committee for Environmental Protection (CEP) representatives of the Antarctic Treaty Consultative Parties to request their cooperation. By studying the relevant literature and through good contacts with relevant scientists, we were able to settle on six locations as test sites, for which population data are available. These were the test sites Ardley Island, Point Thomas, Torgersen Island and Kopaitic (consisting of Kopaitic Island and Schmidt Peninsula), which are situated in the northern part of the Antarctic Peninsula, and the more southerly, continentally situated test sites Cape Bird (consisting of Cape Bird N and M) and Adélie Land (consisting of Le Mauguen Island, Jean Rostand Island, Claude Bernard Island, Petrels Island and Lamarck Island).

At each of these sites, diverse scientists carried out **counts of the species *P. papua*, *P. antarctica* and *P. adeliae* (gentoo, chinstrap and Adélie penguins) at the beginning of December 2011**. However, those working at the Cape Bird test site were unable to finish preparing their count data and send them on time. For all sites, apart from Kopaitic, there are historical count data available. Whereas the above-mentioned species breed in the Antarctic summer, the species *Aptenodytes forsteri* (emperor penguin) breeds in the Antarctic winter. As part of the collaboration between the *German Aerospace Centre* (Deutsches Zentrum für Luft- und Raumfahrt e. V. - DLR) and the *Alfred Wegener Institute of Polar and Marine Research* (AWI), it was therefore arranged for counts to be carried out of the emperor penguin colony located close to the research station Neumayer III during the Antarctic winter of 2012. It is expected that these results will be analysed and incorporated with the rest by October 2012.

Remote sensing data and processing the data

The satellites for this project were chosen so that they covered a broad spectrum of spatial and spectral characteristics. **Landsat7**, with 30m in the multispectral band, has a rather coarse spatial resolution, but covers a large spectral range in the mid-wavelength and far infrared regions. **RapidEye**, selected for the mid-range spatial area, records multispectral data with 5m ground resolution and is the only sensor for this range that has five multispectral bands. Two high-resolution platforms were chosen. The first was **QuickBird2**, with 0.6m in PAN, for which there are images of the Antarctic from as early as 2002, and the second was **WorldView2**, which is the only high-resolution sensor with eight multispectral bands. A total of 17 images from QuickBird2, WorldView2 and WorldView1 were purchased from European Space Imaging (EUSI), either as new images or from the archives. Commissioned by EUSI, DigitalGlobe tried a number of times to obtain images of Ardley and Torgersen as well, in the 2011/2012 breeding season, using QuickBird2 and WorldView2. However, this was not possible because of nearly permanent cloud cover. There are, however, suitable historical QuickBird2 or WorldView2 images of these sites. No analysis of RapidEye archive data was possible in this study because they were not available in time.

As regards radar data, only **TerraSAR-X SAR data** were used in this study. TerraSAR-X is an X-Band-SAR system with a 3.1cm wavelength. The images were taken in diverse imaging modes, with reference both to resolution (StripMap with 3m and SpotLight with up to 1m) and polarisation (Single-Pol (HH) and Dual-Pol (HH/VV)). In all 23 StripMap and

8 SpotLight TerraSAR-X SAR images were analysed. Before the analyses a pre-processing of the satellite images consisting of radiometric and geometric correction was carried out.

Assessment of the possibilities and limitations of the diverse image recording systems

The possibilities and limitations of the individual image recording systems are determined on the one hand by their availability and on the other hand by their ability to detect penguins or guano.

Availability

For the Antarctic, the availability of usable optical satellite data is restricted mainly by **weather conditions and the lack of light** during the Antarctic winter. Particularly in the northern part of the Antarctic Peninsula, the most important factor that limits availability is the frequent cloud cover. In contrast, in the continental coastal areas weather conditions are much more suitable for obtaining optical images. Images taken shortly before or shortly after the Antarctic winter have the disadvantage that, depending on the topography of the site, there are likely to be hard shadows, which make any analysis more difficult, or even impossible.

The **Landsat7** platform has the advantage that the images are available to anyone promptly and without cost. There is comprehensive spatial coverage of the Antarctic coastal areas. In addition, there are incomplete but free archive data available, for Landsat7 going back to 1999 and for Landsat4 going back to 1982. Landsat7 only flies over the same spot every 16 days. However, in theory the temporal coverage by Landsat7 is greater as the edges of the image swaths overlap. This overlapping increases towards the South Pole, so that the more southerly colonies are theoretically recorded more often. However, the Scan Line Corrector Failure, which affects all Landsat7 images as of 2003, becomes increasingly large towards the edge of the image, with the result that images where a colony is at the edge are only very rarely usable, which again greatly restricts availability. In practice this means that in some years, where bad weather conditions are more frequent, there may be no usable images, or only images that are hard to analyse, during the period from December to February, which is normally the ideal time for detecting colonies of rock-breeding penguins. In our experience, there are for instance four times as many usable images per season for Cape Bird than for the more northerly Ardley Island.

In contrast to Landsat7, the satellites **WorldView1, WorldView2 and QuickBird2** only record images of the Antarctic to order. Although they face the same restrictions such as weather and lack of daylight, due to their swivelling sensor they achieve much greater coverage, taking many more images in a short period. Thus, even limited periods with cloud-free skies can be used to obtain images. Even so, it is possible that in a particular season no usable images of certain colonies can be made. Due to weather conditions, it was not possible to obtain any images of Ardley und Torgersen Island for the 2011/2012 season, although over a period of just under two months these colonies were overflown a number of times by WorldView1, WorldView2 and QuickBird2. There are a lot of gaps in the records of historical images, both in time and place. Another disadvantage is the relatively high purchase cost (at least US$1,800 per current image).

Detectability

Detectability is linked to the spectral and spatial resolution of the sensor and to the methods employed in each case. Therefore, we give a summary below of these two aspects. Subpixel analysis provided no usable results.

The **analysis of the Landsat7** images showed that not all penguin colonies studied could be detected equally easily. **For colonies to be detectable with certainty, the area of the colony covered with guano had to measure at least 3,000m^2 and contain more than 1,000 – 5,000 occupied nests.** A further decisive factor was the density of nest groups within the colony. If the individual nest groups were spread over a wide area, as on Ardley Island, then detection was impossible. Thus, colonies with a density lower than 0.12 occupied nests per m^2 of the occupied colony sector (the area bounded by nest groups) could not be detected by Landsat7. The shape of the colony and the classes of land cover surrounding it also influenced detectability, especially if the above-mentioned parameters were around the minimum values given. Colonies with the same area and number of nests were easier to detect with Landsat7 if they were compact (e.g. Lamarck Island) than if they were long and sinuous in form. Colonies situated on ground that offered a strong contrast (e.g. dark volcanic rock on Cape Bird) were significantly easier to detect than colonies where the area was partly covered with or surrounded by vegetation, which is spectrally similar to guano (e.g. Point Thomas). It was not possible to distinguish between different rock-breeding penguin species with the Landsat7 images.

Due to the restrictions mentioned above, we only succeeded in detecting the colonies of Cape Bird, Adélie Land and Kopaitic Island. Experience gained from the analyses showed that manual delineation provided the best results as regards colony area. The drawback of manual delineation is, among other things, that it is very time-consuming if large areas need to be examined. However, as the colonies are all relatively small in relation to the resolution of Landsat7, time was not an important factor. On the contrary, manual delineation was the fastest method for analysing individual images. One disadvantage was that manual interpretation is very subjective. The colony boundaries could be interpreted very differently by different individuals.

We were also able to detect penguin colonies using supervised classification and the ratio approach. It can be seen that the results of area determination vary greatly between the individual colonies. It can also be seen that the classification results of both methods worsen considerably in line with a decline in colony area. The **minimum threshold of the colony area for results that can still be used for a quantitative analysis is around 40,000m^2**. Altogether, both methods gave comparable results.

The **analysis of the panchromatic WordlView1** images showed that it is relatively difficult to detect penguin colonies on rocky surfaces and that it is only possible at all under certain conditions. The approximate location and size of the colony to be detected must be known and its brightness value must be clearly distinguishable from its surroundings. Only manual image interpretation was able to give usable results under these special conditions.

For **QuickBird2 and WorldView2, no minimum threshold could be found** for the detectability of colonies or their nest groups. In fact, we detected all the colonies, including the smallest. With the help of **manual image interpretation**, we were even able to recognise single nests and larger groups of penguins. Despite the high spatial resolution of 50cm – 60cm, no single penguins standing on rocks were detectable. There were problems above all with images taken at the start of the breeding season and in which the colony was under a considerable covering of snow. On the one hand, snow covered the lower-lying potential nesting places and on the other hand, it can be assumed that at the beginning of the breeding season there was not a sufficient accumulation of detectable guano. It was also possible to detect all colonies with **supervised classification and the ratio approach**, though with significant variations in quality between the individual images. The largest variations were in snow-covered images (Torgersen 2007 and Ardley Island 2009), and also those with mist (Point Thomas 2011). No correlation can be seen between quality of the classification and colony area. It can also be recognised that supervised classification gives better results under bad conditions than the ratio approach. With the QuickBird2 and WorldView2 images **no definitive distinction between penguin species could be made**. Only at the colony near the Pieter J. Lenie Field Station (USA) was it possible to surmise that Adélie penguin nests could be distinguished in an area otherwise dominated by gentoo penguins. Due to a lack of up-to-date count data and mapping data, it was not possible to reach a definitive conclusion as to whether these really were Adélie penguins.

If all the results from QuickBird2 and WorldView2 images are compared, it becomes clear that the images from WorldView2, with a maximum 10cm higher spatial resolution and equipped with four additional spectral bands, had no significant advantage over the QuickBird2 images when it came to detecting penguin colonies. The additional multispectral bands also offered no advantages in practice, as they are all in the visible spectrum or the near-infrared region, where the reflection of guano does not differ significantly from that of the land cover classes that are to be distinguished.

While the DLR can provide positive examples as regards the detectability of colonies of the species *A. forsteri* (emperor penguin) using **TerraSAR-X**, no penguin colonies of the species *P. papua*, *P. antarctica* and *P. adeliae* (gentoo, chinstrap and Adélie penguins) could be detected by means of TerraSAR-X SAR data. Even with the inclusion of the shape files of the colonies derived from the optical satellite data, no correlation could be identified in relation to radar backscattering properties. This is true of both Single-Pol and Dual-Pol-SAR images. This can very probably be attributed to the fact that with a 3.1 cm wavelength for TerraSAR-X, the radar backscattering properties are not – or not significantly – altered by a thin layer of guano on scree or rock. The composition of the ground in the breeding areas of these species is what makes them significantly different from the areas where emperor penguin colonies breed. Emperor penguins breed on sea ice, and guano deposits significantly alter the radar reflectivity of the sea ice.

Assessment of the detectability of changes in colonies

In order to detect changes between different seasons, we first had to determine the extent of changes in the detectable area over one year. We needed to exclude the possibility that area changes detected in images from different years might be attributable to the variability within a single year. We were then able to investigate whether and to what extent it was possible to detect changes in the size of those parts of the colony that are covered with guano. Based on these results, we were able to analyse whether there is any correlation between changes in area detected and changes in the number of breeding pairs from one season to another.

Area changes in the course of a season

Four Landsat7 images of Cape Bird (2010/2011 season) and three of Adélie Land (2008/2009 season) were available to use as examples for detecting area changes within a season. For both sites it was established that the detectable area increased towards the end of the season and, in the case of Cape Bird, the area decreased again after the actual breeding season. It is assumed that one reason for this is an increasing **accumulation of guano during the course of the breeding season**. Another reason is that there is usually **snow on the ground in images from the start of the season,** which covers breeding sites situated at lower levels. A comparison of all three methods shows that the changes measured are relatively large, although the changes detected by manual interpretation are the smallest. It is also noteworthy that only in the case of Cape Bird N were moderate changes recorded for all methods. With Landsat7 it appeared that for large colonies, area changes from one year to another could only be detected by manual interpretation if they were greater than 13% and with supervised classification or the ratio approach if they were greater than 17%. In contrast, in the smaller colonies only changes of between 20% and 105% could be detected, which raises doubts about the practical use of such methods for change detection of small colonies with Landsat7 images. However, as this analysis only considered one season and two colonies, the results are not representative and should be tested with additional time series analyses.

Detectability of changes in the number of breeding pairs

The basis assumption for detecting changes in the number of occupied nests is that they correlate with area changes in the colonies. This roundabout way using area change is necessary as individual penguins brooding on rocks cannot be comprehensively detected with any certainty. For this reason the area changes detected in Landsat7 and QuickBird2 images from different years were compared with changes in numbers of occupied nests. As the only ground-based area and population measurements available were measurements of Ardley Island that corresponded to a QuickBird2 image from the 2005/2006 season, the area changes measured could not be verified but could only be evaluated as to their plausibility.

For Adélie Land we examined the differences between four **Landsat7** images from different seasons and for Cape Bird we compared two Landsat7 images. The analyses of the Adélie Land and Cape Bird M colonies gave predominantly implausible results. The reason for this can be found in the limited spatial resolution of Landsat7 and the small size of the colonies. The implausible area changes detected are too strongly influenced by imprecision resulting from the methods used, rather than being the result of actual changes in colony area. In contrast, for the large Cape Bird N colony it was established that there was no correlation between area change and a change in the number of occupied nests. In the period from 2001 to 2007, the absolute number of occupied nests doubled, but no significant change in colony area was recorded. This is probably because there is first an increase in density of the nest groups, and only when all the best nesting sites are taken and penguins have to seek space elsewhere is there an increase in area. Thus, it is only when a specific threshold value has been exceeded that the colony increases in area. Other authors have shown that nest density can vary greatly, from 0.1

to 3.1 breeding pairs per m^2. The results of area measurements using supervised classification and the ratio method deviated significantly from those obtained by manual determination (50 - 80%), with the result that in practice only very large area changes could be detected with certainty using these methods.

We were able to do a **multitemporal analysis for QuickBird2** images for three colonies each on two different dates. With manual interpretation of Adélie Land images it was only when there were large changes in area (>26%) and large changes in the number of occupied nests (>15 %) that a correlation could be established between the two. On the one hand, this could be because small changes in area could not be detected due to the imprecision of measurements with this method. On the other hand it could also mean that changes in area only occur once a specific increase in the density of occupied nests per m^2 has been reached. For Ardley Island, however, no correlation could be established. For Torgersen Island it was not absolutely clear whether the correlation we found could be ascribed to actual area changes or was due to factors related to the images. It was possible to establish without any doubt a decrease in area at Point Thomas and an increase near the Pieter J. Lenie Field Station, which is situated a few kilometres south of Point Thomas. Due to a lack of count data, we could not reach any conclusion regarding a correlation with a possible change in the number of occupied nests. The investigations of Cape Bird N supported the observations made with Landsat7, as no area change could be measured with the QuickBird2 images either. However, there were also no count data of occupied nests for these QuickBird2 images. With the QuickBird2 images, too, supervised classification and the ratio analysis produced relatively large deviations from manual determination. Supervised classification, with a maximum deviation of 27%, gave significantly more accurate results than the ratio analysis with a maximum deviation of 45% from manual delineation.

Due to the absence of historical images, we could not reach any clear conclusions as to the suitability of **WorldView1** images for change analysis. However, examination of the individual images and the results of other authors indicate that changes in colony area can be detected using panchromatic images, if the approximate area is known *a priori* and the colony is situated on a substrate that offers a strong contrast.

A multitemporal analysis was carried out of a number of consecutive **SAR images**, with the same imaging geometry, of Ardley Island, Point Thomas and Kopaitic Island/Schmidt Peninsula (colonies of the species *P. papua*, *P. antarctica* and *P. adeliae*). In each case there were either four or six consecutive images. The analysis provided no usable results with regard to changes in penguin colonies. For the species *A. forsteri*, data must first be collected during the next Antarctic winter, so as to be able to carry out a multitemporal analysis.

Assessment of the efficiency of the method and the possibility of automation

The **possibility of automating the analysis procedure was tested** for supervised classification and ratio analysis for Landsat7, QuickBird2 and WorldView2. To this end, regional (matched to colonies from one region with similar land cover classes) and cross-regional (matched to all colonies of different regions) signature catalogues and ratio combinations were created in each case and tested with supervised classification and ratio analysis.

There were only enough images available from **Landsat7** to test automation of the analysis methods adequately. We were able to use a total of seven images to create regional signature catalogues and up to 15 images to create cross-regional signature catalogues or ratio combinations. This is important as the automated analysis methods applied in this project require the broadest possible range of spectral variations of the land cover classes that occur in the images. Both supervised classification and ratio analysis provided usable results for all the colonies tested. The colonies were detected on all the images of Cape Bird, Adélie Land and Kopaitic Island. In this process, it made no difference whether regional or cross-regional analyses were carried out. The quality of both analysis methods depended greatly on the area size of the colonies to be detected. Thus, once again it was only with Cape Bird N that the deviations from manual delineation were so small that minor changes in colony area could be detected with certainty. It was not possible to test detectability in the vicinity of sites with large areas of vegetation. The problems in detecting the Point Thomas colony suggest that vegetation near colonies can hamper automation. Vegetation is also an important factor in differentiating between the two analysis methods. In one test the ratio approach failed to distinguish between guano from Cape Bird and the vegetation of Point Thomas. In contrast, our experiences using supervised classification in this project indicated that such a distinction is possible. When the cross-regional signature catalogue created using the images from Cape Bird, Adélie Land and Kopaitic Island was applied to King George Island, the results were not promising. In principle, however, the Antarctic lends itself to automation due to the comparatively limited variability of the land cover classes. For test purposes, therefore, further images of the Cape Bird region, which had not previously been examined, were classified with the cross-regional signature catalogue using supervised classification and ratio analysis. As a result, two further colonies were detected – on Beaufort Island and Cape Crozier – which were previously unknown to the person processing the images. However, the process also highlighted the problem of false classifications, as the ratio method falsely classified light-toned stone as guano in the Antarctic Dry Valleys. In order to minimise such errors, it would be sensible to classify only the coastal strips and islands, rather than the totality of the Landsat7 images.

For the assessment of **QuickBird2** there were only at most two images of the same colony available, and for WorldView2 only one. As a result, we were unable to carry out a conclusive regional analysis using supervised classification and ratio analysis. For the cross-regional analysis there were also too few images recorded under comparable conditions for us to reach a definitive conclusion regarding the possibility of automation. The analyses performed in spite of this problem showed that an automated analysis seems to be possible, at least for the images of Cape Bird and Adélie Land. In contrast, an automated ratio analysis of Ardley and Torgersen Island can be completely ruled out, as at those sites guano could not be distinguished from other land cover classes without significant false classifications. In summary, it appears much more difficult to achieve automation with the methods tested in this project when using QuickBird2 and WorldView2 images than with the Landsat7 images. The QuickBird2 and WorldView2 images gave rise to many more false classifications. The reason for this lies in the high spatial resolution, which means that there are a wide variety of land cover classes in a small area.

Using **TerraSAR-X SAR** data we were unable to detect penguin colonies of the species *P. papua*, *P. antarctica* and *P. adeliae* (gentoo, chinstrap and Adélie penguins), so that the question of automation does not arise.

Proposals for implementing an international monitoring project

In order to establish monitoring of penguin populations throughout the Antarctic, it is essential that there be cooperation between **science** (Scientific Committee on Antarctic Research - SCAR) and **politics** (Antarctic Treaty Consultative Meeting - ATCM), with the additional involvement of **other players** (e.g. Convention on the Conservation of Antarctic Marine Living Resources - CCAMLR). As well as the political will, other crucial elements are communication (the willingness to exchange data), secure funding and, not least, the drive and energy of the relevant scientists. For this reason, this initiative should be discussed jointly by the above-mentioned bodies and aims and methods should be worked out which can meet with the approval of all concerned.

Complete long-term data sets for Antarctic bird populations are rarely available, and the penguin species that breed in the Antarctic are no exception. Up to now, Antarctic-wide comprehensive records have only been created for the emperor penguin. The essential prerequisite for creating Antarctic-wide records of the three Pygoscelis species (Adélie, chinstrap and gentoo penguins), and of the macaroni penguin (*Eudyptes chrysolophus*), is that the Antarctic bodies above work together and provide mutual support.

The **SCAR 'Expert Group on Birds and Marine Mammals'** (SCAR EG-BAMM) is seen as the most suitable body for the coordination of data collection. This expert group belongs to the 'Standing Scientific Group on Life Sciences' (SSG-LS). According to its constitution, the SCAR EG-BAMM brings together expert knowledge in the fields of Antarctic ornithology and mammalogy, and supports research that sheds light on the role of birds and seals in the marine and terrestrial ecosystems of Antarctica. The group also applies and interprets available scientific data to contribute to the protection and management of Antarctic birds and mammals. For example, SCAR EG-BAMM collects information about the population status and population trends of individual species in the Antarctic Treaty Area. Since the 1980s, the former SCAR 'Bird Biology Subcommittee' (BBS) of the 'Working Group on Biology' has collected and published information. However, the last overview is more than 10 years old. The 'Australian Antarctic Data Centre (AADC)' has developed and administers a password-protected database, and its long-term data formed the basis for the analysis for that overview.

The plan is to present the results of this project at the XXXII 'SCAR and Open Science Conference', which takes place in Portland, Oregon, USA, in July 2012, and to discuss them within the EG-BAMM. The results of the EG-BAMM meeting will be taken up by the SCAR SSG-LS.

Parallel to this, Germany plans to introduce the project results at the next **Antarctic Treaty Consultative Meeting (ATCM) and to its Committee for Environmental Protection (CEP)**. In advance of the project, the Federal Environment Agency has made contact with CEP representatives of other Treaty Parties in order to prepare the monitoring initiative connected with the project and to try and attract support.

An agreement with representatives of the **Convention of the Conservation of Antarctic Marine Living Resources (CCAMLR)** is also desirable. This is seen as important, as the

CCAMLR, in its ‘Ecosystem Monitoring Program’ (CEMP), collects data on penguin populations in the Antarctic and therefore has relevant experience and has drawn up standards in this regard (CEMP Standard Methods).

Outlook

The previous sections described the possibilities and limitations of using satellites to monitor penguin colonies in the Antarctic. What methodology could be applied to creating a programme to monitor penguin populations throughout the Antarctic? For future investigation, the present study suggests a process comprising **three levels of research, to be conducted in parallel**:

Level 1

We were able to show that Landsat7 images could be used to detect large colonies of penguins that do not breed on ice (>1,000 – 5,000 occupied nests), although the accuracy of results was limited due to the relatively low spatial resolution. On the positive side, the data are available free of charge and provide comprehensive coverage. Images are available of the whole of Antarctica from 1999 onwards and they can be analysed very efficiently with a high degree of automation. We therefore propose that **Landsat7 images, which comprehensively cover all ice-free coastal areas** of the Antarctic, be taken on an annual basis. This is, in particular, to detect large colonies of Adélie penguins, but also chinstrap, gentoo and macaroni penguins south of 60° south. At the same time, data available from the literature should be collected and compared with these satellite data. In order to minimise the area of uncertainty, for example where there is interference from vegetation (especially in the Antarctic Peninsula region), the open questions with respect to detectability need to be resolved. It would also be interesting to investigate Landsat7 images from previous years, in order to detect changes in colony size from that period.

Level 2

In order to obtain quantitative records of changes in colony area, it is also necessary to order images from **high-resolution sensors** (e.g. QuickBird2 or WorldView2), which have to be paid for. These could be used, in particular, in the Antarctic Peninsula region – where there are in some cases major changes in Adélie penguin populations – to obtain selected detailed data (in comparison to the Landsat7 images) of **approximately 30 representative colonies**. These could be analysed, at an acceptable cost, through manual image interpretation. In parallel, these **colonies should be visited and counted at least once during the period of the study, and information relevant to remote sensing (e.g. relief structure, vegetation cover and rock type) recorded.** This could be done through arrangements with the countries involved, for example by organising national supply ships to collect data on their way to research stations. In this respect, too, international cooperation would be necessary and sensible.

Level 3

At **10 selected colonies** or connected groups of nests, in parallel to the **high-resolution satellite images (*cf.* Level 2), species composition and density (adults with juveniles, where appropriate up to crèche age) should be recorded on the ground in the course of the breeding season**. This includes **mapping the colony borders** using accurate satellite navigation (GPS/GLONASS) as well as recording the number of individual birds, where necessary with the help of aerial photographs (e.g. photographs taken from gas-filled balloons). The purpose of creating a more comprehensive data base than that achieved with the present study is to reach a better correlation between the colony areas determined using the satellite images and the number of occupied nests. This would also include investigations of population changes over the years and within a single season, and also research on identifying and determining species. We should like to point out here that chinstrap and gentoo penguins played a subordinate role in this pilot study due to a comparative lack of data. These species should be taken into consideration in a future project, as should macaroni penguins. Finally, we would expect the further work done on these issues to lead to improved automation of the process.

Cost estimates for satellite images

If a monitoring programme as proposed here were carried out over three years, we estimate that the costs of obtaining **satellite data would total approximately US$250,000** (Level 1: no costs, Level 2: US$170,000 and Level 3: US$80,000).

Further investigations

Further investigations should be carried out to improve the accuracy of semi-automatic and automatic image analysis, both for Landsat7 images and images with high spatial resolution (e.g. QuickBird2 or WorldView2). Among other things, object-based approaches to complement the pixel-based classification investigated in this project are considered to be particularly promising. In order specifically to improve automatic image analysis, more satellite images (time series) of a colony will be needed (*cf.* Level 3).

The present study will be extended in September 2012 by the results of research on emperor penguins, which breed during the Antarctic winter. For this, satellite images will be taken with WorldView2 and RapidEye of the emperor penguin colonies in the vicinity of Neumayer Station III and Dumont d'Urville, shortly before the breeding season in April to May and shortly after the breeding season in July to September. Furthermore, Terra-SAR-X images of the same colonies will be taken during the breeding season in July. Ground counts are also planned there for the 2012 season.