Adventures in atmospheric science

Professor Gregory Hakim leads a project testing the application of objective network design to data collection devices in Antarctica. By improving climate and weather monitoring, it will increase the safety of research as well as rescue flights in the region

Could you briefly describe your academic background?

A significant part of my research experience over the past decade has involved weather analysis and prediction. Data assimilation is a critical component of this process because it provides the link between observations and numerical models used to make forecasts. Essentially, data assimilation takes the information from observations and blends it with an accurate short-term forecast to produce the starting point (ie. the 'analysis') for a subsequent forecast.

One way to improve forecasts is to take additional observations, which leads to questions about where and what should be measured. There has been considerable interest in 'adaptive observations,' where custom one-off measurements are made to improve a specific aspect of one weather forecast. I am interested in extending these ideas to the augmentation or adjustment of fixed networks for long-term climate monitoring and improved weather forecasts.

Why did you choose Antarctica as a study site?

Antarctica is a particularly good site for several reasons. Weather observations are critical for the safety of base operations and the logistics associated with fieldwork, and weather stations are expensive to install and difficult to maintain, which limits their number. Finally, Antarctic climate change is not occurring uniformly across the continent, which makes monitoring any changes difficult. Moreover, the Antarctic station network is sparse and expensive to adjust, making it an ideal test bed for our network design theory.

Why is objectivity so crucial in environmental observations?

Weather observing networks have typically grown organically from supporting a specific objective, such as weather observations at airports, to ancillary objectives such as climate monitoring. However, the stations were not installed to meet these particular objectives. This motivates an objective approach, where one defines some performance measures, some constraints such as funding, and then optimally determines how to maximise the performance measure. To give a simple shipping analogy: while one can randomly pick a shipping method and route, it is clear there are optimal ways to maximise return on investments, for example by using large container ships and great circle routes. This is a data-driven mathematical problem that requires an objective solution. Similarly, there are ideal locations for environmental observations that maximise the performance of the network at minimum cost.

Which geographical and statistical variables govern the effectiveness of a weather station?

That depends strongly on what one wants to measure. For example, we have found that if one wants to monitor the climate of Antarctica as measured by the continent-wide average temperature, there is a very specific place in East Antarctica to install a station. Another example concerns making weather forecasts for a specific base of operations. Depending on the lead time of the forecast, one will place observations in different locations to reduce forecast errors at the station – so again, it depends on the objectives.

How do you use information theory to achieve improved modelling?

We have extended our theory in such a way that it is directly comparable to maximising the relative entropy from information theory, and this leads to some interesting results. Our method tends to favour locations with large spatial correlation; by measuring these locations, a lot can be learned about a large area. By definition, these locations have low entropy, because they are redundant with the surrounding locations. The information theory approach tends to pick locations that have very small spatial correlation; these locations have high entropy and unique information that is not obtainable by going to other places. One way to think about this contrast in results is in terms of the two classical applications of information theory: compression and error correction. In the compression case, one picks out the bits that are most unpredictable since the rest may be gleaned from a limited set of data. In the error correction case, one adds redundancy to ensure that the message is not lost if some bits are contaminated.

At what stage are you in your current investigations?

We have nearly reached the point where we can make specific recommendations for station locations, provided a performance measure is supplied. We are running tests to check our predictions by removing existing station data and performing simulation experiments for new stations. The results are very promising. We believe they will provide a highly cost-effective approach to monitoring weather and climate in Antarctica.

Station to station

Researchers at the **University of Washington**, USA, are using the Antarctic Observational Network as an ideal test bed for their network design theory. The project's findings have far-reaching implications for environmental data collection in the southern polar region

THE INTERNATIONAL GEOPHYSICAL Year held in 1957-58 marked the start of the Antarctic Observational Network (AON), designed to record weather and climate data in the region. In the 1970s and 1980s, the Network dramatically increased in size with the development of Automatic Weather Stations (AWS) designed to withstand the southern continent's harsh environment. The AWS transmit their weather data to satellites stationed in a polar orbit around the Earth, but despite the increased size of the current network, coverage of Antarctica remains sparse, especially towards the interior.

Antarctica is the Earth's coldest and windiest continent. Despite containing roughly 70 per cent of the planet's fresh water resources, the continent is also the driest, with little precipitation, especially inland. These harsh and varied conditions make the work of the scientists who maintain and study the environmental data network extremely challenging. In addition, the sheer size of the Antarctic continent – more than half the size of North America – presents scientists working on and studying the AWS system with major logistical challenges. This highlights the importance of maximising the performance of existing monitoring stations and has prompted researchers to study ways of optimising the configuration of the Antarctic AWS network.

OBJECTIVE BY DESIGN

Existing stations in environmental monitoring networks such as the AON tend to be situated according to practical constraints such as perceived cost or accessibility benefits. This means that many existing stations may not be placed in the most advantageous geographical position for data collection, or indeed for fully realised cost benefits. With this challenge in mind, a team at the University of Washington, USA, has embarked on a new project – Objective Observing Network Design Applied to Antarctica. With a background in atmospheric sciences, the project's Principal Investigator, Professor Gregory Hakim, has a longstanding interest in weather analysis and prediction. Using ensemble sensitivity developed in earlier work, Hakim and his colleagues are applying their novel approach to network design to the Antarctic network. With the help of co-Principal Investigator Eric J Steig, graduate student Natalia Hryniw and researchers Karin Bumbaco and Guillaume Mauger, Hakim is testing an optimal network design theory on the AON weather stations. "Our project provides tools to measure the performance of stations in the existing Antarctic network, and an objective basis for reconfiguring or augmenting the network," Hakim explains.

MESOSCALE MODELS

Two more project collaborators – Jordan Powers and Kevin Manning from the US National Center for Atmospheric Research (NCAR) – focus on the Antarctic Mesoscale Prediction System (AMPS). The System was established in 2000 to support the US Antarctic Program conducted at McMurdo Station, the main American base in Antarctica. AMPS provides synoptic and mesoscale model output for researchers, with the intention of improving the development of Antarctic weather models. The system uses a 3D variational algorithm (3DVAR) to assimilate radiosonde (a device fixed to weather balloons to collect atmospheric data), surface and satellite data. In addition, the 00Z Global Forecasting System (GFS) provides a background estimate. Hakim and his team use data from AMPS to predict the optimum distribution of the AWS.

SPATIAL COVERAGE

The project builds on a previous study led by Assistant State Climatologist Karin A Bumbaco: Evaluating the Antarctic Observational Network with AMPS. Also involving Hakim, Mauger, Hryniw and Steig, this earlier work used AMPS data from 2008-12 to evaluate the spatial coverage of the AWS network, with a focus on temperature and pressure. The research team has evaluated the performance of the system using multivariate linear regression. Removing seasonal variations to assess the network's ability to detect sub-seasonal variations highlighted some significant gaps in the coverage of the AWS stations, especially around the Antarctic's Ronne Ice Shelf. This study assessed the spatial coverage

INTELLIGENCE

OBJECTIVE OBSERVING NETWORK DESIGN APPLIED TO ANTARCTICA

OBJECTIVES

To decide where to place new stations or how to augment an already existing network by evaluating the validity of an ensemble sensitivity approach to network design.

KEY COLLABORATORS

Dr Guillaume S Mauger; **Natalia Hryniw**, graduate student; **Karin A Bumbaco**, Assistant State Climatologist; **Professor Eric J Steig**, University of Washington • **Dr Jordan Powers**; **Kevin Manning**, National Center for Atmospheric Research

FUNDING

National Science Foundation – award no. 1043090

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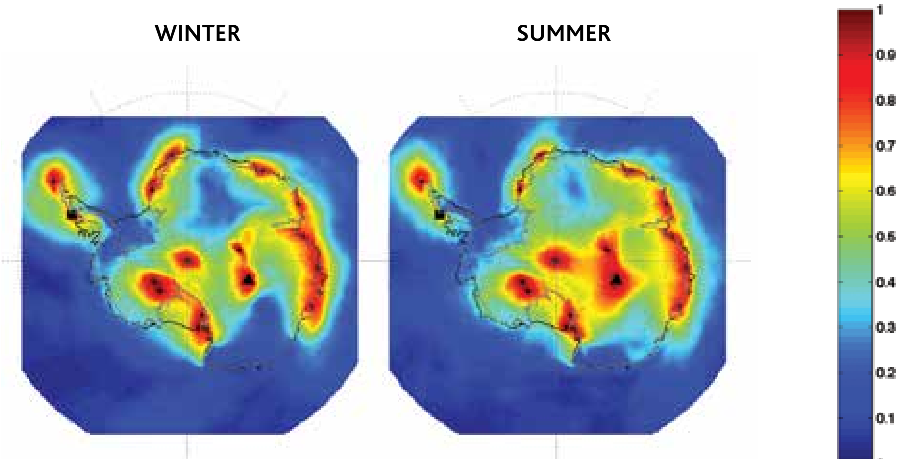
GREGORY HAKIM graduated with a BSc in Atmospheric Science and Mathematics from the University of Albany in 1990. He went on to complete both an MS and PhD in Atmospheric Science from the same university. Hakim joined the Department of Atmospheric Sciences at the University of Washington in 1999 where he is now Professor and Department Chair. He was Chair on the President's Advisory Committee on University Relations; University of Washington Representative at the University Corporation for Atmospheric Research (UCAR), University Corporation for Atmospheric Research (UCAR), Boulder, Colorado; and is Member of the National Center for Atmospheric Research (NCAR)'s Earth Systems Laboratory Advisory Committee and TIGGE-LAM expert panel (THORPEX).



Fraction of temperature variance explained for AWS stations that reported 90 per cent of the time during the four-year period. (From Bumbaco et al. 2014)

of the AON prior to the researchers considering optimal network design.

In their latest project, Hakim and his colleagues apply Bayesian updating to the collected data. This technique describes how a prior understanding of something is altered once new information has been received. The team also applies Kalman filter theory to their data to ensure that the probability distributions of the analysed information are adjuted to refelct the information from a new selected station. "This theory allows us to start with a prior understanding based on the current weather observing network, and to determine how that understanding changes by placing a new observation at specific locations," Hakim elaborates. "This evaluation is done for all locations, or only for locations that satisfy certain constraints, such as accessibility." The researchers are then able to identify sites with the greatest reduction in uncertainty in the performance measure.

MONTE CARLO DRAW

The sophistry of techniques available for the team's analysis presents its own challenges as the calculations they perform are large and require special optimisation, as Hakim notes: "Since calculations are based on a limited sample of data, error estimation has been a critical aspect of this project, thus we have developed a Monte Carlo error estimation technique". Using this technique allows the researchers to determine the best locations for monitoring the regional variations in the Antarctic climate.

Taking random draws of ensembles from the AMPS data, the group used 10,000 Monte Carlo iterations for each of the three regions. They discovered that the ideal location for a station in West Antarctica would be in a band between Byrd and the Ross Ice Shelf, while for East Antarctica the optimal position would be near the Mega Dunes, filling a gap in the current network to the west of Vostok. For the Antarctic Peninsula, the researchers found that the best site for AWS would be on either side of the mountains near Palmer Land. The results for best station locations produced by this technique tended to be non-intuitive, emphasising the importance of the objective approach advocated by Hakim.

ALL ABOUT THE WEATHER

Utilising the data generated by AMPS has allowed the University of Washington researchers to demonstrate that more stations are needed to record weather data in West Antarctica than in the east. The current AWS network leaves large regions of Antarctica insufficiently covered, especially on a daily timescale. By employing an optimal network design approach, the team will be able to rectify this shortcoming in the current Antarctica surface weather measurement network. "We have shown it is possible to achieve a similar performance from a small network of optimally placed observing sites as compared to a much larger number of stations on a regular grid," emphasises Hakim.

The expense of installing and maintaining monitoring devices in the Antarctic environment makes the continent an ideal location for Hakim and his colleagues to pursue their studies into objective optimal network design. Their work will allow future Antarctic research programmes to find better locations for weather stations, to optimise their data collecting abilities and make them more cost-effective. Over the longer term, the team's work will lead to more localised and accurate weather data collection for the Earth's southern-most continent, improving the safety for research flights and rescue missions, and ultimately allowing for a better assessment of climate change across this vast and under-studied region.