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Observations of Antarctic Polynya With Unmanned Aircraft Systems

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Working in the polar environment is always challenging, particularly during the winter, when environmental conditions are harshest. With hurricane force winds, frigid temperatures, and the potential to alter the global thermohaline circulation, the Terra Nova Bay region of Antarctica in the western Ross Sea is an environment where acquiring observations of local atmospheric and oceanic interactions is critical and also extremely challenging.

An important feature of Terra Nova Bay is a recurring polynya—an area of nearly ice-free water surrounded by sea ice and land. Strong katabatic winds (cold, negatively buoyant air that flows downslope under the influence of gravity) drain from the interior of the continent and blow over the open water of the polynya, resulting in large upward fluxes of heat and moisture. Sea ice production occurs as a result of the large transfer of heat from sea to air, with the newly formed sea ice blown offshore, effectively removing freshwater from the coastal ocean. The high-salinity water created through this process becomes part of the global thermohaline circulation as Antarctic bottom water. Coastal polynyas, such as the one in Terra Nova Bay, are of interest to atmospheric scientists and oceanographers due to the intense air-sea coupling and the impact of these fluxes on the state of the atmosphere and ocean.

Surveys With Unmanned Aircraft

Instrumented unmanned aircraft systems (UASs), whose use in polar regions recently has become more common, are potentially effective tools for observing coastal polynya environments.

In late austral winter 2009, four Aerosonde® UASs were used to make atmospheric and surface observations in the vicinity of Terra Nova Bay (see Figure 1). The UAS observations made as part of this Antarctic deployment were the first wintertime in situ atmospheric observations over the polynya. In addition, the flights—up to 17 hours in duration—were the longest UAS flights to date in the Antarctic.

During the monthlong field campaign, the UASs flew a total of 130 flight hours, covering a distance of more than 11,000 kilometers. The first flight of the field campaign was on 7 September and the last was on 27 September. A total of 16 UAS flights were flown during this time, with eight of them being science flights (other flights tested aircraft and instrument systems) to Terra Nova Bay.

For each UAS flight, onboard instrumentation collected observations of the in situ atmospheric state (temperature, humidity, pressure, and winds) at the aircraft flight altitude and observations of the underlying ocean or ice skin temperature. Depending on the scientific goals of each flight, other instruments were on board that allowed for measuring net shortwave and longwave radiative fluxes, atmospheric profiles, surface roughness and ocean wave state, and images of the surface state.

Scientific Goals and Preliminary Results

The following are the primary science questions being addressed by this project: (1) What atmospheric processes control the size of the Terra Nova Bay polynya? (2) How do changes in the atmospheric state alter the amount of heat and moisture removed from the ocean in the polynya, and what impact does this have on the development of Antarctic bottom water? (3) How does the presence of the polynya modify the katabatic airstream as it passes over the polynya?

The UAS flights over the polynya were designed to collect data that will help to

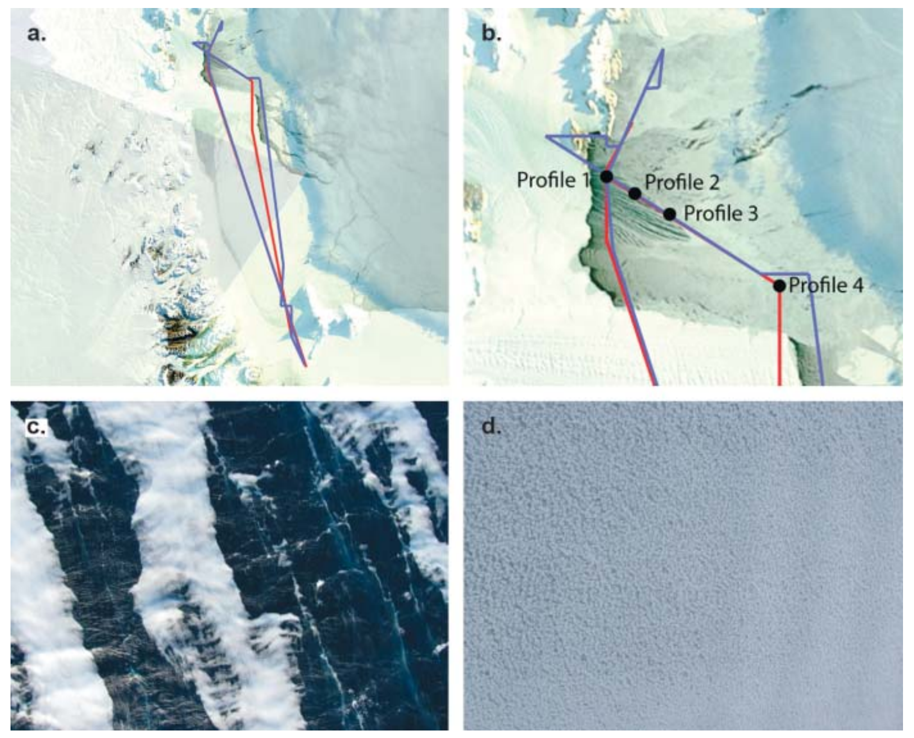

Fig. 1. Map of unmanned aircraft flights on 24 September 2009. Red and purple lines in Figure 1a show the flight paths between the Pegasus runway in the south and Terra Nova Bay to the north. Figure 1b shows the location of the crosswind and downwind flight legs and profiles. Figures 1c and 1d are aerial photographs of the surface at the location of profiles 1 and 3, respectively.

answer these questions. Analysis of the data collected is ongoing, and preliminary results from one of the UAS missions are presented here.

To document the modification of the katabatic airstream as it passed over the polynya at Terra Nova Bay, two Aerosonde® UASs were flown on 24 September. Upon reaching Terra Nova Bay, the UASs first flew an approximately south to north transect across the bay to identify the location of the strongest off-continent katabatic flow. Once the location of the peak wind was identified, the UASs flew flight legs parallel to the strongest winds, allowing for observation of the downstream evolution of the atmosphere and ocean surface state over the polynya (Figures 1a and 1b). Vertical profiles of the atmosphere from 100 to 1000 meters were made at four locations along the downwind flight leg (Figure 1b; see also http://cires.colorado.edu/~cassano/tnb_eos/tnb_aerosonde_profiles.jpg). These profiles were acquired while the UASs flew spiral ascent/descent flight patterns with a radius of 750 meters. Digital photographs from the aircraft allowed for determining the surface state at each profile location.

Profiles 1 and 2 were located above a region with large areas of open water and bands of wind-accumulated frazil ice (loose ice that resembles slush; Figure 1c). Profile 3 was located at the downwind edge of the polynya, where the sea was covered by pancake ice (small, round plates of sea ice; Figure 1d). Profile 4 was located beyond the downwind edge of the polynya over thicker young ice that displayed some ridging and rafting. Ridging and rafting occur as the ice pack experiences convergence, with ridging causing the ice to buckle, while rafting occurs as one sheet of sea ice rides up and over another sheet of sea ice. Both processes lead to the creation of thicker sea ice.

The temperature profiles indicate downwind warming of the air mass as it passed over the polynya, with the warming confined to below 600 meters above ground level (agl). The relative humidity was found to increase downstream over the polynya, with moistening initially occurring mainly below 150 meters agl (profile 2). By profile 4, the moistening was most pronounced up to 500 meters agl. The wind speed was observed to decrease with downwind distance over the polynya. The wind speed at profile 1 shows a well-defined low-level jet, typical of katabatic flows. This jet becomes indistinct by profile 2, with wind speeds decreasing within the lowest 600 meters agl from profile 1 to profile 4, indicating momentum transfer from the atmosphere to the surface.

Analysis of the other data collected during this field campaign is ongoing, with the goal of answering the science questions listed above. A second field campaign at Terra Nova Bay could be conducted when a high-vertical-resolution ocean mooring is present in the bay to allow for a more thorough analysis of the coupling between the atmosphere and ocean states.

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Active Source Seismic Experiment Peers Under Soufrière Hills Volcano

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Characterizing internal structures of active volcanoes remains an enigmatic issue in geosciences. Yet studies of such structures can greatly improve hazard assessments, helping scientists to better monitor seismic signatures, geodetic deformation, and gas emissions, data that can be used to improve models and forecasts of future eruptions.

Several passive seismic tomography experiments—which use travel times of seismic waves from natural earthquakes to image underground structures—have been conducted at active volcanoes (Hawaii's Kilauea, Washington's Mount St. Helens, Italy's Etna, and Japan's Unzen), but an inhomogeneous distribution of earthquakes compromises resolution. Further, if volcanic earthquakes are dominantly shallow at a given location, passive methods are limited to studying only shallow features. Thus, active source experiments—where seismic waves from the explosion of deliberately set charges are used to image below the surface—hold great potential to illuminate structures not readily seen through passive measures.

On the West Indies island of Montserrat, volcanic earthquakes are typically shallower than 4 kilometers deep. To get the deeper data needed to three-dimensionally (3-D) image the volcano's plumbing system, an active source seismic experiment, called the Seismic Experiment with Air-gun source of the Caribbean Andesitic Lava Island Precision Seismo-geodetic Observatory (SEA-CALIPSO) [see *Mattioli et al.*, 2004], was carried out in December 2007 (see Figure 1).

Before this experiment, knowledge of the deep structure of Montserrat and its signature volcanic center, the Soufrière Hills volcano, was limited, with proposed models based on restricted geophysical, geological, and petrological data. Now analysis of data from SEA-CALIPSO has generated high-resolution images of Montserrat's structure, volcanic edifices, and adjacent crust. These images will advance scientists' understanding of crustal evolution in arc systems, magma storage and transport systems, and volcanic processes.

Montserrat's Volcanic Complexes

Three centers of volcanism have been previously identified on Montserrat, with nonoverlapping volcanic activity: Silver Hills (active around 2600–1200 thousand years ago), Centre Hills (active around 950–550 thousand years ago), and Soufrière Hills–South Soufrière Hills (active for the past 170 thousand years). Each complex is about 6 kilometers south of its neighbor, suggesting migration rates of 5–9 kilometers every million years.

The Soufrière Hills volcano is the only currently active volcanic center on Montserrat. Noneruptive volcano-seismic swarms at Soufrière Hills occurred about every 30 years in the late nineteenth and the twentieth centuries, but with the exception of a minor seventeenth-century lava effusion, no historical eruptions were recorded on Montserrat prior to the 1990s.

In 1995, small to moderate steam and ash eruptions began in July and were followed by lava dome growth and sporadic pumiceous explosions. By 1997, pyroclastic flows had forced the evacuation of the southern two thirds of Montserrat and had decisively destroyed the capital city of Plymouth, the seaport, and the airport, causing collapse of the island's economy. Plymouth currently is buried and abandoned.

Since 1995, one cubic kilometer of lava has erupted. Twenty-one people and innumerable animals have been killed, and more than 60% of the population has left. The eruption remains dangerous: A lava dome collapse in February 2010 of 40–50 million cubic meters produced large pyroclastic flows and added a square kilometer of new land to the eastern coastline.

The current eruption has been studied in detail [*Druitt and Kokelaar*, 2002], but knowledge of deep structure is scarce and elements of the magmatic system under Soufrière Hills are imprecisely determined. For example, the magma reservoir top has been estimated at about 5 kilometers deep on the basis of mineral assemblages, melt inclusion data, and deepest earthquakes near the conduit. However, recent data from global positioning systems suggest that a much deeper reservoir is exerting pressure, causing the surface to deform [*Mattioli et al.*, 2010].