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Exploring Arctic Transpolar Drift During Dramatic Sea Ice Retreat

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The Arctic is undergoing significant environmental changes due to climate warming. The most evident signal of this warming is the shrinking and thinning of the ice cover of the Arctic Ocean. If the warming continues, as global climate models predict, the Arctic Ocean will change from a perennially ice-covered to a seasonally ice-free ocean. Estimates as to when this will occur vary from the 2030s to the end of this century. One reason for this huge uncertainty is the lack of systematic observations describing the state, variability, and changes in the Arctic Ocean.

The Damocles project (Developing Arctic Modelling and Observing Capabilities for Long-Term Environmental Studies) is helping to fill the need for long-term observations of the lower atmosphere, the sea ice, and the upper Arctic Ocean in order to better predict extreme climate events such as the disappearance of sea ice in summer.

Damocles, which is a major contribution of the European Union to the International Polar Year (IPY), has a substantial in situ observational component, using drifting sea ice camps as well as autonomous platforms. The first-year ice camp for the project was based around the schooner *Tara*, which was frozen into the ice north of the Laptev Sea (79°53N, 143°E) on 4 September 2006, emulating Fridtjof Nansen's groundbreaking *Fram* expedition of 1893–1896 (Figure 1).

The concept of the *Tara* Damocles mission also can be compared with the SHEBA (Surface Heat Budget of the Arctic Ocean) experiment that occurred 10 years ago when the Canadian Coast Guard icebreaker *Des Groseillers* drifted for 1 year, beginning in October 1997, in a limited area of the Beaufort Gyre.

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Drifting to the North Pole: Nansen's Dream

Escort and supply of the *Tara* was combined with the Nansen and Amundsen Basins Observational System (NABOS) program that deploys moorings at the periphery of the Arctic Ocean, to deploy jointly some ice-tethered platforms and additional moorings, and to share costs for using the Russian icebreaker *Kapitan Dranitsyn*.

After *Kapitan Dranitsyn* escorted *Tara* into the ice at about 80°N and 143°E and delivered kerosene, a bulldozer, and scientific equipment, *Tara* immediately started to move northward in the Transpolar Drift, which is the main branch of the Arctic sea ice drifting from the Laptev Sea north of Siberia to the Fram Strait between Spitsbergen and Greenland. On 9 December 2007, *Tara* crossed Fram Strait at 80°N and 0° longitude, completing her drift across the Arctic Ocean in about 15 months, 3 times faster than predicted to traverse more than 2000 kilometers.

Tara followed a more northerly route than the *Fram,* approaching the North Pole at 88°32N on 28 May 2007 (Figure 1). Measurements and maintenance of the instruments were carried out by the overwintering eight-member crew of the schooner. Fifteen scientists from the Damocles consortium joined the crew in April 2007 for a 1-week intensive measurement campaign to repair some instruments damaged during winter storms, start new observations such as profiling temperature and winds from 0- to 2000-meter altitude, and enhance snow and ice measurements (Figure 2). Two aircraft—a DC-3 and a Twin Otter, both provided by Kenn Borek Air Ltd., Calgary, Canada—operated in difficult conditions from Longyearbyen (Svalbard), Norway, to *Tara* at 88°N and 135°E, successfully transferring personnel and equipment and performing airborne measurements.

Atmosphere and Ocean Observations

In order to understand the interaction between ocean/sea ice and the atmospheric boundary layer, continuous measurements were taken from September 2006 until December 2007, including standard meteorological parameters, turbulent fluxes using two three-dimensional ultrasonic anemometers to measure wind speed and direction, and radiation budget and atmospheric soundings. During summer 2007, one hundred vertical profiles of air temperature, relative humidity, wind speed, and direction using a tethered balloon were taken. Upper ocean vertical profiles of temperature and salinity were taken from the surface down to more than 1000-meter depth on alternate days. Figure 2 shows an air-ice-ocean profile extending from 1300-meter altitude down to 1000-meter depth.

Air temperature generally decreased adiabatically, at 1°C per 100 meters in the surface layer (a few hundreds of meters thick). A strong temperature inversion layer extended from 300- up to 800-meter altitude with temperature increasing by more than 12°C. In the ocean, a 3°C temperature inversion was also present, between 100- and 200-meter depths. Both inversion layers are due to long-range horizontal advection of warm air and water masses from subtropical regions. The upper ocean is characterized by a shallow, cold, and fresh mixed layer extending from the surface to about 20- to 30-meter depth. A cold halocline is then well separated from a deeper thermocline at 100 meters, where temperature rises from –2°C to +2°C in the core of the Atlantic layer at 300-meter depth.

On 24 April 2007, sixteen buoys were air dropped on sea ice in a regular 400- × 400-kilometer grid centered on *Tara*. Buoys measured position, air pressure, and temperature approximately every hour, transmitting data via the Argos satellite system in near real time. The goal of the experiment—the first with such a high spatial and temporal observation density in the central Arctic—was to measure the drift of the central Arctic pack ice, and the relative motion within the pack (deformation, divergence, rotation), and to relate these to passing atmospheric pressure patterns. At the end of August 2007, the buoys had traveled between 470 and 570 kilometers from their initial positions, while the area of the array increased by about 25%. The average speeds of the ice buoys ranged from 6.5 to 10.5 centimeters per second, with a maximum hourly drift speed of 40 centimeters per second. At the end of August 2007,

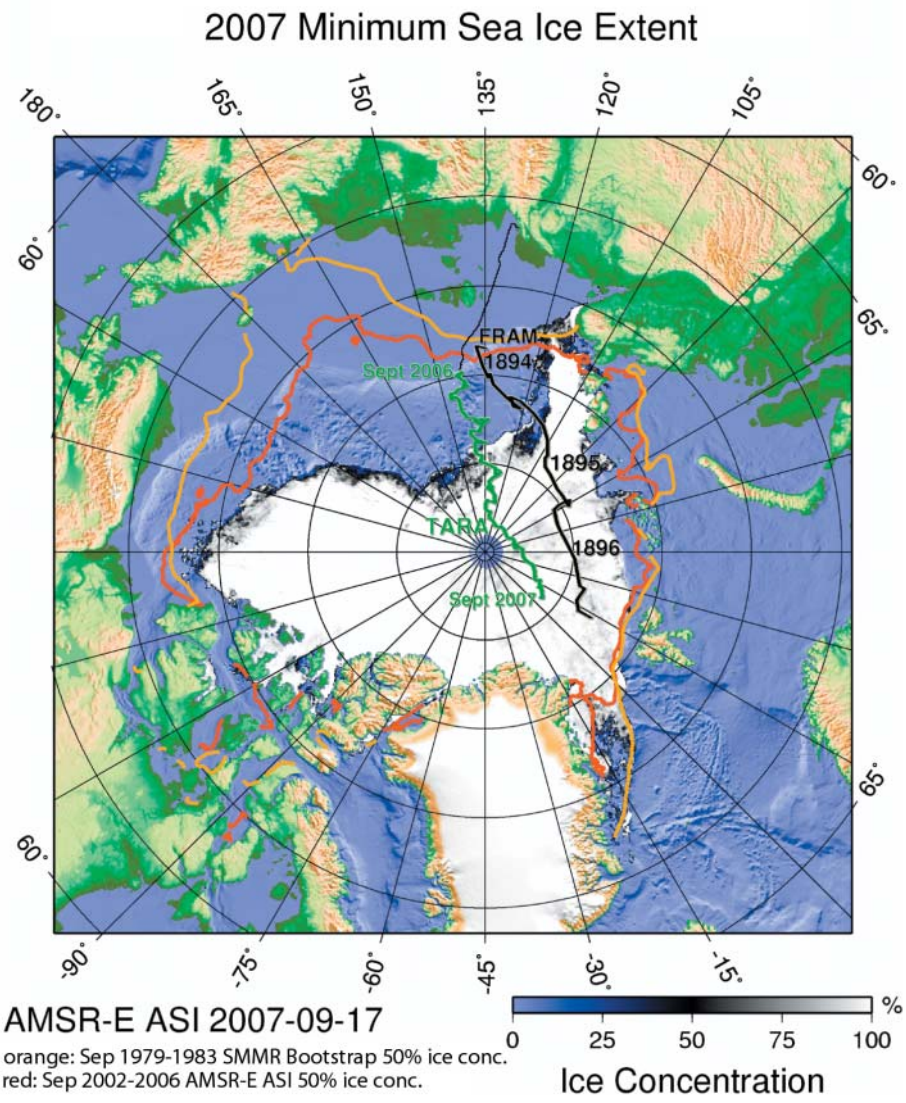

Fig. 1. The drift track of Ice Station Tara *from September 2006 to September 2007 and the drift track of the* Fram *(1894–1896) are represented. The bottom topography is shown together with sea ice summer minimum extent in 2005 and 2007.*

nine of the 16 buoys were still operating, though that number dropped to five by mid-October 2007. Most buoys were lost during the summer melt period, drowned in melt ponds.

Sea Ice and Snow Observations

Surface measurements of sea ice and snow were designed both to collect long time series describing the state of the pack ice for process studies and to obtain validation data for the airborne freeboard technique (which consists of measuring the level difference between the sea surface and the top of the snow covering the ice, or the top of the ice in case snow has melted away), remote sensing methods, and numerical modeling. The in situ monitoring program at *Tara* included weekly sea ice coring to obtain density and salinity profiles, ice thickness measurements with an electromagnetic induction device, snow pit studies to sample snow from top to bottom for measuring snow physical parameters, and snow thickness profiles along a stake line.

Automatic instruments deployed at the site included an ice mass balance buoy, which monitors melting or growth of the surface and underside of the ice floe, as well as a vertical temperature profile of the ice floe. Spectral surface albedo and the penetration of the solar radiation through snow and sea ice were measured beneath the floe continuously. A time-lapse camera was used to monitor surface changes and melt. Broadband and spectral radiation components (incoming, reflected, and transmitted) were measured continuously over an entire seasonal cycle, including summer transitions (the onset of melting and freezing) when most significant changes occur. Regular station maintenance was essential to achieving high-quality data sets. Together with the comprehensive snow and ice observations and numerical studies, the results will increase the understanding of atmosphere-snow-ice interactions, enhance the interpretation of remote sensing data, and contribute to the understanding of biological processes in and under sea ice.

Other autonomous instruments included tiltmeter buoys deployed at five sites across the Arctic Ocean—including one at *Tara*—to monitor long-period swell waves penetrating into the ice cover from the open ocean at the Greenland Sea. The buoy array will allow a comprehensive evaluation of the long-period wave field in the Arctic Ocean, an improved understanding of the role of the ice cover in modifying this energy, and an estimation of the sea ice thickness along the propagation path.

Ice-cover deformation in a 2-kilometer radius of the *Tara* was monitored using a network of GPS buoys. Five seismometers were deployed over a 2- × 2-kilometer zone centered on *Tara* to record local ice quakes

that generate seismic waves caused by the brittle deformation of the ice cover over a 5-month period. Coupled with the continuous monitoring of GPS displacements, these ice quakes will reveal how the pack ice deforms at the kilometric scale and hence how the ice strain is locally accommodated in intermittent bursts of fracturing events in relation to changes in external forcing.

As well as providing essential logistics, the Twin Otter was used to acquire laser scanner data over the sea ice. The scanner was mounted together with necessary GPS modules in the photography hatch of the aircraft, and it mapped the ice surface elevation in a 250-meter-wide swath at a relative accuracy of 5 centimeters and a spatial resolution of 1 meter. Together with a geoid model and a lowest-level filtering algorithm, these laser data make it possible to measure the sea ice/snow freeboard and thus determine ice thickness (using suitable density values) as well as detailed geometrical mapping of leads (elongated ice-free ocean openings between ice floes) and ridges.

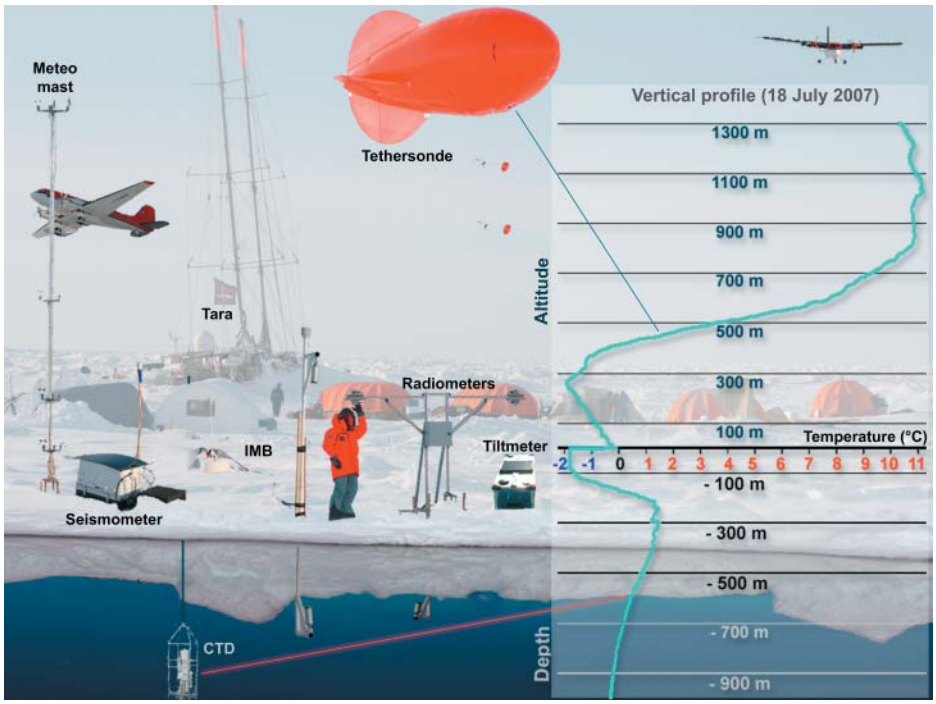

Fig. 2. Ice Station Tara *on 21 April 2007 at 88°N and 135°E. The tents in the background sheltered the Damocles scientific team. Instruments are shown in the foreground together with a vertical temperature profile (taken on 18 July 2007) from 1300-meter altitude down to 1000-meter depth.*

Tara Damocles and SHEBA

In many ways, the *Tara* Damocles mission can be compared with the SHEBA experiment that occurred 10 years ago in a more limited area of the Beaufort Gyre. In 1998, the Arctic sea ice summer minimum extent was 6.56 million square kilometers (National Snow and Ice Data Center), and the extent of open water during summer 1998 in the Beaufort and Chukchi seas was the greatest of the past two decades. In 2007, the Arctic sea ice summer minimum extent was 4.1 million square kilometers (i.e., 2.5 million square kilometers less than in 1998 during SHEBA). The combination of an unprecedented melting on the Pacific side together with a drastic acceleration of the transpolar sea ice drift on the Atlantic side is one way to explain such a dramatic and abrupt decrease of the Arctic sea ice summer minimum extent.

The *Tara* Damocles mission will help to significantly improve our understanding of the Arctic Ocean at a time this ocean is experiencing drastic changes, by providing critical long time series of key climatic variables such as temperature in the lower atmosphere, in the upper ocean, and through the ice; salinity in the ocean; humidity in the atmosphere; winds and currents; and various parameters characterizing sea ice (thickness) and solar radiation (albedo). These are urgently needed to improve numerical modeling predictions, since none of the existing models was able to predict the dramatic changes such as the spectacular retreat of sea ice observed in 2007 in the Arctic Ocean.

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