BAMS
Meeting Summary

Advances and Next Steps in Observing and Modeling Antarctica's Coastal Winds

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Antarctic Coastal Winds: Recent Advances and Future Research Priorities

***What*:** Twenty-four scientists (19 in person and 5 online) met to discuss recent advances and future research priorities in understanding near-surface winds in the Antarctic coastal margins and their role in the climate system.

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1. Background

Westerlies prevail at low levels over most of the Southern Ocean. Within about 400 km of Antarctica, the winds reverse direction and become the polar or coastal easterlies. Closer to the continent, the flow direction is further modified by the complex terrain of the steep coastal slopes. Both the large-scale easterlies and more topographically constrained near-coastal flows are referred to in this report as Antarctic coastal winds (ACWs).

ACWs have global importance due to their impacts on ocean circulation, sea ice, and vulnerable ecosystems. As the planet warms, changes to the large-scale circulation may favor a weakening of the coastal easterlies which encircle Antarctica (Bracegirdle et al. 2008). These winds are intimately connected with the structure and dynamics of the Antarctic Slope Front in the ocean, a barrier between cold, fresh shelf waters, and warm circumpolar deep water (CDW; Thompson et al. 2018). CDW intrusions are in turn a key driver of ice shelf basal melt and hence play an indirect role in sea level rise (Spence et al. 2014). ACWs are tied to sea ice production and motion (Haumann et al. 2014; Holland and Kwok 2012), including over polynya regions where Antarctic Bottom Water is formed (Stewart and Thompson 2012). They are also critical for low-level sublimation of precipitation (Grazioli et al. 2017), blowing snow, and moisture advection toward continental Antarctica (Van Lipzig and Van Den Broeke 2002).

A growing number of ocean and sea ice modeling efforts have been undertaken to better understand and project air–sea–ice coupling in the Antarctic. All of these require detailed information about ACWs. The goal of this workshop, a key final outcome of a Natural Environment Research Council (NERC) project on ACWs, was to bring together meteorologists, climate scientists, and oceanographers to highlight recent progress in understanding ACWs and to identify priorities for interdisciplinary research. This report details many of these recent advances (section 2–5) presented at the workshop and summarizes research priorities which were emphasized by participants (section 6).

2. Structure, dynamics, and future projections

A recent NERC-funded collaboration between the British Antarctic Survey (BAS), the National Oceanography Centre (NOC), and the U.K. Met Office investigated the structure and dynamics of Antarctica's coastal winds as well as their representation in model and reanalysis datasets.

Key results from this work on ACWs were highlighted and discussed at the workshop, including a climatology, a detailed evaluation of three reanalyses against satellite and in situ observations, and a momentum budget analysis which shows the varied dynamical drivers of ACWs (Caton Harrison et al. 2022, 2024). Although ACWs offshore can be mostly explained as a geostrophic flow in thermal wind balance, in some regions ACWs appear to be strongly affected by large near-surface diabatic cooling, which induces intense baroclinicity at low levels. The influence of large-scale circulation on the strength of ACWs was explored in a presentation by John King, showing that the Southern Annular Mode (SAM) anticorrelates with the strength of ACWs in East Antarctica, whereas in West Antarctica, pressure variability in the Amundsen Sea sector/southern Pacific Ocean showed the strongest association.

Models contributing to the World Climate Research Programme's phase 6 of the Coupled Model Intercomparison Project (CMIP6) (Eyring et al. 2016) disagree on the magnitude and pattern of projected changes to ACWs (Neme et al. 2022). A presentation given by Cécile Davrinche demonstrated how the use of a regional climate model featuring a turbulent scheme adapted for snow-covered surfaces could help disentangle the relative roles of boundary layer and large-scale factors causing model disagreements. Rolf Zentek also showed climate model projections indicating significant changes in the height and strength of low-level jets over the high-latitude Southern Ocean in the coming century.

3. Extremes

A number of attendees highlighted advances in understanding the short time-scale dynamics and impacts of ACWs, with an emphasis on extremes. Due to the nonlinear relationship with wind stress, infrequent extremes play a disproportionate role in ocean circulation and sea ice forcing.

One group at BAS is currently investigating the impact of winds over complex orography on high temperature extremes and the additional role of atmospheric rivers. Modeling studies have shown that topographically driven föhn winds are important drivers of extreme temperature and melt events over ice shelves (Gilbert et al. 2022; Orr et al. 2023). These frequently co-occur with atmospheric rivers in regions with steep terrain, such as the Antarctic Peninsula (Bozkurt et al. 2018; Wille et al. 2022; Gorodetskaya et al. 2023) and Amundsen Sea Embayment (Francis et al. 2023), where they can impact the stability of ice shelves and sea ice. Hua Lu presented both observational and modeling evidence to show how interactions between large-scale drivers, e.g., atmospheric rivers and synoptic-scale weather patterns and local topography via föhn winds can lead to characteristically different extreme warm events in South Orkney Islands (Lu et al. 2023b). Reanalysis datasets such as ERA5 underestimate the magnitude of extremes mainly due to a lack of realistic representation of complex topography and sea ice (Lu et al. 2023a).

Realistic representation of the compounding influence of atmospheric rivers and föhn conditions on temperature extremes in small islands with complex orography however requires high spatial resolutions, e.g., a 1-km grid spacing configuration. Ella Gilbert presented work showing how atmospheric rivers interact with steep topography to induce föhn warming that impacts the properties and phase of extreme precipitation. These studies demonstrate the complexity of extremes in polar regions. A direct link between ACWs and föhn warming in coastal Antarctica is yet to be explored.

A recent momentum budget analysis has been carried out at the Laboratory for Climate and Environmental Sciences (LSCE) in Paris and at BAS using regional modeling and reanalysis, with results recently published. These examine the balance of terms in detail on short time scales over large sectors of coastal Antarctica, indicating that in most regions large-scale terms dominate with the katabatic term typically playing a secondary role (Davrinche et al. 2024; Caton Harrison et al. 2024).

4. Role in ocean circulation and sea ice

The two main strands presented by oceanographers attending the workshop are the links between winds and Antarctic Bottom Water (AABW) formation and their role in ice shelf stability.

AABW is the densest water mass in the global ocean and is important for the transport of carbon into the abyssal ocean (Orsi et al. 1999). AABW originates predominantly from dense shelf water (DSW) formed in the regions of coastal polynyas on the Antarctic shelf and cascades down into the abyssal ocean supplying the lower limb of the meridional overturning circulation. Variability in AABW has been linked to the effect of ACWs on sea ice advection and formation in both observations and modeling studies. Christina Schmidt presented evidence that near-surface winds influence the spatial distribution and interannual variability of AABW formation via their effect on sea ice. Presented results show how zonal and meridional winds can affect sea ice advection into DSW formation regions as well as export (Schmidt et al. 2023; Silvano et al. 2020; Dinniman et al. 2018; McKee et al. 2011; Timmermann et al. 2002; Morrison et al. 2023). ACWs therefore modify production rates for new sea ice, which in turn impacts DSW and AABW formation. The results also indicate that synoptic wind patterns affecting large-scale sea ice distribution are often more important than localized winds over coastal polynyas.

The prevailing easterly winds around the Antarctic coast induce Ekman transport toward the coast, leading to coastal downwelling which is important for maintaining the Antarctic Slope Front (ASF) (Thompson et al. 2018). In the Amundsen Sea, the steepness of the ASF and the sea surface height gradient control the speed of the Amundsen Sea undercurrent. This current flows eastward along the continental slope and is responsible for transporting warm CDW from the deep ocean onto the continental shelf. This CDW eventually reaches the ice shelves where it drives rapid basal melting. Michael Haigh presented recent modeling work done by colleagues at BAS in this area. Their analysis shows that the direct impact of winds is important for downwelling on short time scales (e.g., Davis et al. 2018). However, on decadal time scales variability in freshwater fluxes from the sea ice north of the continental slope is the first order control on the cross-slope density structure. Through this process, the sea ice controls the Amundsen Sea undercurrent and ice-shelf basal melt (Haigh and Holland 2024).

5. Developments in numerical modeling

Several participants have been working on improving parameterization of processes relevant to ACWs. These efforts were highlighted in talks and a dedicated discussion session.

Flight campaign observations in recent years have been used to test and improve approaches to parameterizing exchanges of momentum, heat, and moisture between the atmosphere and sea ice over the Southern Ocean. Ian Renfrew presented results from this work, highlighting how explicit representation of sea ice form drag has a major impact on the simulation of near-surface winds around coastal Antarctica (Renfrew et al. 2019).

A detailed account of current model development work with the ICOLMDZ model was given by Étienne Vignon and Valentin Wiener. This model couples the atmospheric component of the IPSL Coupled Model and the DYNAMICO dynamical core. A low-complexity parameterization for blowing snow has been evaluated with station measurements from Adélie Land. Preliminary investigation suggests that the export of blowing snow can sometimes enhance the low cloud cover in the cold sector of extratropical cyclones transiting across the high latitude Southern Ocean.

6. Research priorities

a. Observations and observational requirements. Observations of the unique conditions in the Antarctic region are sparse, and more observations are required to monitor climate change and extreme events, understand processes, and evaluate models and for assimilation into reanalyses. It is therefore important to ensure that all observations are accessible and interoperable so that datasets from ship campaigns and other existing datasets can be aggregated into easy-to-use formats. Further efforts are also needed to identify and digitize historical observations of all kinds from the region; some existing and ongoing data rescue efforts at BAS were highlighted. Participants also discussed their struggles to obtain continuous weather station measurements and reliable scatterometry products to inform operations while in the field.

Other discussions focused on participants' efforts to enhance observational capabilities. New wind data in East Antarctica will be provided by the AWACA project (https://awaca.ipsl.fr/). Four sites from the coast of Adélie Land to the high plateau at Dome C in East Antarctica (D17, D47, D85, and DC) will be equipped with a 7-m meteorological mast with three wind speed levels and a sonic anemometer yielding information about turbulence all year long from 2025 to 2028.

Furthermore, a 1.274-GHz pulsed wind profiler radar has been deployed at Dumont d'Urville in December 2023 to scan the 3D wind up to several kilometers, enabling a high-frequency day-and-night supervision of the katabatic layer above the station. Data availability from this radar deployment has been hindered by the difficulties of operating hardware and software in challenging environmental conditions.

Other observational hardware development such as saildrones or sonde observations over shelf regions could be of great use especially in regions not covered by scatterometry products (i.e., on ice-shelves or polynya), with potential for increased coordination of observation activities in future during the planned UN Ocean Decade Action Antarctica InSync aimed at large-scale collaborative and synchronous observation of the Southern Ocean and Antarctica including ocean, land, and atmosphere.

b. Model development. Realistic numerical modeling of near-surface winds at high southern latitudes is challenging due to the influence of complex topography, interactions with varied surface types, high stability, and exceptionally high variability on a range of time scales. Presentations and discussions at the workshop identified some key areas for improvement.

Modeling of momentum exchange between the atmosphere and sea ice has benefited from observation campaigns discussed in section 5. However, participants also emphasized the need to understand the effect of switching to implementation of fully coupled wave models on drag.

Over land, the representation of coastal slope flows is a particular challenge for numerical models, especially in strong wind shear conditions for which common formulations of turbulent mixing length are no longer valid (Grisogono and Belušić 2008). The sharp transition of the flow at the coast—often referred to as "katabatic jumps"—is also difficult to capture with the standard resolutions used in global and regional atmospheric models (Vignon et al. 2020). Numerical instability and error occur due to tight coupling between the wind and turbulence fields (Vignon et al. 2024). Currently, modellers at LMD are testing the sensitivity of the model to varied resolution and physics, with the aim of disentangling structural deficiencies from issues stemming from tuning of parameters. Similar work collaborating with the Met Office is ongoing at BAS, with a focus on the sensitivity of near-surface coastal winds in East Antarctica to model physics. This workshop illustrated that near-surface winds are intimately linked with sea ice production and ocean circulation. An important next step will therefore be to quantify how uncertainties in numerical modeling of ACWs on a range of scales impact the ocean and cryosphere in fully coupled model configurations.

To make best use of new and existing observations, participants highlighted a need for targeted climate model evaluation metrics which can quantify representation of ACWs across models and map onto observational benchmarks (e.g., Russell et al. 2018). Existing research has used reanalysis data, bathymetry, and topography to delineate the boundaries of ACWs

(Hazel and Stewart 2019; Neme et al. 2022; Caton Harrison et al. 2022). One challenge of this work lies in evaluating free-running models against observations of limited duration, for which statistical model weighting approaches were suggested in the discussion. Second, analysis presented at the workshop indicates that separate metrics are needed for east and west Antarctic coastal easterlies, for dynamically distinct terrestrial and offshore winds and for specific hotspots of atmosphere–ocean interaction. To ensure these metrics are informed by the needs of the research community, close collaboration between atmospheric scientists, oceanographers, and sea ice experts will be crucial.

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