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20 Years of Finnish Research on Boundary-Layer Meteorology and Air-Ice-Sea Interaction in the Antarctic

Timo Vihma[1], *Jouko Launiainen*[2] *and Roberta Pirazzini*[1]

[1] Finnish Meteorological Institute, POB 503, 00101 Helsinki, Finland
[2] Department of Physics, University of Helsinki, Helsinki, Finland

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Abstract

Finnish research on boundary-layer meteorology and air-ice-sea interaction in the Antarctic was started in 1989 by the first R/V Aranda expedition to the Weddell Sea. During 20 years eight field expeditions have been made: four in the sea ice zone in the Weddell Sea and four in the Queen Maud Land. The research has focused on atmospheric forcing on sea ice drift, air-sea and air-ice exchange of heat and moisture, radiative fluxes and snow/ice albedo, convection over leads and polynyas, and stable atmospheric boundary layer over snow and ice. In addition to the Finnish field expeditions, the research has been based on other in-situ observations available, remote sensing data, and model experiments on atmospheric boundary-layer and mesoscale dynamics, radiative transfer, snow and ice thermodynamics, and ocean dynamics.

Key words: albedo, Antarctic, atmospheric moisture budget, sea ice, stable boundary layer, surface fluxes, Weddell Sea

1. Introduction

Finland became a consultative party of the Antartcic Treaty in 1989, which included an obligation for research. From 1989 to 1997 the Finnish Antarctic Research Program (FINNARP) was coordinated by the Ministry of Trade and Industry, and from 1998 onwards by the Ministry of Education, which has allocated research funding via the Academy of Finland. In addition, various research institutes and universities have funded Antarctic research. The Antarctic logistics have been organized in close collaboration with, above all, Sweden and Norway, and Finnish scientists have also participated in field campaigns organized by several other nations.

Finnish Antarctic research has involved a broad range of scientific topics. In this review we address research on the atmospheric boundary layer (ABL) and air-ice-sea interaction. In related fields, not included in this review, active research is carried out on ozone and ultraviolet radiation (*Taalas et al.*, 1997), stratospheric dynamics (*Karpetchko et al.*, 2005), physics and chemistry of aerosols (*Virkkula et al.*, 2006) and snow (*Kärkäs et al.*, 2005a,b), as well as glaciology (*Grinsted et al.*, 2003). Research on boundary-layer meteorology and air-ice-sea interaction has been motivated by the importance of surface exchange processes to weather and climate. Especially over the Antarctic, atmospheric models have large errors at and near the surface (*Vihma et al.*, 2002).

This review presents the methodology applied (Section 2), and results for the wind forcing on sea iced drift (Section 3), surface heat budget (Section 4), and boundary-layer meteorology (Section 5). Conclusions are drawn in Section 6.

2. *Field expeditions and methods*

Preparations for Finnish Antarctic research were started by building the Aboa station at the Basen nunatak in the Queen Maud Land (73°03'S, 13°24'E) in 1988–1989. An automatic weather station was deployed at Aboa. In the following austral summer, an expedition by R/V Aranda of the late Finnish Institute of Marine Research (FIMR) was organized. It marked the start of the Finnish research on Antarctic meteorology and air-ice-sea interaction by the University of Helsinki and FIMR. Besides the measurements made during the expedition, marine meteorological buoys deployed in the open ocean, sea ice, and ice shelf edge yielded valuable data. The next field work was carried out in summer 1991–1992 in the framework of Finnish participation in the U.S.-Russian Ice Station Weddell 1 (ISW-1). A second expedition by R/V Aranda took place in summer 1995–1996. In these three field expeditions, the main focus from the point of view of this review was in the interaction between the atmosphere and sea ice: the surface energy budget and the wind forcing on sea ice drift. After the 1995/1996 expedition there was a long gap in marine field work, but studies on air-snow interaction were started in 1999–2000 in the surroundings of Aboa. In summer 2004–2005 Finnish scientists participated in the international Ice Station Polarstern (ISPOL), a drifting station in the Weddell Sea comparable to ISW-1. In summers 2006–2007 and 2007–2008 meteorological field work was carried out at Aboa. The field expeditions are summarized in Table 1.

In addition to the FINNARP field expeditions, the research has been based on other in-situ observations available, remote sensing data, and experiments applying models for atmospheric mesoscale dynamics, radiative transfer, global ocean dynamics, snow and ice thermodynamics, and thermo-hydrodynamics of sub-surface ponds. The models are introduced in Sections 3 and 4. Further, studies based on model products, such as reanalyses and operational analyses of the European Centre for Medium-Range Weather Forecast (ECMWF) and the U.S. National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR), have been applied.

Table 1. Finnish field expeditions including research on boundary-layer meteorology and air-ice-sea interaction.

Summer	Region; ship / station	Scientists	Main activity
1989–1990	Weddell Sea; R/V Aranda	J. Launiainen, K. Rantanen	Buoy deployments on sea ice, open ocean, and ice shelf
1991–1992	Weddell Sea; R/V Akademik Fedorov / Ice Station Weddell	J. Launiainen, K. Rantanen	Buoy deployments on sea ice
1995–1996	Weddell Sea; R/V Aranda	J. Launiainen, T. Vihma, J. P. Uotila, P. Kosloff, T. Purokoski, S. Kalliosaari	Buoy deployments on sea ice, rawinsonde soundings, surface flux measurements
1999–2000	Queen Maud Land, Aboa	E. Kärkäs, K. Rasmus	Radiation and snow properties
2000–2001	Queen Maud Land, SANAE 4, Aboa	K. Rasmus, E. Kärkäs	Radiation and snow properties
2004–2005	Weddell Sea; Ice Station Polarstern	J. Launiainen, M. Johansson, P. Kosloff	Surface flux, snow, and ABL measurements, buoy deployments on sea ice
2006–2007	Queen Maud Land, Aboa	T. Vihma, R. Pirazzini	Surface flux, snow, and ABL measurements
2007–2008	Queen Maud Land, Aboa	M. Johansson	Surface flux, snow, and ABL measurements

3. *Wind forcing on sea ice and the ocean*

3.1 *Experimental studies*

Wind forcing on sea ice drift has been studied on the basis of buoy observations on ice drift and near-surface winds and model analyses of the geostrophic wind. To optimize the spatial and temporal distribution of buoys in the Antarctic sea ice zone, the later FINNARP buoy deployments have been made in coordination with the International Program for Antarctic Buoys (IPAB; www.ipab.aq), which was launched in Helsinki in 1994.

The first FINNARP analyses were based on a buoy deployed on an ice flow in the Weddell Sea on 2 January 1990 (Vihma and Launiainen, 1993). The buoy drifted for 18 months in sea ice, and further two months in the open ocean, yielding a trajectory length of 10 000 km. The buoy included sensors for the atmospheric pressure, wind speed and direction, and air temperature. The drift was tracked and data transmitted via the Argos satellite system. During the ISW-1 expedition in 1991–1992, two buys were deployed in more western regions of the Weddell Sea, and during the R/V Aranda expedition in 1995/1995 seven buoys were deployed on ice floes. During ISPOL in late November and December 2004, 26 buoys were deployed in the western Weddell Sea, three of them being from FINNARP. Drift trajectories of all FINNARP buoys in are shown in Figure 1, and a photo of one of them in Figure 2a.

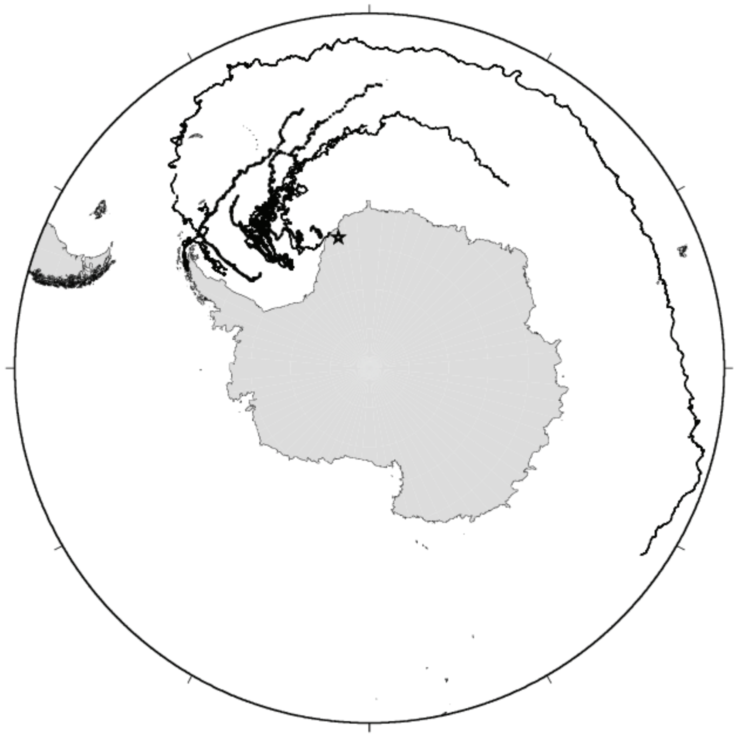

Fig. 1. Drift trajectories of the 14 marine meteorological buoys deployed during FINNARP expeditions in 1989–2005. The star marks the location if the Finnish research station Aboa.

Vihma and Launiainen (1993) and *Vihma et al*. (1996) detected inertial oscillation super-imposed to the wind-induced drift. In the central Weddell Sea the mean ice drift speed was 0.15 m s^{-1}, which was on average 3% of the wind speed with some spatial variability: 3.4% in the ice edge zone and 2.4% in the inner pack ice field. On average, the drift was directed 36° left of the wind direction, but the turning angle was larger in summer than winter. The ice drift was almost parallel to the geostrophic wind based on ECMWF operational analyses, and the drift speed was 2% of the geostrophic wind speed. *Kottmeier et al*. (1997) collected data from partners of the IPAB, and compared all ice drift data against geostrophic winds. In the southwestern Weddell Sea the mean ice drift speed was reduced to less than 0.5% of the geostrophic wind speed and increased rather continuously to 1.5% in the northern, central, and eastern Weddell Sea. *Vihma et al*. (1996) found out that stable atmospheric stratification significantly reduced the wind forcing on the ice drift.

According to *Vihma et al*. (1996), a linear model between the observed wind and ice drift explained 40–80% of the ice velocity variance. The degree of explanation was higher in the central Weddel Sea (40°W) and lower close to the Antarctic Peninsula. Still closer to the Peninsula, the ISPOL buoys yielded about 40% explanation (*Heil et* *al*., 2008). Although not all cyclones were well detected by the ECMWF analyses, the geostrophic wind provided almost as good basis for the general drift estimation as the surface wind observed by the buoys (*Vihma et al*., 1996; *Kottmeier et al*., 1997).

In simple simulations of ice drift trajectories, *Vihma and Launiainen* (1993) found out that on time scales of days the drift was primarily wind-dependent. For time scales of several months, however, purely wind based simulations resulted in a discrepancy between observed and simulated trajectories, but the inclusion of a slow residual current made the simulations significantly better. *Vihma et al*. (1996) found out that for 60–80% of the time, the drift direction deviated less than 45° of the geostrophic wind direction, and for 45–70% of the time less than 45° from the ocean current. *Uotila et al*. (2000) made detailed analyses on the momentum balance of the ice floe, and observed that the drift velocity was highly wind dependent also in winter when the momentum balance was mainly between the internal ice stress and air-ice drag. The drift divergence and shearing were related to the wind forcing, while the array vorticity correlated better with the air pressure. For the air-ice drag coefficient at 10-m height, *Uotila et al*. (2000) found a value of 1.8×10^{-3}, and 0.61×10^{-3} for the geostrophic drag coefficient. The ISPOL data from the western Weddell Sea indicated that sub-day scale ice velocity variations were dominated by tidal and inertial motion (*Heil et al*., 2008).

The ice export out of the Weddell Sea was estimated by *Vihma et al*. (1996) and *Uotila et al*. (2000) utilizing model analyses on the geostrophic wind, observations on the drift's response to the wind, and remote-sensing based information on the ice concentration. The export was calculated across a transect crossing the Weddell Sea from Cape Norvegia to the tip of the Antarctic Peninsula. *Vihma et al*. (1996) demonstrated a large inter-annual and seasonal variability in the ice export. Most of the export took place in winter and spring, export prevailing west of 35°W and import east of it. The volume of the transport was better quantified by *Uotila et al*. (2000), who also utilized sonar-based results on ice draft statistics and obtained an annual mean net export of 50 000 $m^3 s^{-1}$, with a dominating contribution of deformed ice.

Wind is the primary factor building sea ice ridges in the Antarctic. On the basis of helicopter-borne laser profiling during the first FINNARP expedition, *Granberg and Leppäranta* (1999) analysed ridge statistics in the Weddell Sea. The overall ridge frequency in 1990 was 8.4 ridges / km and the average ridge height was 1.32 m, but the spatial variations were large.

3.2 Modelling studies

The purpose of the modelling work has been to develop and test parameterizations for the air-surface momentum flux in conditions of a heterogeneous sea ice cover, i.e., an ice cover broken by leads and polynyas. *Vihma* (1995a) applied a two-dimensional mesoscale boundary layer model to simulate the air flow inside a single grid element of a hypothetical large-scale model. Simulations were run with various sea ice concentrations, polynya widths, and large-scale wind conditions, and the results were compared against various literature-based and proposed parameterization schemes.

Parameterization of surface momentum flux seemed to be most reasonable on the basis of the surface pressure field and a geostrophic drag coefficient depending on the air-surface temperature difference. This is in accordance with the above-mentioned observations on the drift's strong dependence on the geostrophic wind.

Recent studies on the parameterization of wind forcing on sea ice also included participation in global ocean modelling in collaboration with the Texas A&M University (*Stössel et al.*, 2008). Various parameterization schemes were applied and the model sensitivity was analysed. The driving force for sea ice drift was the momentum flux based in one case on the local stratification and roughness over ice, and in the other case on spatially aggregated stratification and roughness. In the case of aggregation, with surface heterogeneity accounted for, the impact of the lower coastal ice concentration led to a larger momentum flux than in the local case. The larger momentum flux enhanced the along and offshore ice drift, leading to corresponding changes in the winter-mean ice-thickness distribution, a reduction in coastal ice concentration, and an increase of heat loss due to sensible heat flux. It even resulted in an increase of Antarctic Bottom Water formation.

The simulated effects of wind forcing on sea ice drift also depend on the description of other aspects of ice dynamics in the model. *Haapala et al*. (2005) studied the importance of sea ice deformation and its presentation in a dynamical model. Their multi-category model explicitly took into account redistribution of undeformed ice into categories of ridged and rafted ice. Under wind forcing typical for the Weddell Sea, the model performance was compared with that of a model that accounts for only two categories. The multi-category model produced larger open water fractions and thicker ice than the two-category model.

4. Surface heat budget

FINNARP studies on the surface heat budget have mostly been based on data analyses from the sea ice zone with estimates for the local turbulent and radiative surface fluxes separately over the sea ice, leads and the open ocean. The studies have also addressed area-averaged fluxes over the heterogeneous sea ice cover. Particular focus has been paid on the surface albedo, which has also been studied over the continental ice sheet. Further, the links between the surface latent heat flux, precipitation, and atmospheric moisture budget have been studied in a circumpolar scale.

4.1 Surface albedo

Pirazzini (2004) carried out extensive analyses on the spatial and temporal variability in the snow and ice surface albedo on the continental ice sheet. The highest degree of variability was observed at Hells Gate Station on the Ross Sea coast. The temperature close to the melting point and the reduced katabatic winds during summer allowed a strong metamorphism of the snow. At Neumayer, a coastal station by the

Weddell Sea, snowfall and drifting snow were more frequent, and the surface albedo was constantly high. The albedo increased by an average of 0.07 from clear days to days with snowfall and overcast sky. The seasonal evolution of snow and ice albedo was found to be correlated with the surface temperature at Hells Gate, but at the other sites the variation in albedo was mainly driven by the variation in cloud cover fraction. The clear-sky diurnal evolution of albedo at Hells Gate showed a trend similar to the one observed at Neumayer Station and at Dome Concordia Station on the high plateau, when only those days with fresh snow at the surface were considered. The albedo steadily decreased during the day for solar zenith angles less than 80°. Snow metamorphism, sublimation during the day, and refreezing and/or crystal formation/precipitation during the night explained the observed trend. *Pirazzini* (2004) also reviewed the various possible error sources in the albedo measurements. For instance, she showed that the small-scale surface roughness elements (sastrugi) at Reeves Névé Station produced a distortion in the measured albedo.

During FINNARP expeditions in 1999–2001, solar broadband and spectral albedo of snow and ice were measured in the Queen Maud Land along a 350-km traverse inland from the coast (*Kärkäs et al.*, 2002) and in the vicinity of the South African Antarctic station SANAE 4 (*Rasmus*, 2006). The results showed that the midday mean broadband snow albedo was from 0.83 (clear skies) to 0.86 (overcast skies) at Aboa, and from 0.81 to 0.83 at SANAE 4. The variations in the spectral albedo were explained by differences in cloud cover (*Rasmus*, 2006).

One of the longest in-situ data sets of snow broadband albedo over Antarctic sea ice was collected during ISPOL from 28 November 2004 to 2 January 2005. During this period, the albedo only showed a small trend from 0.9 to 0.8 (*Vihma et al.*, 2009). The diurnal amplitude of albedo was on average 0.02, but in the days with surface melting the mean amplitude increased to 0.04. As in *Pirazzini* (2004), the diurnal cycle was asymmetric, which probably resulted from the compensating effects of the solar zenith angle and snow metamorphosis.

Laine (2008) applied satellite remote sensing data (AVHRR Polar Pathfinder) to study the regional albedo of the Antarctic ice sheet and sea ice in the springs and summers of 1981–2000. He divided the study region into five longitudinal sectors around Antarctica. The Indian and Pacific Ocean sectors showed a mean ice sheet albedo of 0.85, while a lower value of 0.80 was obtained for the Ross Sea and Bellingshausen-Amundsen Sea sectors. The albedo of the sea ice zone, affected by leads and polynyas, was about 0.60 in the Weddell, Ross, and Bellingshausen-Amundsen Sea sectors and 0.55 in the Indian and Pacific Ocean sectors. All the sectors showed slightly increasing 20-year trends in spring-summer albedo, consistent with decreasing spring-summer temperature trends and slightly increasing sea ice concentration trends. Further discussion on surface albedo follows in Section 4.3.

4.2 Local surface fluxes

FINNARP studies on the local surface fluxes over sea ice, open water, ice shelves, and the continental ice sheet have been based on buoy data from the expeditions in 1989–1996 and from direct radiative and turbulent flux observations from the ISPOL expedition in 2004–2005 and the two Aboa expeditions in 2006–2008. Although the instrumentation of the buoys deployed in 1989–1996 was the most versatile in that time, it did not allow direct flux measurements. The turbulent fluxes were estimated on the basis of observations on the temperature profile as well as the wind speed and air humidity. A lot of effort was made to further develop parameterization schemes for turbulent fluxes on the basis of observations on these basic quantities (*Launiainen and Vihma*, 1990; *Launiainen*, 1995). In addition, the thermodynamic snow/ice model HIGHTSI of *Launiainen and Cheng* (1998) was applied to support the data analyses.

4.2.1 Fluxes over ice and snow

The first analyses were based on data from the five buoys deployed in 1989–1990 and 1991–1992 (*Launiainen and Vihma*, 1994). Over the sea ice in the central and western Weddell Sea, a downward sensible heat flux of 15 to 20 W m^{-2} was observed in winter and 5 W m^{-2} in summer (all fluxes are defined positive towards the snow surface). The winter fluxes showed a large day-to-day variability with a standard deviation of 20 W m^{-2}. The latent heat flux was typically -5 to 0 W m^{-2} in summer (evaporation), while weak condensation prevailed in winter. Also over the continental ice shelf edge, the sensible heat flux was typically from air to snow (15 to 20 W m^{-2}), compensating the negative radiation balance of the snow surface. The analyses based on buoy data from the 1995–1996 expedition yielded basically similar results, but application of the HIGHTSI model to support the data analyses allowed for a better closure of the surface heat budget (*Vihma et al.*, 2002). More attention was also paid to the estimation of the radiative fluxes. The dominating component in the heat budget over ice was the net longwave radiation, which had a mean annual cooling effect of -28 W m^{-2}. This was balanced by the net shortwave radiation (annual mean 13 W m^{-2}), the sensible (13 W m^{-2}) and latent (-3 W m^{-2}) heat fluxes, and the conductive heat flux through the ice (5 W m^{-2}).

Finally the ISPOL expedition in 2004–2005 allowed direct measurements of both radiative and turbulent surface fluxes over sea ice in the western Weddell Sea from 28 November 2004 to 2 January 2005 (*Vihma et al.*, 2009). The net heat flux to the snow pack was 3 ± 2 W m^{-2} consisting of the net shortwave radiation (52 ± 8 Wm^{-2}), net longwave radiation (-29 ± 4 Wm^{-2}), latent heat flux (-14 ± 5 W m^{-2}), and sensible heat flux (-6 ± 5 W m^{-2}). In daytime the snow pack received heat, while it released heat every night. The snow thinning was due to approximately equal contributions of the increase in snow density, melt, and evaporation. During a case of cold-air advection the sensible heat flux was even below -50 W m^{-2}. At night the snow surface temperature was strongly controlled by the incoming longwave radiation.

Rasmus and Beckmann (2007) modelled the thermodynamics and circulation of sub-surface ponds in the Antarctic low-elevation (< 1000 m) blue-ice areas. Their model included a simple parameterization for the surface heat budget over blue ice. In a 50-year integration of the model forced by a global warming scenario (1.5°C temperature increase in 50 years), the results suggested an increase in the subsurface water volume and changes in pond shape and depth, while the surface remained frozen and largely unchanged. *Rasmus* (2009a) further developed the model.

4.2.2 Fluxes over the open water

The estimates of turbulent surface fluxes over leads in the sea ice zone were based on the common assumption that leads are usually so narrow (less than 100 m) that the air temperature, humidity and wind speed are not significantly modified while the air mass flows over a lead, as observed by *Andreas et al*. (1979). This allowed using the data from the buoys on sea ice to estimate the turbulent fluxes over leads. Analogously, buoy data from the edge of the ice shelf were applied for the fluxes over polynyas next to it. The first results (*Launiainen and Vihma*, 1994) indicated that a sensible flux of -300 to -100 W m^{-2} (defined positive towards the sea surface) was typical over leads, except in summer when the flux was close to zero. Over polynyas off the shelf edge, the sensible heat flux was typically from -400 to -100 W m^{-2}. The Bowen ration was 2.9 ± 0.9 (mean and standard deviation) over polynyas and 2.5 ± 0.7 over leads in winter.

Fluxes over leads were estimated also on the basis of the data from 1995–1996 (*Vihma et al*., 2002). The turbulent sensible heat flux was the dominating component in winter, and the net shortwave radiation in summer. Most of the time the surface released heat also via evaporation and net longwave radiation. The net heat flux over leads was positive (up to 270 W m^{-2}) from early October to February. From March through September it had a mean value of -310 W m^{-2}.

4.3 Regional surface fluxes

4.3.1 Data analyses

The regional surface fluxes over fractured sea ice cover were studied utilizing the buoy data from 1996, the HIGHTSI model, satellite Special Sensor Microwave Imager (SSMI) data on the sea ice concentration, sonar results on ice thickness distribution, and output from large-scale meteorological models (*Vihma et al*., 2002). In winter the regional surface sensible heat flux was sensitive to the ice concentration and thickness distribution. The estimate for the area-averaged formation rate of new ice in leads in winter varied from 0.05 to 0.21 m per month depending on the SSMI processing algorithm applied. The buoy observations were compared with the ECMWF operational analyses and the NCEP/NCAR reanalysis. The annual means of the ECMWF sensible and latent heat fluxes were 9 and 7 W m^{-2} too small, respectively, while for the NCEP/NCAR the sensible heat flux was 6 W m^{-2} too large and latent heat flux 5 W m^{-2} too small. The mean 2 m air temperature and surface temperature were 3.5°C and 4.4°C too high, respectively, in the ECMWF, and 3.2°C and 3.0°C too low in the NCEP/NCAR fields. The errors were related to the cloud cover and the surface boundary conditions. Neither of the models recognized leads in the ice pack, and the ice and snow thicknesses were often far from reality. In the NCEP/NCAR the ice thickness was a constant of 3 m with an unrealistically thick snow cover, which may contribute to the cold bias. In the ECMWF model the ice thickness was a constant of 1 m without any snow cover, which may contribute to the warm bias. The cloud cover was insufficient in the NCEP/NCAR model and excessive in winter in the ECMWF model. Initial results of recent model validation with ISPOL observations show, however, much improved performance of especially the ECMWF model.

4.3.2 Development of parameterization methods

Vihma (1995a) studied the parameterization of surface fluxes over a heterogeneous surface consisting of sea ice and polynyas (see also Section 3.2). Various large-scale parameterization methods were compared with results of a fine-scale two-dimensional model. Considering the fluxes of sensible and latent heat, a mosaic method, based on the use of estimates for local surface temperature, air temperature, specific humidity, wind speed, and surface roughness over the ice-covered and ice-free parts of the grid square, performed well in the comparison. Parameterizing the net longwave radiation, an estimate for the subgrid distribution of cloudiness was useful.

Vihma (2004) divided the surface fluxes in two categories: horizontally independent and horizontally interactive fluxes. In the case of horizontally interactive fluxes, the local fluxes at a certain surface type are – at least in some situations – strongly affected by the local fluxes over the neighbouring surface types. Such are the fluxes shortwave radiation, sensible heat, and latent heat. This approach was applied by *Pirazzini and Räisänen* (2008), who addressed the solar shortwave radiation in the boundary zone of the open sea and snow/ice cover. Under overcast skies with multiple reflections between the cloud base and the snow/ice surface, the local value of downwelling solar radiation also depends on the albedo of the neighbouring surface type. *Pirazzini and Räisänen* (2008) derived a simple parameterization for the broadband effective albedo, defined as the albedo of a homogeneous surface that would result in the same downwelling irradiance as locally observed in the presence of a heterogeneous surface. Their method parameterizes the effective albedo using the cloud base height and a surface albedo map as inputs. The parameterization is based on the spatial distribution of surface reflections contributing to the downwelling irradiance at the observation site. The parameterization was validated against reference values of effective albedo derived from three-dimensional backward Monte Carlo and one-dimensional radiative transfer calculations for four idealized surface albedo maps and various specifications of cloud properties. It gave values of effective albedo very close to the reference calculations, performing substantially better than any other approach tested, also when applied to the retrieval of cloud optical depth. The method can be implemented into one-dimensional radiative transfer models or used to interpret broadband irradiance measurements in Antarctic coastal regions and close to the sea ice margin.

4.4 Evaporation and atmospheric moisture budget

Analyses on the atmospheric moisture budget represent a recently started activity in FINNARP (*Tietäväinen and Vihma*, 2008). Over the ice-free parts of the Southern Ocean, the latent heat of evaporation is a major component in the surface heat budget. On the basis of the ERA-40 reanalysis of the ECMWF, in the ice-free region south of 60°S, the monthly mean evaporation ranges from 30 mm in summer to 60 mm in winter. Over the sea ice zone, the values are typically between 5 and 20 mm, while over the continental ice sheet the annual average evaporation minus condensation is only slightly positive. Annually and zonally averaged precipitation exceeds evaporation everywhere south of 50°S. Hence, the precipitation can only be generated by water vapour transport from lower latitudes. The transport is due to transient eddies (most important component), stationary eddies, and mean meridional circulation. *Tietäväinen and Vihma* (2008) also found out that inter-annual variations in water vapour transport are related to the Southern Annular Mode. Hydrological balance was well achieved in the ERA-40 reanalysis: the difference between the water vapour flux convergence (based on analysis) and the net precipitation (precipitation minus evaporation, based on 24-h forecasts) was only 13 mm yr^{-1} (3%) over the Southern Ocean and -8 mm yr^{-1} (5%) over the continental ice sheet. Over the open ocean, the analysis methodology favoured the accuracy of the flux convergence rather than net precipitation.

5. Boundary-layer meteorology

Most FINNARP studies on boundary-layer meteorology have been based on modelling, and most studies have so far addressed the sea ice zone. The data analyses have been made on the basis of buoy, rawinsonde sounding, Aboa weather station, and ISPOL weather mast observations.

5.1 Sea-ice zone

Diurnal cycles in near-surface atmospheric variables have been addressed in two studies. The first FINNARP buoy data from the central Weddell Sea at 73–65°S in 1990 indicated a diurnal amplitude of 1.4°C in the 2-m air temperature in December (*Launiainen et al*., 1991). The buoy data also demonsrated that in addition to season and latitude the diurnal temperature cycle strongly depended on the ice concentration: the more open water around, the smaller was the diurnal cycle. The ISPOL data from the austral summer showed that the diurnal cycle in downward solar radiation drove diurnal cycles in 14 other surface or near-surface variables (*Vihma et al*., 2009). The turbulent fluxes of sensible and latent heat both had an apparent sinusoidal cycle with diurnal amplitudes of 7 and 10 W m^{-2}, respectively. The mean amplitudes of the snow surface temperature and 2-m air temperature were 1.6 and 0.9°C, respectively. For clouds with the base height lower than 300 m, a clear diurnal cycle was detected: the base height rose during the daytime convection and warming. Comparisons against observations from the Arctic sea ice in summer indicated that at ISPOL minor snow melt allowed for larger diurnal cycles.

Launiainen and Vihma (1994) studied air-mass modification over the open ocean during cold-air outbreaks from the continent. The surface sensible heat flux was estimated on the basis of three methods: bulk-aerodynamic method, ABL resistance laws, and the budget method based on the modification of the vertical temperature profile. The results indicated that the sensible heat flux decreased with increasing distance (up to 120 km) off the ice shelf edge.

Idealized modelling of the effect of leads and polynyas on the ABL in winter have been addressed in two studies. The results of *Vihma* (1995a) suggested strong polynya effects on the ABL: localized convection, enhancement of near-surface winds, as well as warming and moistening of the air mass. *Lüpkes et al*. (2008) applied a column model, and analyzed the results at different integration times corresponding to different fetches over the fractured sea ice as a function of wind speed and sea ice concentration. The results demonstrated that for the ice concentration exceeding 90% small changes in the sea ice fraction had a strong effect on the near-surface temperature. A change by 1% caused a temperature signal of up to 3.5 K. A threshold value of about 4 m s^{-1} for the 10-m wind speed divided the air-ice interaction process into a weak-wind and strong-wind regime. In the weak-wind regime, the 10-m air temperature increases from its minimum value, reached for 4 m s^{-1} wind speed, which is in agreement with observations over the Arctic sea ice.

Valkonen et al. (2008) carried out a modelling study with validation against buoy data. They applied the mesoscale model Polar MM5 to simulate a late autumn period, starting as northerly warm airflow over the Weddell Sea ice cover and turning to a southwesterly cold-air outbreak. Four different satellite-derived sea ice concentration datasets were applied to provide lower boundary conditions for Polar MM5. During the period of the cold-air outbreak, the modelled air temperatures were highly sensitive to the sea ice concentration: the largest differences in the modelled 2-m air temperature reached as much as 13°C. The experiments applying sea ice concentration data based on the Bootstrap (*Comiso*, 1986) and ARTIST algorithms (*Kaleschke et al*., 2001) yielded the best agreement with observations. The cumulative fetch over open water correlated with the bias of the modelled air temperature. The sea ice concentration data affected the simulated air temperature in the lower atmospheric boundary layer, but above the temperature and wind fields were more strongly controlled by the boundary layer scheme applied in Polar MM5.

5.2 Continental ice sheet

5.2.1 Boundary-layer effects on local climate

Launiainen et al. (1995) presented climatology at the Aboa station for years 1989–1994. The influence of local topography of the Basen nunatak on the wind direction was evident, with the dominant direction of 30° related to local channelling effects, and a second maximum at around 200° representing the large-scale katabatic flow. Also the wind speeds were affected by the local slopes. The air temperature and wind speed had a clear diurnal cycle in summer, with strongest winds around noon, when the local Nunatak bare surface was heated by solar radiation. *Kärkäs* (2004) continued the analyses including comparisons against the Neumayer station on the ice shelf 350 km from Aboa. She found out that in December – February Aboa is 0.8°C colder than Neumayer, while in June – August Aboa is 2.5 to 3.0°C warmer. The latter was due to prevailing temperature inversion and the location of Aboa at the slope of the Nunatak some 440 m above Neumayer and 250 m above the local glacier surface (Fig. 2b). As an annual mean, Aboa was 0.7°C warmer than Neumayer, and 2.1°C warmer than the site of a Dutch weather station only 10 km from Aboa but on the glacier at an elevation 120 m lower than Aboa.

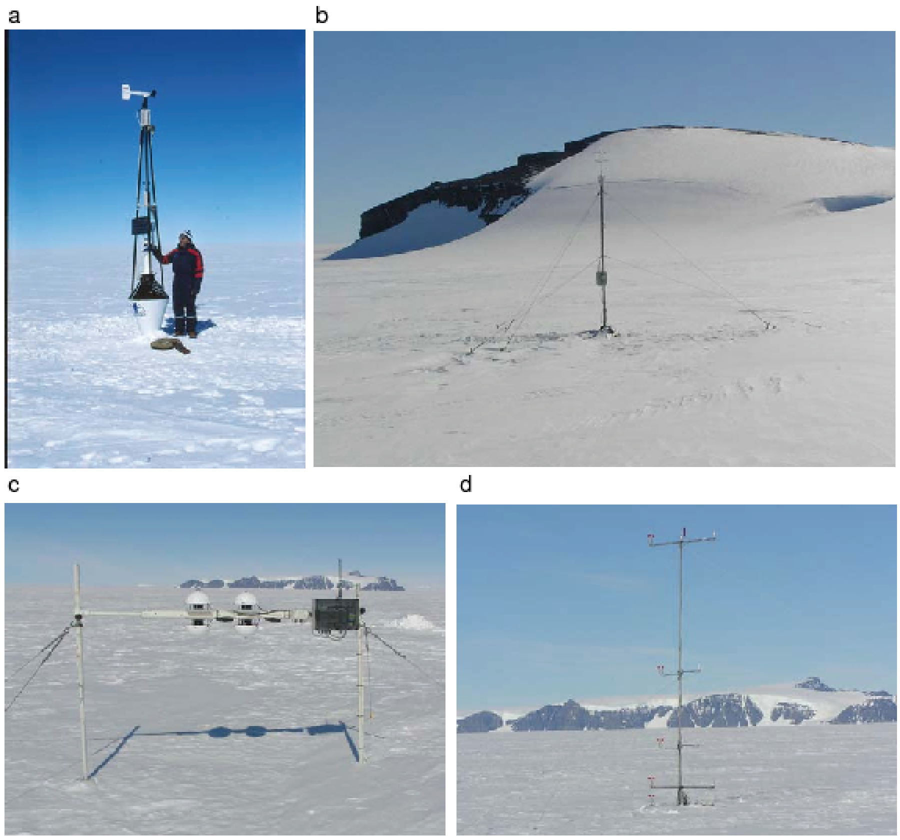

Fig. 2. (a) Drifting buoy deployed in the Weddell Sea in January 1992, and measurements over the continental ice sheet in January 2007: (b) sonic anemometer, (c) radiation sensors, and (d) weather mast. The Basen nunatak is seen in the background in (b) with Aboa at the right edge, and the Plugen nunatak is in the background in (c) and (d).

5.2.2 Stable boundary layer

Stable stratification in the ABL represents a major challenge for climate and numerical weather prediction (NWP) models, and over Antarctica a stable boundary layer (SBL) prevails for most of the year. Model results for near-surface temperature, moisture, wind, and turbulent fluxes show a strong sensitivity to stability functions, i.e., the parameterizations of the turbulent exchange coefficients on the basis of stratification. *Savijärvi* (2009) applied a column model to study the very stable boundary layer in winter conditions on the Antarctic high plateau. Comparisons against historical tower observations at the Plateau Station (79.3°S, 40.5°E) revealed that local representations for the exchange coefficients, allowing weak turbulence even for the Richardson number (Ri) exceeding the critical value of 0.2, produced good simulations of the temperature profiles and wind hodographs, while the schemes preventing turbulence for Ri > 0.2 yielded too little vertical mixing. The formulations used in most NWP and climate models resulted in too much vertical mixing. Over sloping glaciers and nunataks the situation is, however, more complicated, as large-scale model grid cells include subgrid-scale variations in topography, which in SBL tend to generate drainage flows. On the basis of further experiments applying a two-dimensional model *Savijärvi* (2009) suggested that the stability functions should depend not only on stratification but also on the subgrid-scale topography.

In conditions of stable stratification, a flow over mountains generates gravity waves. *Valkonen et al.* (2009) applied the Weather Research and Forecasting (WRF) model with 0.9 km horizontal resolution to simulate the flow over Basen nunatak in summer 2007–2008. The model results were validated against observations from a vertically pointing 54.5 MHz VHF radar. The WRF model generated gravity waves in the periods when these were observed. The gravity wave had a typical vertical wave length of 3–4 km, and a maximum amplitude of 1 m/s in the vertical velocity field. Gravity waves may affect the safety of aircraft landing and take-off on the lee side of the nunatak.

A serious challenge in modelling the Antarctic SBL is related to the small magnitude of turbulent fluxes, which increases the relative importance of the vertical divergence of longwave radiation. By column model experiments (not particularly tailored for the Antarctic) *Savijärvi* (2006) quantified these effects, and suggested that in light-wind conditions the Monin–Obukhov theory should be revised to include radiative effects.

Ongoing work on SBL addresses three topics: effects of katabatic winds on the air temperature, statistical analyses on the wind-induced ABL mixing on the 2-m air temperature, and testing of the results of *Savijärvi* (2009) in a NWP model.

5. Conclusions

The main results of data analyses, modeling studies, and derivation of parameterization schemes are summarized in Tables 2 and 3. The early phases of research were strongly focused to the ice-covered Southern Ocean. During the first ten years, all the expeditions were made to the Weddell Sea, and the main study topics were the atmospheric forcing on sea ice drift and the surface fluxes over the sea ice zone. In 1990s, buoys were essential to obtain information on the wind forcing on Antarctic sea ice drift in scales of $10^2 – 10^3$ km. Today, with improved satellite data available and improved accuracy of atmospheric model products, buoys are no more as important for

Table 2. Main results of data analyses on air-ice-sea interaction and boundary-layer meteorology.

Topic	Main results
Wind forcing on sea ice drift	The ratio of the ice drift speed to the near-surface wind speed (typically 2–3%) and geostrophic wind speed (1–2%) in various seasons and regions. Deviation angles between the drift and wind vectors (typically 30°). Air-ice drag coefficient. Divergence, vorticity and shear of the ice drift. Tidal and inertial motion. Correlation length scales of drift and wind components. (*Vihma and Launiainen*, 1993; *Vihma et al.*, 1996; *Kottmeier et al.*, 1997; *Uotila et al.*, 2000; *Heil et al.*, 2008).
Ice export out of the Weddell Sea	Strong seasonal and inter-annual variability; order of magnitude 50 000 m^3/s; quantitative estimates sensitive to information on ice thickness (*Vihma et al.*, 1996; *Uotila et al.*, 2000).
Surface albedo	Asymmetric diurnal cycle of albedo due to combined effects of solar zenith angle and snow metamorphosis (*Pirazzini*, 2004). Effects of cloud cover, drifting/blowing snow and sastrugi on albedo (*Pirazzini*, 2004). Spatial variation of albedo in the Queen Maud Land (*Kärkäs et al.*, 2002; *Rasmus*, 2006). Satellite data indicates slightly increasing spring and summer albedo trends in 1981–2000 over the sea ice zone (*Laine*, 2008).
Local surface heat budget	Contributions of shortwave and longwave radiation, turbulent fluxes of sensible and latent heat, and conductive heat flux on the heat budget over sea ice and leads, for the annual cycle over the Weddell Sea on the bases of buoy data and parameterizations (*Launiainen and Vihma*, 1994; *Vihma et al.*, 2002) and for early summer in the western Weddell Sea on the basis of direct flux measurements (*Vihma et al.*, 2009).
Regional surface heat budget	The estimate for the area-averaged formation rate of new ice in leads in the Weddell Sea sensitive to information on sea ice concentration. Large-scale model analyses include serious uncertainties in surface fluxes and temperature (*Vihma et al.*, 2002).
Evaporation and atmospheric moisture budget	Contribution of mean meridional circulation, standing eddies, and transient eddies to the southward moisture transport. Evaporation and precipitation rates over the Southern Ocean and Antarctica. Comparison of net precipitation and water vapour flux convergence. Effect of SAM on inter-annual variations in water vapour transport. (*Tietäväinen and Vihma*, 2008).
Local climate at the Aboa station	Effects of topography on the wind and effects of solar radiation and inversions on the air temperature (*Launiainen et al.*, 1995; *Kärkäs*, 2004).

large-scale studies, but the high temporal and spatial resolution of GPS buoy data is essential to study the atmospheric forcing on the small scale divergence, vorticity and shear of the ice field, as was extensively done in ISPOL. In the turn of the century the research activities expanded to the continental ice sheet, above all in the region of the Aboa station. The radiative fluxes and surface albedo of snow and continental ice became active study topics, and the number of scientists involved strongly increased.

Table 3. Main results of modelling studies and derivation of parameterization schemes.

Topic	Main results
Surface exchange and ABL processes	Algorithm for calculation of turbulent surface fluxes from wind, temperature, and humidity observations at different levels (*Launiainen and Vihma*, 1990). Richardson number as a function of the Obukhov length (*Launiainen*, 1995). Extended mosaic method for the area-averaged turbulent surface fluxes over heterogeneous sea ice (*Vihma*, 1995). Construction of a thermodynamic snow and ice model (*Launiainen and Cheng*, 1998). Sensitivity of the ABL temperatures on sea ice concentration (*Valkonen et al*., 2008; *Lüpkes et al*. (2008). Effects of subgrid-scale variations in topography on the background turbulence in a stable ABL (*Savijärvi*, 2009). First validated simulation of gravity waves generated by a small Antarctic nunatak (*Valkonen et al*., 2009).
Wind forcing on sea ice and the ocean	Benefits of a multi-category ice model in simulating open water formation in sea ice (*Haapala et al*., 2005). Effects of surface heterogeneity on the air-ice-water momentum flux and further to deep water formation (*Stössel et al*., 2008)
Albedo of heterogeneous surface	Parameterization for effective snow albedo under overcast sky and its application in the retrieval of cloud optical depth (*Pirazzini and Räisänen*, 2008).
Sub-surface ponds in blue ice	Effects of climate change on the subsurface water volume (*Rasmus and Beckmann*, 2007; *Rasmus*, 2009a).

The main motivation and challenges for the research have been (a) to better understand and model the Antarctic climate system and (b) to improve NWP models for the Antarctic. These challenges are closely related to those in the Arctic, and bi-polar links are strong in the Finnish research on boundary-layer meteorology and air-ice-sea interaction. For example, among the modelling studies reported here, several are process-oriented with the results equally (*Vihma*, 1995a; *Lupkes et al*. 2008; *Pirazzini and Räisänen*, 2008) or almost equally (*Valkonen et al*., 2008; *Savijärvi*, 2009) applicable for the Arctic and Antarctic.

The Finnish research activity in the field has significantly increased with 12 of the papers cited in this review being published or in press in 2008–2009. Four doctoral theses have been made (*Vihma*, 1995b; *Uotila*, 2000; *Kanto* (née Kärkäs) 2006; *Pirazzini*, 2008), one is in press (*Rasmus*, 2009b), and several are under work.

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