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96

SURFACE INFLUENCE ON THE MARINE AND COASTAL ANTARCTIC ATMOSPHERE

TERESA VALKONEN

FINNISH METEOROLOGICAL INSTITUTE
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No. 96

SURFACE INFLUENCE ON THE MARINE AND COASTAL ANTARCTIC ATMOSPHERE

Teresa Valkonen

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ACADEMIC DISSERTATION in meteorology

To be presented, with the permission of the Faculty of Science of the University of Helsinki, for public criticism in auditorium Physicum E204 (Gustaf Hällströmin katu 2b) on August 7th, 2013, at 12 o'clock noon.

Finnish Meteorological Institute
Helsinki, 2013

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ISBN 978-951-697-785-3 (paperback)
ISSN 0782-6117
Unigrafia Oy
Helsinki 2013
ISBN 978-951-697-786-0 (pdf)
http://ethesis.helsinki.fi
Helsinki 2013
Helsingin yliopiston verkkojulkaisut

FINNISH METEOROLOGICAL INSTITUTE

Published by Finnish Meteorological Institute

P.O. Box 503
FI-00101 Helsinki, Finland

Series title, number and report code of publication
Finnish Meteorological Institute
Contributions 96, FMI-CONT-96

Date
June 2013

Authors
Teresa Valkonen

Name of project

Commissioned by

Title
Surface influence on the marine and coastal Antarctic atmosphere

Abstract

The Antarctic region plays an important role in the global climate system, and it contributes to the future of global climate through changes in regional factors, such as sea ice, atmospheric circulation patterns and moisture distribution.The aim of this thesis is to improve the understanding of the influence of the Earth surface on the marine and coastal Antarctic atmosphere. The thesis outlines the characteristics of typical phenomena of the Antarctic environment both near the surface and higher in the atmosphere, and describes the challenges related to numerical modelling in the region.

The work is based on combined use of several observational data sets and regional numerical modelling. Marine atmosphere and its reprensentation in regional modelling was studied based on observational data collected on two research projects called 'Short Timescale Motion of Pancake Ice', and 'Ice Station Polarstern'. The coastal atmosphere was studied based on data from the Movable Atmospheric Radar for Antarctica from Queen Maud Land and the Integrated Global Radiosonde Archive from 11 coastal stations. Model simulations were made using two regional-scale atmospheric models: the Fifth-Generation Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model (MM5) and the Weather Research and Forecasting (WRF) model.

The boundary layer over the marine Antarctic was found to be strongly governed by the presence or absence of sea ice. The major challenges related to the modelling of the atmosphere over Antarctic sea ice were associated with clouds, boundary layer processes and sea ice and snow description. The model sensitivity to different physical parameterisation schemes was most profound in the lowest parts of the atmosphere. The results confirm that numerical simulations reproduce relatively accurately the basic meteorological surface variables, such as temperature, humidity, air pressure, wind speed and wind direction, over ice-covered ocean, but the turbulent and radiative fluxes that affect those variables were not that well depicted. To minimise the modelling errors, the sea ice conditions should be updated frequently with advanced description of ice and snow processes. The modelling benefits also from advanced cloud schemes with prediction of the vertical distribution of cloud water and ice content.

The vertical structure of the atmosphere over the coastal Antarctic was found to be featured by internal gravity waves and temperature and humidity inversions. Gravity waves generated by a small mountain peak emerging above the ice sheet were found to reach the lower stratosphere. This implies that even small mountains can generate strong gravity waves, and it is possible to simulate them when applying high horizontal resolution in the model. Humidity inversions were found to be, nearly all the time, present on multiple levels in the coastal Antarctic atmosphere. The presented statistics for humidity inversions can be used as a baseline for further studies addressing moisture changes in the Antarctic atmosphere.

Publishing unit
Finnish Meteorological Institute, Meteorological Research Unit

Classification (UDC)
551.509.313.43
551.510.411
551.511.31
551.571.1

Keywords
atmospheric boundary layer, internal gravity waves, humidity inversions, numerical modelling, sea ice

ISSN and series title
0782-6117 Finnish Meteorological Institute Contributions

ISBN
978-951-697-785-3 (paperback), 978-951-697-786-0 (pdf)

Language
English

Pages
114

Price

Sold by
Finnish Meteorological Institute / Library
P.O. Box 503, FI-00101 Helsinki, Finland

Note

ILMATIETEEN LAITOS

Julkaisija	Ilmatieteen laitos PL 503, 00101 Helsinki	Julkaisun sarja, numero ja raporttikoodi Finnish Meteorological Institute Contributions 96, FMI-CONT-96 Julkaisuaika Kesäkuu 2013

Tekijä(t)
Teresa Valkonen

Projektin nimi

Toimeksiantaja

Nimike
Pinnan vaikutus ilmakehään Antarktiksen meri- ja rannikkoalueilla

Tiivistelmä

Antarktiksella on tärkeä rooli maapallon ilmastosysteemissä. Se vaikuttaa merkittävästi maapallon ilmaston tulevaisuuteen paikallisten tekijöiden, kuten merijään, ilmakehän virtausrakenteiden ja kosteusjaukauman muutosten kautta. Tämän väitöskirjatyön tavoitteena on lisätä ymmärrystä maapallon pinnan vaikutuksesta ilmakehään Antarktiksen meri- ja rannikkoalueilla. Väitöskirja selvittää alueelle tyypillisten ilmiöiden ominaisuuksia pinnan lähellä sekä ylempänä ilmakehässä, ja määrittää alueen numeeriseen mallinnukseen liittyviä haasteita.

Työ perustuu useiden havaintoaineistojen hyödyntämiseen ja alueelliseen numeeriseen mallinnukseen. Merialueen ilmakehää ja sen kuvausta alueellisessa mallinnuksessa tutkittiin kahden tutkimusprojektin, 'Short Timescale Motion of Pancake Ice' ja 'Ice Station Polarstern', keräämän havaintoaineiston avulla. Rannikkoalueiden ilmakehän tutkimus perustui Movable Atmospheric Radar for Antarctica -tutkahavaintoihin Kuningatar Maudin Maalta ja radioluotauksiin 11 rannikkoasemalta. Mallisimulaatiot tehtiin käyttäen kahta alueellista ilmakehämallia: MM5 (the Fifth-Generation Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model) -mallia ja WRF (Weather Research and Forecasting) -mallia.

Ilmakehän rajakerrosta Antarktiksen merialueella määrittää ensisijaisesti se, onko alueella merijäätä vai ei. Suurimmat haasteet merijään yläpuolisen ilman mallittamiseen liittyivät pilviin, rajakerrosprosesseihin ja merijään ja lumen kuvaukseen. Mallin herkkyys eri fysikaalisille parametrisointimenetelmille oli selkein ilmakehän alimmissa osissa. Tulokset osoittavat, että numeerinen mallinnus voi merijään peittämällä merellä kuvata suhteellisen tarkasti meteorologisia perussuureita kuten lämpötilaa, kosteutta, ilmanpainetta, tuulen nopeutta ja tuulen suuntaa, mutta turbulenttiset ja säteilyvuot, jotka noihin suureisiin vaikuttavat, ovat huonommin mallinnettuja. Mallinnusvirheiden pienentämiseksi merijää tulisi syöttää mallisysteemiin riittävän usein sisällyttäen mukaan jään ja lumen prosessit yksityiskohtaisesti kuvattuina. Lisäksi mallinnusta parantavat edistyneet pilvien parametrisointimenetelmät, joissa on mukana pilviveden ja jään pystyjakauman ennustaminen.

Ilmakehän pystyrakenteelle Etelämantereen rannikkoalueilla on tyypillistä sisäiset gravitaatioaallot ja lämpötila- ja kosteusinversiot. Pienen jäätikön yläpuolelle nousevan vuorenhuipun kehittämien gravitaatioaaltojen osoitettiin ulottuvan stratosfäärin alaosiin. Tämä viittaa siihen, että myös suhteellisen pienet vuoret voivat synnyttää voimakkaita gravitaatioaaltoja. Mallinnuksella osoitettiin, että aallot on mahdollista simuloida käyttäen tarkkaa horisontaalista resoluutiota. Kosteusinversioiden havaittiin olevan lähes jatkuvasti läsnä useissa eri kerroksissa Etelämantereen rannikkoalueen ilmakehässä. Esitettyjä kosteusinversioiden ilmastotilastoja voidaan käyttää pohjana Antarktiksen ilmakehän kosteuden muutosten jatkotutkimuksille.

Julkaisijayksikkö
Meteorologinen tutkimus

Luokitus (UDC)	Asiasanat
551.509.313.43 551.510.411 551.511.31 551.571.1	ilmakehän rajakerros, gravitaatioaallot, kosteusinversiot, numeerinen mallinnus, merijää

ISSN ja avainnimike
0782-6117 Finnish Meteorological Institute Contributions

ISBN
978-951-697-785-3 (paperback), 978-951-697-786-0 (pdf)

Kieli	Sivumäärä	Hinta
englanti	114	

Myynti	Lisätietoja
Ilmatieteen laitos / Kirjasto PL 503, 00101 Helsinki	

To *Hulda* and *Arvid*,
my pride and joy,
who have taught me more than any book I have read

Acknowledgements

This dissertation would not have been possible without the guidance and help of several individuals and institutes.

The work was funded by the Academy of Finland through Antarctic research projects at University of Helsinki (UH) and the Finnish Meteorological Institute (FMI). I would like to thank, first and foremost, my advisors Hannu Savijärvi and Timo Vihma, as well as the departmental leadership, for providing me the opportunity to join the projects and the academic research community. This thesis would have remained a dream had it not been Hannu's encouragement and kind words over the years. Timo has always been genuinely interested in my research, and I am truly grateful for his contribution of time and dedication.

Over the past few years, the work has been carried out as a visiting scientist at the Norwegian Meteorological Institute (MET Norway) in Oslo. I am grateful to Harald Schyberg and Jørn Kristiansen for welcoming me into their department.

I would like to thank all co-authors, reviewers and mentors who have shared their time and experience with me. Without their input, I would neither have had the data to work with nor the ideas to make the improvements needed. Special thanks to Tiina Nygård who is a co-author, a proofreader and a peer, and most importantly, a good friend. Also, I would like to thank Hilkka Pohjola and Charles Wetherill for helping me with the language.

For a successful scientific career, or simply being able to finish the PhD, it is important to have a sense of belonging to the science community. I would like to thank everyone at FMI, UH, MET Norway and University of Oslo who has been there to make this happen. Also, I would like to thank the scientists of the Association of Polar Early Career Scientists (APECS) all over the world for unbelievable enthusiasm, energy and support.

During these years of dissertation work, I have not only learned how to be a scientist, but also I have become a wife and a mother. I owe my deepest gratitude to my husband Janne. He has spent countless hours proofreading and listening to me talk about my work. He has always believed in me, even when I doubted myself. Together we have found the solutions to make it possible for me to conduct this work. Finally, I am grateful to our lovely children, Hulda and Arvid. They have made me stronger and happier than I ever could have imagined, also as a scientist.

Oslo, June 2013

Teresa Valkonen

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List of original publications

This thesis consists of an introductory review, followed by four research articles. The papers are reproduced with the kind permission of the journals concerned. In the introductory part, these papers are cited according to their Roman numerals.

I **Valkonen, T.**, T. Vihma, and M. Doble (2008). Mesoscale modelling of the atmospheric boundary layer over the Antarctic sea ice: a late autumn case study. *Monthly Weather Review*, **136**, 1457–1474.

II **Valkonen, T.**, T. Vihma, M. M. Johansson, and J. Launiainen (2013). Atmosphere - sea ice interaction in early summer in the Antarctic: evaluation and challenges of a regional atmospheric model. *Quarterly Journal of the Royal Meteorological Society*, submitted.

III **Valkonen, T.**, T. Vihma, S. Kirkwood, and M. M. Johansson (2010). Fine-scale model simulation of gravity waves generated by Basen nunatak in Antarctica. *Tellus*, **62A**, 319–332.

IV Nygård, T., **T. Valkonen** and T. Vihma (2013). Antarctic Low-Tropospheric Humidity Inversions: 10-Year Climatology. *Journal of Climate*, doi:10.1175/JCLI-D-12-00446.1. in press.

1 Introduction

The Antarctic region has *an important role in the global climate system*. It can be considered as the heat sink in the Southern Hemisphere, and therefore it has a large impact on the atmospheric circulation at high and mid latitudes. The role of the Antarctic as a heat sink is mainly a result of two reasons. Firstly, the region receives less solar radiation annually at the top of the atmosphere than the lower latitudes because of its geometric position related to the sun. And secondly, a high fraction of the radiation which reaches the Earth surface is reflected back into the atmosphere because of the high albedo of the snow and ice covering the region.

The most striking feature of the Southern Ocean around the Antarctic continent is *the seasonal cycle of sea ice and surface temperature*. The Antarctic sea ice experiences 15% decrease every summer from its maximum of 19 million square kilometres, an area larger than the continent itself. Sea ice is an important component of the climate system as the ice on top of the ocean acts as an insulator limiting the heat and moisture exchange between the ocean and atmosphere. The heat and moisture exchange strongly affects the atmospheric stability and the formation of clouds and precipitation. Furthermore, the sea ice directly affects atmosphere through its high albedo, allowing the surface to reflect most of the solar radiation back to the atmosphere. While the Arctic sea ice has experienced a strong decrease in area over the recent years, the Antarctic sea ice has, in contrast, slightly expanded (Parkinson and Cavalieri, 2012). The average sea ice expansion has been shown to be caused by wind-driven regional changes (Holland and Kwok, 2012). However, the observed and projected temperature increase in the marine Antarctic is likely to cause a decrease in ice cover in future (Solomon *et al.*, 2007), which may then lead to amplified warming as a result of the ice-albedo feedback mechanism. Challenges in the understanding of the interaction between the ocean and atmosphere are partly due to the lack of adequate observations of atmosphere and sea ice from the region. Satellite measurements provide wide spatial and temporal coverage of these both in limited horizontal and vertical resolution, while detailed in situ observations over the Southern Ocean are mainly based on drifting buoys and field campaigns which are always limited in time and space. It is essential to increase knowledge on the processes taking place over Antarctic sea ice as the Southern Ocean has great potential to contribute to global climate variability and change through changes in sea ice (King and Turner, 1997).

The Antarctic continent strongly influences the whole Southern Hemisphere, which is, in general, largely dominated by water masses. The Antarctic Peninsula is a barrier both to the oceanic and atmospheric zonal flow around the continent, and it has a large influence on the circulations of the hemisphere. The mountains of the peninsula and other mountainous areas of the coastal region are effective generators of *internal gravity waves in the atmosphere*. Orographic gravity waves are formed when slopes and mountain peaks cause vertical displacement of air in stably stratified atmosphere. As gravity waves have an impact on the tropospheric and stratospheric circulations and chemistry, they have generated considerable research interest over the years. Most of the previous studies on Antarctic gravity waves have focused on the middle-troposphere and stratosphere (Yoshiki and Sato, 2000; Fritts and Alexander, 2003; Baumgaertner and McDonald, 2007; Plougonven *et al.*, 2008) or mesosphere and lower thermosphere (Preusse *et al.*, 2008), and previous observational studies on orographic gravity waves in the Antarctic have been based on satellite remote sensing (Baumgaertner and McDonald, 2007), radiosonde data (Yoshiki and Sato, 2000), and a combination of radiosonde, mast and microbarograph data (Egger *et al.*, 1993; Rees *et al.*, 2000). The detailed properties of gravity waves, specially the ones generated by small mountain peaks emerging above the ice sheet, known as nunataks, require clarification.

The coastal region of the Antarctic is an active transition zone between the Southern Ocean and the high Antarctic Plateau. The region is particularly known for persistent and strong surface winds. The strong radiative cooling in the interior generates katabatic winds where the cold air near the surface flows towards the coasts. This katabatic flow has traditionally believed to dominate the low-level circulation. However, it has been suggested that the adjustment process between the Antarctic topography and the pressure field may primarily govern surface winds (Parish and Cassano, 2003). The topography also strongly influences the distribution of precipitation and clouds. The surface elevation of the ice sheet rises from the coast to the interior, resulting in decreasing mean temperatures. Consequently, the annual mean total column moisture decreases from its maximum near the coast to the minimum in the interior (Turner and Pendlebury, 2004). Furthermore, the orography effectively prevents the cyclones containing moisture, clouds and precipitation to penetrate to the higher elevations. It is recognised that possible changes in *atmospheric water vapour* and clouds, and their interactions with radiation, may play a key role in climate change in the Antarctic (Bromwich *et al.*, 2012).

Vertical distribution of water vapour has potential to be a significant contributor to polar climate in the future. Humidity inversions are layers in the atmosphere where specific humidity increases with altitude. Previous work on humidity inversions have focused only on the Arctic (Curry, 1983; Sedlar and Tjernström, 2009; Devasthale *et al.*, 2011; Solomon *et al.*, 2011; Vihma *et al.*, 2011; Kilpeläinen *et al.*, 2012; Sedlar *et al.*, 2012) where they have been found to be associated with

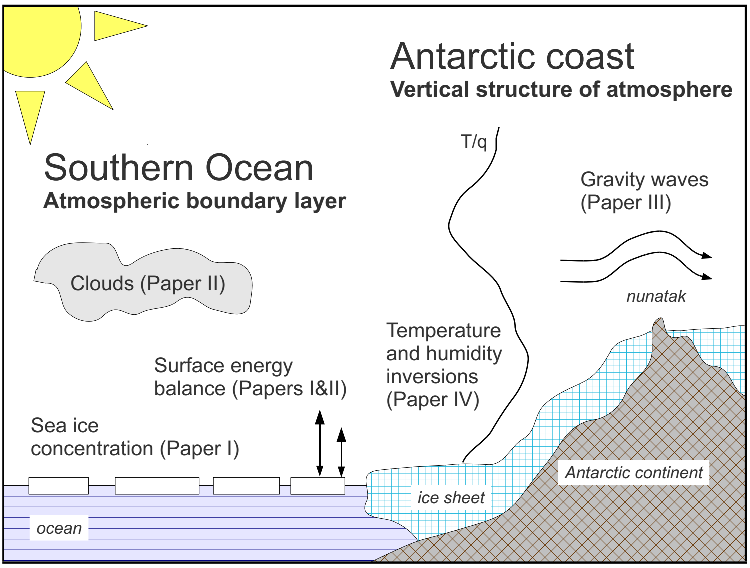

FIGURE 1. Schematic illustration of processes and phenomena addressed in this thesis.

temperature inversions. Recent studies by Sedlar *et al.* (2012) and Solomon *et al.* (2011) have demonstrated that humidity inversions have significant implications for cloud growth and persistence. But despite the significance of the humidity inversions in the Arctic, the characteristics of the Antarctic humidity inversions have remained largely unstudied.

As the observations of the Antarctic atmosphere are relatively sparse and infrequent, much of current knowledge regarding the Antarctic climate system is based on numerical models. Numerical models can give us more information about variables which can not be easily observed, and they help us to understand interactions between different variables in the system. Numerical weather prediction and climate models are based on a set of thermo-hydrodynamical equations, known as primitive equations, which represent the conservation of momentum, mass, heat and water in the atmosphere. Numerical methods are applied to solve those equations in time and space. Some of the processes in the atmosphere are so fine-scale, not fully understood or the physical relationships are too complex to be presented directly by the basic model equations. Those processes have to be included in the model system through parameterisations. Typical processes to parameterise in an atmospheric model are clouds, convection, radiation, turbulence and heat conduction below the surface.

Both regional-scale and global general circulation atmospheric models are known to be less accurate in the Polar regions than in the lower latitudes (Tjernström *et al.*, 2005; Chapman and Walsh, 2007). Many of the parameterisation schemes are developed and evaluated in the mid-latitudes, and have not been tested thoroughly in the Antarctic environment. Moreover, model simulations over the Antarctic commonly apply relatively coarse grid sizes not allowing the model to resolve fine-scale structures of atmosphere. Much research in recent years has focused on the modelling challenges faced in Arctic sea ice regions (e.g. Wyser *et al.*, 2008; Bromwich *et al.*, 2009; Ries *et al.*, 2010; Kilpeläinen *et al.*, 2011; Porter *et al.*, 2011; Wilson *et al.*, 2012), or on the simulation of influence of mountains on the atmosphere (Noel and Pitts, 2012), but less research has focused on combining observations and detailed three-dimensional atmospheric model experiments from the Antarctic sea ice regions and over small coastal nunataks.

The goal of this thesis is to improve the understanding of the interactions between atmosphere and surface over the marine and coastal Antarctic by combining regional atmospheric modelling and observational data of various scales. The work outlines the characteristics of typical phenomena of the marine and coastal Antarctic environment both near the surface and higher in the atmosphere, and describes the modelling challenges faced over the particular study area. The increased knowledge will eventually help to improve numerical modelling in the region. Specifically, the focus of this thesis is on

- **Characteristics of the atmospheric boundary layer over ice-covered ocean and the challenges related to the numerical modelling in the region:** The aim is to determine the sensitivity of the boundary layer to sea ice concentration description and parameterisation schemes, and to identify the factors generating errors in model simulations.

- **Vertical structure of the atmosphere over the coastal Antarctic:** Internal gravity waves as well as temperature and humidity inversions are typical atmospheric phenomena of the coastal Antarctic. The aim is to investigate their characteristics, structure, and challenges related to them in regional numerical modelling.

These main processes and phenomena addressed in this thesis are illustrated in FIGURE 1.

The thesis is organised as follows: the observations which form the basis for the thesis are introduced in Chapter 2, the model simulations are briefly described in Chapter 3 and the main results are presented and discussed in Chapter 4. Chapter 5 concludes the thesis and provides some suggestions for future work.

2 Observational data

Surface influence on atmosphere over the marine and coastal Antarctic have been studied in this thesis based on several observational data sets. The data sets and their purpose are briefly introduced and summarised in this chapter. Locations of the observation sites are marked on the map in Figure 2.

Marine atmosphere and its representation in regional modelling were studied based on the observational data collected from two research projects called Short Timescale Motion of Pancake Ice (STiMPI; Doble and Wadhams, 2003) and Ice Station Polarstern (ISPOL; Hellmer *et al.*, 2008). The data from the two projects represent the opposite seasons of Antarctic sea ice area. The STiMPI campaign took place in late autumn 2000 at the season of sea ice growth, and ISPOL in early

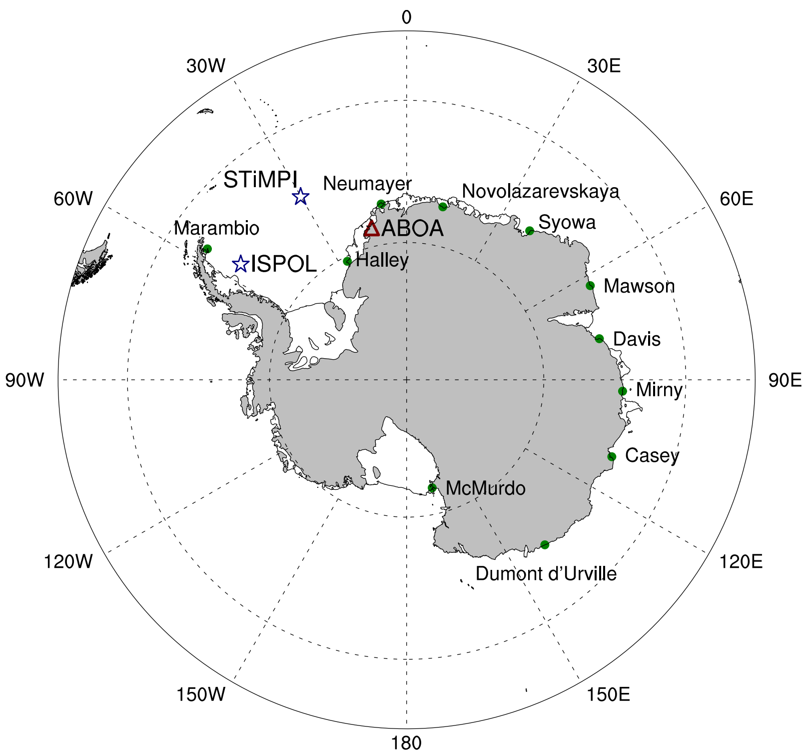

Figure 2. Locations of the observation sites. Measurement campaigns on sea ice are marked with blue stars, Aboa research station of Finland with brown triangle and the radiosonde stations with green filled circles.

summer 2004-2005 during sea ice retreat. On the STiMPI campaign, six drifting buoys were deployed in the eastern Weddell Sea. The buoys drifted within the consolidated pack ice measuring the atmospheric pressure, air temperature, wind speed and wind direction at the height of 1 m above sea level. Data from a 48-hour period in late May 2000 was analysed and used for model evaluation in this thesis (Paper I). At ISPOL campaign a few years later, the research vessel Polarstern was moored to an ice floe in the western Weddell Sea and drifted within the ice for 36 days. Measurements on turbulent and radiative fluxes from ice as well as basic weather station observations and radiosonde measurements from on-board the ship were used for the analysis and the model evaluation (Paper II). The physical distance between the locations of the campaigns was approximately 1000 km.

Wind fields of coastal atmosphere were studied based on the measurements of the Movable Atmospheric Radar for Antarctica (MARA) over a small nunatak in Queen Maud Land (Paper III). MARA is an interferometric VHF radar (Kirkwood *et al.*, 2007) which was in operation for 10 weeks during the field season 2007–2008 on the Basen nunatak near the Aboa research station of Finland and the Wasa station of Sweden. The data from it were used to investigate gravity waves generated by the nunatak. It is possible to determine continuous profiles of vertical and horizontal winds and root-mean-square velocity fluctuations representing turbulence from the MARA radar signals. On the basis of the radar data, three strong gravity wave cases were identified, analysed and compared against the results from model simulations. Surface measurements of temperature, wind speed and turbulent fluxes made near the Aboa station were also used for the model evaluation.

Vertical structure of temperature and water vapour over the coastal Antarctic was studied utilising the enhanced version of the Integrated Global Radiosonde Archive (IGRA) from 11 coastal stations for period of 2000–2009 (Paper IV). IGRA is a comprehensive global data set of quality-assured radiosonde observations (Durre *et al.*, 2006). It includes the common atmospheric variables such as pressure, temperature, dew point, wind speed and wind direction as well as some derived variables like water vapour pressure and relative humidity. In addition to IGRA data set, other sounding variables and cloud observations from the Reference Antarctic Data for Environmental Research (READER) were utilised to interpret the results of water vapour profiles.

These different data sets from relatively wide spatial and temporal scales provide an attractive combination of data to investigate the interactions between the atmosphere and the surface over the marine and coastal Antarctic. With the addition of numerical modelling, they offer invaluable information on the structure and processes of the Antarctic atmosphere.

3 Model simulations

Model simulations in this study were made using regional-scale atmospheric models. Atmosphere over sea ice was studied applying a polar version of the fifth-generation Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model (MM5; Grell *et al.*, 1994) in late autumn (Paper I) and the polar-optimised Weather Research and Forecasting model (WRF; Skamarock *et al.*, 2008) version 3.2 in early summer (Paper II). Gravity waves generated by a small nunatak were simulated applying WRF version 2 (Paper III). Both of MM5 and WRF have been developed for research and operational applications by a collaborative partnership in the United States. Development and support of the MM5 model was gradually stopped after 2004 when the WRF model was ready for extensive use, and the code of MM5 was finally frozen in 2006, which was the reason to use two different models in this work. Both of the models have been operationally used for Antarctic weather forecasting as part of the Antarctic Mesoscale Prediction System (AMPS; Powers *et al.*, 2003) and they have been found to be highly capable tools for polar applications (Bromwich *et al.*, 2005, 2009; Hines and Bromwich, 2008; Cassano *et al.*, 2011; Hines *et al.*, 2011).

The main objective of Paper I was to improve understanding of the atmospheric boundary layer sensitivity to sea ice concentration. A 48-hour period in late autumn was simulated applying four different satellite-derived sea ice concentration data sets as the lower boundary of a regional model MM5. Paper II focused on evaluating a regional atmospheric model and identifying the main challenges related to simulation of atmosphere over the Antarctic sea ice in early summer. Model simulations for the period of 35 days were performed applying different physical parameterisation schemes. In Paper III, high-resolution model simulations were made for three periods in 2007–2008 when radar measurements indicated occurrence of gravity waves. The results of the model simulations were compared against surface observations and upper atmosphere measurements, and the characteristics of modelled gravity waves were studied.

In all the simulations, two or three-way nested polar stereographic domains were used in order to obtain high enough horizontal resolution for the application. The outermost domains are marked on the map in Figure 3. The model simulations were initialised by the European Centre for Medium-Range Weather Forecasts (ECMWF) operational analysis or re-analysis. Both model systems (MM5 and WRF) include a large number of available options for physical parameterisation of sub-grid scale processes. The applied schemes were chosen and tested depending on the application. More detailed description of the model simulations can be found in Papers I, II and III.

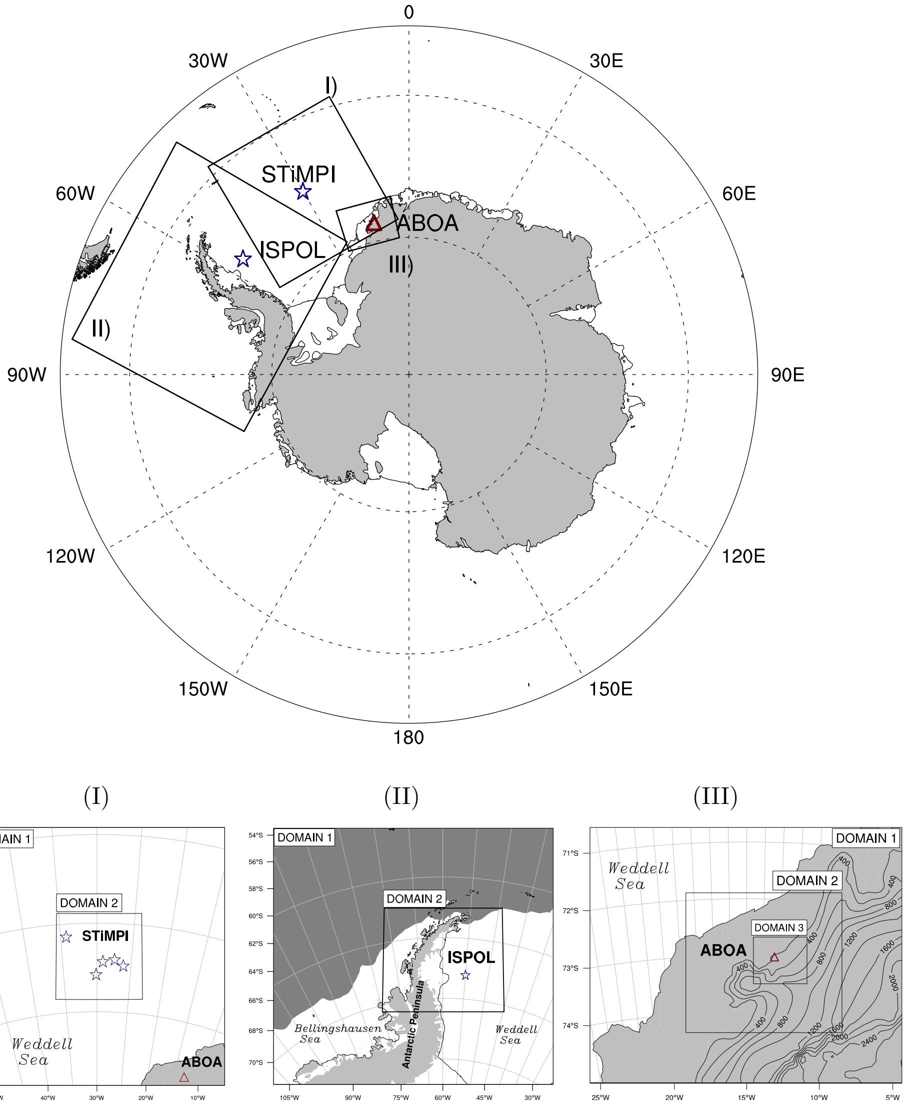

FIGURE 3. Locations of the outermost model domains in PAPERS I, II AND III on the Antarctic map. The subfigures below show the model domains applied in respective papers in more detail.

4 Main results

The main results of the papers included in this thesis are presented and discussed in the following sections. Section 4.1 covers Papers I and II, and Section 4.2 reviews the results of Papers III and IV.

4.1 Atmospheric boundary layer over ice-covered ocean

Antarctic sea ice has a strong seasonal cycle, and the study periods of this work were from the opposite seasons, in May and December, representing the sea ice growth and melt seasons. The surface energy balance and the boundary layer characteristics were found to be strongly governed by the presence or absence of sea ice. A significant direct impact of sea ice is related to the surface albedo characteristics. Typically only less than 10% of solar radiation is reflected from ice-free ocean, whereas the albedo of snow-covered sea ice can be higher than 85%, as measured on the ISPOL campaign in the western Weddell Sea (Paper II). Ice formation, precipitation and snow melt change the surface albedo dramatically, which affects the surface energy balance through radiative fluxes. Another important effect of sea ice is its role as an insulator between atmosphere and ocean. It strongly limits the exchange of heat and moisture, which further impacts the atmospheric stability, vertical structure, formation of clouds and precipitation. During the ice growth season in late-autumn and winter, air-sea temperature difference is typically large, and open water areas, such as leads and polynyas, provide remarkable flux of heat. STiMPI campaign did not provide direct flux measurement but simulated area-averaged surface sensible heat fluxes were found to be up to 60-90 W/m^2 over the Weddell Sea in late autumn (Figure 10 of Paper I). During the summer melt season, the surface sensible heat flux observations were much more moderate at the average, the atmospheric boundary layer was typically neutrally stratified and surface and near-surface temperatures were limited by 0°C with periods below freezing temperatures (Figure 2 of Paper II).

In the experiments made in early summer and late autumn, models performed well in simulating synoptic-scale variations and relatively accurately in mean surface values of basic meteorological variables (Papers I and II). Particularly situations where temperatures remained close to 0°C were simulated accurately, but the model performance was poorer in lower temperatures. Temperature errors in these cold situations had opposite signs in the simulations made in different seasons. In the late autumn case study (Paper I), simulated temperature was positively biased regardless the applied sea ice data set or parameterisation scheme. In the simulations made in early summer (Paper II), the amplitude

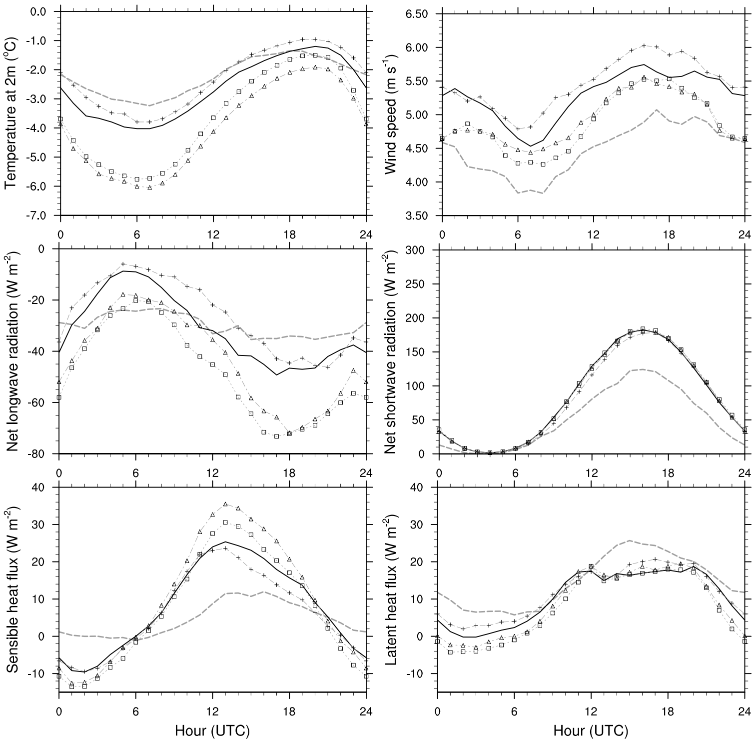

FIGURE 4. Mean diurnal cycles of 2-m temperature, wind speed, net longwave radiation, net shortwave radiation, sensible heat flux, and latent heat flux on the Weddell Sea in early summer. The observations are marked with a gray dashed line and the WRF simulations with other lines (a black full line for Experiment E1, a gray dotted line with plusses for E2, and a gray dotted line with rectangles for E3, a gray dotted line with triangles for E4). The details of the model experimentation can be found in PAPER II. (Modified from Figures 3a, 3e, 4e, 4f, 5a and 5b of PAPER II. Used with permission.)

of diurnal cycles of surface variables was generally overestimated and the surface temperature was negatively biased at nighttime (FIGURE 4). The reasons for the differences in the model performance were found in physical parameterisations schemes and description of sea ice, which are now discussed in more detail.

The description of sea ice concentration was found to be very important for simulating the near surface temperatures in late autumn (PAPER I). During northerly winds in conditions of observed air temperatures above -5°C, the differences between the experiments applying different sea ice concentration data sets at the lower boundary were minor and all the biases were small. In contrast during the period of a cold-air outbreak, the modelled air temperatures near the surface and in the whole atmospheric boundary layer were highly sensitive to the sea ice concentration data applied. Temperature differences between the two extreme experiments, applying the Bootstrap and NASA Team sea ice concentration data sets, were up to 13°C at the end of the simulation period, as shown in FIGURE 5. Ice concentrations in the data sets were mainly high varying between 80% and 95% in the study area. The patterns in sea ice concentration data sets and simulated air temperature were clearly collocated but the temperature depended also, and most importantly, on the cumulative open-water fetch, which is the distance of open water that the wind has blown over. These findings provide support for those of Kaleschke *et al.* (2001), Vihma and Brümmer (2002), Vihma *et al.* (2005) and Drusch (2006) made on model sensitivity of ice concentrations over the northern ice-covered seas. In their studies, the influence of sea ice fraction on the surface temperature and turbulent heat fluxes was large. However, they found relatively small sensitivity of near-surface or mixed layer temperatures to the altered sea ice data applied at the lower boundary. Over the Antarctic sea areas sea ice concentrations are generally lower than in the Arctic and cumulative fetches over open water are typically a lot larger than, for example, in the Baltic Sea. Simulation of vertically integrated cloud water suggested that the large temperature differences resulted from the differences in surface turbulent fluxes without major effect from cloud radiative forcing.

In the early summer experiments (PAPER II), the largest errors of surface energy balance were related to the simulation of radiation fluxes (FIGURE 4). The simulated shortwave radiation flux was clearly overestimated at daytime. However, the positive bias cannot directly control the nighttime temperature errors. The temperature errors at nighttime were mainly driven by errors in longwave radiation and turbulent fluxes. Temporal variations in the errors of cloud cover generated large errors in the longwave radiation. At the same time, turbulent mixing near the surface in the model simulations was too effective, which would usually result in warming of the surface and neutral stratification of air. As the static stability increased, typically at nighttime, the underestimation of the downward longwave radiation flux, however, started to dominate over overestimation of the sensible heat flux, and generated the cold temperature bias at the surface (Figure 16 of PAPER II).

The model sensitivity to physical parameterisation schemes was, in general, relatively small in mean values, but temporal variations of model performance between the different schemes were large (PAPERS I AND II). The model sensitivity to different schemes was most recognised at the lowest parts of the atmosphere. Above the boundary layer, the choice of turbulence scheme was more important

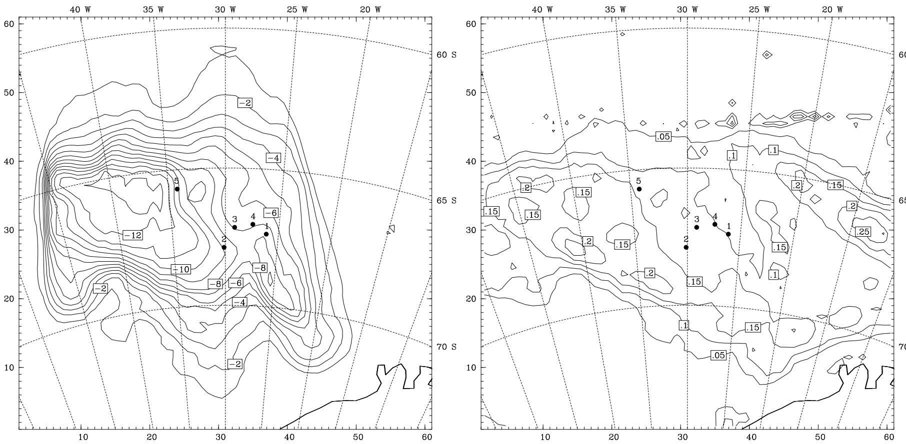

Figure 5. Differences in temperature (left) and sea ice concentration (right) between simulations with the bootstrap and the NASA Team sea ice concentration data sets at the end of the 48-h simulations in late autumn. (Figure 7 of Paper I, ©American Meteorological Society. Used with permission.)

than the choice of sea ice concentration data set (Paper I), even though the sensitivity to any physical parameterisation scheme was, in general, low above the boundary layer (Papers I and II). The sensitivity test of cloud microphysics parameterisation showed that cloud simulation benefits from advanced parameterisation with prediction of the vertical distribution of cloud water and ice content (Paper II). Vertical distribution of observed water vapour over the coastal Antarctic will be discussed later in Section 4.2.

The modelling results are in line with previous modelling studies applying Polar WRF over the Arctic Ocean in summer (Bromwich *et al.*, 2009). Most atmospheric models have problems with diurnal cycles even in the mid-latitudes (Svensson *et al.*, 2011; Steeneveld *et al.*, 2008; Zhang and Zheng, 2004). Generally, the models tend to underestimate the amplitude of the diurnal cycles of near-surface temperature, as found by Steeneveld *et al.* (2008), but, in contrary, the diurnal temperature cycle amplitudes were overestimated in this study for the reasons mentioned before. Previous modelling studies from the Polar areas by Tjernström *et al.* (2005) and Rinke *et al.* (2006) show that in regional atmospheric models, the simulated fluxes are mostly unreliable.

Over ice-covered oceans, the simulation of turbulent fluxes is particularly challenging because the temporal changes of ice cover can be both rapid and complete, which are difficult to describe in numerical models in detail. The ice changes affect thoroughly the surface conditions and the atmospheric stratification in the boundary layer. As the sea ice concentration was found to have a large impact on model values near and at the surface, more accurate sea ice description in the model system is likely to improve the simulations over the region. Moreover, the sensitivity simulations showed that the change of the atmospheric parameterisations does not necessarily remarkably improve the simulations over an ice-covered region if there remains a problem in ice treatment in the model system. Updating the sea ice conditions with reliable remote sensing data and applying more advanced prediction of sea ice and snow is needed to more accurately simulate the atmosphere over Antarctic sea ice.

4.2 Vertical structure of atmosphere over the coastal Antarctic

Coastal zone of the Antarctic continent is an active transition zone between the Southern Ocean and the high Antarctic Plateau. Internal gravity waves and temperature and humidity inversions are an essential part of the vertical structure of atmosphere in this region.

In the Antarctic coastal regions, the generation and propagation of internal gravity waves is possible throughout the year as the atmosphere is almost all the time stably stratified. Basen nunatak, with a height of approximately 350 m from the underlying glacier, was the origin to three separate gravity wave cases during the field season 2007–2008. The gravity waves were mainly orographically forced with less influence of thermal effects, and they were found to be the most recognised in vertical wind velocity fields. All the gravity wave cases lasted for 30–60 hours, and they had an amplitude of 0.2–0.8 m/s in vertical wind velocity with the largest amplitudes at the altitude of 2.0–3.5 km. A typical gravity wave over Basen nunatak is illustrated in Figure 6. In agreement with previous studies by Whiteway and Duck (1996) the gravity wave was found to be strongest during strong winds. In one of the cases, the gravity wave was found to reach the lower stratosphere, which challenges the previous study by Yoshiki and Sato (2000) who suggested that topographically generated gravity waves usually reach only altitudes below 5 km in the Antarctic. Gravity waves over Basen nunatak were found to have the largest amplitude of the vertical wind velocity at nighttime. At nighttime, the stratification in the atmospheric boundary layer was stable, sensible heat flux downward and the height of the atmospheric boundary layer was shallowest. However, gravity waves were also generated in the afternoon, in neutral stratification, because the vertical displacement of the air reached the stable layer above the neutral boundary layer. Measurements on gravity waves

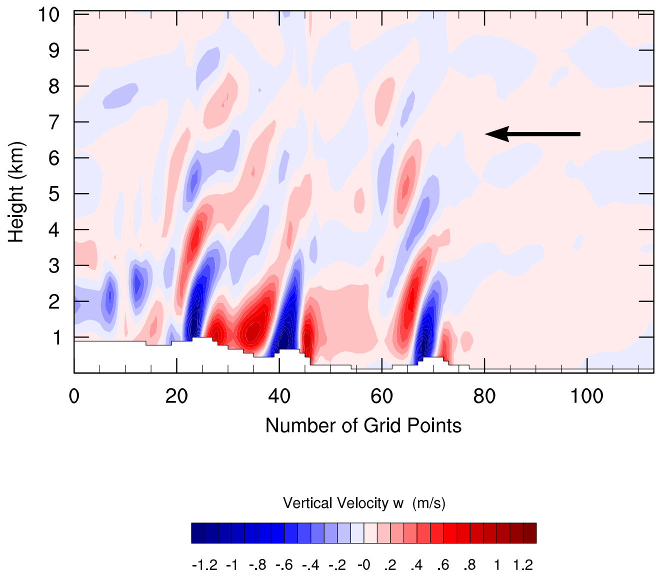

FIGURE 6. Cross-section of modelled vertical wind velocity for 2008-01-12 12UTC. Basen nunatak is located at grid point 70 on the horizontal axis. The arrow indicates the flow direction. (Figure 10c of PAPER III. Used with permission.)

over Basen nunatak were conducted in local summertime. A higher occurrence of gravity waves is expected in the winter when the stratification is more stable.

Layers where the specific humidity increases with height were almost all the time observed throughout the seasons in the coastal Antarctic atmosphere (Figure 5 of PAPER IV). These humidity inversion layers were typically found simultaneously on multiple (2–4) different levels both near the surface and elevated up to several kilometres. Despite the large differences in near-surface specific humidity, radiation conditions and the average cyclone activity between the seasons, the average seasonal variability of inversion properties, such as depth and strength, was generally low. Earlier studies by Devasthale *et al.* (2011), made in the Arctic, reported that humidity inversions were present only 20% of the time in summer. Possible reasons for the discrepancy between the polar areas could be different characteristics of flow patterns, atmospheric stratification, moisture transport, and differences in methodology.

Characteristics of water vapour distributions were found to vary remarkably in space. The occurrence and the mean number of humidity inversions in a profile as well as median strength and depth varied more between the stations than between the seasons. This spatial variability is linked to the water vapour content of the air and the physical characteristics of surface. The amount of water vapour varies strongly between the station locations, and the inversion properties, specially inversion strength, seem to be connected to the near-surface specific humidity. Large-scale circulation patterns, such as the Southern Annual Mode, are known to control the water vapour transport and convergence (Tietäväinen and Vihma, 2008) that seem to affect humidity inversion properties. Furthermore, physical conditions of the surface and the surrounding environment were found to have an effect on humidity distributions. The strongest surface-based humidity inversions were found at the stations located on an ice shelf on relatively flat and homogeneous surface (Halley and Neumayer) whereas the stations with strong katabatic winds (Dumont d'Urville and Mawson) had commonly a humidity maximum near the surface. In addition, the mean number of humidity inversions in a profile had the largest temporal variability at Halley (Figure 6 of Paper IV), where the annual mean directional constancy of wind was low, and the smallest variability at Novolazarevskaya and Syowa, where the directional constancy of wind was higher.

Temperature inversions were found more frequently than humidity inversions but the number of separate inversions in a profile was smaller for temperature inversions than for humidity inversions. Humidity inversions were thicker and the base height was higher than that of temperature inversions at all the stations. Roughly a half of the humidity inversion were occurring simultaneously at the same layer with temperature inversions. The results confirm that temperature inversions are important factors generating the humidity inversions but cannot alone provide an explanation for generation of humidity inversion.

Accurate numerical model simulations are a necessity for properly depicting the vertical structure of the atmosphere. That applies both internal gravity waves and humidity and temperature inversions. Typical weather prediction and climate model simulations are not able to capture the small scale vertical structures, such as small gravity waves and the inversions, due to the coarse grid sizes. Regional atmospheric models can simulate in higher horizontal and vertical resolution on a limited area than global models. However, even the high-resolution simulations have their challenges in quantitatively capturing the vertical structure of atmosphere. The model simulations made on the coastal Antarctic succeeded to simulate the gravity waves applying 0.9 km horizontal grid size in the periods when the waves were observed over the Basen nunatak. The shape of the vertical wind patterns in radar observations and model simulations showed similar type of behaviour (Figure 7 and 8 of Paper III). The main differences were related to the timing of largest vertical wind velocities and heights of the maxima and minima. Root-mean-square velocity fluctuation of radar measurements and the Richard-

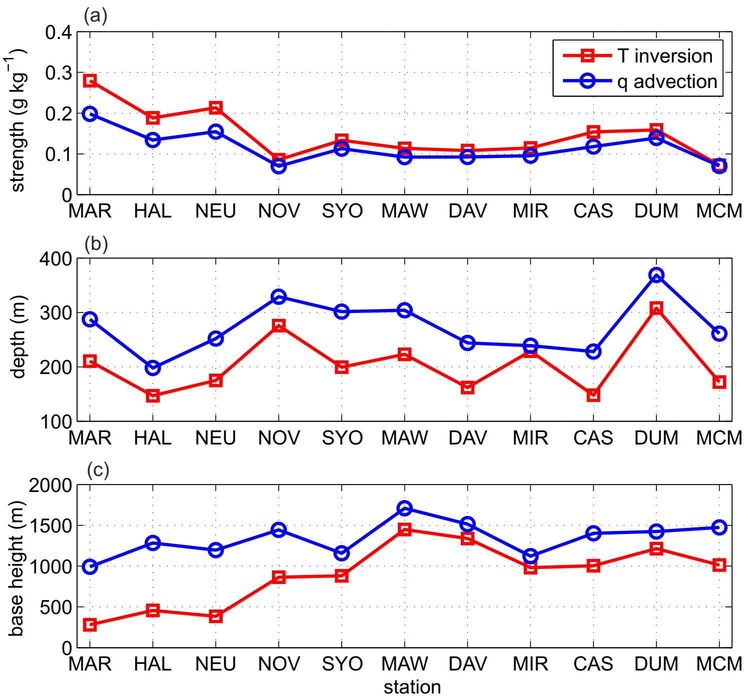

FIGURE 7. (a) Median strength, (b) median depth, and (c) median base height of humidity inversions accompanied by a temperature inversion or a vertical increase in water vapour advection at 11 coastal stations. Abbreviations below each subfigure refer to the station names shown in FIGURE 2. (Figure 13 of PAPER IV. ©American Meteorological Society. Used with permission.)

son number of modelled atmosphere qualitatively followed the same pattern. The timing of the variability of surface variables was captured but the diurnal cycle of air temperature was overestimated, mainly because of unrealistic surface albedo values used in the model system. The spatial differences around the nunatak were not as distinguishable in the simulations as they were in the surface observations. That was explained by low-resolution description of land-use and partly inaccurate orography data set used in the model system. The result supports the previously-mentioned importance of the accurate description of surface properties to accurately model the near surface properties.

Beyond the three-dimensional flow patterns, numerical modelling of the vertical structure of atmosphere can help us to understand interactions between different variables in the system. The water vapour advection derived from ERA-

Interim reanalysis of ECMWF (Dee *et al.*, 2011) increased from the inversion base to the inversion top in approximately 60% of the observed humidity inversions demonstrating that water vapour advection is typical characteristics of humidity inversions and may help to generate and support them. Both temperature inversion and vertical increase in water vapour advection were found in 36% of the humidity inversions, which supports the idea of humidity inversions being affected by several simultaneous processes. Humidity inversions accompanied by a vertical increase of water vapour advection were found to be weaker, deeper and located at higher elevations than inversions accompanied by a temperature inversion (FIGURE 7). However, global numerical reanalysis, such as ERA-Interim, are known to have challenges in simulating the water vapour and thermodynamics over the polar areas (Serreze *et al.*, 2012; Jakobson *et al.*, 2012; Bracegirdle and Marshall, 2012). It has been suggested that the ability to simulate humidity inversions could be used as a metric for model performance (Devasthale *et al.*, 2011). There is a clear need for investigations on representation of vertical distribution of water vapour in global reanalyses and other numerical model products, and to test the interactions between different generating and supporting mechanisms of humidity inversions.

The work provides exceptional information of characteristics of vertical structures of atmosphere over the coastal Antarctic. Gravity waves, particularly the orographic mountain waves, are known to affect the larger-scale waves and circulation patterns. The changes in those patterns may influence the moisture transport and vertical distribution of water vapour in the trosposphere. Details of potential interactions between gravity waves, atmospheric moisture distribution and precipitation remain to be identified.

5 Conclusions and future work

Prior work has documented several aspects of surface influence on the marine and coastal Antarctic atmosphere; Lachlan-Cope (2005), for example, reports that the sensitivity of near-surface air temperature to Antarctic sea ice concentration varies spatially in a global climate model, and Rees *et al.* (2000) present a climatology of internal gravity waves over the Brunt Ice Shelf. However, less attention has been paid to combining regional-scale or high-resolution atmospheric modelling with continuous detailed observations over sea ice or a single coastal nunatak, and climatological research on humidity inversions on coastal Antarctic atmosphere has not taken place. In this thesis, different versions of regional atmospheric models were tested and evaluated against observations over sea ice in two seasons and over a coastal nunatak, and the statistical characteristics of observed humidity inversions in coastal Antarctic atmosphere were investigated.

The boundary layer over the marine Antarctic is strongly governed by the presence or absence of sea ice. The largest errors in simulating the near surface temperatures occurred in cold situations. The major challenges related to the modelling of the atmosphere over Antarctic sea ice were found to be associated with clouds, boundary layer processes and sea ice and snow description. The model sensitivity to different physical parameterisation schemes was most profound in the lowest parts of the atmosphere.

The vertical structure of the atmosphere over the coastal Antarctic is characterised by internal gravity waves as well as temperature and humidity inversions. Gravity waves generated by a small nunatak were found to reach the lower stratosphere. That broadens the knowledge of how high the orographic gravity waves generated by small nunataks can extend in the Antarctic. Humidity inversions were found to be present, nearly all the time, on multiple levels in the coastal Antarctic atmosphere.

Numerical model simulations showed that, on average, it is possible to obtain a relatively accurate model performance for basic meteorological surface variables such as temperature, humidity, air pressure, wind speed and wind direction. However, the turbulent and radiative surface fluxes that affect those variables are not that well reproduced by models. The errors tend to partly compensate for each other, which makes it possible to get a good performance on the average. However, the temporal errors in some of the model variables, such as surface fluxes, can be large. To minimise the errors, sea ice conditions should be updated frequently with advanced description of ice and snow processes. The modelling benefits also from advanced cloud schemes with prediction of the vertical distribution of cloud water and ice content.

It is essential to better understand the subgrid-scale physical processes and improve their parameterisation in atmospheric models to be able to improve modelling of the Antarctic and Southern Ocean and our understanding of the Antarctic climate system. More detailed observations on cloud characteristics, sea ice and vertical structure of atmosphere in a high temporal and spatial resolution are needed to determine the spatial and seasonal differences of atmospheric model performances and to gain knowledge on the interactive processes between the Earth surface and atmosphere.

The results on atmospheric vertical structure provide compelling evidence that humidity inversions are common in the Antarctic, and they are a good starting point for further work focusing on moisture distribution both in the Antarctic and Arctic. Future work is planned to evaluate representation of moisture distribution in atmospheric models, particularly in global reanalysis, in the Antarctic, and a climatological study based on radiosondings is planned for the Arctic. Further investigations, both observational and modelling, are needed to fully understand the implications of humidity inversions on clouds and radiation.

Despite any inaccuracies and uncertainties, atmospheric models are good tools in applied and interdisciplinary research as the models can provide us detailed information on three-dimensional structure of the atmosphere in high spatial and temporal resolution. For example, aerosol and ozone concentrations are found to vary significantly over the coastal Antarctic (Virkkula *et al.*, 2009), and applying high-resolution modelling has potential to better explain the impact of small-scale topography and gravity waves on these concentrations.

Summaries of the original publications

The contents of Papers I–IV and the author's contribution are shortly summarised below.

I **Valkonen, T.**, T. Vihma, and M. Doble (2008). Mesoscale modelling of the atmospheric boundary layer over the Antarctic sea ice: a late autumn case study. *Monthly Weather Review*, **136**, 1457–1474.

Paper I presents regional-scale atmospheric modelling experiments with evaluation for the Antarctic sea ice zone in late autumn. The main objective of the paper was to improve understanding of the atmospheric boundary layer sensitivity to sea ice concentration. During the period of cold-air outbreak the simulated air temperatures were highly sensitive to the sea ice concentration applied at the lower boundary. The sea ice concentration data affected the modelled air temperature in the lower parts of the atmospheric boundary layer but above it the temperature and wind fields were more strongly controlled by the turbulence scheme applied in the model.

The author was responsible for all the model experiments, and for a major part of the data analysis and writing.

II **Valkonen, T.**, T. Vihma, M. M. Johansson, and J. Launiainen (2013). Atmosphere - sea ice interaction in early summer in the Antarctic: evaluation and challenges of a regional atmospheric model. *Quarterly Journal of the Royal Meteorological Society*, submitted.

Paper II evaluates performance of a regional atmospheric model over Antarctic sea ice and identifies the main modelling challenges related to simulating the atmosphere over the Antarctic sea ice in early summer. The synoptic scale variations were well captured but the diurnal amplitude of most of the surface variables was overestimated and simulations were characterised by a cold temperature bias at nighttime. The major simulation challenges were found to be associated with clouds, atmospheric boundary layer processes and the processes in the sea ice and snow.

The author was responsible for all the model experiments, and for a major part of the data analysis and writing.

III **Valkonen, T.**, T. Vihma, S. Kirkwood, and M. M. Johansson (2010). Fine-scale model simulation of gravity waves generated by Basen nunatak in Antarctica. *Tellus*, **62A**, 319–332.

Paper III reports high-resolution model simulations of gravity waves generated by a small nunatak in Queen Maud Land, Antarctica. The regional-scale atmospheric model applied in the study simulated gravity waves in the periods when these were observed. The modelled wave characteristics were qualitatively similar to the observed ones, although quantitative differences existed. The gravity waves were found to be strongest during nighttime, when the surface sensible heat flux was downwards.

The author was responsible for all the model experiments, and for a major part of the data analysis and writing.

IV Nygård, T., **T. Valkonen** and T. Vihma (2013). Antarctic Low-Tropospheric Humidity Inversions: 10-Year Climatology. *Journal of Climate*, doi:10.1175/JCLI-D-12-00446.1. in press.

Paper IV studies statistical characteristics of humidity inversions at 11 Antarctic coastal stations using radiosonde data from the Integrated Global Radiosonde Archive for 2000–2009. Humidity inversions on multiple levels were found to be very common throughout the year. The humidity inversions were more common in summer in the Antarctic than in the Arctic. Both temperature inversion and vertical increase in water vapour advection were often associated with humidity inversions. The results on humidity inversion statistics provide a good baseline for further studies addressing changes in atmospheric moisture in the Antarctic and weather prediction and climate model evaluation.

The author performed water vapour advection calculations from the global reanalysis data, participated in the result interpretation and writing of the manuscript, and discussed the study at all stages.

References

Baumgaertner AJG, McDonald AJ. 2007. A gravity wave climatology for Antarctica compiled from Challenging Minisatellite Payload/Global Positioning System (CHAMP/GPS) radio occultations. *Journal of Geophysical Research* **112**(D05103), doi:10.1029/2006JD007504.

Bracegirdle TJ, Marshall GJ. 2012. The Reliability of Antarctic Tropospheric Pressure and Temperature in the Latest Global Reanalyses. *Journal of Climate* **25**(20): 7138–7146.

Bromwich D, Monaghan A, Manning K, Powers J. 2005. Real-time forecasting for the Antarctic: An evaluation of the Antarctic Mesoscale Prediction System (AMPS). *Monthly Weather Review* **133**(3): 579–603, doi:10.1175/MWR-2881.1.

Bromwich DH, Hines KM, Bai LS. 2009. Development and testing of Polar Weather Research and Forecasting model: 2. Arctic Ocean. *Journal of Geophysical Research* **114**: D08122, doi:10.1029/2008JD010300.

Bromwich DH, Nicolas JP, Hines KM, Kay JE, Key EL, Lazzara MA, Lubin D, McFarquhar GM, Gorodetskaya IV, Grosvenor DP, Lachlan-Cope T, van Lipzig NPM. 2012. Tropospheric clouds in Antarctica. *Reviews of Geophysics* **50**, doi:10.1029/2011RG000363.

Cassano JJ, Higgins ME, Seefeldt MW. 2011. Performance of the Weather Research and Forecasting Model for Month-Long Pan-Arctic Simulations. *Monthly Weather Review* **139**: 3469–3488.

Chapman WL, Walsh JE. 2007. Simulations of Arctic temperature and pressure by global coupled models. *Journal of Climate* **20**(4): 609–632, doi: 10.1175/JCLI4026.1.

Curry JA. 1983. On the formation of continental polar air. *Journal of the Atmospheric Sciences* **40**: 2278–2292.

Dee DP, Uppala SM, Simmons AJ, Berrisford P, Poli P, Kobayashi S, Andrae U, Balmaseda MA, Balsamo G, Bauer P, Bechtold P, Beljaars ACM, van de Berg L, Bidlot J, Bormann N, Delsol C, Dragani R, Fuentes M, Geer AJ, Haimberger L, Healy SB, Hersbach H, Holm EV, Isaksen L, Kållberg P, Köhler M, Matricardi M, McNally AP, Monge-Sanz BM, Morcrette JJ, Park BK, Peubey C, de Rosnay

P, Tavolato C, Thepaut JN, Vitart F. 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society* **137**(656): 553–597.

Devasthale A, Sedlar J, Tjernström M. 2011. Characteristics of water-vapour inversions observed over the Arctic by Atmospheric Infrared Sounder (AIRS) and radiosondes. *Atmospheric Chemistry and Physics* **11**(18): 9813–9823.

Doble MDC, Wadhams P. 2003. Pancake ice formation in the Weddell Sea. *Journal of Geophysical Research* **108**(3209), doi:10.1029/2002JC001273.

Drusch M. 2006. Sea Ice Concentration Analyses for the Baltic Sea and Their Impact on Numerical Weather Prediction. *Journal of Applied Meteorology and Climatology* **45**: 982–994, doi:10.1175/JAM2376.1.

Durre I, Russell SV, Wuertz DB. 2006. Overview of the integrated global radiosonde archive. *Journal of Climate* **19**: 53–68.

Egger J, Wamser C, Kottmeier C. 1993. Internal atmospheric gravity waves near the coast of Antarctica. *Boundary-Layer Meteorology* **66**: 1–17.

Fritts DC, Alexander MJ. 2003. Gravity wave dynamics and effects in the middle atmosphere. *Reviews of Geophysics* **41**(1): 1003, doi:10.1029/2001RG000106.

Grell GA, Dudhia J, Stauffer DR. 1994. A discription of the fifth-generation Penn State/NCAR mesoscale model (MM5). Technical Report NCAR/TN-398+STR, NCAR. 122 pp.

Hellmer HH, Schröder M, Haas C, Dieckmann GS, Spindler M. 2008. The ISPOL drift experiment. *Deep-Sea Research Part II* **55**: 913–917.

Hines KM, Bromwich DH. 2008. Development and testing of Polar Weather Research and Forecasting (WRF) Model. Part I: Greenland ice sheet meteorology. *Monthly Weather Review* **136**(6): 1971–1989, doi:10.1175/2007MWR2112.1.

Hines KM, Bromwich DH, Bai LS, Barlage M, Slater AG. 2011. Development and Testing of Polar WRF. Part III: Arctic Land. *Journal of Climate* **24**(1): 26–48, doi:10.1175/2010JCLI3460.1.

Holland PR, Kwok R. 2012. Wind-driven trends in Antarctic sea-ice drift. *Nature Geoscience* **5**: 872–875, doi:10.1038/NGEO1627.

Jakobson E, Vihma T, Palo T, Jakobson L, Keernik H, Jaagus J. 2012. Validation of atmospheric reanalyses over the central Arctic Ocean. *Geophysical Research Letters* **39**, doi:10.1029/2012GL051591.

Kaleschke L, Lüpkes C, Vihma T, Haarpaintner J, Bochert A, Hartmann J, Heygster G. 2001. SSM/I sea ice remote sensing for mesoscale ocean-atmosphere interaction analysis. *Canadian Journal of Remote Sensing* **27**(5): 526–537.

Kilpeläinen T, Vihma T, Manninen M, Sjöblom A, Jakobson E, Palo T, Maturilli M. 2012. Modelling the vertical structure of the atmospheric boundary layer over Arctic fjords in Svalbard. *Quarterly Journal of the Royal Meteorological Society* **138**: 1867–1883, doi:10.1002/qj.1914.

Kilpeläinen T, Vihma T, Olafsson H. 2011. Modelling of spatial variability and topographic effects over Arctic fjords in Svalbard. *Tellus Series A* **63**(2): 223–237, doi:10.1111/j.1600-0870.2010.00481.x.

King JC, Turner J. 1997. *Antarctic meteorology and climatology.* Cambridge University Press: New York. 409pp.

Kirkwood S, Wolf I, Dalin P, Nilsson H, Mikhailova D, Belova E. 2007. Polar mesosphere summer echoes at Wasa, Antarctica (73° S) - first observations and comparison with 68° N. *Geophysical Research Letters* **34**(L15803), doi: 10.1029/2007GL030516.

Lachlan-Cope T. 2005. Role of sea ice in forcing the winter climate of Antarctica in a global climate model. *Journal of Geophysical Research: Atmospheres* **110**(D3): 2156–2202, doi:10.1029/2004JD004935.

Noel V, Pitts M. 2012. Gravity wave events from mesoscale simulations, compared to polar stratospheric clouds observed from spaceborne lidar over the Antarctic Peninsula. *Journal of Geophysical Research: Atmospheres* **117**(D11): 2156–2202, doi:10.1029/2011JD017318.

Parish TR, Cassano JJ. 2003. The role of katabatic winds on the Antarctic surface wind regime. *Monthly Weather Review* **131**: 317–333, doi:10.1175/1520-0493(2003)131¡0317:TROKWO¿2.0.CO;2.

Parkinson CL, Cavalieri DJ. 2012. Antarctic sea ice variability and trends, 1979-2010. *The Cryosphere Discussions* **6**: 931–956, doi:10.5194/tcd-6-931-2012.

Plougonven R, Hertzog A, Teitelbaum H. 2008. Observation and simulations of a large-amplitude mountain wave breaking over the Antarctic Peninsula. *Journal of Geophysical Research* **113**(D16113), doi:10.1029/2007JD009739.

Porter DF, Cassano JJ, Serreze MC. 2011. Analysis of the Arctic atmospheric energy budget in WRF: A comparison with reanalyses and satellite observations. *Journal of Geophysical Research-Atmospheres* **116**, doi:10.1029/2011JD016622.

Powers J, Monaghan A, Cayette A, Bromwich D, Kuo Y, Manning K. 2003. Real-time mesoscale modeling over Antarctica The Antarctic Mesoscale Prediction System. *Bulletin of the American Meteorological Society* **84**(11): 1533+, doi: 10.1175/BAMS-84-11-1533.

Preusse P, Eckermann S, Ern M. 2008. Transparency of the atmosphere to short horizontal wavelength gravity waves. *Journal of Geophysical Research* **113**(D24104), doi:0.1029/2007/JD009682.

Rees JM, Denholm-Price JCW, King JC, Anderson PS. 2000. A climatological study of internal gravity waves in the atmospheric boundary layer overlying the Brunt Ice Shelf, Antarctica. *Journal of Atmospheric Science* **57**: 511–526.

Ries H, Schluenzen KH, Bruemmer B, Claussen M, Mueller G. 2010. Impact of surface parameter uncertainties on the development of a trough in the Fram Strait region. *Tellus Seris A* **62**(4): 377–392, doi:10.1111/j.1600-0870.2010.00451.x.

Rinke A, Dethloff K, Cassano J, Christensen J, Curry J, Du P, Girard E, Haugen J, Jacob D, Jones C, Koltzow M, Laprise R, Lynch A, Pfeifer S, Serreze M, Shaw M, Tjernstrom M, Wyser K, Zagar M. 2006. Evaluation of an ensemble of Arctic regional climate models: spatiotemporal fields during the SHEBA year. *Climate Dynamics* **26**(5): 459–472, doi:10.1007/s00382-005-0095-3.

Sedlar J, Shupe MD, Tjernström M. 2012. On the Relationship between Thermodynamic Structure and Cloud Top, and its Climate Significance in the Arctic. *Journal of Climate* **25**: 2374–2374, doi:10.1175/jcli-d-11-00186.1.

Sedlar J, Tjernström M. 2009. Stratiform cloud-inversion characterization during the arctic melt season. *Boundary-Layer Meteorology* **132**(3): 455–474.

Serreze MC, Barrett AP, Stroeve J. 2012. Recent changes in tropospheric water vapor over the arctic as assessed from radiosondes and atmospheric reanalyses. *Journal of Geophysical Research* **117**(D10104), doi:10.1029/2011JD017421.

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Duda MG, Huang XY, Wang W, Powers JG. 2008. A description of the advanced research wrf version 3. Technical Report NCAR/TN–475+STR, NCAR TECHNICAL NOTE.

Solomon A, Shupe MD, Persson POG, Morrison H. 2011. Moisture and dynamical interactions maintaining decoupled Arctic mixed-phase stratocumulus in the presence of a humidity inversion. *Atmospheric Chemistry and Physics* **11**(19): 10 127–10 148.

Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, MTignor, Miller H (eds). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Steeneveld GJ, Mauritsen T, de Bruijn EIF, Vilà-Guerau de Arellano J, Svensson G, Holtslag AAM. 2008. Evaluation of Limited-Area Models for the Representation of the Diurnal Cycle and Contrasting Nights in CASES-99. *Journal of Applied Meteorology and Climatology* **47**: 869–887.

Svensson G, Holtslag AAM, Kumar V, Mauritsen T, Steeneveld GJ, Angevine WM, Bazile E, Beljaars A, de Bruijn EIF, Cheng A, Conangla L, Cuxart J, Ek M, Falk MJ, Freedman F, Kitagawa H, Larson VE, Lock A, Mailhot J, Masson V, Park S, Pleim J, Soderberg S, Weng W, Zampieri M. 2011. Evaluation of the Diurnal Cycle in the Atmospheric Boundary Layer Over Land as Represented by a Variety of Single-Column Models: The Second GABLS Experiment. *Boundary-Layer Meteorology* **140**(2): 177–206, doi:10.1007/s10546-011-9611-7.

Tietäväinen H, Vihma T. 2008. Atmospheric moisture budget over Antarctica and Southern Ocean on the basis of ERA-40 reanalysis. *International Journal of Climatology* **28**: 1977–1995. Doi: 10.1002/joc.1684.

Tjernström M, Žagar M, Svensson G, Cassano J, Pfeifer S, Rinke A, Wyser K, Dethloff K, Jones C, Semmler T, Shaw M. 2005. Modelling the Arctic Boundary Layer: An Evaluation of Six Arcmip Regional-Scale Models using Data from the Sheba Project. *Boundary-Layer Meteorology* **117**(2): 337–381.

Turner J, Pendlebury S (eds). 2004. *The International Antarctic Weather Forecasting Handbook*. British Antarctic Survey: Cambridge. 663pp.

Vihma T, Brümmer B. 2002. Observations and modelling of the on-ice and off-ice air flow over the northern Baltic Sea. *Boundary-Layer Meteorology* **103**: 1–27.

Vihma T, Kilpeläinen T, Manninen M, Sjöblom A, Jakobson E, Palo T, Jaagus J, Maturilli M. 2011. Characteristics of Temperature and Humidity Inversions and Low-Level Jets over Svalbard Fjords in Spring. *Advances in Meteorology* **2011**, doi:10.1155/2011/486807.

Vihma T, Lüpkes C, Hartmann J, Savijärvi H. 2005. Observations and modelling of cold-air advection over arctic sea ice. *Boundary-Layer Meteorology* **117**: 275–300, doi:10.1007/s10546-004-6005-0.

Virkkula A, Asmi E, Teinilä K, Frey A, Aurela M, Timonen H, Mäkelä T, Samuli A, Hillamo R, Aalto P, Kirkwood S, Kulmala M. 2009. Review of aerosol research in Aboa and the surroundings. *Geophysica* **45**(1-2): 163–181.

Whiteway JA, Duck TJ. 1996. Evidence for critical level filtering of atmospheric gravity waves. *Geophysical Research Letters* **23**(2): 145–148.

Wilson AB, Bromwich DH, Hines KM. 2012. Evaluation of Polar WRF forecasts on the Arctic System Reanalysis Domain: 2. Atmospheric hydrologic cycle. *Journal of Geophysical Research-Atmospheres* **117**, doi:10.1029/2011JD016765.

Wyser K, Jones CG, Du P, Girard E, Willen U, Cassano J, Christensen JH, Curry JA, Dethloff K, Haugen JE, Jacob D, Koltzow M, Laprise R, Lynch A, Pfeifer S, Rinke A, Serreze M, Shaw MJ, Tjernstrom M, Zagar M. 2008. An evaluation of Arctic cloud and radiation processes during the SHEBA year: simulation results from eight Arctic regional climate models. *Climate Dynamics* **30**(2-3): 203–223, doi:10.1007/s00382-007-0286-1.

Yoshiki M, Sato K. 2000. A statistical study of gravity waves in the polar regions based on operational radiosonde data. *Journal of Geophysical Research* **105**(D14): 17 995–18 011.

Zhang D, Zheng W. 2004. Diurnal cycles of surface winds and temperatures as simulated by five boundary layer parameterizations. *Journal of Applied Meteorology* **43**(1): 157–169, doi:10.1175/1520-0450(2004)043¡0157:DCOSWA¿2.0.CO;2.

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ISBN 978-951-697-785-3 (paperback)
ISBN 978-951-697-786-0 (pdf)
ISSN 0782-6117
Unigrafia Oy
Helsinki 2013