With the effects of global warming particularly pronounced in the Arctic, there has been an increased interest in observing climate, weather, and sea state in the high latitudes. However, because of sparse surface and atmospheric observations, weather forecasts for the Arctic are considerably less accurate than for the midlatitudes. This also limits the quality of sea ice information since it is based on observations and weather-dependent interpretations of remote-sensing data.

The objective of the EU-funded project IOMASA (2003–2005) was to improve our knowledge of the Arctic surface and atmosphere by using satellite information, which is continuously available but currently not optimally exploited. We present the four components of an integrated approach to improving Arctic observing: 1) remote sensing of the polar atmosphere; 2) sea ice emissivity modeling and sea ice concentration retrieval; 3) improving numerical weather prediction (NWP) models by assimilating the results of components 1 and 2; and 4) setting up a real-time processing system and a user interface to prove the usefulness of this concept.

**ATMOSPHERIC REMOTE SENSING.** We developed an algorithm that retrieves the total water vapor (TWV, also total precipitable water or total column water vapor) content of the atmosphere from data acquired by AMSU-B (Advanced Microwave Sounding Unit B, aboard NOAA’s polar orbiting satellites). AMSU-B is designed for humidity soundings (retrieval of humidity profiles) using mainly three channels near the strong water vapor line at 183.31 GHz. In the dry conditions typical of polar regions in the winter and spring, however, humidity soundings fail because the weighting functions all peak near the surface. At the dawn of the new millennium, Miao et al. developed an algorithm that overcomes this situation: It can retrieve the TWV under sufficiently dry antarctic conditions using data from the satellite humidity sounder SSM/T2 (Special Sensor Microwave Water Vapor Profiler; similar to AMSU-B). This algorithm is nearly independent of the potentially unknown surface emissivity.

In IOMASA, we adapted the Miao et al. algorithm for use with AMSU-B data and arctic conditions. Then, based on a linear relation between the emissivities at 89 and 150 GHz, we extended the algorithm so that it can retrieve TWV content above about 7 kg m$^{-2}$, the upper limit of the original algorithm, to about 13 kg m$^{-2}$; see Fig. 1 for an example.

**SEA ICE EMISSIVITY MODELS.** Since the radiance received at the satellite generally contains contributions from both the atmosphere and the surface, the surface emission model relationships are needed for the retrieval of both surface and atmospheric parameters. While there are physical microwave models describing the atmosphere, the open ocean, and partly the land, covering a wide range of microwave frequencies and polarizations, such models are generally missing for ice-covered polar regions. As a consequence, current retrieval...
procedures for sea ice concentration (i.e., the percentage of ice-covered sea surface within the sensor’s footprint) from passive microwave satellite observations are empirically based. In IOMASA, two types of emissivity models have been developed. First, an empirical emissivity model has been established for both the AMSR-E (Advanced Microwave Scanning Radiometer for EOS) microwave frequencies in the range from 6.9 to 89 GHz, and for the AMSU frequencies (23 to 183 GHz). This model has been used for the assimilation of satellite microwave data into numerical weather prediction models (see below). In a more detailed study, an algorithm to retrieve surface emissivity at AMSU-A and -B window channels from AMSU data was developed and used to determine typical emissivities of first-year and multiyear ice and to explore the dependence on the scan angle and the seasonal variation. Secondly, a sea ice version of the Microwave Emission Model for Layered Snowpacks (MEMLS) has been developed. MEMLS is a multilayer “forward” model. From the microphysical snow and ice profile (including layer depth, snow grain size, density, salinity, and physical temperature), MEMLS computes the microwave brightness temperature, emissivity, and effective temperature. In addition to helping assess important parameters influencing the emissivity of the ice/snow surface, the model has been used to extensively evaluate sea ice concentration algorithms.

**SEA ICE CONCENTRATION ALGORITHMS.**

Comparison of seven of the most frequently used sea ice concentration algorithms over high-concentration sea ice showed that those with the shorter penetration depth (i.e., using mainly near–90-GHz information) tend to produce significantly better statistics than the algorithms at 19 and 37 GHz, which are most frequently used in the present day. During winter, the root-mean-square difference of the near–90-GHz ice concentrations with respect to the ship and SAR data used as reference was consistently smaller. All passive microwave algorithms tended to report more ice concentration variability than was observed in the reference data. The study provides a solid basis for the interpretation of sea ice concentration retrievals not only in operational meteorological applications but in climate and oceanographic applications.

For example, a comparison of sea ice area derived using the seven sea ice concentration algorithms showed significant differences in trends during 1991–2004 (Table 1). The differences—between 15% and 20% of the total downward trend in winter—are caused by systematic changes in the atmosphere and sea ice surface. During summer melt, all algorithms show poor skill regardless of the different channel combinations.
ASSIMILATION OF SATELLITE OBSERVATIONS INTO NWP MODELS. While assimilation of satellite microwave observations into NWP models is routine over the open ocean, this is much more difficult over sea ice due to its high and highly varying emissivity. This contribution to the satellite-received signal is considered a stochastic error in the atmospheric signal during the assimilation procedure. In IOMASA, observations by the temperature sounder AMSU-A over sea ice were successfully assimilated into the operational HIRLAM 3D-Var (High Resolution Local Area Model, Three-Dimensional Variational analysis), and a new approach for estimating microwave sounding channel emissivity over sea ice was developed using information from the EUMETSAT OSI SAF (Satellite Application Facility on Ocean and Sea Ice).

Setting an upper and lower rejection threshold on the difference between observed brightness temperatures and corresponding values estimated from the first-guess NWP profiles served as the quality control for the observations. Rejection thresholds were estimated using a novel approach developed specifically to handle cloud contamination with an asymmetric distribution of the difference between the observed and modeled brightness temperatures (Tveter and Thyness detailed the approach in a 2005 article). Assimilating AMSU-A observations over sea ice using this approach improved the predictions of mean sea level pressure (MSLP) and temperature profiles, especially in northern areas.

To assess the effect of the assimilation of AMSU-A observations over ice, the NWP model (HIRLAM 3D-Var) was run once without assimilating these data—the reference run—and once assimilating these data—the experiment run. The impact of the AMSU-A observations can be particularly large, as in the 24-h forecast for 14 March 2005, 0000 UTC (Fig. 2). There is a low-pressure system in the Barents Sea between Norway and Spitsbergen, which has different shape, strength, and position in the experiment and reference runs. Thus, assimilating AMSU-A observations from ice regions has an effect much farther south, over the Barents Sea. In other words, the influence of added observations above the sea ice propagates southward. This is not surprising, since there is a northerly flow from the sea ice regions, and upper-air charts (not shown) indicate that over parts of the area such a flow extends to the mid- and upper troposphere. To verify which of the two forecasts for this area is closest to reality, one could compare with the model analyses over the Barents Sea or with observations (Fig. 3). Usually, the differences between the analyses of the reference and experiment runs are much smaller than the differences between the forecasts. However, the enlarged chart of the analyses from the two runs valid at the same time (Fig. 3) still shows surprisingly large differences (exceeding 10 hPa in some regions), just like the differences between the two forecasts (Fig. 2). The reason must be that there are very few conventional observations in the region, which by assimilation could make the two cycles approach each other.

We now look at the wind observations of two island stations shown in Fig. 3: West of the low pressure center, wind observations at the Bjørnøya station, an open location, nicely represent the large-scale flow. The observed wind, however, does not correspond well to the isobars in either the reference or the experiment model. The match with the experiment, however, is significantly better. The same is true at Hopen Island, just southeast of Spitsbergen. Also, the observed pressure values at these stations match the experiment better. We conclude that in this situation...
the differences between two 24-h forecasts are basically maintained in the analysis, and the errors in the reference run are kept. The added AMSU-A observations affect the model for a long time and improve the simulated circulation pattern in the Barents Sea.

A second example comparing the reference and experiment runs is the assimilation of the previously described TWV retrievals into the HIRLAM 3D-Var, using the same code as the Swedish Meteorological and Hydrological Institute (SMHI) operational HIRLAM suite in 2006. The model was run for January 2005, once in a reference run, and once with the TWV retrievals assimilated. The two runs were compared against each other and also against a few selected surface synoptic observation stations and radiosonde stations near the polar ice cap. Inclusion of TWV retrievals increased water vapor and cloudiness in the Arctic. A closer study of the model performance revealed large biases of the temperatures below 900 hPa in the reference run, and it is likely that improved scores arose from reducing the temperature bias by assimilating the TWV retrievals. The TWV retrievals provided more water vapor and clouds and therefore a warming, which

<table>
<thead>
<tr>
<th>Period</th>
<th>BRI</th>
<th>CF</th>
<th>CP</th>
<th>NT</th>
<th>NT2</th>
<th>N90</th>
<th>TUD</th>
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<tbody>
<tr>
<td>Annual ice area</td>
<td>-42.1±6.1</td>
<td>-40.8±6.1</td>
<td>-46.0±6.3</td>
<td>-46.0±6.3</td>
<td>-45.5±6.3</td>
<td>-38.1±6.0</td>
<td>-43.5±5.8</td>
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<tr>
<td>Winter ice area</td>
<td>-36.1±5.0</td>
<td>-32.9±6.7</td>
<td>-43.8±7.8</td>
<td>-45.5±7.9</td>
<td>-43.4±7.4</td>
<td>-35.2±7.3</td>
<td>-40.1±6.6</td>
</tr>
</tbody>
</table>

Fig. 3. Weather situation on 14 Mar 2005, 0000 UTC, focused on the Barents Sea: Model analysis (black: reference; green: experiment using AMSU-A over sea ice) and selected station observations.
was just what the model needed. It is very likely that
the negative bias in the reference run was due to the
lack of heat flux through sea ice, which is computed
in the Interaction Soil Biosphere Atmosphere (ISBA)
surface scheme developed by Noilhan and Mahfouf
in the mid 1990s. Forecasters at SMHI saw similar
negative temperatures over the Baltic Sea. When the
ISBA scheme was corrected in the SMHI operational
suite, the problem was significantly reduced.

RELEVANCE AND IMPLICATIONS. IOMASA
extended expertise in remote sensing of the polar
atmosphere, modeling and retrieval of sea ice, and
modeling and assimilation of the polar atmosphere.
It has promoted the scientific cooperation and in-
tegration between European universities and research
institutes, and has contributed to transferring new
technologies from research institutes (University of
Bremen, Danish Remote Sensing Centre of Technical
University of Denmark) to operational services
(Danish Meteorological Institute, Norwegian Me-
teorological Institute, Swedish Meteorological and
Hydrological Institute). The results achieved in
IOMASA will lead to improved numerical weather
prediction, in particular over Northern Europe, and
to improved ice concentration retrieval and ice chart-
ing in polar regions. The results also point out that
the snowpack on sea ice is the major unknown for
sea ice concentration and type retrieval. The snow
metamorphism occurring over the freezing season
causes the snow grains to grow slowly after deposi-
tion, leading at the higher microwave frequencies to
a slight but continuous decrease of the emissivity.
Moreover, the emissivity of the snow is influenced
by melt and snowfall events. Within the current EU
project DAMOCLES (Developing Arctic Modeling
and Observing Capabilities for Long-term Environ-
mental Studies), the development of the sea ice and
snow emissivity as a function of the meteorological
history is modeled by combining a thermodynamic
and an emissivity model of the sea ice, driven by
an atmospheric circulation model.

The new assimilation schemes and the im-
proved surface flux scheme are to be brought into
the HIRLAM reference system, where it can easily
be used by all interested institutions (the weather
services of Denmark, Finland, Iceland, Ireland, the
Netherlands, Norway, Spain, and Sweden use HIR-
LAM operationally). The work on sea ice emissivity
and concentration has been taken up by the EUMET-
SAT OSI SAF. The distribution system at www.seaice.
dk/iomasa provides a wealth of ice/weather and ocean
information and detailed project information. Many
IOMASA activities are continuing under the EU
Integrated Project DAMOCLES (Developing Arctic
Modeling and Observing Capabilities for Long-term
Environmental Studies; www.damocles-eu.org).

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