THE HELSINKI TESTBED

A Mesoscale Measurement, Research, and Service Platform

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A mesoscale observation network in the Helsinki area—funded and maintained by both public and private sources—demonstrates its value to researchers, forecasters, and the public.

Since 2005, the Finnish Meteorological Institute (FMI) and Vaisala—both headquartered in the greater Helsinki area in Finland—have established and maintained a mesoscale weather observational network in southern Finland called the Helsinki Testbed (Dabberdt et al. 2005a). The Helsinki Testbed is an open research and quasi-operational program designed to advance observing systems and strategies, understanding of mesoscale weather phenomena, urban and regional modeling, and applications in a high-latitude coastal environment. Specifically, the observing instrumentation focuses on meteorological observations of meso-gamma-scale (1–10 km) phenomena that are often too small to be detected adequately by traditional observing networks.

The original motivation of the Helsinki Testbed was to develop an internationally recognized platform where scientists can deploy their measurement devices and monitor small-scale weather phenomena. Such an environment could serve as an instrument intercomparison network and a place where novel measurements could be prototyped, applications could be developed, and commercial solutions could be pursued.

In a generic sense, a test bed is defined as "a working relationship in a quasi-operational framework among measurement specialists, forecasters, researchers, private sector, and government agencies, aimed at solving operational and practical regional problems

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with a strong connection to the end-users" (Dabberdt et al. 2005b, 970–971). The primary funding for the Helsinki Testbed came from the Finnish Technology and Innovation Agency (Tekes) and FMI (both government agencies), and Vaisala (private sector). Other partners and end users include academic institutions (University of Helsinki, Helsinki University of Technology), other government agencies (Finnish Road Enterprise, Finnish Road Administration, Radiation and Nuclear Safety Authority, Helsinki Metropolitan Area Council—the air quality authority) and private industry (Insta DefSec, Destia, Fortum, Teollisuuden Voima, Finavia). In this way, the Helsinki Testbed demonstrates one way that the interaction among the public, academic, and private sectors—under much discussion in the United States (White 2001; NRC 2003)—can be manifest, especially as such interaction concerns the proposed Nationwide Network of Networks (NRC 2009).

"Outcomes from test beds are more effective observing systems, better use of data in forecasts, improved services, products, and economic/public safety benefits" (Dabberdt et al. 2005b, p. 971). Specifically, the objectives of the Helsinki Testbed are to (i) provide input and verification data for mesoscale weather research models, operational forecast models, and dispersion models; (ii) provide better understanding of mesoscale processes that can be adapted for developing weather forecast and dispersion modeling systems; (iii) calibrate and validate satellite data; (iv) create an integrated information system (e.g., the Helsinki Testbed data archive); (v) develop end-user products; and (vi) disseminate mesoscale meteorological and air-quality data for both the public and the research communities.

In this article, we aim to illustrate how the cooperation among the different partners has evolved since 2005 and how the above-listed objectives are being met. We accomplish these goals by describing the instrumentation and organization of the Helsinki Testbed through its two completed phases, as well as a third phase, which is currently in progress. In addition, we present the major results and achievements of the Helsinki Testbed, evaluating its successes and shortcomings.

FINLAND AND HELSINKI

The five Nordic countries include Finland, Iceland, Norway, Sweden, and Denmark. If Finland were a state in the United States, it would be the fifth biggest (338,000 km^2). Most of Finland is relatively flat and low elevation, except in northernmost Finland where the highest peak, Halti (1324 m), stands near the border with Norway. Finland is bounded by two basins of the Baltic Sea: the Gulf of Bothnia to the west and the Gulf of Finland to the south. Over 74% of Finland is covered with forest (it is Europe's most forested country), and 10% of Finland is composed of more than 187,000 lakes larger than 500 m^2. The population of 5.3 million people is distributed mostly in the south, giving an average density of 16 inhabitants km^{-2}, equivalent to the population density of Colorado. This population is technologically savvy: in 2008, 98% of Finnish households had a mobile phone and 76% had Internet access (see more information online at www.stat.fi/til/jvie/2008/index_en.html).

Helsinki is the most populous city in Finland (1.5 million people in the greater metropolitan area) and is located on the southern coast of Finland at roughly 60°N. In this northern environment, the yearly variation of possible sunshine hours is pronounced. For example, the sun is above the horizon in Helsinki only about five hours during the winter solstice, but nearly 20 hours during the summer solstice. Local standard time [Eastern European Time (EET)] is 2 h earlier than UTC (EET = UTC + 2 h).

Despite its northern location, Finland experiences deep, moist convection and severe weather during the summer (mostly hail and convective winds). Recently, the severe-weather climatology of Finland has begun to be documented: mesoscale convective systems (Punkka and Bister 2005), tornadoes (Teittinen and Brooks 2006), cloud-to-ground lightning (Tuomi and Mäkelä 2008; Mäkelä et al. 2011), hail (Tuovinen et al. 2009; Saltikoff et al. 2010b), and heavy rain (Saarikalle 2009). Possible convective weather during the relatively short warm season includes derechos (e.g., Punkka et al. 2006), tornadic supercells (e.g., Teittinen et al. 2006), and microbursts (e.g., Järvi et al. 2007).

DESCRIPTION OF THE NETWORK. The domain of the Helsinki Testbed is roughly 150 km by 150 km, covering much of southern Finland and the Gulf of Finland, including the city of Helsinki (Fig. 1). Table 1 summarizes the instrumentation deployed in the Helsinki Testbed. The skeleton of the Helsinki Testbed network was established from the existing observation networks of FMI and the Finnish Road Administration. To achieve a dense network of weather stations, these existing sites were supplemented with more than 100 new Vaisala WXT510 weather transmitters. Most of these stations were installed at 44 cell phone base-station masts. In general, two or four transmitters were deployed at different heights on a mast to determine bulk vertical profiles of temperature and humidity and derive static stability.

Since 2005, other data sources within the Helsinki Testbed have included an increased number of radio soundings, ceilometers, precipitation weighing

Table 1. Weather observations in the Helsinki Testbed during the initial measurement campaigns.	
No.	**Site type**
46	FMI weather stations
34	FMI precipitation stations
5	New weighing precipitation gauge stations
13	Off-line temperature loggers in greater Helsinki area
22	Weather transmitters at surface level
191	Road weather stations, with a total of 58 road weather cameras
311	**Surface weather stations, total**
44	Pairs of weather transmitters on cell-phone base-station masts
5	Optical backscatter profilers (new ceilometers)
6	FMI ceilometers
2	FMI C-band Doppler radars
3	Dual-polarization Doppler radar
3	Radio sounding stations
1	UHF wind profiler with RASS
—	Total lightning network
4	Visiting research instruments: 2 POSS precipitation occurrence sensor systems (Environment Canada) 1 Doppler lidar (University of Salford, United Kingdom) 1 Doppler sodar (Finnish Defense Forces and VTT)

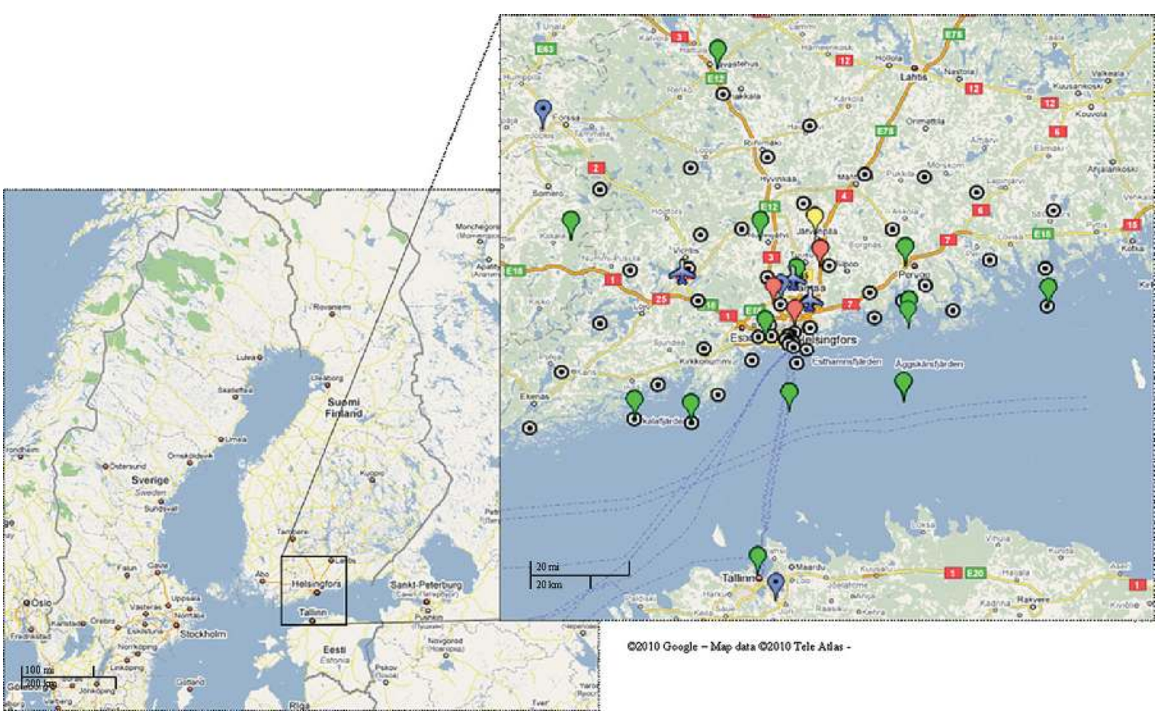

Fig. 1. Location of the Helsinki Testbed domain at the south coast of Finland. Black circles denote the location of masts equipped with weather stations, green balloons denote the location of FMI automatic weather stations, blue balloons denote the location of sounding stations, red balloons denote the location of dual-polarization weather radars, and the yellow balloon denotes the location of the vertically pointing Doppler radar.

gauges, a wind profiler with radio acoustic sounding system, a disdrometer, precipitation occurrence sensor systems (POSSs), hydrometeor size distribution detectors, special versions of weather transmitters equipped with photosynthetically active radiation (PAR) sensors, trace gas concentration and flux measurements, a total lightning location system, a Doppler lidar, and a Doppler sodar. Currently the area is covered by four Doppler radars, three of which have dual-polarimetric capabilities. After the initial measurement campaigns, the number and type of observations have evolved, but most of these observations have continued to serve the public, users, and research efforts.

In 2007, the Testbed instrumentation was supplemented with the University of Helsinki–FMI Station for Measuring Ecosystem–Atmosphere Relations (SMEAR-III) urban measuring station. The station includes a 31-m flux tower equipped with meteorological instrumentation at several heights (Järvi et al. 2009a). Measurements include radiation components and profiles of the air temperature and wind. The fluxes of sensible heat, momentum, carbon dioxide, aerosol particle number, and water vapor are measured on the top of the tower with the eddy-covariance technique (Vesala et al. 2008; Järvi et al. 2009b,c). Atmospheric stability (i.e., the Obukhov length) can also be calculated continuously from these sensible heat and momentum fluxes. Various high-resolution aerosol particle and gas concentration measurements are performed from an air-conditioned container located next to the tower. These measurements include size distributions of aerosol particle numbers, chemical composition of particles, and their optical properties.

PHASE 1: MEASUREMENT CAMPAIGNS.

The Helsinki Testbed initially was designed to demonstrate the benefits of additional meteorological observations for forecasting meso-gamma-scale weather phenomena. Although the Helsinki Testbed was conceived by FMI and Vaisala, other corporate and governmental agencies contributed by providing their data, showing the private or societal need, acting as end users, and funding the project. Real-time data were made publicly available, and intense measurements were performed during five specific month-long measurement campaigns between August 2005 and August 2006. For convenience, each of the campaigns was named for a typical mesoscale phenomenon or forecasting activity of that season: nowcasting (August 2005), precipitation type (November 2005), stable boundary layer (January–February 2006), sea breeze (May 2006), and convection (August 2006). However, additional observing periods were subsequently conducted to complement the datasets of the original campaigns. The following sections introduce some initial analyses of the Helsinki Testbed data.

Nowcasting. The term nowcasting refers to short-range forecasts primarily for the next two hours. On this time scale, weather information is mainly based on observations and rather simple extrapolations of past and present weather. Users of nowcasts include aviation and road-maintenance organizations. Mobile interfaces, local radio, TV, and Internet have made nowcasts more available to the public. In the first Helsinki Testbed campaign, data for nowcasts were made available to organizers and the public through the Internet and various mobile devices (cell phones, Blueberry-type gadgets, and laptops with GPRS modems) during the 2005 Helsinki World Championships of Athletics (track and field).

During these championships, a cold front arrived over Finland from the southeast during the afternoon of 9 August 2005 (Fig. 2). Severe thunderstorms developed along the front, many of which organized into a larger mesoscale convective system. Based on satellite images and NWP guidance, FMI released a special warning for the public via radio and TV broadcasts in the morning, approximately 8 h before the storm hit Helsinki. One measure of the severity of this storm is that such special warnings are released only once or twice a year. This weather event interrupted both the games and television broadcasting because of heavy rain and lightning. During the thunderstorm, more than 500 cloud-to-ground lightning flashes occurred in Helsinki and nearby towns. The storm gave the Helsinki Testbed a lot of media attention with the headline in a local newspaper reading "Spectators were flooded with 1.5 million liters of rainwater." (The quantity of water was integrated from the rainfall intensity measurements and the surface area of the stadium.) Several authorities of the championships and spectators of the event used the Testbed data to watch the arrival of the heavy thunderstorm. However, no one was expecting the storm to have such intensity, nor were any safety or contingency plans available to deal with such a phenomenon.

The case described above and another urban flash flood case in 22 August 2007 suggested that FMI could improve its nowcasting service for heavy rainfall. Consequently, Tekes funding was received for the development of a real-time automatic warning system prototype at 1-km grid spacing across Finland.

The service that is being developed contains two novel components. First, based on ensembles of radar-based nowcasts, probability distributions are calculated for accumulated precipitation over several periods of length and for many lead times. The forecasts are updated every 5 min, after each new volume scan of the radar network. Second, the real-time user interface is based on Internet and cell phones. All customers can define their personal risk profiles of heavy rainfall interactively (i.e., they can set probability thresholds of precipitation for given locations, accumulation periods, and applications). A warning text message is generated and is sent automatically when the forecast probability exceeds the threshold set by the customer. The first full prototype of the system is planned to operate in the summer of 2011. The Helsinki Testbed provides an observational and verification environment for this new service.

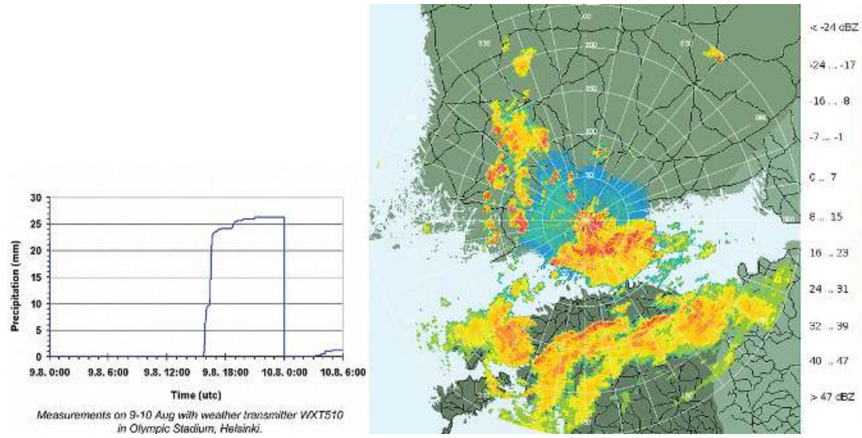

Fig. 2. (left) Accumulated precipitation during 9–10 Aug 2005 measured with a weather transmitter at the stadium in Helsinki. (right) Radar reflectivity factor (dB*Z*) up to a range of 250 km from the Vantaa C-band radar, located 10 km north of Helsinki, at 1550 UTC 9 Aug 2005 [500 m CAPPI up to a range of about 50 km and 0.5° elevation angle PPI at longer ranges, as per the pseudo-CAPPI method of Capsoni et al. (2001) and Saltikoff et al. (2010a).]

Mixing height determination. Stable boundary layers frequently occur in the cool season and are a challenge for adequately describing the boundary layer in numerical weather prediction (NWP) and air quality models. Determining the height of the boundary layer or the mixing height (MH) is not straightforward and not a routine observation. Radio soundings have traditionally been used, but ceilometers could provide better spatial and temporal resolution. Both radio sounding and ceilometer data from the Helsinki Testbed were used to estimate the MH during the stable boundary layer campaign.

One so-called objective method to estimate the MH is the idealized-profile method (Steyn et al. 1999). However, Hägeli et al. (2000) and Eresmaa et al. (2006) found that the form of this profile was insufficient to detect the MH when the backscattering coefficient profile had more than one aerosol layer. Therefore, an advanced method, which can account for up to three aerosol layers in the backscattering profile, was derived by Eresmaa et. al. (2011, manuscript submitted to *Atmos. Chem. Phys.*) and sets a more robust idealized profile using multiple profiling devices from the Helsinki Testbed.

The revised method fits an idealized backscattering coefficient profile $B(z)$ to the measured profile by minimizing the root-mean-square deviation between them. The idealized three-step profile method produces three estimates for the MH and the one connected to the largest decrease of the backscatter is chosen to mark the MH. However, some local specificities are used to constrain the procedure: the maximum estimate for the MH was set to 2200 meters and the MH was not allowed to exceed the height of the cloud. Since water droplets dominate the backscattering profile, this method is applicable only when the sky is clear.

To evaluate these MH estimates from ceilometer data, we have used radio sounding profiles treated with two traditional MH estimation methods according to stability conditions. Under convective situations, we estimated the MH from the radio soundings by the simple parcel method following the dry adiabat starting at the surface up to its intersection with the actual temperature profile (Holzworth 1964, 1967). However, instead of using the surface temperature, we used the mean temperature of the superadiabatic layer near the surface. In stable and neutral situations, we used the Richardson number profile method used by Joffre et al. (2001) with a critical number of 1 to estimate the equilibrium mixing height.

A total of 113 clear-sky cases were analyzed. A comparison between mixing heights estimated by the ceilometer and those calculated from radio sounding data is displayed in Fig. 3. The correlation between

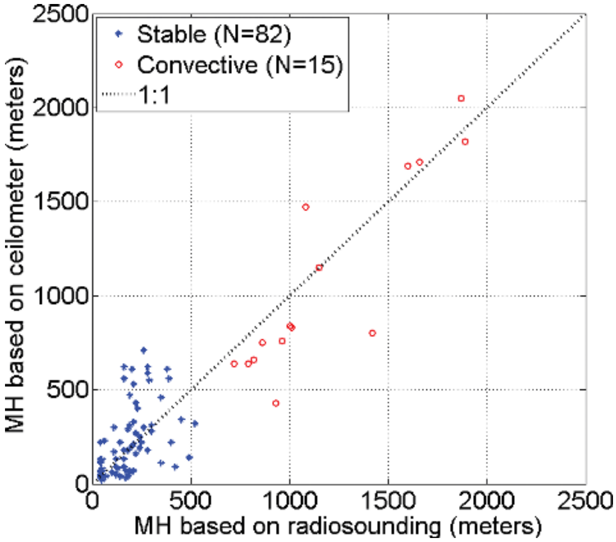

Fig. 3. Comparison between mixing heights (m) determined by the radio soundings and mixing heights (m) determined by the ceilometers in Vantaa, Finland, during the period 2 Jan 2006–13 Mar 2007. The blue circles represent the mixing heights in stable situations, and the red squares represent mixing heights in convective situations.

mixing heights estimated from ceilometer and radio sounding observations is significant.

This three-step method can also be used to study the difference in mixing heights between urban and rural sites across the Helsinki Testbed area. These differences in mixing heights might be a result of the urban heat island effect, which would be greatest during winter nights under clear skies and weak winds (e.g., Oke 1987), which also favor the formation of a temperature inversion. Thus, our focus was on winter observations, especially during surface temperature inversions, and the urban heat island effect on the MH was examined with 24 days of data from five ceilometers situated in urban, suburban, and rural sites.

The higher temperatures observed at the urban sites did not increase the urban mixing heights. On the contrary, the highest averaged MH values were obtained at the rural observation site. On average, the MH in the rural site was 120 m higher than the MH at the urban site. The most probable reason for this apparent contradiction is that ceilometers require high aerosol concentrations. The near-surface backscattering was lower at the rural sites on average than at suburban and urban sites, which leads to higher uncertainties in using aerosol profiles as a basis for mixing height estimates. If no sharp aerosol concentration gradient exists between the boundary layer and the free atmosphere, the mixing height will often be overestimated.

Thus, the comparison between mixing heights estimated by ceilometer and radio soundings contributed to establish that the ceilometer can be used for MH estimation. Additionally, the comparison between several urban and rural sites across the Helsinki Testbed revealed that the use of ceilometer for mixing height estimation requires strong backscattering near the surface to retrieve realistic values for mixing height.

Precipitation type. Currently, data from the Helsinki Testbed are used for development, testing, and validation of radar-based operational precipitation-type products. Dual-polarization radar hydrometeor classification algorithms (e.g. Liu and Chandrasekar 2000; Straka et al. 2000; Lim et al. 2005) can be useful in identifying different precipitation types. But because the minimum observation altitude increases from the radar, an extension of these methodologies from hydrometeor typing at the height of the radar beam to hydrometeor typing at Earth's surface is, however, still needed. For example, shallow freezing levels and abrupt changes in the melting-layer height pose difficulty for such algorithms. Unfortunately, shallow freezing levels are typical in northern Europe during the cool season, and such low freezing levels mean a mixture of precipitation types at the surface. For example, 1% to 5% of the total precipitation in southern Finland from September to May falls as partially melted snow (Drebs et al. 2002). Also, convective hail- or graupel-producing weather is not uncommon in Finland. Typically, the hail season starts in May and extends to early September (Tuovinen et al. 2009; Saltikoff et al. 2010b). The Helsinki Testbed's combination of dual-polarization radars and surface-based instrumentation provides an excellent platform for studying such low freezing-level events.

On the afternoon of 11 May 2009, an event meeting the abovementioned criteria occurred within the Helsinki Testbed when FMI received a number of reports from the public of partially melted graupel up to 1 cm in diameter. The observed radar reflectivity factor from the University of Helsinki dual-polarization C-band weather radar (KUM) shows values ranging from −10 to 55 dBZ (Fig. 4a), with the largest values occurring just to the east of the radar. The reflectivity field does not exhibit a defined brightband signature. Separating the hydrometeor types is somewhat clearer from the copolar correlation coefficient measurements (Fig. 4b), where values smaller than 0.98 indicate either wet snow or graupel as a dominant hydrometeor type and values larger than 0.98 correspond either to rain or dry snow. RHI measurements of the copolar correlation coefficient (Fig. 4c) indicate that the freezing-level height (e.g., Liu et al. 1994; Zrnic and Ryzhkov 1999) changed from 1.25 to 0.85 km and back within 40 km, as indicated by the dashed arcs in the plan position indicators (PPIs) (Figs. 4a,b).

We would expect that changes in the freezing-level height would correspond to changes in the surface temperature. In this case, surface temperature observations can be used as an additional input parameter to radar-based hydrometeor classification schemes. To demonstrate this point, 4 h of temperature and measurements at two Helsinki Testbed locations are shown in Fig. 5. Those observations exhibit an approximately 40-min lag between the eastern site and the western site as the precipitation moves from west to east during the event (Fig. 5). During the storm's passage, the temperature fell by about 6°C and rose again, also illustrated by a melting-layer height change of about 400 m (Fig. 4c).

Weather transmitters are capable not only of making precipitation intensity measurements but also of discriminating between rain and hail, as shown in Fig. 5. During this precipitation event, the WXT sensor in Espoo Suvisaaristo reported the occurrence of hail at 1100 UTC. This surface observation corresponds to the high-reflectivity cell ($Z_h > 50$ dBZ) that is 5 km to the east of the radar at 30 min after the WXT hail measurements (Fig. 4a). This cell is characterized by somewhat depressed copolar correlation values (<0.99 in Fig. 4b), which also indicates the presence of hail. Furthermore, a three-body scattering signature characteristic of hail occurrence (e.g., Hubbert and Bringi 2000), shown as an area with copolar correlation coefficient values smaller than 0.5, is apparent east of the cell (Fig. 4a).

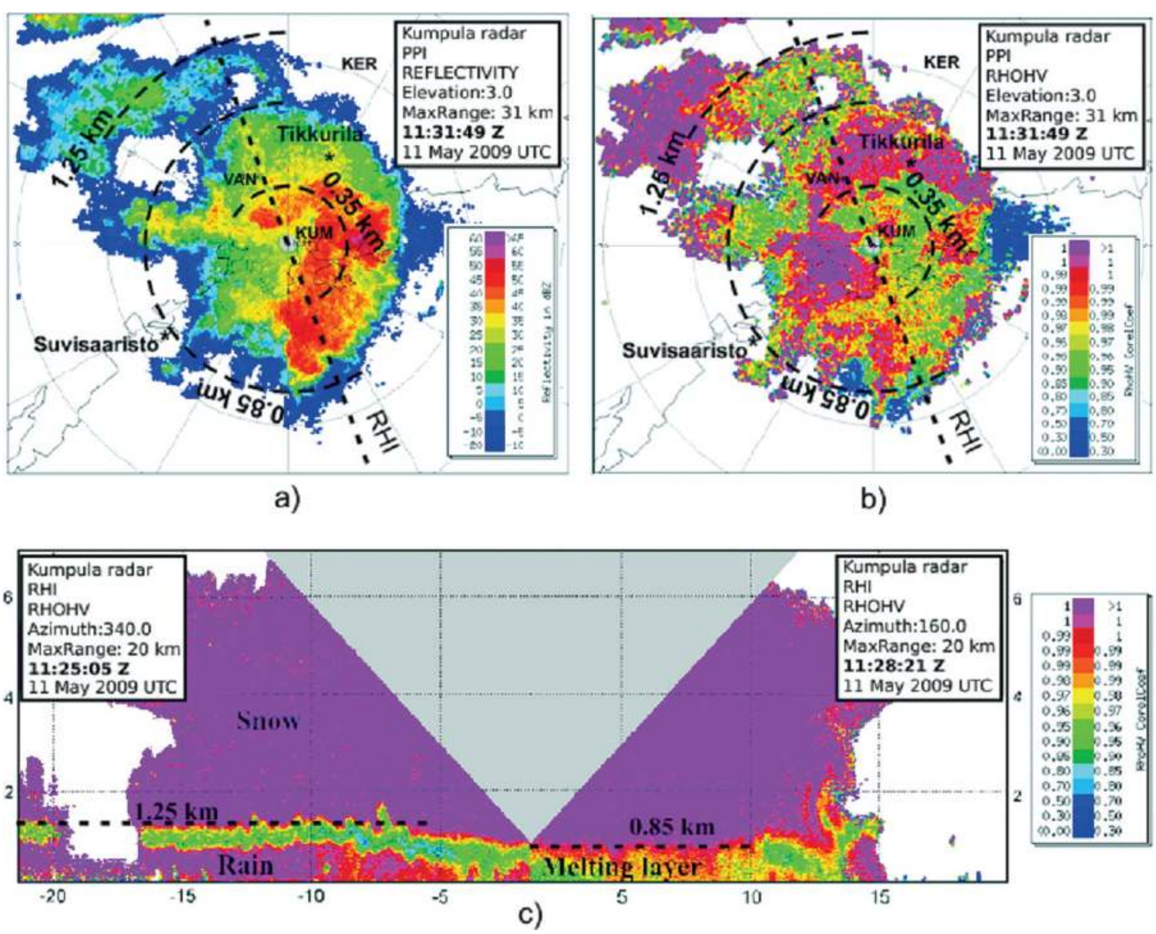

Fig. 4. University of Helsinki Kumpula radar data from a rainfall event on 11 May 2009. (a) PPI (3° elevation angle) of radar reflectivity factor (dBZ); (b) PPI (3° elevation angle) of copolar correlation coefficient fields; (c) RHI observations of the copolar correlation coefficient, taken (left) over land at 1125 UTC and (right) over sea at 1128 UTC.

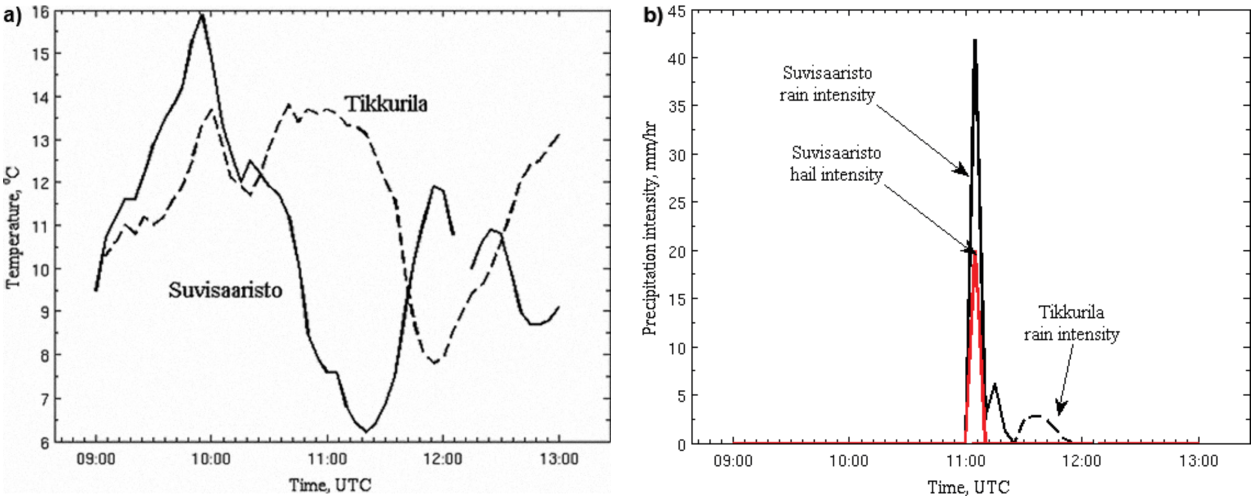

Fig. 5. Time series of (a) air temperature and (b) precipitation intensities measured by the WXT at Espoo Suvisaaristo and Vantaa Tikkurila sites during 11 May 2009. The WXT instrument is capable of separating rain and hail contributions to precipitation intensities, and thus can serve as a hail detection device.

This combination of dual-polarization radar and surface observations is currently used to refine radar-based precipitation classification techniques in the TEKES-funded heavy rainfall warning system project.

Surface fluxes. Turbulent flux measurements of sensible heat, water, carbon dioxide, and aerosol particles with the eddy-covariance technique are rare in urban areas and are usually limited to shorter measurement campaigns collecting an incomplete suite of measurements (e.g., Nemitz et al. 2002; Grimmond et al. 2004; Moriwaki and Kanda 2004; Mårtensson et al. 2006; Vogt et al. 2006; Coutts et al. 2007). Thus, the diversity of urban areas is not yet adequately covered by experimental studies, and more long-term studies from a variety of cities are needed (Vogt et al. 2006). One contribution to improving the variety of long-term measurements is the SMEAR-III flux tower in the Helsinki Testbed.

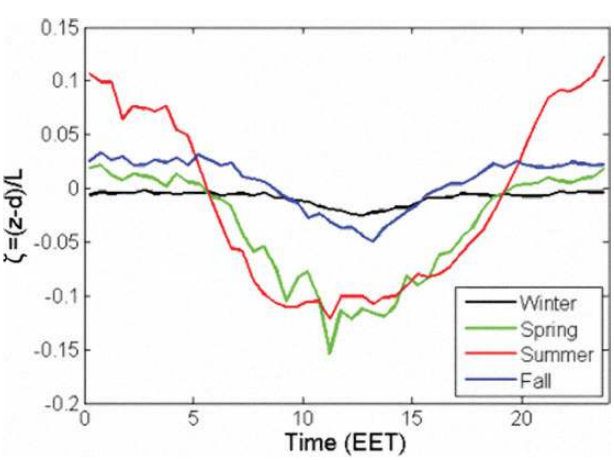

Fig. 6. The median diurnal behavior of atmospheric stability (as measured by the dimensionless parameter *ζ*, with *L* being the Obukhov length and z the height corrected by the displacement height *d*) calculated from the eddy-correlation measurements at the SMEAR-III station in Kumpula, Helsinki, in 2008. Data are divided into winter (December–February), spring (March–April), summer (May–August), and autumn (September–November). [EET = UTC + 2 h; adapted from Fig. 8h in Järvi et al. (2009a).]

The upstream fetches to the SMEAR-III tower can be grossly classified into three sectors: (i) a heavily trafficked main road leading to the Helsinki city center, (ii) mostly buildings, small roads, and parking lots, and (iii) parkland and vegetation (Vesala et al. 2008). The annual cycles of sensible and latent heat fluxes within each sector indicate that the average sensible heat flux typically exceeds the latent heat flux (heat consumed in evapotranspiration), reaching 300 W m^{-2} over urban and road surfaces in summer and 100 W m^{-2} in winter (Järvi et al. 2009a). The average latent heat flux is the highest in summer over the vegetated sector, attaining 150 W m^{-2} (Vesala et al. 2008). Comparing the three different sectors, the average emission rates of carbon dioxide and aerosol particle number are highest in the road sector where their average diurnal maxima reach 20 μmol m^{-2} s^{-1} and 0.8×10^9 m^{-2} s^{-1}, respectively (Vesala et al. 2008; Järvi et al. 2009c). In contrast, the vegetated sector behaves as a sink for carbon dioxide in summer with a downward flux of 8 μmol m^{-2} s^{-1}. Our analyses show how both carbon dioxide and aerosol particle number fluxes correlate with traffic densities (Järvi et al. 2009c).

Atmospheric stability derived from eddy-covariance calculations displays a strong annual variation (Fig. 6). The strongest diurnal amplitude was observed during the summer when daytime solar radiation keeps the local boundary layer unstable whereas stable conditions prevail at night. On the other hand, during the winter, the local nocturnal boundary layer remained unstable, likely due to the urban heat island effect induced by anthropogenic heat fluxes (e.g., Oke 1987; Piringer and Joffre 2005).

This knowledge can be used for planning urban development and managing city energy and material cycles. An additional urban flux tower is currently planned closer to the city center.

PHASE 2: UBICASTING—FOCUSING ON LOCAL ANALYSIS. The second phase of the Helsinki Testbed continued during 2007–09 under the Tekes-financed Ubicasting (ubiquitous weather forecasting) project. The main focus was to begin developing the forecasting and analysis system. Additionally, development began on services for road maintenance, nuclear power safety preparedness, public transport, dispersion of hazardous substances, and air quality.

One major benefit of a dense observing network is the ability to assimilate more data into analysis and prediction systems. Thus, improved initial conditions were tested with the Helsinki Testbed data fed into the Local Area and Prediction System (LAPS), developed by the National Oceanic and Atmospheric Administration (NOAA) (Snook et al. 1995; http://laps.fsl.noaa.gov) and implemented by FMI. LAPS is an assimilation system that ingests available observations together with first-guess meteorological fields [currently from the latest forecast of the European Centre for Medium-Range Weather Forecasts (ECMWF) model with grid spacing of approximately 16 km] to create a three-dimensional analysis of the atmosphere every hour over southern Finland (i.e., covering the Helsinki Testbed domain) with a 1-km horizontal resolution.

All Helsinki Testbed surface, radiosonde, radars, and satellite data—NOAA Advanced Very High Resolution Radiometer (AVHRR) and Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI)—are assimilated into the LAPS system. The final analyses are currently evaluated for nowcasting applications by duty forecasters. Additionally, LAPS analyses are being tested as input background fields for other forecast models (e.g., NWP, air quality, road weather).

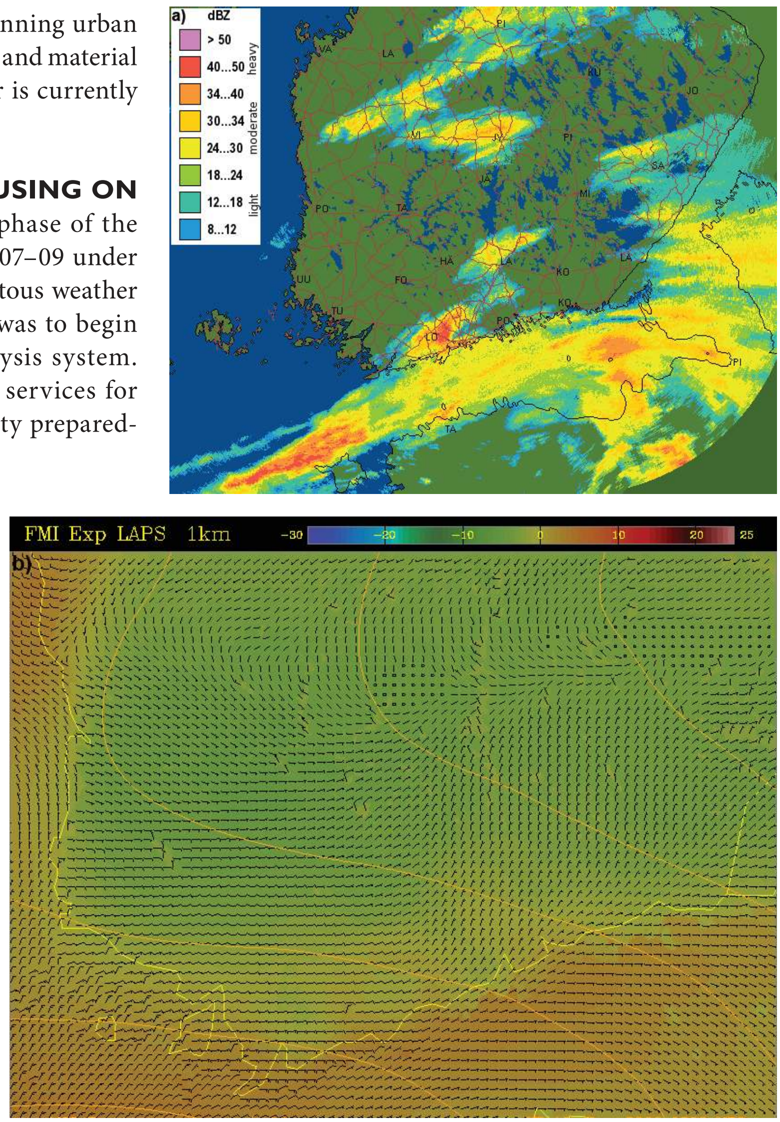

Fig. 7. Weather situation at 0300 UTC 10 Nov 2009 over southern Finland. (a) Radar reflectivity factor (dBZ) [500-m CAPPI up to a range of about 50 km and 0.5° elevation angle PPI at longer ranges, as per the pseudo-CAPPI method of Capsoni et al. (2001) and Saltikoff et al. (2010a)]. (b) Temperature (°C, with color shading scale on top of figure), mean sea level pressure (hPa, in solid orange lines), and wind field (full barb and half-barb denote 5 and 2.5 m s^{-1}, respectively) as analyzed by LAPS.

To show the impact of the Helsinki Testbed surface data, we perform an experiment consisting of two LAPS runs: one reference run without surface observations (LAPS_ref) and a second run using Helsinki Testbed surface observations (LAPS_htb). Each run lasts for 6 h with analyses generated every hour.

We took as a test a classical transient situation characterized by a weakening high pressure area giving way to an approaching frontal line from the south on 10 November 2009. The precipitation (Fig. 7a) fell as snow over land and mainly as rain over the sea. Over southern Finland, the wind was from the east and temperatures were above freezing over the water, whereas over the land areas, the winds were from the northeast or north and temperatures were below freezing (Fig. 7b).

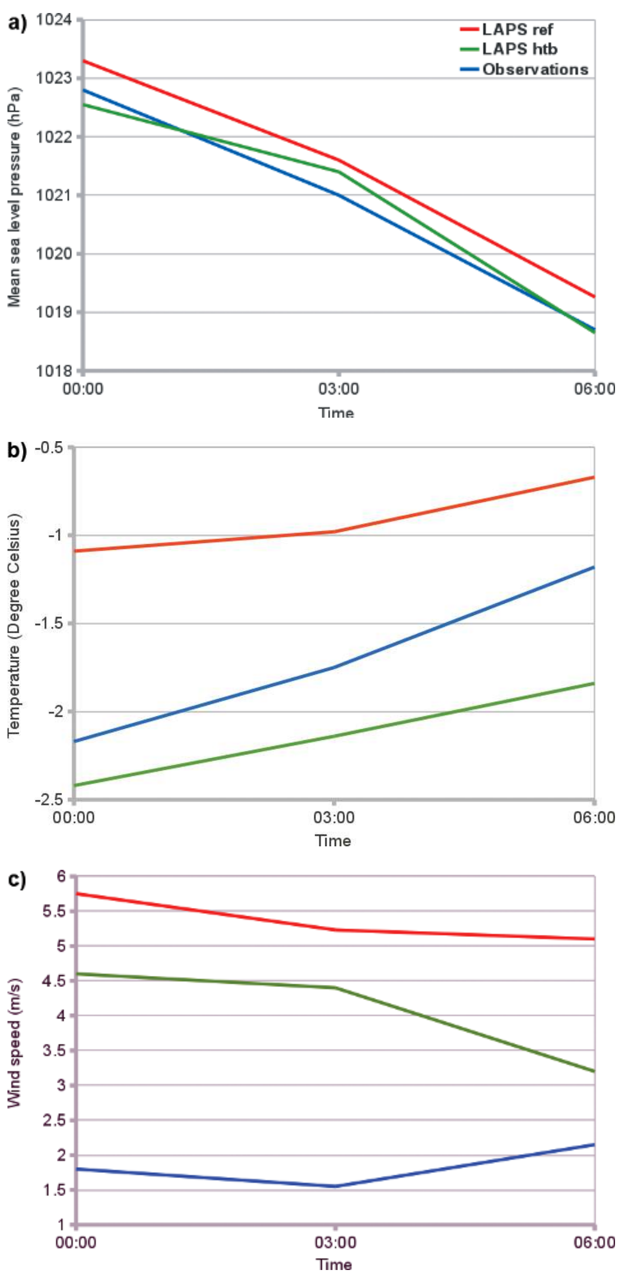

Fig. 8. Comparison between synoptic observations (blue lines) and LAPS runs without Helsinki Testbed observations (LAPS_ref; red line) and LAPS runs with Helsinki Testbed observations (LAPS_htb; green line), for (a) mean sea level pressure, (b) temperature, and (c) wind speed between 0000 and 0600 UTC 10 Nov 2009.

The verification was performed against seven or eight synoptic stations not included in the LAPS analysis. The LAPS output was verified against synoptic observations (surface pressure, temperature, and wind speed) for every third 1-h period. LAPS outputs are computed from the four closest grid points and interpolated to the location of the synoptic station.

The LAPS analysis is improved when Helsinki Testbed observations are included for all three parameters (Fig. 8). For mean sea level pressure, the analyses containing Testbed data are slightly better than for synoptic data (Fig. 8a). The LAPS temperature is also closer to observed values than the reference run but has a negative bias (Fig. 8b). The magnitude of wind speed is slightly improved by the inclusion of Helsinki Testbed observations (Fig. 8c).

Further developments of LAPS are being pursued as a part of a ubiquitous atmospheric information production system for public, commercial, and export uses. In particular, we plan to perform systematic verification, input sensitivity analyses, short-term forecasting model coupling, and introduction of new input data. Extending the domain to all of Finland has enabled a much broader utility than was initially foreseen. We are currently exploring LAPS for providing initial fields for the High-Resolution Limited-Area Model (HIRLAM) and Applications of Research to Operations at Mesoscale (AROME) weather forecasting models at FMI, the Expert System for Consequence Analysis using a PErsonal computer (ESCAPE) and the air quality and emergency modeling system (SILAM) air-quality models, the FMI road-weather model, and other end-user applications.

PHASE 3: UBICASTING 2—FOCUSING ON SERVICES. The second phase of Ubicasting started in mid-2009 and will continue until mid-2011. The main objectives for the Ubicasting 2 project are to mature and evaluate the LAPS system towards operational applications from an integrated perspective involving different actors such as industrial, commercial, scientific, civil authority, public partners, and end users. This means improving old and developing new mesoscale applications for providing ubiquitous weather-related services in the fields of aviation, road maintenance, nuclear power safety preparedness, public transport, dispersion of hazardous substances, and urban air quality. Thus, Ubicasting 2 ties together atmospheric research and socioeconomic concerns, providing an end-to-end value chain from theoretical foundations to real-life applications.

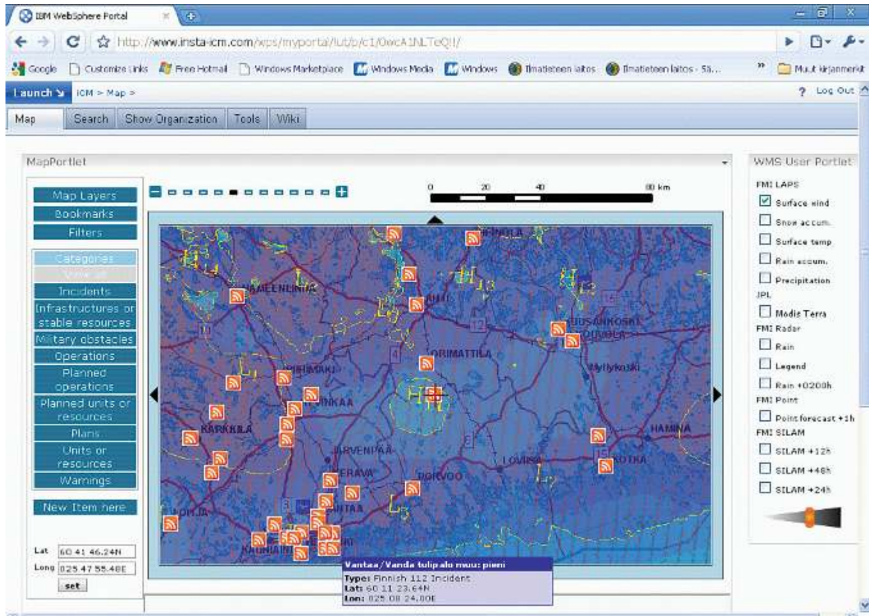

Fig. 9. Nuclear safety application. The LAPS wind field analysis is centered around the Loviisa nuclear power plant. Different data layers are selectable on the right side of the screen. For example, the latest radar observations, 2-h radar extrapolations, satellite cloud observations, a point forecast for Loviisa, and SILAM dispersion model calculations are selectable as partially transparent layers. In addition, emergency alerts can be displayed using RSS-feed symbols.

The project can also be divided into three main components. The first component represents the evaluation and continued development of the LAPS production system, with the goal of producing an hourly data assimilation and modeling cycle over Finland, resembling the U.S. National Weather Service's Rapid Update Cycle (RUC) model (Benjamin et al. 2004a,b) and the Rapid Refresh model (Benjamin et al. 2007). The second component is to improve modeling of the atmospheric boundary layer, the mixing height, and urban air quality by developing improved parameterization schemes and by coupling finescale observation, analysis, and forecasting systems together. The third component develops and validates road maintenance, weather, air quality, and dispersion applications. Two new application areas are also started: aviation meteorology and public transportation. The aviation service includes wind forecast products, automated trends, and automated terminal area forecasts (TAFs) for air traffic control, whereas the public transportation application will distribute real-time weather data to public transportation vehicles. The third component seeks to improve the services of governmental authorities and to advance the commercial partners' competitiveness and penetration to new markets.

Additionally, we will evaluate dispersion applications for nuclear hazard preparedness exercises and industrial emergency response services. For these purposes, the area around the Loviisa nuclear plant east of Helsinki has been included in the Helsinki Testbed, and an additional observation network was

THE HELSINKI TESTBED ON THE WEB

Access to real-time data from the Helsinki Testbed: http://testbed.fmi.fi/

Access to the LAPS analysis for all of Finland: http://testbed.fmi.fi/history_browser-laps finland-public.php

Helsinki Testbed Course Content from the University of Helsinki: http://testbed.fmi.fi/Course.en.html

SMEAR-3 station information: www.atm.helsinki.fi/SMEAR/

Helsinki Testbed press releases and workshop information: http://testbed.fmi.fi/About_Testbed.en.html

Helsinki Testbed Frequently Asked Questions: http://testbed.fmi.fi/docs/faq.html

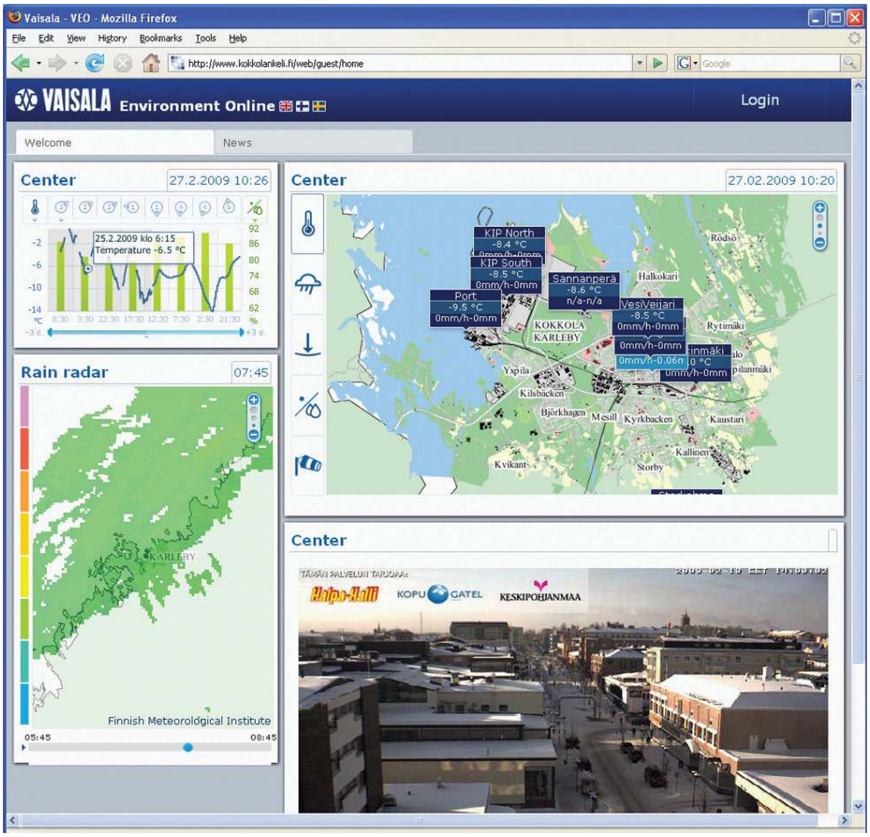

Fig. 10. Industrial weather application. The public site of the Kokkola industrial Web portal is shown here. The top left corner shows a combined time series of observations and a 2-day point forecast for Kokkola. The bottom left corner shows the radar imagery. The top right map presents the current weather from observing sites in the Kokkola Testbed.

established in the small industrial city of Kokkola in northwest Finland. In cooperation with our industrial partners, these special applications were created and implemented, including tailor-made user interfaces (Figs. 9 and 10). Both demonstrations are currently running operationally with real-time data and model runs. The future of these demonstration projects will depend on cost–benefit evaluation that will be completed by the industrial providers and end users.

PUBLIC SUPPORT FOR THE HELSINKI TESTBED. The Helsinki Testbed is popular with the public, as is evident from Web site statistics: during the nearly 10-month period from 1 July 2009 to 27 April 2010 Helsinki Testbed was visited more than 4,500,000 times by over 950,000 unique visitors. The approximate time spent on the site per visit was 25 minutes. During the severe storm in the Helsinki area that flooded roads and shut down the Finnish broadcasting system on 22 August 2007, the Helsinki Testbed Web site faced 26,000 different visitors, suggesting that tens of thousands of citizens must be accustomed to the regular and free service. Yet another encouraging sign from outside the meteorological community was when the Helsinki Testbed won the first prize in the community category of the "Productive Idea of the Year 2006" national contest organized by the Junior Chamber International of Finland.

But perhaps the most telling evidence of the value of the Testbed data to the public is the results of user surveys conducted in 2006 and 2008, both producing similar results. In 2008, a voluntary Web-based survey lasting one month was available on the Helsinki Testbed Web page—over 6300 people responded, which is surprising for a month-long, involuntary survey. On a scale from 1 to 5, 81% of the respondents indicated the maximum interest (5) in using the service in the future, and an additional 17% replied with a 4. Of the respondents, 52.5% said they have recommended the service to others, and 47.4% indicated that they would be ready to do so. Seventy-five percent of respondents said that they used the data for private purposes or simply have a general interest in the weather, 15% said that they used the data in their profession, and 2% said that they used the data in scientific research. Respondents found the most valuable information to be the weather radar imagery, and the most popular surface station variables were temperature, precipitation, and wind. Map and time series displays seemed to be equally popular, whereas map animation pages consistently received the most page loads.

COOPERATION THROUGH RESEARCH PROJECTS. The Helsinki Testbed has attracted research and development projects that benefit from mesoscale weather observations. More than 15 projects have used the Helsinki Testbed, ranging from academic theses to research and development projects performed by commercial companies and national and international projects (Table 2). The Helsinki Testbed has served as a development test site for several dual-polarization radar projects: development of the Hydroclass hydrometeor classification algorithm, studies of multidisciplinary use of polarimetric weather radar (birds and insects), and development of pattern recognition algorithms.

One of the projects made possible by the Helsinki Testbed was a 4-yr project funded by the Academy of Finland (the Finnish equivalent of the National Science Foundation) to study the interaction of fronts with the near-surface boundary layer. Schultz and Roebber (2008) showed that the numerical simulation of cold fronts often does not match observations, leading to questions about how the stability of the prefrontal boundary layer and mixing within the frontal zone affect frontal structure. Because the ceilometers, the instrumented 300-m Kivenlahti radio tower, and the other instrumented towers provide exceptional vertical profiles of the atmospheric structure very near the surface over a large region, the Testbed instrumentation is exceptionally well matched to provide observational data to validate dynamical models of fronts interacting with boundary layers.

The Helsinki Testbed has acted closely with the Soilweather project coordinated by Agrifood Research Finland to provide weather and soil moisture services for agriculture. During 2007–08, the Soilweather project established an in situ weather observation network in southern Finland (Kotamäki et al. 2009). This network practically forms an embedded observation network within the Helsinki Testbed domain at the scale of the Karjaanjoki River basin (2050 km^2). In March 2009, the Soilweather data were submitted to the Helsinki Testbed database, and the data were made accessible to the public through the Testbed web site.

The Helsinki Testbed data have also been used in developing new data quality-control and fault-detection methods and maintenance strategies for dense observation networks (Hasu et al. 2006a,b; Hasu and Koivo 2007).

Currently, the Helsinki Testbed has been selected as one official calibration and validation ground site for the National Aeronautics and Space Administration's (NASA's) Global Precipitation Measurement (GPM) satellite mission (Smith et al. 2007; http://

Table 2. Selected Helsinki Testbed projects and collaborations.

Agrifood Research Finland's Soilweather project 2007–08	Data integration to FMI on-duty forecaster's workstation and to FMI public weather services
EU PREVIEW (PREVention Information and Early Warning) 2005–08	Vaisala's product development projects
NASA's Cloudsat, and Global Precipitation Measurement Mission (GPM) with Helsinki Testbed acting as calibration and validation test site, Academy of Finland	NOAA Earth System Research Laboratory Global Systems Division cooperation with LAPS system implementation
COST Action ES0702 (European ground-based observations of essential variables for climate and operational meteorology) 2008–12	Green Net Finland, a consortium of environmental business and public organizations, innovation project as performed for business ventures
Combining and quality of surface weather station and dual polarization radar data (PIPO) 2007–08, Tekes	EnviTori (2008–10) project for establishment of environmental data marketplace, Tekes
Ubicasting—Ubiquitous weather services 2007–11, Tekes	Second phase of European Space Agency's Co-operative Earth Observation Sensors project (2008–09) seeking innovative ways how remotely sensed earth observation data and related data collected in situ can be exploited
Finnish Wind Atlas project 2008–09	Several theses for atmospheric science students at the University of Helsinki, FMI, and Helsinki University of Technology
Data integration to FMI weather and warning services for authorities	Heavy rainfall warning system, Tekes
The interaction of fronts with the near-surface boundary layer, Academy of Finland	Multidisciplinary use of polarimetric weather radar, Tekes
Energy and Environment Strategic Centre for Science, Technology and Innovation, Tekes	

gpm.gsfc.nasa.gov/). This selection has interested other satellite remote-sensing communities to use data from the Helsinki Testbed. For example, NASA's CloudSat team will organize a flight measurement campaign in autumn 2010 in the Helsinki Testbed area. The CloudSat campaign will also support GPM algorithm development.

EVALUATING THE SUCCESS OF THE HELSINKI TESTBED. Dabberdt et al. (2005b, p. 980) suggested that a successful test bed would have six outcomes. We evaluate the successes and shortcomings of the Helsinki Testbed relative to these six outcomes.

Address the detection, monitoring, and prediction of regional phenomena. The Helsinki Testbed has certainly addressed the detection and monitoring of local mesoscale weather phenomena through the field campaigns during phase 1, especially the sea breeze and stable boundary layers, both features that were unable to be detected well before the surface and lower-tropospheric profiling capabilities of the Helsinki Testbed. The prediction component to improve initial conditions in the forecast models is in development, and first results have been obtained using HIRLAM and LAPS.

How to determine the optimal station density (however that is measured) will depend on the particular forecasting or dispersion model, the research setting, or the service application. For example, the Helsinki Testbed has observed highly localized and rare events, such as the tornado that passed through the Tali golf course on 28 August 2005. Automatic weather stations seldom report hail, but the WXTs reported hail on 28 June 2005. Another benefit to the network is the profiles of surface temperature and humidity in the surface layer, which is helpful for understanding the development of the sea breeze along the Gulf of Finland.

HOW DATA FROM THE HELSINKI TESTBED WEB PAGE GET USED

Two online user surveys (2006 and 2008) were conducted on user experiences with the testbed.fmi.fi Web services. According to the survey results, the services have been used for the following activities (where needed, the responses have been translated into English from Finnish):

Jogging
Bicycling
Motorsports
Sailing
Golfing
Storm chasing
Building project
Aviation
Radio astronomy
Walking dogs
Ice skating and skiing
Bird migration observations
Fishing
Grilling
Timing of farm work
Deciding how to go to work or school (e.g., public transport, biking)
Flight planning for civil aviation
Sporting events
Fire department work
Lawn mowing
Estimating the occurrence of overnight frost
Estimating whether there is threat for falling trees during high wind speeds
Coating of roofs
Emergency center work
Predicting the spread of forest fire

Engage experts in the phenomena of interest. The Helsinki Testbed has engaged experts globally to study weather phenomena in southern Finland, as Table 2 shows. One example is the GPM and Cloudsat missions where winter and light precipitation validation studies are done using Helsinki Testbed observations. The Helsinki Testbed has also been used to facilitate research instruments of various groups (e.g., Bozier et al. 2007) and case studies (e.g., Muenkel 2007). One of the reasons for David Schultz moving to Finland was to use the data from the network of instrumented towers and high density of surface observations to study frontal structure in the near-surface boundary layer.

Cooperation through research projects describes well the wide range of experts that has been engaged to use Helsinki Testbed.

These include hydrology, road weather, nuclear safety, industry safety, flight safety, air quality, instrument design, and wind energy.

Define expected products and outcomes, and establish criteria of measuring success. Because of the large community of atmospheric scientists in Helsinki, there seems to have been an almost build-it-and-they-will-come attitude about the Helsinki Testbed. As such, the end products of the Helsinki Testbed were not entirely obvious from the start. Furthermore, criteria for measuring success were not predetermined. However, the Helsinki Testbed has served in development, testing, and validation for several types of weather sensors and, as such, one of the initial goals is met. The management and structure of the Helsinki Testbed has stabilized during the three phases of the project. This and the operational services developed in phase 3 will provide us guidance about what can be expected from the Helsinki Testbed in the future.

Provide special observing networks needed for pilot studies and research. Table 2 provides a long list of research projects that resulted from or used Helsinki Testbed data, instrumentation, or both. Additionally, Testbed data have been freely and openly accessible through the Researcher's Interface, fostering research long after phase 1 ended. Now in phase 3, pilot applications are being developed to more closely involve stakeholders and demonstrate the benefit of data from

QUOTES OBTAINED FROM THE USER SURVEY

"The Testbed is one of the most beneficial services of the FMI, because it seems to be the only service I can use to predict weather exactly at my location."

"As a bicyclist and a bike courier, I am interested in the information provided because it helps in preparing work and free-time trips."

"I inform my colleagues about precipitation before leaving from work to home, and, if necessary, I distribute umbrellas and raincoats to them."

"We have two small kids, and this service provides guidance in planning outdoor activities. Also, I live in an area sensitive to flooding, and this service gives excellent information on wind speeds, directions, and sea level pressure. Please do not stop this service."

"I use it to see if it is safe to go to our island cottage by boat. Wind speed and direction are an excellent service, as well as the rain and temperature. I can check the rain if I want to stay dry during my journey. I hope this service remains online, as it is a great helper and safety tool."

"I use the Testbed frequently, like watching a clock. I could not be without it."

"Since the beginning of the Testbed, I have not gotten wet even once while motorcycling. My humblest thanks for the service."

"The Testbed has made me and my children enthusiastic to study the weather because phenomena can be seen quite accurately on your map."

"The best I can get for my tax money."

"I always check Testbed rain and wind maps when I go paddling, and, if needed, I can check from a mobile phone on the pier before starting the trip."

"Being a teacher, I like to follow the weather. I have also used the site for student assignments (statistics, mathematics, physics). Also when deciding on school events (sports, outdoor activity days), the final decision is made by looking at the Testbed animations, if in doubt."

"Because the service also works on a mobile phone, I can use the Testbed even when driving in my Cabriolet to avoid summertime showers."

"This is an excellent service for estimating the movement of rain areas and storm chasing. One always knows what the weather is like during the next few hours. Why do you need TV weather forecasts?!"

"We install devices on radio masts owned by mobile phone operators in the greater Helsinki area. I mostly watch the wind and rain graphics in order to make a decision whether it is worthwhile to start climbing the mast to work."

"Life without Testbed would be hard!"

a dense mesoscale observation network for specific end users.

Define strategies for achieving the expected outcomes. Initially, no customized strategy other than research project plans and characteristic test bed features (Dabbert et al. 2005b) was defined to obtain the expected outcomes. The lack of a preplanned strategy is mainly because the Testbed has evolved and it has consisted of several projects with specific goals and topics. A new broader strategy for Helsinki Testbed is currently under development.

Involve stakeholders in the planning, operation, and evaluation of the Testbed. Some commercial and government stakeholders were involved early on (sharing and providing data). Public comments at two survey points involved their feedback (uniformly positive). Although the public interest and research importance of the Helsinki Testbed have been demonstrated, questions remain about the value of the data to each stakeholder, the cost effectiveness of research results, and quantifying actual improvements in forecasting, modeling, and warning services. One goal of the Helsinki Testbed is to create outstanding and economically attractive weather services for people and industries. Clearly, no parties are likely to support the network infrastructure unless they make a profit from it or see it is as a vital part of their strategy. As an indication of what we believe justifies our efforts, a recent study by the Technical Research Centre of Finland (VTT) showed at least a fivefold return on societal benefits from investments in weather services in Finland (Leviäkangas 2009; Leviäkangas and Hautala 2009). Whether the Helsinki Testbed can achieve the full fivefold benefit to society, or at least the break-even point, remains to be seen with future cost–benefit analyses.

OUTLOOK. Initially, the Helsinki Testbed was a research project envisioned to have a limited period of existence, but its popularity has now partially transformed it into a quasi-operational weather observation network. Some parts of the core network infrastructure can be said to have passed the proof-of-concept stage, whereas other functional features should be revisited or expanded. As we have seen in the past with the Helsinki Testbed, we expect the network to continue in the future, albeit with occasional reevaluation and rearrangement occurring along the way. We expect that such evaluation does occur in a testing environment. In this sense, the term *test bed* has been a good name for the network because it stresses the continually evolving process described by Dabberdt et al. (2005b, their Fig. 1).

The World Weather Research Program (WWRP) has encouraged the continuation of test bed activities, while recognizing that further clarification of issues associated with test beds is required before formal acceptance of their role in WWRP can be adopted (CMA 2005, 26–30). Issues to be addressed by the WMO include mechanisms for overall scientific management and reporting arrangements to WWRP, as well as legal and intellectual property issues.

In the future, the Helsinki Testbed will be jointly operated as a quasi-operational platform by FMI and Vaisala. The Helsinki Testbed continues to be open to researchers around the world to test measuring and modeling systems. Data for research and development continue also to be freely accessible on the project web site for the foreseeable future through the Researcher's Interface (http://testbed.fmi.fi).

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