Uncertainty Estimation and Visualization of Wind in Weather Forecasts

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Abstract: The Collaborative Symbiotic Weather Forecasting system, CSWF, let individual users do on-demand small-region, short-term, and very high-resolution forecasts. When the regions have some overlap, a symbiotic forecast can be produced based on the individual forecasts from each region. Small differences in where the center of the region is located when there is complex terrain in the region, leads to significant differences in the forecasted values of wind speed and direction. These differences reflect the uncertainty of the numerical model. This paper describes two different ways of presenting these differences using a traditional map based approach on a laptop and a display wall, and an augmented reality approach on a tablet. The approaches have their distinct advantages and disadvantages depending on the actual use and requirements of the user.

1 INTRODUCTION

Visualization of uncertainty in weather forecasts are often done using a colored range around a mean value on a curve, or a mean value with some number representing the expected variation around this value. This works well for single value parameters, like temperature or snow depth. For parameters represented by two values like wind where both speed and wind direction has uncertainties, avoiding clutter in the visualization may limit the methods used.

This paper studies using two different ways of visualizing uncertainty of wind forecasts computed by the Collaborative Symbiotic Weather Forecasts (CSWF) system on a 2D map. The CSWF system use a professional fully featured and widely used numerical atmospheric model, the WRF (Michalakes et al., 2002), set up to produce a forecast for a small area, e.g., a few kilometers across, and for a short time period, e.g., 6 hours. Previous work has documented that when using background meteorological data from national weather services, a single CSWF forecast can be computed on-demand in a few minutes on a typical multi-core 2012 model year PC (Fjukstad et al., 2013). Compared to pre-computed forecasts from weather services, the CSWF system gives a user access to all result parameters of a forecast. Consequently, a user can do highly customized visualizations.

While a user always can produce a forecast locally, the CSWF system can also collect forecasts from other CSWF systems. The forecasts are amalgamated into a symbiotic forecast with the uncertainty estimates. The CSWF system amalgamates different users' forecasts when they are for areas with only slightly different geographical centers. The small difference in center locations can result in significant differences in the model representation of the topography. This can result in significant differences in the forecasts. The differences can be seen as representing the uncertainty of a single forecast. This uncertainty is most typically largest in areas with complex terrain, like the area around the city of Tromsø, Norway, with fjords and steep mountains.

Uncertainty in meteorological data has been explored in many ways. The ensemble prediction system, EPS (Molteni et al., 1996), and probability forecasting have made several types of visualization part of the standard toolkit for weather services. One example is the spaghetti diagrams[1] where one isoline in a contoured map is shown for several EPS forecasts at the same time.

This paper reports on a few forecast visualization approaches for wind forecasts and their suitability on computers ranging from a tablet, a PC, to a large high-resolution tiled display wall. The wind forecasts are of small areas, for a short period of time, and where the user is situated within the forecasted area.

[1]http://tinyurl.com/pj6owmx

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The first approach for visualizing uncertainty is similar to a wind rose, alternatively using individual glyphs for what can be labeled as wind chaos. Wind is described by at least two dimensions, direction and speed, and both are be visualized at the same time on a map. The visualization is complicated because the individual forecasts done by the CSWF systems usually have slightly different grid placements, and therefore each wind forecast have slightly different locations.

The second option is labeled wind immersion. Wind is visualized from the viewpoint of a user standing within the forecast area. Using a tablet with a forward looking camera and sensors for geographical location, tilt, pitch and direction, the location and view window of the camera can be quite accurately determined. A user points the camera in any direction, and can see the output from the camera on the tablet display with the corresponding wind forecast overlaid.

2 RELATED WORK

Uncertainly visualization of 2D vector flow have been subject to research by many groups. Isolines or isosurfaces may be extended for showing uncertainties (Pothkow and Hege, 2011). In this paper two approaches are used. Either Tukey (Tukey, 1977) type box plots for time series or glyph based (Wittenbrink et al., 1996; Hlawatsch et al., 2011) for 2D maps. Lodha et. al (Lodha et al., 1996) presents glyphs as one of several ways of visualizing uncertainty. The method used depends on the source of the uncertainty, ie. observations with measurements errors, positioning errors or temporal uncertainties.

Wind roses[2] are often used for describing the variations of wind direction and speed at a location. The wind direction are often limited to a small sett of sectors, the number of occurrences in each sector are used for the length of the plot and colors for indication frequencies of different wind speeds. Two different datasets from the same location can also be combined into one plot, as in (Carvalho et al., 2012). An overview of some uncertainty visualization is found in (Brodlie, 2008; Brodlie et al., 2012). In (MacEachren, 1992) several ways of visualizing bivariate data is explored, including the need to visualize both the originating data and the uncertainty at the same time. This is useful when when visualizing uncertainty in wind forecasts because both direction and wind speed have their independent uncertainties that needs to be visualized at the same time.

[2] http://www.wcc.nrcs.usda.gov/climate/windrose.html

3 ARCHITECTURE

The CSWF systems is architected around two abstractions; The forecast abstraction and the forecast presentation abstraction. Due to the very different capabilities of different devices it was found to be beneficial to separate the forecasts themselves from the presentation. The architecture is illustrated in Figure 1.

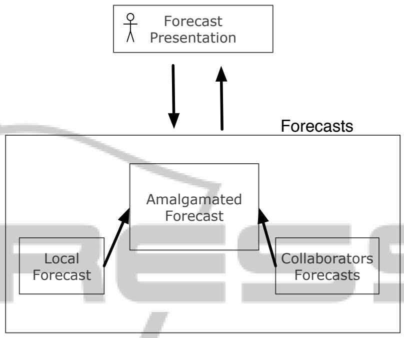

Figure 1: The CSWF system architecture.

The forecast abstraction deals with everything about production, collaboration, processing and storage of local forecasts, forecasts from collaborating users and amalgamated forecasts. This abstraction encapsulates the most computing intensive parts of the system and are meant to be located on one or more stationary computers under the users control.

The forecast presentation abstraction provides the user interface to the CSWF system. This part of the system is highly dependent on the actual device used. The prototype uses applications on many different devices from mobile telephones to large Display walls.

4 DESIGN

The design of the CSWF system is based on a client-server model. The server is assumed located on a computer under the user's full control and is assumed to be accessible from all the users devices. The design is illustrated in Figure 2.

The user's device communicates with the forecast abstraction frontend using HTTP and a REST-full (Fielding, 2000) API. This simplifies both the server and the client, as no state is maintained when communicating between devices and the server.

The functionality of the home server is partitioned into separate parts allowing for incremental development and maintenance of the parts. Simple service level agreements, SLA's between the parts have been written allowing for independent development. The

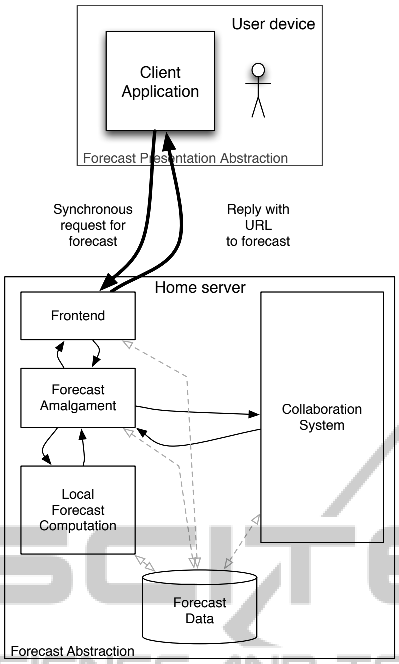

Figure 2: This CSWF system design.

design also allows for the various parts of the home server to be executed on different computers. The execution of the numerical atmospheric model is most likely to be done on a dedicated stationary desktop computer, preferably with many CPUs and/or many cores. Part of the pre-processing and preparing for visualization also requires a standard desktop computer.

5 IMPLEMENTATION

The CSWF system is a set of multi-threaded processes. Each sub-system comprises of one or several processes. All server processes are compiled for running on either Linux or OS X. The 3.4 version of the WRF atmospheric model is compiled for running on a Linux computer. When executing the CSWF system on an OS X computer, we either compute the WRF model on the same machine using a virtualized Linux environment or on a separate Linux computer.

Many of the services are so lightweight that they can even be executed on a Raspberry Pi[3] computer. This does not include the WRF model and some of the pre-visualization production.

The CSWF system prototype supports a limited number of data types. The WRF model results are stored as NetCDF files[4]. Some of the presentation applications use KML files[5]. Other applications use images, HTML pages and simple text files. Most such files are generated as part of the local forecast production.

Applications for the forecast presentation abstraction have been implemented for a small range of platforms and operating systems. This include applications for iPhones, iPads, mobile device web browsers, web browsers on laptops or stationary devices and also a simple data conversion programs to create data usable in the standard visualizing desktop application DIANA (Martinsen et al., 2005) developed by the Norwegian Meteorological Institute.

The forecast presentation application is written in Objective C for iPhones/iPads. Javascript is used to visualize forecasts in a browser. For special devices like a display wall, we used C++ and Python to visualize the forecasts. C and Python was used for the other processes and for controlling purposes. The WRF atmospheric model is mostly written in Fortran, using MPI for internal communication.

5.1 Firewall and NAT

Access to a CSWF system at home from a roaming mobile device is complicated because the home networks are often behind firewalls, and use network address translation, NAT. The CSWF system can be accessed from devices on external networks using NAT traversal techniques (Müller et al., 2010). In the prototype, no techniques for NAT traversal are used. The CSWF system is expected to be accessible by correct setup of firewalls, possibly using Simple Network Management Protocol (SNMP) and Universal Plug & Play (UPnP).

5.2 Background Data

Forecast presentation applications can request forecasts for any small geographical area for a 6-hour period. The prototype is limited to an area including Scandinavia because of limitations in disk space for the background topographical and other data. Global coverage of these static background data sets is freely available, and takes around 10 GB of storage at the current spatial resolution. With this background data the user will have the potential of creating forecast for anywhere on the globe. Background meteorological data is available from many sources. The prototype uses the global dataset from NOAA's NOMAD[6] service.

[3]http://www.raspberrypi.org/
[4]http://www.unidata.ucar.edu/software/netcdf/
[5]https://developers.google.com/kml/documentation/
[6]http://nomads.ncep.noaa.gov/

6 USER APPLICATIONS

Several prototype forecast presentation applications for Linux, OS X and iOS have been created. Some of these are described briefly in the following sections. Each user will be able to use the applications on various platforms to specify and adjust the visualization of the meteorological parameters for various specific purposes.

The following sections presents some of the applications with focus on visualizing uncertainty in weather forecasts from the CSWF system. All applications exist as prototypes and most are in daily use.

6.1 iPhone and iPad

To visualize forecasts in 2D and on typical mobile platforms, a browser on the forecast presentation device is used. The browser runs a small Javascript visualization script that uses the Google Maps API. The script pulls in image tiles from CSWF and renders them on the presentation device. See Figure 3.

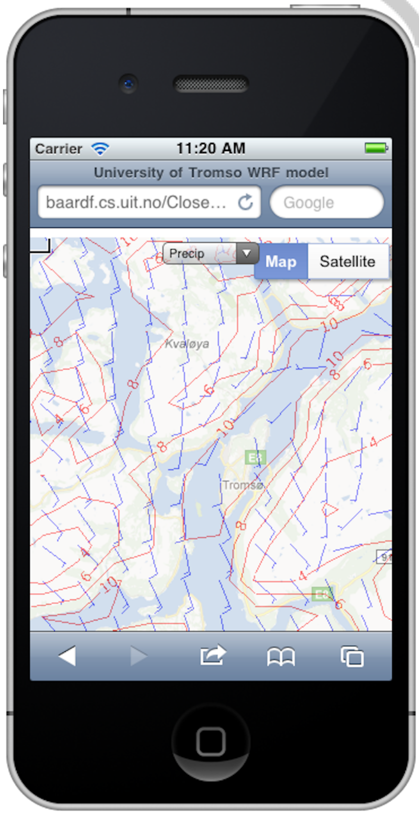

Figure 3: An example showing wind and temperature on a smart phone.

An application for a tablet that shows the current view of the back facing camera overlaid with meteorological information have also been created. Using data from the GPS, the compass and the accelerometers on the device, we know where the device is located, which way the camera is facing and the tilt of the device.

The user can request a forecast centered on the GPS location of a tablet, and then explore the weather forecast by pointing the tablet's camera into the surrounding landscape to study on the tablets display the weather forecast superimposed with the camera image.

To view data from another location, the user must physically move around. A screen shot of the application with two different types of visualization is shown in Figures 4 and 5. This application uses a device with a screen size usable for detailed visualization. The device has communication capabilities sufficient to receive the data in KML format, and has the processing power to do the visualization on the device.

Figure 4: Screenshot of tablet with camera and an example of overlaid meteorological information

6.2 Home Computer

Data from the CSWF system can be visualized in a browser or in standard visualization applications, like the DIANA system. Visualizing the uncertainty in the forecasts from the CSWF system can be done using two slightly different techniques. On is utilizing all forecast for a specific time in a classical wind rose where the length of each arrow represents the wind speed, and the direction represent the wind direction. See Figure 6. Here all the forecasts are relocated to the nearest grid point in the local forecast produced

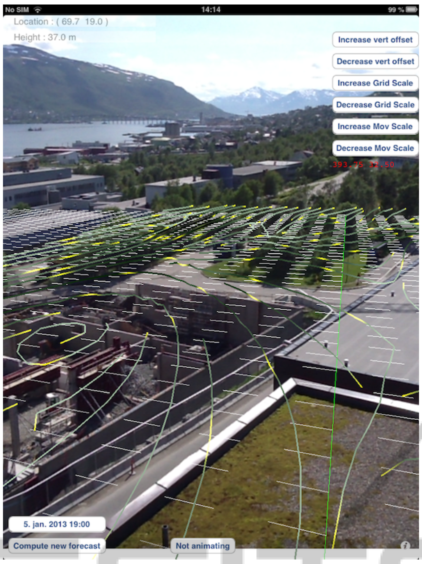

Figure 5: Screenshot of tablet with streamlines with colored points that can be animated to illustrate wind speed.

bye the user. All 28 available forecasts are used in the figure.

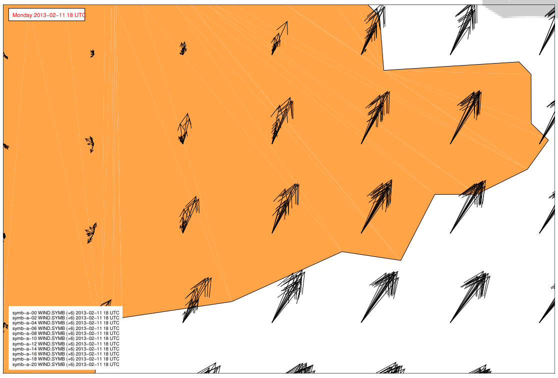

Figure 6: Many forecasts visualized as a classical wind rose using individual glyphs for each forecasts originating in the same location using the local forecast grid. A legend outside the shown area on the figure shows the length-to-speed.

One other way of illustrating the uncertainty of the small number of forecasts is illustrated in Figure 7. Here a small number of forecast are visualized using the original grid from each forecast. The length represents the wind speed and the direction the wind direction. As can be seen this can very easily get very crowded and only 10 different forecasts are used in this figure.

6.3 Display Wall

The TromsøDisplay Wall (Anshus et al., 2013) consists of 28 PCs driving 28 projectors for a total screen

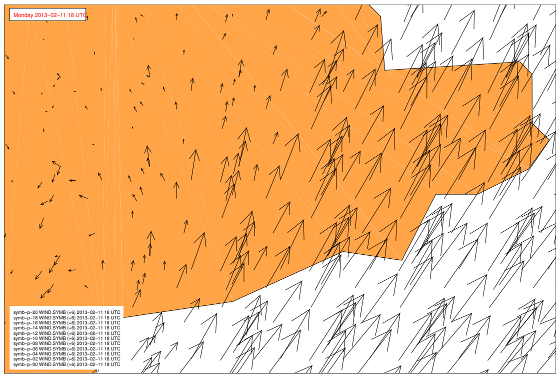

Figure 7: Many forecasts visualized on the same time. Individual glyphs for each forecast originating in each forecasts grid. A legend outside the shown area on the figure shows the length-to-speed.

size of 22Mpixels. Applications can be executed on a PC utilizing a very large virtual VNC frame buffer (Stødle et al., 2007) used by the 28 viewers in the driving PCs.

Using the DIANA system allows for utilizing the whole display for visualizing all forecasts as illustrated in Figure 8. One example where the very large pixel count is used for visualizing many individual forecasts at the same time is illustrated in Figure 9.

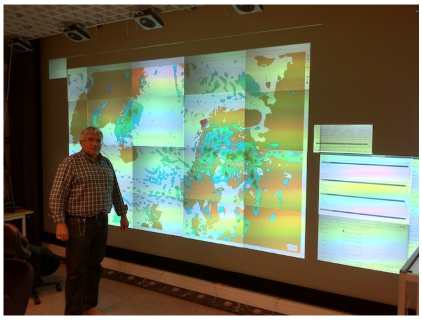

Figure 8: The DIANA application used on the display wall

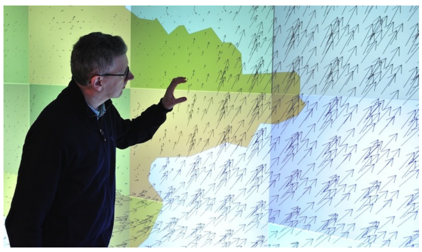

Figure 9: Example of many forecasts at the same time on a large display wall.

7 RESULTS

The prototype of the CSWF system demonstrates that individually produced numerical weather forecasts can be combined for a better estimation of some of the uncertainties in the forecasts. The combined forecasts and the uncertainty estimation can be illustrated with Figure 10. The figure shows the observed wind speeds at two measuring stations approximately 3 km from each other. The observed wind speed is a solid curve. The figures also show the locally produced forecast with the dashed curve. The collaborative exchanged forecasts with 27 other CSWF systems randomly spread around the location of the local forecasts are collected, and the mean and standard deviation of the wind speed is calculated for each point in the local forecast grid. This symbiotic forecast is illustrated in the Figure using a box plot/candlestick form showing the box for ± one standard deviation, and the whiskers for ± two standard deviations. The Figure contains 6 hour forecasts and observations valid at 18 UTC each day.

The top part of Figure 10 shows the results from station on top of the Island in an area with high trees. The forecast model predicts often to strong wind. This is the expected performance of the WRF model in an area with increased ground-induced turbulence from the trees.

The bottom part of Figure 10 shows the results from the Tromsø airport. The wind gauge is situated in an open field by the runway. The forecast model has better skill at this station. This is also the expected performance of the model. The observed wind speed in the lower part of the figure is clearly outside the range from the CSWF system in only three of 19 days, and the mean of the CSWF forecasts better than the single local forecast on all but one, days.

8 DISCUSSION

We compared actual observed values for wind speed and direction with a single as well as a symbiotic forecast. A single forecast typically does not quite match reality. However, it is relatively close. This is a validation that it is meaningful to do even a single forecast, and that the approach used by CSWF to do so is sound meteorologically. The WRF model used by CSWF have earlier also been independently validated (Carvalho et al., 2012). A symbiotic forecast more often matches the actual wind than a single forecast. Only rarely is the actual observed wind significantly outside the uncertainty range of the symbiotic forecasts. A way of illustrating a single and a symbiotic forecast against observed wind speed and directions, is given in Figure 10. The figure visualizes the uncertainty and distribution of the uncertainty using a candlestick/box plot type visualization.

In Figure 10 a set of forecasts of wind speed, is compared against the observed wind speed at a **specific** point in time, which is a very strict comparison. The single local forecasts have some skill in forecasting the wind speed, and the combined forecasts from the CSWF system have even better skill.

When validating high-resolution numerical models, it is a problem that the spatial resolution may be better than the resolution of some of the meta-data associated with the observation. In our case, the actual geographical location of the measuring point for wind speed at the airport was not the location given by the meta-data. For historical reasons the location of the meteorological stations at airports have been listed as the location of the barometer. However, in our case this was approximate one kilometer from the location of the wind sensor.

Visualizing a set of forecasts from the CSWF system using the DIANA application on a desktop computer and on the large display wall illustrates the effect of the display size on the usability of the visualization. The wind rose-like approach illustrated in Figure 6 was judged as usable on both devices. The compact form easily visualizes the complete set of 28 forecasts and the effectively illustrates uncertainty in both wind speed and direction. The main difference between the desktop computer and the display wall is that on the display wall a larger area can be viewed at the same time. A more compact glyph integrating both variation and spread could also have been used. Since this approach will display all forecasts, outliers that would be masked using aggregate glyphs, are easily recognized. This is particularly noticeable in locations with large variation in wind direction. Using individual glyphs for each forecasts also allows the user to identify possible specific dangerous combinations of wind speed and direction, that may be masked using an aggregated glyph. The wind rose method will of cause increase the burden on the user to interpret the plots correctly compared to aggregated glyphs.

However, using the wind chaos approach illustrated in Figure 7 is very different on the two devices. On the desktop, only a few of the 28 available forecasts could be usefully visualized at the same time. With 28 forecasts simultaneously visualized, the desktop display simply filled up with arrows, and no pattern could be discerned. The much larger number of pixels available on the display wall allows for much more information and allowed for all 28 forecasts to be shown while it was still possible to iden-

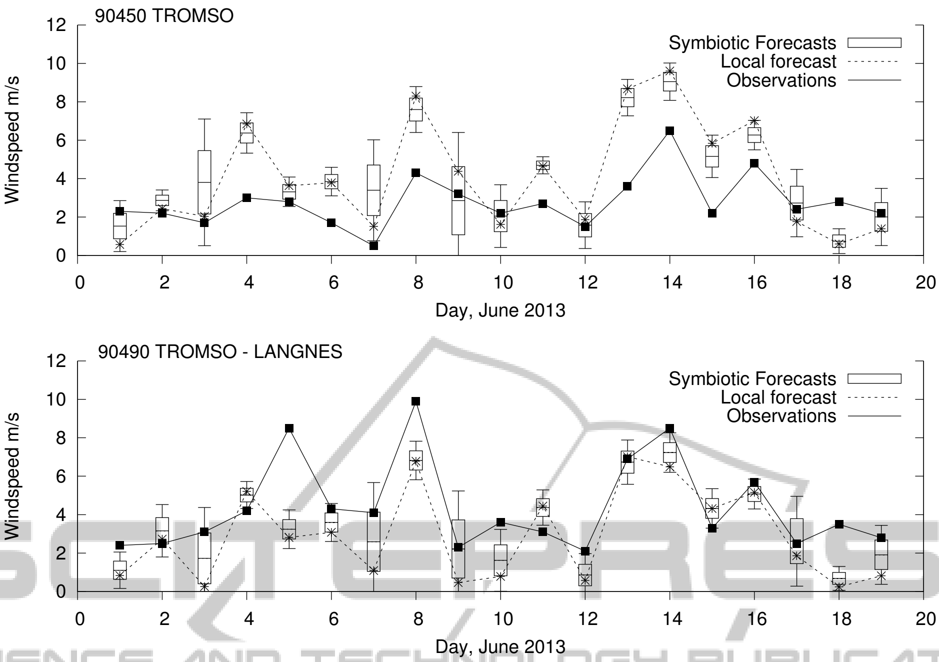

Figure 10: Local forecasts using dashed lines and stars, CSWF system forecasts using box plot with whiskers and observed wind speeds using solid lines and filled rectangles. The two measuring stations are approximate 3 km apart, illustrating the large spatial variations in model forecasts and especially in the observations.

tify areas with large variation and therefore large uncertainty. This is also illustrated in Figure 9. This also preserves the actual grid location of each forecast, allowing for a better understanding of the spatial distribution of the wind speed and direction.

The augmented reality see through effect using a tablet as illustrated in Figures 4 and 5, is more restricting in terms of how the uncertainty is visualized. For each wind arrow shown in Figure 4 the Probability Density Function, PDF, of the uncertainty is known and can be represented by, say, the standard deviation in that point. This value can then be used for coloring the wind arrow where the size and direction represents the values from the local forecasts. A color gradient from green to red, representing small to large uncertainties is therefore possible. In the same way the streamlines illustrated in Figure 5 illustrate the uncertainty at points in the grid by varying the width. The direction and speed is illustrated by using colored sections that are animated moving along the streamlines in a speed proportional to the wind speed at that point. A possible extension would be to implement graduated glyphs like the Noodles system (Sanyal et al., 2010) along the streamlines. Using individual isolines for a parameter, a contour boxplot (Whitaker et al., 2013) could also be used for this type of augmented reality visualization.

9 CONCLUSIONS

The two different approches for visualizing the uncertainty of weather forecasts generated by the Collaborative Symbiotic Weather Forecast system clearly have their uses in different settings and for different purposes.

The augmented reality visualization demands that the user is located within the forecasted area and have good visual overview around.

The map-based visualization can be used regardless of actual location and is also suitable for use on very large displays.

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