5.11 The Impact of Low-Cost Lagrangian Drifters on Tropical Cyclone Analyses and Forecasts

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1. Introduction

Technological advancements in micro and nanotechnology have inspired a concept for a new observing system called Global Environmental Micro Sensors (GEMS). The system features a wireless network of in situ, buoyant airborne probes that will be designed to remain suspended in the atmosphere for days and take measurements of temperature, humidity, pressure, and wind velocity that are commonly used as dependent variables in numerical weather prediction (NWP) models. As a result, it will not be necessary to develop complex algorithms for assimilating such data into research or operational models.

Although Lagrangian drifters have been used in meteorology for nearly 50 years, the novel aspect of the GEMS system is the integration of micro and eventually nanotechnology to develop probes with significantly lower mass, size, and cost. Given these attributes, large ensembles of probes could be deployed for research and operational missions thereby greatly expanding the amount of in situ observations, especially over data sparse oceanic regions. The GEMS system would be ideal for adaptive or targeted observing campaigns such as tropical cyclone reconnaissance where it is only cost effective and practical to obtain in situ, high-resolution, spatial and temporal measurements over limited domains.

This paper provides a description of the proposed GEMS system and highlights a series of high resolution, mesoscale observing system simulation experiments (OSSEs) for Hurricane Floyd (1999). The concept design is described in section 2 and section 3 highlights the simulation systems. Finally, Section 4 describes the preliminary set of OSSEs for Hurricane Floyd using simulated GEMS data.

2. Concept Design

Each GEMS probe will be self-contained with a power source to provide sensing, data processing, location, and communication functions. Candidate power sources include batteries, micro fuel cells, supercapacitors and thin film solar cells. Batteries are probably the most developed of these technologies for small, portable electronics; however, several research and corporate research initiatives have been undertaken to develop fuel cells as a viable power source, since they have the potential to significantly increase the operating offering long life in electronic products. Recent advances in electrochemical double layer capacitors have demonstrated dramatically increased energy storage capacity, making them a potential power component for a GEMS probe if used in conjunction with a thin film solar cell to recharge the capacitor for night time operation. Active power management will be necessary in order to regulate power consumption, especially at night.

The probe is envisioned to be a constant altitude balloon filled with helium to provide buoyancy. The probe shell would consist of a polymer composite laminate and would contain a thin-film photovoltaic array, printed circuits for the communication and processing electronics, and a patch antenna for communications. Micro sensors similar to those used in rawinsondes will measure temperature, humidity, and pressure. The probes will report their positions and velocities from an onboard micro global positioning system and use one-way radio frequency communication with low-earth orbiting satellites to relay data to ground stations.

The shell radius must be large enough so that the volume of helium makes the probe neutrally buoyant (i.e. with zero terminal velocity) at pre-determined altitudes. The level of neutral buoyancy can be controlled by adjusting the shell volume with lighter payloads requiring smaller shell radii to achieve neutral buoyancy at the same altitude.

3. Simulation System

The case selected for this study was the initial genesis and rapid strengthening of Floyd over the central Atlantic Ocean from 6-12 September 1999. Floyd developed from a tropical depression in the central Atlantic on 10 September 1999 and nearly became a category 5 hurricane prior to landfall in the central Bahamas. The storm later re-curved and weakened to a strong category 2 hurricane making landfall in North Carolina on 16 September 1999.

The Advanced Regional Prediction System (ARPS; Xue et al. 2000; Xue et al. 2001) coupled with a Lagrangian particle model (LPM) was used to simulate the dispersion of observations collected by an ensemble of probes. The probes were assumed to be passive

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tracers moving independent of one another and transported by the wind. The LPM tracked the location of each probe based on three-dimensional wind components and updated probe position using the resolvable-scale components of wind velocity directly from the ARPS model, as well as turbulent velocity fluctuations. A parameterization scheme for wet deposition or precipitation scavenging was included in the LPM to simulate the impact of frozen and liquid precipitation on probe trajectory and possible washout (Seinfield and Pandis 1998).

A large number of simulated probes can be deployed at any time during the model integration, and at any latitude, longitude, and altitude within the three-dimensional ARPS domain. For this study, a new strategy was developed to simulate probe deployment within Floyd from the typical "ALPHA" flight pattern (including eye wall penetration) of reconnaissance aircraft (see http://www.ofcm.gov/nhop/06/pdf/f-chap5.pdf). The probes were released at 12-h intervals from 36 through 108 h of the simulated initial genesis and strengthening of the storm. During each simulated reconnaissance mission, 12 probes were deployed approximately every minute for a total of 1,140 probes per flight. The level of neutral buoyancy for each probe was based on mass and varied between 500 to 9000 m. Although probes rapidly reached their simulated level of neutral buoyancy once deployed, substantial altitude changes did occur due to strong vertical motions especially within the tropical cyclone environment.

4. Data Impact Study

4.1 Methodology

An initial OSSE was run to assess the impact of probe measurements on Floyd genesis and strengthening. The OSSE methodology following Atlas (1997) and Lord (1997) consists of a nature and data assimilation experiments. The nature run is considered "truth", and trajectories of all simulated GEMS probes were tracked from this model simulation. The ARPS was used for the nature run to simulate measurements of temperature, humidity, pressure, and horizontal wind components at GEMS probe locations.

The model used for the data assimilation run was the Pennsylvania State University/National Center for Atmospheric Research Fifth-generation Mesoscale Model (MM5; Grell et al. 1995). Simulated GEMS observations were continuously assimilated into the MM5 at specified times. No other in situ or remote sensing data were used for the data assimilation runs. The MM5 was configured in such a manner as to generate a significantly different solution from a nature simulation. This configuration was selected to approximate the differences between a state-of-the-art model and the real atmosphere (Atlas 1997).

An ARPS 15-km nature run (domain A, Figure 1) was initialized using Aviation Model (AVN) analysis fields from 1200 UTC 6 September 1999 and run for 5 days to simulate deployment and dispersion of GEMS probes. Additional AVN analysis fields were obtained at 12-h intervals to provide lateral boundary conditions throughout the entire model run. A one-way nested 3-km domain covering a portion of the central Atlantic ocean (domain B, Figure 1) was initialized at 1800 UTC 9 and run until 0000 UTC 11 September 1999. A depiction of the actual track of Floyd in relation to the ARPS grid configurations is shown by the black line in (Figure 1).

The MM5 assimilation run was initialized using the AVN analysis fields from 1800 UTC 10 September 1999 and integrated for 6 h. The MM5 simulation was configured with a 12-km domain covering nearly the same area as the ARPS 15-km (domain A, Figure 1). Simulated GEMS data from ARPS were assimilated into MM5 using Newtonian nudging or four-dimensional data assimilation, in which the model variables are driven towards the observations by a forcing term added to the model equations (Stauffer and Seaman 1990). The simulated observations were assimilated into the MM5 at 30-minute intervals throughout the entire 6 h simulation as depicted in the timeline shown in Figure 2.

It is important to note that a tropical cyclone bogussing scheme is available in MM5 but not used during this study. The goal of the OSSE described here is to determine whether the 12-km MM5 could spin up a mature hurricane during a short (< 6 h) data assimilation period using only coarse resolution operational analyses and simulated GEMS data from the 3-km nature run. Note all experiments represent an upper bound on the potential forecast impact, as observations are assumed perfect with no associated error.

A total of three MM5 sensitivity runs were conducted along with the initial ARPS nature simulation. The first MM5 experiment included data from all probes released within the ARPS nature run. However, sensitivity experiments 2 and 3 reduced the total number of probes to 10% and 1%, respectively. The approximate number of simulated observations ingested at 30-minute intervals for each experiment is summarized in Table 1. Data thinning was performed by excluding probes randomly without replacement throughout the assimilation domain to reduce the effective resolution of the assimilated data.

4.2 Results

The results discussed in this section show that simulated GEMS data can be used to map out the four dimensional storm structure and near real-time intensity changes over very small time scales. It is important to reiterate that the ARPS nature (3 km) and MM5 (12 km) assimilation experiments were conducted using different grid spacing so the ARPS simulation is generating finer scales of motion within the storm that cannot be resolved in MM5. Therefore, the assimilation experiments will not generate the exact storm structure even when assimilating high-resolution data.

Maximum wind speeds from 0600 UTC 9 to 1200 UTC 10 September 1999 within the ARPS 3-km nature run as well as those extracted from GEMS probes are shown in Figure 3. The wind speeds from ARPS were obtained by identifying the maximum winds on any pressure level, while the values representing the GEMS probes were the maximum value reported by any probe at a given time. The simulated wind speeds shown in Figure 3 also represent maximum sustained winds not wind gusts. Note that the simulated probes indicate a very similar trend to the ARPS gridded values in both the magnitude of the maximum wind speeds and increase with time as the simulated storm strengthens from 78 to 108 h.

Simulated GEMS data assimilated into the MM5 during a 6-h period from 1800 UTC 10 to 0000 UTC 11 September 1999 suggest that such observations can also be used to initialize and spin-up a strong tropical cyclone using a mesoscale model without bogussing a vortex. Figure 4 shows the simulated mean sea-level pressure from the ARPS and all MM5 (full, 10%, and 1%) experiments over the 6-h data assimilation period. During all MM5 simulations, the storm deepens from ~1005 hPa at 1800 UTC to less than 980 hPa by 0000 UTC 11 September. However the experiment assimilating only 1% of GEMS data deepens at a much slower rate than both the 10% and full data experiments. Note that for the full and 10% MM5 simulations, the storm deepens at nearly the same rate (Figure 4).

A similar trend in generating the storm strength is shown by the maximum wind speeds simulated within the storm (Figure 5). In all the data assimilation experiments, the maximum wind speeds increase from less than 20 m s^{-1} to greater than 45 m s^{-1} during the 6-h assimilation window. For both the full and 10% MM5 simulations, the maximum wind speeds increase to greater than 50 m s^{-1} within 1 hour; however for the 1% experiment the maximum wind speeds do not exceed this value until after 22 UTC 10 September 1999.

The 900 hPa wind fields simulated at 0000 UTC 11 September 1999 for the nature and all data assimilation experiments are shown in Figure 6. Additionally, the inner core of maximum wind speeds surrounding the eye of Floyd within each simulation is illustrated as an inset for each panel of Figure 6. The most significant result is that the MM5 full data experiment, and to a certain extent the 10% simulation, generated a very similar wind field to that of the ARPS nature run (Figure 6). In fact the MM5 full data experiment depicts a very similar eye-wall wind structure and magnitude compared to that from the nature simulation (inset in upper right hand panels of Figure 6a and Figure 6b). The two-dimensional structure of storm degrades somewhat when only 10% of the simulated GEMS data was included in the MM5 simulation (Figure 6c). Further degradations were evident in the overall wind field and inner storm core when only 1% of the simulated GEMS data were assimilated in MM5 (Figure 6d).

Vertical cross-sections of wind speed and potential temperature further illustrate the impact of simulated GEMS data on the development and strength of the storm (Figure 7). The cross sections from each experiment were taken at 0000 UTC 11 September 1999 from south to north across the core of the storm (line AB in Figure 6). The cross sections indicate that the full data MM5 experiment had a similar structure in the vertical wind speeds and potential temperature profiles compared to that simulated within ARPS (compare Figure 7a to Figure 7b). This result is most evident in the structure of the inner core including the diameter of eye, the eye-wall tilt with height, and the relative minimum in potential temperature denoting the warm core near the center of the storm. In fact, the MM5 full data experiment accurately depicted the overall asymmetry and slightly stronger winds located in the northern eye-wall consistent with westward storm motion.

As shown in the 900 hPa wind fields (Figure 6), the MM5 simulation including only 10% of the GEMS data appeared only slightly weaker in terms of wind speed and the vertical potential temperature gradients, but still looked very similar to the overall structure (including asymmetry) observed within ARPS (compare Figure 7a to Figure 7c). However, when only 1% of the GEMS data was included in the MM5 simulation, the vertical structure was relatively weak and disorganized compared to ARPS (compare Figure 7a and Figure 7d). This result clearly indicates that 1% of the simulated GEMS probes (~47 per time) were not sufficient to generate the strength and structure of the cyclone as depicted by the ARPS nature run and even by the MM5 full and 10% data experiments.

5. Summary and Conclusions

This paper described the aspects of the GEMS system including probe components and operation as well as a series of high resolution, mesoscale observing system simulation experiments for Hurricane Floyd (1999).

The data assimilation results using OSSEs show that simulated GEMS data can be used to map the four dimensional storm structure and near real-time intensity changes over very small time scales. Additionally, the results demonstrate that high-resolution in situ data can be used to initialize and spin up a strong tropical cyclone from a weak low-pressure system over a short data assimilation window, without using a tropical cyclone bogussing scheme. In fact, only 10% of the simulated high-resolution GEMS probes (~478 per assimilation time) were needed to generate a mature hurricane within MM5 at 12-km grid spacing without using a bogus vortex.

Studies such as the one highlighted in this paper could help to identify the appropriate mix of data from current and future observing systems that will maximize the impact on tropical cyclone analysis and forecasting. If a GEMS system can be implemented practically with such capability in a cost-effective manner, it could provide more than just incremental improvements in the ability to observe and predict tropical cyclones for research and operational meteorology.

Based on the very encouraging results obtained from this preliminary data impact study, further work dealing with high resolution mesoscale OSSEs for tropical cyclones is proposed as follows:

- Add realistic errors to the simulated GEMS observations for all variables.
- Simulate current in situ observing platforms including dropsondes and manned/unmanned aircraft as well as current/next generation remote sensors such as the stepped frequency microwave radiometer (Jiang 2006).
- Expand data-impact studies to include other cases and longer time periods.
- Use more advanced modeling and data assimilation systems (e.g. use the hurricane Weather Forecasting and Research model with three or even four-dimensional variational schemes).

6. References

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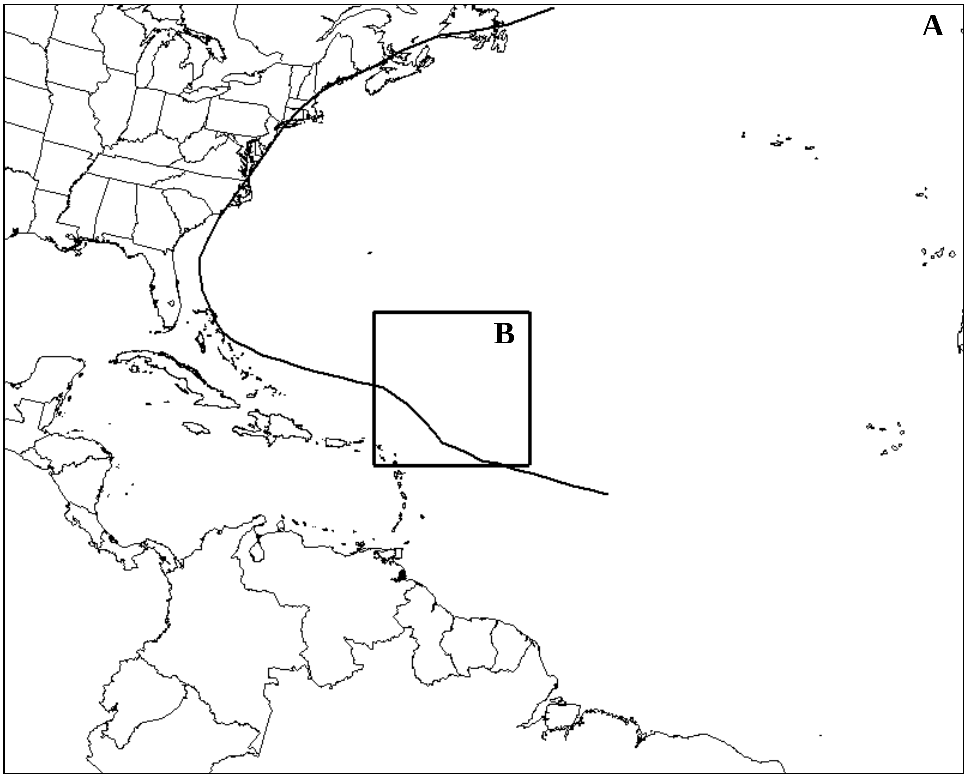

Figure 1. Grid configuration for the ARPS nature and MM5 simulations. Grid A represents the outer ARPS 15-km and MM5 12-km domains, while grid B denotes the ARPS 3-km domain. The actual track of Floyd is shown by the black line.

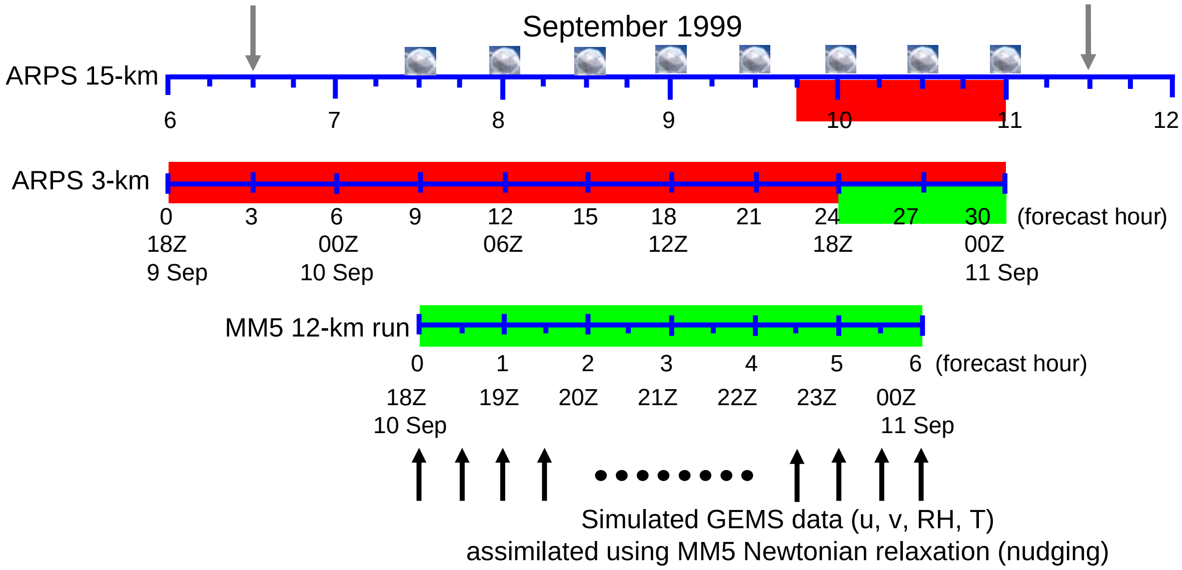

Figure 2. Schematic of the ARPS nature and MM5 timeline and data assimilation methodology. The start and stop times for each of the following simulations are denoted by: ARPS-15 the grey arrows, ARPS 3-km the red shading, and MM5 12-km the green shading. The simulated GEMS deployment times are illustrated by the spherical probes above the ARPS 15-km timeline.

Table 1. Average number of simulated observations assimilated into each MM5 sensitivity experiment per time.

Experiment	**Average number of observations per ingest time**
Full	4785
10%	478
1%	47

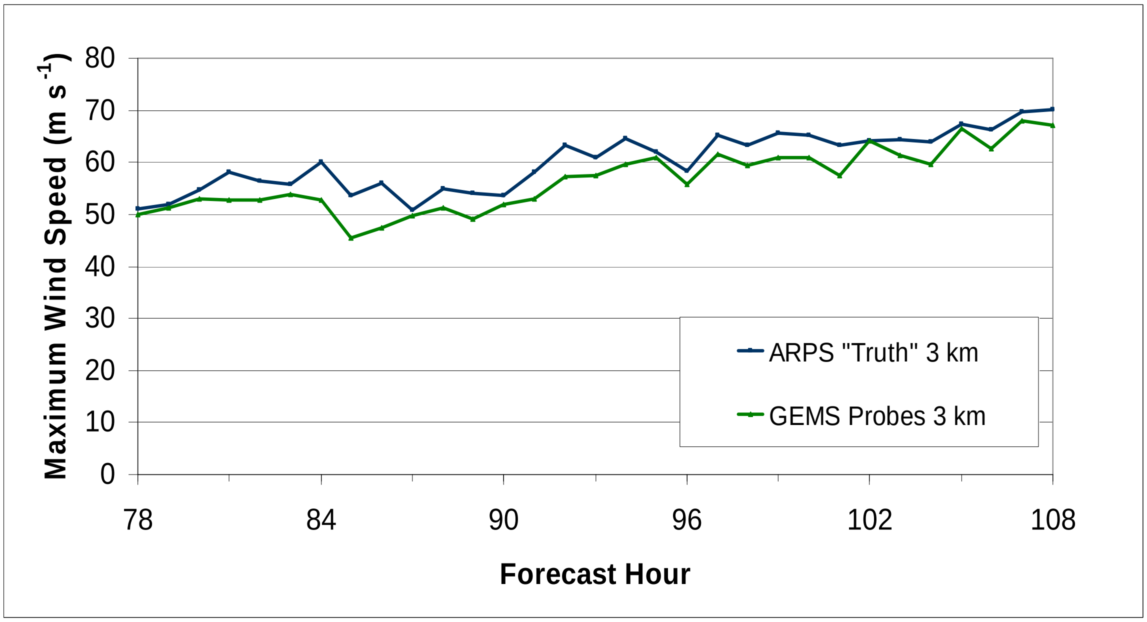

Figure 3. Maximum wind speeds (m s^{-1}) from the ARPS 3-km nature simulation and simulated GEMS probes within Floyd from 0600 UTC 9 to 1200 UTC 10 September 1999.

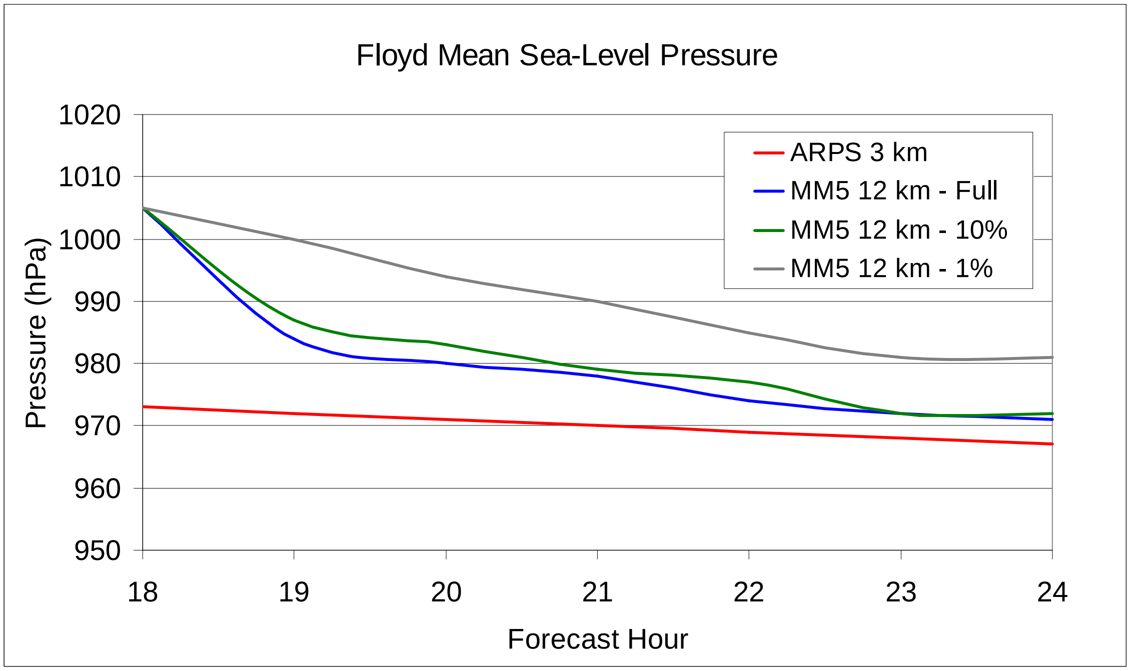

Figure 4. Floyd central sea-level pressure (hPa) for the ARPS nature simulation (red), MM5 full (blue), 10% (green), and 1% (grey) data experiments from 1800 UTC 10 to 0000 UTC 11 September 1999.

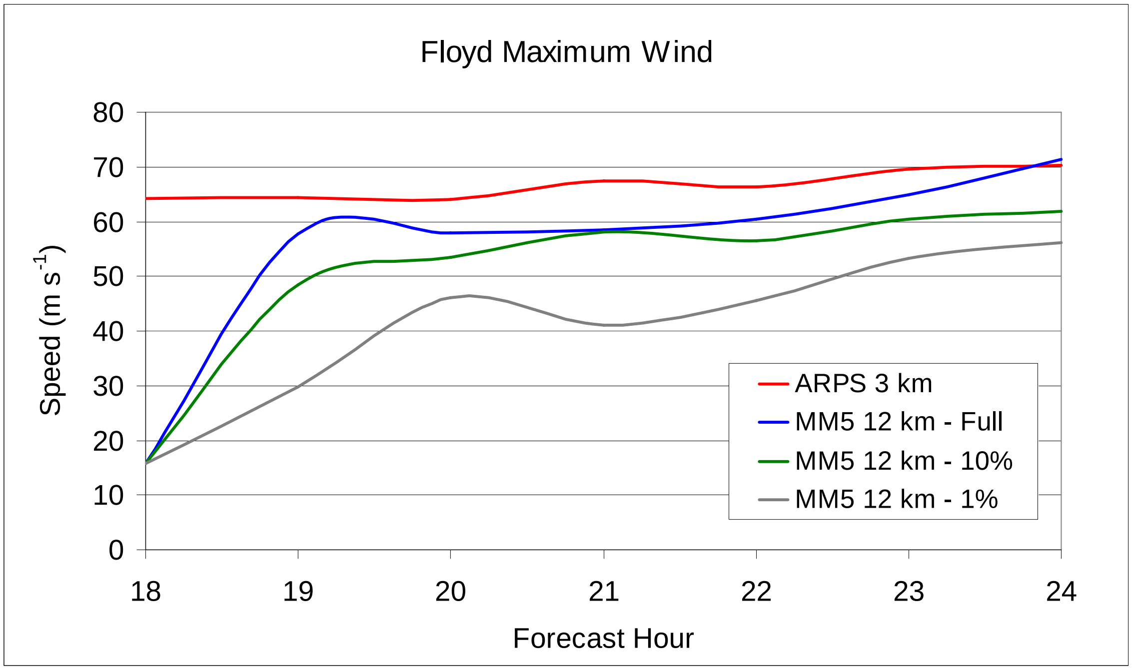

Figure 5. Floyd maximum wind speeds (m s^{-1}) for the ARPS nature simulation (red), MM5 full (blue), 10% (green), and 1% (grey) data experiments from 1800 UTC 10 to 0000 UTC 11 September 1999.

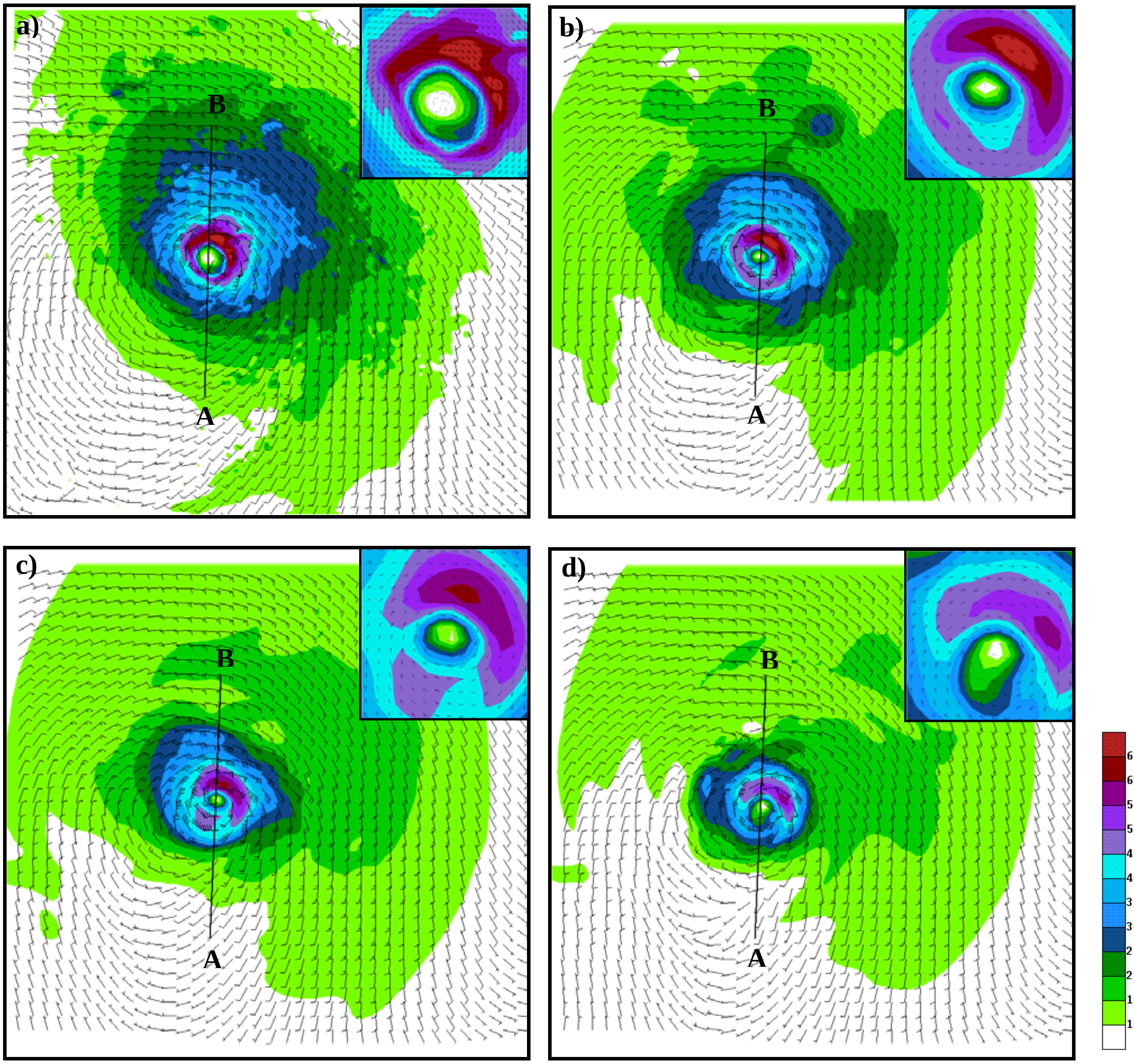

Figure 6. 900 hPa wind speeds (m s^{-1}) for the (a) ARPS 3-km nature simulation, (b) MM5 full data, (c) 10%, and (d) 1% data experiments at 0000 UTC 11 September 1999. The inner core of maximum wind speeds surrounding the eye of Floyd within each simulation is illustrated in the inset for each panel. The speeds are denoted by the wind barbs in each panel (5 m s^{-1} increment) and the colors according to the key provided to the right of panel d.

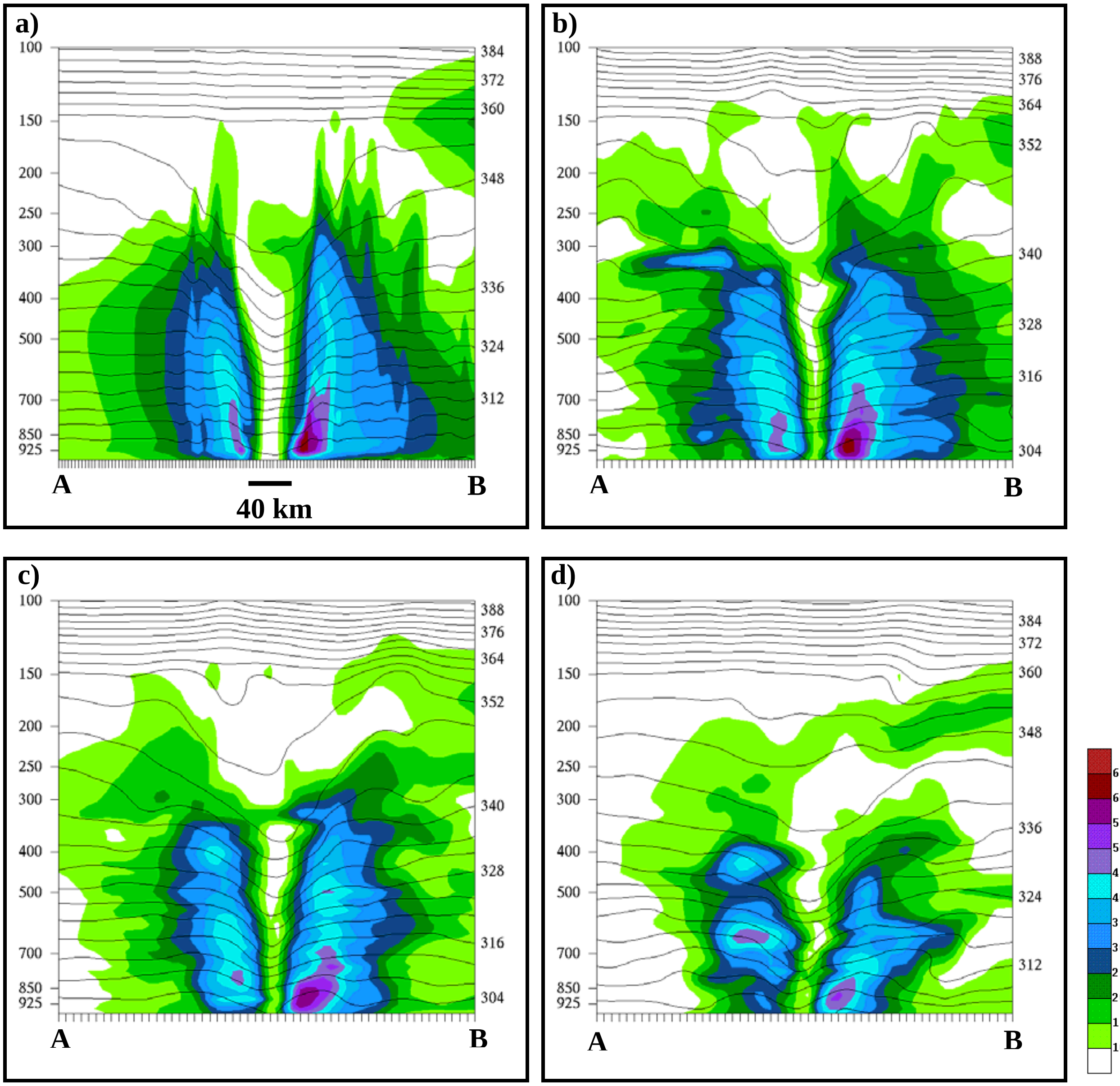

Figure 7. Vertical cross sections of wind speed (m s^{-1}) and potential temperature (K) for the (a) ARPS 3-km nature simulation, (b) MM5 full data, (c) 10%, and (d) 1% data experiments taken from point A to B (dark line in Figure 6) at 0000 UTC 11 September 1999. The speeds are denoted by the colors according to the key provided to the right of panel d.