On the Utility of Airborne MEMS for Improving Meteorological Analysis & Forecasting

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Objectives

- **Improve weather analyses / forecasts using airborne Global Environmental MEMS Sensors (GEMS)**
- **Guide present / future design of GEMS for meteorological applications**
- **Assess cost effectiveness / life cycle support requirements for prototype GEMS**

Motivation

- **Economic incentives to improve weather forecasts & mitigate the impact of weather on life/property**
  - ~ $1 trillion of the U.S. economy has weather sensitivity (e.g. aviation, construction, agriculture)
  - Severe weather in the U.S. causes billions of dollars in damages annually
- **In-situ observations not distributed evenly or densely enough around the globe – GEMS can:**
  - Enable more complete coverage over oceans, high latitudes, & other data sparse regions
  - Provide means to assess more accurately the magnitude of regional/global climate change
  - Monitor weather over politically sensitive regions including battlefield conditions
- **Remote sensors (e.g. satellites, Doppler radars) do not provide complete measurement suite**
- **Satellite observations have limitations with vertical resolution, accuracy, and cloud obscuration**

Simulation Models

Advanced Regional Prediction System (ARPS)

- **Public domain software (Center for Analysis and Prediction of Storms)**
- **Three-dimensional, non-hydrostatic limited-area dynamical model**
- **Compressible Navier-Stokes equations for atmospheric flows**
- **Storm-scale (0.1 km) to regional-scale (1000 km) weather phenomena**
- **Comprehensive physical parameterizations**
  - Radiation, turbulence, clouds, precipitation
  - Surface heat, moisture, momentum fluxes & land-surface energy budget
- **ARPS Data Analysis System to generate initial condition**
  - Data ingest & quality control
  - Objective analysis

Lagrangian Particle Model (LPM)

- **Embedded in ARPS**
- **Track sensor position (x, y, z) each model time step (Δt)**

$$x(t + \Delta t) = x(t) + [\, u(t) + u'(t)\,]\,\Delta t$$

$$y(t + \Delta t) = y(t) + [\, v(t) + v'(t)\,]\,\Delta t$$

$$z(t + \Delta t) = z(t) + [\, w(t) + w'(t) + w_d\,]\,\Delta t$$

u, v, w ➔ resolvable-scale velocity components obtained directly from ARPS
u', v', w' ➔ turbulent velocity fluctuations based on 1st-order Markov scheme
w_d ➔ vertical slip velocity for gravitational settling

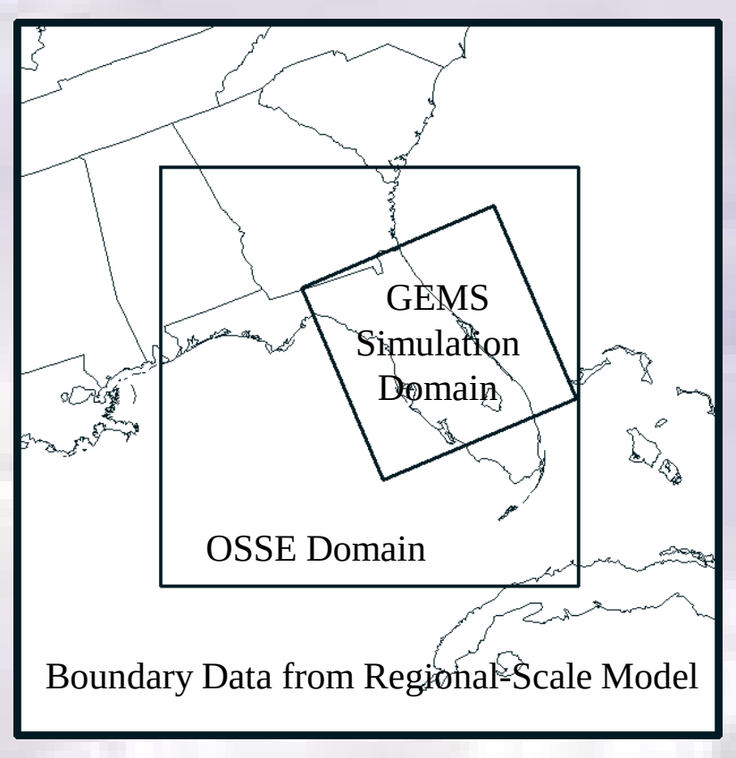
$$w_d\,(r_a, r_d, g, d, \mu) = 0.08 \text{ m s}^{-1}$$

r_a ➔ air density (1.14 kg m^{-3})
r_d ➔ sensor density (2500 kg m^{-3})
g ➔ acceleration due to gravity (9.81 m s^{-2})
d ➔ sensor diameter (0.00004 m)
μ ➔ dynamic viscosity of air (0.000018 kg m^{-1} s^{-1})

- **Sensors treated as passive tracers moving independent of one another**
- **Sensor lifetime assumed infinite until impact w/ ground or carried beyond model domain**
- **Air density variations on w_d ignored**
- **Sensor interactions with hydrometeors ignored**

Virtual Weather Scenarios

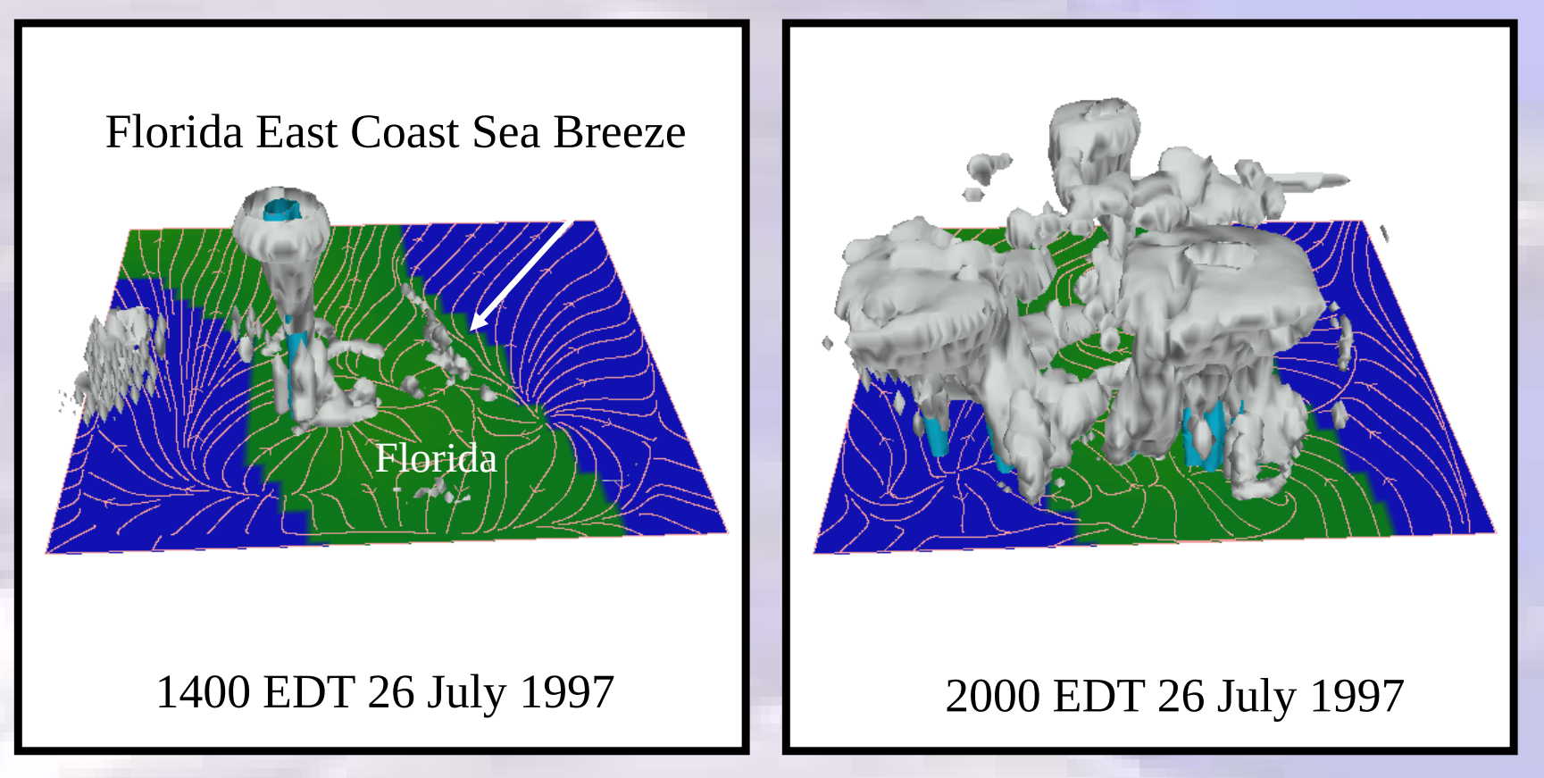
- **Historical weather data (Severe storms, hurricanes, etc.)**
- **ARPS + LPM provide simulated GEMS observations at any point in time / space**
- **Case study (26 – 27 July 1997)**
- **ARPS / LPM configuration (CONTROL)**
  - 5-km horizontal grid resolution (500 x 500 km² domain)
  - 30 unevenly spaced vertical layers (0 to ~16 km)
  - 12-h simulation (0800 – 2000 EDT 26 July)
  - Sensors released from 25 stations across Florida
    - *19 sensors per station at 50 m & 0.5 km increments from 0.5 – 9 km*
    - *6-hour release period (0800 – 1400 EDT 26 July)*



Boundary Data from Regional-Scale Model

3D Visualizations of Simulated Weather

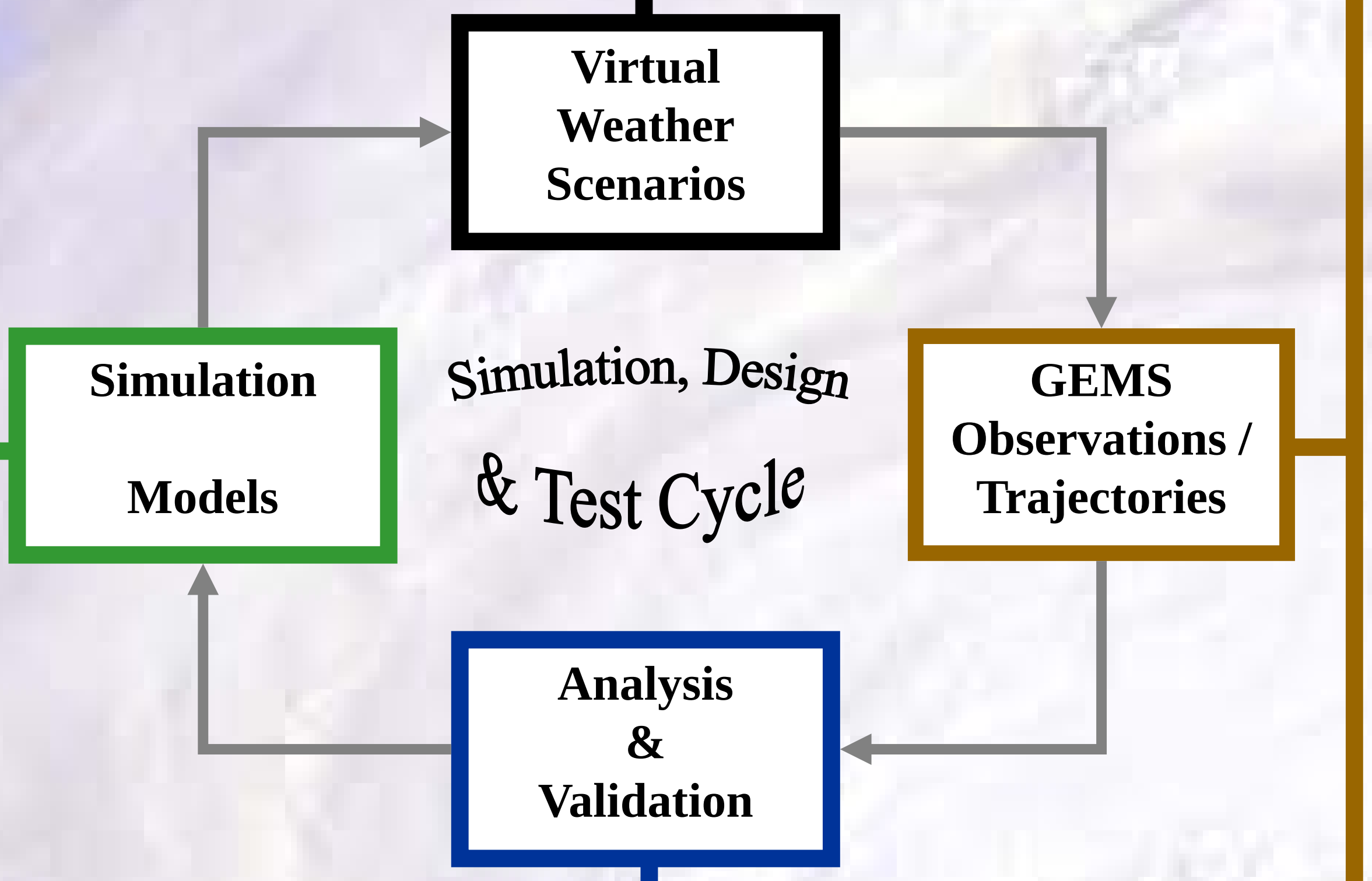
White = Cloud ; Blue = Precipitation; Orange = Surface Streamlines



Florida East Coast Sea Breeze

1400 EDT 26 July 1997

2000 EDT 26 July 1997



Virtual Weather Scenarios

GEMS Observations / Trajectories

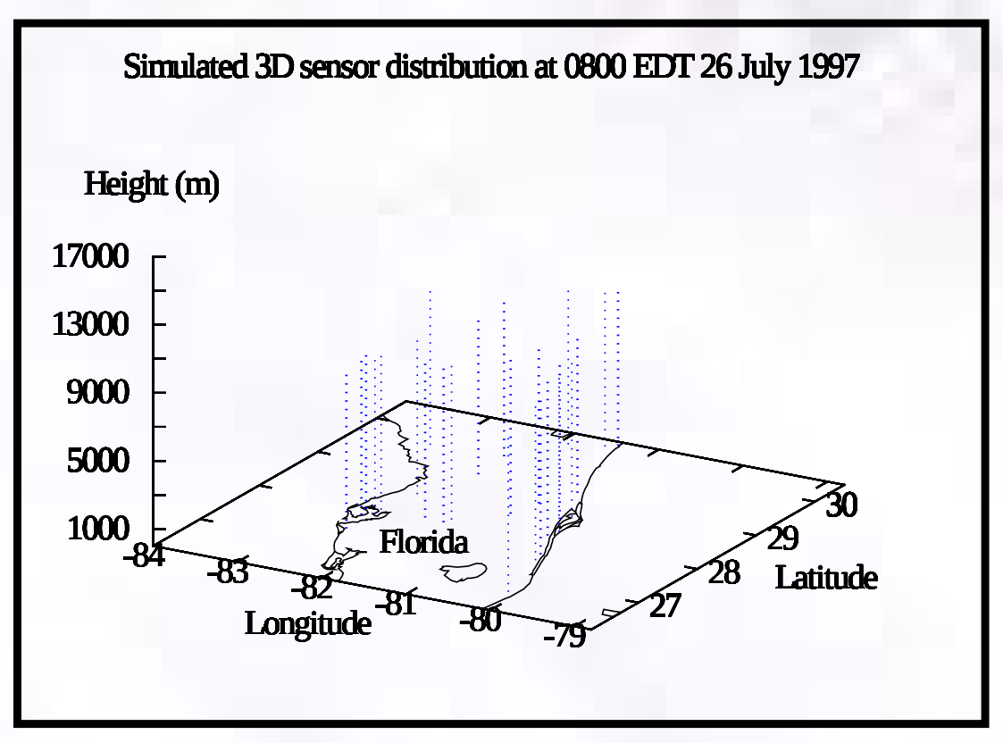
Analysis & Validation

Simulation Models

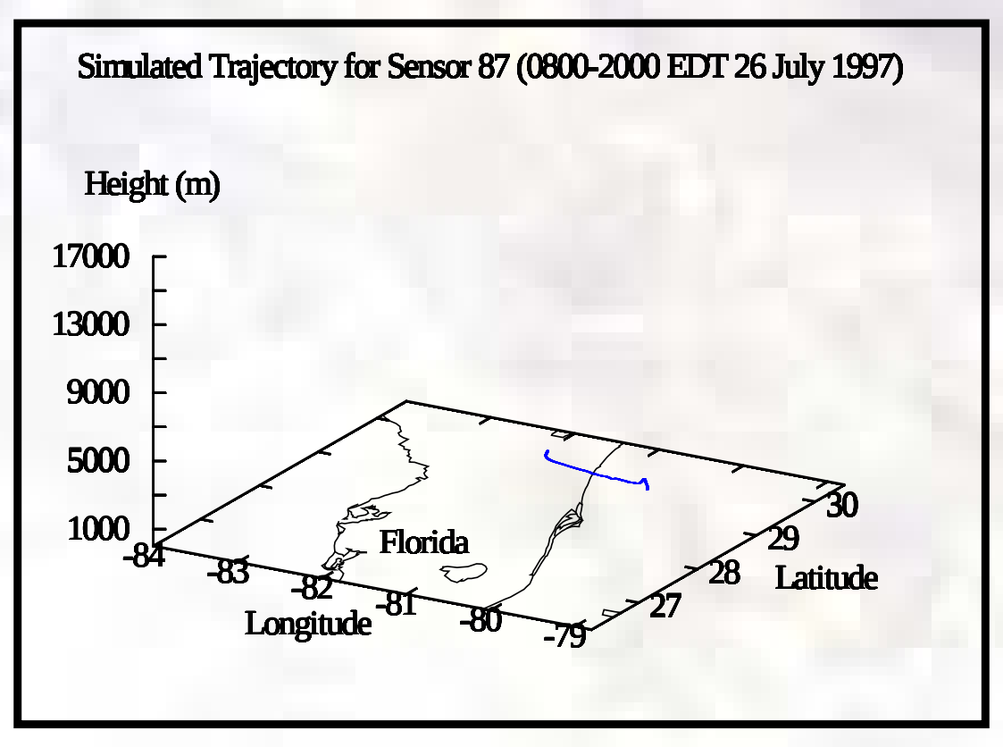
Simulation, Design & Test Cycle

GEMS Observations / Trajectories

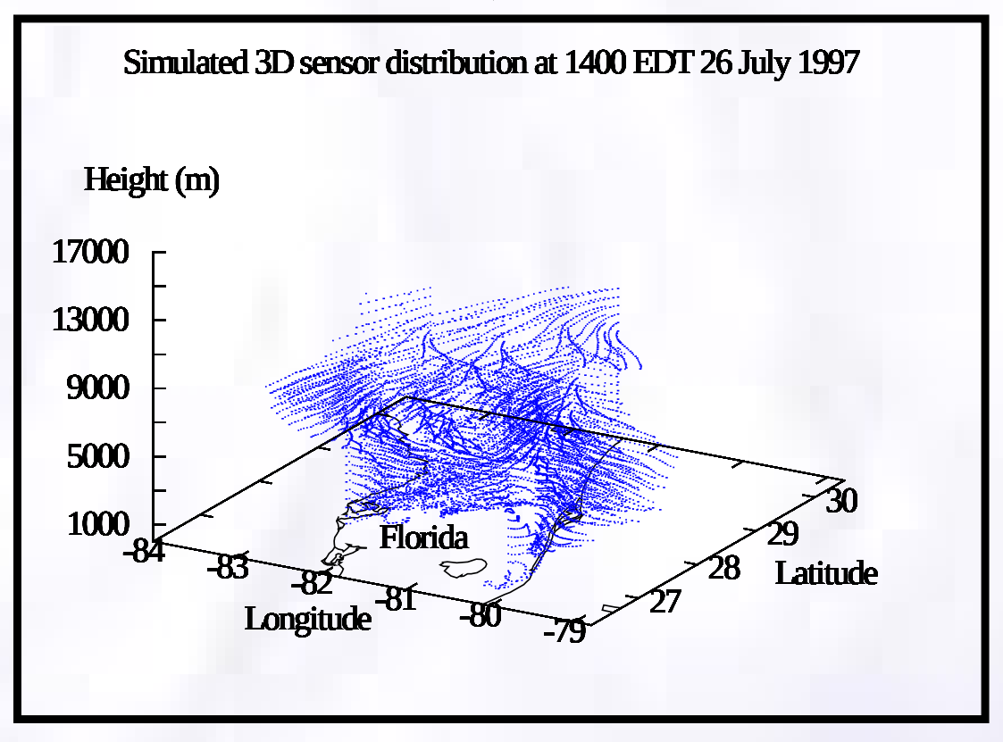
- **Extract simulated observations of pressure, temperature, humidity, wind velocity**
- **Include random component to simulate measurement error**
- **Plot sensor dispersion / trajectories (depends on weather scenario / deployment pattern)**
- **Examine ensemble statistics & individual sensor observations for realism**



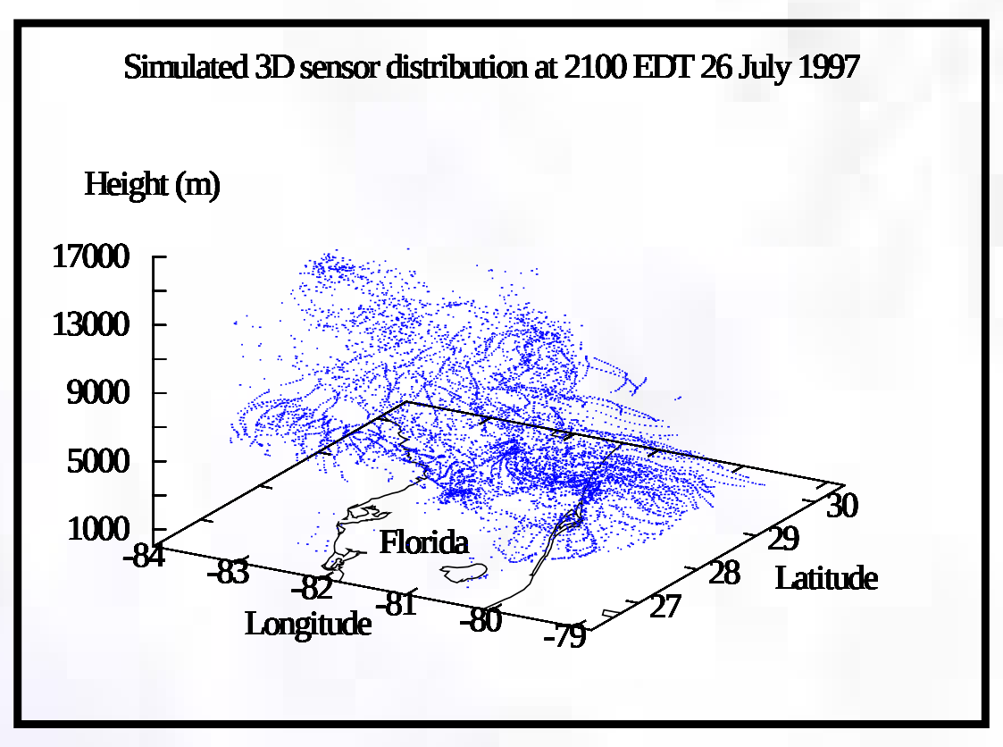
Simulated 3D sensor distribution at 0800 EDT 26 July 1997



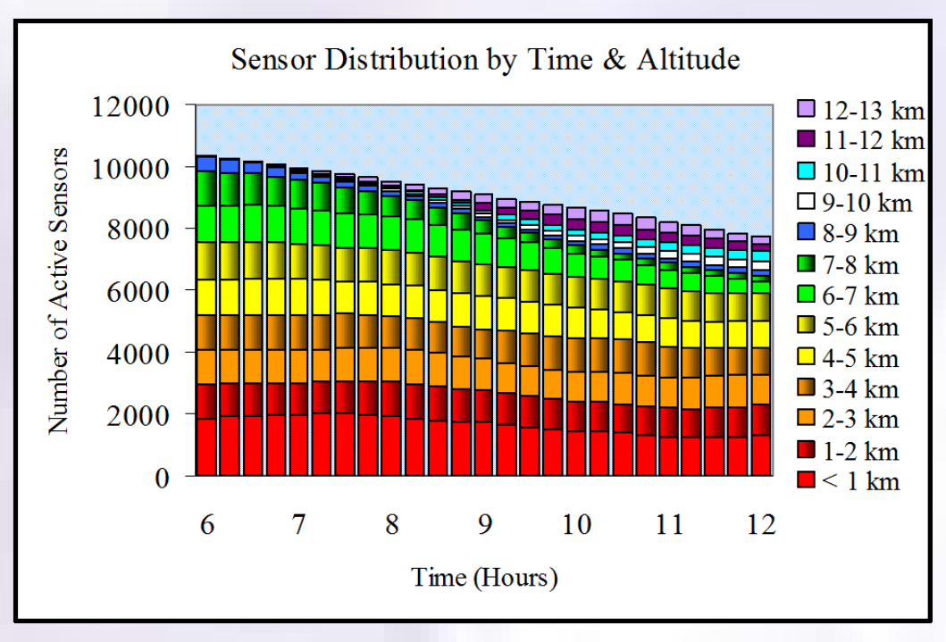
Simulated Trajectory for Sensor 87 (0800-2000 EDT 26 July 1997)



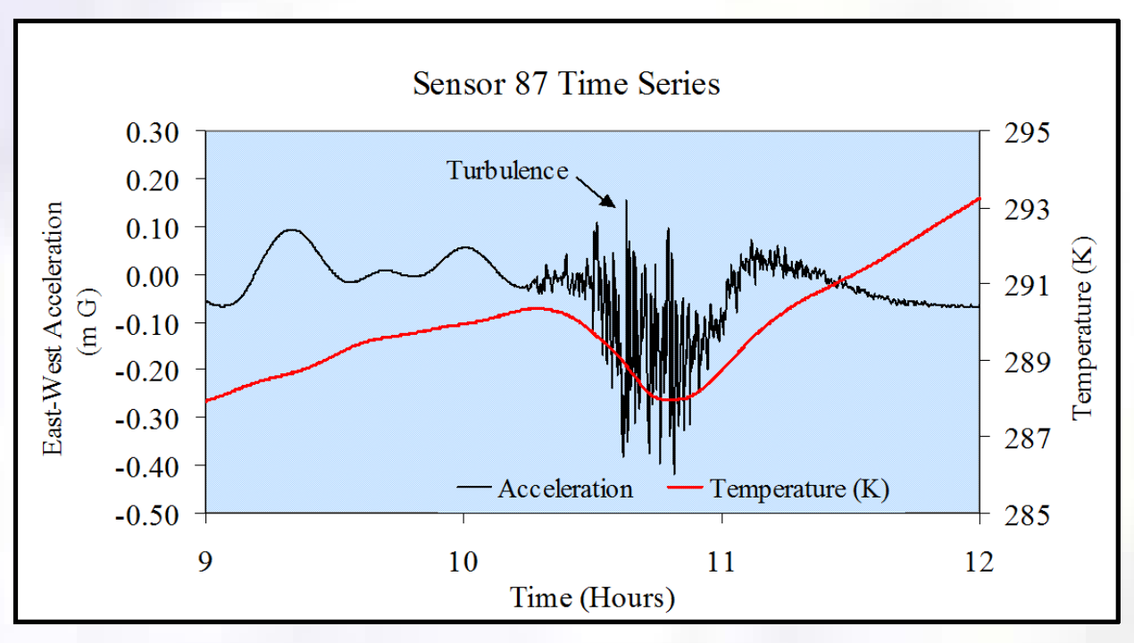
Simulated 3D sensor distribution at 1400 EDT 26 July 1997



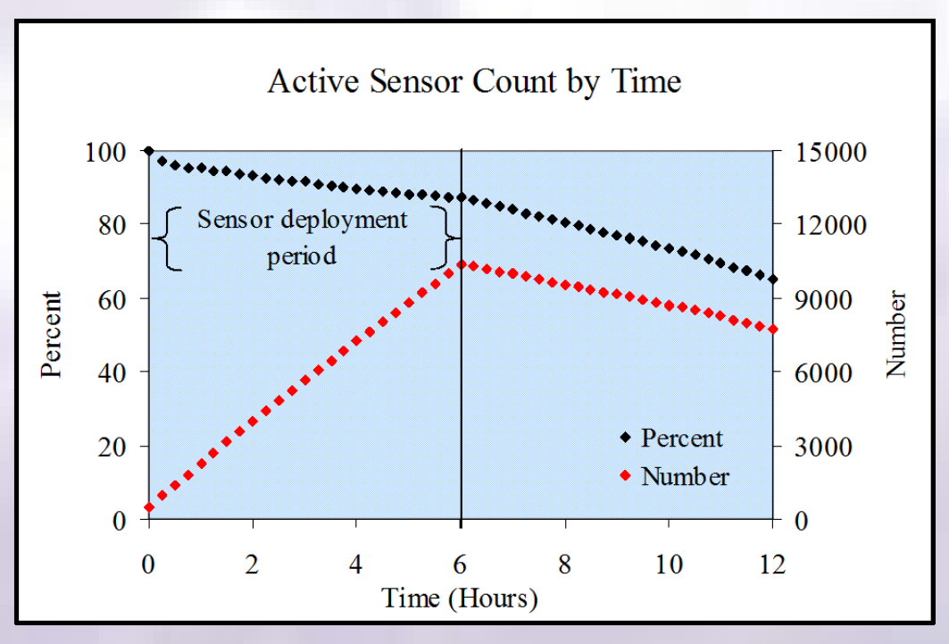
Simulated 3D sensor distribution at 2100 EDT 26 July 1997



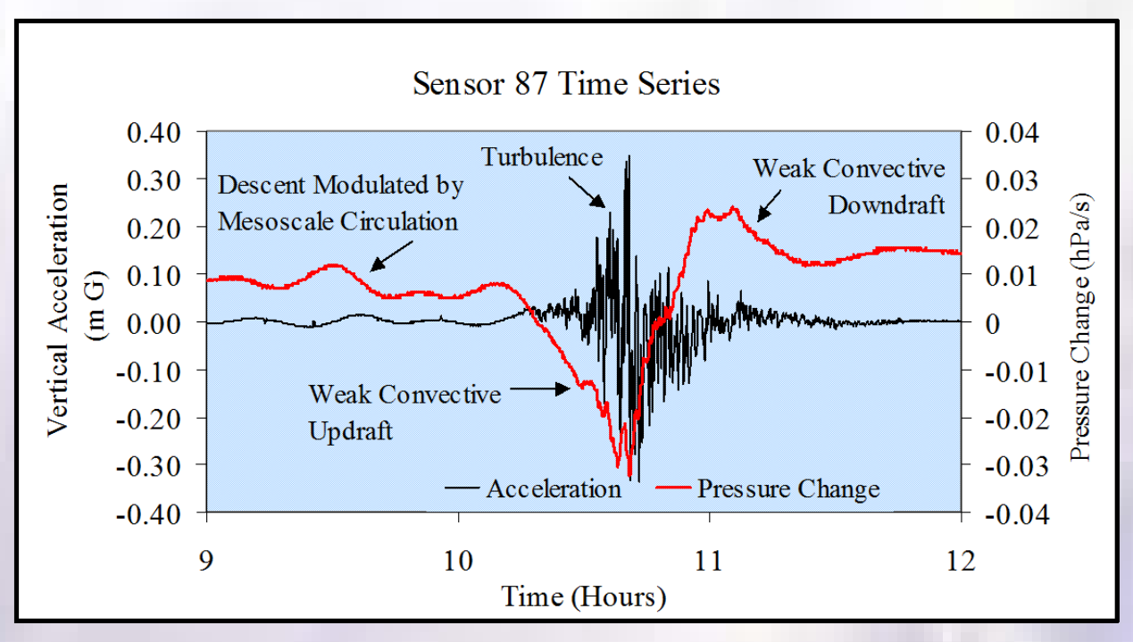
Sensor Distribution by Time & Altitude



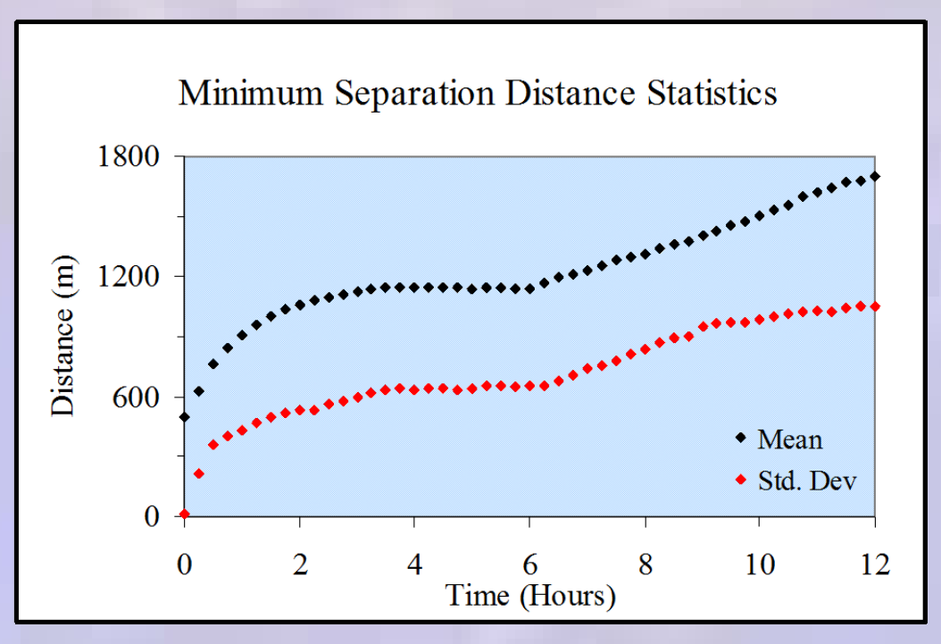
Sensor 87 Time Series



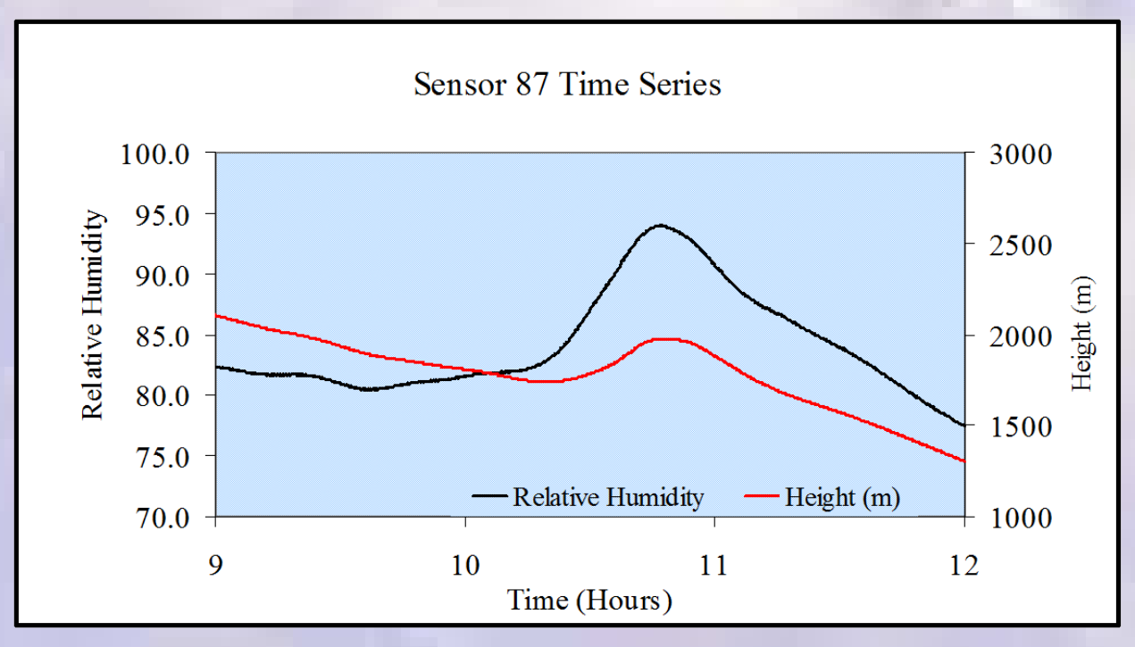
Active Sensor Count by Time



Sensor 87 Time Series

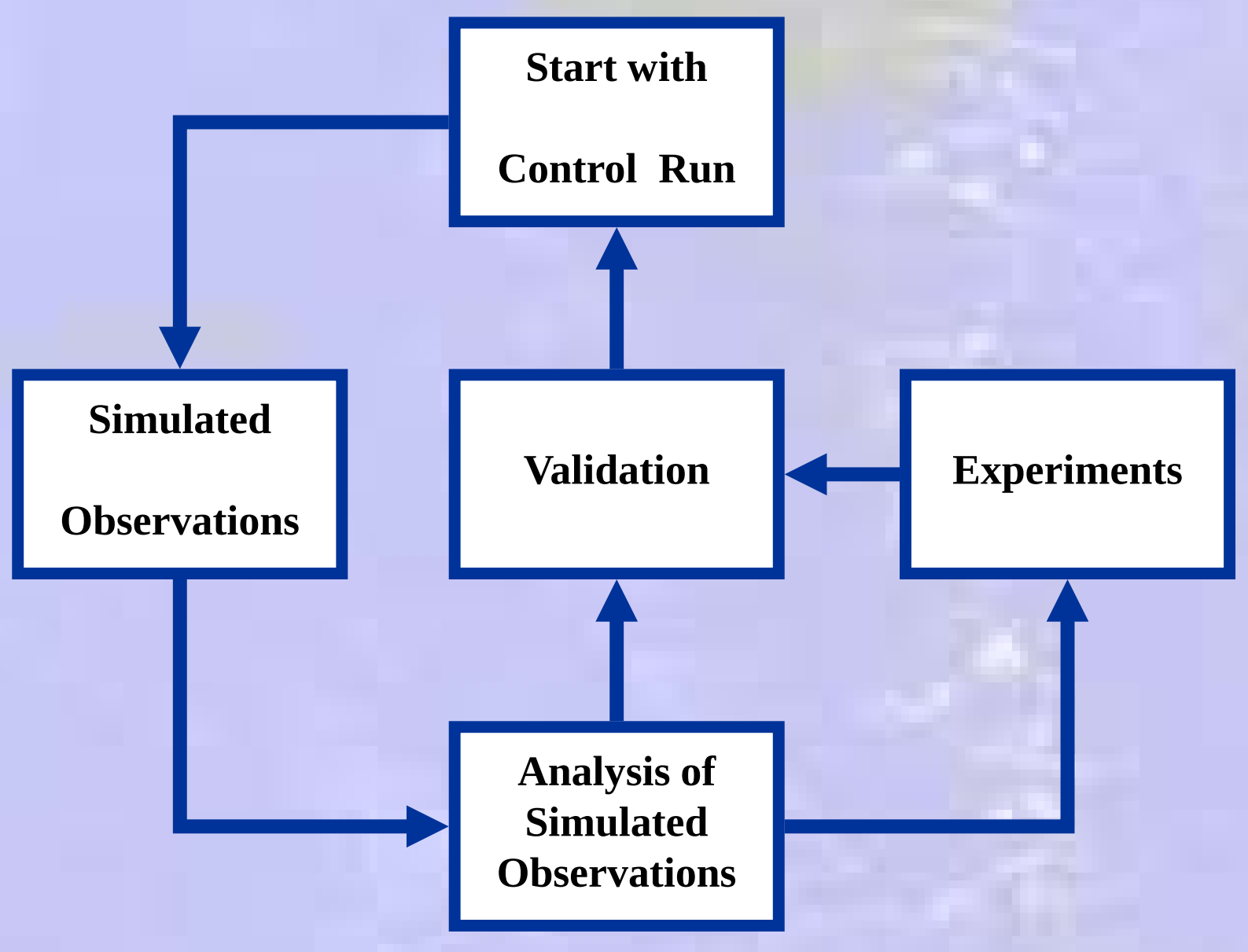


Minimum Separation Distance Statistics



Sensor 87 Time Series

Analysis & Validation



Start with Control Run

Simulated Observations

Validation

Experiments

Analysis of Simulated Observations

- **Impact of GEMS observations on weather analyses / forecasts**
- **Observing System Simulation Experiments (OSSE)**
- **Assess sensitivity to**
  - Multiple weather scenarios & deployment strategies
  - Sensor accuracy, separation distance & sampling frequency
- **Simulation results help refine GEMS design specifications**
  - Data storage & processing
  - Measurement accuracy for position, pressure, temperature, & humidity
  - **Networking and navigation algorithms**
  - **Communications environment**

Summary / Future Vision

- **Simulation studies – Proof of Concept**
  - State-of-the-science Numerical Weather Prediction model
  - Lagrangian Particle Model (LPM)
- **Deployment / evaluation of prototypes – Next Phase**
  - Limited static / dynamic tests at selected sites (similar to Smart Dust tests by Pister et al. @ Berkeley)
  - Leverage resources by testing prototypes during multi-agency field experiments
  - Larger-scale deployments via unmanned aerial vehicles (UAV), balloons, aircraft
  - Assess environmental impacts
- **GEMS: A revolutionary new observing technology for the 21st century - Future**
  - Regional & global deployment for operational weather analysis / forecasting
  - Special deployments for military operations, hurricane reconnaissance, research experiments, etc.
  - Ultra high spatial / temporal resolution measurements available for any region of the world with active sensors

Background is Hurricane Floyd (0859 EDT 14 Sept 1999)
Image produced by Dr. Dennis Chesters @ Goddard Space Flight Center