Using a High-Resolution Global Climate Model to Simulate Extratropical Cyclones with Large Storm Surge Potential

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Background

Storm surge caused by Hurricane Sandy triggered a need for new research on inundation and associated risk. However, observational records of coastal water levels are limited, which increases uncertainty in risk analyses such as exceedance probabilities.

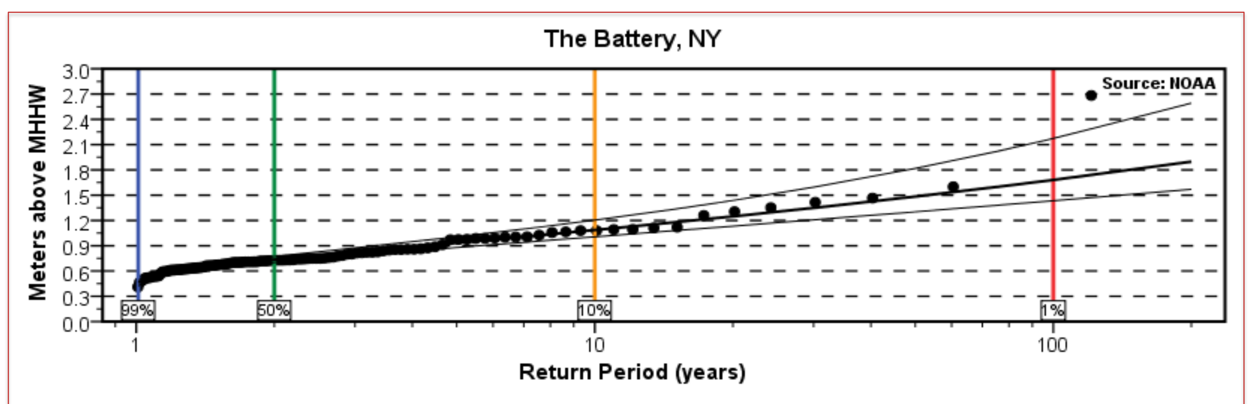

Fig. 1. Annual exceedance probability curve for storm tide at The Battery with 95% confidence intervals. Dots indicate the annual maximum water levels after removing the long-term trend in sea level. The position of the rightmost dot indicates the number of years of data used in the calculation. [NOAA Tides and Currents website: tidesandcurrents.noaa.gov]

Figure 1 above displays probabilities of storm tide levels for over 100 years of observational data, while our exceedance curve calculation (fig. 2) includes 88 years due to limited availability. Both plots suggest a >1,000-yr mean return period of a Sandy-level inundation (with a 300-yr lower bound), and demonstrate the magnitude of uncertainty associated with a high flood level and limited range of data. Different metrics are often used to quantify coastal inundation. Storm tide refers to the actual water level relative to a fixed datum and includes the effects of both the astronomical tide and meteorologically-induced water rise. Storm surge refers to the latter effect, and is defined as the difference between the storm tide and the astronomical tide, which removes the dependence of the storm timing relative to astronomical forcing. Compared to figure 2, the mean return period of a Sandy-level storm surge lowers to 500 years with a lower bound around 120 years (fig. 3).

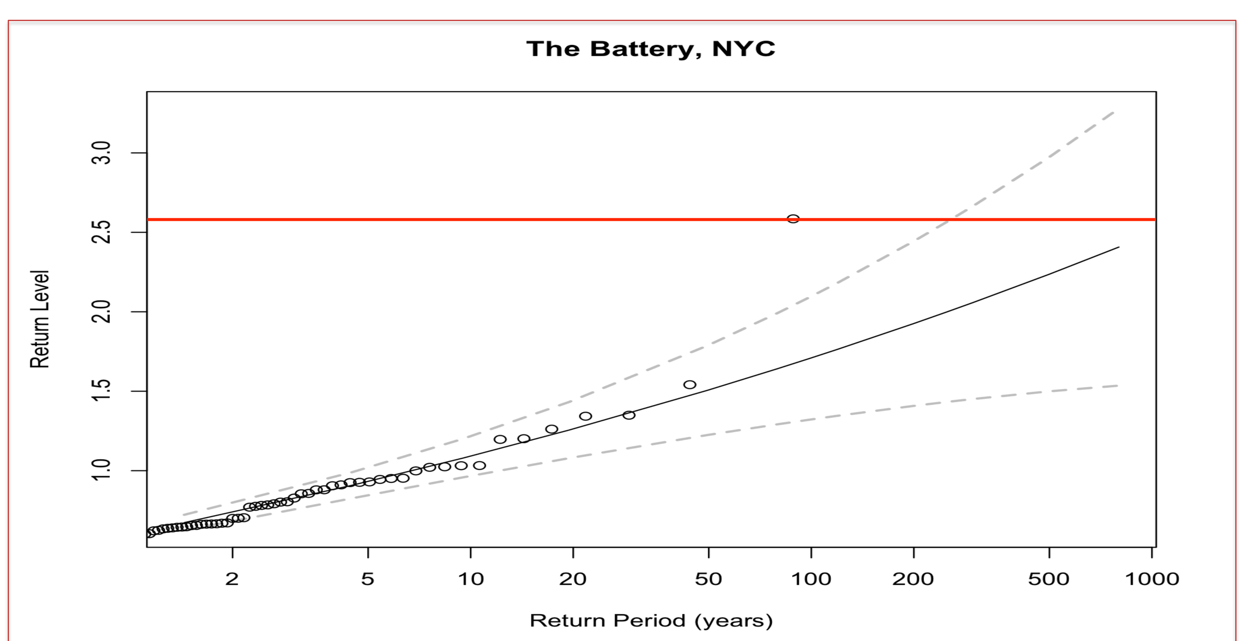

Fig. 2. Annual exceedance probability curve for storm tide at The Battery with 95% confidence intervals (1926 – 2013). Dots indicate the annual maximum water levels after removing the long-term trend in sea level. The position of the rightmost dot indicates the number of years of data used in the calculation. Mean return level of a Sandy-level inundation event is > 1,000 years.

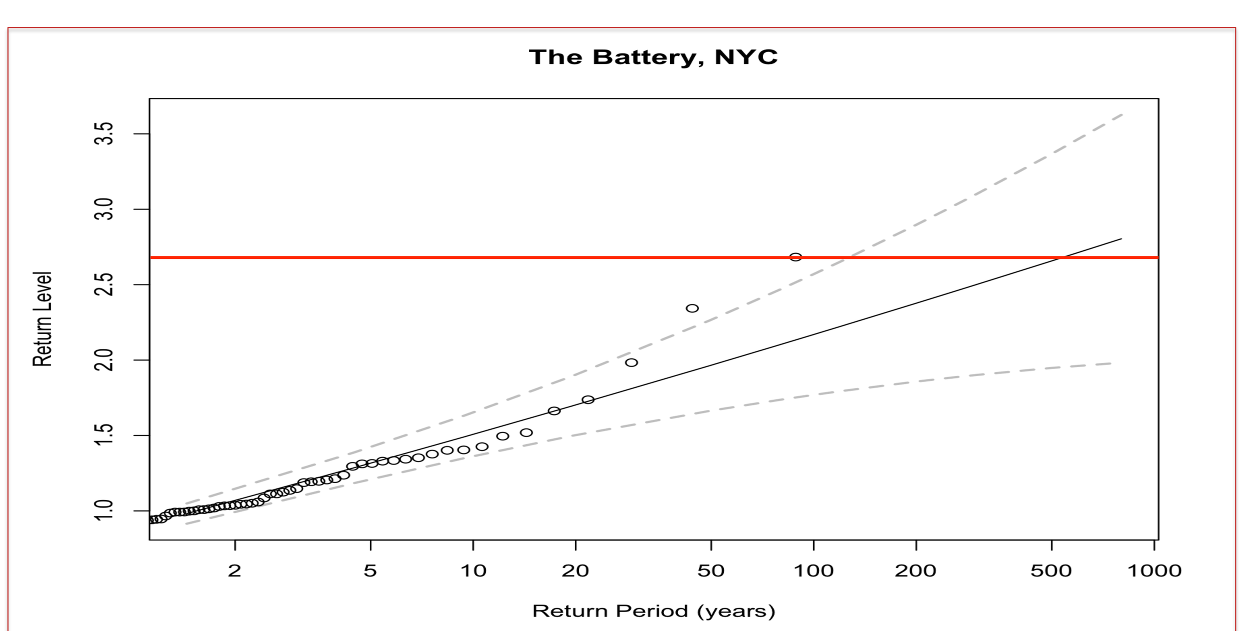

Fig. 3. Annual exceedance probability curve for storm surge at The Battery with 95% confidence intervals (1926 – 2013). Dots indicate the annual maximum surge after removing the long-term trend in sea level. The position of the rightmost dot indicates the number of years of data used in the calculation. Mean return level of a Sandy-level storm surge event is roughly 500 years.

Most of the uncertainty in these return period calculations is due to difficulty in resolving the tail of the distribution from limited observations. Global climate models provide a means of simulating a much larger sample of potential surge-producing events, allowing for better resolution of the tail of the frequency distribution. Since 17 of the 20 greatest storm surge events at The Battery in New York City occurred in association with extratropical cyclones (see below), we examine the ability of a coupled atmosphere-ocean general circulation model with 50km atmospheric resolution (GFDL CM2.5[1]) to realistically simulate extratropical cyclones in the western North Atlantic Ocean that are capable of producing large surges.

Date (GMT)	Surge (m)	Type of Storm	Date (GMT)	Surge (m)	Type of Storm
10/30/2012 1:00	2.683	Hybrid	10/27/1943 4:00	1.372	EC
11/25/1950 20:00	2.339	EC	12/27/2012 5:00	1.352	EC
9/27/1985 17:00	1.982	Hurr.	1/25/1979 2:00	1.350	EC
12/11/1992 17:00	1.736	EC	10/31/1991 9:00	1.342	EC
9/12/1960 18:00	1.660	Hurr.	3/6/1962 19:00	1.331	EC
3/29/1984 14:00	1.517	EC	11/12/1968 15:00	1.327	EC
11/10/1932 5:00	1.490	EC	10/25/1980 18:00	1.310	EC
11/17/1935 21:00	1.421	EC	2/20/1927 19:00	1.309	EC
3/13/1993 22:00	1.403	EC	1/8/1996 6:00	1.295	EC
11/7/1953 10:00	1.398	EC	2/4/1961 10:00	1.233	EC

Results

To reduce uncertainty and provide credible return period estimates, it is important that GFDL CM2.5 realistically simulates intense extratropical cyclones of the type that produce large surge events. We address this question by first comparing model and MERRA reanalyses[2] wind speeds, as winds are an important driver of storm surge. Since record lengths differ greatly, (861 years from CM2.5 vs. 35 years from MERRA), we use the following methods of comparison:

- Portion CM2.5 data into equal, non-overlapping 35-year periods to match the length of MERRA observations (1979 – 2013)
- Calculate CM2.5 maximum wind speed over each period
- Calculate average of these maximum values over all 35-year periods, which can be interpreted as the typical maximum value that might be expected during any arbitrary period of that length

Second, we compare CM2.5 sea level pressure with MERRA by examining individual storms from the full record. We observe if overall intensity and structure are similar by analyzing strength and size of extratropical cyclones through pressure maps.

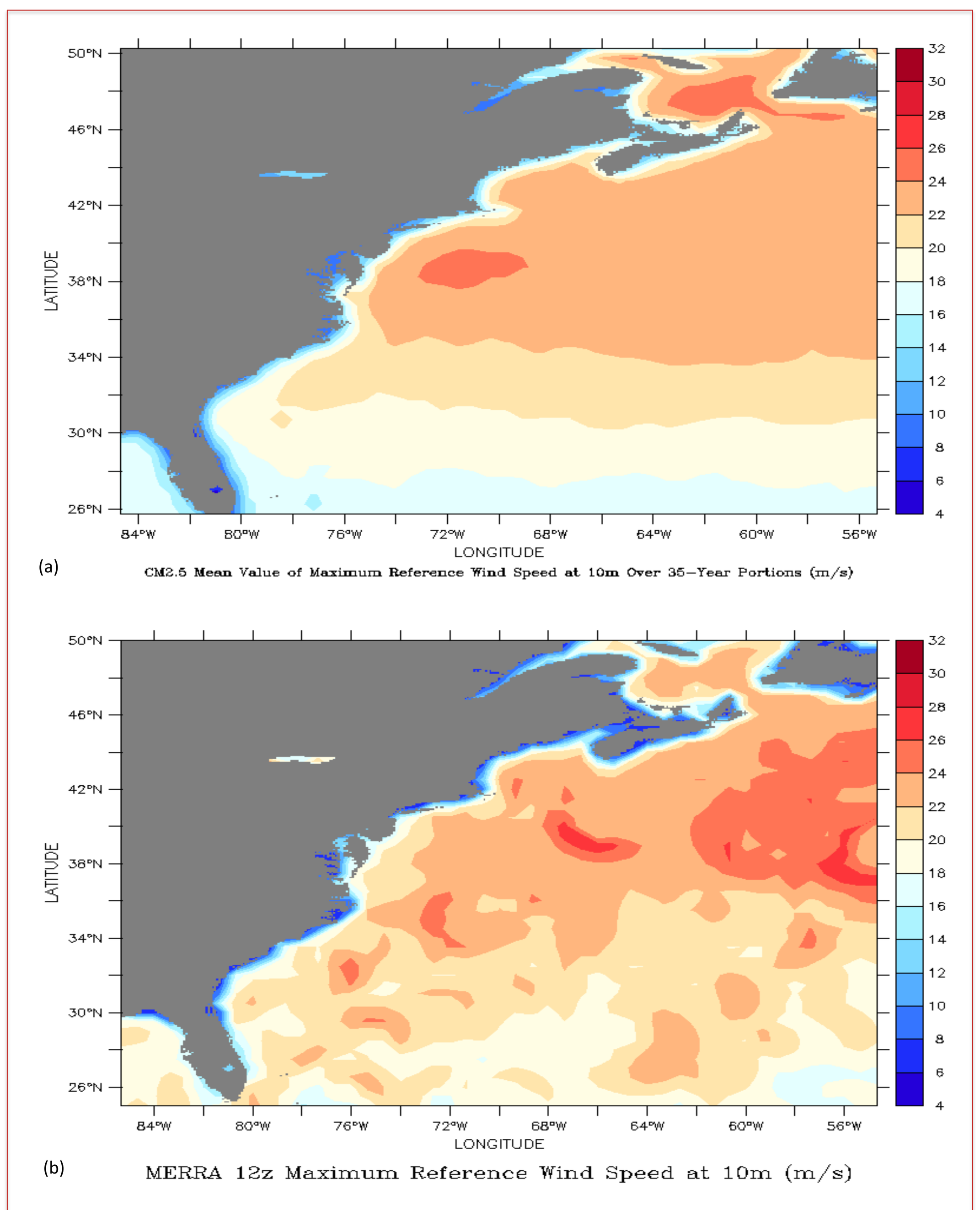

Fig. 4. Comparison of near-surface (10m) wind speeds from CM2.5 and MERRA. (a) Mean value of maximum CM2.5 wind speed during each 35-yr period. (b) Maximum MERRA wind speed during 35-yr period of record (1979 – 2013).

Figure 4 above indicates that maximum wind speeds during the MERRA period are comparable to a typical 35-year sample of CM2.5 wind speeds, particularly in the middle latitudes, suggesting that the model is producing realistic extratropical cyclone activity. (The MERRA wind speeds are systematically higher than the CM2.5 mean in the subtropics, probably due to underestimation of tropical cyclone winds in CM2.5). The maximum over all 35-yr periods of maximum winds (not shown) exhibits similar variability to (b), with larger speed over most of the region. This illustrates that the large number of realizations in the full model provide more opportunities for extreme events to occur, such as the strong extratropical cyclones shown in figure 5. The right column

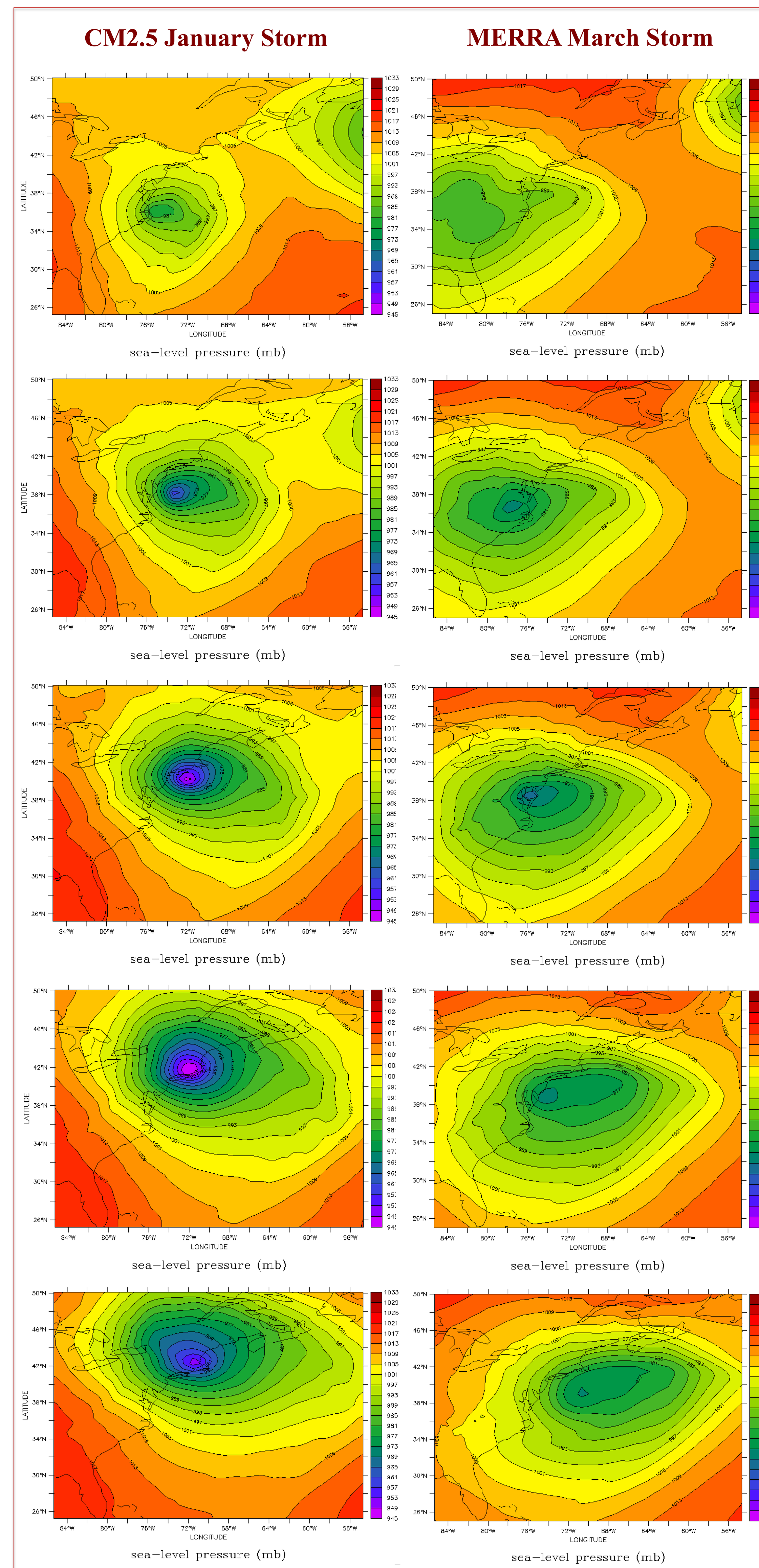

Fig. 5. Five-panel maps of sea-level pressure (mb) for a strong extratropical cyclone in CM2.5 (left) and MERRA (right).

shows the progression of the March 29, 1984 storm, which produced the third highest recorded surge at The Battery by an extratropical cyclone. The CM2.5 January storm displays similar features and a comparable size, but possesses a stronger pressure gradient and deeper core. Thus, it is likely that the full CM2.5 run contains extratropical cyclones that are capable of producing greater storm surges than might appear in the much shorter observational record. This should enable us to better define the tail of the distribution of extreme events by reducing uncertainty in return period calculations.

Future Research

Topics of future plans for research include:

- Use an extratropical cyclone tracker for performing statistical analyses of extratropical cyclone climatology over the North Atlantic Ocean, including genesis, track, and lysis densities[3].
- Identify a large subset of potential surge-producing storms in the mid-Atlantic region for further analyses using a storm surge model.
- Estimate storm surge risk from extratropical cyclones using CM2.5 meteorological conditions to force a storm surge model.
- Compare the characteristics of tropical cyclone storm surge with extratropical cyclone storm surge in the New York City region[4].
- Analyze the response of extratropical cyclone-induced storm surge risk to projected 21st century changes in climate and sea level[5].

References

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