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ADJONT-BASED ANALYSIS OF OBSERVATION IMPACT ON TROPICAL CYCLONE INTENSITY FORECASTS

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1. Introduction

An accurate estimate of the relative contributions of discrete observation types to the accuracy of a numerical weather prediction (NWP) forecast is of value to both the research and operational communities, especially when the forecast includes a high-risk event such as a tropical cyclone (TC). It has been observed that while TC track prediction has improved steadily for over the last few decades, improvement of TC intensity prediction has lagged (e.g. DeMaria and Gross 2003). Therefore the question may be asked: “What features of the analysis is the TC intensity forecast most sensitive to, and which assimilated observations impose the largest impact on the TC intensity forecast?” An examination posed in this way attempts to further our understanding of the environmental features and dynamical processes most important to the intensity of the modeled TC, as well as connecting those important features to the observational network in a way that evaluates the relative strengths and weaknesses of various observing platforms.

In this study, the impact of every observation assimilated into the initial (analysis) state of an NWP model on the forecast intensity of a modeled TC is estimated using an adjoint technique. The sensitivity of the TC intensity forecast to perturbations of the initial state is estimated explicitly, and this information is used to derive an observation-impact for each assimilated observation. In this way, observations can be compared to one another (e.g. by calculating the cumulative impact of all observations of a given type) in order to discover which observations impact the intensity forecast most strongly. Both 24-hr and 48-hr forecasts are compared, to determine if there are significant differences in the sensitivity of a short forecast versus a longer-range forecast to the initial state or the impact of the observing system.

Section 2 describes the adjoint-method for estimating sensitivity of the TC intensity forecast to the initial state and the observation-impact. Results from a composite-study of forecasts for Hurricane Sandy (2012) are presented in Section 3. Conclusions and directions for future research are discussed in Section 4.

2. Methodology

For a given NWP forecast, one can define the total observation-impact as the difference in forecast TC intensity between a simulation initialized from the analysis state (including all assimilated observations) and a simulation initialized from the background state (the analysis first-guess including no assimilated observations), typically defined as a 6-12 hour longer simulation verifying at the same time (providing the first-guess at the chosen analysis-period). The difference in forecast TC intensity is by definition the result of the assimilation of the entire observing network.

The adjoint of the data assimilation and forecast systems can be employed to estimate the individual contribution of each assimilated

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observation to the difference between these two forecasts (Langland and Baker 2004). Typically this is calculated for a global energy-based error-norm of the short-range forecast (Cardinali 2009, Gelaro et al. 2010), providing an estimate of how much each individual observation contributes to reducing a general metric for forecast error, relative to a forecast where no observations were assimilated.

We focus here on The Navy Global Environmental Model (NAVGEM) and Naval Research Laboratory Variational Data Assimilation System – Accelerated Representer (NAVDAS-AR). The error-norm is replaced with a simple function describing the intensity of a TC in the final forecast state. Let this function, known as the *response function* (R), be defined as the integrated vorticity in a box 7°x7° (D) centered on the forecast position of the TC, extending from the surface through the bottom 10 sigma-levels of the model:

$$R = \sum_{i,j \in D} \sum_{k=1}^{10} \zeta_{i,j,k} \qquad (1)$$

The adjoint of the NAVGEM, defined as the transpose of the tangent-linear approximation to the nonlinear model, takes as its input the gradient of R with respect to the final state $\mathbf{x}_f$. The adjoint model will then evolve this gradient backward through time along the trajectory defined by the nonlinear NAVGEM simulation, to produce the gradient of R with respect to the initial state $\mathbf{x}_0$:

$$\begin{aligned} \mathbf{x}_0 &\rightarrow [NWP\ MODEL] \rightarrow \mathbf{x}_f \rightarrow R(\mathbf{x}_f) \\ \partial R/\partial \mathbf{x}_0 &\leftarrow [ADJ\ MODEL] \leftarrow \partial R/\partial \mathbf{x}_f \end{aligned} \qquad (2)$$

This is known as the *sensitivity gradient*, defining the sensitivity of R to the model initial state. Perturbations to the model initial state in regions of strong sensitivity can impose a significant change on R, defined at the final forecast time. Here, $\partial R/\partial \mathbf{x}_0$ represents the sensitivity of the forecast TC intensity to potential perturbations of the initial state.

The observation-impact estimate is derived by taking the inner product of the sensitivity gradient with the innovation imposed by an assimilated observation – this produces an estimate of how much an individual observation y_i impacts R, using the DA system adjoint $\mathbf{K}^T$: $o_i \approx \langle \mathbf{K}^T (\partial R_{fa}/\partial \mathbf{x}_a + \partial R_{fb}/\partial \mathbf{x}_b), (\mathbf{y}_i - H(\mathbf{x}_b)) \rangle$. Here, o_i represents the impact of observation y_i on the forecast intensity of the TC, and R_{fa} and R_{fb} represent the intensity of the TC in simulations initialized with the analysis state $\mathbf{x}_a$ and background state $\mathbf{x}_b$, respectively. Due to constraints related to the linearity assumption, this observation-impact estimate is only quantitatively valuable for short-range forecasts.

The adjoint is used to calculate $\partial R_{fa}/\partial \mathbf{x}_a$ and o_i for both 24-hr and 48-hr forecast trajectories. The sensitivity gradient for compositing chosen as the 24-hr (48-hr) integration backward from a 30-hr (54-hr) forecast, thereby providing the gradient $\partial R_{fb}/\partial \mathbf{x}_b$, the sensitivity of the forecast TC intensity in the model run initialized from the background state. In this way, the question addressed becomes: **"Before any observations are assimilated, where would analysis increments produce the largest impact on TC intensity?"** – this is done in order to avoid a situation where the model trajectory (and therefore, the sensitivity gradient) is strongly constrained by the very observations we wish to independently assess.

Storm-centered composites of the sensitivity gradient are computed for 24-hr and 48-hr forecasts of Hurricane Sandy (2012) for all six-hourly forecasts from 0600 UTC 24 December – 1800 UTC 28 December 2012. Observation-impact is computed for each forecast, and the absolute value of o_i is summed across each observation type, to provide an estimate of the impact of each observation-type on a particular forecast. The absolute value is chosen since o_i can either be positive (the observation contributed to increasing forecast TC intensity) or negative (the observation contributed to decreasing forecast TC intensity), and the focus here is on assessing only the *magnitude* of the impact observations impose on the forecast. This measure of observation-impact for each forecast is then averaged across all forecasts to provide an analysis of the impact of various parts of the observing system on Sandy's intensity forecast at both 24-hr and 48-hr forecast ranges.

3. Composite Analysis

3a – Sensitivity Gradient

Sandy's 24-hr intensity sensitivity to wind perturbations at roughly 500 hPa demonstrates some dynamical features of interest (Fig. 1). The sensitivity is defined as the length of a vector composed of the sensitivity to the zonal and meridional components of the wind field: $\partial R / \partial \left|\vec{V}_b\right| = \left|\left(\partial R/\partial u_b, \partial R/\partial v_b\right)\right|$ - this way, the sensitivity gradient takes both the potential impact of a zonal or meridional wind perturbation into account. A perturbation to the initial wind field in the shaded region (e.g. due to the assimilation of a wind observation in that location) has the potential to impact Sandy's 24-hr intensity forecast.

While the sensitivity of Sandy's 24-hr intensity forecast appears to remain close to the TC vortex itself, there is a distinct bias to the northwest quadrant of the storm, and a portion of sensitivity extending upstream toward the exit region of a nearby branch of the polar jet. This enhanced sensitivity to the west and northwest of Sandy is consistent with the importance of Sandy's interaction with a midlatitude trough to its northwest through a large portion of its evolution. Small perturbations to regions within the trough and between the trough and Sandy have the potential to influence Sandy's 24-hr intensity forecast.

When the trajectory-length is increased to a 48-hr intensity forecast, Sandy's sensitivity to initial wind perturbations increases in magnitude and extends further both upstream and downstream, but still with a pronounced upstream bias (Fig. 2). The increase in total magnitude of sensitivity indicates that a given wind perturbation generally has the capacity to impose a larger impact on the 48-hr intensity of

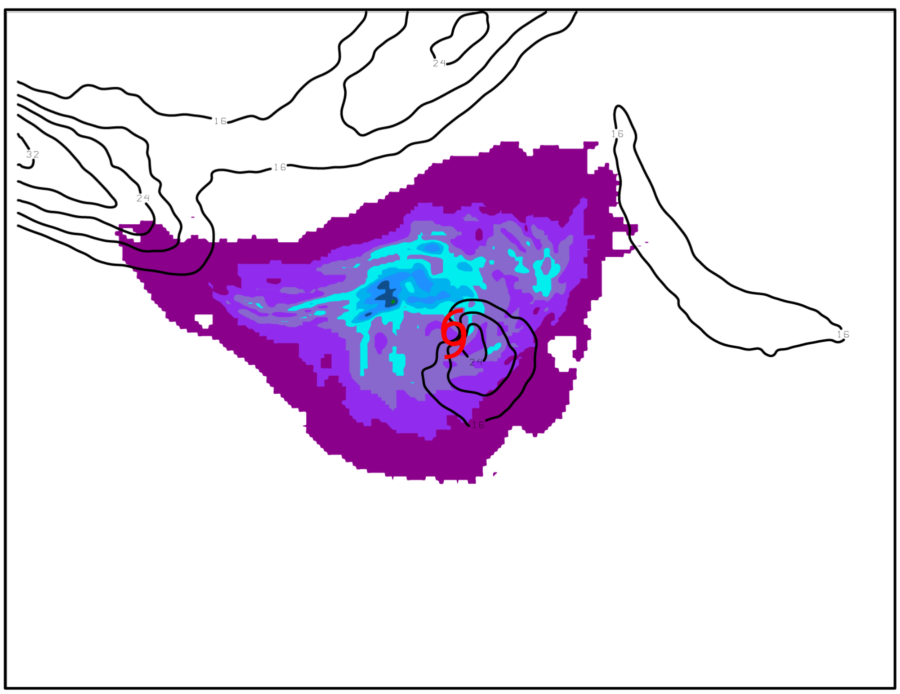

Figure 1. Storm-centered composite of isotachs (black contours every 4 m s^{-1} starting at 16 m s^{-1}) and sensitivity of Sandy's 24-hr intensity forecast to initial wind perturbations (shaded every $3x10^{-7}$ m^{-1}). The red symbol identifies the location of Sandy in the composite. The composite is performed on a sigma-level near 500 hPa.

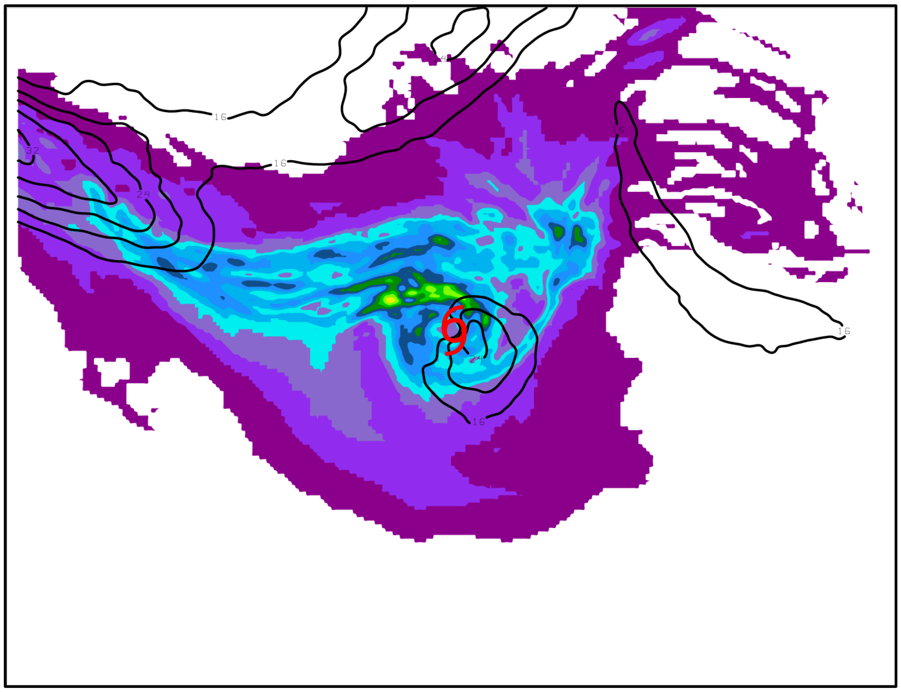

Figure 2. Storm-centered composite of isotachs (black contours every 4 m s^{-1} starting at 16 m s^{-1}) and sensitivity of Sandy's 48-hr intensity forecast to initial wind perturbations (shaded every $3x10^{-7}$ m^{-1}). The red symbol identifies the location of Sandy in the composite. The composite is performed on a sigma-level near 500 hPa.

Sandy than it can on the 24-hr intensity. The increased sensitivity upstream and downstream of the TC indicates that perturbations more remote from Sandy can impact the intensity of the 48-hr forecast in a way that they could not influence the 24-hr forecast. A difference-plot of these sensitivity gradients (Fig. 3) shows that Sandy's 48-hr intensity forecast is more sensitive to initial wind perturbations at this level almost everywhere, both near the TC as well as remote from the TC, especially in dynamically important regions such as the exit region of the polar jet to Sandy's northwest. Note that the distance from the center of the composite to the border on the west or east side is roughly 40 degrees of longitude.

The sensitivity to wind perturbations in the lower troposphere displays a migration of sensitivity toward outer radii for the sensitivity of the 48-hr forecast, compared to the 24-hr forecast (Fig. 4a). This means that wind perturbations near the TC at this level impose a smaller impact on the 48-hr intensity forecast than they do on the 24-hr forecast, while wind perturbations further from the TC become more important. A zonal cross-section through the core of the TC vortex shows that the sensitivity of the 48-hr forecast also migrates into the middle and upper troposphere, and away from the surface (Fig. 4b). The enhanced upstream sensitivity in the 48-hr forecast at mid levels (see Fig. 3) exists within a deep layer of enhanced sensitivity between 700 – 200 hPa.

3b – Observation Impact

The adjoint-estimated observation impact is computed for each observation at each analysis-period. The impact of a particular observation type *j* within the observing system is defined here as the sum of the absolute value of observation-impact from all observations *i* of that type:

$$o_j = \sum_{i \in j} |o_i| \qquad (4)$$

the resulting observation-impacts are then averaged across all analysis-periods to produce a mean impact by observation type.

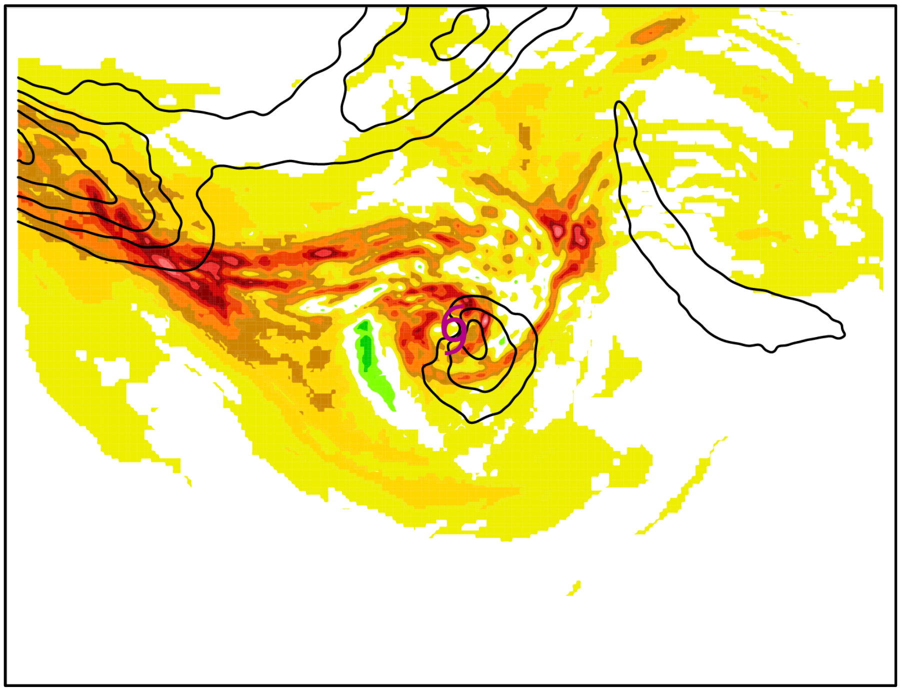

Figure 3. Storm-centered composite of isotachs (black contours every 4 m s^{-1} starting at 16 m s^{-1}) and difference in sensitivity of Sandy's 48-hr intensity forecast to initial wind perturbations to sensitivity of the 24-hr intensity forecast (shaded every $1x10^{-7}$ m^{-1}). Warm (cool) colors indicate regions where the 48-hr forecast is more (less) sensitive to initial wind perturbations than the 24-hr forecast. The composite is performed on a sigma-level near 500 hPa.

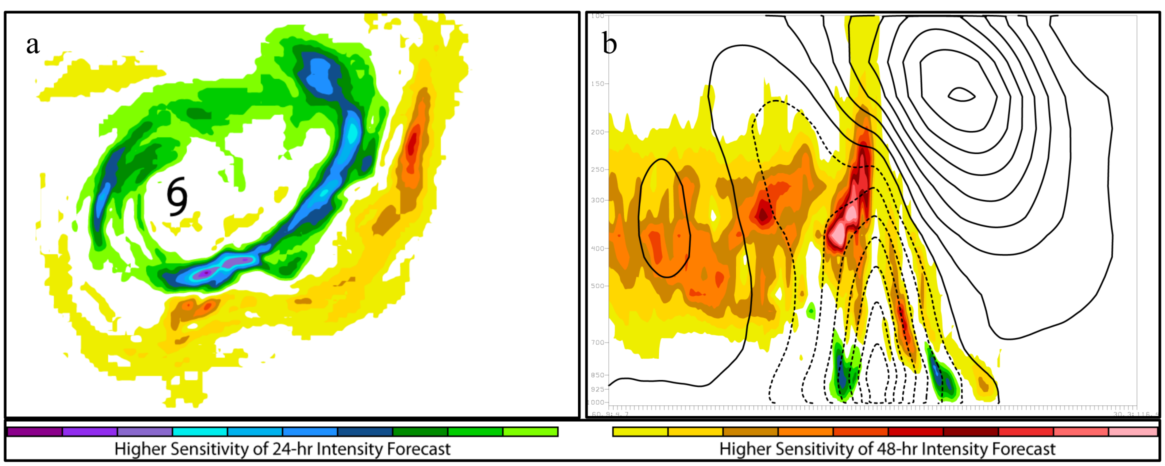

Figure 4. Storm-centered composite of difference in sensitivity of 48-hr and 24-hr intensity forecast of Sandy with respect to initial wind perturbations (shading every $1x10^{-7}$ m^{-1}). Warm (cool) colors indicate regions where the 48-hr intensity forecast is more (less) sensitive to initial wind perturbations than the 24-hr forecast. (a) Composite at a sigma-level near 850 hPa. (b) Zonal cross-section through TC core with composite streamfunction (black contours every $5x10^{-8}$ m^2 s^{-1}).

An analysis of this nature demonstrates that Sandy's 24-hr intensity forecast is most sensitive to MDCRS aircraft observations (Fig. 5, shaded portion). MDCRS observations are collected from commercial (passenger and parcel-delivery) aircraft on flights across the continental US; on-board instrumentation takes in-situ measurements of temperature and wind speed and direction, and these observations are reported back and collected for assimilation.

perturbations is higher on average (see Fig. 3). Observations from MDCRS, AMVs, and radiosondes are still the most important observation types at 48-hrs, but it is it is clearly observed that some observation-types experience a much larger increase in impact than others. For example, AMDAR (another aircraft observation type) roughly triples in value between 24-hr and 48-hr forecasts, while bogus TC vortex observations ("TC-Synth") experience

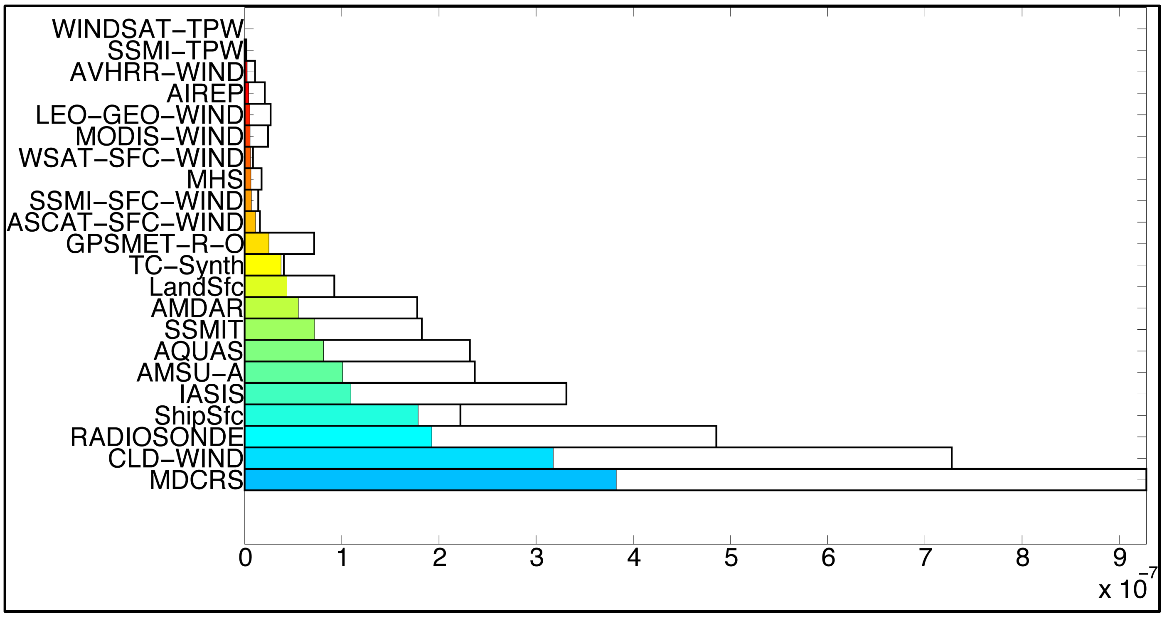

Figure 5. Cumulative impact of observations on Sandy's 24-hr intensity forecast (shaded region of bars) and 48-hr intensity forecast (black outlines).

almost no increase in impact at all. The modest increase in impact from MODIS and LEO/GEO AMVs indicates an increased sensitivity to high-latitude features in the 48-hr forecast.

The importance of these observations to Sandy's intensity forecast may come from two sources. First, Sandy made landfall along the US eastern seaboard, which is the site of significant aircraft activity. MDCRS observations are available to help define the environment that Sandy eventually propagates into when it makes landfall. Second, Sandy's evolution is so strongly influenced by its interaction with a midlatitude trough that moved across the continent, where MDCRS observations were collecting data for days leading up to their eventual interaction. Wind observations produced by tracking features in satellite imagery ("CLD-WIND", also known as Atmospheric Motion Vectors, or AMVs) are also critical to the forecast, as are radiosondes. Comparing the 24-hr impact to the 48-hr impact, it is clear that most if not all observation types impose a larger impact on the 48-hr intensity forecast. This is consistent with the fact that the sensitivity of the 48-hr forecast to initial

Individual observations in the system provide a wide range of impacts on the TC intensity forecast; most observations provide very little impact, while a small minority of observations contribute a significant amount. When observations within a 4000 km, 1000 km, or 250 km radius of the TC are binned by their impact and these bins are plotted in log-space, they conform to a straight line (Fig. 6a), indicating a power-law distribution.

One behavior of a power-law distribution is that a significant amount of the total (in this case, the total observation-impact within a given radius) is contributed to by a very small minority of very high-impact members. This means that

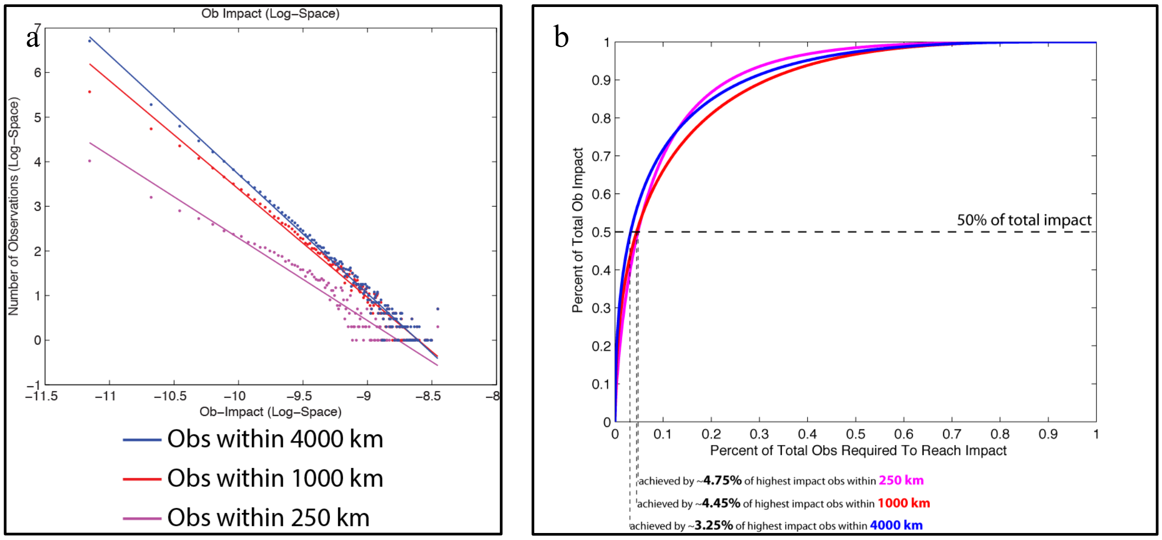

Figure 6. (a) Rank histogram of 24-hr observation-impact in log-space for observations within 4000 km (blue), 1000 km (red), and 250 km (magenta) of the TC, with linear best-fit approximations overlaid. (b) Plot of the percentage of total observation impact (ordinate) and the percentage of highest-impact observations necessary to achieve that percentage (abscissa), for all three radii. The 50% of total impact line is provided by a dashed black line.

much of the impact of the entire observing system on Sandy's intensity forecast comes from very few observations.

To demonstrate this, observation-impact was summed in each of these three radii, and then observations were ranked by their impact. Starting with the highest-impact observation, the number of observations needed in order to reclaim a given percentage of the total impact was calculated (Fig. 6b). Focusing on the 50% line, it appears that in order to reclaim 50% of the total impact from observations within any of the chosen radii, one only needs to include between 3.25% (for the 4000 km radius) and 4.75% (for the 250 km radius) of the observations, so long as those are the observations expressing the highest impact. This indicates that collectively, the remaining 95% – 97% of observations in any of these radii are only contributing the other half of the impact on the forecast intensity.

4. Conclusions

The sensitivity of NAVGEM intensity forecasts of Hurricane Sandy (2012) to perturbations of the initial state, and the impact of assimilated observations on intensity forecasts, were estimated using the NAVGEM and NAVDAS-AR adjoint system. The sensitivity and observation-impact characteristics of 24-hr and 48-hr forecasts were compared, and it was shown that the 48-hr forecast typically exhibits higher magnitude of sensitivity to wind perturbations than the 24-hr forecast, especially in the mid to upper troposphere. Enhanced sensitivity appears far upstream of the TC vortex, focusing on dynamically important regions of the upstream environment, such as the exit region of a nearby branch of the polar jet. Sensitivity extends beyond 40 degrees of latitude upstream of the TC for the 48-hr intensity forecast, in a layer between 700 – 200 hPa.

Observation-impact estimates show that MDCRS observations (u,v,T) are the highest-impact observation type, followed by AMVs from geostationary satellite imagery, and radiosondes. Observations impose a larger impact on the 48-hr forecast than they do on the 24-hr forecast, consistent with the higher sensitivity of the 48-hr forecast discussed previously. Some observation types derive a much larger increase in impact at 48-hrs than others. In general, observation-impact follows a power-law distribution, where a very small minority of high-impact observations contributes a significant portion of the total impact of all observations. Within radii of 4000 km, 1000 km, and 250 km of the TC, only 3.25 – 4.75% of the highest impact observations are responsible for half of the total impact, with the remaining 95 – 97% of observations contributing the other half.

These results illustrate model behavior that may help inform the future evolution of the observing system, if TC intensity forecasting beyond 24-hrs is considered a high priority. In order to impact the TC intensity forecast at these longer ranges, new observations must produce analysis increments that project onto the sensitivity gradients observed for forecasts at longer range. This means that observations must: (1) cover a broad geographic area, (2) provide data in the middle to upper troposphere, and (3) be numerous enough that the 3 – 5% of high-impact observations that contribute half of the impact on the forecast can be discovered.

Ultimately, it appears that satellite observations are well-suited to this task, having the required areal coverage, producing observational data in the middle to upper troposphere, and being capable of producing data with spatial and temporal resolution sufficient to identify the minority of high-impact observations that will contribute to the forecast.

5. References

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