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SIXTH INTERNATIONAL WORKSHOP on TROPICAL CYCLONES

Topic 3.3 : **Targeted observation and data assimilation in track prediction**

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3.3.1. **Introduction**

The objective of this report is to document recent progress since IWTC-5 on the topic related to the Targeted observation and data assimilation in track prediction. The report begins by reviewing the background of targeted observations, followed by an introduction to the techniques specifically used for targeted observations and data assimilation to improve tropical cyclone track prediction. These findings are discussed along with some tentative recommendations on these important scientific issues to the workshop.

To optimize limited aircraft and satellite resources, making targeted observations only in the critical areas that will have the maximum influence on numerical weather forecasts of tropical cyclones (TC) is important. Therefore, targeted observing strategies for aircraft missions and satellite products must be developed. The prerequisite for devising the observing strategy is to identify the sensitive areas that will have the greatest influence in improving the numerical forecast, or minimizing the forecast error.

In aircraft missions in the early 1990s, sensitive areas were subjectively decided through synoptic analysis or some limited numerical model sensitivity tests. For example, the areas around the surface low centers or the upper-level jet streams were considered to be the sensitive areas that needed to be observed to affect the atmospheric characteristics around the weather systems. It has been demonstrated (Burpee et al. 1996 and Aberson and Franklin 1999) that these basic observing strategies resulted in notable improvements in model predictions of tropical cyclones.

Rather than using subjective analysis, scientists have recently developed some objective techniques (e.g., adjoint method, singular vectors, and various usages of ensemble forecast system (EFS)) to design targeted observations. These techniques can not only test the atmospheric predictability of numerical models, but also identify the sensitive areas at the model initial time. It is expected that taking extra observations in these sensitive areas can reduce the error of the model forecast.

Pu et al. (1998) used the adiabatic version of National Centers for Environmental Prediction (NCEP) operational T126/L28 global spectral model to study the forecast sensitivity to initial analysis differences by using the adjoint method and quasi-inverse linear method. They found that these two methods were somewhat complementary. The quasi-inverse linear sensitivity is reliable in pinpointing the region of origin of a forecast difference, and this is particularly useful for cases in which the ensemble forecast spread indicates a region of large uncertainty, or when a specific region requires improved forecasts. The adjoint sensitivity is useful for identifying areas that have maximum impact on the region of interest, but are not necessarily the regions actually leading to observed differences. Pu et al. propose that both methods can be useful for targeted observing systems.

To address the life cycle of cyclones evolving over the North Atlantic Ocean, the Fronts and Atlantic Storm-Track Experiment (FASTEX) was held from January to February 1997 (Joly 1997). The targeted observation strategies included both the subjective analysis and objective sensitive areas for this experiment. The objective sensitivity studies were carried out on the basis of several products (Emanuel and Langland 1998): singular vectors calculated by the adjoint of the linear tangent model of the Navy Operational Global Atmospheric Prediction System (NOGAPS) model (Gelaro et al. 1999); perturbation mean square enstrophy (mean square vorticity) integrated over the 800-900 hPa layer by the tangent linear and adjoint model of the Météo- France Numerical Weather Prediction model (Bergot et al. 1999): singular vectors from the European Center for Medium-range Weather Forecasts (ECMWF) (Montani et al. 1999); and ensemble transform method from the NCEP global model (Bishop and Toth 1999).

An interagency field program called the North Pacific Experiment (NORPEX) during the winter of 1998 directly addressed the issue of observational sparsity over the North Pacific basin, which is a major contributing factor for short-range forecast failures of landfalling Pacific winter systems that affect the United States (Langland et al. 1999). The objective targeting in NORPEX was built upon experiences gained during the FASTEX. However, the targeted observations were performed using two objective methods: singular vectors computed using the NOGAPS and the ensemble transformation applied to the NCEP and ECMWF global ensemble forecasts.

3.3.2 **Recent techniques for targeted observations for tropical cyclones**

For operational surveillance missions in Atlantic hurricanes conducted by the NOAA (Aberson 2003) and the DOTSTAR (Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region; Wu et al. 2005), four sensitivity techniques have been used to determine the observation strategies.

3.3.2.1 Deep-Layer Mean wind variance

Based on the deep-layer mean (DLM) or 850-200 hPa steering flows from the NCEP EFS Global Ensemble Forecasting System (EFS; Aberson 2003), areas with the largest (DLM) wind ensemble spread represent the sensitive regions at the observing time. The DLM wind ensemble spread is chosen because tropical cyclones are generally steered by the environmental DLM flow, and the dropwindsondes from the NOAA Gulfstream IV sample this flow. Aberson (2003) demonstrated that using only the subset of observations in the areas of high NCEP EFS DLM wind variance improved the TC track forecasts more than using uniformly-sampled observations. While the variance in the DLM wind may amplify in the model and be propagated into a chosen verification region at some future time, it may also decay. Aberson (2003) showed that this strategy selected structures at the observing time that most significantly reduced the forecast error variance near the tropical cyclone, but not necessarily within a particular verification region at a verifying time.

An example for this DLM method is shown in Fig. 3.3.1 for Typhoon Meari (2004) in the western North Pacific. The DLM wind variance indicates that, at the planned observing time of 1200 UTC 25 Sep 2004, the sensitive areas will be to the northeast and southwest of the center of Meari.

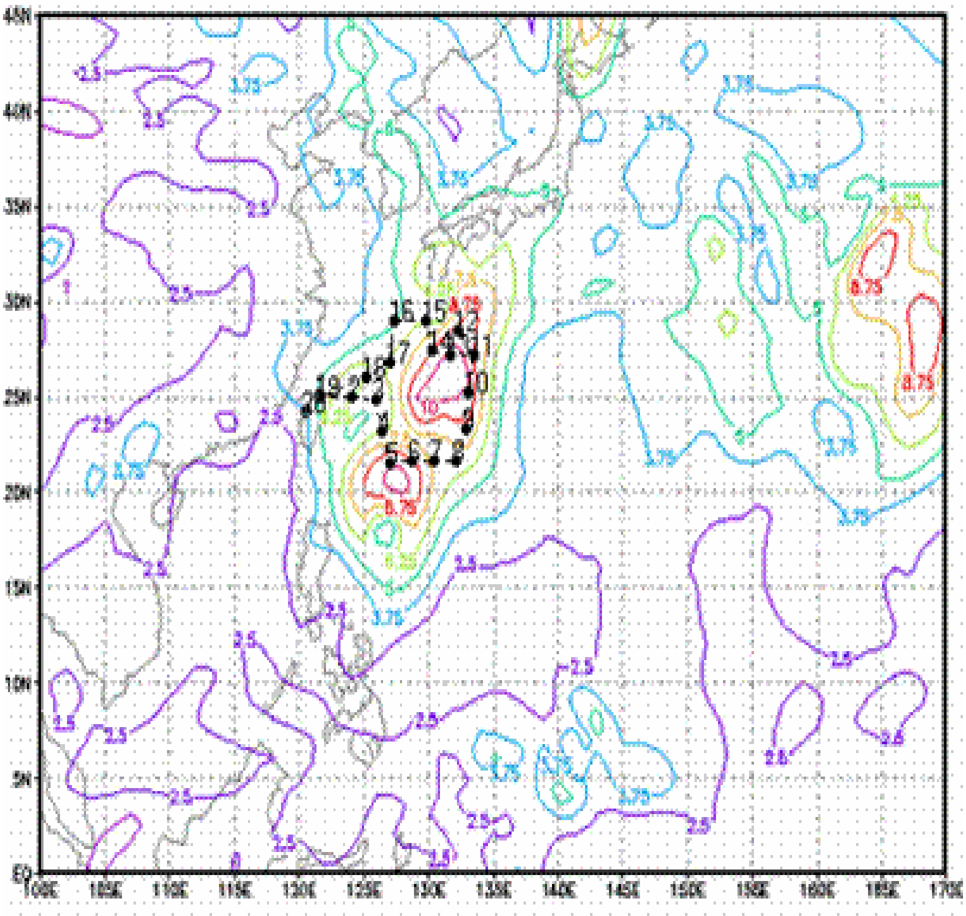

Fig. 3.3.1 NCEP Deep-Layer Mean (DLM) wind variance for Typhoon Meari (2004) at 1200 UTC 25 Sep 2004. The black dots represent the locations where the dropwindsondes were deployed in a DOTSTAR mission.

3.3.2.2 Ensemble Transform Kalman Filter (ETKF)

This technique predicts the reduction in forecast error variance for feasible deployments of targeted observations based, in this case, on the NCEP EFS (Majumdar et al. 2006). The ensemble transform Kalman Filter (ETKF) (Bishop et al. 2001), like the first technique, uses the differences between ensemble members to estimate regions for observation missions. The ETKF takes the approach of DLM wind variance further. Though DLM wind variance indicates areas of forecast uncertainty at the observation time, it does not correlate initial condition uncertainty with the errors in the forecasts. The ETKF explicitly correlates errors at the observing time with errors of the forecasts. That is, the ETKF identifies ensemble variance that impacts the forecasts in the verifying area at the verifying time.

The ETKF uses operational ensemble forecast perturbations to reduce forecast error variance that would be achieved by targeted observations. The analysis error covariance matrix $\mathbf{P}^r(t_o)$at the observing time (t_o) pertaining to the routine observational network comprised of rawinsondes and satellite-based temperature fields is found by solving the Kalman filter error statistics equation:

$$\mathbf{P}^r(t_o)=\mathbf{P}^i(t_o)-\mathbf{P}^i(t_o)\mathbf{H}^{rT}(\mathbf{H}^r\mathbf{P}^i(t_o)\mathbf{H}^{rT}+\mathbf{R}^r)^{-1}\mathbf{H}^r\mathbf{P}^i(t_o), \quad (1)$$

where $\mathbf{H}^r$ and $\mathbf{R}^r$ are the observation operator and error covariance matrices, respectively, and $\mathbf{P}^r$ is the analysis error covariance matrix at the initial time. The analysis error covariance matrix $\mathbf{P}^q(t_o)$ for the observational network augmented by the q^{th} hypothetical "test-probe" of targeted observations with operator $\mathbf{H}^q$ and error covariance matrix $\mathbf{R}^q$ is then expressed as

$$\mathbf{P}^q(t_o)=\mathbf{P}^r(t_o)-\mathbf{P}^r(t_o)\mathbf{H}^{qT}(\mathbf{H}^q\mathbf{P}^r(t_o)\mathbf{H}^{qT}+\mathbf{R}^q)^{-1}\mathbf{H}^q\mathbf{P}^r(t_o). \quad (2)$$

The associated "signal covariance" matrix valid at the verification time (t_v) is given by

$$\mathbf{S}^q(t_v)=\mathbf{M}\mathbf{P}^r\mathbf{H}^{qT}(\mathbf{H}^q\mathbf{P}^r\mathbf{H}^{qT}+\mathbf{R}^q)^{-1}\mathbf{H}^q\mathbf{P}^r\mathbf{M}, \quad (3)$$

where $\mathbf{M}$ propagates perturbations from t_o to t_v. The ensemble forecast perturbations at t_v are used to rapidly compute the trace of $\mathbf{S}^q(t_v)$ in the verification region. The ETKF "summary map" represents this signal variance as a function of the central location of adjacent 3×3 test-probes at 1^o lat./long. resolution. The test-probe location that produces the highest signal variance is deemed optimal for targeting.

For the observing mission of Typhoon Meari (2004), the ETKF technique indicates that in addition to the area around the typhoon center some sensitive areas appear in the northern part of Meari (Fig 3.3.2).

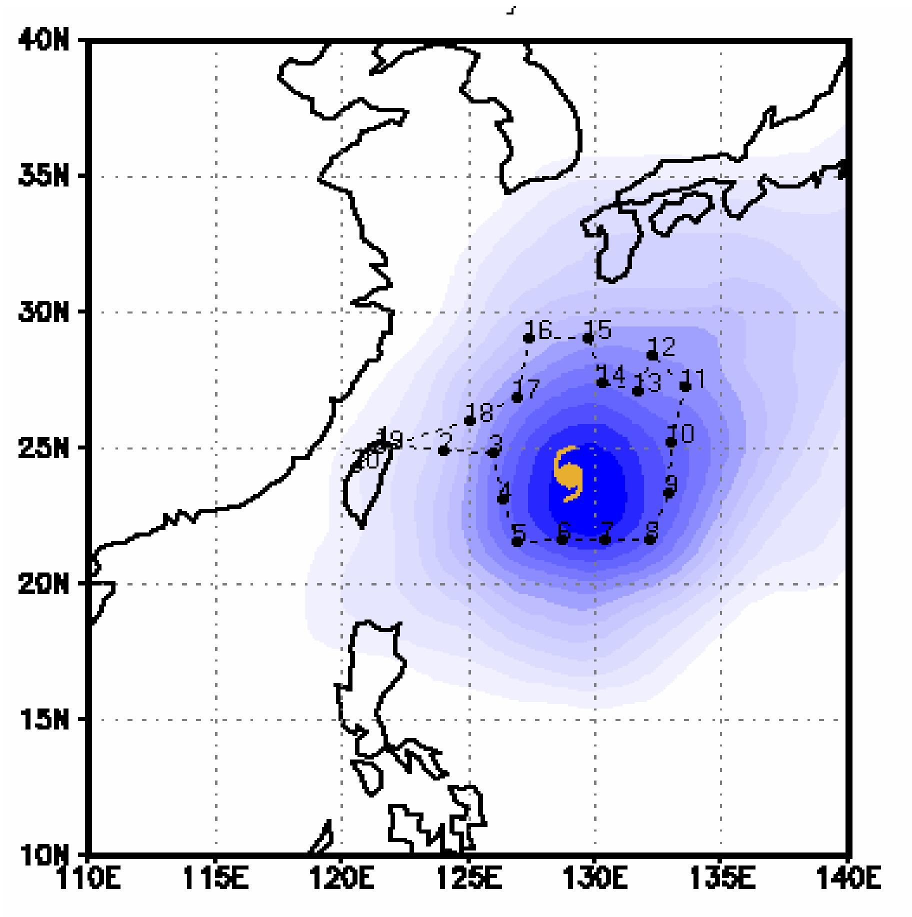

Fig. 3.3.2 As in Fig. 3.3.1, except for the NCEP ETKF summary map for Typhoon Meari (2004).

3.3.2.3 Singular Vector (SV) technique

The SV technique maximizes the growth of a total energy or kinetic energy norm (e.g., Palmer et al. 1998; Peng and Reynolds 2006) using the adjoint and forward-tangent models of the Navy Operational Global Atmospheric Prediction System (NOGAPS; Rosmond 1997; Gelaro et al. 2002), and also the ensemble prediction system (EPS) of Japan Meteorological Agency (JMA).

The leading singular vector (SV) represents the fastest growing perturbation to a given trajectory (such as a weather forecast) in a linear sense (Peng and Reynolds 2006). Consider a nonlinear model M, acting on a state vector $\mathbf{x}$, such that $M(\mathbf{x}_0)=\mathbf{x}_t$, where the subscript refers to the integration time. Let $\mathbf{x}_0'$ represent some perturbed initial state, such that $\mathbf{x}_0' - \mathbf{x}_0=\mathbf{p}_0$ and $M(\mathbf{x}_0')-M(\mathbf{x}_0)=\mathbf{p}_t$. For linear perturbation growth, the initial perturbation can be propagated forward in time using the forward-tangent propagator, $\mathbf{L}$, representing the model equations of M linearized about the nonlinear trajectory, such that

$$\mathbf{L}\mathbf{p}_0 \cong \mathbf{p}_t \qquad (4)$$

Then L can be represented by its singular values and initial- and final-time SVs as :

$$\mathbf{L} = \mathbf{E}^{-1/2}\mathbf{U}\mathbf{D}\mathbf{V}^{\mathbf{T}}\mathbf{E}^{\mathbf{1}/2}, \tag{5}$$

where **V** (**U**) are matrices with columns composed of the initial (final) SVs, and **D** is a diagonal matrix whose elements are the singular values of **L**. Here **E** is the matrix that defines how the perturbations are measured. Thus, the SVs form an **E**-orthonormal set of vectors at the initial and final times. The SVs satisfy the eigenvector equation $\mathbf{L}^T\mathbf{E}\mathbf{L}\mathbf{y}_n = d_n^2\mathbf{E}\mathbf{y}_n$ where $\mathbf{y}_n = \mathbf{E}^{-1/2}\mathbf{v}_n$, and d_n and $\mathbf{v}_n$ are the n^{th} singular value and initial-time SV, respectively. The leading SV maximizes the ratio of the final perturbation energy to the initial perturbation energy:

$$\frac{\langle \mathbf{p_t}; \mathbf{E}\mathbf{p_t} \rangle}{\langle \mathbf{p_0}; \mathbf{E}\mathbf{p_0} \rangle} \tag{6}$$

where < > represents a Euclidean inner product. The 2^{nd} SV maximizes this ratio under the constraint of being orthogonal to the first SV, the 3^{rd} SV maximizes this ratio under the constraint of being orthogonal to the first two SVs, and so on. For complex models such as dynamical tropical cyclone models, the eigenvector equation may be solved in an iterative fashion using the forward and adjoint propagators linearized about a particular forecast.

The sensitivity areas for Typhoon Meari (2004) determined from the NOGAPS SV method are shown in Fig. 3.3.3. The sensitive areas at the observing time are in the northern and southern regions of Meari, with maximum values to the south of the typhoon center. The sensitive area far to the northwest represents the location of the mid-latitude trough at that time. It is expected that this mid-latitude trough may have some influence on the future track of Meari.

Another singular vector method is calculated from the JMA EPS (Yamaguchi, personal communication 2006). A typhoon EPS that is planned to be operational in 2007 has been developed using the linearized model and its adjoint version adopted for the JMA global 4D-Variational analysis system. The linearized model and adjoint consist of full dynamics based on Eulerian integrations and full physical processes including representations of vertical diffusion, gravity-wave drag, large-scale condensation, long-wave radiation, and deep cumulus convection. Two kinds of singular vectors can be calculated: dry and moist singular vectors. Dry singular vectors, which are expected to identify the most unstable dynamical modes of the atmosphere such as a baroclinic mode, are obtained using simplified physical processes that only include vertical diffusion. Moist singular vectors are acquired using full physics, and thus require nearly twice as much computation costs as for the dry ones but capture of the uncertainty in areas such as a tropical region or typhoon surroundings where moist processes are dominant.

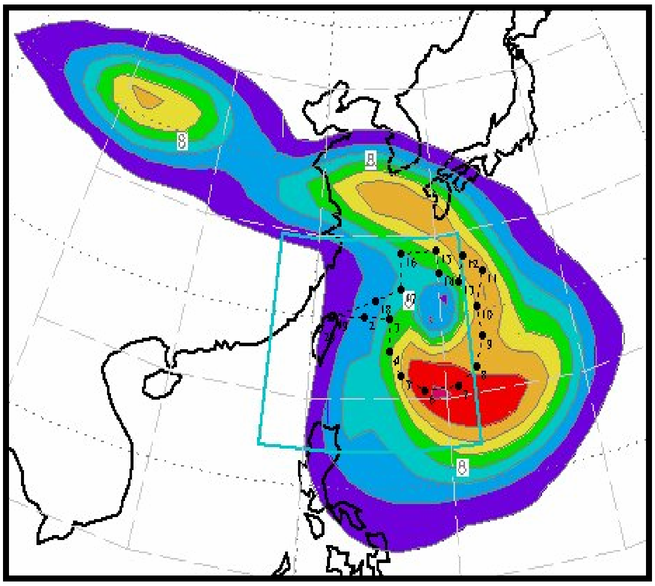

Fig. 3.3.3 As in Fig. 3.3.1, except for the NOGAPS Singular Vector approach for Typhoon Meari (2004).

The sensitive areas for the JMA moist SV method for Typhoon Etau (2003) are given in Figure 3.3.4. The maximum values are in the southwest quadrant of the typhoon. At least with the first 25 singular vectors (Fig. 3.3.5), the JMA dry SV does not have a similar structure around the tropical cyclone.

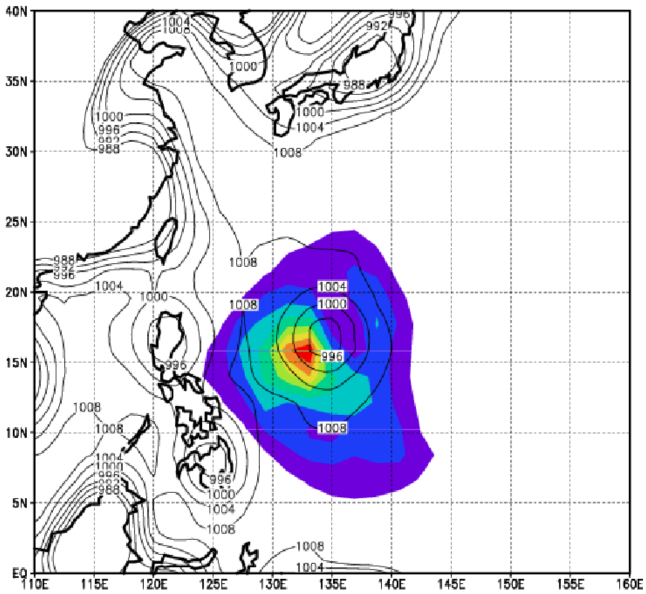

Fig. 3.3.4 JMA moist Singular Vector for Typhoon Etau (2003) (from Yamguchi).

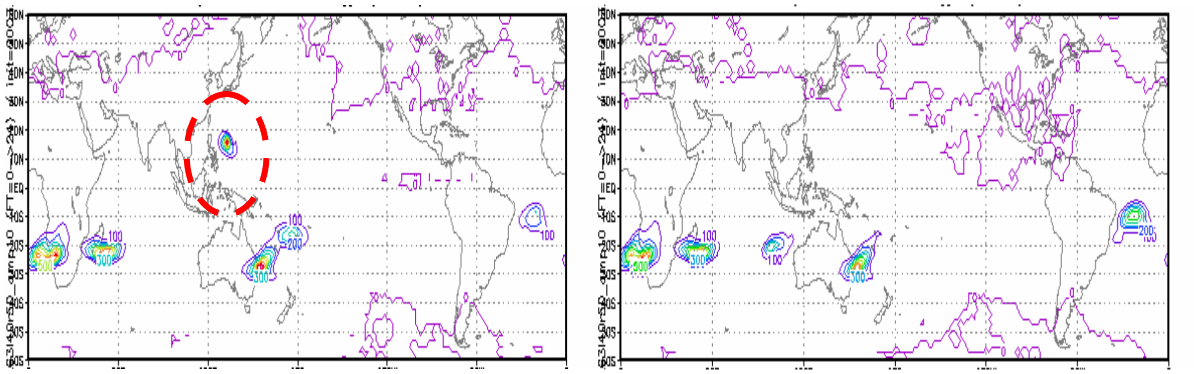

Fig. 3.3.5 JMA (right) dry singular vectors, and (left) moist singular vectors for Typhoon Etau (2003) (from Yamaguchi).

3.3.2.4 Adjoint-Derived Sensitivity Steering Vector (ADSSV)

By appropriately defining the response functions to represent the steering flow at the verifying time, a simple vector (ADSSV, defined below)has been designed to clearly demonstrate the sensitivity locations and the critical direction of the typhoon steering flow at the observing time (Wu et al. 2006).

Because the goal is to identify the sensitive areas at the observing time that will affect the steering flow of the typhoon at the verifying time, the response function is defined as the DLM wind within the verifying area. A 600 km by 600 km square area centered on the MM5-simulated storm location at the verifying time is used to calculate the background steering flow as defined by Chan and Gray (1982). Two responses functions are then defined: R1, which the 850-300 hPa deep-layer area average (Wu et al. 2003) of the zonal component (u); and R2, the average of the meridional component (v) of the wind vector, i.e.,

$$R_1 \equiv \frac{\int_{850hPa}^{300hPa}\int_A u \quad dxdydp}{\int_{850hPa}^{300hPa}\int_A dxdydp}, \text{ and } R_2 \equiv \frac{\int_{850hPa}^{300hPa}\int_A v \quad dxdydp}{\int_{850hPa}^{300hPa}\int_A dxdydp}. \qquad (4)$$

By averaging, the axisymmetric component of the strong cyclonic flow around the storm center is removed, and thus the vector of (R_1, R_2) represents the background steering flow across the storm center at the verifying time. To interpret the physical meaning of the sensitivity, a unique new parameter called the Adjoint-Derived Sensitivity Steering Vector (ADSSV) is designed that relates the sensitive areas at the observing time to the steering flow at the verifying time. The ADSSV with respect to the vorticity field (ς) is

$$ADSSV \equiv \left(\frac{\partial R_1}{\partial \varsigma}, \frac{\partial R_2}{\partial \varsigma}\right), \qquad (5)$$

where the magnitude of ADSSV at a given point indicates the extent of the sensitivity, and the direction of the ADSSV represents the change in the response of the steering flow due to a vorticity perturbation placed at that point. For example, if at a given forecast time the ADSSV vector at one particular grid point points to the east, an increase in the vorticity at this point at the observing time would be associated with an increase in the eastward steering of the storm at the verifying time.

The ADSSV based on the MM5 forecast (Fig. 3.3.6) mostly extends about 300-600 km from the north to the east of Typhoon Meari. The directions of the ADSSVs in these areas indicate greater sensitivity in affecting the meridional component of the steering flow.

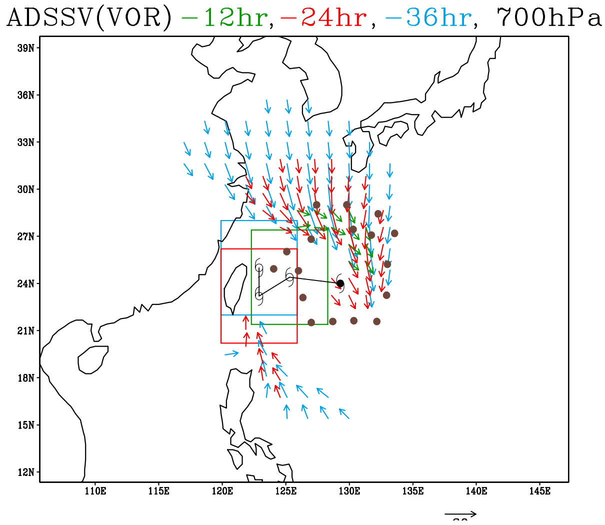

Fig. 3.3.6 The sequence of ADSSVs based on the -12 h, -24 h, and -36 h MM5 forecasts for Typhoon Meari (2004).

3.3.3. **Comparison of targeted observing guidance for track prediction**

Targeted dropwindsonde observations have been collected in the synoptic environment of hurricanes (Aberson 2003) and typhoons (Wu et al. 2005) to improve operational track forecasts. Although these dropwindsonde observations have been shown to have a positive impact in improving the accuracy of global model track forecasts, the scientific basis for how observations influence forecasts of TC motion and structure remains unexplored. Furthermore, the benefits of assimilating additional observations from different platforms on multiple spatial and temporal scales using novel data assimilation methods have not been adequately studied.

Techniques to “target” observations to improve TC forecasts require an accurate representation in the numerical model, data assimilation scheme, and the error propagation and growth. Although several techniques are being tested and compared (Majumdar et al. 2006), they all require evaluation and an improved scientific understanding in the TC environment.

Majumdar et al. (2006) conducted a detailed comparison of different targeting techniques. Based on comparisons for 78 two-day forecasts of Atlantic tropical cyclones during the 2004 season, they found that the ECMWF and NOGAPS TESVs (total energy singular vector) offer similar guidance for adaptive sampling on large scales, although smaller-scale aspects local to the tropical cyclone may differ. For major hurricanes, the ETKF and TESV guidance usually both indicate that the optimal locations for adaptive sampling are in a region around the storm. In contrast, the ETKF and TESV guidance is often in considerable disagreement for weaker storms. The sensitivity areas from the ECMWF ETKF resembled those for the NCEP ETKF more for major hurricanes than for weak tropical cyclones, and the NCEP ETKF areas often resembled those based on the NCEP DLM Wind Variance.

In a data denial study using the NCEP global model looking at these techniques in the Atlantic, 31 cases from 2004 and 2005 were studied; in each case, the operational cycle with all dropwindsonde data (GSAL) and a parallel run with none of the dropwindsonde data (GSNO) are used. Three additional runs were completed: (i) only those dropwindsonde data that meet the targeting requirements specified in Aberson (2003) are assimilated (GSTG); (ii) those dropwindsondes that meet the sampling strategy specified in Aberson (2003), but with targets defined by the ETKF are assimilated (GSET); and (iii) those dropwindsondes that meet the sampling strategy specified in Aberson (2003), but with targets defined by the NOGAPS singular vectors are assimilated (GSSV). From Table 3.3.1, the 84-h forecasts with ETKF targeting are statistically far better than those from the standard sampling at the 95% level. However, the 12-h and 24-h forecasts with ETKF targeting are statistically far worse than those from the standard sampling at the 90% level.

Table 3.3.1 Average track errors (km) for a homogeneous sample of GSET, GSAL, and GSNO.

FCST TIME	12h	24h	36h	48h	60h	72h	84h	96h	108h	120h
GSAL	41.2	69.6	107.7	127.8	182.5	256.8	291.5	348.3	369.9	385.7
GSNO	67.1	93.7	134.1	169.3	193.3	265.5	239.2	299.1	316.8	356.2
GSET	46.2	80.5	114.4	143.0	176.7	239.9	257.3	326.8	356.2	399.4
#CASES	23	23	22	21	20	20	19	18	16	14

For targeting based on the the DLM wind variance, only the 108-h forecasts with ensemble spread targeting (GSTG) are statistically far better than those from the standard sampling (GSAL) at the 95% level (Table 3.3.2). However, the inclusion of all dropsondes (GSAL) and the GSTG targeted approach both lead to significantly poorer track forecasts between 84 h and 120 h.

Table 3.3.2 Average track errors of GSTG and comparison with the GSAL and GSNO.

FCST TIME	12h	24h	36h	48h	60h	72h	84h	96h	108h	120h
GSAL	48.4	76.9	110.7	140.6	207.5	289.6	327.0	397.1	459.6	523.0
GSNO	68.1	89.2	123.1	163.5	210.4	292.8	271.4	328.2	339.5	388.1
GSTG	51.5	82.2	111.3	148.2	219.0	289.9	307.3	388.0	413.9	506.1
#CASES	21	21	21	21	21	21	19	17	14	12

In the comparison of the DLM wind variance and the ETKF method together (Table 3.3.3), the ensemble spread targeting is not statistically far different from the ETKF targeting at the 90% level at any forecast time.

Table 3.3.3 Average track error (km) for a homogeneous sample of GSET, GSTG, and GSAL and GSNO.

FCST TIME	12h	24h	36h	48h	60h	72h	84h	96h	108h	120h
GSAL	46.6	78.9	114.5	149.3	210.0	300.5	345.6	419.2	456.0	509.9
GSNO	74.1	104.4	138.0	186.6	233.3	313.1	272.4	335.8	362.3	410.8
GSET	53.4	87.4	110.0	149.8	208.4	284.4	306.5	391.5	440.6	526.4
GSTG	52.6	86.7	110.5	151.3	214.1	283.9	311.2	392.6	418.0	499.8
#CASES	15	15	15	15	15	15	14	13	11	9

Only two cases with the NOGAPS SVs have been run, not enough to calculate statistical significance.

The results of these tests suggest that the targeting and sampling strategy described in Aberson (2003) and from the ETKF are appropriate for the design of flight tracks to improve the tropical cyclone track forecast. Both techniques provide forecasts that are statistically significantly better than those with no sampling during the first three days of the forecast. The sample sizes are larger than those in the HRD synoptic flow experiment (Burpee et al. 1996), and are therefore expected to be robust. Although the singular vector technique is showing promise, it was for a very limited sample of cases.

Etherton et al. (2006) qualitatively discussed the observational sensitivity results in 2005 Atlantic season for three strategies: DLM wind variance, ETKF, and ADSSV. The DLM wind variance approach tends to produce sensitivity areas that are very near the center of the tropical cyclone. The ETKF tends to produce a bit more information regarding which features, other than the tropical cyclone, are important to the future track forecast. By construction, the ADSSV rarely, if ever, selects targets in the immediate vicinity of the center of the tropical cyclone. Instead, a ring around the storm is usually the target area, although areas to the south, west, and east are more common than locations to the north of the center of a cyclone.

3.3.4 **Further discussions**

As shown by Aberson and Etherton (2006) and Huang and Wu (2006), both the targeted observations and the appropriate assimilation of data [such as the advances in the bogused vortex scheme with variational data assimilation (Xiao et al. 2000; Zou and Xiao 2000; Pu and Braun 2001; park and Zou 2004; Wu et al. 2006) and the ensemble transform Kalman filtering method for hurricane study (Aberson et al. 2006)] from different platforms [such as satellites (GOES by Zou et al. 2001; TRMM by Pu et al. 2004; Bauer et al. 2006a, b) and field programs (CAMEX-4, Kamineni et al. 2006)] with different spatial and temporal resolutions and error characteristics (Fisher 2003; Berre et al 2006, Westrelin et al 2006) will play a very important role in improving tropical cyclone track forecasts. Further development and comparison of the targeting strategies and the improvement of the data assimilation techniques remain important tasks for the future.

Note that there has been significant progress in our understanding of the basic oceanic and atmospheric processes that occur during the passage of TCs. Central to these assertions is the need to isolate fundamental physical processes involved in the interactions through detailed process studies using experimental, empirical, theoretical and numerical approaches. As found from measurements, these approaches are needed to improve predictions of not only TC tracks, but also intensity and structure.

Some general issues of concerns from the THORPEX report (provided by Steve Tracton) on targeted observations are worth noting here:

1) Although the impact of observation is greater when selected in a sensitive area, the few observations deployed cannot make a substantial impact on the forecasts.

2) The statistical evaluation of the significance of the measured impact requires a large number of cases.

3) Current diagnostics used to evaluate forecasts provides a good assessment of the validity of forecasts (skill), but it may not be sufficient to reveal whether these improvements are relevant to applications (value).

4) The use of climatological sensitivities may lead to improvements on average and be more cost effective than targeted observations on demand.

5) Overall, there was a considerable question as to the value of targeting, especially when isolated from the more general issues of observing system sensitivities in design of an “optimal” mix of available observing platforms.

3.3.5 **Recommendations**

Tentative recommendations in this topic group are outlined below, though further elaboration from the workshop is needed:

1) More emphasis on the dependence of targeting impacts upon the data assimilation system and expectations/limitations.

This is especially critical in the tropics, where data assimilation is handicapped by weakly balanced flow dependent structure functions and larger (than extratropics) uncertainties/deficiencies in the physics of the assimilating forecast model, especially in regard to high resolution regional systems.

2) More studies of varying definitions, interpretations, and significance of sensitive regions (e.g., different methods, metrics)

3) More work on sampling strategies in sensitive areas, e.g., immediate storm environment for shorter range prediction versus remote areas relevant to longer range forecasts – including the impact of large scales in meso-scales models.

4) More work on metrics to assess the impact of targeting – or more generally on any changes in the observation network.

In particular we need to look at the impacts on the variability in ensemble predictions. Thus, for example, track error is only a first order measure – single deterministic forecast which may or may not be representative of an ensemble of forecasts. The end game is whether the observation sensitivity translates to decreased uncertainty (narrower envelope about track – ensemble spread is (should be) more related to the level of uncertainty than skill of any particular single forecast run).

5) Emphasis of the potential value of OSEs and OSSE’s (e.g., Wu et al. 2006) in assessing potential observing system impacts prior to actual field programs.

6) Stronger efforts to develop alternative observing platforms (other than the dropwindsondes) for targeting, especially adaptively selecting satellite observations by revising the data thinning algorithms currently used.

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