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Abstract

This study examines the relative impact of assimilating T-TREC retrieved winds ($V_{\text{TREC}}$) versus radial velocity ($V_r$) on the analysis and forecast of Typhoon Jangmi (2008) using an ensemble Kalman filter. The $V_{\text{TREC}}$ and $V_r$ data at 30 min intervals are assimilated into the ARPS model at 3 km grid spacing over four different assimilation windows that cover, respectively, 0000 – 0200, 0200 – 0400, 0400 – 0600, and 0000 – 0600 UTC, September 2008. The assimilation of $V_{\text{TREC}}$ data produces better analyses of the typhoon structure and intensity than the assimilation of $V_r$ data during the earlier assimilation windows but during the later assimilation windows when the coverage of $V_r$ data on the typhoon from four Doppler radars is much improved, the assimilation of $V_r$ outperforms $V_{\text{TREC}}$ data. The combination of $V_{\text{TREC}}$ and $V_r$ data, either by assimilating both $V_{\text{TREC}}$ and $V_r$ data in all cycles, or assimilating $V_{\text{TREC}}$ in the first cycle and $V_r$ in the remaining cycles (labeled $V_{\text{TFVR}}$), further improves the analyses of the typhoon structure and intensity compared to assimilating $V_{\text{TREC}}$ or $V_r$ data alone. Quantitative verifications of 24-hour forecasts of the typhoon show that the $V_{\text{TFVR}}$ assimilation experiments produces forecasts that best match the best track data and also have the highest precipitation prediction skills. The track forecast errors in experiment that assimilate $V_{\text{TREC}}$ data through the later cycles are the largest. The behaviors are discussed based on the coverage, information content, and accuracy of the various forms of data.
1. Introduction

Ground-based Doppler radars provide three-dimensional wind and precipitation observations of tropical cyclones (TCs) at high temporal and spatial resolution when TCs move within the range of coastal radars. These observations help improve our understanding of important processes within the TC inner core and the outer rainbands [Blackwell, 2000; Corbosiero et al., 2006; Hong and Chang, 2005; Lee et al., 2000; Lee and Bell, 2007; Zhao et al., 2008]. Efforts have been made to assimilate the radial velocity ($V_r$) and reflectivity ($Z$) from ground-based Doppler radars into high resolution NWP model to improve the TC forecasts, and the data assimilation (DA) methods used include the three-dimensional variational (3DVAR) method [Xiao et al., 2007; Zhao and Xue, 2009; Zhao et al., 2012; Zhao and Jin, 2008], the ensemble Kalman filter (EnKF) [Dong and Xue, 2013; Xue and Dong, 2013; Zhang et al., 2009], and the ensemble-variational hybrid method [Li et al., 2012]. Results have shown that the assimilation of $V_r$ and/or $Z$ has positive impacts on TC intensity and track forecasting.

For typical S-band operational weather surveillance radars, e.g., the WSR-88D (Weather Surveillance Radar-1988 Doppler) of the United States and the CINRAD-98D (China New Generation Radar-1998 Doppler) of China, the maximum range of $Z$ observations is about twice as that of $V_r$. By tracking the motion of radar echo, the T-TREC technique [Wang et al., 2011] can produce retrieved winds ($V_{TREC}$) with a much larger coverage than $V_r$ data. The inner-core TC circulation can be captured much sooner by the retrieved $V_{TREC}$ than $V_r$ when a TC approaches a coastal radar [Wang et al., 2011]. This reflectivity-derived $V_{TREC}$ also has both radial and cross-beam wind components, and therefore contains more complete wind information than $V_r$. The assimilation of
\( V_{\text{TREC}} \) into numerical models thus has the potential to improve the TC forecasts at a longer lead time and to enable earlier warnings to the coastal community. The drawback with the T-TREC data is that they have lower spatial resolutions (10 km) than Vr data (~250 m).

Two recent studies examined the impact of \( V_{\text{TREC}} \) assimilation on the analyses and forecasts of typhoons [Li et al., 2013; Wang et al., 2014, W14 hereafter]. Li et al. [2013] assimilated \( V_{\text{TREC}} \) data using the WRF 3DVAR system [Barker et al., 2004; Xiao et al., 2005] for Typhoon Meranti (2010) before it made landfall in Fujian Province of China. \( V_{\text{TREC}} \) or Vr data from a coastal radar were assimilated for single time assimilations at different lead times. Results show that \( V_{\text{TREC}} \) DA generally produced better analyses of the typhoon structure and intensity than direct assimilation of Vr data. The subsequent forecasts for the typhoon track, intensity, structure, as well as precipitation were also better, although the differences became smaller for the latter analysis times when Vr data coverage improved as the typhoon approached the radar.

W14 examined the impacts of \( V_{\text{TREC}} \) data through cycled DA using EnKF for Typhoon Jangmi (2008) that passed over the northern part of the Taiwan Island. Cycled assimilation of \( V_{\text{TREC}} \) data retrieved from the radar located at Hualian, Taiwan, produced more significant improvements to the analysis and forecast of Jangmi’s intensity and structure than Vr data with the same 3-hour assimilation window. Sensitivity experiments show that \( V_{\text{TREC}} \) DA built up a reasonably strong vortex in 1 hour while longer assimilation windows were required for Vr assimilation to realize similar effects. Though the difference assimilating the two data types decreased when the assimilation window became longer, the superior performance of \( V_{\text{TREC}} \) assimilation was still evident.
In W14, the Hualian radar $V_r$ or $V_{TREC}$ were assimilated from 0000 to 0300 UTC 28 September, 2008 when the center of Jangmi was still far from the Taiwan Island and only part of its inner core region was captured by the radar. With Jangmi moving closer to the Taiwan Island, more of its inner core is within the coverage of the $V_r$ data of the Hualian and additional Taiwan operational radars. With such changes, the relative impacts of assimilating $V_r$ or $V_{TREC}$ may also change, but the dependency of the impact on assimilation window has not been investigated in published studies, as far as we know.

When a TC or its inner core move into the range of $Z$ ($\sim 460$ km), assimilating $V_{TREC}$ data can help build up the vortex early. After the TC gets closer to land and falls into the range of $V_r$ data ($\sim 230$ km), it is possible to assimilate both $V_r$ and $V_{TREC}$ together. Advantages over assimilating $V_r$ or $V_{TREC}$ individually are expected because $V_r$ data have finer spatial resolutions and contain more detailed structures while $V_{TREC}$ data also contain retrieved cross-beam component and have larger spatial coverage (W14).

Being mainly derived from $Z$ data, $V_{TREC}$ is independent of $V_r$. The impact of assimilating both $V_r$ and $V_{TREC}$ has not been examined in previously published studies.

Therefore, as a natural extension of W14, we examine in this study the relative impact of assimilating $V_r$, or $V_{TREC}$ or both in DA windows with different lengths and lead times (relative to landfall), on the analysis and forecasting of Typhoon Jangmi, using data from up to 4 radars over the Taiwan Island. The EnKF DA method will again be used. In addition, a ‘hybrid’ configuration is also tested in which $V_{TREC}$ data are assimilated in the first cycle while $V_r$ data are assimilated in the later cycles. This study aims to provide guidance on the optimal utilization of the two types of radar data for improving TC track and intensity forecasting near TC landfall.
The rest of this paper is organized as follows. Section 2 describes the forecast model, radar data, and experimental design. The individual impacts of $V_{\text{TREC}}$ and $V_r$ from single or multiple radars in different assimilation windows are discussed in section 3. Section 4 presents the results assimilating $V_{\text{TREC}}$ and $V_r$ together using various configurations. Quantitative verifications for track, intensity, and precipitation from all experiments are given in Section 5. Conclusions and discussions are given in section 6.

2. Model, radar data, and experimental design

a) The prediction model

The prediction model and its configuration follow W14. The Advanced Regional Prediction System [ARPS; Xue et al., 2000; Xue et al., 2001] is used as the prediction model. The physical domain is $2400 \times 2400 \times 25$ km$^3$ and has a 3 km horizontal grid spacing (Fig. 1). The mean vertical grid spacing is 500 m with the grid spacing near the surface being 20 m. Model physics include the Lin ice microphysics scheme [Lin et al., 1983], Goddard Space Flight Center (GSFC) long- and short-wave radiation parameterization, a two-layer force-restore soil-vegetation model [Ren and Xue, 2004], 1.5-order turbulent kinetic energy (TKE)-based subgrid-scale turbulence [Deardorff, 1980] and PBL parameterization [Xue et al., 1996].

b) Radar data processing and quality control

Four operational S-band radars of Taiwan (Fig. 1), including those at Hualian (HLRD), Wufenshan (WFRD), Kenting (KTRD), and Chigu (CGRD), are used in this study. $V_r$ and $Z$ data are first manually edited to dealiase radial velocity and remove ground clutter. For $V_r$ assimilation, the $V_r$ data are interpolated in the horizontal to the
ARPS model columns, but kept on the elevation levels in the vertical. The processing and use of the $V_{TREC}$ data generally follows W14. $V_{TREC}$ is retrieved from reflectivity data from HLRD between 0000 and 0600 UTC, 28 September 2008 every 30-min. HLRD in this case was closest to the typhoon and provided the best data coverage. T-TREC analyses are performed within a 300 km radius of the typhoon center from 1 to 8 km with a vertical spacing of 1 km. The horizontal grid spacing of $V_{TREC}$ is 10 km, and the retrieved wind data are directly assimilated. More details on the T-TREC technique can be found in Wang et al. [2011].

To assess the reliability of the retrieved $V_{TREC}$ data, the percentage cumulative histogram of the absolute differences between observed $V_r$ and the radial component of the $V_{TREC}$ at all $V_r$ data levels from 0000 UTC to 0600 UTC, 28 September 2008 are shown in Fig. 2a. The scatter-plot of the data pairs is shown as an inset of the figure. The percentage of differences less than 4 m s$^{-1}$ is over 70% while the average root mean square difference (RMSD) is 3.9 m s$^{-1}$. The scatter plot shows a uniform distribution along the diagonal with the correlation coefficient between observed $V_r$ and the radial component of $V_{TREC}$ being 0.99 (Fig. 2a), indicating no bias with the independent $V_{TREC}$ retrieval. The RMSDs at different times of the 6-hour period are also plotted in Fig. 2b. There is a general increase of RMSD from about 3.4 m s$^{-1}$ at 0000 UTC to about 4.3 m s$^{-1}$ at 0600 UTC as Jangmi approached Taiwan Island. The closer is Jangmi to the island, the less valid is the conserved reflectivity advection assumption of the T-TREC method due to the new convection triggering induced by the interaction between the TC and terrain including the Central Mountain Range of Taiwan (Fig. 1), which leads to larger retrieval errors. Overall, the time-averaged RMSD of about 3.9 m s$^{-1}$ is acceptable, which is
consistent with the corresponding error statistics of less than 4 m s\(^{-1}\) from data samples examined in *Wang et al.* [2011]. Based on the above discussion on observation error statistics, standard deviations for \(V_r\) and \(V_{\text{TREC}}\) are specified as 2 m s\(^{-1}\) and 5 m s\(^{-1}\), respectively, the same as W14, in the EnKF DA.

c) EnKF experimental design

Five groups of experiments are conducted to examine the individual and combined impact of \(V_r\) and \(V_{\text{TREC}}\) (Table 1). “VrHL”, “Vr4RD”, and “TREC” assimilate \(V_r\) from HLRD only (\(V_{\text{HL}}\)), \(V_r\) from all four radars (\(V_{\text{4RD}}\)), and \(V_{\text{TREC}}\), respectively (Table 1). “TRECVr” assimilates both \(V_{\text{4RD}}\) and \(V_{\text{TREC}}\) data at each cycle. In “TFVR”, \(V_{\text{TREC}}\) data are assimilated in the first cycle, and \(V_{\text{4RD}}\) data are assimilated in the remaining cycles. Studies [Li *et al.*, 2013; W14] have demonstrated that even single-time assimilation of \(V_{\text{TREC}}\) can be effective in building up the TC vortex. The continuous cycles of \(V_{\text{4RD}}\) data can potentially provide more detailed structures.

The 6-hour period from 0000 to 0600 UTC is divided into three stages according to the \(V_r\) coverage for Jangmi (Fig. 1). In the first two hours (0000 to 0200 UTC), the inner core region of Jangmi is only partly covered by the \(V_r\) data of HLRD. From 0200 to 0400 UTC, the inner core is fully observed by HLRD and partly observed by WFRD (Fig. 1). In the last two hours (0400 to 0600 UTC), the inner core is fully covered by HLRD and WFRD. All the aforementioned five groups of experiments (including VrHL, Vr4RD, TREC, TRECVr and TFVR) are performed with four different assimilation windows (AWs), which cover, respectively, 0000 to 0600 UTC (AW06), 0000 to 0200 UTC (AW02), 0200 to 0400 UTC (AW24), and 0400 to 0600 UTC (AW46). The digital suffices in the experiment names, i.e., “06”, “02”, “24”, and “46”, indicate the four
different AWs (Table 1). At the end of the DA window of each experiment, a
deterministic forecast is launched and run through 0600 UTC, 29 September 2008. The
experiments with the DA window suffix “02” share the same DA configuration with the
experiments with suffix “06” during the first two hours but their forecasts start earlier at
0200 UTC. Apart from the DA experiments, a baseline control forecast (CNTL) without
radar DA runs from 0000 UTC, 28 September to 0600 UTC 29 September 2008,
initialized from the operational NCEP GFS analysis.

Similar to W14, an initial 40-member ensemble is created by adding mesoscale
perturbations to the GFS analysis at 1800 UTC, 27 September. Convective-scale
perturbations are further introduced into the ensemble forecasts 30 min before the first
radar DA, e.g., at 2330 UTC, 27 September for AW06 and AW02, 0130 UTC, 28
September for AW24, and 0330 UTC, 28 September for AW46 (see Fig. 3). The
configurations of perturbations are the same as W14. The DA schemes are illustrated in
Fig. 3.

The same as W14, covariance localization radii of 50 (10) km in the horizontal
and 4 km in the vertical are chosen when assimilating $V_{TREC}$ ($V_r$) data. A posterior
relaxation-to-prior adaptive covariance inflation [Whitaker and Hamill, 2012] with $\alpha=0.9$
is applied at those model grid points directly influenced by observations to help maintain
the ensemble spread. Localization and inflation parameters are chosen based on the
experience obtained from Dong and Xue (2013) and a set of sensitivity experiments.
3. Individual assimilation of $V_{\text{TREC}}$ or $V_r$ with different assimilation windows

In this section, the relative impacts of assimilating $V_{\text{TREC}}$, $V_{\text{HL}}$, or $V_{\text{4RD}}$ data on the intensity and structure analyses for different AWs are examined. The analyses considered in the following are the ensemble means.

The minimum sea level pressures (MSLPs) and maximum surface winds (MSWs) during the assimilation cycles for four AWs from VrHL, Vr4RD and TREC groups are plotted in Fig. 4, along with the average best track (ABT) data from the Japan Meteorological Agency (JMA), Taiwan Central Weather Bureau (CWB), and Joint Typhoon Warning Center (JTWC). The plus and minus one standard deviation of the mean best track data are also plotted, encompassing the grey areas. The use of the average is to reduce uncertainty with the best track data, as was done in W14.

The $V_{\text{HL}}$ data coverage for Jangmi is improved as the distance of Jangmi from land is decreased in the later assimilation windows. As a result, the assimilation of $V_{\text{HL}}$ improves the analysis more effectively with closer distances: the maximum MSLP reduction increases from 9.6 hPa in VrHL02 to 26.3 hPa in VrHL24 (Fig. 4a). Compared to $V_{\text{HL}}$ data, $V_{\text{4RD}}$ data provide better coverage on Jangmi’s inner core, especially in the later time period from 0400 to 0600 UTC (see Fig. 1). The final analyzed MSLP differences between VrHL and Vr4RD are 5.5 hPa, 8.2 hPa, 12.5 hPa for AW02, AW24, and AW46, respectively. When Jangmi’s inner core falls into the range of $V_{\text{4RD}}$ completely in window “46”, the MSLP reduction of $V_{\text{4RD}}$ assimilation at 0500 UTC is clearly larger than the small changes in the earlier windows and the final analyzed MSLP is around 940 hPa, close to the best track value of 930 hPa.
For all three 2-hour AWs, the experiments assimilating $V_{\text{TREC}}$ always have the
strongest analyzed vortices compared to assimilating $V_r$ from either one or four radars.
The MSLP evolutions from $V_{\text{TREC}}$ assimilation experiments in three different assimilation
windows are similar with each other. The final MSLPs are always around 935 to 937 hPa
(Fig. 4a). Consequently the final analysis differences between assimilating $V_{\text{HL}}$ and
$V_{\text{TREC}}$ decrease from 35 hPa, 25 hPa to 14 hPa in three assimilation windows as Jangmi
moved closer to land (Fig. 4a). When $V_{\text{HL}}$, $V_{\text{4RD}}$ or $V_{\text{TREC}}$ data are assimilated
continuously from 0000 through 0600 UTC, the advantage of assimilating $V_{\text{TREC}}$ over $V_r$
data is much decreased. The final MSLP differences between assimilating $V_{\text{TREC}}$ and $V_{\text{HL}}$
or $V_{\text{4RD}}$ are about 8 hPa and 0.5 hPa respectively, with the 6-hour AW.

Consistent with MSLP analyses, the analyzed MSWs of $V_{\text{rHL}}$ or $V_{\text{r4RD}}$
experiments generally increase as Jangmi moved closer to Taiwan in later assimilation
windows (Fig. 4b), due to the improved $V_r$ coverage on the TC, in both the horizontal,
and at lower levels (< 1 km). The final analyzed MSWs of $V_{\text{rHL}}$ experiments are closer
or even stronger than the ABT MSW of 54 m s$^{-1}$ in AW24, AW4, and AW06. The
analyzed MSWs of $V_{\text{r4RD24}}$, $V_{\text{r4RD46}}$, and $V_{\text{r4RD06}}$ in later cycles are at least 7 m s$^{-1}$
lower than those in $V_{\text{rHL24}}$, $V_{\text{rHL46}}$, and $V_{\text{rHL06}}$. When the analysis has to be fit to
more observations, the fit to individual observations tends to be poorer; this appears to be
a reason for the lower values of the analyzed MSW. This can be seen more clearly
between the MSWs of $V_{\text{rHL}}$ and $V_{\text{r4RD}}$ during 0000-0200 UTC (Fig. 4b).

The analyzed MSWs of TREC experiments for all three 2-hour windows are close
to each other with their final MSWs being between 43 and 45 m s$^{-1}$ (Fig. 4b),
approximately 10 m s$^{-1}$ below the ABT values. At 0600 UTC, they are generally within 2
standard deviations of the ABT values. As pointed out in W14, this difference can be attributed to the underestimation of maximum wind speed in VTREC data due to the relative smoothness of their fields [Tuttle and Gall, 1999; Wang et al., 2011].

Overall, the intensity analyses from VTREC assimilation are not sensitive to the AWs used since the inner core is quite well covered by VTREC throughout the 6-hour period. The assimilation of VTREC is able to establish a strong vortex in a short period (< 1 h) as evidenced by the sharp reduction of MSLP in the first two 30 min cycles, which is mostly achieved via model adjustment during the forecast period (Fig. 4a). The fact that the retrieved VTREC better represents the closed vortex circulation significantly accelerates the model adjustment of pressure towards the analyzed wind circulation. This point as well as the pressure-wind adjustment process was discussed in detailed in Wang et al. (2014).

The analyzed intensity from Vr data is clearly better towards the end of the 6-hour period, as more Vr data become available. When only Vr data from the single Hualian radar are assimilated, it takes the full 6-hour AW for the analyzed TC to reach an adequate intensity. When Vr data from all four radars are assimilated, a two-hour AW at the end is sufficient. The analyzed intensities in V4RD46 and V4RD06 are actually stronger than the corresponding VTREC experiments and are closer to the ABT data. Given the ability for VTREC data to quickly establish an intense typhoon vortex, and the ability of Vr data in giving more accurate typhoon intensity after sufficient data are assimilated, it appears beneficial if both types of data are assimilated together. After all, they are independent forms of observations. This will be examined in section 4.
To see more clearly how the intensity of the analyzed typhoon vortex changes within the assimilation windows, we show in Fig. 5 time-radius Hovmöller diagrams of the analyzed azimuthally averaged tangential wind speed at 500 m height during the assimilation cycles from three groups of experiments: those that assimilate $V_{HL}$, $V_{4RD}$, and $V_{TREC}$ data, respectively. The analyzed vortices from $V_{HL}$ assimilation intensify slowly during assimilation cycles in all four different windows (Fig. 5a, d, g, j). The-low level circulations are weak and broad with the maximum wind speed barely exceeding 40 m s$^{-1}$ and a large radius of maximum wind (RMW) of about 80 km before 0400 UTC. After 0400 UTC, the low-level vortex intensifies quickly with the strongest wind exceeding 45 m s$^{-1}$ and the radius of RMW decreased to about 40 km, benefits from the better $V_r$ data coverage. The analyzed vortex in Vr4RD experiments strengthens faster than in VrHL experiments in terms of the wind speed and RMW, especially during the later AWs in Vr4RD46 and Vr4RD06, when Jangmi’s inner core is covered by multiple radars (Fig. 5b, e, h, k). We note here that the analyzed MSW is sensitive to local perturbations in the wind fields; their values are not the best indicator of the vortex intensity. In comparison, the azimuthally averaged tangential wind speed represents the intensity of vortex circulation better, and generally has relation with the MSLP when a balance between the wind and pressure fields are reached (usually through model adjustments during the assimilation cycles as discussed in Wang et al. 2014). The final analyzed tangential winds of Vr4RD experiments are much stronger than those of VrHL experiments, which is consistent with the lower MSLP values. In general, $V_{TREC}$ assimilation helps to build a reasonably strong vortex with strong winds over 45 m s$^{-1}$ and a RMW of about 35 km in one hour (Fig. 5c, f, i, l).
To see the vertical structure of analyzed vortices, the final analyzed azimuthally averaged tangential wind speed and horizontal temperature anomaly from the VrHL, Vr4RD, and TREC groups are presented in Fig. 6. The temperature anomaly is defined as the deviation from the horizontal average within a 180 km radius [Liu et al., 1999]. The VrHL experiments all have a weak, broad and relatively shallow vortex. The warm core anomalies are less than 8 K and the 40 m s$^{-1}$ contours are all below 6 km (Fig. 6a, b, c, d). The axisymmetric circulations are stronger and warm core anomalies are more intense in Vr4RD experiments than the corresponding VrHL experiments. In the experiments with AW02 and AW24, the analyzed vortex at the lower levels are weak, due to limited V$_{4RD}$ coverage at the low levels. As Jangmi moved near land and the inner core became well covered by the four radars in Vr4RD46 and Vr4RD06, the analyzed vortices are actually stronger and deeper than in TREC46 and TREC06. The 45 m s$^{-1}$ contours extend to a radius of 60-70 km and reach 6 km in height (Fig. 6g and h). In different windows, experiments assimilating V$_{TREC}$ have compact, strong, and deep vortices with RMWs of about 30 km and a 30 m s$^{-1}$ wind speed contour that extends as high as 8 km (Fig. 6i, j, k, l). However, the analyzed circulations are weaker than those assimilating V$_{4RD}$ in AW46 and AW06. These results again suggest that there is benefit in directly assimilating Vr data from all available radars.

4. Combined assimilation of V$_{TREC}$ and V$_{4RD}$ data

Suggested by the results of earlier experiments, V$_{TREC}$ and V$_{4RD}$ are assimilated together in TRECVr and TFVR experiments, with two different configurations (Table 1). TRECVr experiments assimilate both V$_{TREC}$ and V$_{4RD}$ data in all cycles. Within the serial EnKF DA, V$_{TREC}$ data are assimilated before V$_{4RD}$ data. In TFVR (V$_{TREC}$ first and V$_{r}$
rest) experiments, \( V_{\text{TREC}} \) data are assimilated in the first cycle while \( V_{\text{4RD}} \) data are assimilated for the remaining cycles. Hereafter, the datasets used in TREC\( \text{Vr} \) and TFVR experiments are referred to as \( V_{\text{TREC}\text{Vr}} \) and \( V_{\text{TFVR}} \), respectively.

The analysis and forecast MSLPs and MSWs during the assimilation cycles for four AWs from TREC\( \text{Vr} \), TFVR, TREC, and \( V_{\text{4RD}} \) experiments are plotted in Fig. 7. The MSLP analyses and forecasts during DA cycles from TREC and TREC\( \text{Vr} \) experiments are almost identical for all AWs, except that the MSLPs of TREC\( \text{Vr} \) are slightly lower than TREC in AW24 and AW46 experiments (Fig. 7a). In experiment TFVR06, higher MSLP values are obtained from 0100 through 0330 UTC, when \( V_{\text{TREC}} \) data are no longer assimilated, compared to experiments TREC06 and TREC\( \text{Vr} \)06. At 0200 UTC, the analyzed MSLP in TFVR02 is about 947 hPa, which is about 10 hPa higher than in TREC02 and TREC\( \text{Vr} \)02. The MSLP of TFVR06 does, however, decrease steadily and becomes slightly smaller than those of TREC06 and TREC\( \text{Vr} \)06 experiments, with the final value being about 935 hPa at 0600 UTC. The MSLP values during analysis cycles of TFVR24 are also larger than those TREC24 and TREC\( \text{Vr} \)24; the final analyzed MSLP is approximately 6 hPa higher than those of TREC24 and TREC\( \text{Vr} \)24. For AW46, the MSLPs from TFVR46 are similar to those of TREC46 and TREC\( \text{Vr} \)46. Compared to the corresponding \( V_{\text{4RD}} \) experiments, the assimilation of \( V_{\text{TREC}} \) in the first cycle generally speeds up the reduction of the analyzed MSLP significantly, especially when the \( V_{\text{4RD}} \) coverage is limited (Fig. 7a).

The assimilation of \( V_{\text{4RD}} \) in addition to \( V_{\text{TREC}} \) in TREC\( \text{Vr} \) experiments further improves the MSW analyses (Fig. 7b) compared to TREC only experiments, which agrees with the early findings on the relative impacts of \( V_{\text{4RD}} \) and \( V_{\text{TREC}} \) assimilation on
MSWs. Consistent with the MSLP results, the MSW in TFVR06 is also weaker before 0400 UTC and stronger after 0400 UTC compared to TREC06. The MSWs of TFVR24 are also weaker than TREC24 and TRECVr24, while the final MSW analysis of about 43 m s\(^{-1}\) is similar to those in TREC24 and TRECVr24. Experiment TFVR46 produces even stronger MSW analyses than TRECVr46, with the final analyzed MSW slightly overestimated compared to the ABT. In general, the assimilation of \(V_{\text{TREC}}\) at the first cycle benefits the MSW analysis, compared to experiments that assimilate \(V_{4\text{RD}}\) throughout. Overall, combined assimilation of \(V_{\text{TREC}}\) and \(V_{4\text{RD}}\) data can produce better intensity analyses than assimilating them individually.

To investigate the impact of additional \(V_{4\text{RD}}\) data in the TRECVr experiments, the horizontal winds at 3 km height after the first analysis at the beginning of AW for TREC02 and TRECVr02 at 0000 UTC, TREC24 and TRECVr24 at 0200 UTC, TREC46 and TRECVr46 at 0400 UTC are plotted in Fig. 8. Due to the limited coverage of \(V_{4\text{RD}}\), the wind analyses of TRECVr02 and TREC02 at 0000 UTC are very similar (Fig. 8a, b). At 0200 UTC, the additional \(V_{4\text{RD}}\) data enhance the horizontal winds in the northeast quadrant of typhoon (Fig. 8c, d). When the inner core is fully covered by \(V_{4\text{RD}}\) at 0400 UTC, the inner circulation is again noticeably enhanced by additional \(V_{4\text{RD}}\) data (Fig. 8e, f). These results show that the additional \(V_{4\text{RD}}\) data in TRECVr experiments do tend to further enhance the typhoon circulation, compared to the \(V_{\text{TREC}}\)-only experiments when the \(V_{4\text{RD}}\) data coverage is good.

In Fig. 9, we plot the azimuthally averaged tangential wind and temperature anomaly from TRECVr and TFVR to examine the vertical structure of the final analyses. Compared to corresponding TREC experiments (Fig. 6i, j, k, l), the axisymmetric
circulations of TRECVr experiments (Fig. 9a, b, c, d) are generally enhanced by the additional V4RD data. The azimuthal averaged tangential wind speed of over 45 m s^-1 is extended to a higher level, especially for AW46 and AW06. The warm core location and intensity in the TRECVr experiments are similar to those of TREC experiments but stronger than in Vr4RD experiments (Fig. 6, Fig. 9). With AW02, the axisymmetric structure of TFVR02 is much stronger than that of Vr4RD02 while weaker than TREC02 (Fig. 9e), which is consistent with the MSLP analyses. For AW24, the axisymmetric circulation of TFVR24 (Fig. 9f) at low levels is enhanced compared to Vr4RD24 (Fig. 6f), but still weaker compared to TRECVr24 (Fig. 9b). The analyzed vertical structures in TFVR46 and TFVR06 (Fig. 9g, h) are similar to those in Vr4RD46 and Vr4RD06 (Fig. 6g, h), suggesting that V4RD data in the latter cycles play a more dominant role.

Overall, assimilating both V TREC and V r data produces better intensity and structure analyses than assimilating V TREC or V4RD data individually. By assimilating VTFVR, the analyzed intensity and structure are also improved compared to V4RD assimilation. Although the vortices from TFVR experiments are still weaker than TREC experiments for AW02 and AW24 due to relatively short windows and/or not so good V4RD data coverage, the TFVR experiments for AW46 and AW06 that have much better V4RD data coverage in later cycles have slightly better intensity and structure analyses than the pure TREC experiments, suggesting that underweighting the use of V TREC data when direct radial velocity data from multiple radars become available is desirable.

5. Quantitative verification of forecasts

The impacts of assimilating V TREC, V HL, V4RD, V TRECVr, and V TFVR on the intensity and structure analyses were presented in the previous sections. In this section,
the impacts on the intensity and track forecasting of typhoon Jangmi is further investigated by verifying the forecasts starting from the final ensemble mean analyses against the ABT data. The 12-hour accumulated precipitation and the corresponding equitable threat scores [ETS, Gandin and Murphy, 1992] from all experiments are verified against the observations. The observed rainfall is obtained from the quantitative precipitation estimation and segregation using multiple sensor system [QPESUMS, Gourley et al., 2002] provided by the Central Weather Bureau of Taiwan.

5.1 Verification of intensity and track forecasts against the ABT

The predicted typhoon tracks, MSLPs, MSWs from CNTL, Vr4RD and TREC experiments are plotted along with the ABT in Fig. 10. From 0000 UTC 28 to 0600 UTC 29 September, Jangmi first moved towards northwest, then turned into a more westward path toward Taiwan. After making landfall at about 08:30 UTC, Jangmi turned northwestern, it further turned towards north-northeast right after its center passed over Taiwan Island (Fig. 10a). The track of CNTL has a large westward and southward bias with a mean track error of about 65 km. All three turns of Jangmi’s track are captured well by the Vr4RD experiments at locations close to the ABT, with the mean track errors of around 50 km for the four assimilation windows. With the earlier AW02, assimilating $V_{TREC}$ produces the track forecast that is close to that of Vr4RD. A northeastward track bias starts to show up and increase with the later AWs when assimilating $V_{TREC}$. The predicted track of TREC24 still captures the three turns but the first westward turn is too weak, and the mean forecast track error is 65 km. In TREC46 and TREC06 that assimilate $V_{TREC}$ data until 0600 UTC, the first and second turns are completely missing and the mean 24-hour track errors are 70-80 km. A detailed analysis on the cause of the
large track errors in TREC46 and TREC06 is the subject of a follow-on study. Initial analyses suggest that the asymmetric circulation was not retrieved accurately in the T-TREC winds, which affected the subsequent tracking forecasting.

The typhoon intensity in CNTL is too weak compared to ABT, and does not change much during the forecast period. The intensity forecasts are significantly improved in Vr4RD and TREC experiments compared to CNTL. The forecasts of TREC experiments are in general closer to the ABT than those of Vr4RD experiments in terms of both MSLP and MSW (Fig. 10b, c). The TREC46 and TREC06 experiments have the best (strongest) intensity forecasts among all experiments, but their stronger vortices are at least partly due to the northward bias of the forecast track, which almost missed landfall.

To further quantify the forecast quality, the 24-hour average MSLP, MSW and track errors from the VrHL, Vr4RD, TREC, TRECIR, and TFVR DA experiments for all AWs are plotted in Fig. 11 along with those of CNTL experiment that did not perform radar DA. The group mean errors for every group of experiments (e.g., the mean of the 24-hour averaged MSLP errors from Vr4RD experiments, including Vr4RD02, Vr4RD24, Vr4RD46, and Vr4RD06) are also plotted to provide a synopsis on track and intensity errors. The group mean here is just an indicator for the average performance of each data type for various assimilation windows, it does not necessarily have much physical meaning given that it is the average of experiments with different assimilation window lengths. It is clear that $V_{4RD}$ assimilation produces better intensity and track forecast than $V_{HL}$ assimilation for every AW. The $V_{4RD}$-assimilating group mean MSLP, MSW, and
track errors are 17.2 hPa, 5.5 m s$^{-1}$, and 49 km, respectively, compared to the 20 hPa, 8.3 m s$^{-1}$, and 61 km of the VrHL group (Fig. 11).

The northeast track bias of TREC experiments is largely corrected by assimilating V$_{4RD}$ data in addition: the westward track deflection at 0600 UTC is better captured by TREC Vr46 and TREC Vr06 (not shown) than the corresponding TREC experiments, resulting in smaller track errors (Fig. 11c). The TREC Vr group mean track error is reduced to about 59 km. Meanwhile, TFVR experiments well predict all three turns of Jangmi’s track (not shown). The track forecasts of TFVR experiments are comparable to those of Vr4RD experiments, with a group mean error of about 49 km (Fig. 11c).

Compared to the TREC and TREC Vr experiments, the TFVR experiments generally have much better track forecasts.

Assimilating V$_{TREC}$ and V$_{4RD}$ together in TREC Vr experiments gives better track forecasts than TREC experiments and much improved intensity forecasts over Vr4RD experiments. The group mean intensity error is more than 30% smaller than that of Vr4RD group (Fig. 11a, b). The assimilation of V$_{TREC}$ in the first cycle in TFVR experiments improves the intensity forecasts compared to Vr4RD experiments (Fig. 11a, b). The group mean MSLP and MSW errors are approximately 14 hPa and 4.4 m s$^{-1}$, respectively, that are about 20% smaller than those of Vr4RD.

In this particular case of typhoon Jangmi, the intensity and precipitation forecasts depend largely on the track forecast. The track forecast, especially the westward turn at 0600 UTC, can be more important than the general intensity forecast. A “good” intensity forecast with a highly biased track forecast should not be considered as a good TC forecast since wrong areas will be affected. Among all DA experiments, TFVR and
Vr4RD have the best track forecasts with the group errors being about 49 km in both cases. The track forecasts from TREC experiments are too biased. TFVR has smaller group mean MSLP and MSW errors of 14 hPa and 4.4 m s\(^{-1}\), smaller than the 17.2 hPa and 5.5 m s\(^{-1}\) of the Vr4RD group. The improvement to intensity forecast from TFVR over Vr4RD is even larger with the earlier AW02 and AW24 (Fig. 11a, b). These results suggest that the configuration that assimilates \(V_{\text{TREC}}\) in the first cycle and \(V_r\) in later cycles has the potential to improve both track and intensity forecasts of TCs.

5.2 Verification of precipitation

The 12-hour accumulated precipitations from all experiments are presented in Fig. 12 together with the observations. The rows from top to bottom represent precipitation forecasts from earlier to later AWs. For the 12-hour accumulated precipitation valid at 1400 UTC (first row of Fig. 12), prominent in the data is a strong precipitation band along the central mountain region (CMR, Fig. 1, Fig. 12a); two precipitation maxima are located over northern and southern Taiwan (separated by the 24 N). These observed maxima are significantly under-predicted in VrHL02 and Vr4RD02 (Fig. 12b, c), but better predicted by TREC02, TREC\(V_r\)02, and TFVR02 (Fig. 12d, e, f). The northern rainfall maximum is best captured by TREC02, while the TREC\(V_r\)02 has the best forecast of the southern rainfall maximum. After two hours, the 12-h accumulated rainfall ending at 1600 UTC shifted somewhat to the south (Fig. 12g). There is still under-prediction of the two precipitation centers in all forecasts. TREC\(V_r\)24 and TFVR24 predict the north and south centers, respectively, better than others. Ending at 1800 UTC (third and fourth row of Fig. 12), observed 12-hour precipitation continues to shift to the south, resulting in very heavy precipitation around 23.5°N, Taiwan.
heavy precipitation pattern is well captured by VrHL46, Vr4RD46, VrHL06, and Vr4RD06, but the rainfall amount is too low (Fig. 12n, o, t, u). The predicted rainfall location, pattern and magnitude in TFVR06 over southern Taiwan appear to be closest to the observations among the accumulations ending at 1800 UTC. As a result of their northward biased tracks, TREC46, TRECVR46, and TFVR46 predict precipitation in northern Taiwan that happens to match observations quite well, but the precipitation over southern Taiwan has large northward biases (Fig. 12p, q, r). The same is true with TREC06 and TRECVR06, and over northern Taiwan the predicted precipitation is too strong (Fig. 12v, w).

The ETSs of the 12-hour accumulated precipitation for experiments with different AWs are plotted in Fig. 13. For AW02, VrHL02 and Vr4RD02 have low ETSs for all rainfall thresholds, corresponding to previously noted under-prediction of precipitation (Fig. 13a). The ETSs of TRECVR02 are generally the highest among this group of experiments, especially for heavier precipitation (>150 mm). For AW24, the spread of ETSs is greatly reduced, partly due to improvements in VrHL24 and Vr4RD24, which benefited from improved Vr data coverage. TFVR24 now has the highest ETSs for most thresholds in this group of experiments (Fig. 13b). For AW46, the ETSs of TREC46 are the lowest in general, due to the large track error. Other experiments have comparable ETSs (Fig. 13c). For the long 6-hour window AW06, the ETSs of TREC06 are the lowest for strong precipitation while those of TFVR06 are the highest for strong precipitation (Fig. 13d). For weaker precipitation, the differences are smaller.

To highlight the general relative impacts of assimilating different data groups, the group mean ETSs of the 12-hour accumulated precipitation from VrHL, Vr4RD, TREC,
TRECVr, and TFVR are presented in Fig. 14. Generally, the TFVR group has the highest ETSs for thresholds above 50 mm; this group hence has the best precipitation forecast skill. This can be attributed to the best intensity and track forecasts the group has. The assimilation of both $V_{TREC}$ and $V_{4RD}$ in TRECVr also gives higher ETSs than assimilating $V_{TREC}$ or $V_{4RD}$ only. Consistent with the intensity and track forecasting results, the precipitation forecasts of Vr4RD group are also better than those of VrHL group.

6. Summary and discussion

W14 compared the assimilation of $V_{TREC}$ versus $V_r$ data from a single Doppler radar on the Taiwan Island over a 1, 2 or 3 hour window after the center of Typhoon Jangmi (2008) first moved into the radial velocity coverage of the radar. Thirty-minute assimilation cycles were used with an ensemble Kalman filter. Results demonstrated that $V_{TREC}$ assimilation is more effective than $V_r$ assimilation, and thus can potentially provide better TC initialization and improved forecasts with longer lead times than $V_r$ data can. The larger spatial coverage of $V_{TREC}$ data and the more complete wind information (including cross-beam component) it contains are believed to be the primary reasons for the superior performance of $V_{TREC}$ over $V_r$ data.

As a follow-up to W14, this study further examines the relative impacts of assimilating $V_r$, $V_{TREC}$ or their combinations in assimilation windows (AWs) that span different time periods before Jangmi landfall over Taiwan. Specifically, data during 0000 UTC to 0600 UTC 28 September 2008 from four coastal operational Doppler radars located at Hualian (HLRD), Wufenshan (WFRD), Chigu (CGRD), and Kenting (KTRD) of Taiwan are used. The 6-hour window is further split into three 2-hour windows, in which $V_r$ data from the radars have different degrees of coverage on the TC inner core
Four sets of experiment are performed that have, respectively, AWs of 0000 to 0200 UTC (AW02), 0200 to 0400 UTC (AW24), 0400 to 0600 UTC (AW46), and 0000 to 0600 UTC (AW06). Assimilation cycles are again 30-min long in all cases. For each set of experiments, five forms of data are assimilated; they are: \( V_r \) from HLRD radar only (labeled \( V_{HL} \)), \( V_r \) from all four radars (labeled \( V_{4RD} \)), T-TREC-retrieved winds (\( V_{TREC} \)), both \( V_{TREC} \) and \( V_{4RD} \) (labeled \( V_{TRECVR} \)) in every cycle, and \( V_{TREC} \) in the first cycle and \( V_{4RD} \) in the remaining cycles (labeled \( V_{TFVR} \)).

The assimilation of \( V_{TREC} \) data (derived from the reflectivity data of Hualian radar) generally produces better intensity and structure analyses of the typhoon than \( V_{HL} \) for all AWs due to the added cross-beam wind information and the larger data coverage. Even for the 6-hour AW that has better \( V_{HL} \) coverage near the end, the advantage of assimilating \( V_{TREC} \) is still evident. The assimilation of \( V_{4RD} \) also produces better intensity and structure analyses than \( V_{HL} \) for all AWs. For earlier AWs when the inner core is only partly covered by \( V_{4RD} \), \( V_{TREC} \) assimilation produces better intensity and structure analyses than \( V_{4RD} \) assimilation. When the inner core region has very good \( V_{4RD} \) coverage (in AW46 and AW06), \( V_{4RD} \) experiments improve the structure and maximum surface wind analyses compared to corresponding TREC experiments.

For \( V_r \) assimilation, the more \( V_r \) observations in the inner core region are assimilated, the better are the intensity and structure analyses obtained. The assimilation of \( V_{4RD} \) and \( V_{HL} \) within the 6-hour AW produces better analyses than 2-hour AWs; a later 2-hour AW window with a better \( V_r \) coverage also leads to a better analysis. However, the assimilation of \( V_{TREC} \) is not sensitive to the AW used because it can spin up strong typhoon vortex quickly within one hour.
The trade-off between $V_{TREC}$ and $V_{4RD}$ assimilation indicated the potential benefit of assimilating $V_{TREC}$ and $V_{4RD}$ together. Doing so is found to improve the analyzed typhoon intensity and the axisymmetric circulation compared to assimilating $V_{TREC}$ or $V_{4RD}$ alone. Assimilating $V_{TREC}$ in the first cycle then $V_{4RD}$ in the remaining cycles ($V_{TFVR}$ assimilation) improves the typhoon intensity and structure analyses compared to always assimilating $V_{4RD}$, especially for AW02 and AW24. However, assimilating $V_{TREC}$ still produces better intensity and structure analyses than $V_{TFVR}$ assimilation for AW02 and AW24.

In the case of typhoon Jangmi, track forecast is important as it affects the landfall time and location and hence also intensity and precipitation forecasts. Consistent with the quality of intensity and structure analyses, the $V_{4RD}$ assimilation also leads to better forecasts than $V_{HL}$ assimilation in terms of both track and intensity. The assimilation of $V_{TREC}$ produces overall the best intensity forecasts among all DA experiments as it is quick at establishing a strong vortex, but the track forecast errors of $V_{TREC}$ DA experiments are the largest overall. This large track error is believed to be due to the inaccurately retrieved asymmetric circulation associated with the increasing T-TREC retrieval error the Jangmi precipitation is partially over land [Wang et al., 2014]. The assimilation of $V_{4RD}$ in addition to $V_{TREC}$ substantially improves the track forecasts compared to $V_{TREC}$ assimilation only; however, the track error is still much larger than $V_{4RD}$ DA experiments. $V_{TFVR}$ and $V_{4RD}$ DA experiments produce the best track forecasts, while $V_{TFVR}$ experiments have better intensity forecasts due to the improved intensity analysis compared to $V_{4RD}$ experiments. In general, the $V_{TFVR}$ assimilation leads to the best track and intensity forecasts among all DA experiments.
Qualitative and quantitative evaluations of precipitation forecasts also show that \(V_{TFVR}\) experiments have the highest precipitation forecast skills for moderate to heavy precipitation, which is consistent with the best track and intensity forecasts. The assimilation of \(V_{TREC}\) and \(V_{4RD}\) together also gives higher precipitation forecast skills than assimilating \(V_{TREC}\) or \(V_{4RD}\) alone. Although the intensity and track forecasting behaviors are different, \(V_{TREC}\) and \(V_{HL\, DA}\) experiments generally have similar, lower precipitation forecast skills. Considering the intensity, track, and precipitation forecasts together, the assimilation of \(V_{TREC}\) data in the first cycle and then assimilating \(V_r\) data from all four available radars in the remaining cycles produce most positive impact on Jangmi forecasting near Taiwan.

Based on the results of experiments performed in this study, some recommendations for radar data assimilation configuration for a typhoon approaching coastal radars are made here: When a good reflectivity data coverage is available from a coastal radar on an approaching typhoon, T-TREC wind retrievals are to be performed. The retrieved T-TREC winds are assimilated in the first 1 or 2 cycles using an advanced data assimilation method such as the EnKF, the assimilation can usually establish the typhoon vortex circulation quite well. As the typhoon moves closer to the coast, \(V_r\) data coverage from the coastal radars improves, the assimilation of \(V_r\) data is then preferred over the often less accurate T-TREC data, especially when multi-Doppler radar coverage is available. The original \(V_r\) data usually contain more circulation details than T-TREC retrievals. However, because this recommendation is based on the results of a single case, and a specific radar network, the generality of the results will require testing with more cases, in future studies. To understand why the track forecasts starting from the analyses...
of T-TREC assimilation experiments were poorer in this case, detailed analyses will be
performed and reported in a follow-on paper.

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Fig. 2. (a) Percentage cumulative histogram of the difference between observed Doppler radar radial velocities and the radial component of T-TREC-retrieved winds for Typhoon Jangmi from 0000 UTC to 0600 UTC 28 September, 2008, every 30 min. Insert in upper right shows a scatter plot of retrieved radial velocity versus radial velocity measurements. N is the total number of radial velocity samples. R and E represent the correlation coefficient and the root mean square difference (RMSD), respectively. (b) RMSD between measured Doppler radial velocities and the radial component of T-TREC-retrieved winds from 0000 UTC to 0600 UTC every 30 min.

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Table 1. Summary of experiments with and without radar data assimilation using different observations types, the number of radars, and assimilation periods.

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<th>Observations assimilated</th>
<th>Assimilation period</th>
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Fig. 12. 12-hour accumulated precipitation for (first column) observations, (second column) VrHL group, (third column) Vr4RD group, (fourth column) TREC group, (fifth column) TRECVr group, and (sixth column) TFVR group. The 1-4 rows are valid at 1400 UTC, 1600 UTC, 1800 UTC and 1800 UTC, 28 September, respectively.
Fig. 13. Equitable threat scores of the 12-hour accumulated precipitation forecasts from experiments of different assimilation windows, (a) 0000 – 0200 UTC, (b) 0200 – 0400 UTC, (c) 0400 – 0600 UTC and (d) 0000 – 0600 UTC.
Fig. 14. The averaged equitable threat scores of the 12-hour accumulated precipitation forecasts from assimilation groups VrHL, Vr4RD, TREC, TRECvR, and TFVR.