Satellite Microwave TC Warm-core Retrieval for a 4D-Var Vortex Initialization Using a Nonhydrostatic Axisymmetric Model with Convection Accounted for

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Outline

- Satellite microwave retrievals of TC warm cores and TPW
- Description of the RE model and its adjoint model
- 4D-Var VI experiment design and numerical results
- Summary and conclusion

Motivation

Hurricane vortex initialization over oceanic regions

Past

Data-void

Bogus

Bogus and/or Observations →

Future

Data-rich

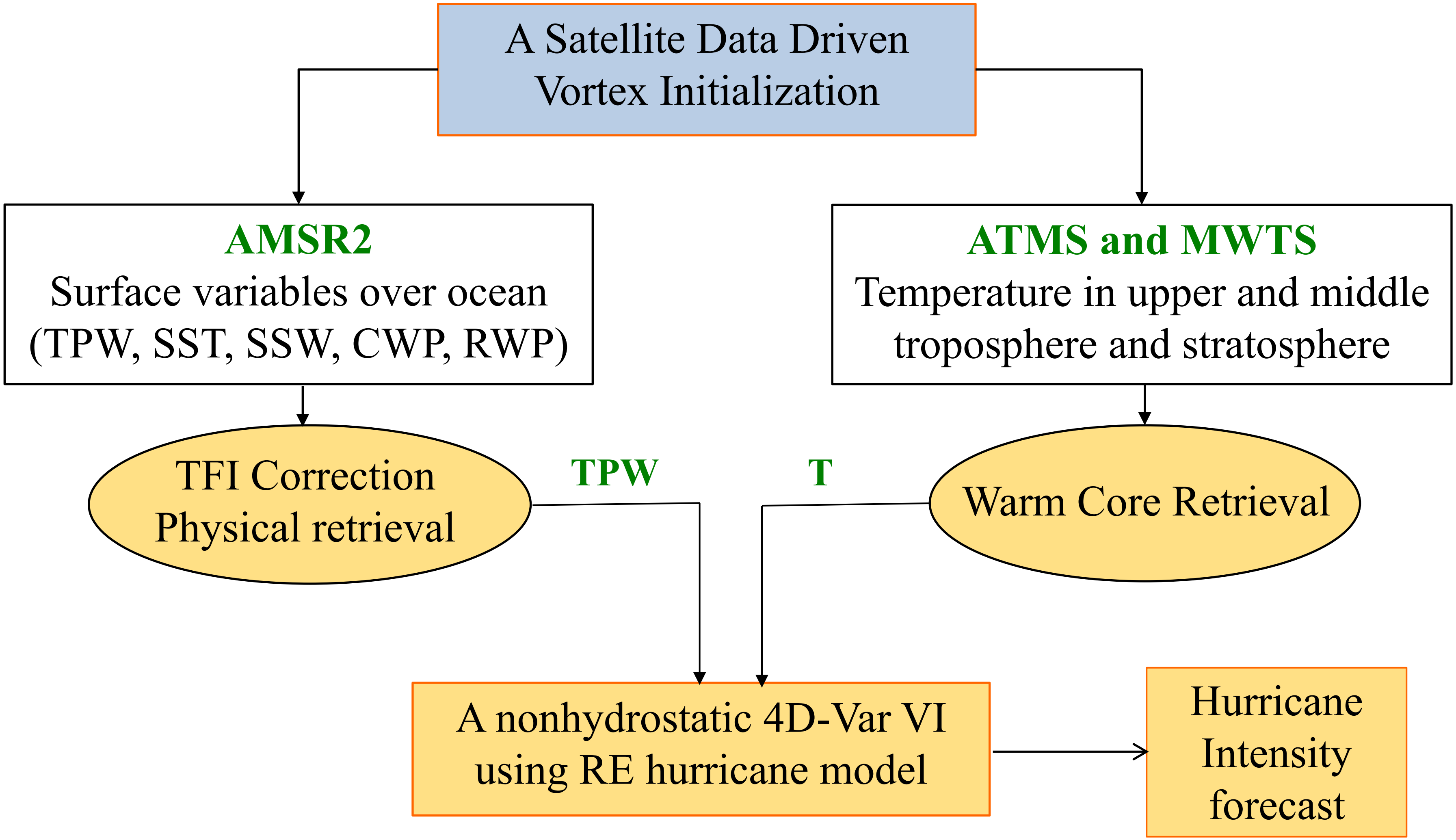
Observation-based

Zou X., and Q. Xiao, 1999: Studies on the initialization and simulation of a mature hurricane using a variational bogus data assimilation scheme. *J. Atmos. Sci*., **57**, 836-86.

Park K., and X. Zou, 2004: Toward developing an objective 4D-Var BDA scheme for hurricane initialization based on TPC observed parameters. *Mon. Wea. Rev.,* **132**, 2054-2069.

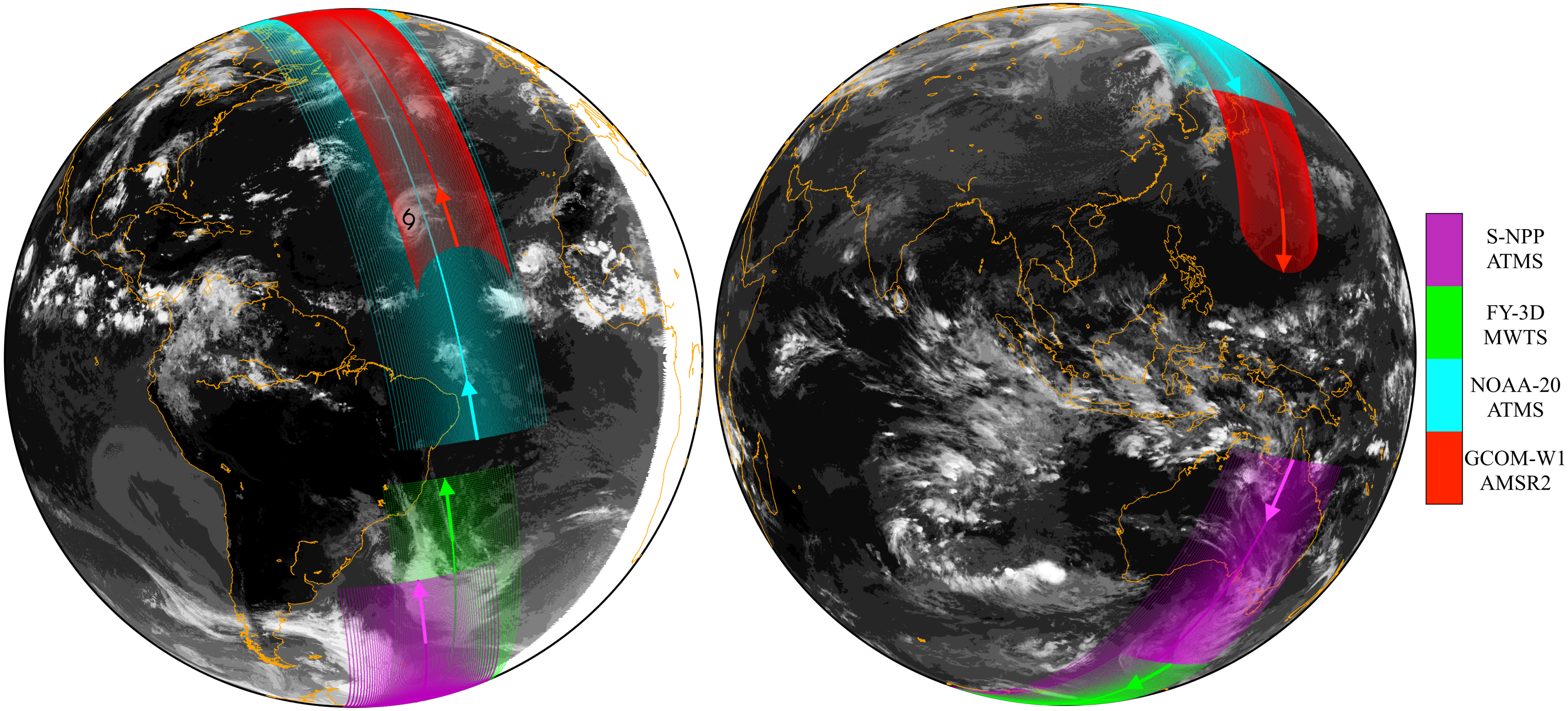
Park K., 2004: Incorporating TPC observed parameters and QuikSCAT surface wind observations into hurricane initialization using 4D-Var Approaches. Ph. D. Thesis. Department of Florida State University. United States.

4D-Var Satellite Vortex Initialization (VI)



Tian, X., and X. Zou, 2019: A comprehensive 4D-Var vortex initialization using a nonhydrostatic axisymmetric hurricane model. *Tellus A: Dynamic Meteorology and Oceanography.*, doi: 10.1080/16000870.2019.1653138.

Hurricane Florence Observed by Satellite Series



- The center of Hurricane Florence at 1500 UTC 4 September 2018 was covered by the swaths of both NOAA-20 ATMS and AMSR2 at the time.
- The AMSR2, NOAA-20 ATMS, MWTS, and S-NPP ATMS swaths can all observe the same hurricane four times in a one-hour time interval twice daily.

Hurricane Warm Core Retrievals with Microwave Temperature Sounders

The atmospheric temperature at a specific level *T(p)* is expressed as a weighted linear combination of brightness temperature observations at different channels (Tian and Zou, 2018)

$$T_\theta(p) = C_0(p,\theta) + \sum_{i=i_{1,p}}^{i_{2,p}} Ci(p,\theta) T_{b,\theta}^{obs}(i)$$

$T_\theta(p)$ – atmospheric temperatures

$C_i(p,\theta)$ – regression coefficients trained with ECMWF temperatures

$T_{b,\theta}^{obs}(i)$ – ATMS brightness temperatures at channels 5-15

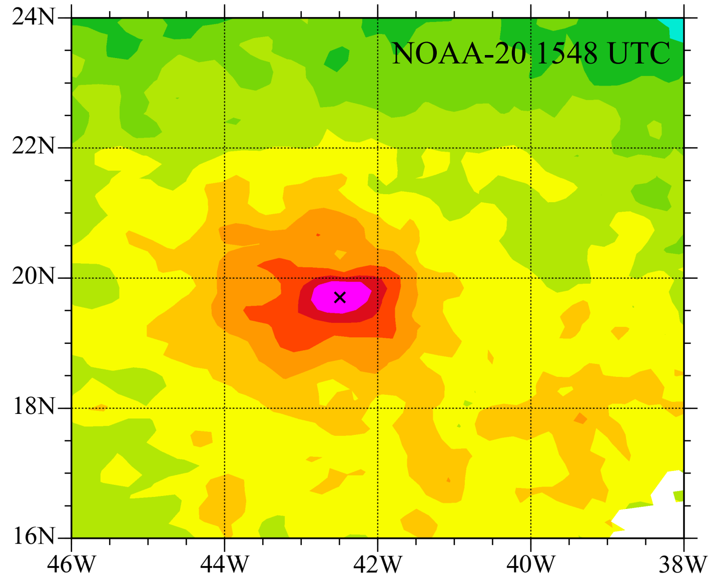
θ – local zenith angle denoting scan positions

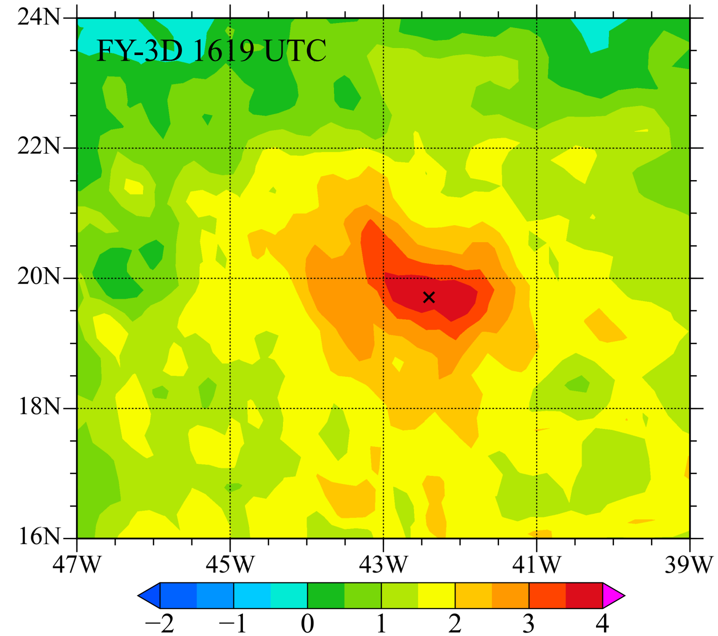
Tian, X. and X. Zou, 2016: ATMS and AMSU-A derived warm core structures using a modified retrieval algorithm. *J. Geophy. Res.*, **121**, 12,630-12,646.

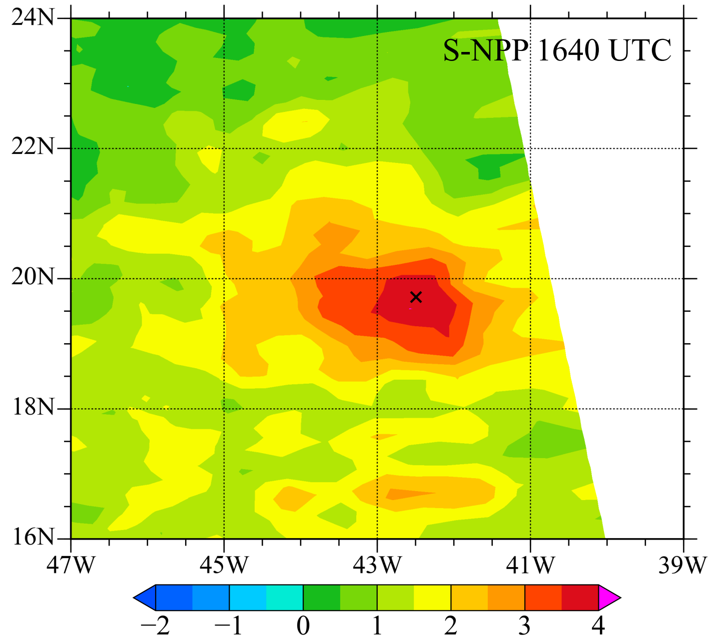
Tian, X. and X. Zou, 2018: Polar-orbiting satellite microwave radiometers capturing size and intensity changes of Hurricane Irma and Maria (2017). *J. Atmos. Sci.*, **75**, 2509-2522.

Zou, X. and X. Tian, 2018: Hurricane warm core retrievals from AMSU-A and remapped ATMS measurements with rain contamination eliminated. *J. Geophy. Res.*, **123**, 10,815-10,829.

Warm Core Structures at 250 hPa

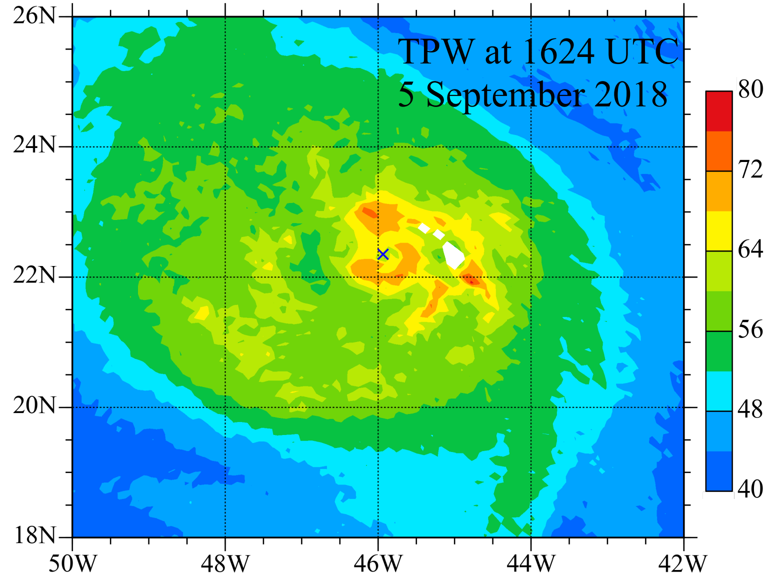


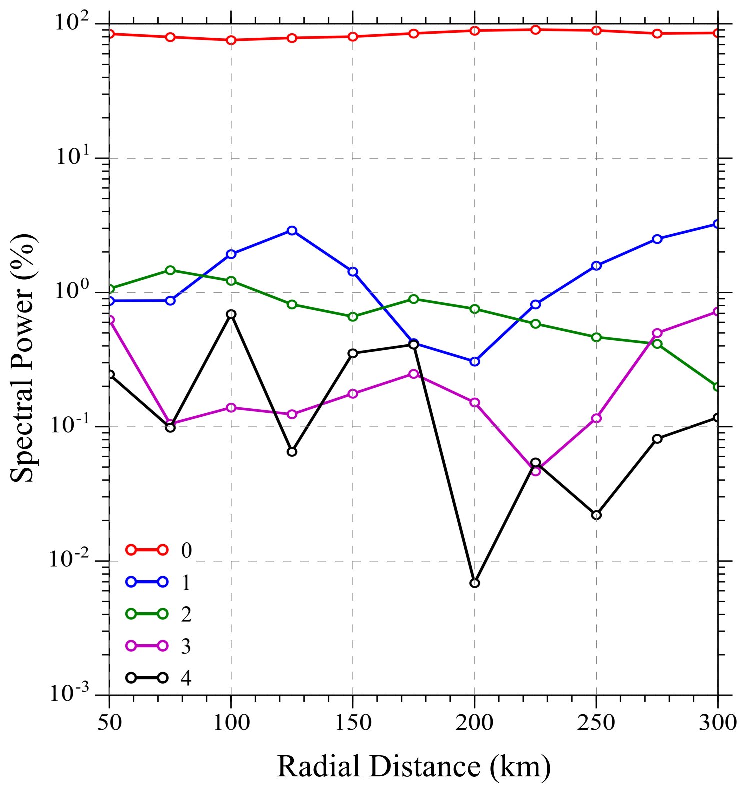




- Hurricane Florence was covered three times within a period of one hour
- Even within an hour, the peak intensities of the warm core have been rapidly evolving

TPW retrieval from AMSR2



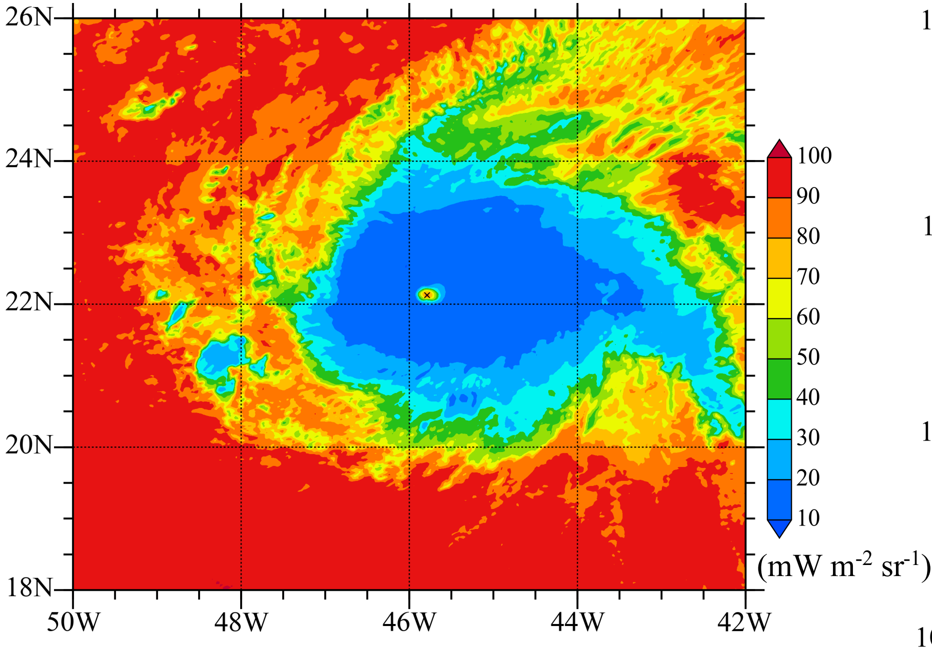


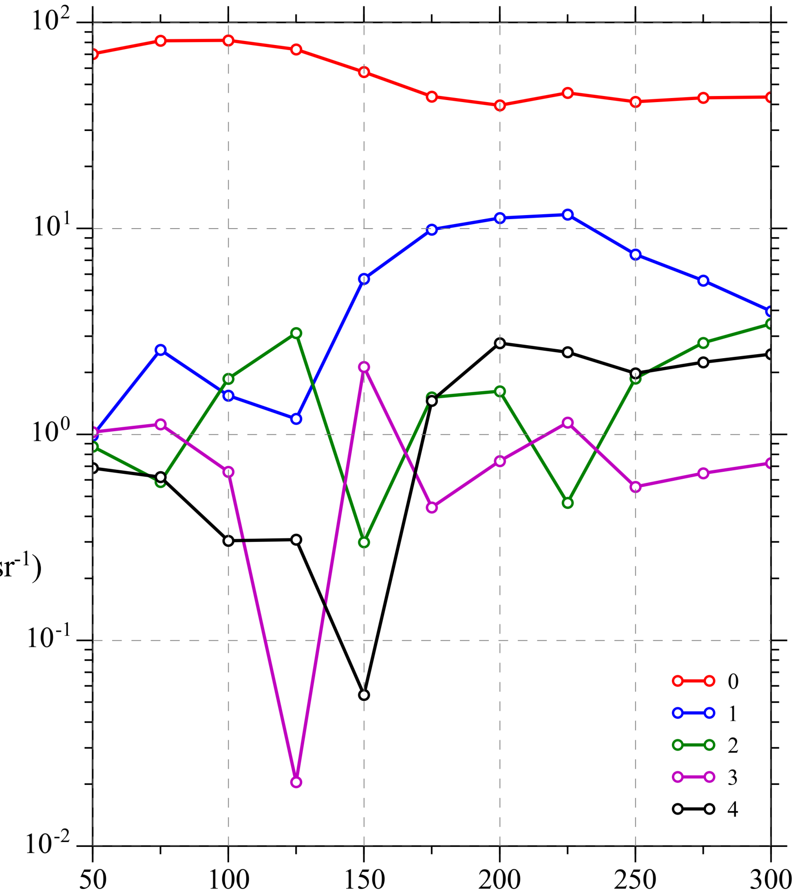
- Over oceans, AMSR2 radiance observations can be used to retrieve geophysical products such as TPW, the LWP, SSW and SST (Wentz and Meissner, 2000)

- The TPW fields within TCs retrieved from AMSR2 observations are highly axisymmetric, as The wavenumber-0 component accounts for about 90% of the total spectra from the center to the 300-km radial distance

Wentz, F. J. and Meissner, T. 2000. Algorithm Basis Document (ATBD) AMSR Ocean Algorithm, 2nd Ed. IEEE, Santa Rosa, CA

Azimuthal Spectral Analyses





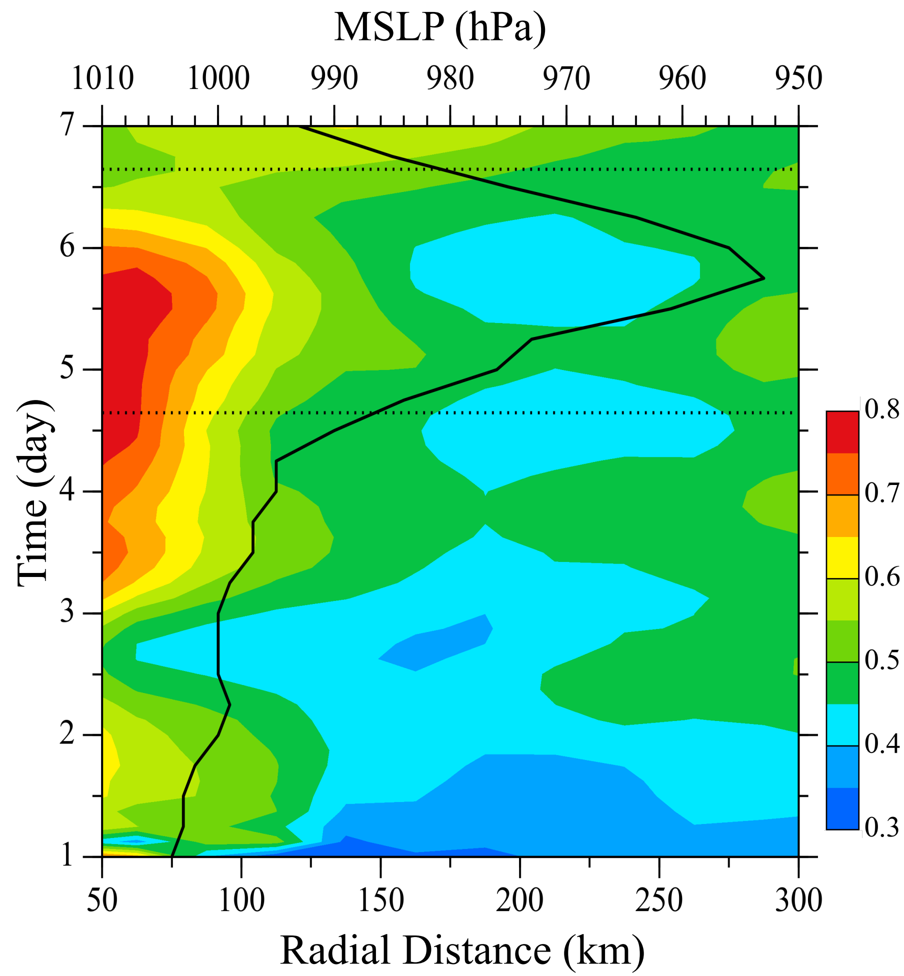
A spectral analysis is conducted on the spatial distribution of radiances observed by GOES-16 ABI channel 13 at 1500 UTC 4 September 2018.

Axisymmetry of Hurricane Florence

- The wavenumber-0 spectrum percentage (i.e., the axisymmetric component) was calculated from GOES-16 ABI Ch13 radiance observations during 1–7 September 2018 at 3-hour intervals

- Florence is characterized by an increased axisymmetry as it went through intensification during 4–6 September 2018

- Due to the strong impact of convection, regions of large axisymmetry are confined to relatively small radial distances



A Nonhydrostatic Axisymmetric Hurricane Model (Rotunno and Emanuel, 1987)

$$\frac{du}{dt}-\left(f+\frac{v}{r}\right)v=-c_p\bar{\theta}_v\frac{\partial\pi}{\partial r}+D_u$$

$$\frac{dv}{dt}+\left(f+\frac{v}{r}\right)u=D_v$$

$$\frac{dw}{dt}=-c_p\bar{\theta}_v\frac{\partial\pi}{\partial r}+g\left\{\frac{\theta-\bar{\theta}}{\bar{\theta}}+0.61\left(q_v-\bar{q}_v\right)-q_l\right\}+D_w$$

$$\frac{\partial\pi}{\partial t}+\frac{\bar{c}^2}{c_p\bar{\rho}\bar{\theta}_v^2}\left\{\frac{1}{r}\frac{\partial\left(ru\bar{\rho}\bar{\theta}_v\right)}{\partial r}+\frac{\partial\left(w\bar{\rho}\bar{\theta}_v\right)}{\partial z}\right\}=0$$

$$\frac{dq_v}{dt}=M_{q_v}+D_{q_v}$$

$$\frac{d\theta}{dt}=M_\theta+D_\theta+R$$

$$\frac{dq_l}{dt}=M_{q_l}+D_{q_l}$$

$u-$ radial wind

$v-$ tangential wind

$w-$ vertical wind

$\theta-$ potential temperature

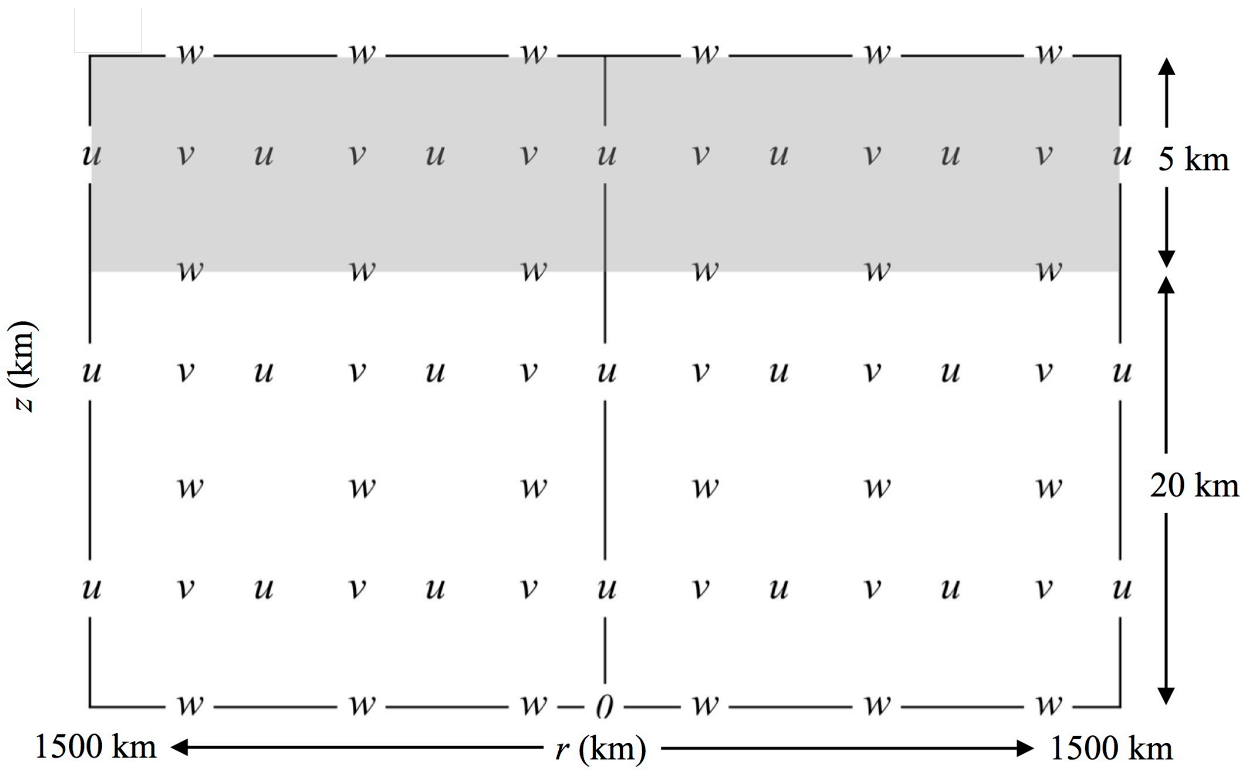
q_v- water vapor mixing ratio

q_l- liquid water mixing ratio

$\pi-$ pressure perturbation

The RE model simulates axisymmetric and compressible flow evolutions on the *f*-plane. The governing equations are written in a cylindrical coordinate (r, ϕ, z).

Staggered Grids



The model variables are placed on a staggered grid, whose alignment is shown in the figure above. Variables including θ, π, q_v and q_l also sit on the grids of v.

A rigid lid is placed on the upper boundary. The 5 km at the top of the domain serves as a sponge layer to dissipate vertically propagating gravity waves with a Newtonian damping term on the right hand side on all the prognostic equations.

RE Tangent Linear (TLM) and Adjoint (ADJ) Model

The forecast at time t_r from an initial time t_0 made by the nonlinear RE model can be written symbolically as

$$\mathbf{x}(t_r) = \mathbf{Q}_r(\mathbf{x})\mathbf{x}_0$$

Linearization of the RE model gives the so-called tangent linear model (TLM), which can be written as

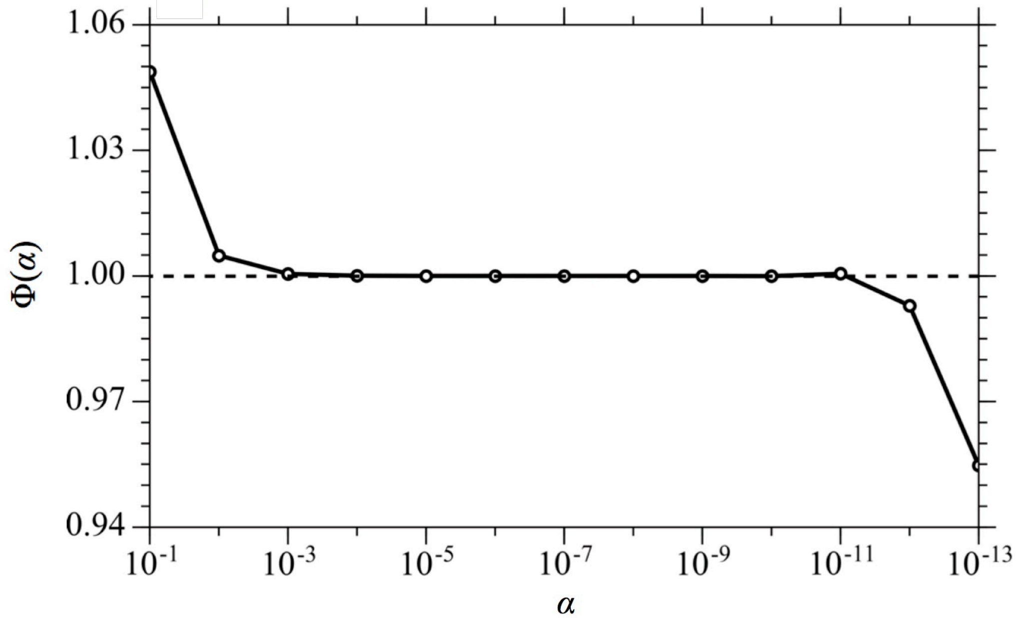
$$\mathbf{x}'(t_r) = \mathbf{P}_{\mathrm{r}}(\mathbf{x})\mathbf{x}'_0 = \frac{\partial \mathbf{Q}_r}{\partial \mathbf{x}}\mathbf{x}'_0$$

The adjoint model is then defined as

$$\hat{\mathbf{x}}^r = \mathbf{P}_r^T(\mathbf{x})\hat{\mathbf{x}}(t_r)$$

$$\hat{\mathbf{x}}(t_r) = (\mathit{forcing\ term}), r = R,\ R-1,\ \ldots,\ 0$$

Correctness Check of TLM and ADJ



The correctness of TLM may be checked following the relationship of

$$\Phi(\alpha)=\frac{\left\|\mathbf{Q}_r(\mathbf{x}+\alpha\mathbf{h})-\mathbf{Q}_r(\mathbf{x})\right\|}{\alpha\mathbf{P}_r\mathbf{h}}=1+O(\alpha)$$

The correctness of the adjoint model can be checked by the following equality

$$\left(\mathbf{P}_r\mathbf{x}_0^{'}\right)^T\left(\mathbf{P}_r\mathbf{x}_0^{'}\right)=\left(\mathbf{x}_0^{'}\right)^T\mathbf{P}_r^T\left(\mathbf{P}_r\mathbf{x}_0^{'}\right)$$

With the same setup as in the equation of TLM correctness check, the LHS of the equation above is

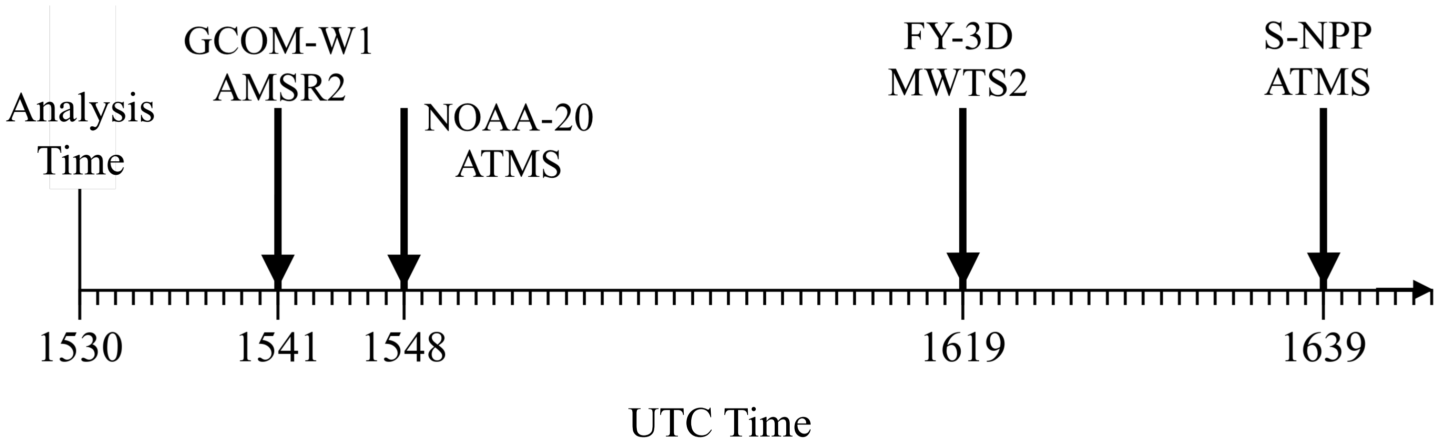
1914897.7637156348,

the RHS is

1914897.7637156344,

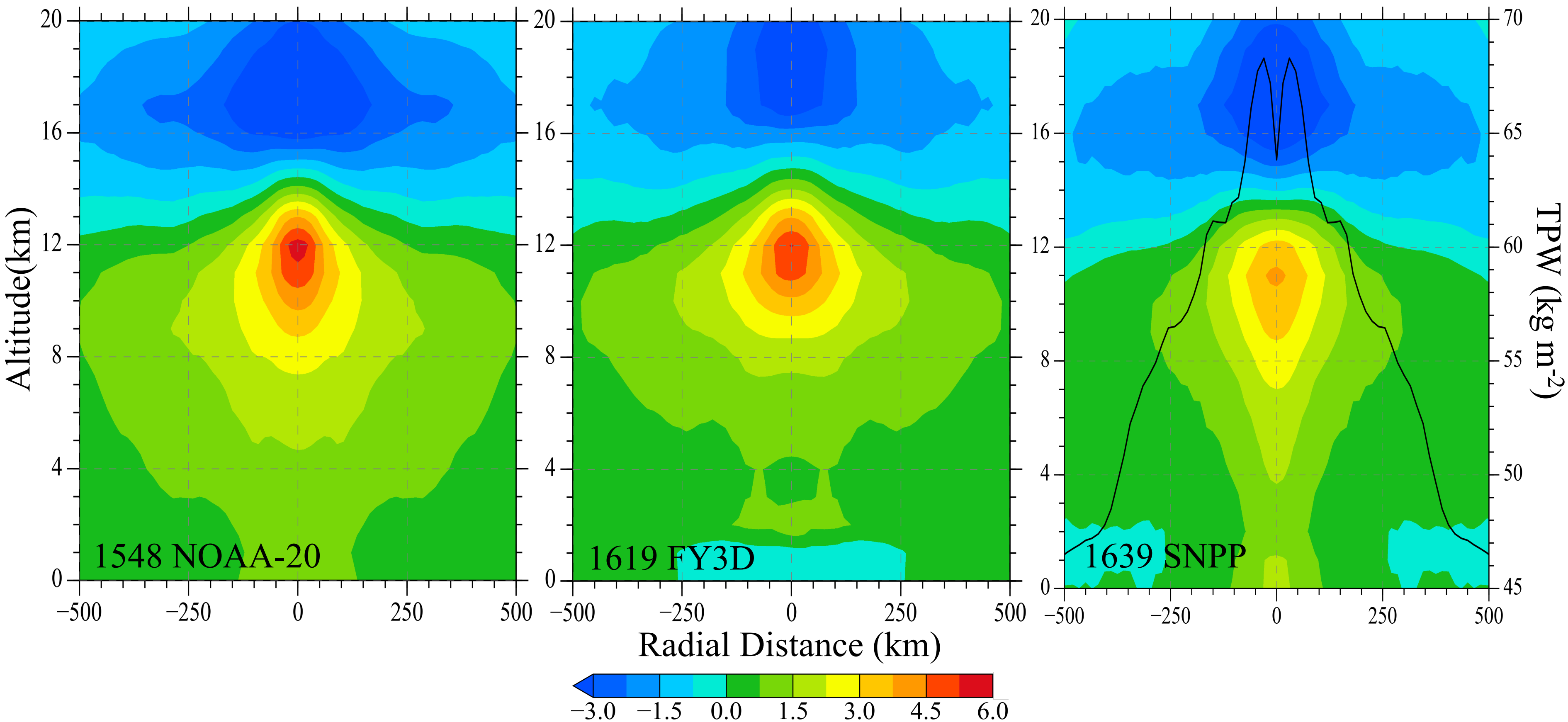
achieving a more than 16-digit accuracy.

Hurricane Florence Experiment Setup



The measurements from AMSR2, NOAA-20 ATMS, MWTS and S-NPP ATMS observed the center of Hurricane Florence at 1541, 1548, 1619 and 1639 UTC 4 September 2018 will be assimilated to obtain an optimal analysis at 1530 UTC.

Axisymmetric Components in Observations



- The azimuthally averaged potential temperature anomalies are positive and negative below and above an altitude of about 13-14 km at the center and 11-12 km near the center
- Hurricane eye was resolved by AMSR2 as the dip of TPW shows at the center.

4D-Var Vortex Initialization Experiment Design

The axisymmetric components of the TPW and warm cores are assimilated in the 4D-Var VI experiments. A cost function defined below is then minimized in a 4D-Var VI experiment

$$J(\mathbf{x}_0)=\frac{1}{2}(\mathbf{x}_0-\mathbf{x}_b)^T\mathbf{B}^{-1}(\mathbf{x}_0-\mathbf{x}_b)+\frac{1}{2}\sum_{r=0}^{N}\left(H_r(\mathbf{x}_r)-\mathbf{y}_r\right)^{-1}\mathbf{O}_r^{-1}\left(H_r(\mathbf{x}_r)-\mathbf{y}_r\right)$$

$\mathbf{x}_0$ is the analysis vector at t_0
$\mathbf{x}_b$ is the background field
$\mathbf{y}_r$ is microwave retrievals of TPW and the warm core at $\mathbf{t}_r$
$\mathbf{H}_r$ is the observation operator connecting observation and model state variables

Minimization of the Cost Function

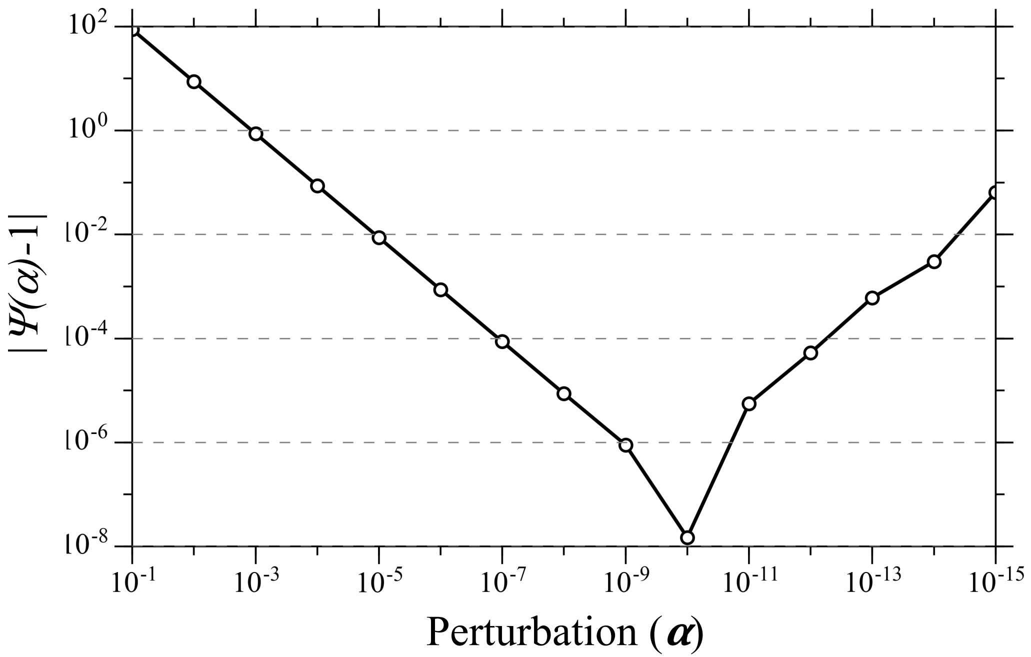
The gradient of J with respect to $\mathbf{x}_0$ can be calculated by the following mathematical expression

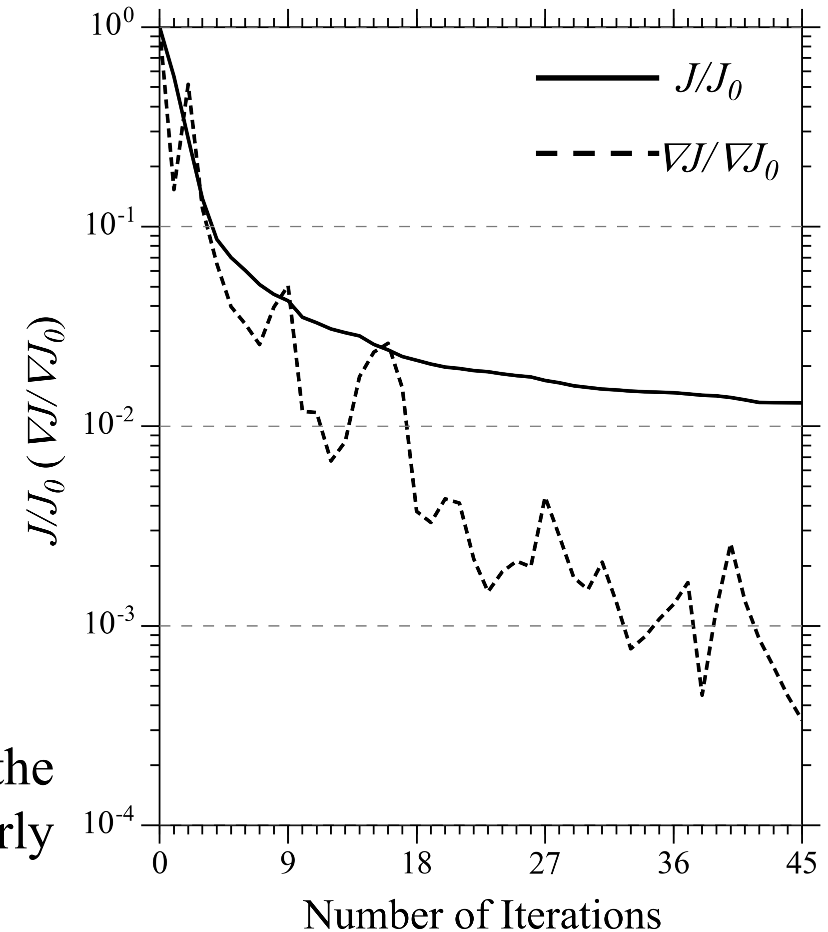
$$\nabla_{\mathbf{x}_0} J = \mathbf{B}^{-1}(\mathbf{x}_0 - \mathbf{x}_b) + \sum_{r=0}^{N} \mathbf{P}_r^T \mathbf{H}_r^T \mathbf{O}_r^{-1} \left(H_r(\mathbf{x}_r) - \mathbf{y}_r \right)$$

Similar with the TLM, the correctness of the gradient may be checked as shown in the equation below

$$\psi(\alpha) \equiv \frac{J(\mathbf{x}_0 + \alpha \mathbf{h}) - J(\mathbf{x}_0)}{\alpha \mathbf{h}^T \nabla J(\mathbf{x}_0)} = 1 + O(\alpha)$$

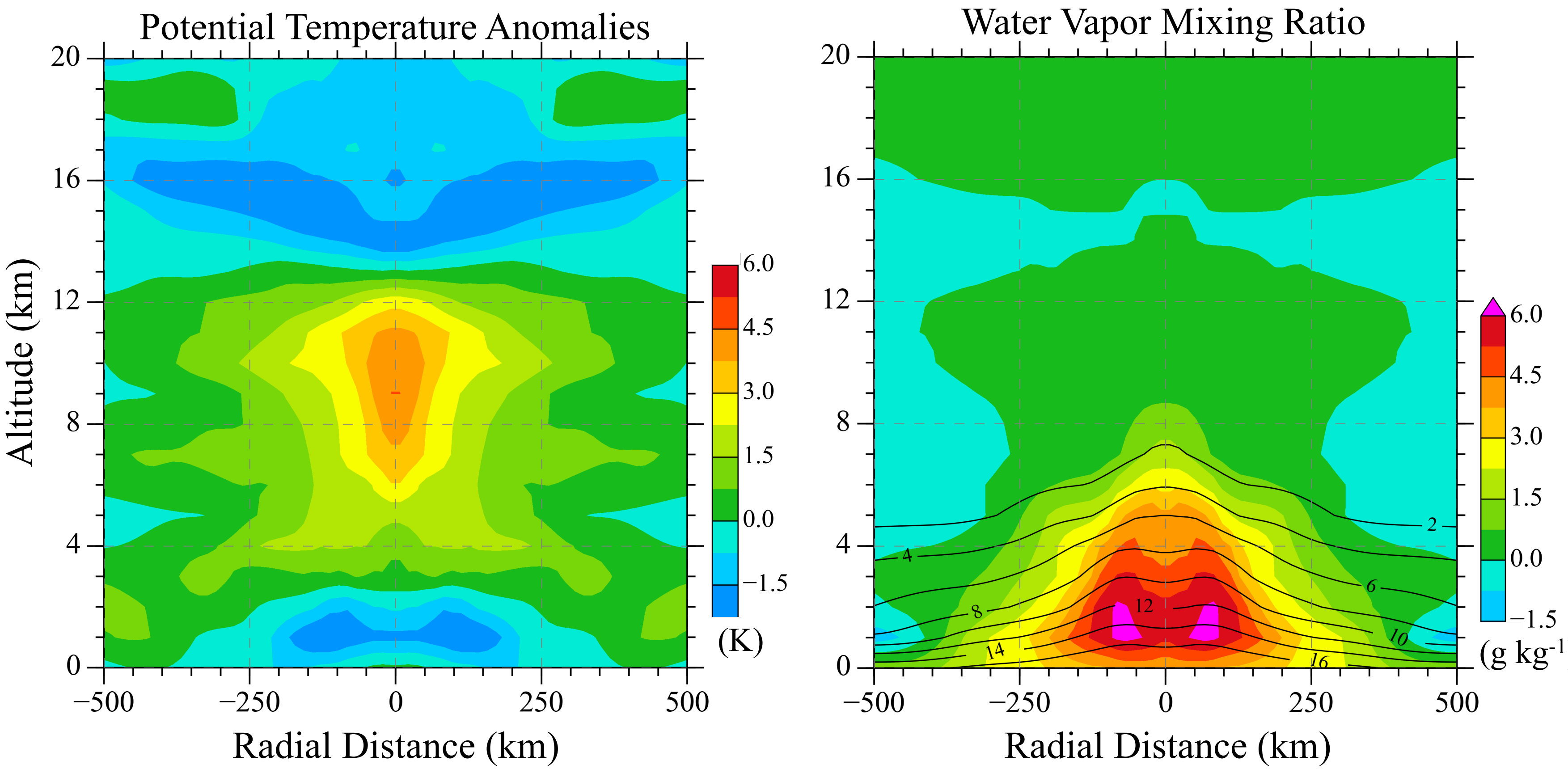
Convergence of the Minimization





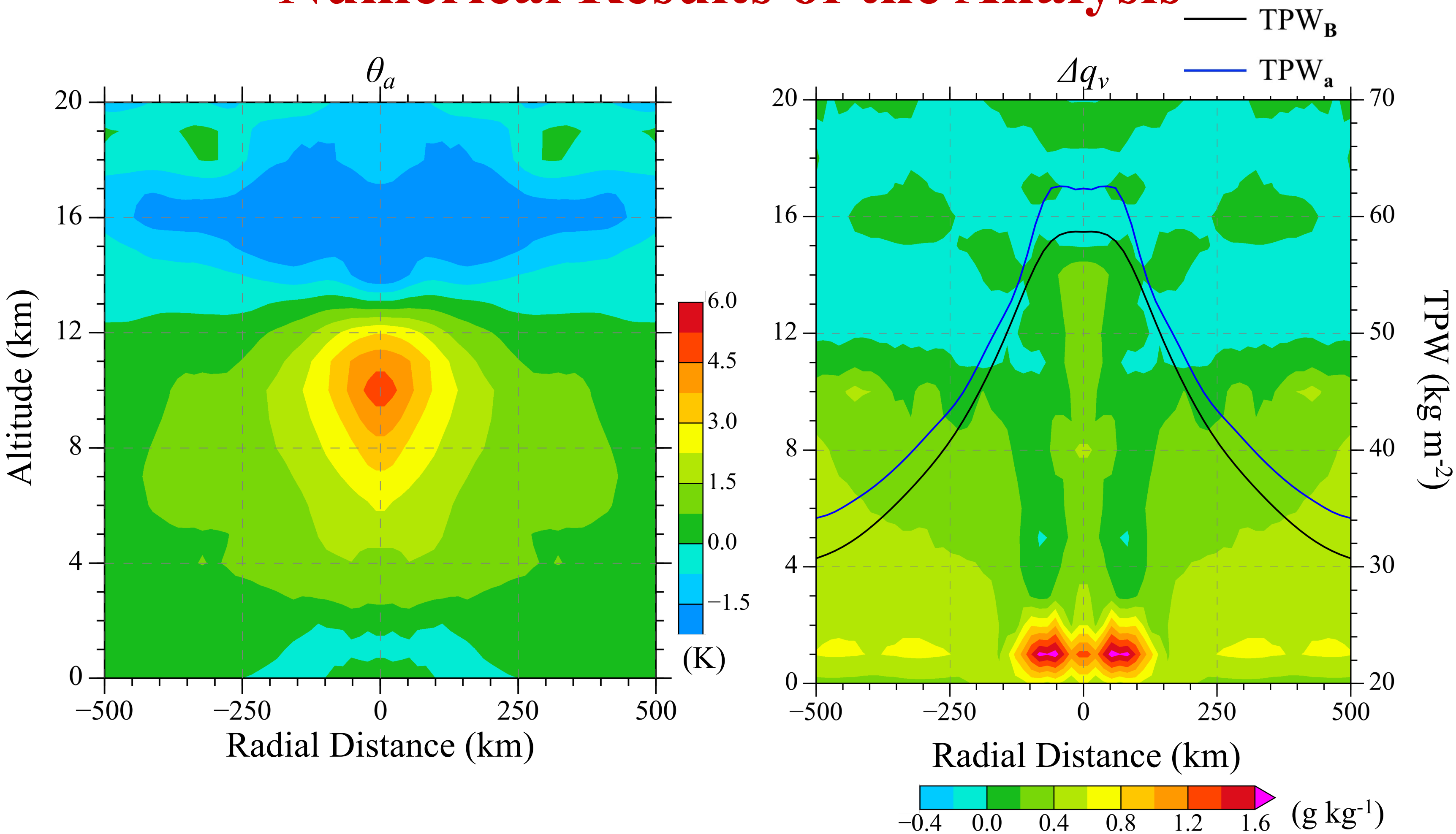
- The variation in $|\Psi(\alpha)\text{-}1|$ with respect to the perturbation magnitude parameter $\boldsymbol{\alpha}$ linearly approaches unity as expected
- The cost function decreases by two orders of magnitude and the norm of the gradient by more than three orders in 45 iterations

Background at 1530 UTC



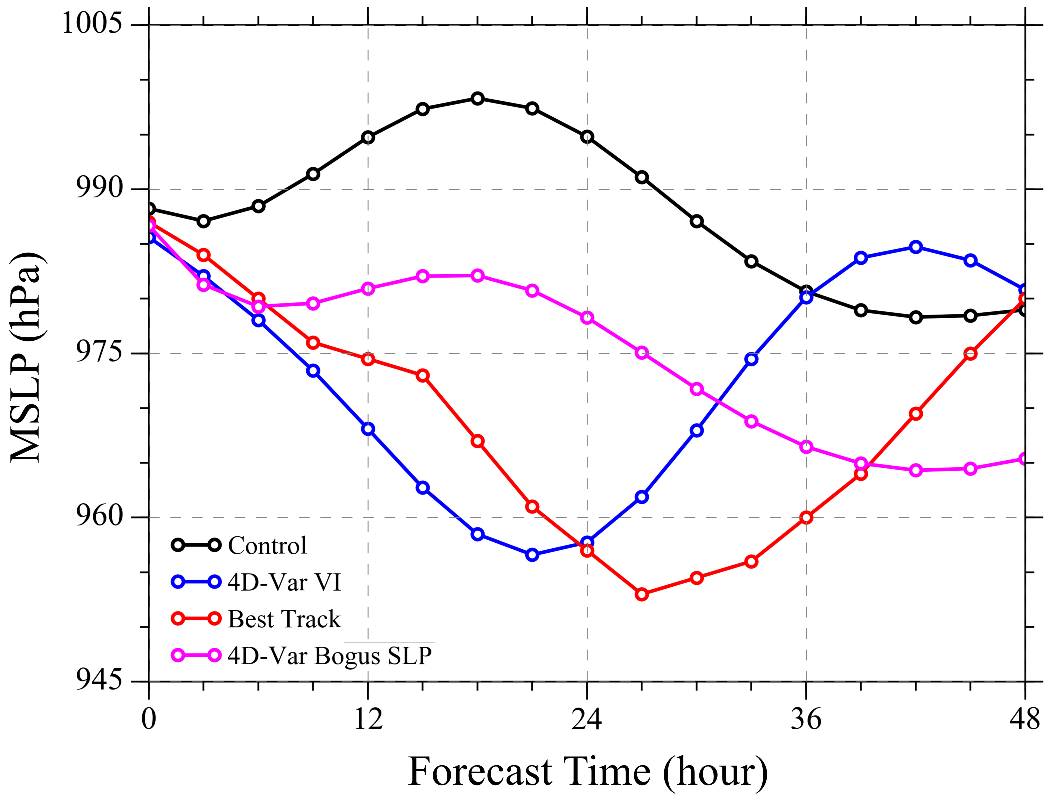
The background field is obtained by running a 3.5-hour forecast with RE model initialized by the azimuthally averaged ERA5 reanalysis at 1200 UTC 4 September 2018.

Numerical Results of the Analysis



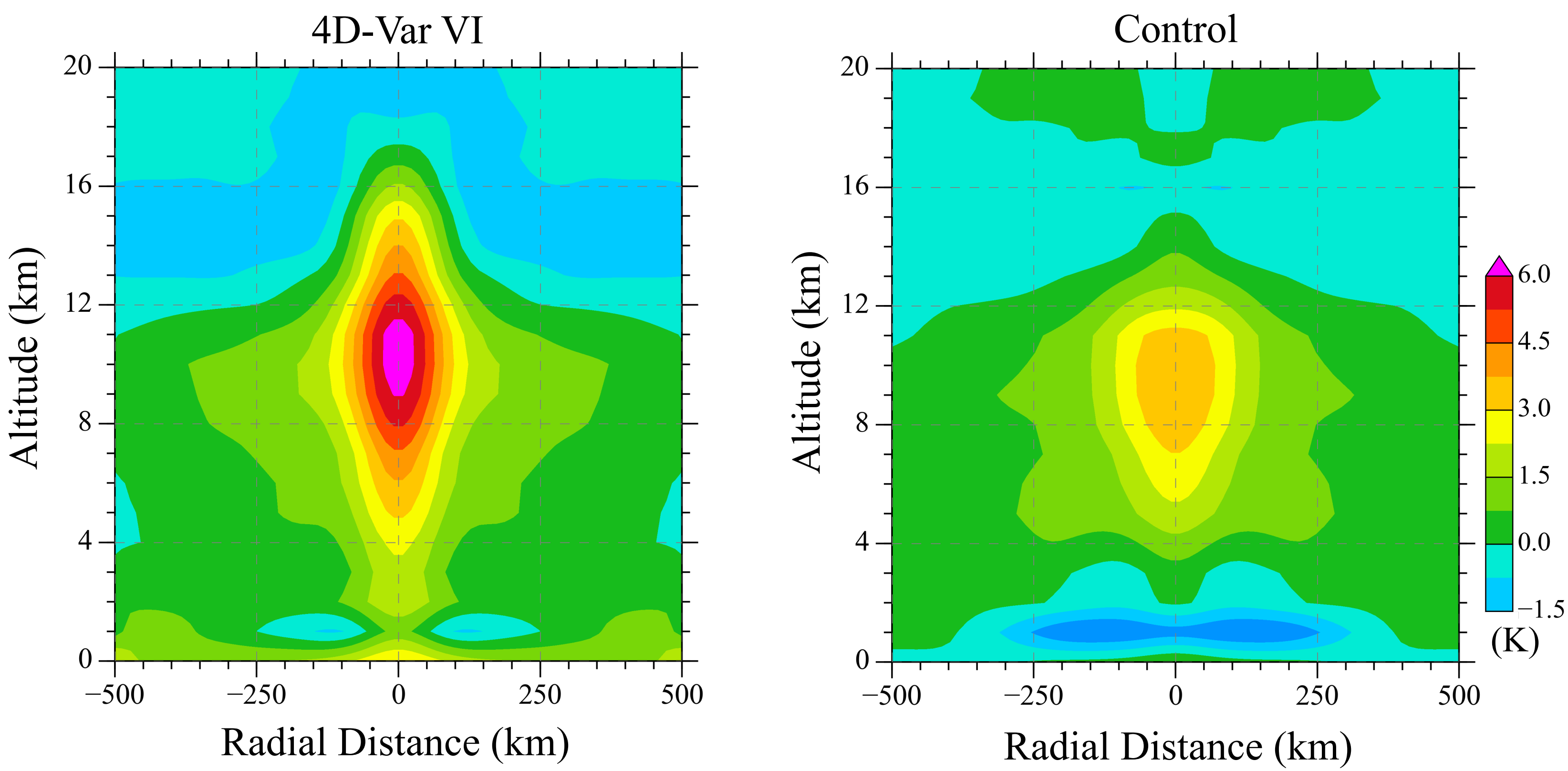
- Compared with the background, the location of maximum warm core is slightly higher as in the observations
- TWP values in the analysis were also increased.

Impacts on Intensity Forecast



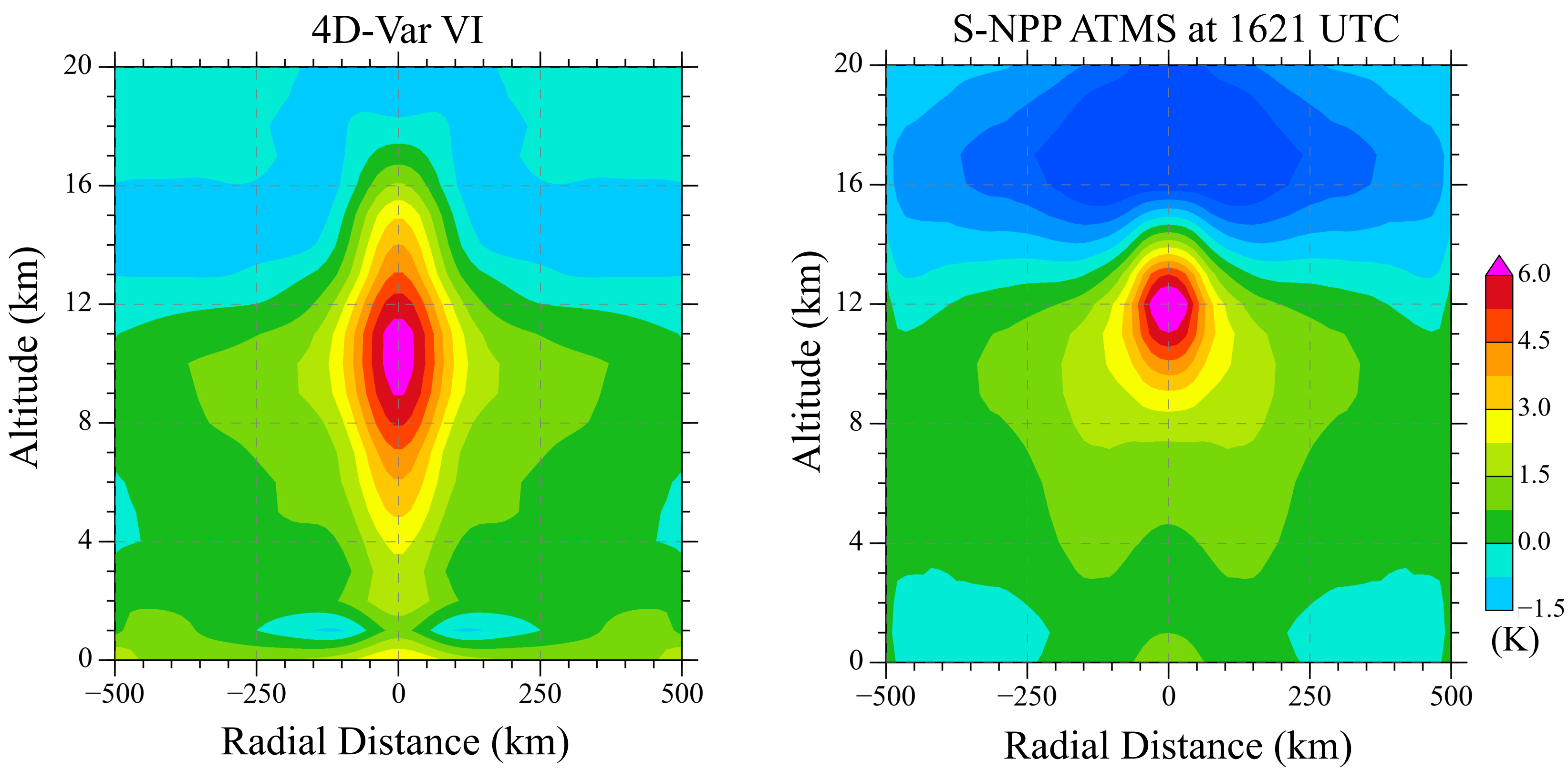
- Three forecasts were made with the nonlinear RE model with initial conditions with and without observations assimilated
- The 4D-Var VI experiment captures reasonably well the variation in intensity during the 24-h period but not the control experiment

Potential Temperatures in 24-Hour Forecasts



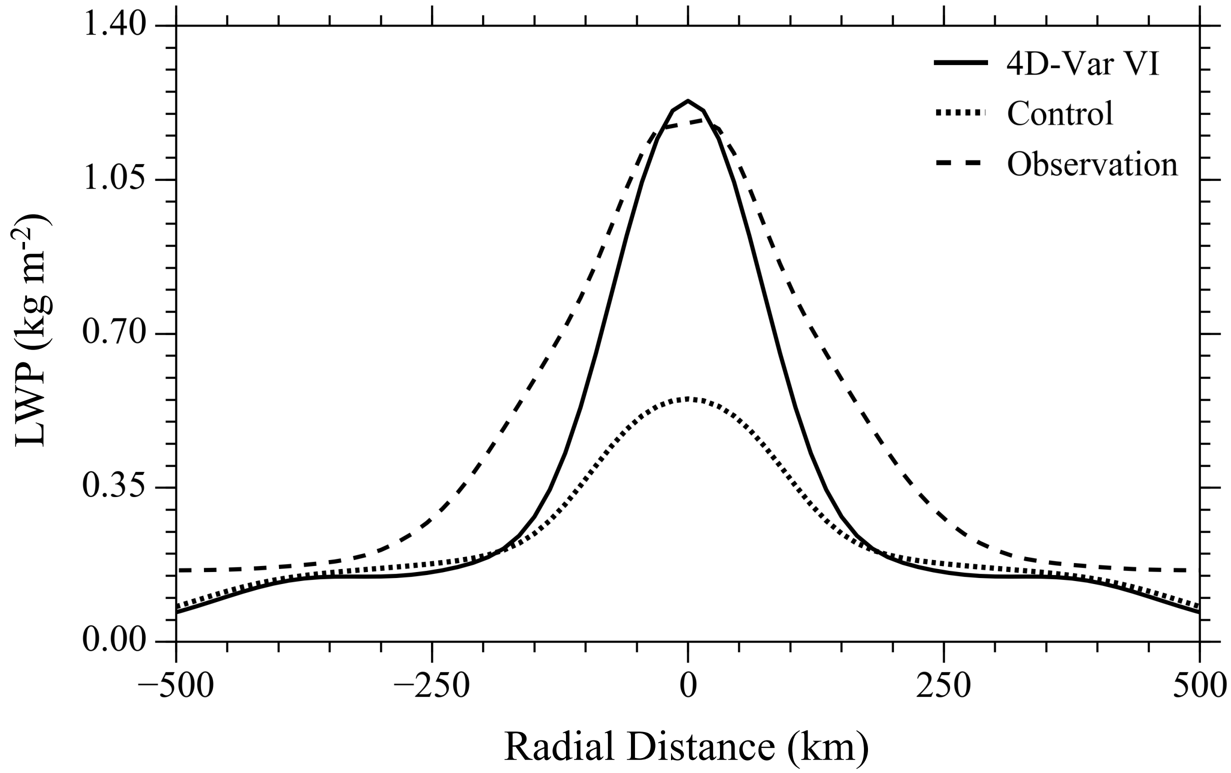
- Both experiments show well-defined hurricane warm core structures
- The warm core intensity from the control experiment is significantly weaker than that from the 4D-Var VI experiment.

Forecasts vs Observations



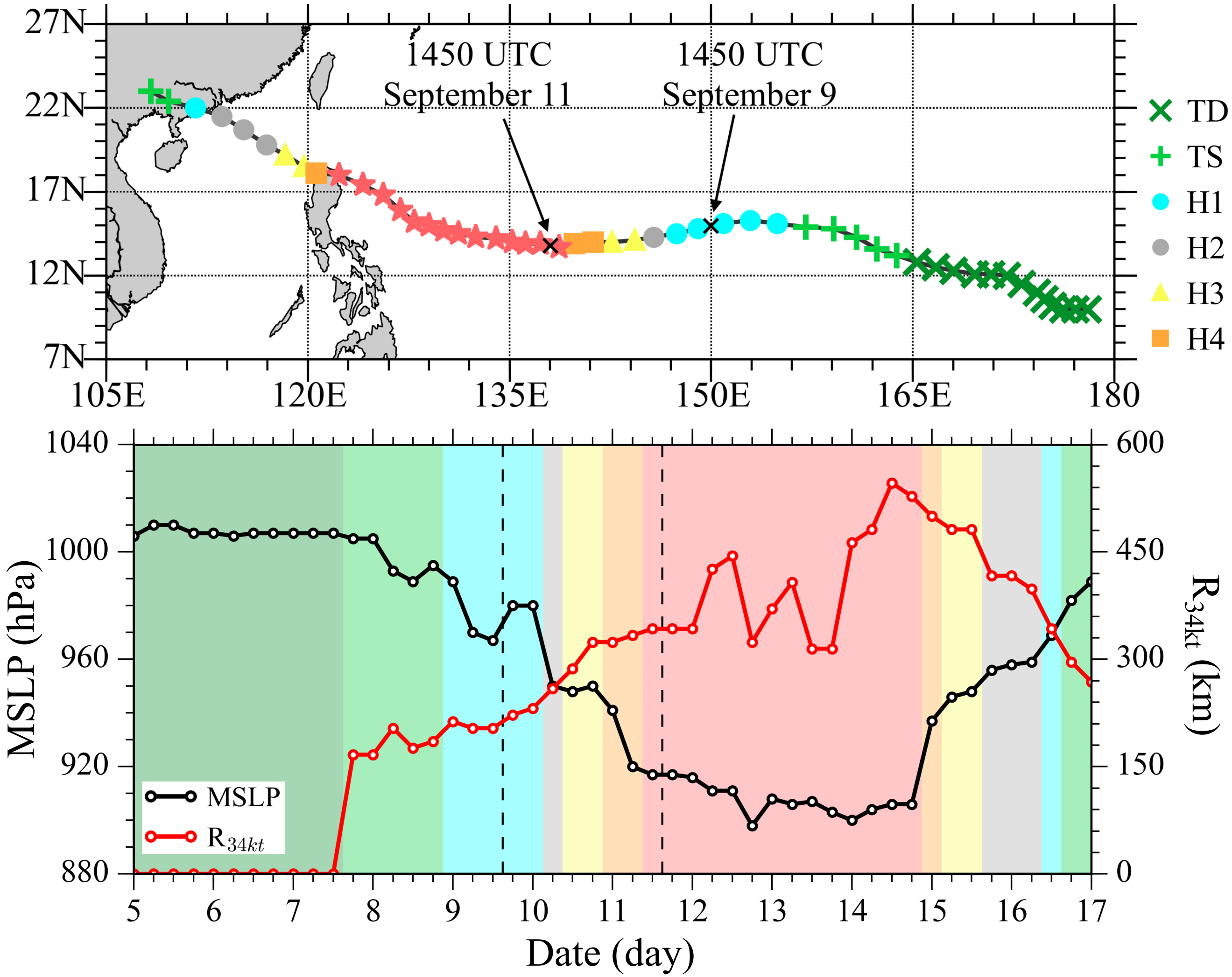
- The overall structure of the potential temperature and intensities are comparable to the observed ones.

LWP in 24-Hour Forecasts



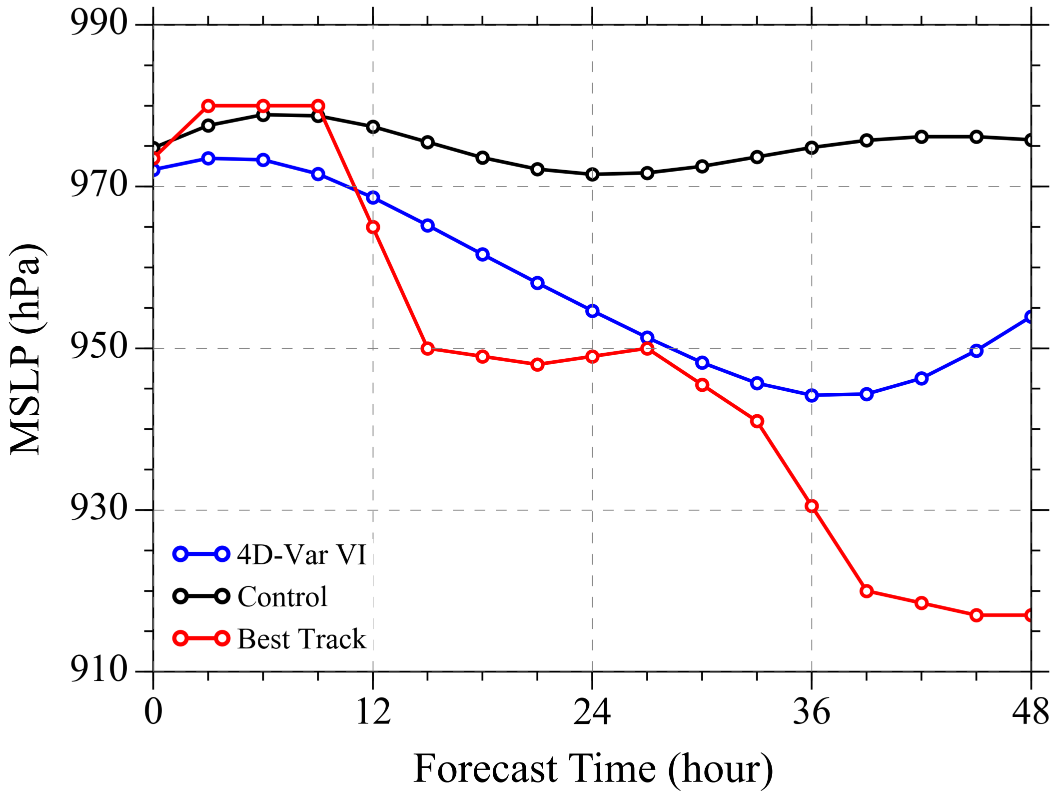
The 24-h forecast of LWP compared quite favorably with the retrievals from AMSR2 measurements in maximum values near the storm center and the decreasing rate of LWP along the radial distances.

Typhoon Mangkhut



The analysis time is 1450 UTC 9 September 2018, which was the time when Typhoon Mangkhut started to intensify to its peak strength.

LWP in Forecasts



The observations were available at 1454 UTC from NOAA-20 ATMS, 1521 UTC from AMSR2 and 1545 UTC from S-NPP ATMS on September 9, 2018.

Summary of 4D-Var VI

- The proposed 4D-Var VI system allows the retrievals from satellite observations to be assimilated into a nonhydrostatic axisymmetric numerical model
- Initial conditions obtained by the 4D-Var VI was well adapted to the forecast model because of the constraint of model dynamics
- The intensity forecasts in case of Hurricane Florence and Typhoon Mangkhut are dramatically improved as well as inner structures of the predictions
- Future efforts will be to incorporate the 4D-Var VI system into realistic models for vortex initialization, such as the MPAS-Atmosphere model