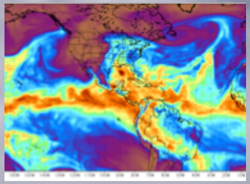
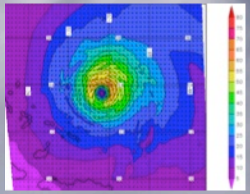
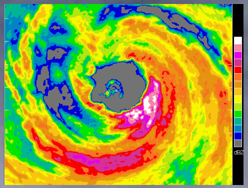
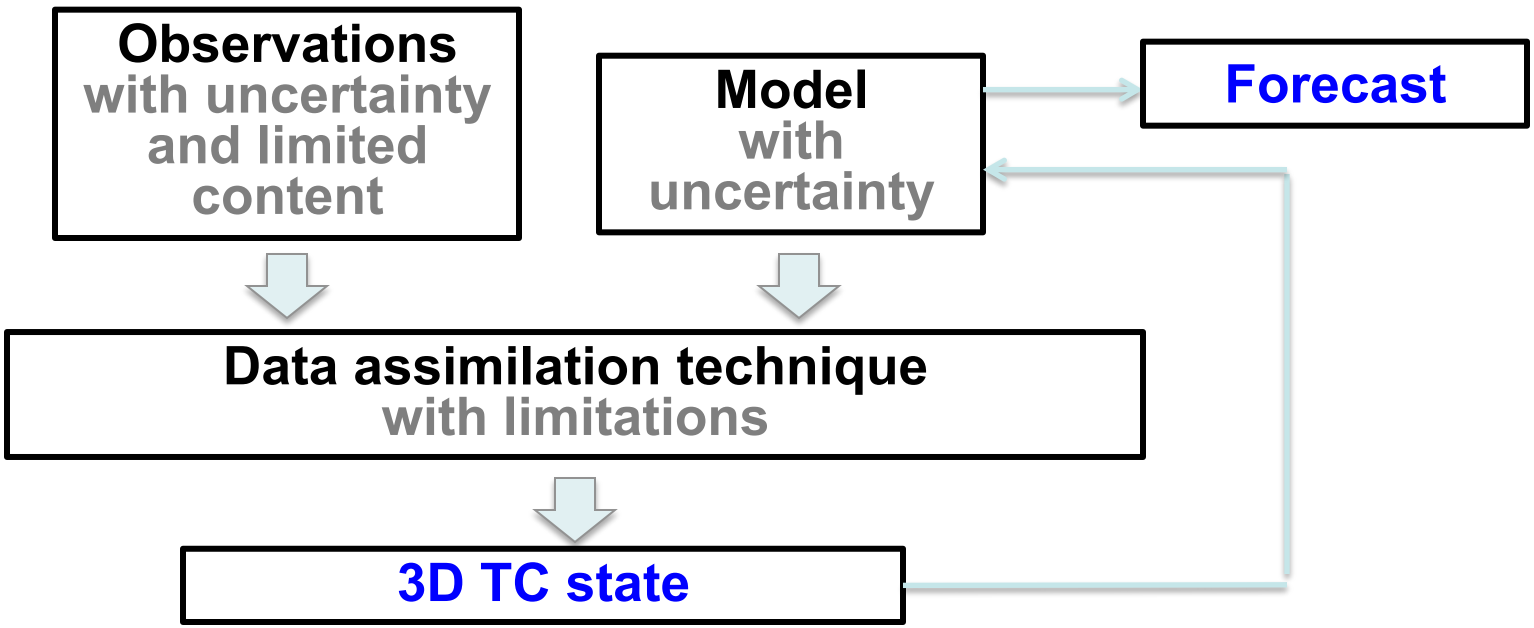
Data Assimilation for Tropical Cyclones

Tomislava Vukicevic
AOML Program Review
4-6 March 2014

Motivation

What observations will result in accurate and precise representation and forecasts of tropical cyclone inner core in numerical models?



Strategy

- Develop advanced data assimilation research technology for HWRF model
- Establish capability to do systematic evaluation of observation impacts
- Integrate modeling, observing and physical analysis expertise in HRD into data assimilation and impact analysis
- Transition new knowledge and technology to the operational and research community

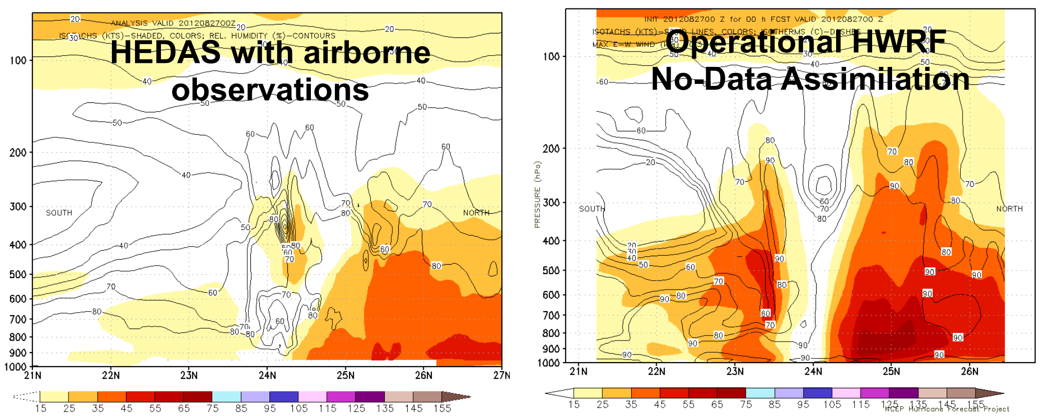
DA systems developed at HRD

- **Hurricane Ensemble Data Assimilation System (HEDAS)**
  - Inner-core DA with HWRF model
    - Ensemble Kalman Filter technique
    - Applies to high-resolution inner nest of HWRF model
    - Storm-relative approach to using observations
    - End-to-end software system with capability for real-time, retrospective and idealized applications

- **Regional OSSE/OSE system for HWRF model**
  - Regional DA with HWRF model
    - Includes GSI, EnKF-GSI-hybrid and HEDAS options
    - Applies to a large domain uniform resolution grid
    - End-to-end software system with capability for long-term continuous cycling
    - Observation types: conventional, satellite radiance, airborne and satellite-based products

Impact of airborne inner-core observations on TC analysis and forecast

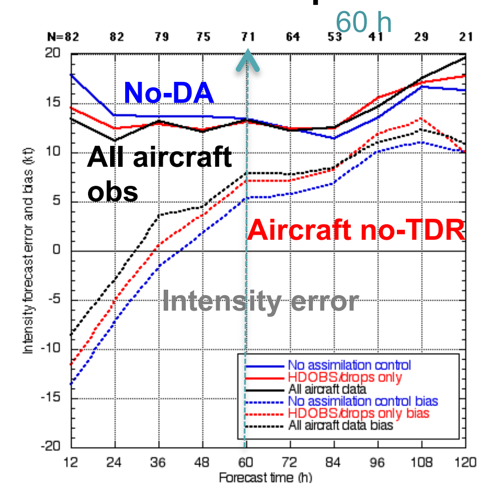
HEDAS real-time experiments since 2010 during hurricane season

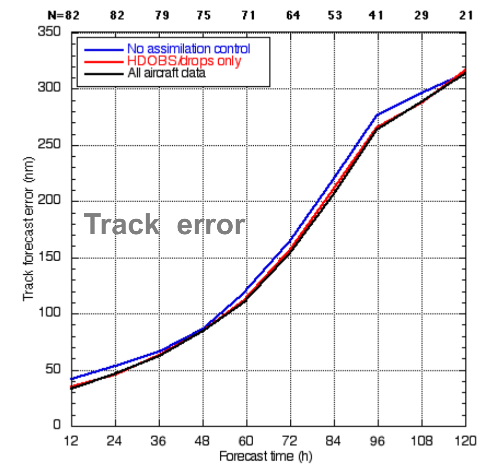


Wind and RH for Hurricane ISAAC 2012

- The experiments demonstrate positive impact of the reconnaissance observations on representing the initial vortex structure with HWRF model
- Motivated use of the reconnaissance observations in the operational HWRF system

HFIP-project: multi-season Recon-data impact study

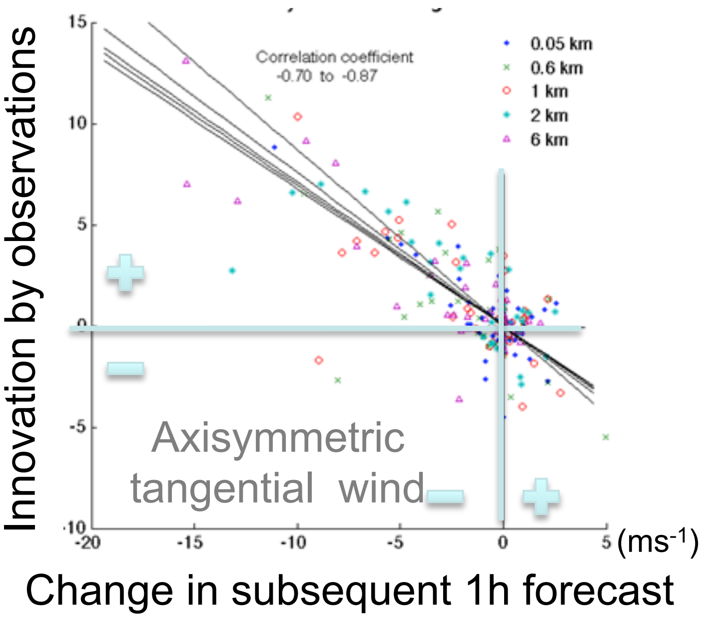




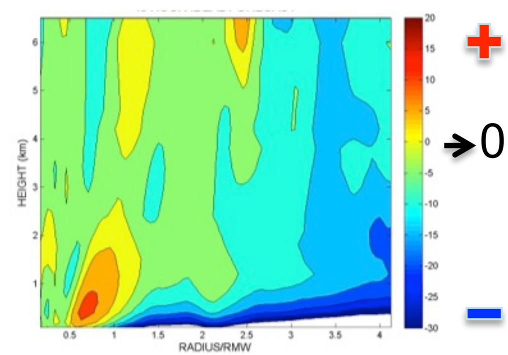
[Credit: Sim Aberson (HRD)]

Understanding and improving the impact of observations

- Weak secondary circulation, inconsistent with strong primary circulation after innovations
- Insufficient content of observations



Possible solution: A weak constraint balance in DA



Deviation from gradient balance in span-up vortex in HWRF

- Tendency for vortex spin-down for hurricane strength storms during cycling with observations and in subsequent short-term forecast

- Currently testing application of Sawyer-Eliassen solution for secondary circulation, given the primary circulation and diabatic and frictional stress forcing based on forecast

Optimizing the impact on intensity forecast

What is optimal impact ?

- Currently used operational BT metric of TC intensity is not suitable for impact assessment

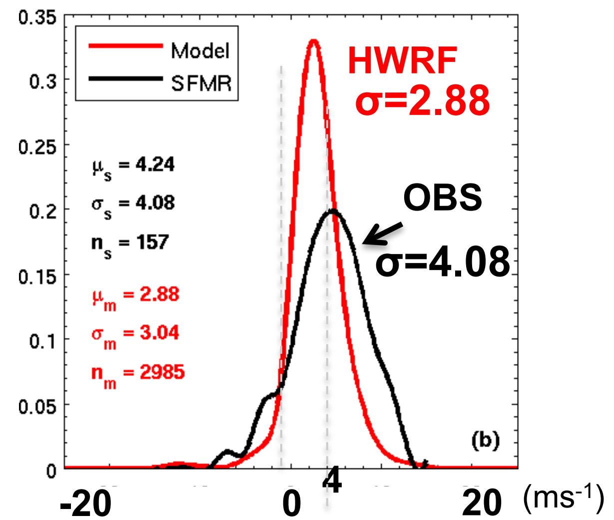
Alternative verification metric

$$V^*_{max} = (V_0 + V_1)(rmw) + \varepsilon$$

wave 0 and 1 amplitude — *residual*

rmw is at $max(V_0+V_1)(r)$

PDF of residual using $[V_0+V_1]^{SFMR}$ and V^{BT}_{max}



- Residual is within expected uncertainty of BT data
- Low wavenumber intensity determines maximum achievable skill and practical predictability

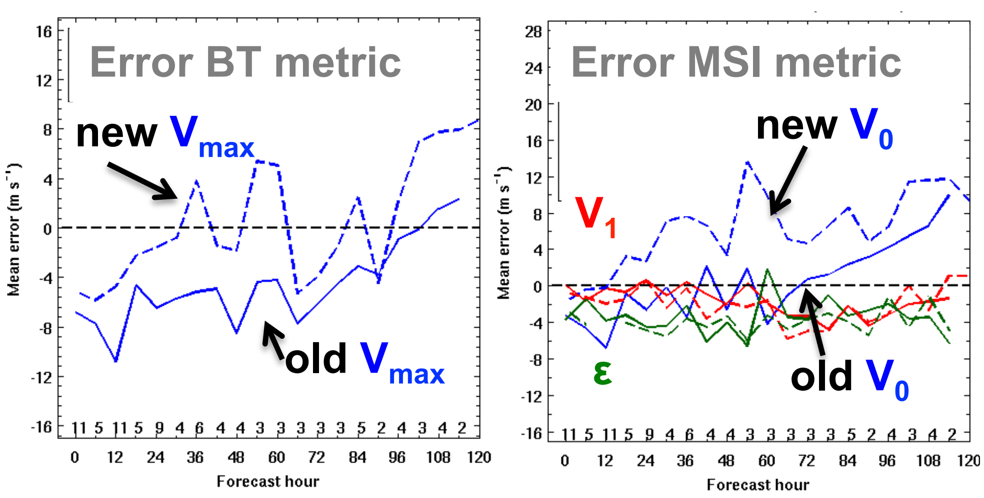
Optimizing the impact on intensity forecast

What is optimal impact ?

- Currently used operational BT metric of TC intensity is not suitable for impact assessment
- Incorrect assessment of impact is possible using the BT metric due to error compensation

$$V^*_{\max} = (V_0 + V_1)(rmw) + \varepsilon$$

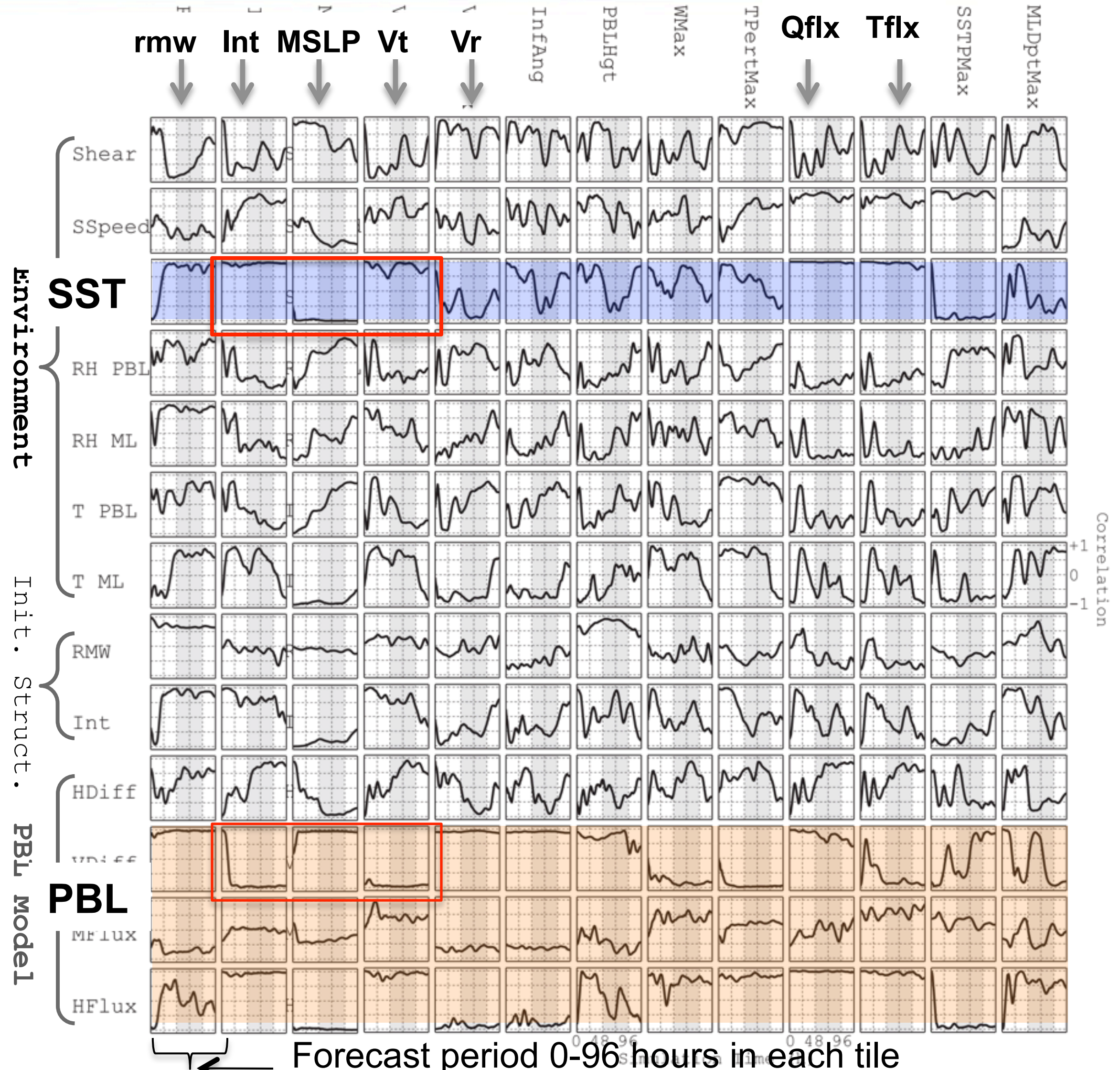
Verification of impact using BT and MSI metrics



- Observation impacts should focus on improving the low-wavenumber intensity prediction
- Need satellite-based surface wind retrievals to complement reconnaissance data for the low-wavenumber intensity verification

Representing the model errors in DA

- **Model errors have significant impact on the accuracy of data assimilation**
- Ensemble-based correlations between forecast and control parameters in HWRF
- Complex and even opposing impacts of different control parameters
- Optimal approach would be to dynamically estimate the model ensemble as part of DA using the observations



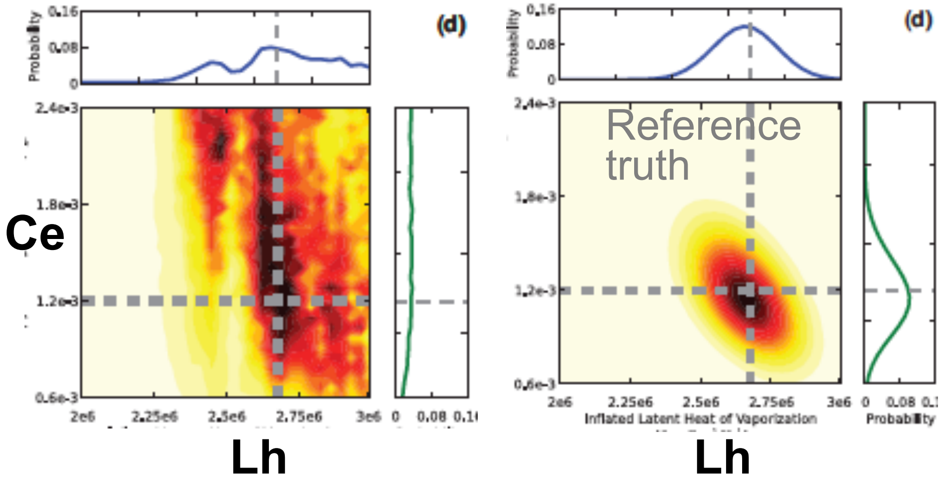
Positive feedback between DA and model

- Model errors could be reduced by parameter estimation using the process relevant observations

- Estimation of Latent heat of vaporization (Lh) and enthalpy exchange coefficient (Ce) using an axisymmetric TC vortex model

- Types of observations used:
  - Tangential wind maximum
  - 2D kinematic field within vortex core

Joint probability distribution of parameter values



- Parameters could be well optimized with respect to the kinematic field observations but not with respect to the peak intensity

AOML's Regional OSSE efforts

Ongoing and planned regional OSSEs

- To determine potential impact of UAS and to optimize sampling strategies for both UAS and hurricane reconnaissance aircraft.
- To evaluate advanced hyperspectral sounders in both geostationary and polar orbit
- To evaluate microwave sounders in geostationary orbit
- To evaluate alternative wind lidar technologies
- To evaluate constellations of GNSS satellites such as COSMIC and CYGNSS

Summary

- Developed advanced data assimilation research technology for HWRF model with focus on TC inner-core state analysis and forecast
- Established infrastructure to do systematic evaluation of observation impacts for the existing and proposed future observations (OSE and OSSE studies)
- The research on observation impact also includes evaluating, understanding and enhancing capability of DA and the forecast model
    - Storm relative DA for TC inner core
    - Dynamically balanced initial condition
    - Model error representation in ensemble DA
    - Improving the verification of observation impacts
    - Dynamic optimization of model parameters
    - Satellite data assimilation in all-sky condition

QUESTIONS?

Publications from DA research since 2009

Vukicevic, T., Uhlhorn E., Reasor P., Klotz B. : A novel multi-scale intensity metric for evaluation of tropical cyclone intensity forecasts. J. Atmospheric Sciences doi: http://dx.doi.org/10.1175/JAS-13-0153.1, 2014

Uhlhorn E., Klotz B., Vukicevic T., Reasor P., Rogers R. : Observed Hurricane Wind Speed Asymmetries and Relationships to Motion and Environmental Shear. Monthly Weather Review. doi: http://dx.doi.org/10.1175/MWR-D-13-00249.1, 2014

Rio-Berrios, R., T. Vukicevic, and B. Tang. Adopting model uncertainties for tropical cyclone intensity prediction. Monthly Weather Review, 142(1):72-78, doi: 10.1175/MWR-D-13-00186.1 2014

van Lier-Walqui, M., T. Vukicevic, and D.J. Posselt Linearization of microphysical parameterization uncertainty using multiplicative process perturbation parameters. Monthly Weather Review, 142(1):401-413, doi:10.1175/MWR-D-13-00076.1 2014

Aksoy, A. Storm-relative observations in tropical cyclone data assimilation with an ensemble Kalman filter. Monthly Weather Review, 141(2):506-522, doi:10.1175 MWR-D-12-00094.1 2013

Aksoy, A., S.D. Aberson, T. Vukicevic, K.J. Sellwood, S. Lorsolo, and X. Zhang. Assimilation of high-resolution tropical cyclone observations with an ensemble Kalman filter using NOAA/AOML/HRD’s HEDAS: Evaluation of the 2008-2011 vortex-scale analyses. Monthly Weather Review, 141(6):1842-1865, doi:10.1175/ MWR-D-12-00194.1 2013

Lorsolo, S., J. Gamache, and A. Aksoy. Evaluation of the Hurricane Research Division Doppler radar analysis software using synthetic data. Journal of Atmospheric and Oceanic Technology, 30(6):1055-1071, doi:10.1175/JTECH-D-12-00161.1 2013

Rogers, R.F., S.D. Aberson, A. Aksoy, B. Annane, M. Black, J.J. Cione, N. Dorst, J. Dunion, J.F. Gamache, S.B. Goldenberg, S.G. Gopalakrishnan, J. Kaplan, B.W. Klotz, S. Lorsolo, F.D. Marks, S.T. Murillo, M.D. Powell, P.D. Reasor, K.J. Sellwood, E.W. Uhlhorn, T. Vukicevic, J.A. Zhang, and X. Zhang. NOAA’s Hurricane Intensity Forecasting Experiment (IFEX): A progress report. Bulletin of the American Meteorological Society, 94(6):859-882, doi:10.1175/BAMS-D-12-00089 2013

Vukicevic, T., A. Aksoy, P. Reasor, S. Aberson, K. Sellwood, and F. Marks. Joint impact of forecast tendency and state error biases in Ensemble Kalman Filter data assimilation of inner-core tropical cyclone observations. Monthly Weather Review, 141(9):2992-3006, doi:10.1175/MWR-D-12-00211.12013

Aksoy, A., S. Lorsolo, T. Vukicevic, K.J. Sellwood, S.D. Aberson, and F. Zhang. The HWRF Hurricane Ensemble Data Assimilation System (HEDAS) for high-resolution data: The impact of airborne Doppler radar observations in an OSSE. Monthly Weather Review, 140(6):1843-1862,doi:10.1175/MWR-D-11-00212.1 2012

Lorsolo, S., and A. Aksoy. Wavenumber analysis of azimuthally-distributed data: Assessing maximum allowable gap size. Monthly Weather Review, 140(6): 1945-1956, doi:10.1175/MWR-D-11-00219.1 2012

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Publications from DA research since 2009 continued

Coddington, O., P. Pilewskie, and T. Vukicevic. The Shannon information content of hyperspectral shortwave cloud albedo measurements: Quantification and practical applications. Journal of Geophysical Research, 117:D04205, 12 pp., doi:10.1029/2011JD016771 2012

van Lier-Walqui, M., T. Vukicevic, and D.J. Posselt. Quantification of cloud microphysical parameterization uncertainty using radar reflectivity. Monthly Weather Review, 140(11):3442-3466,doi:10.1175/MWR-D-11-00216.1 2012

Polkinghorne, R., and T. Vukicevic. Data assimilation of cloud-affected radiances in cloud resolving model. Monthly Weather Review, 139(3): 755-773, doi:10.1175/MWR3360.1 2011

Aksoy, A., D.C. Dowell, and C. Snyder. A multicase comparative assessment of the ensemble Kalman filter for assimilation of radar observations, Part II: Short-range ensemble forecasts.Monthly Weather Review, 138(4):1273-1292, doi:10.1175/2009MWR3086.1 2010

Coddington, O.M., P. Pilewskie, J. Redemann, S. Platnick, P.B. Russell, K.S. Schmidt, W.J. Gore, J. Livingston, G. Wind, and T. Vukicevic. Examining the impact of overlying aerosols on the retrieval of cloud optical properties from passive remote sensing. Journal of Geophysical Research, 115:D10211, 13 pp., doi:10.1029/2009JD012829 2010

Posselt, D.J., and T. Vukicevic. Robust characterization of model physics uncertainty for simulations of deep moist convection. Monthly Weather Review, 138(5):1513-1535, doi:10.1175/2009MWR3094.1 2010

Vukicevic, T., O. Coddington, and P. Pilewskie. Characterizing the retrieval of cloud properties from optical remote sensing. Journal of Geophysical Research, 115:D20211, 14 pp.,doi:10.1029/2009JD012830 2010

Aksoy, A., D.C. Dowell, and C. Snyder. A multicase comparative assessment of the ensemble Kalman filter for assimilation of radar observations, Part I: Storm-scale analyses. Monthly Weather Review, 137(6):1805-1824, doi:10.1175/2009MWR3086.1 200

HEDAS CONFIGURATION in 2013

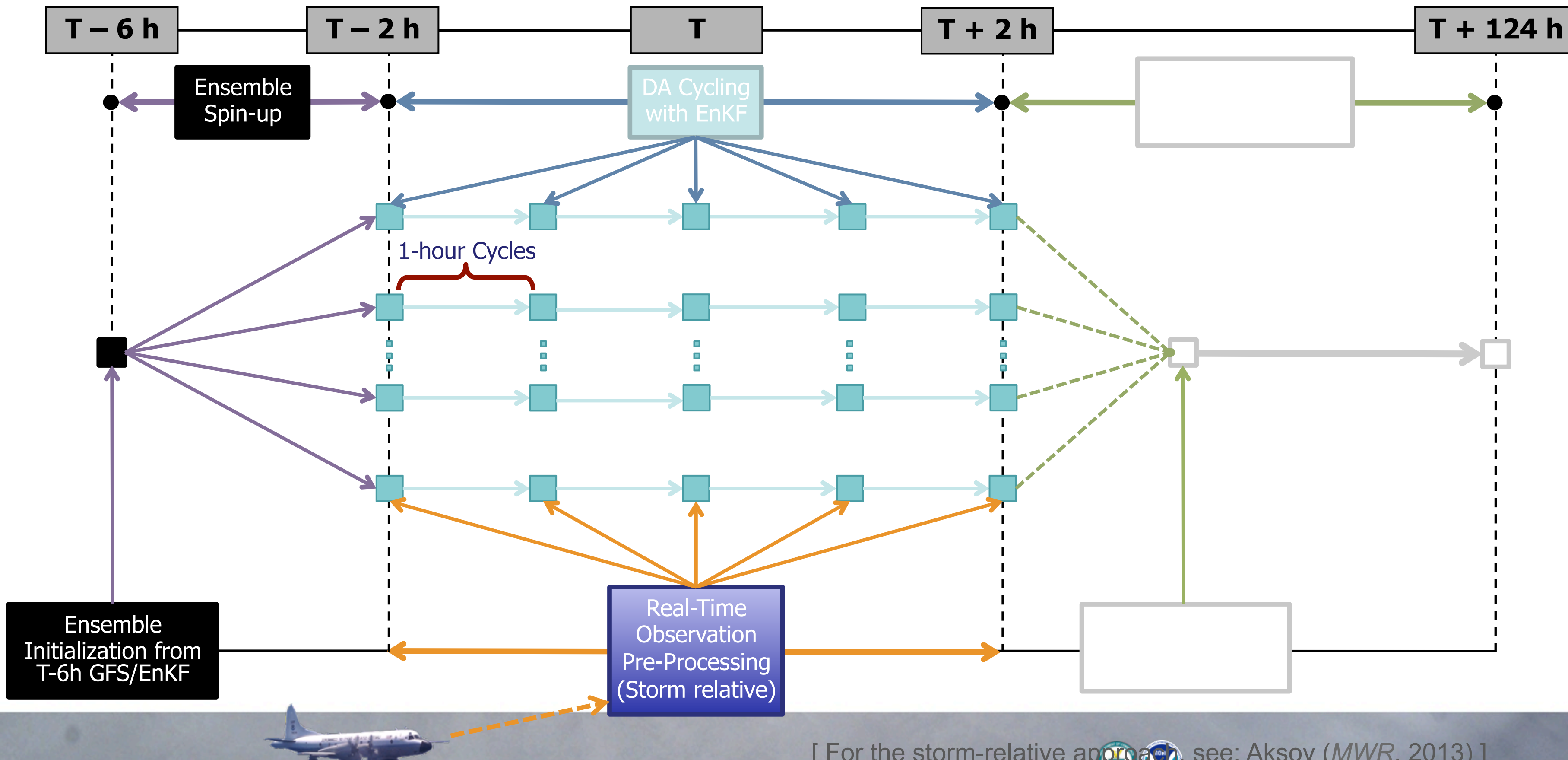
An ensemble-based **EnKF** data assimilation system **interfaced with NOAA's HWRF model (2012 version, no ocean)**

Ran **near real time in 2013** on NOAA's Jet supercomputer (supported by **NOAA HFIP project**)

Focuses on **data assimilation in the hurricane inner core** (in a 3-km inner nest)

Assimilates aircraft data (radar, dropsonde, flight level, SFMR surface wind speed) from NOAA P-3 and G-IV, Air Force Reserve C-130, and NASA Global Hawk aircraft, **and satellite AMVs, AIRS and GPS-RO retrieved T/Q profiles**

Published papers: Aksoy et al. (*MWR*, 2012 & 2013); Aksoy (*MWR*, 2013); Vukicevic et al. (*MWR*, 2013)



[For the storm-relative approach, see: Aksoy (*MWR*, 2013)]

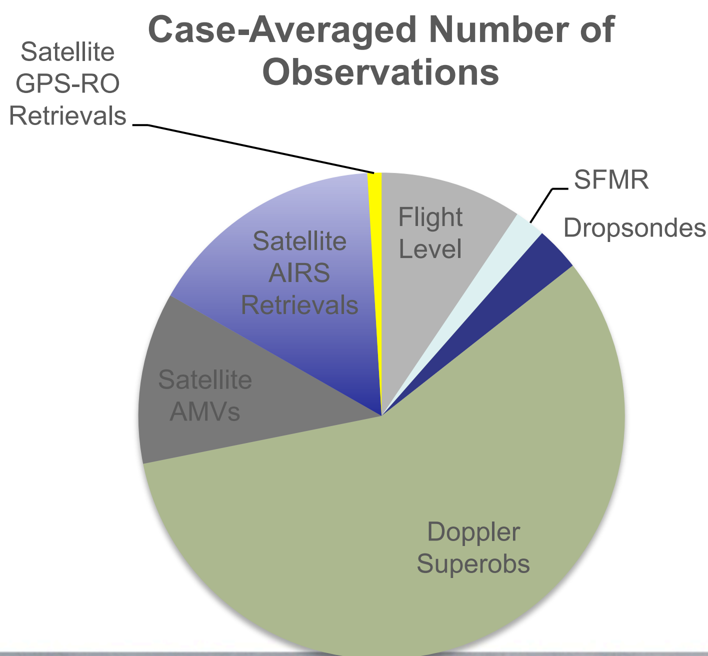
HEDAS CASES in 201

		FLIGHT LEVEL				SFMR			Dropsondes					Doppler Superobs				Satellite AIRS	Satellite GPS-RO	
STORM	DATE	P-3	Air Force	G-IV	Total	P-3	Air Force	Total	P-3	Air Force	G-IV	HS-3	Total	P-3	G-IV	Total	Satellite AMVs	Retrievals	Retrievals	Total
Fernand	2013082600	0	1,478	0	1,478	0	346	346	0	0	0	0	0	0	0	0	952	0	0	**2,776**
Gabrielle	2013082918	0	0	0	**0**	0	0	**0**	0	0	0	88	**88**	0	0	**0**	2,308	8,214	52	**10,662**
Gabrielle	2013083000	0	0	0	**0**	0	0	**0**	0	0	0	1,702	**1,702**	0	0	**0**	1,766	0	0	**3,468**
Gabrielle	2013083006	0	0	0	**0**	0	0	**0**	0	0	0	784	**784**	0	0	**0**	1,416	8,442	0	**10,642**
Gabrielle	2013083112	0	0	36	**36**	0	0	**0**	0	0	35	0	**35**	0	44	**44**	1,998	0	0	**2,113**
Gabrielle	2013083118	0	0	1,200	**1,200**	0	0	**0**	0	0	1,749	0	**1,749**	0	9,249	**9,249**	2,324	654	0	**15,176**
Gabrielle	2013090418	0	1,486	0	**1,486**	0	216	**216**	0	0	0	426	**426**	0	0	**0**	4,184	5,712	118	**12,142**
Gabrielle	2013090500	0	0	0	**0**	0	0	**0**	0	0	0	1,359	**1,359**	0	0	**0**	3,044	0	0	**4,403**
Gabrielle	2013090506	0	0	0	**0**	0	0	**0**	0	0	0	0	**0**	0	0	**0**	3,152	3,630	205	**6,987**
Gabrielle	2013090512	0	1,302	0	**1,302**	0	245	**245**	0	42	0	260	**302**	0	0	**0**	3,642	0	355	**5,846**
Gabrielle	2013090618	2,440	2,016	370	**4,826**	512	360	**872**	0	0	0	0	**0**	0	0	**0**	5,108	2,062	388	**13,256**
Gabrielle	2013090712	0	0	0	**0**	0	0	**0**	0	0	98	0	**98**	0	804	**804**	3,278	0	395	**4,575**
Gabrielle	2013090718	4,624	260	80	**4,964**	1,020	0	**1,020**	0	0	1,626	949	**2,575**	55,566	0	**55,566**	3,538	6,084	0	**73,747**
Gabrielle	2013090800	332	1,150	0	**1,482**	87	177	**264**	0	16	0	1,182	**1,198**	0	0	**0**	2,348	0	0	**5,292**
Gabrielle	2013090806	0	0	0	**0**	0	0	**0**	0	0	0	1,181	**1,181**	0	0	**0**	3,280	6,818	198	**11,477**
Gabrielle	2013091018	33	624	0	**657**	9	150	**159**	0	78	0	0	**78**	0	0	**0**	3,602	2,121	201	**6,818**
Eight	2013090518	0	868	0	**868**	0	202	**202**	0	0	0	0	**0**	0	0	**0**	1,876	2,986	29	**5,961**
Eight	2013090600	0	664	0	**664**	0	103	**103**	0	0	0	0	**0**	0	0	**0**	954	0	191	**1,912**
Ingrid	2013091218	0	816	0	**816**	0	166	**166**	0	0	0	0	**0**	0	0	**0**	804	1,586	31	**3,403**
Ingrid	2013091300	6	428	0	**434**	3	69	**72**	0	0	0	0	**0**	0	0	**0**	848	0	184	**1,538**
Ingrid	2013091312	0	1,778	0	**1,778**	0	357	**357**	0	13	0	0	**13**	0	0	**0**	1,261	0	195	**3,604**
Ingrid	2013091318	432	0	1,108	**1,540**	103	0	**103**	0	0	1,075	0	**1,075**	0	15,554	**15,554**	1,534	669	163	**20,638**
Ingrid	2013091400	1,194	1,691	0	**2,885**	311	245	**556**	157	18	0	0	**175**	20,372	0	**20,372**	1,067	0	0	**25,055**
Ingrid	2013091406	415	0	0	**415**	88	0	**88**	0	0	0	0	**0**	0	0	**0**	1,321	466	171	**2,461**
Ingrid	2013091412	1,546	1,808	204	**3,558**	391	353	**744**	226	84	80	0	**390**	26,089	2,071	**28,160**	1,527	0	364	**34,743**
Ingrid	2013091418	704	0	943	**1,647**	175	0	**175**	122	0	1,124	0	**1,246**	8,513	8,272	**16,785**	2,027	1,891	5	**23,776**
Ingrid	2013091500	1,476	1,904	0	**3,380**	350	446	**796**	191	31	0	0	**222**	10,683	0	**10,683**	1,883	0	0	**16,964**
Ingrid	2013091506	643	0	0	**643**	172	0	**172**	102	0	0	0	**102**	5,889	0	**5,889**	1,511	3,471	0	**11,788**
Ingrid	2013091512	1,318	2,304	207	**3,829**	327	532	**859**	244	226	52	0	**522**	19,603	1,793	**21,396**	1,641	0	200	**28,447**
Ingrid	2013091518	311	0	890	**1,201**	98	0	**98**	20	0	1,444	0	**1,464**	3,809	14,001	**17,810**	2,245	572	586	**23,976**
Ingrid	2013091600	2,593	1,927	0	**4,520**	581	377	**958**	307	103	0	0	**410**	16,430	0	**16,430**	1,626	0	0	**23,944**
Ingrid	2013091612	0	1,366	0	**1,366**	0	323	**323**	0	22	0	0	**22**	0	0	**0**	1,326	0	204	**3,241**
Karen	2013100218	0	1,588	0	**1,588**	0	330	**330**	0	0	0	0	**0**	0	0	**0**	2,500	2,196	366	**6,980**
Karen	2013100300	28	880	0	**908**	7	159	**166**	0	0	0	0	**0**	0	0	**0**	1,782	0	0	**2,856**
Karen	2013100306	0	0	0	**0**	0	0	**0**	0	0	0	0	**0**	0	0	**0**	2,060	5,446	0	**7,506**
Karen	2010100312	0	1,902	0	**1,902**	0	434	**434**	0	0	0	0	**0**	0	0	**0**	1,884	0	3	**4,223**
Karen	2010100318	1,024	1,881	0	**2,905**	242	367	**609**	123	57	0	0	**180**	6,082	0	**6,082**	4,030	2,281	196	**16,283**
Karen	2010100400	1,604	1,363	0	**2,967**	460	305	**765**	289	0	0	0	**289**	12,805	0	**12,805**	4,549	0	0	**21,375**
Karen	2010100406	1,126	1,410	641	**3,177**	279	410	**689**	134	99	985	0	**1,218**	7,429	0	**7,429**	4,089	1,471	0	**18,073**
Karen	2010100412	1,831	860	502	**3,193**	472	213	**685**	302	42	1,043	0	**1,387**	7,004	0	**7,004**	4,858	0	0	**17,127**
Karen	2010100418	985	1,935	0	**2,920**	236	441	**677**	108	64	0	0	**172**	1,929	0	**1,929**	4,925	6,661	0	**17,284**
Karen	2010100500	1,999	1,685	0	**3,684**	496	432	**928**	293	90	0	0	**383**	12,158	0	**12,158**	4,703	0	0	**21,856**
Karen	2010100506	1,214	1,452	0	**2,666**	285	296	**581**	163	64	0	0	**227**	1,054	0	**1,054**	3,197	5,879	0	**13,604**
Karen	2010100512	1,709	643	0	**2,352**	405	159	**564**	224	22	0	0	**246**	107	0	**107**	3,066	0	0	**6,335**
Karen	2010100518	0	2,067	0	**2,067**	0	483	**483**	0	102	0	0	**102**	0	0	**0**	2,667	1,277	192	**6,788**
		29,587	**41,536**	**6,181**	**77,304**	**7,109**	**8,696**	**15,805**	**3,005**	**1,173**	**9,311**	**7,931**	**21,420**	**215,522**	**51,788**	**267,310**	**113,701**	**80,589**	**4,992**	**581,121**

HEDAS CASES in 2013 - BREAKDOW

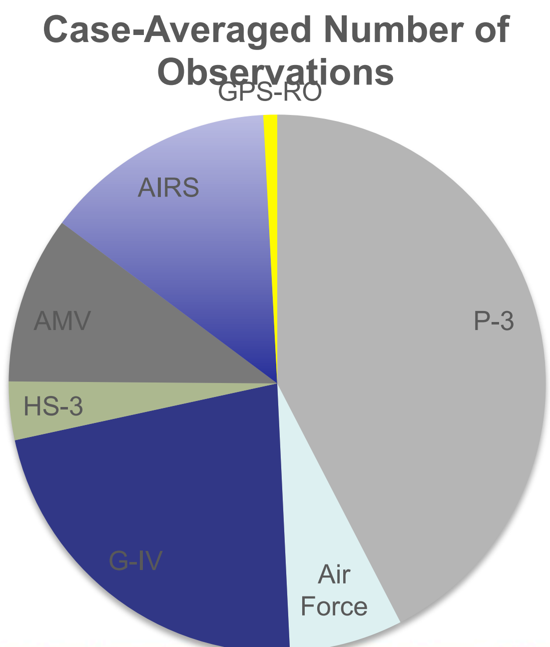
By Observing Platform

Platform	Num. Obs.	Num. Cases	Avg. Num. Obs.
Flight Level	77,304	37	2,089
SFMR	15,805	35	452
Dropsondes	21,420	33	649
Doppler Superobs	267,310	21	12,729
Satellite AMVs	113,701	45	2,527
Satellite AIRS Retrievals	80,589	23	3,504
Satellite GPS-RO Retrievals	4,992	24	208
Total	**581,121**	**45**	**12,914**



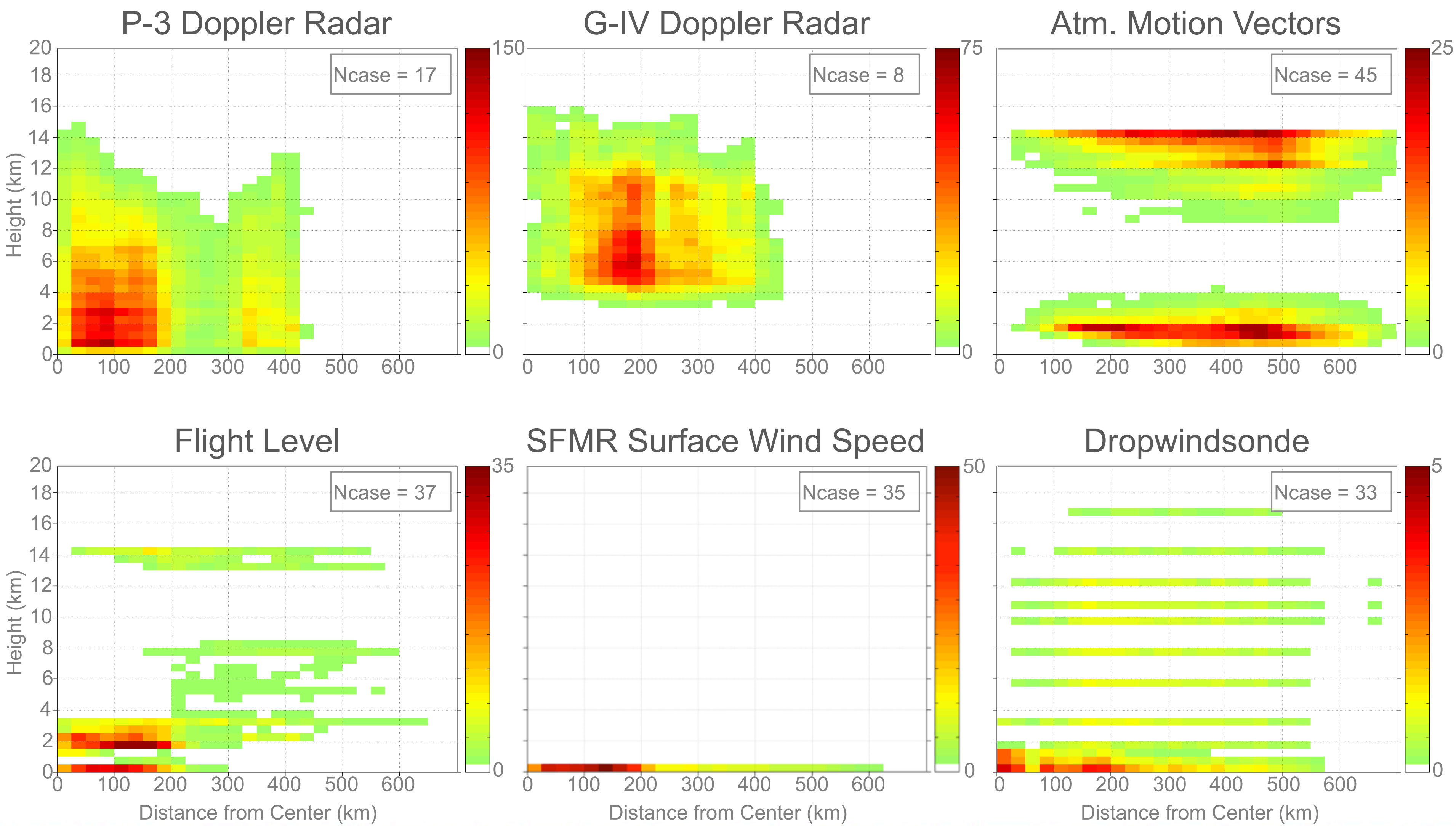
By Observing Aircraft

Aircraft	Num. Obs.	Num. Cases	Avg. Num. Obs.
P-3	255,223	24	10,634
Air Force	51,405	30	1,714
G-IV	67,280	12	5,607
HS-3	7,931	9	881
AMV	113,701	45	2,527
AIRS	80,589	23	3,504
GPS-RO	4,992	24	208
Total	**581,121**	**45**	**12,914**



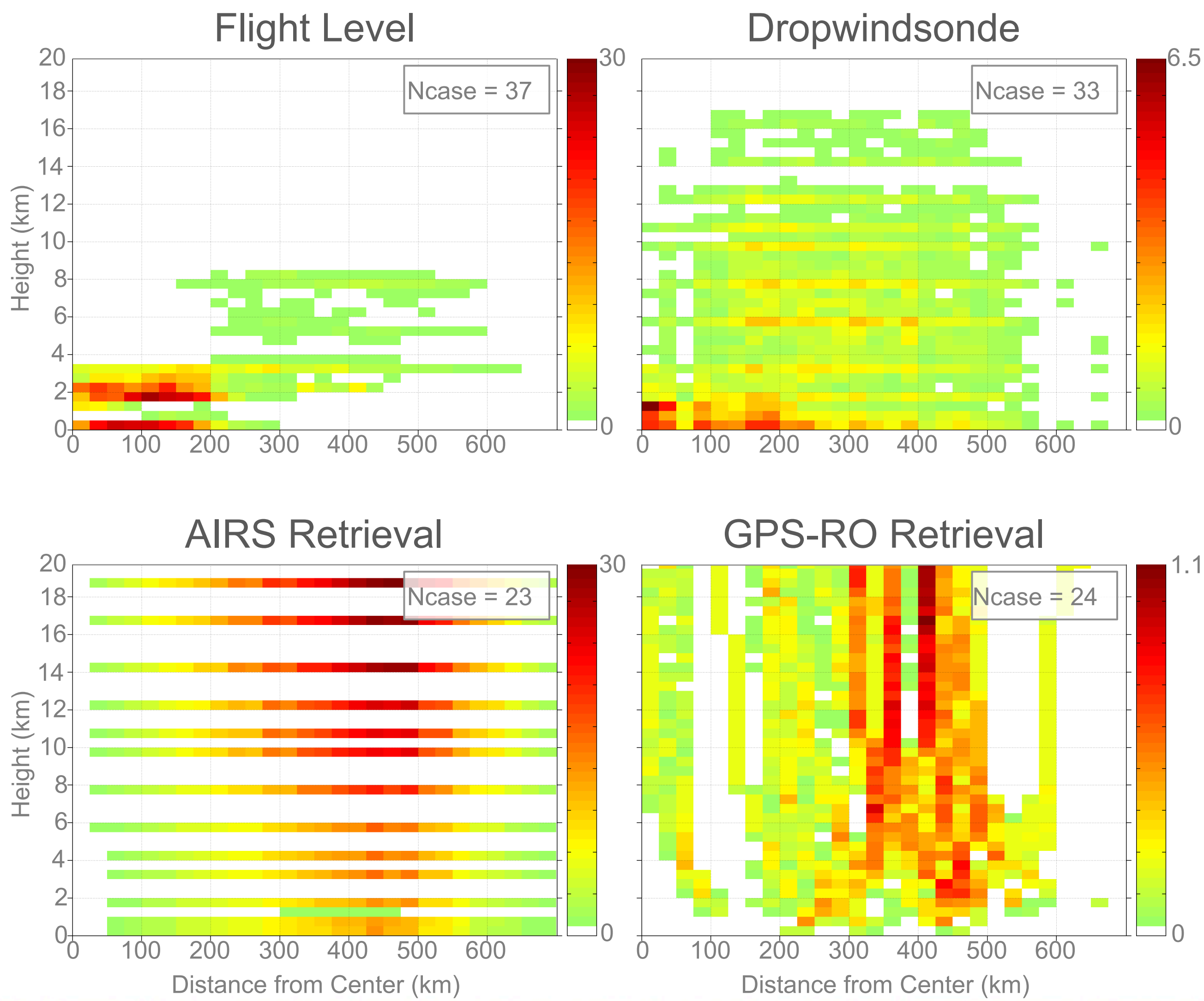
HEDAS CASES in 2013 – OBS. LOCATION

WIND OBS. (Case-averaged ob. density within 25 km radius, 0.5 km height)



HEDAS CASES in 2013 – OBS. LOCATION

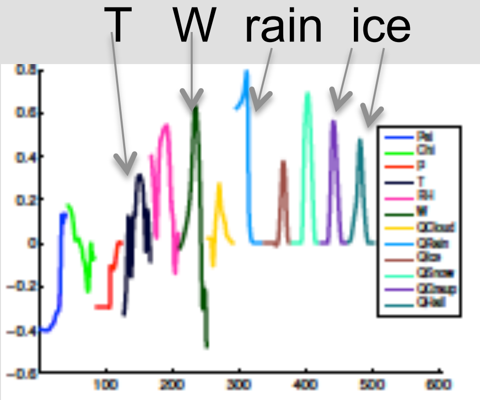
THERMO. OBS. (Case-averaged ob. density within 25 km radius, 0.5 km height)



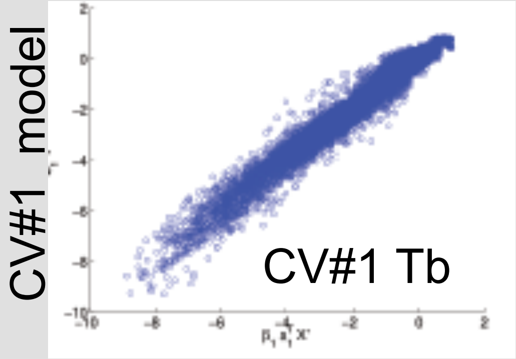
Assimilation of all-sky satellite radiance observations

- Satellite radiance data that are sensitive to hydrometeors are not assimilated in the current operational systems, resulting in over 95% of observations being unused within TC regions
- A novel method is developed for representing relationship between microwave brightness temperature (Tb) observations and forecast model variables based on canonical correlations between principal components in both spaces
- Results in a robust and computationally efficient observation operator for assimilation of all-sky radiances

Collaboration with JPL/NASA



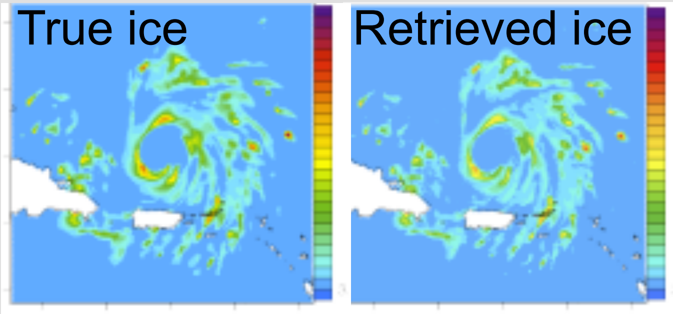
Representation of model state by CV#1



Strong correlation between state and observations using leading CVs

CCVs reduce degrees of freedom in DA by 80%

OSSE using 1D-VAR DA for hurricane Earl case



True state well retrieved starting from a constant background