Diagnosing Forecast Sensitivity for Field Campaigns using Adjoints: Making Sense of Sensitivity

Outline

- Background
- Extratropical Cyclones
- Atmospheric River Events
- Tropical Cyclones
- Gravity Waves
- Conclusions

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Research Sponsors: NRL, ONR, NASA

Why is Numerical Weather Prediction so Challenging?

Chaotic system: Sensitive dependence on initial conditions. "*Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?*"
Edward Lorenz

Highly complex multi-scale system that must be simplified (discretized, parameterized) to be modeled. "*Tyranny of Scales dominates simulation efforts*" NSF Blue Ribbon Panel on Simulation-based Engineering Science

Coupled system (land/ocean/ice/solar)

Adjoint-based tools allow us to simplify the system such that we can answer basic questions:

- **What do rapidly-growing perturbations look like?**
- **How and where is a forecast of a particular event sensitive to the initial state?**
- **Can we relate adjoint sensitivity to our physical understanding of the atmosphere?**
- **Can we use adjoint sensitivity to inform mesoscale observing strategies (field campaigns)?**

Adjoint Applications

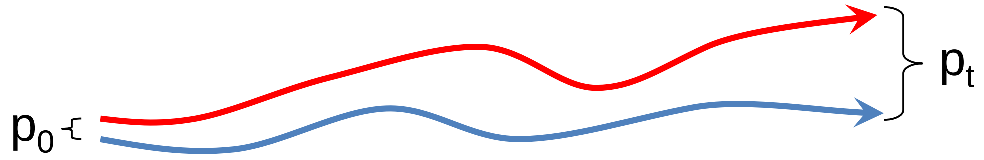
Data Assimilation		Predictability	
Variational Methods 4DVar (Sasaki 1970; Le Dimet & Talagrand 1986; Rabier et al.2000)	Forecast Sensitivity Observation Impact (Langland & Baker 2004; Gelaro & Zhu 2009; Ishibashi 2018)	Sensitivity Analysis (Langland et al. 1995; Ancell & Hakim 2007; Hoover 2011; Doyle et al. 2014; Reynolds et al. 2019)	Singular Vectors (Palmer et al. 1994;Gelaro et al. 1998; Lang & Jones 2012; Leutbecher & Lang 2013)
Error Tracking (Rabier et al. 1996; Klinker et al. 1998; Reynolds & Gelaro 2001)	Targeting (Langland et al. 1999; Reynolds et al. 2007; Mujumdar 2016)	Param. Estimation (Navon 1998; Janiskova & Morcrette 2005; Ito et al. 2016)	Stability Analysis (Farrell 1988, 1989; Schmidt 2007; Feliks et al. 2014; Kerswell 2018)

Adjoint Challenges (see Overview in Errico 1997)

- Tangent *linear* model used to relate a forecast metric to an earlier forecast or initial state
  - Standard evaluation procedures to make sure TLM is valid
- Applications to highly non-linear physical systems (convection, tropical cyclones)
  - Linearized physics & dynamics can be achieved; Nonlinear extensions (Mu 2000, etc.)
- Representations of on-off switches (highly nonlinear) in parameterizations
  - Automated tools & best practices available (Janiskova et al. 1999; Lopez 2016)

Adjoint Sensitivity

Characterize stability of system by examining the behavior of perturbation growth in linear framework

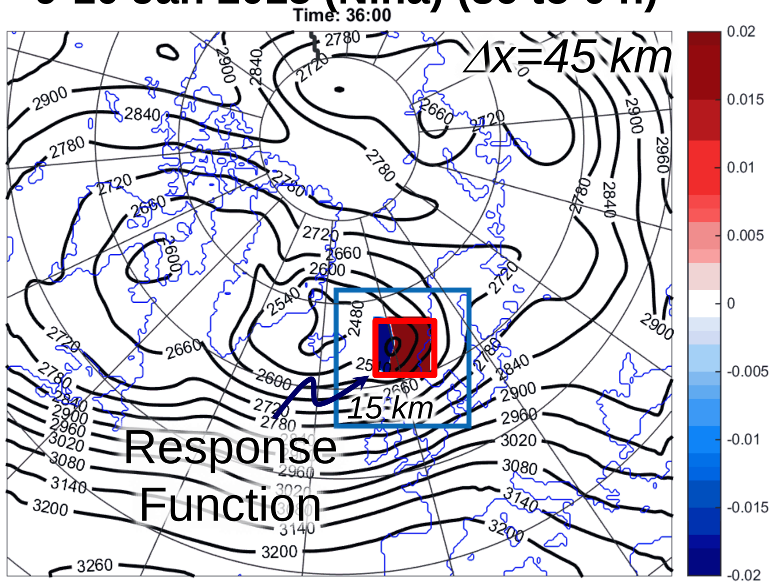


Nonlinear	Tangent Linear	Adjoint	
$p_t = Mx_0 - M(x_0 + p_0)$	$p_t = M_{0,t}\, p_0$	$$\frac{\partial J}{\partial \mathbf{x}(t_0)} = \mathbf{M}^T \frac{\partial J}{\partial \mathbf{x}(t_n)}$$	Sensitivity of response function (J) at time t_n to the state at time t_0
Nonlinear Model; State vector; Perturbation vector	Tangent forward propagator or Tangent Linear Model (TLM)		

Adjoint allows for the mathematically rigorous calculation of forecast sensitivity of a response function (J) to changes in the initial state

Forecast Sensitivity/Observation Impact (FSOI, Langland and Baker 2004): Uses the adjoint of the nonlinear model and the DA system adjoint to calculate impact of each ob on 24-h forecast error

9-10 Jan 2015 (Nina) (36 to 0 h)



COAMPS® Moist Adjoint Model

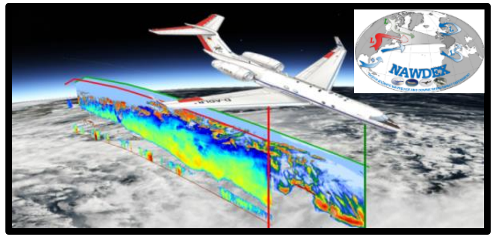
- Dynamics: Nonhydrostatic (5-45 km, nesting option)
- Physics: PBL, surface flux, microphysics, cumulus
- Ocean: 1D mixed layer model
- Response Functions, J: KE, Precip, Clouds, Q, TE, PV, SST, ML depth
- Optimal Perturbations: ~1 K, 1 m s^{-1}, 1 g kg^{-1}

Field Campaigns

Extratropical Cyclones

➢ North Atlantic Waveguide and Downstream Impact Exp. (2016) (NAWDEX)
- Objective: Quantify the effects of diabatic processes on wave guide (Schäfler et al. 2018)
- HALO, DLR Falcon, French Falcon, UK BAe-146, Dropsondes, remote sensors (wv & wind lidars)

➢ Atmospheric River Reconnaissance (2018-19) (AR Recon) (Marty Ralph, Scripps)
- Objective: Improve forecasts of atmospheric rivers & their impact.
- AF C130s, NOAA G-IV; Dropsondes; buoys



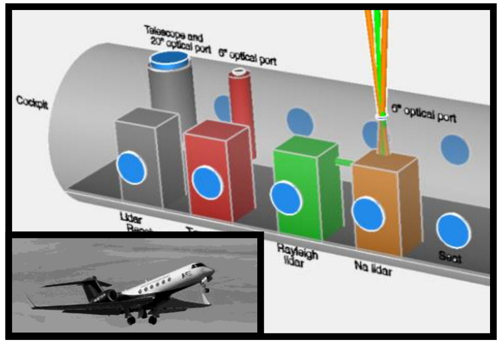
Tropical Cyclones

➢ NASA Hurricane and Severe Storm Sentinel (HS3) (2012-14) (HS3) (Braun et al. 2016)
- Objective: Understand the inner-core and environmental processes influencing TCs
- 2 NASA Global Hawks, dropsondes, remote sensors

➢ NOAA Sensing Hazards with Oper. Unmanned Tech. (2016) (SHOUT)
- Objective: Improve forecasts of tropical cyclone track and intensity impacting the U.S.
- NASA Global Hawk, dropsondes

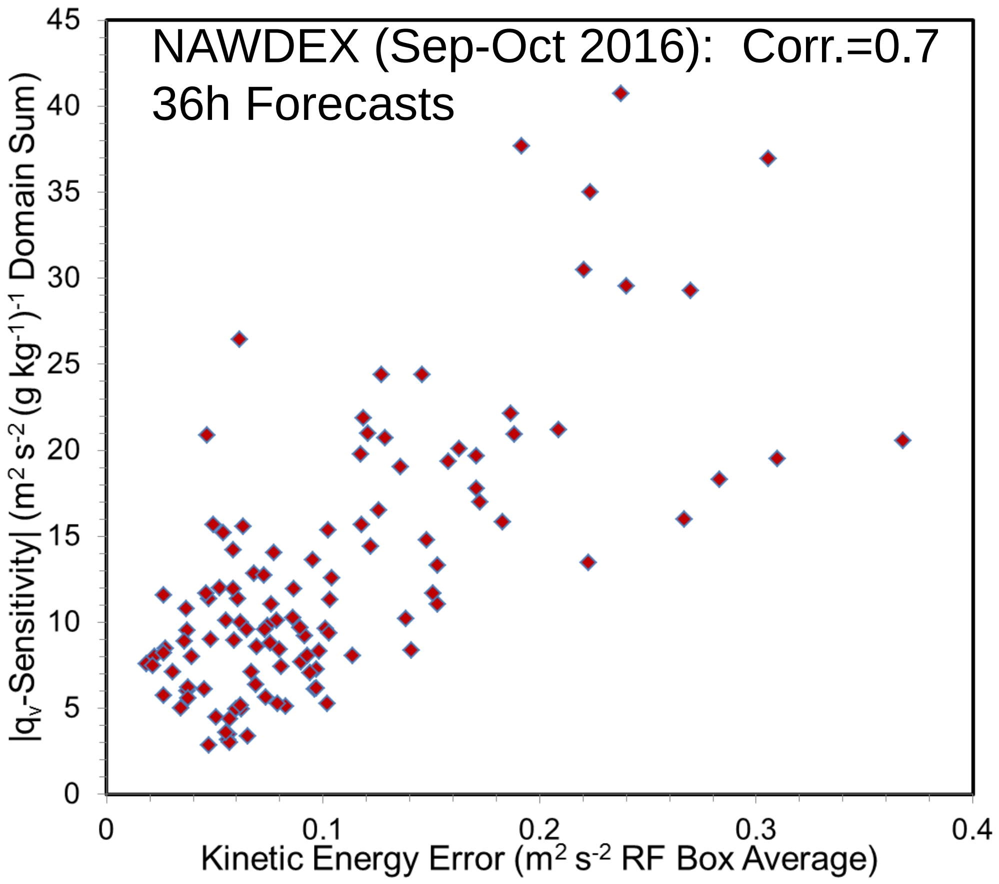
Gravity Waves

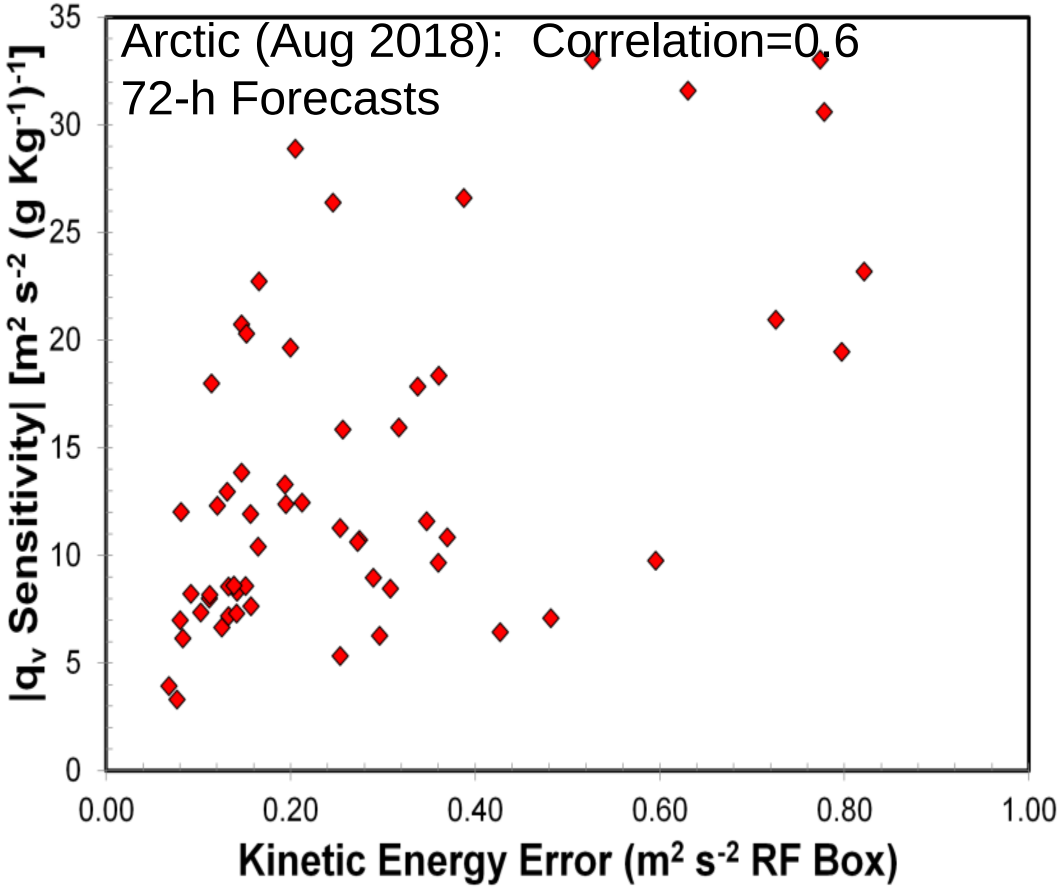
➢ Deep Propagating Gravity Wave Experiment (2014) (HS3) (Fritts et al. 2016)
- Objective: New understanding of gravity wave dynamics from the surface to 100 km
- NCAR G-V, DLR Falcon, dropsondes, remote sensors (lidars), ground based lidars, profilers



Adjoint Sensitivity and Forecast Errors

KE Error vs. Water Vapor Sensitivity [$|\partial J / \partial q_v|$ at 0h]





- NAWDEX real time sensitivity forecasts: Adaptive response function for precip & KE used to guide GV, radiosondes
- Episodic periods of strong sensitivity corresponds to many of the major IOPs during NAWDEX
- Key Finding: Moisture sensitivity magnitude & forecast error are well correlated (N. Atlantic, Arctic, US W. Coast)

Extratropical Cyclones: NAWDEX

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NAWDEX Objective: Quantify the effects of diabatic processes on disturbances to the wave guide and their influence on predictability & downstream high-impact weather.

Extratropical transition (ET) of ex-Karl during NAWDEX

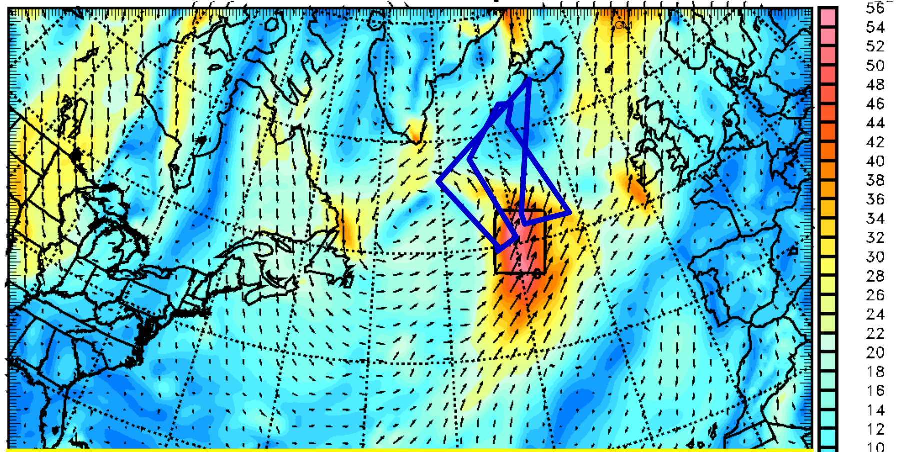
i) Moisture and PV sensitivity couplets near TS Karl prior to ET

ii) Enhancement of warm conveyor belt (WCB) 48h

iii) Downstream ridge building (72 h)

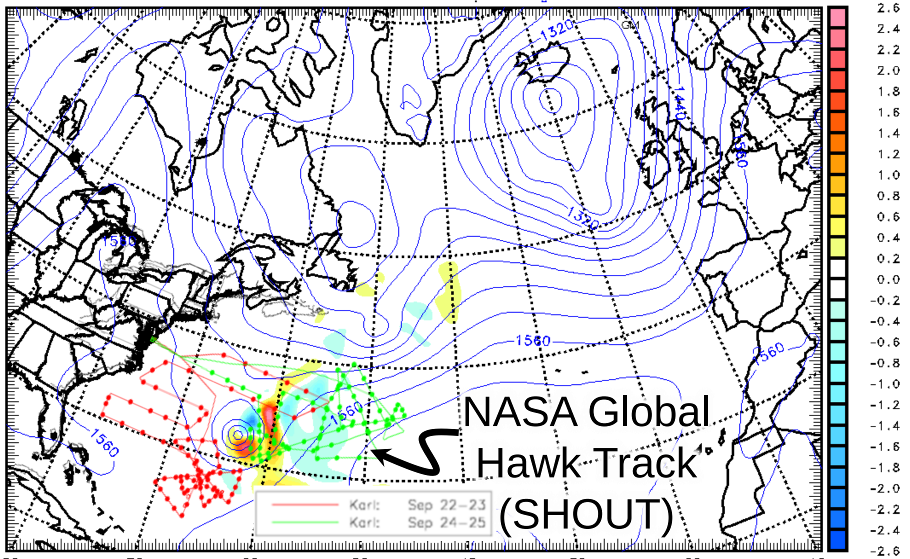
iv) High-impact precipitation

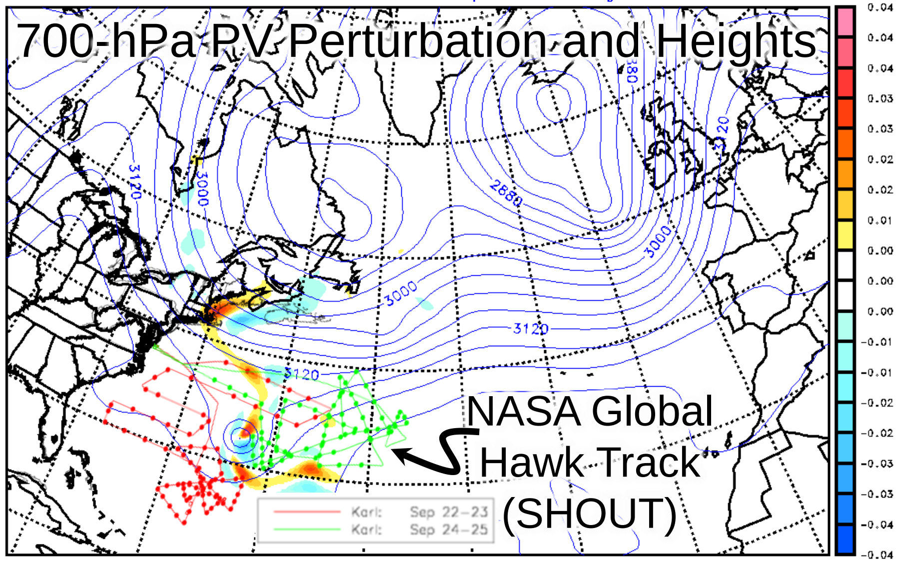
48-h 850-hPa Optimal U'+U

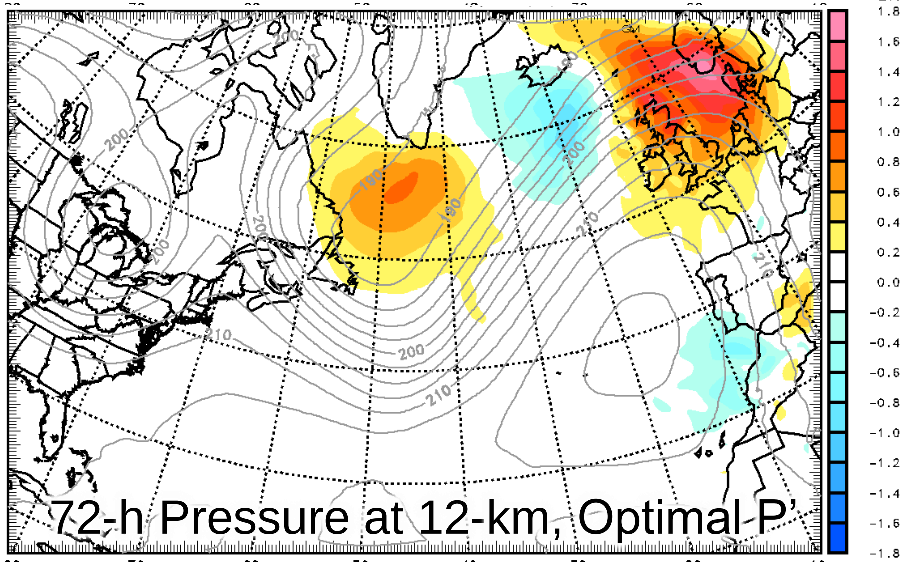


Evolved optimal perturbations lead to a strengthened WCB to > 40 m s^{-1} at 850 hPa

850-hPa Moisture Sensitivity and Heights





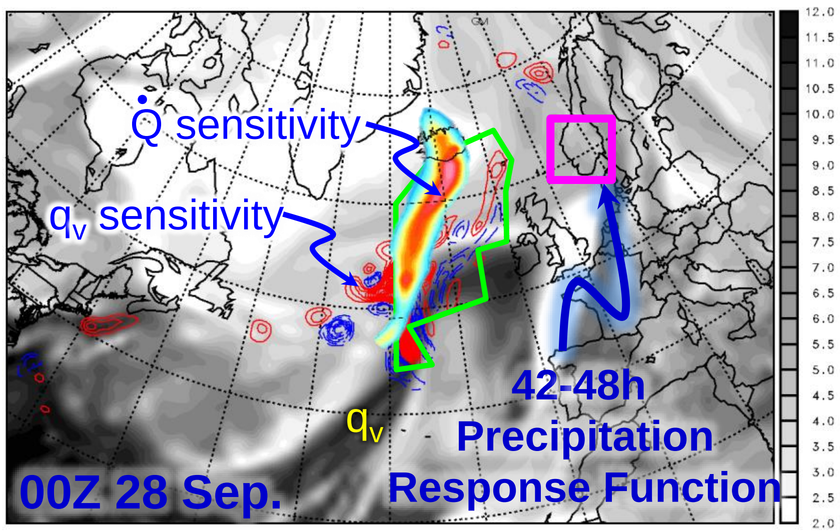


NAWDEX PIs: Andreas Schäffler, Georg Craig, Heini Wernli, John Methven, Gwendal Rivière, James Doyle

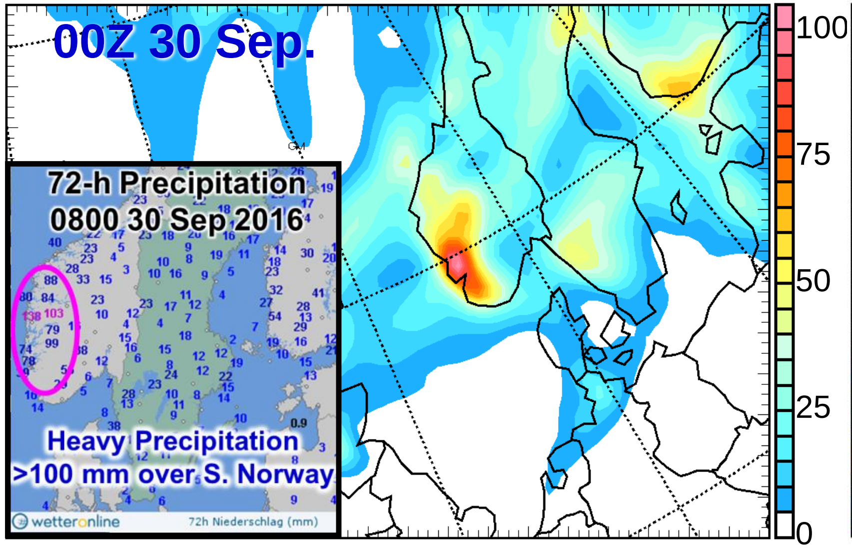
SHOUT PIs: Gary Wick, Robbie Hood, Jason Dunion (NOAA)

Extratropical Cyclones: NAWDEX

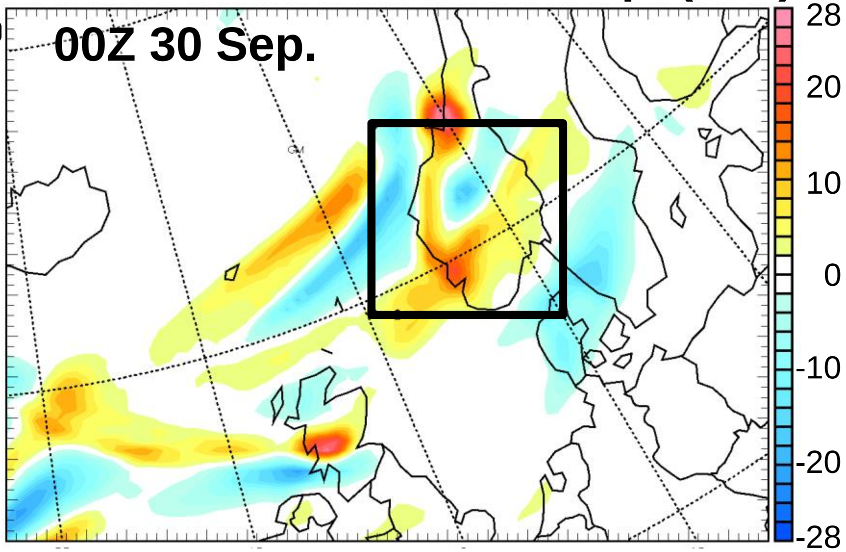
850-hPa q_v (gray) 48-h q_v sensitivity



Nonlinear 48-h Precipitation (mm)

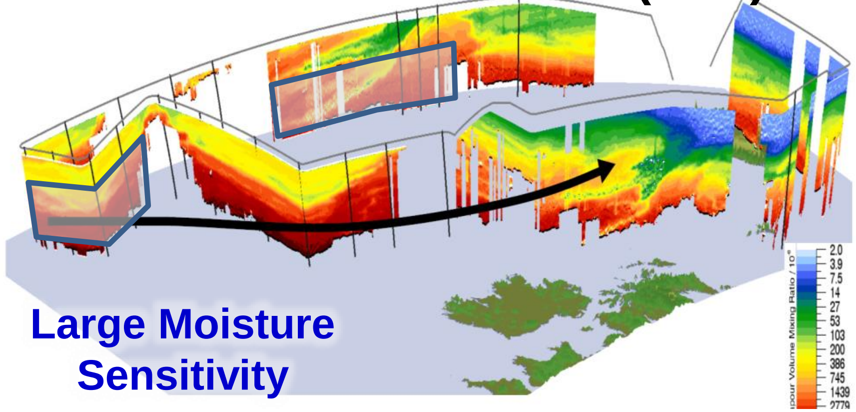


TLM 42-48-h Pert. Precip. (mm)



- Following ET of ex-Karl, a high-impact heavy precipitation event occurred in Scandinavia associated with an Atmospheric River (AR)
  - Over 100 mm precipitation over SW Norway
- Fine-scale sensitivity regions of moisture and temperature along the AR (gradients of moisture & temp.) within an ascending moist plume
- Diabatic heating sensitivity (6h) coincident and sensitivity 'filaments'
- Optimal perturbations result in 25 mm/6h of precipitation

Water Vapor Volume Mixing Ratio
HALO WALES Lidar (DLR)



Adjoint Optimal Perturbation Energetics

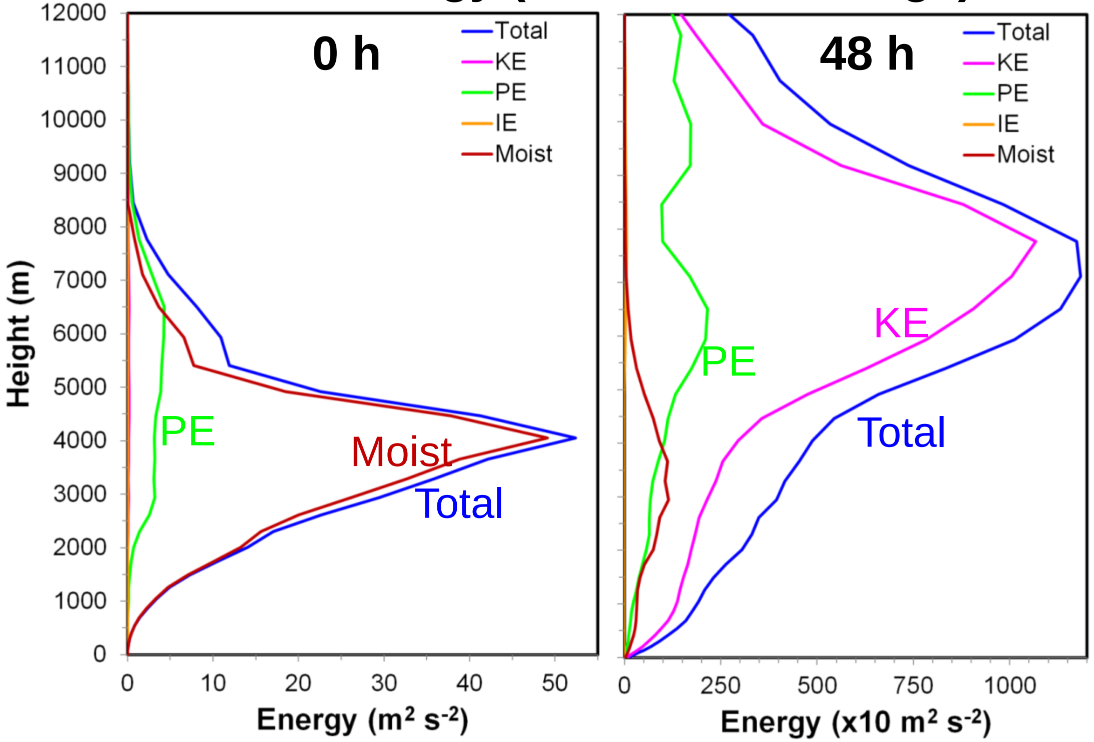
Storm 'Desmond' (2015) Diagnostics

$$E = \frac{1}{2A}\int\left[(u'^2 + v'^2 + w'^2) + \frac{C_p}{T_r}T'^2 + \frac{RT_r}{p^2_{sr}}p'^2 + \frac{l_v^{\,2}}{C_pT_r}q_v'^2\right]dAd\sigma$$

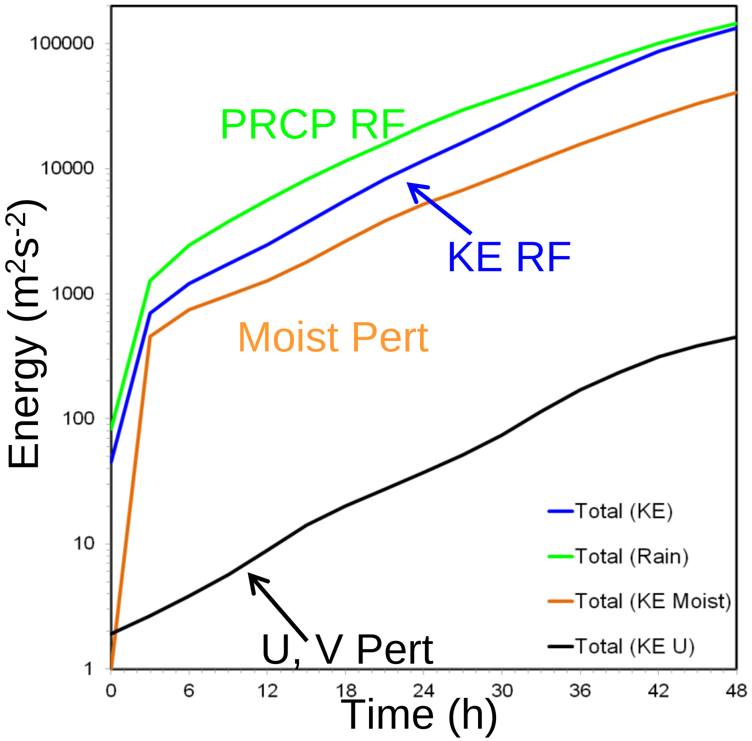
Errico (2000)

Total KE PE IE Moist

TLM Energy (Horizontal Average)



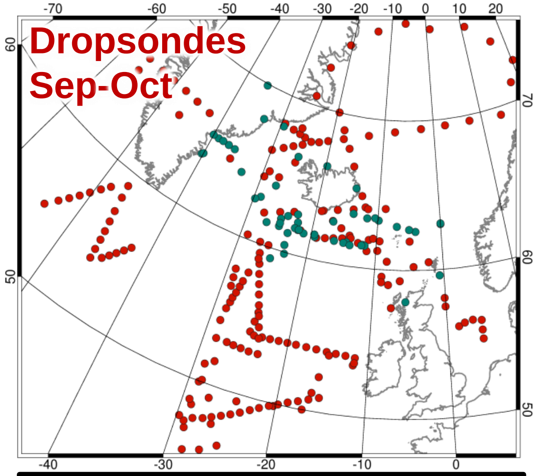
TLM Dry Energy Evolution

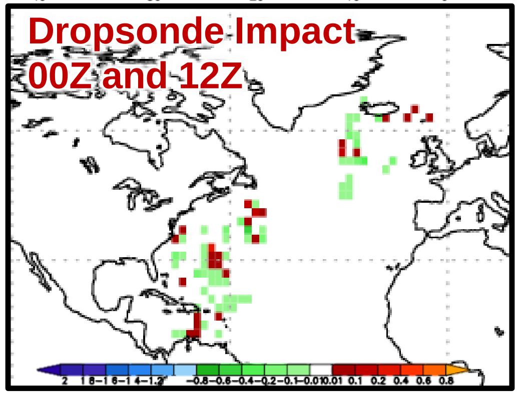


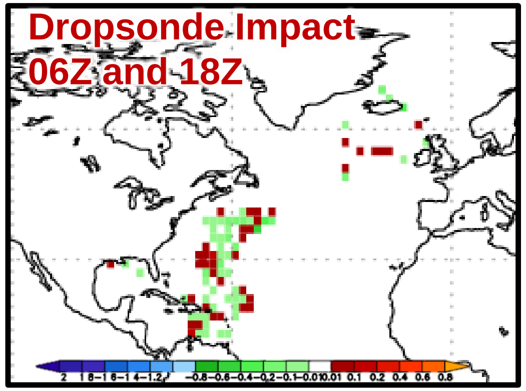
- Energy peaks in the mid-levels at initial time, and grows *rapidly* in the vertical
- Transient (non-modal, Farrell 1989) rapid growth in the first 3 h, followed by steady growth to 48h
- Moist perturbation only experiment grows rapidly; U perturbation more slowly

Doyle et al. (2019, in revision)

NAWDEX FSOI



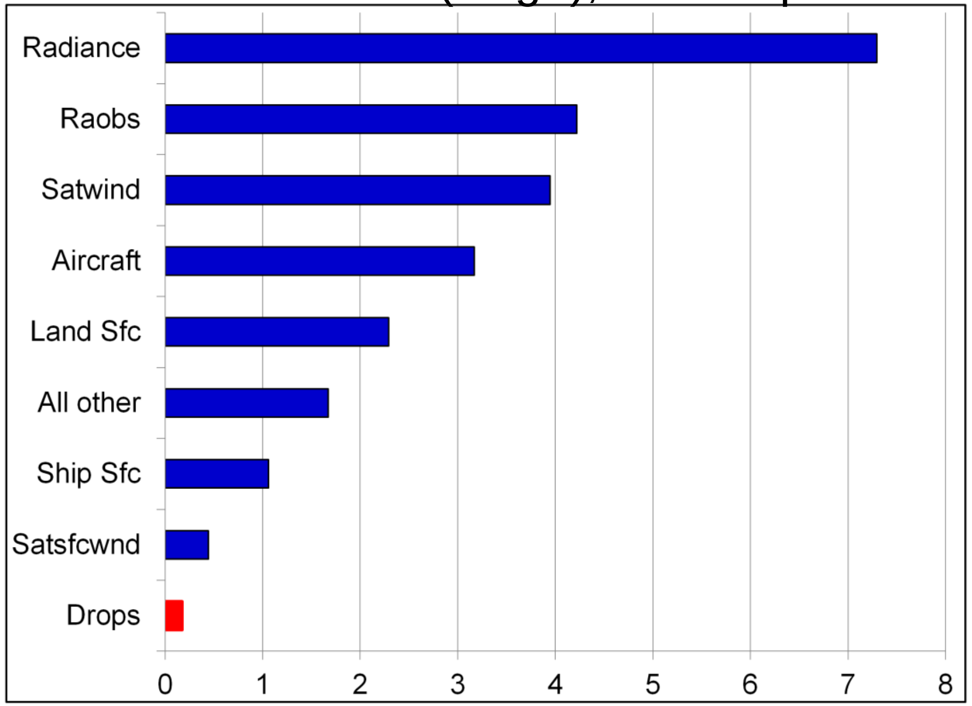




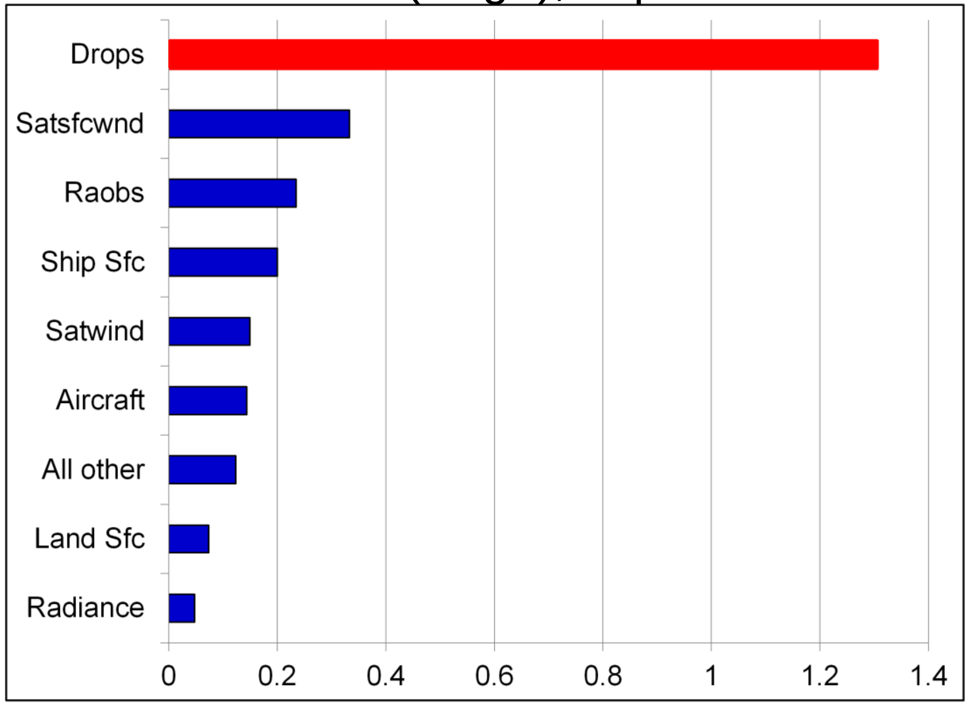
Navy NAVGEM Forecast Sensitivity Observation Impact (FSOI) (24h)

September 16-30, 2016 (Over NAWDEX Region using Global Total Energy Norm)

Error Reduction (J kg^{-1}); Total Impact



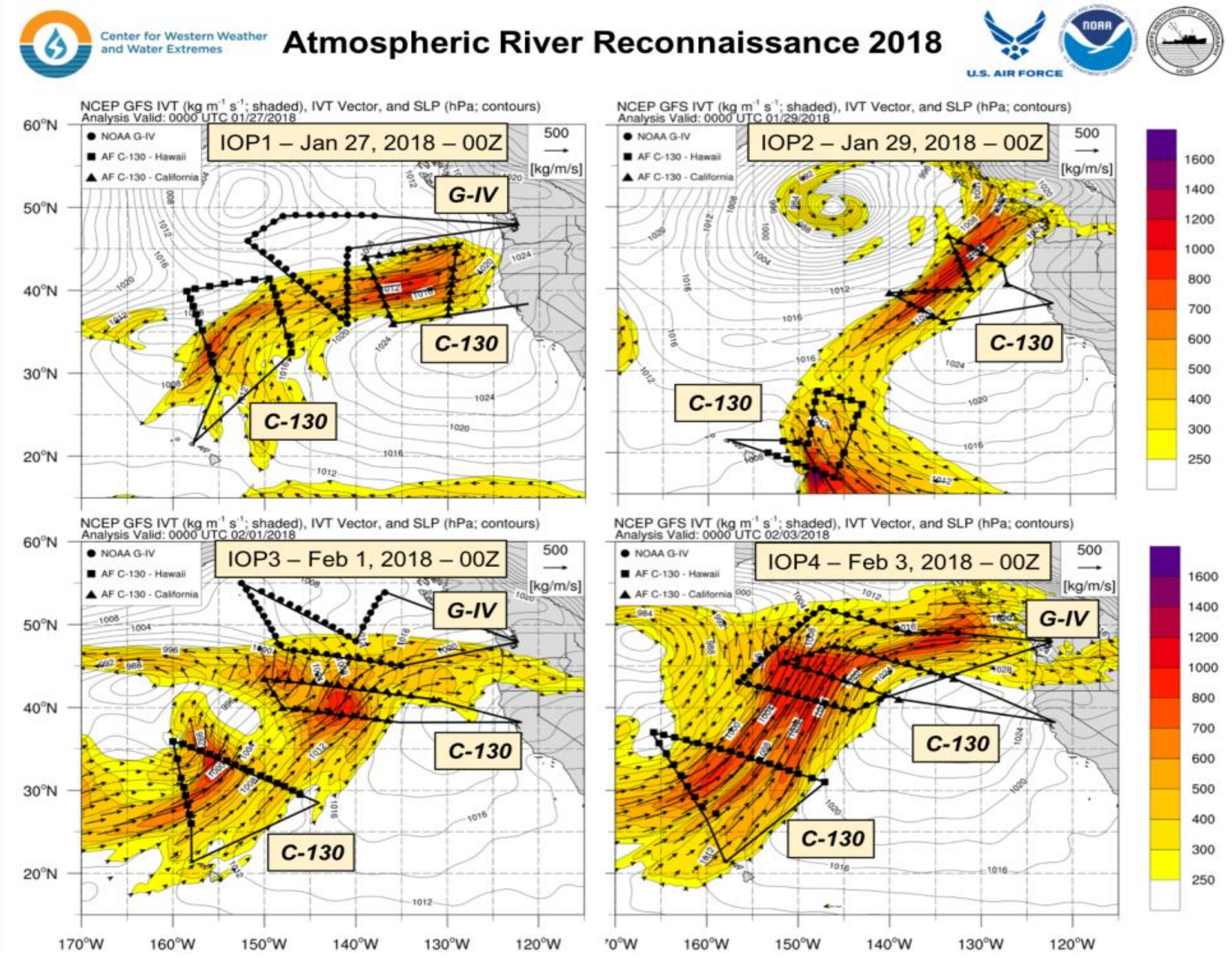
Error Reduction (J kg^{-1}); Impact Per Obs.



- During NAWDEX, 289 dropsondes were deployed by HALO, French Falcon, BAe146
- Forecast Sensitivity/Observation Impact (FSOI): Uses the adjoint of NAVGEM (31 km) and the hybrid 4-D VAR DA to calculate impact of each ob. on 24-h forecast error
- NAWDEX (and SHOUT) dropsondes during September were the most impactful observations assimilated in NAVGEM (per observation basis)

In collaboration with Rolf Langland (NRL)

Atmospheric Rivers: AR Recon

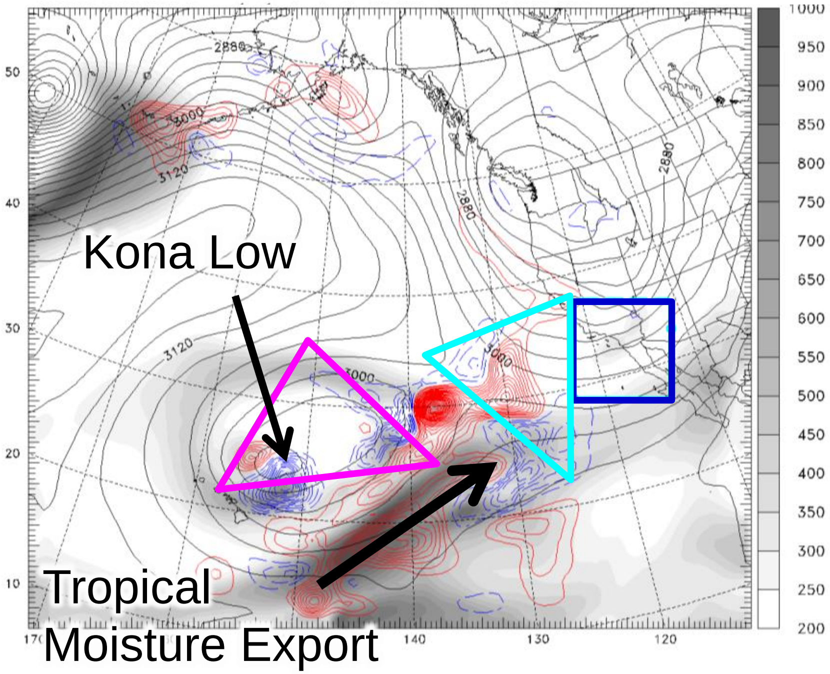


- Multi-agency effort (PI: Marty Ralph CW3E, Scripps/UCSD) in 2018/19 to deploy dropsondes in order to improve short-term AR forecasts on the U.S. West Coast
- NRL COAMPS adjoint sensitivity was used along with other products to inform flight plans. Sensitivity typically highlighted lower-tropospheric moisture in/near ARs and Warm Conveyor Belts (WCBs)
- Forecast Sensitivity Observation Impact (FSOI) and Data Denial Experiments with the Navy Global Forecast System (NAVGEM)

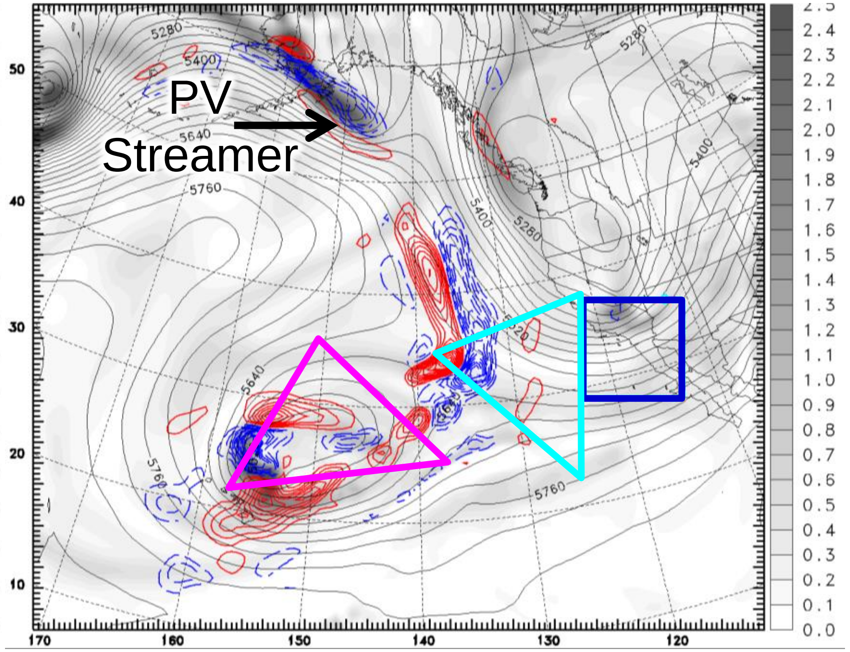
Atmospheric Rivers: AR Recon

COAMPS Adjoint Sensitivity Valid at 00Z 11 Feb (48h Adjoint) [Response Function Precip. (72-96h)]

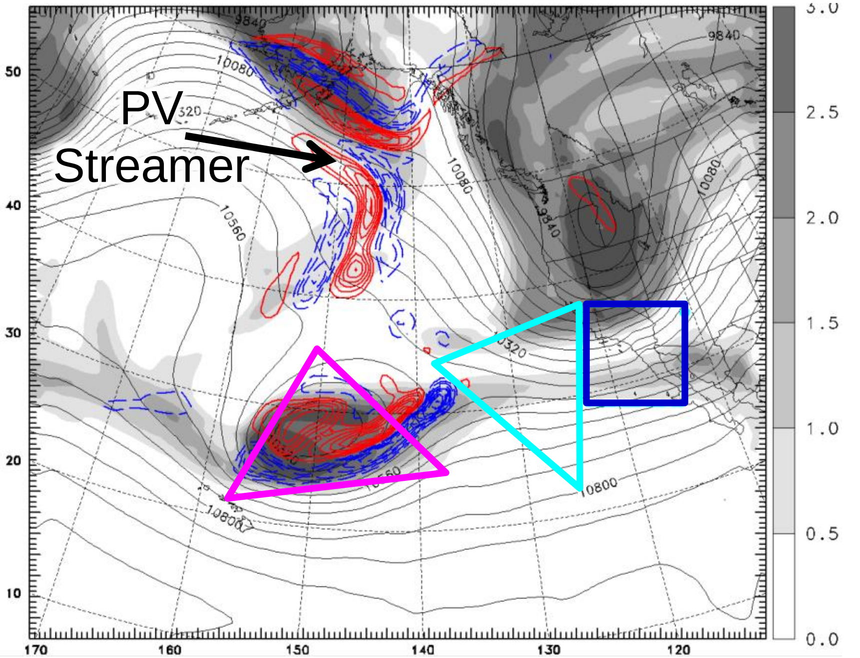
IVT (gray fill), 700 hPa Heights (contours)
700 hPa Water Vapor Sensitivity (blue/red)



500 hPa PV (gray fill) & Heights (contours);
500 hPa PV Perturbation (blue/red)



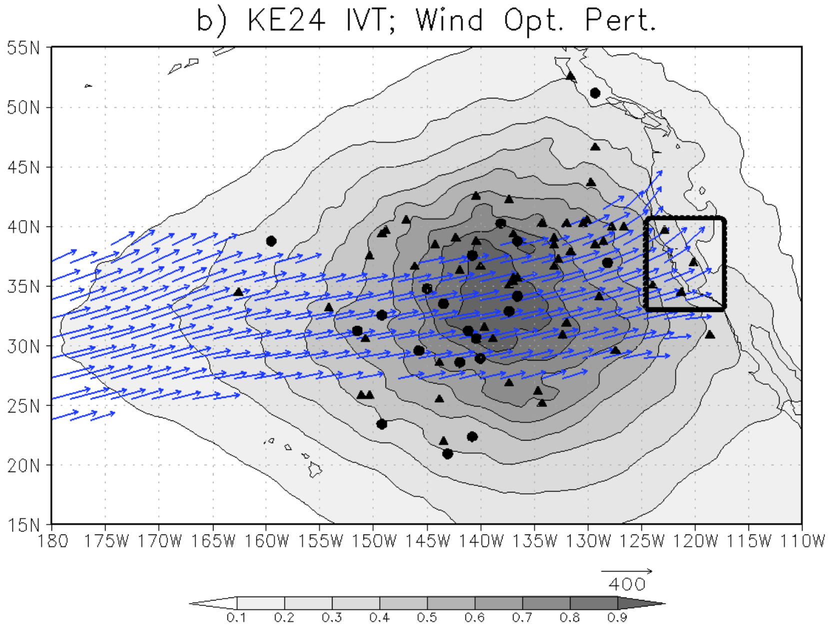
250 hPa PV (gray fill) & Heights (contours);
250 hPa PV Perturbation (blue/red)

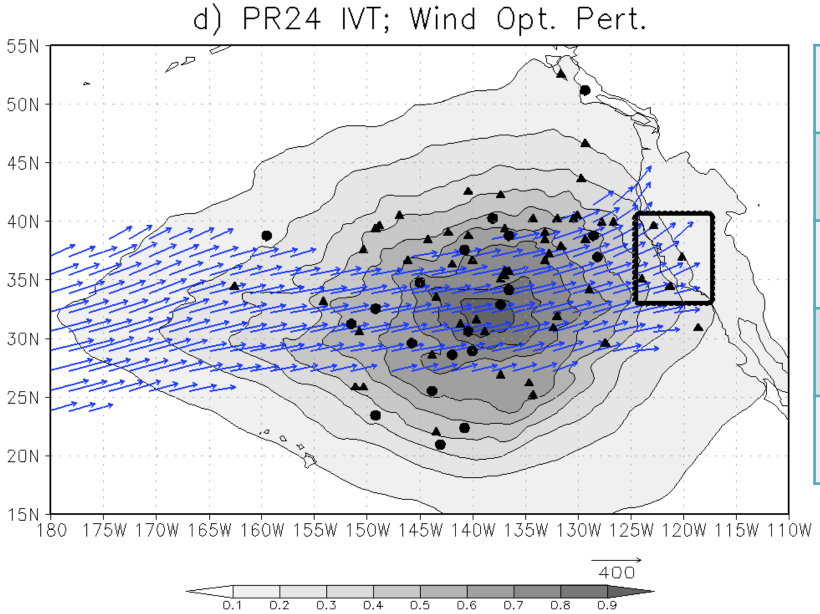


- Adjoint sensitivity diagnostics performed in real time in support of AR Recon in 2018-2019
- High-impact event exhibiting large model differences even for short-range forecasts. COAMPS adjoint along with Ensemble Sensitivity (Ryan Torn) showed sensitivity to all three features:
  - Kona Low, tropical moisture export (ascending plume, WCB?), PV streamer, and phasing of PV anomalies

Atmospheric Rivers: AR Recon

COAMPS Adjoint diagnostics
- 00Z and 12 Z Jan-Feb 2017 (drought-busting months)
- Two CA response functions, rainfall (PR) and kinetic energy (KE), 24-h and 36-h





Experiment	KE24	PR24
Linear Wind Pert.	1.15 m/s	0.55 mm
Nonlinear Wind Pert.	0.95 m/s	0.47 mm
Linear Precip. Pert.	0.35 m/s	0.71 mm
Nonlinear Precip. Pert.	0.28 m/s	0.73 mm

- Sensitivity for different response functions are similar on average, located near baroclinicity & IVT maxima
- Case studies show sensitivity largest in sub-saturated AR regions, inflow and ascent regions of WCBs.
- KE sensitivity twice as efficient at producing wind perturbations as PR sensitivity. PR sensitivity twice as efficient at producing precipitation perturbations as KE sensitivity.
- Targeting should be metric dependent.

Reynolds et al. 2019 (MWR)

Atmospheric Rivers: AR Recon

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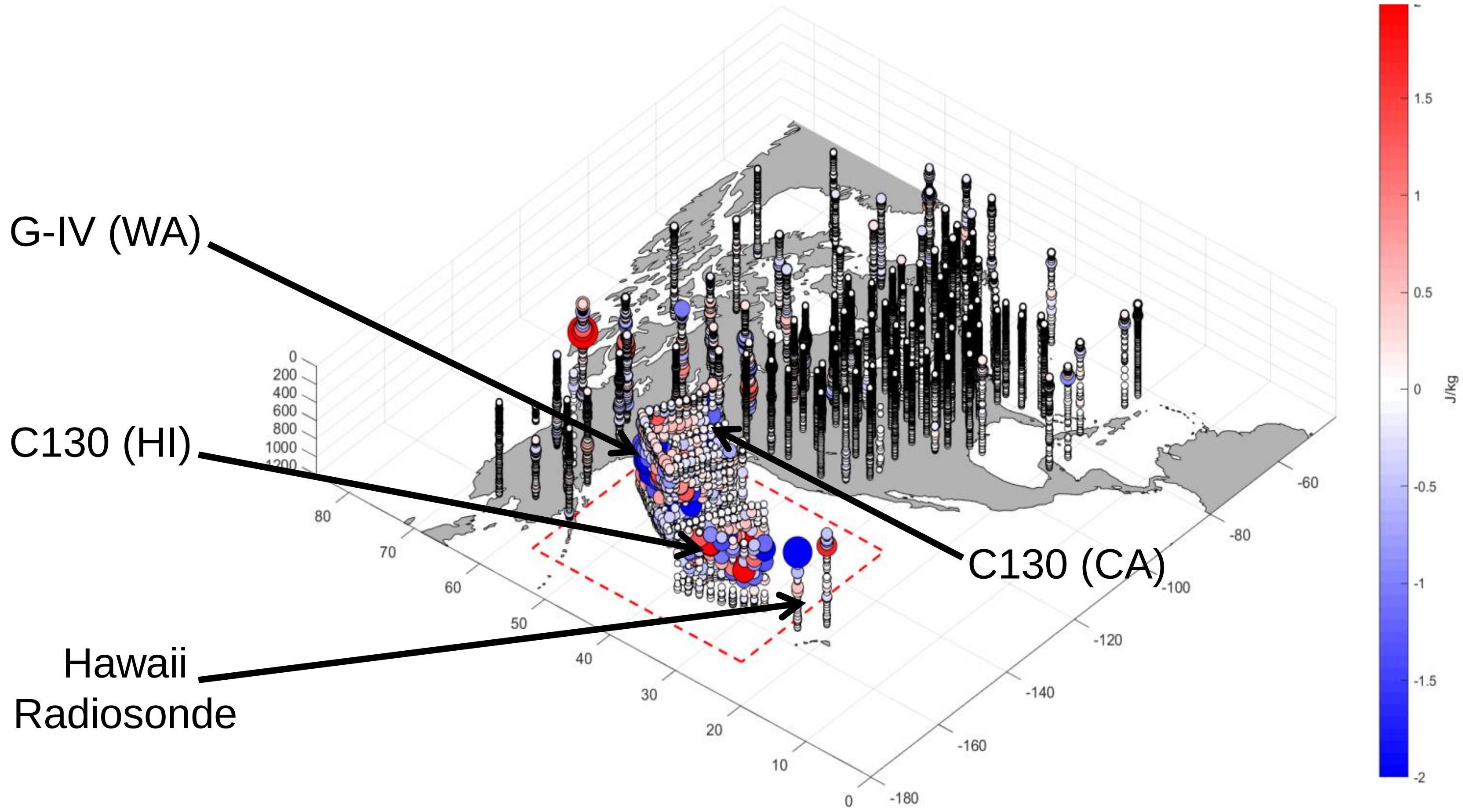
IOP 3: 2018020100 Observation Impact for Dropsondes and NA Radiosondes in NAVGEM: Wind Observation Impact



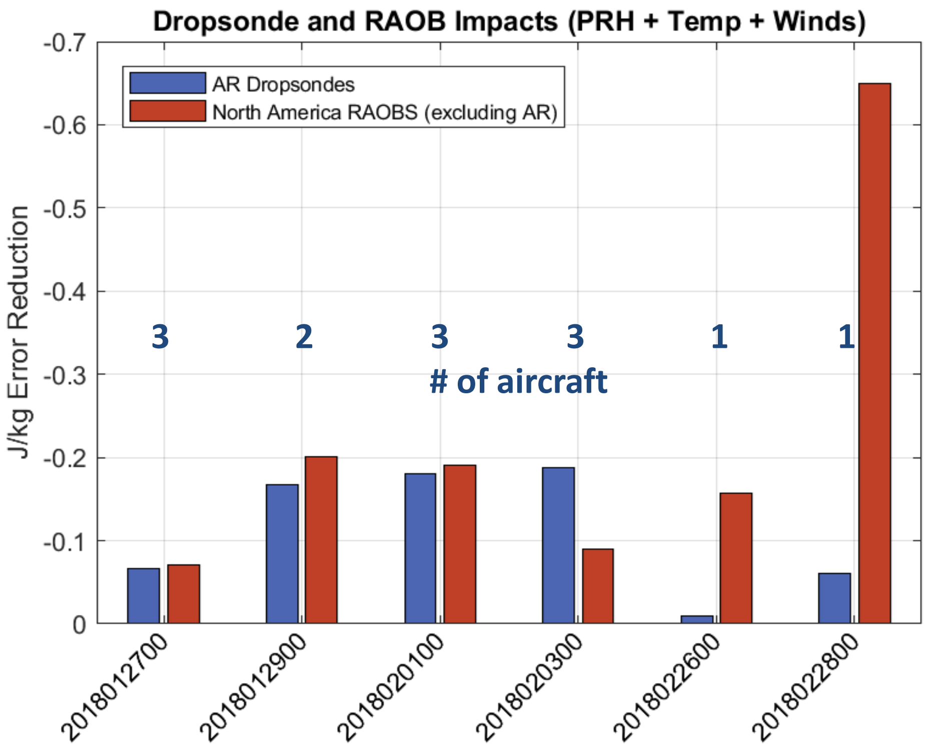
Wind observation impacts (10^{-3} J kg^{-1}) for 2018020300. Size and color of spheres displayed corresponds to the FSOI value for each *u* + *v* combination.

FSOI using NAVGEM and the hybrid 4D-VAR (NAVDAS-AR) DA system to calculate impact of each ob on 24-h forecast error

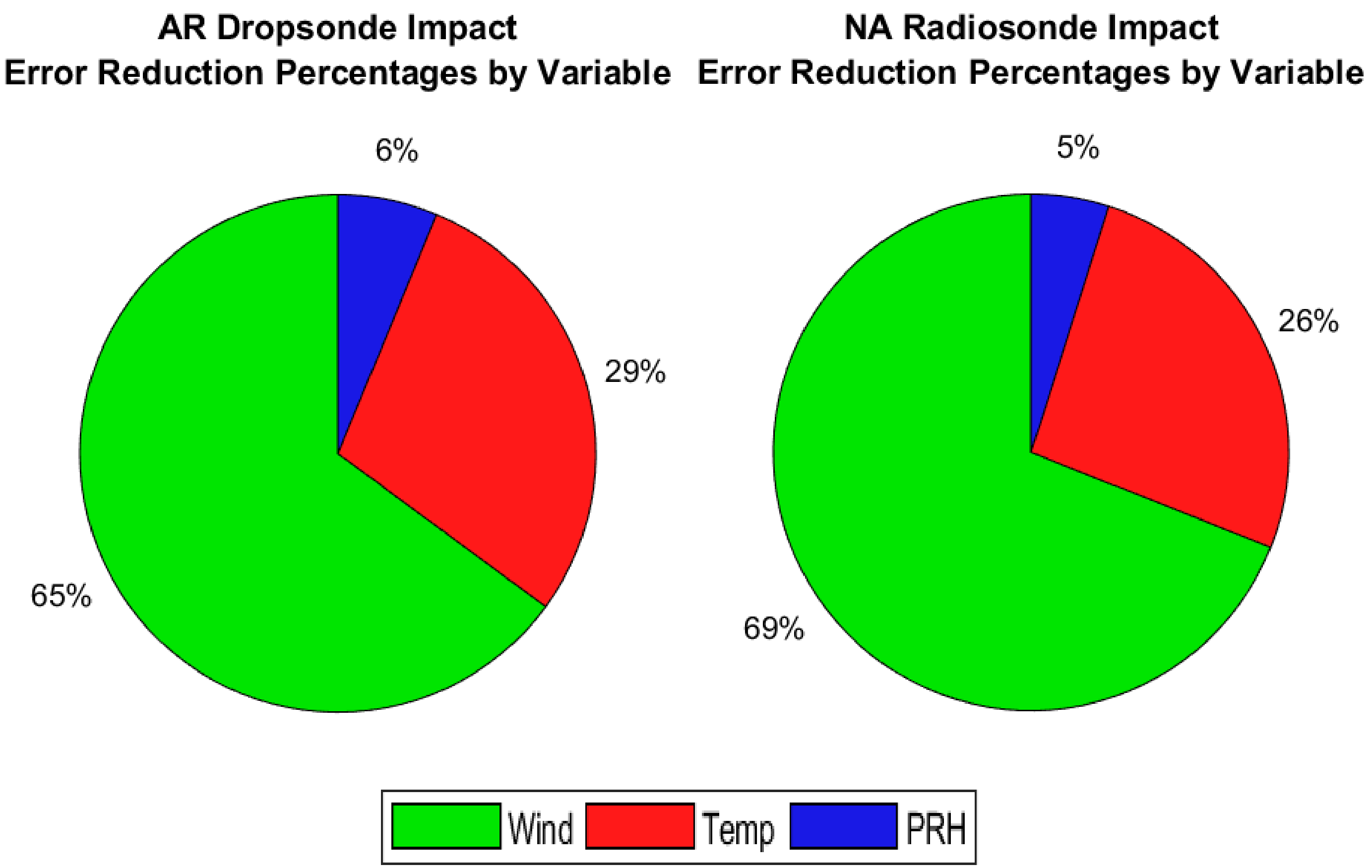
- Forecast error is measured in terms of global moist total energy
- Compare impact of AR RECON dropsondes to North American Radiosondes (NA RAOBS)
- Quantify impact as a function of variable

Stone et al. MWR 2019

Atmospheric Rivers: AR Recon



24-h Forecast Error (global moist TE) reduction for dropsondes (blue), NA RAOBS(red)



Impact of AR RECON comparable to NA Radiosondes. Per ob impact much higher.

Impact of moisture observations on error reduction is smaller than impact of winds or temperature. Fair number of moisture observations rejected in DA

Stone et al. MWR 2019

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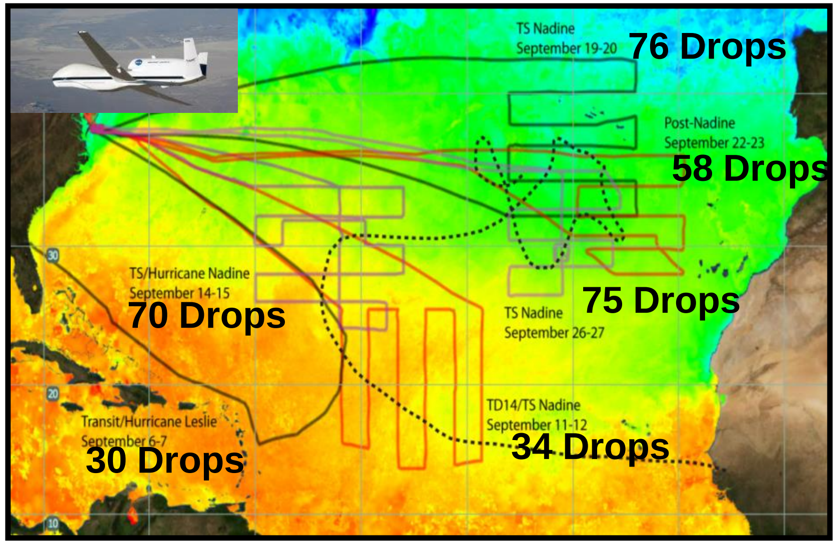
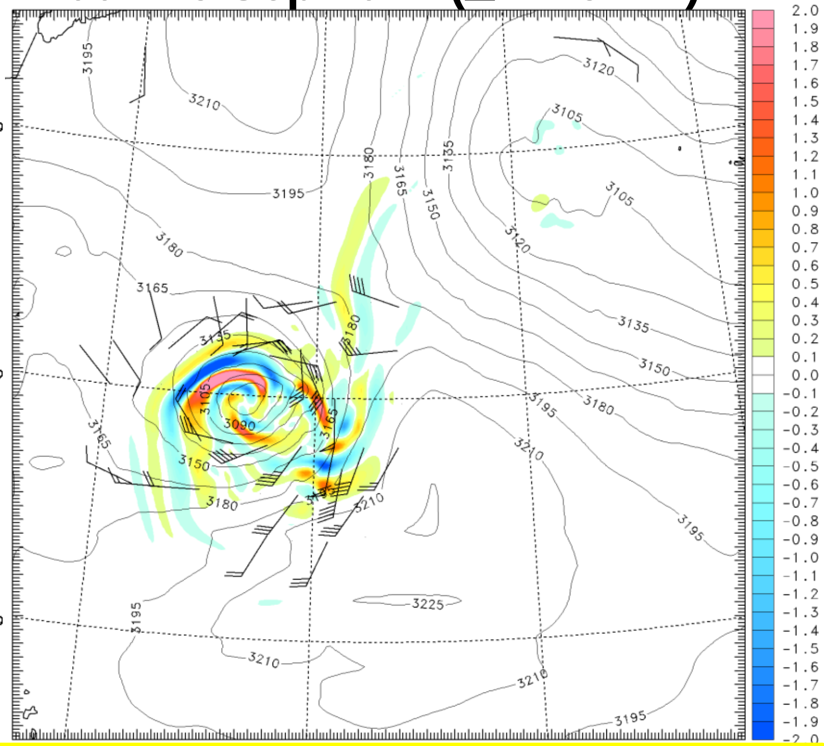
Tropical Cyclones: HS3

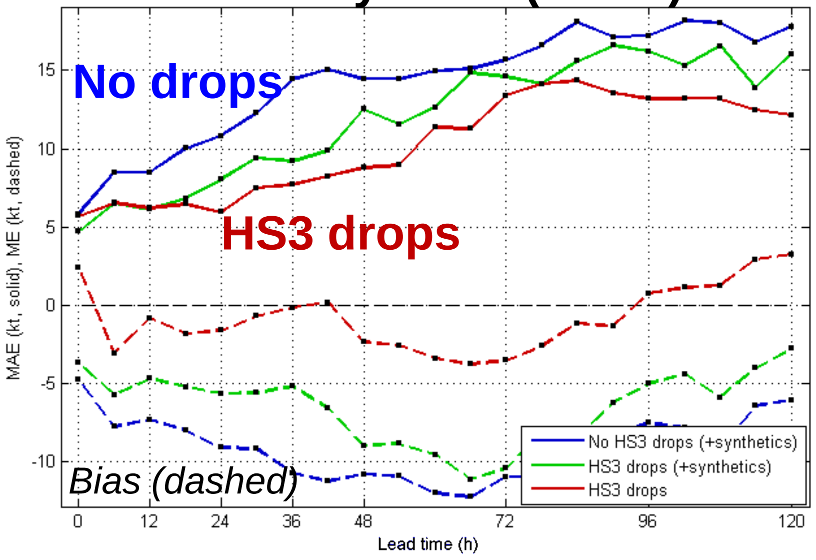
Global Hawk Flight Tracks: Nadine



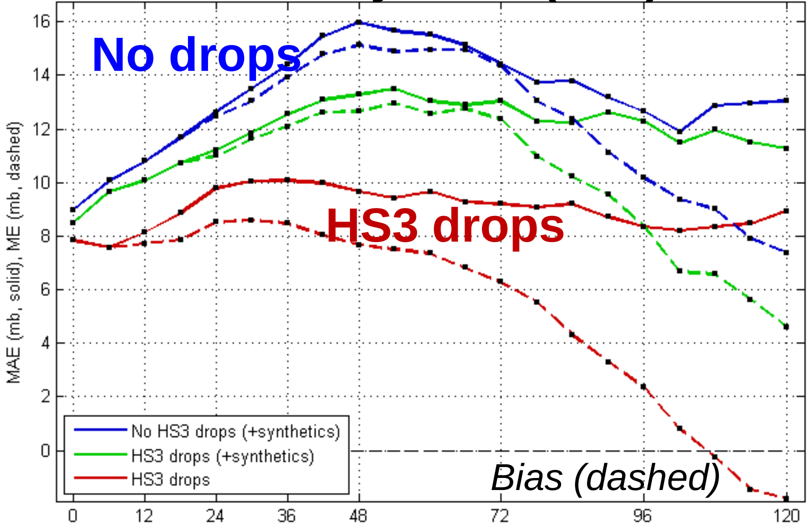
700-hPa ζ Sensitivity (24 h)
00Z 15 Sep 2012 (Δx=15 km)



Intensity Error (knots)



Intensity Error (hPa)



- Nadine was one of the longest-lived TCs in the N. Atlantic on record
- Sensitive regions in Nadine were often well observed by HS3 dropsondes
- Dropsonde impact experiments performed for 19-28 Sep. (3 flights)
  - ➢ HS3 drops
  - ➢ HS3 drops with synthetics
  - ➢ No drops with synthetics
- COAMPS-TC intensity & track are markedly improved using HS3 drops.

HS3 PIs: Scott Braun and Paul Newman (NASA)

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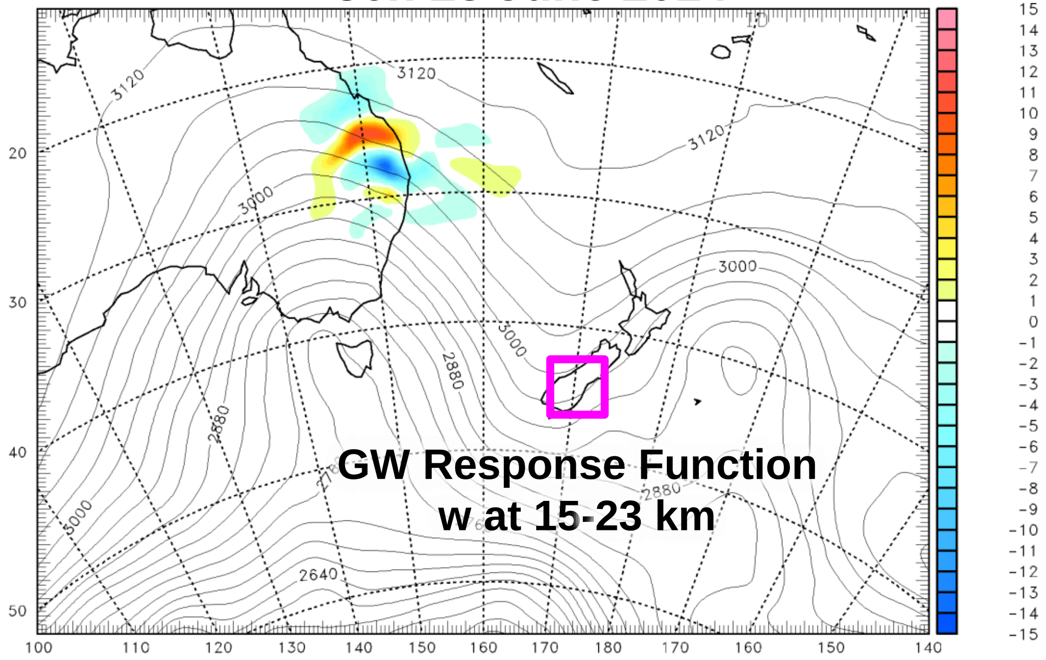
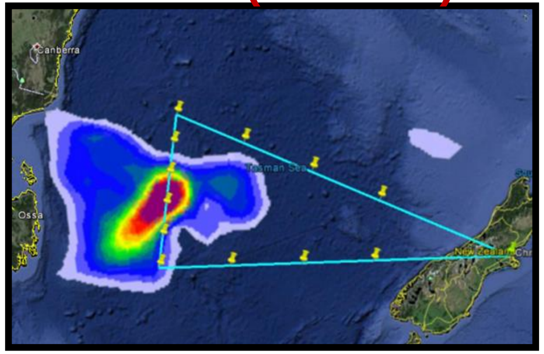
Gravity Wave Predictability: DEEPWAVE

700-hPa w-Sensitivity & Heights 36h 28 June 2014

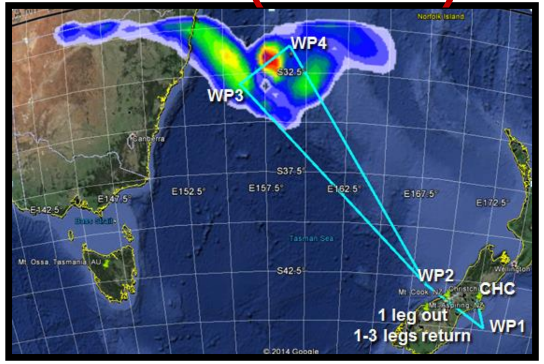


24-h Adjoint Sensitivity

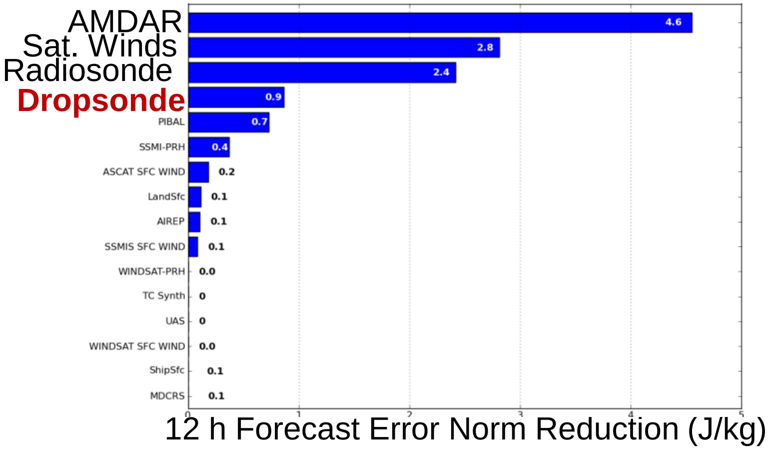
RF03 (13 June)



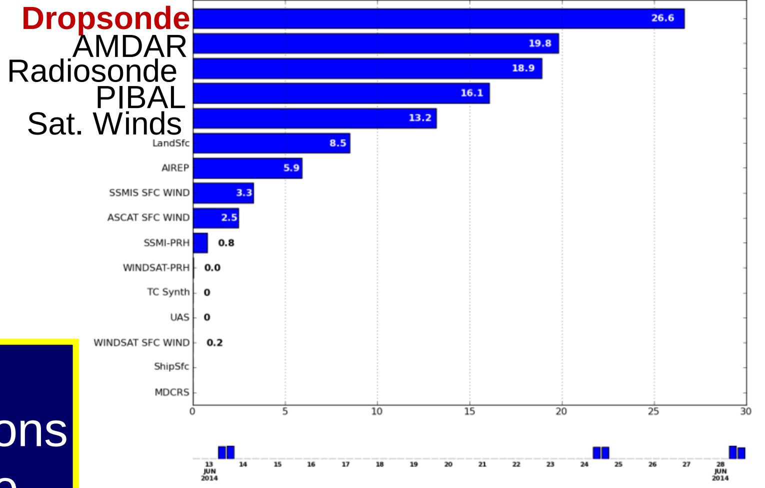
RF11 (28 June)



COAMPS Total Impact



Impact (Per Observation)



- DEEPWAVE (2014): Gain new insight into deep propagating gravity waves
- Diagnose gravity wave launching sensitivity (*first time*) & use to inform G-V missions
- Key Findings: i) Sensitivity located ~1200 km upstream, ii) perturbations enhance cross-mountain winds, stability, & gravity wave launching, iii) DEEPWAVE dropsondes are most impactful ob (per ob) in COAMPS 3D-Var assimilation exps.

Conclusions

- Highly-sensitive fine-scale regions of moisture & temperature often embedded in diabatically-active areas (e.g., WCBs) leading to fast perturbation and forecast error growth (sensitivity correlated with fcst errors)

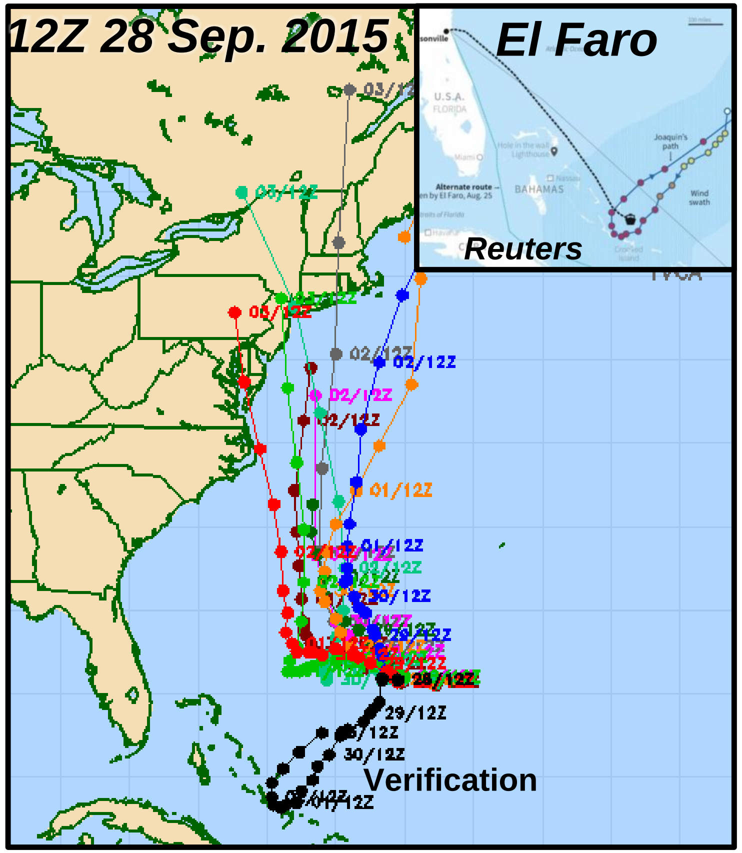
- Observation Impact Studies
  - Dropsondes (NAWDEX, AR-Recon, HS3, DEEPWAVE) can have a large positive impact on forecasts
    - Net impact of AR Dropsondes comparable to N. American RAOBS (much larger per-ob impact)
  - FSOI studies for AR-Recon show winds and temperature are more impactful than moisture (inadequacies in moisture assimilation, and process and representation errors?)

- Gaps
  - Disentangle model & analysis errors in highly-sensitive diabatically-active regions (field campaigns obs?)
  - Improved moisture and cloud assimilation methods are needed (guided by field campaign obs.?)
  - Utilize adjoint-based tools to better identify key forecast errors, dynamics, processes, & scale interactions

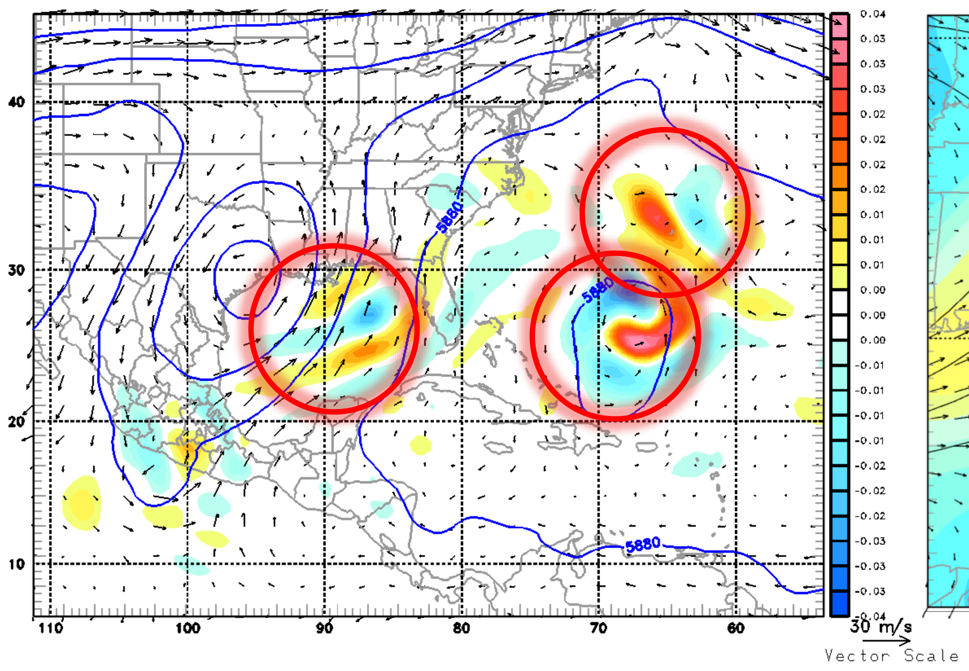
- Future Directions:
  - Adjoint sensitivity on convective permitting scales, atmospheric rivers (AR Recon), Arctic cyclones (ONR)
  - Utilize adjoint tools, FSOI, and data denial studies to tease out important error sources

Extra Slides

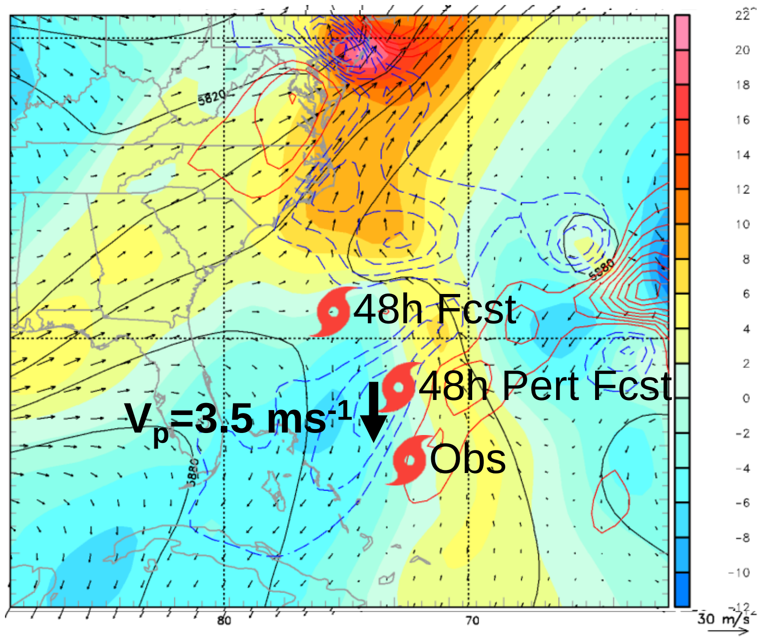
Tropical Cyclones: TCI



500-hPa ζ Sensitivity, Winds, GHT (48h)
12Z 28 September 2015



500-hPa V-wind, Heights, Optimal V
12Z 30 September 2015 (48h)



- Category 4 hurricane devastated the Bahamas; Took the lives of 33 crewmembers of the cargo ship El Faro
- Early track forecasts from operational hurricane models were especially poor
- ONR Tropical Cyclone Intensity (TCI) Experiment (NASA WB-57 with dropsondes
- Key sensitivities: i) winds around the TC; ii) TUTT to NE, iii) upstream trough (regions of ascent & diabatic heating)
- Small adjoint perturbations change steering flow and shift the position southward closer to observed TC

Atmospheric Rivers: AR Recon

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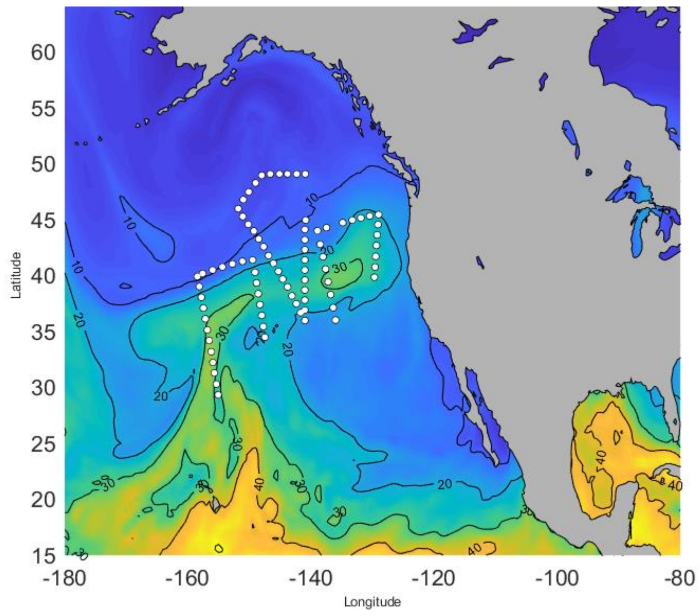
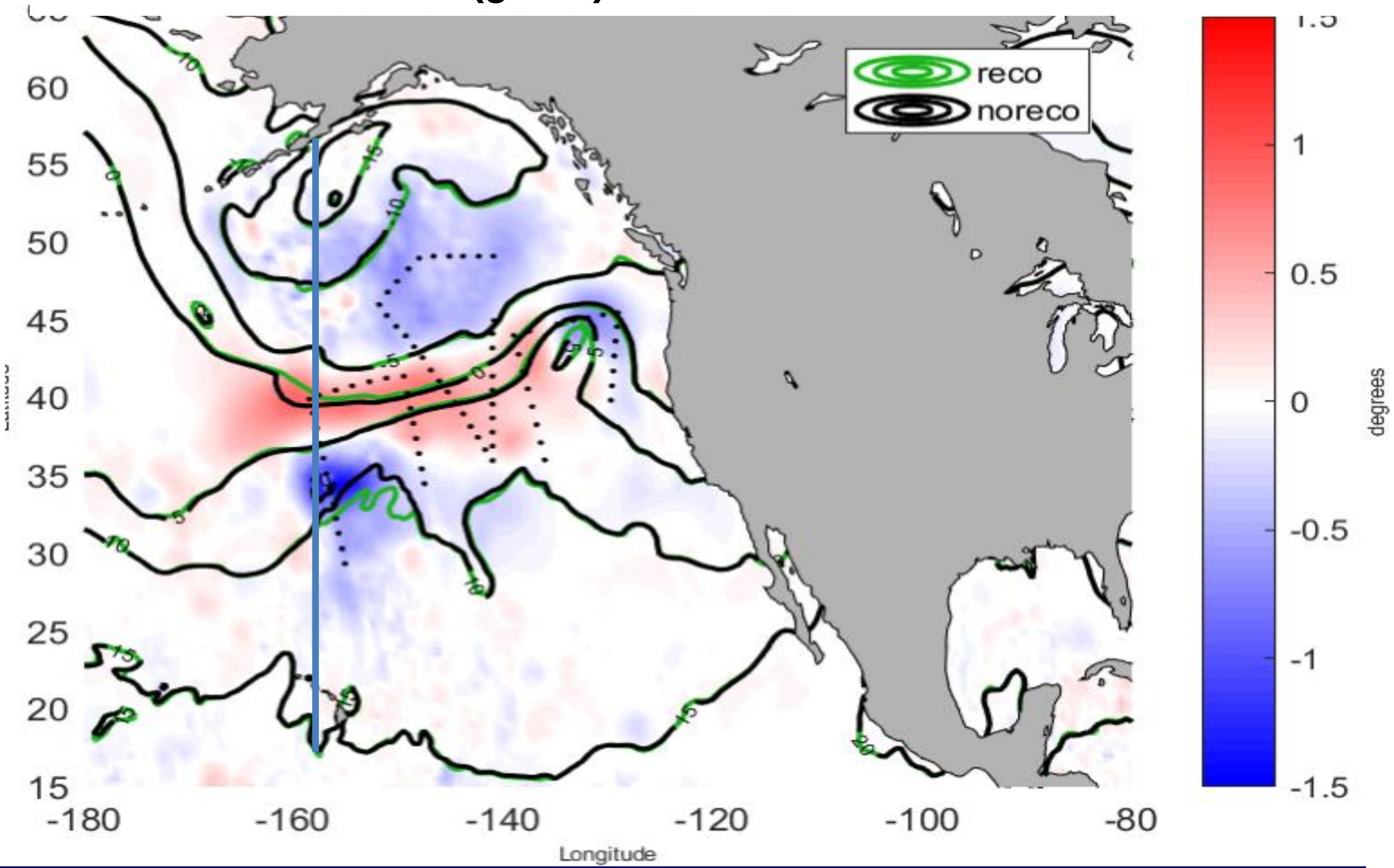
Analyzed Total Precipitable Water



27JAN Case: 850-hPa temperature analysis for control (black) and RECON (green). Difference field shaded.

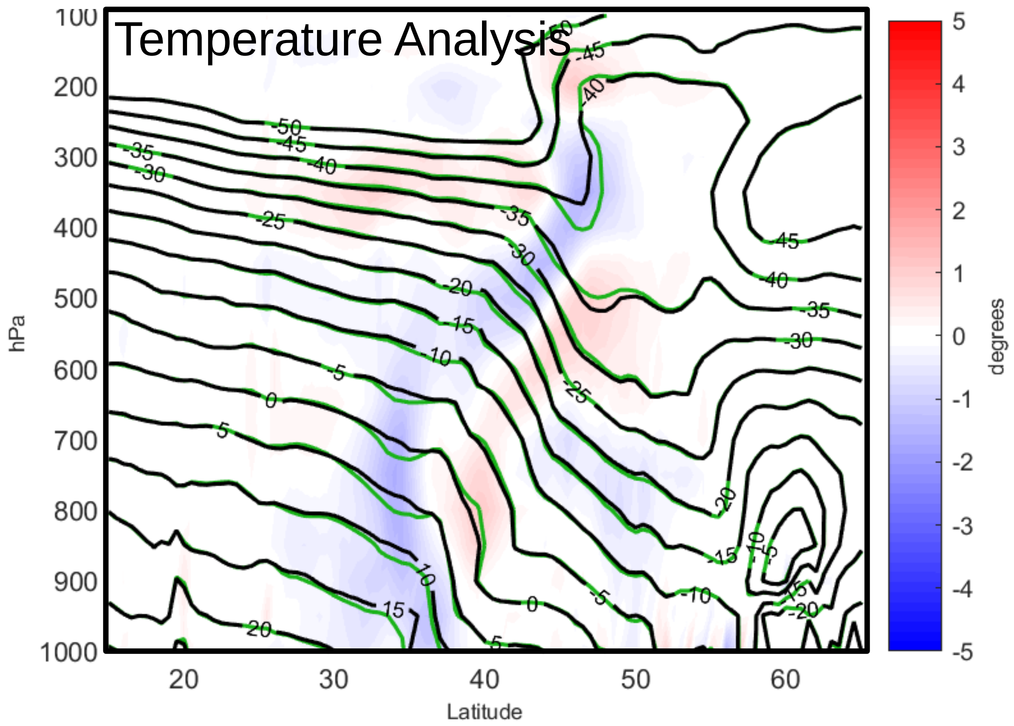


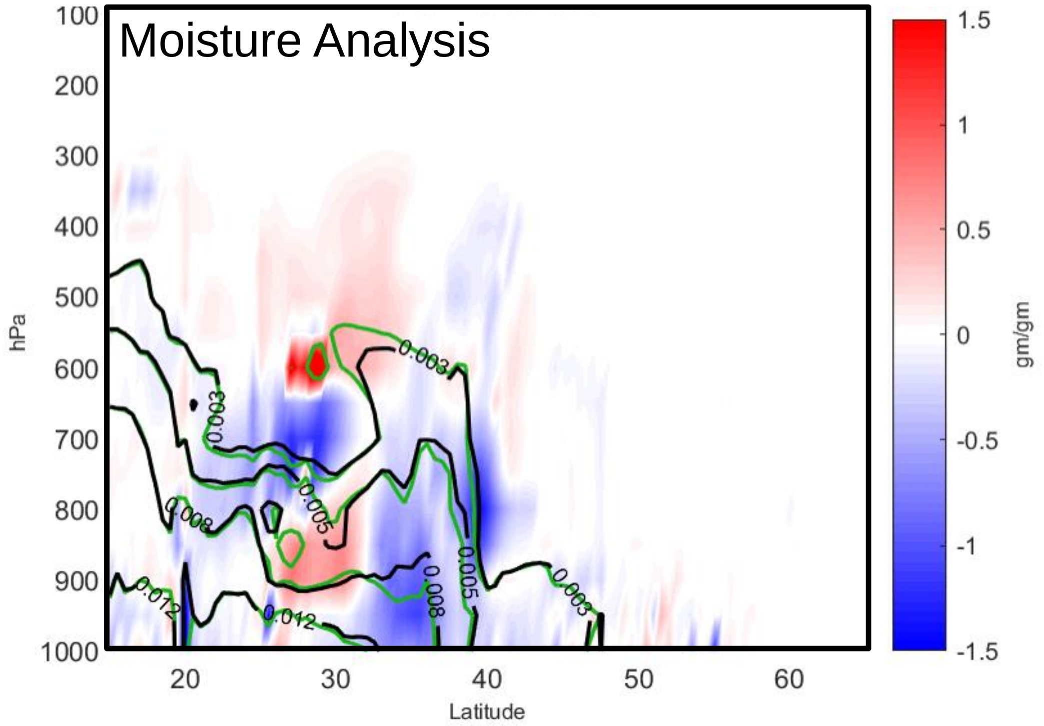
Stone et al. 2019 (MWR)

Impact of RECON on 800-hPa temperature fairly large scale and wide-spread

Atmospheric Rivers: AR Recon

27JAN Case: Temp. Analysis (left) and Moisture Analysis (right) at 155W for Control (black), RECON (green). Difference field shaded.





Temperature increments related to frontal features. Moisture increments are more complex. Can we get more impact from moisture observations?

- Representativeness error (better results at higher resolution)?
- Function of the background covariances? Testing different hybrid formulations.
- Function of model biases, assigned error variances?

Atmospheric Rivers: AR Recon

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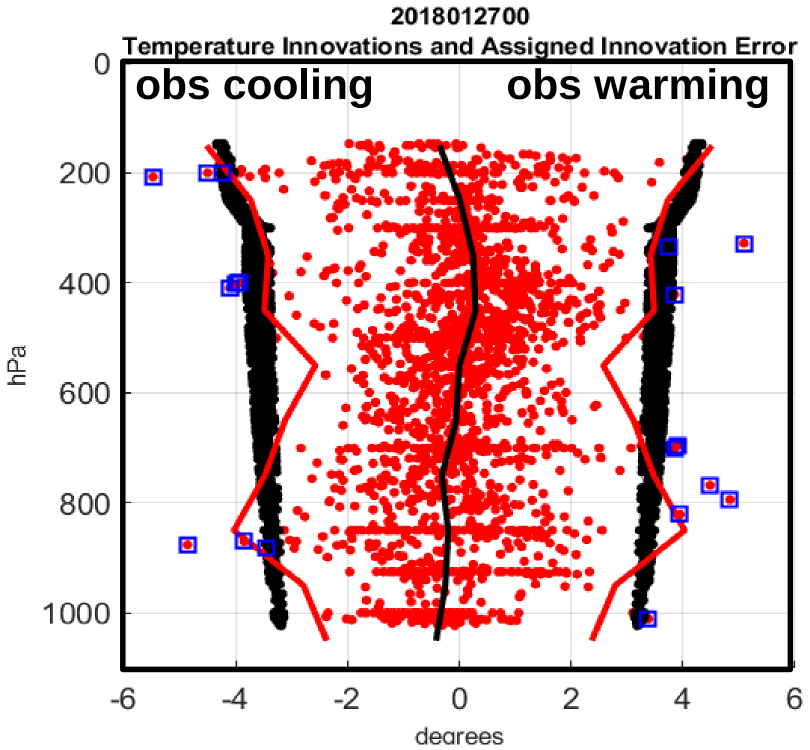
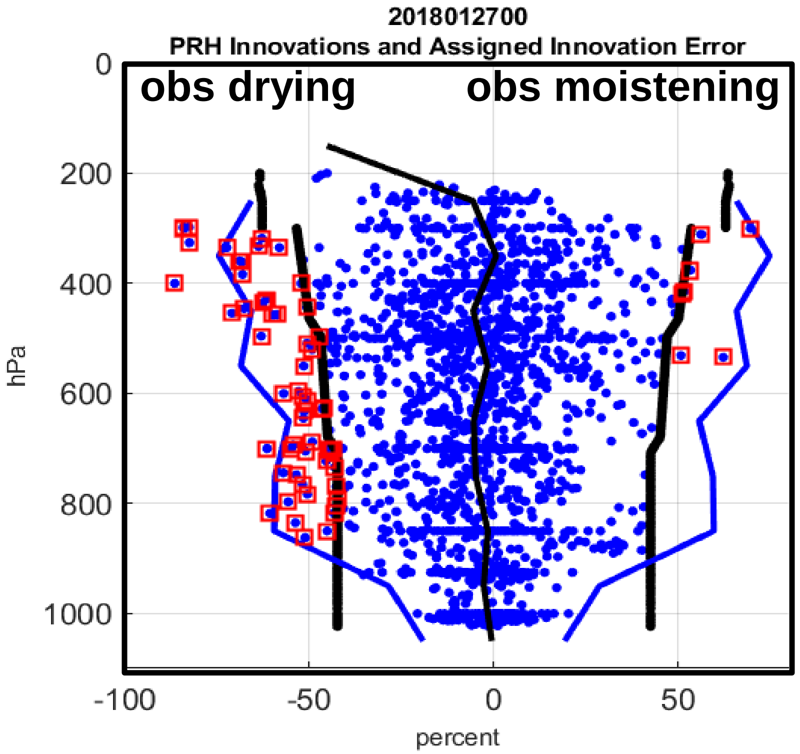
Temperature



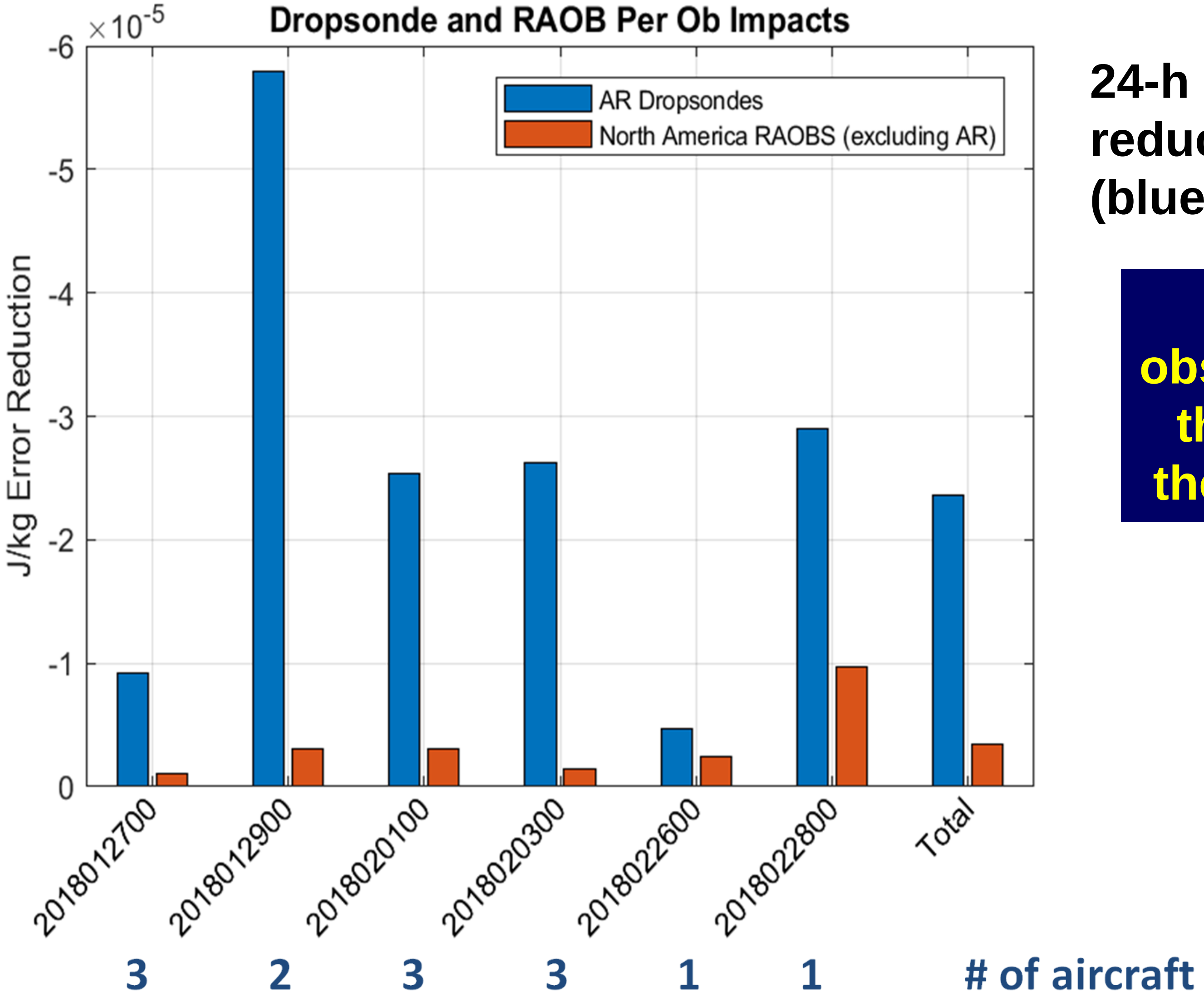
Pseudo Relative Humidity



Innovations (dots), mean assimilated obs (thin black line), specified error variance (black marks), 3-sigma departure check (color lines), rejected innovations (squares).

- Good match for temperature
- Specified error variance for pseudo RH smaller than actual innovation variance: Too many obs being rejected (not fully correcting moist bias)

NAVGEM FSOI Studies

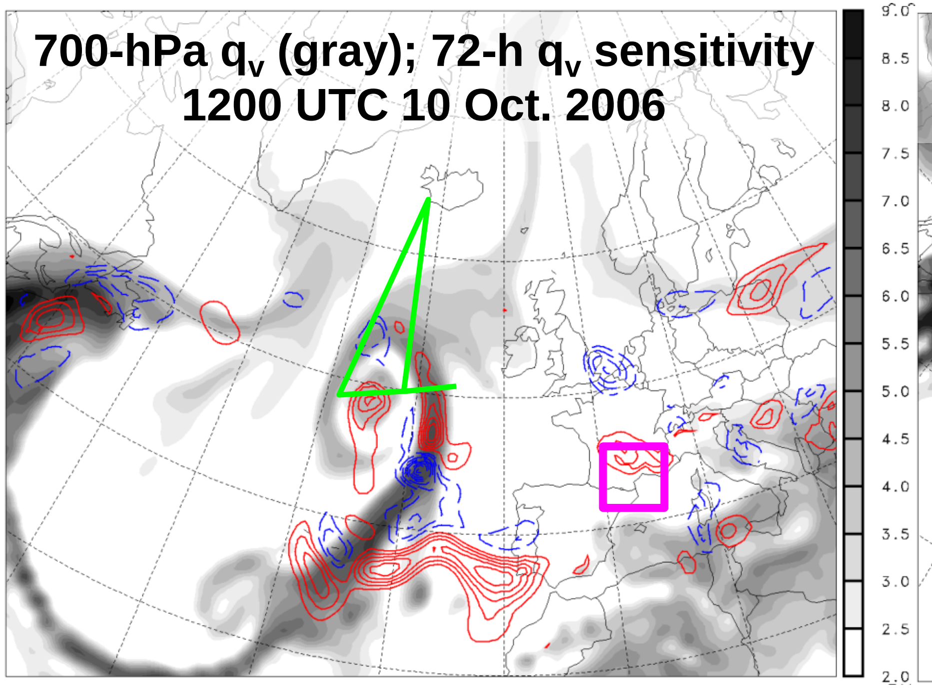


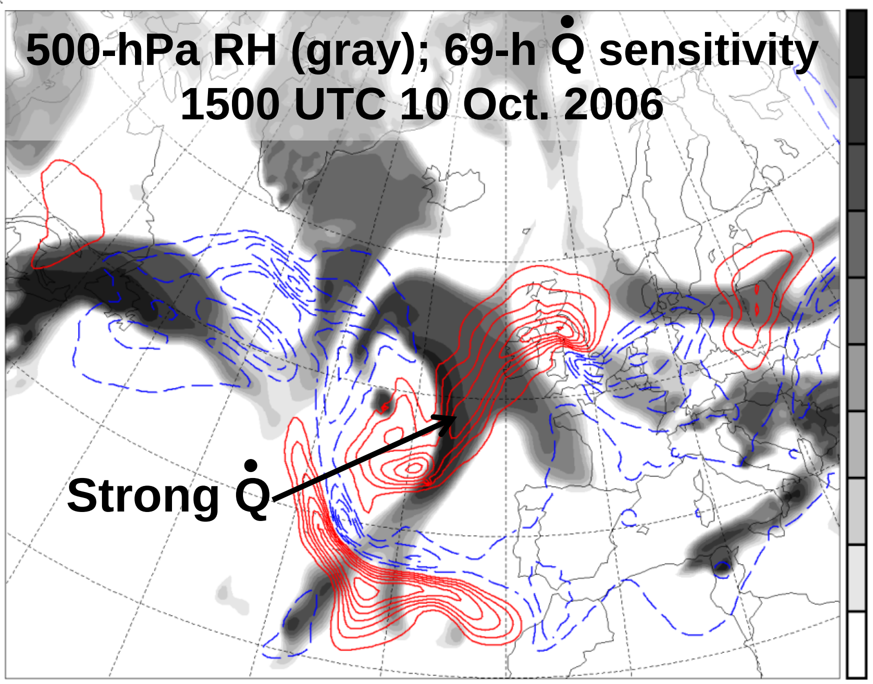
24-h Forecast Error (global moist total energy) reduction *per observation* for dropsondes (blue), NA RAOBS(red) and both (purple)

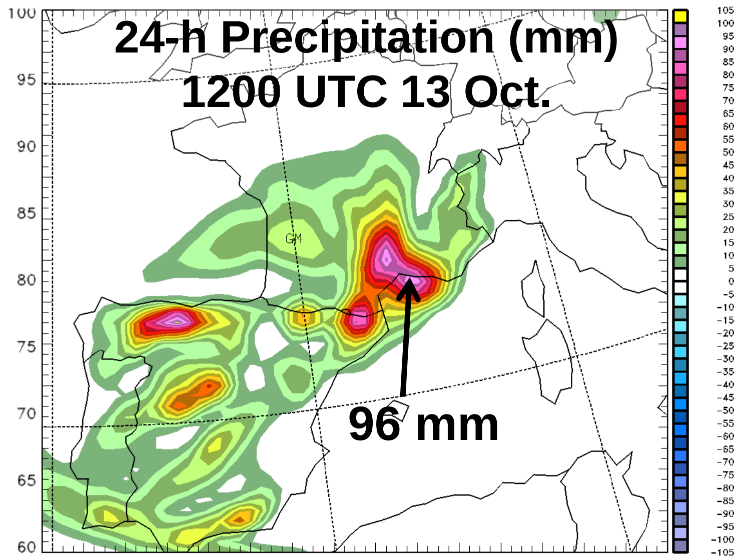
As the number of dropsonde observations is substantially smaller than the number of NA RAOB observations, the per ob impact is several times larger.

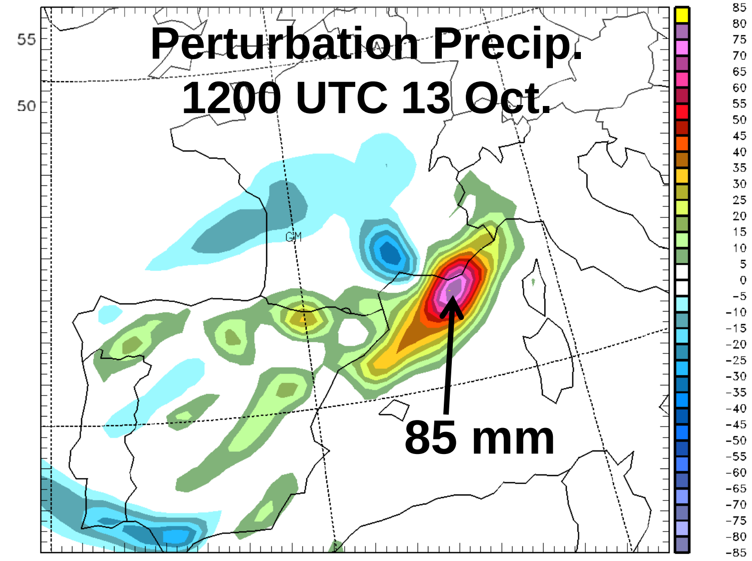
Stone et al. 2019 (MWR)

Extratropical Cyclones: NAWDEX









- More than 250 mm precipitation over Southern France
- Large q_v and latent heat sensitivity near Storm Sanchez
- 25-75 mm/24h rainfall associated with optimal perturbations