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Adjoint Sensitivity and Impact of Atmospheric River Reconnaissance Observations for North Pacific Forecasts

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Outline

Part I: Adjoint sensitivity study comparing precipitation (PR) and KE response functions *(Reynolds, Doyle, Ralph, and Demirdjian, 2019: Adjoint sensitivity of North Pacific Atmospheric River Forecasts. Mon. Wea. Rev., 147, 1871-1897.)*

- Case study for Oroville Dam Crisis: 2017020612
- Average characteristics
- For work exploring mechanisms of perturbation growth, please see *Demirdjian et al., 2020: A case study of the physical processes associated with the atmospheric river initial condition sensitivity from an adjoint model. J. Atmos. Sci. (early online release)*

Part II: AR RECON Study *(Stone, Reynolds, Doyle, Langland, Baker, Lavers, and Ralph, 2020 Atmospheric River Reconnaissance Observation Impact in the Navy Global Forecast System. Mon. Wea. Rev., 148, 763-782.)*

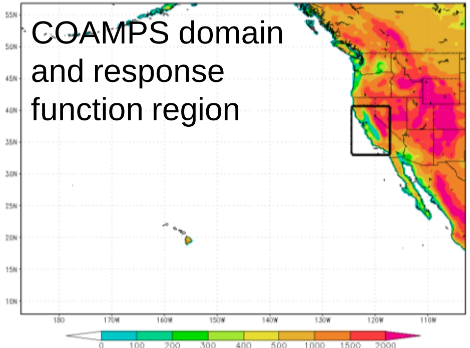
- Forecast Sensitivity/Observation Impact (FSOI)
- Increment statistics
- Preliminary data denial studies

COAMPS Adjoint System

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

COAMPS® Moist Adjoint Model

- Dynamics: nonhydrostatic, nested
- Physics: PBL, surface fluxes, microphysics
- 37-km resolution, 24-h and 36-h optimization times
- Response function (RF) J:
  - **KE RF in box (1 km deep);**
  - **PR RF (21-24h precipitation in box),**
- Optimal Perturbations (1 m/s, 1 K, 1 g/kg)
- Cases: 00Z and 12Z 01JAN to 20FEB 2017



Case Study: Oroville Dam Crisis

- 330 mm rain between 6-10 FEB2017
- Potential collapse of emergency spillway led to evacuation of 188,00 people (spillway held).

Optimal Perturbation Case Study: Initial Time Perturbations (2017020612)

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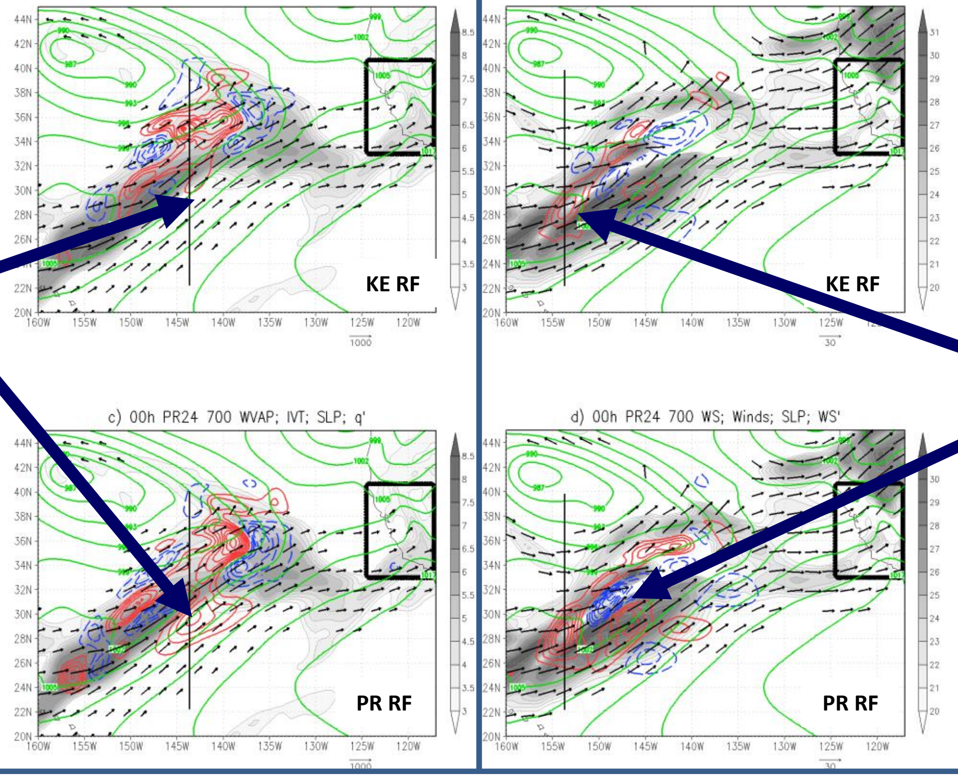
Structures between KE and PR RFs similar but differ in detail

700-hPa Water Vapor (gray scale), IVT (vectors), SLP (green), 700-hPa q opt. pert. (red +/ blue -, CI=0.05 g/kg)

700-hPa wind speed (gray scale), winds (vectors), SLP (green), 700-hPa wind speed opt. pert. (red +/blue -, ci=.01 m/s)



Optimal perturbations align with the edges of the AR/WCB at initial time

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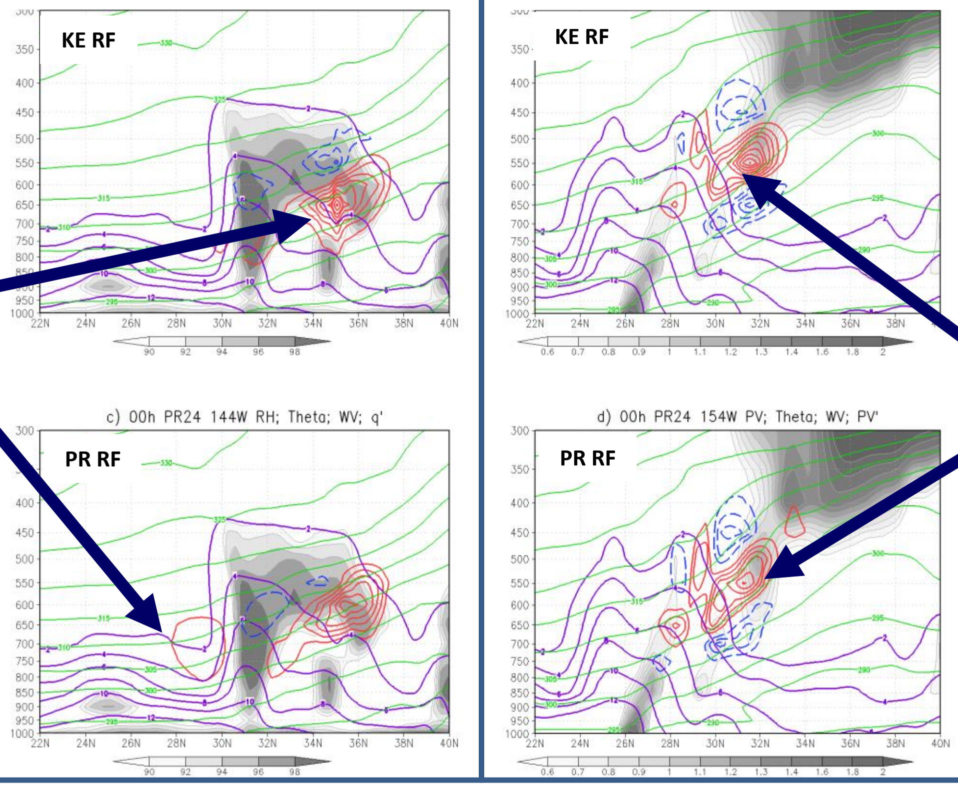
Optimal Perturbation Case Study: Initial-time Perturbations (2017020612)

Optimal perturbations tend to occur on the edges of the ARs (large moisture gradients) and “fill in” subsaturated regions

144W, RH (gray scale), Theta (green), Water Vapor (purple), q opt. pert. (red +/blue -, ci=.1 g/kg)

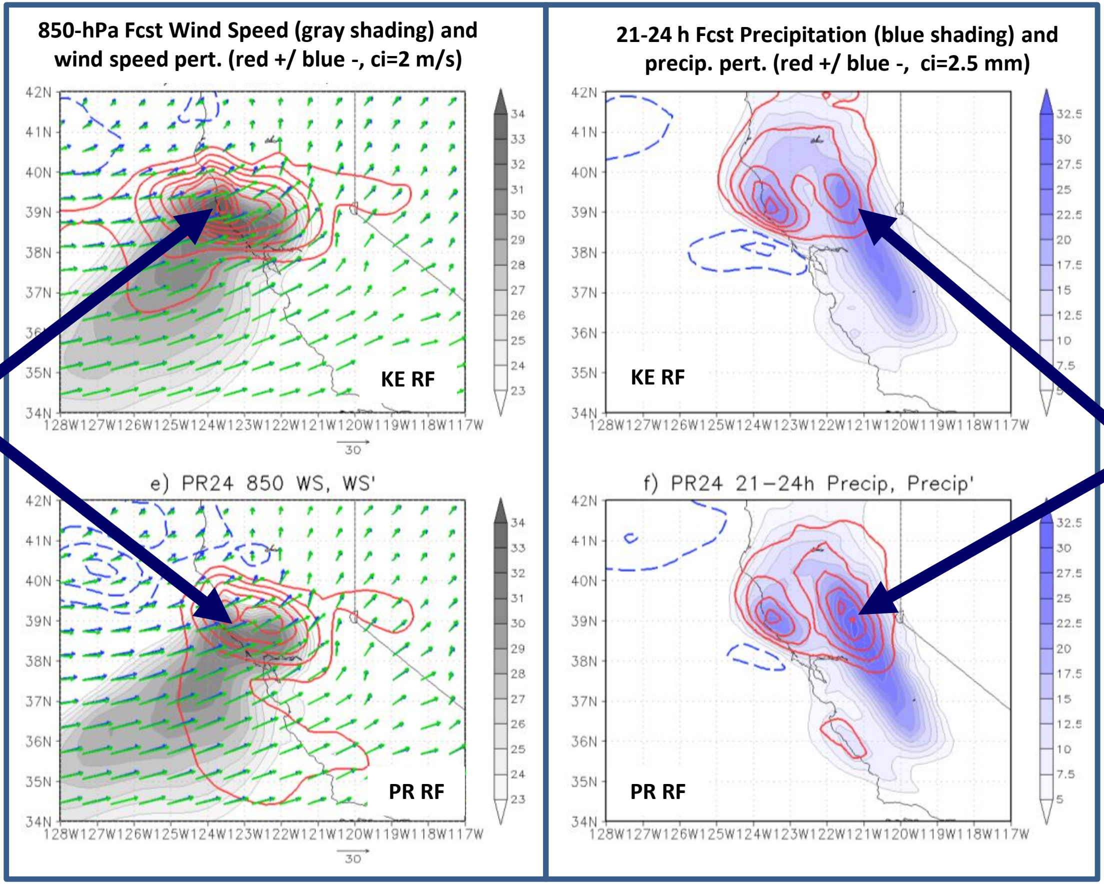
154W, PV (gray scale), Theta (green), Water Vapor (purple), PV opt. pert. (red +/blue -, ci=0.007 PVU)



Optimal perturbations try to fill/ connect mid-upper tropospheric and lower-tropospheric PV features

Optimal Perturbation Case Study
24-h Perturbed Forecasts (2017020712)

Maximum wind speed perturbation twice as large in KE RF (19 m/s) than in PR RF (11 m/s)

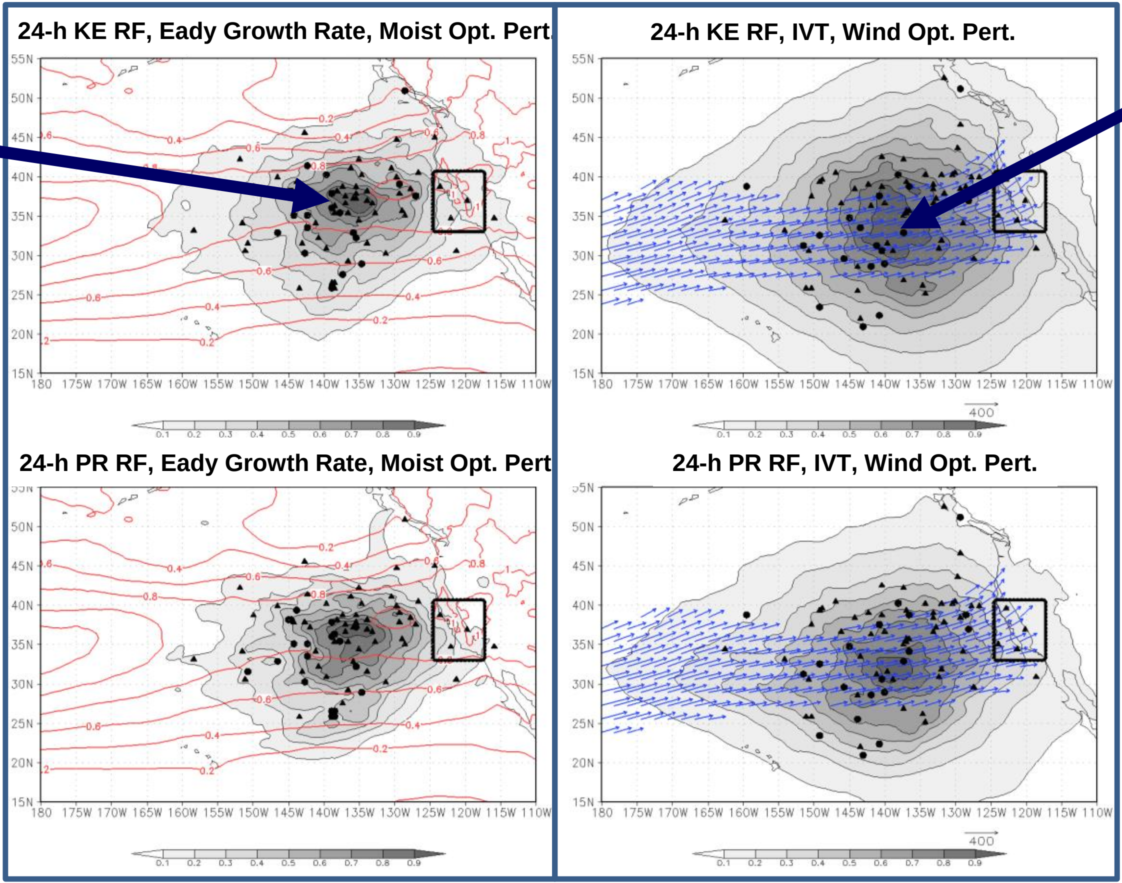


Increase in precipitation over 10 mm in both cases, but more spatially extensive for PR RF (50% increase over N. Sierra)

Jan-Feb 2017 Vertically-integrated Absolute Values of Optimal Perturbation (normalized by maximum value)

Maximum sensitivity located near Eady growth rate max

Maximum sensitivity in strong IVT region

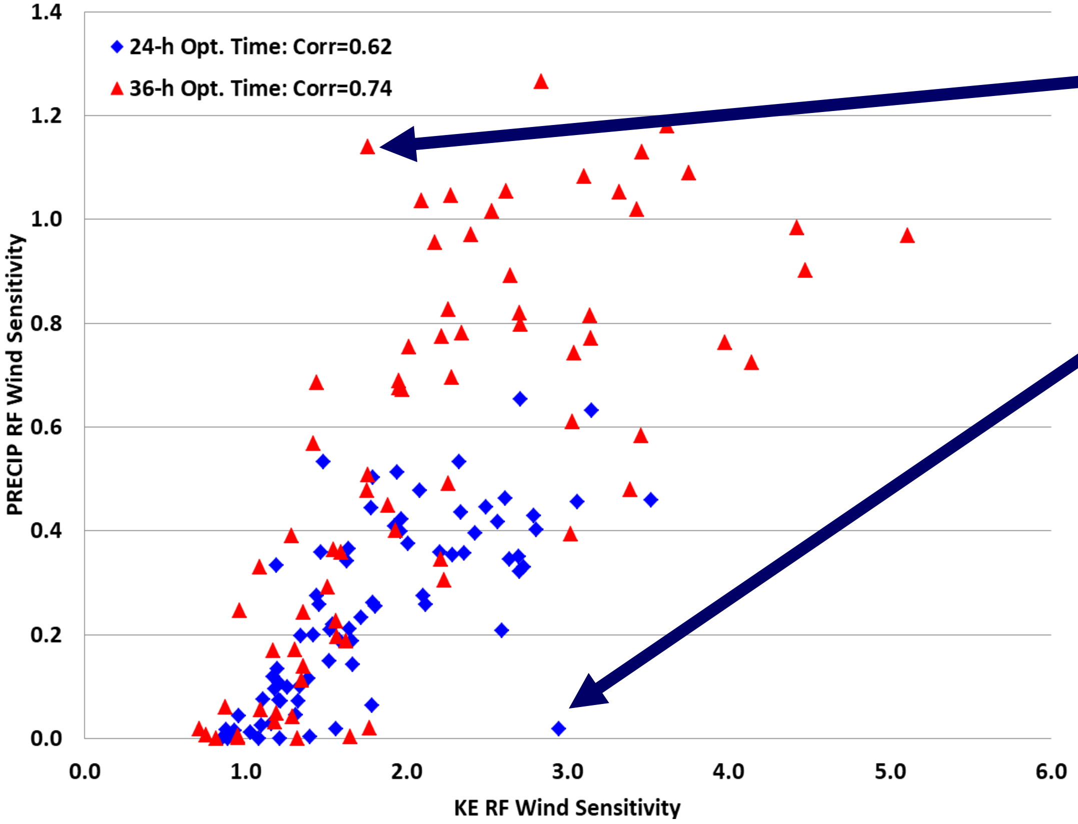


In an average sense, KE and PR sensitivity similar

Dots show location of maximum for each case; large variability/case dependence

KE RF Sensitivity vs PR RF Sensitivity

Domain-averaged absolute value of KE RF sensitivity vs. PR RF sensitivity



PR sensitivity large but KE sensitivity moderate

PR sensitivity small but KE sensitivity large

Observation targeting will be metric dependent

Summary Part I

- Sensitivity on edges and in subsaturated regions of the AR/WCB; moist sensitivity confined to lower troposphere (extra slide), wind sensitivity often occurs in/near both lower and mid-level dynamic features

- KE and PR sensitivity patterns differ in detail and result in substantially different perturbations: adaptive observing should be metric dependent

- Forecast error correlated with initial sensitivity magnitude: adjoint diagnostics relevant for predictability studies (extra slide)

Outline

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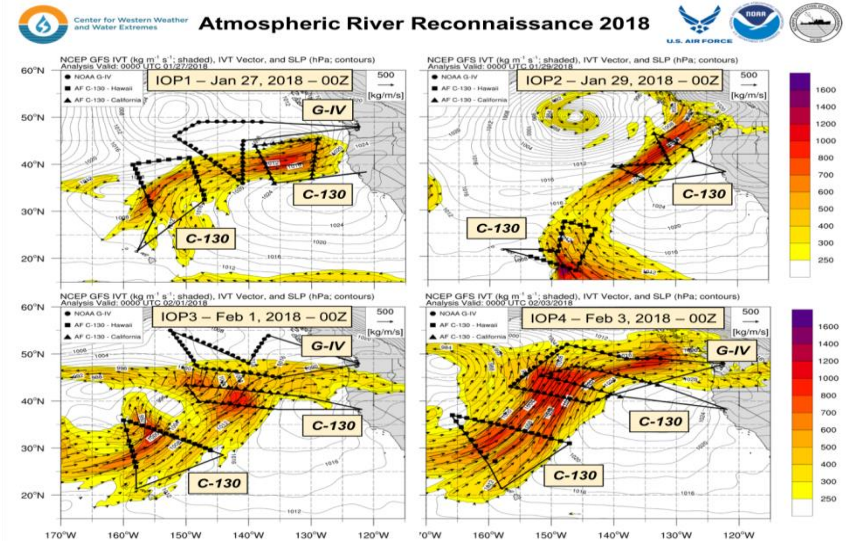
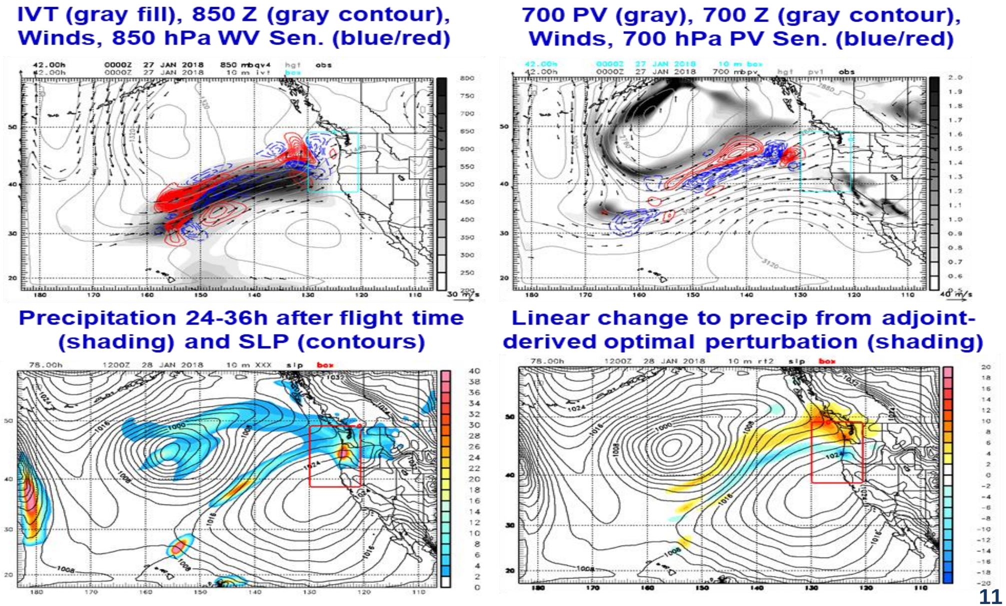
- Forecast Sensitivity/Observation Impact (FSOI)
- Increment statistics (extra slides)
- Preliminary data denial studies

Part II: AR RECON 2016, 2018, 2019, 2020



NRL COAMPS forecast / adjoint produce sensitivity of forecast west coast precipitation to changes in the initial state. Used with other products for flight planning.



COAMPS adjoint highlights the AR (particularly edges) and relevant dynamics (short waves, mid-upper level PV features).

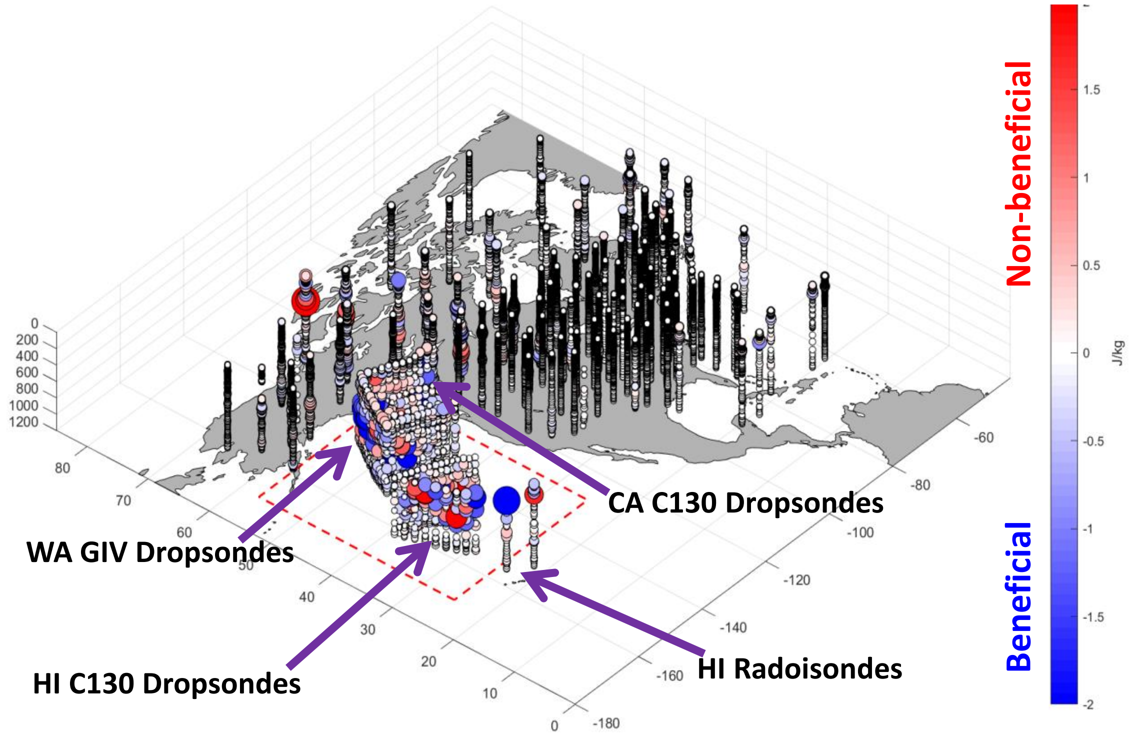
Observation Impact Studies with NAVGEM

The Navy Global Environmental Model (NAVGEM) is used to look at impact of AR RECON obs on analyses and short term forecasts

- **Forecast Sensitivity/Observation Impact (FSOI, Langland and Baker 2004): Uses adjoints of NAVGEM and hybrid 4-d VAR DA system (NAVDAS-AR) to calculate impact of each ob on 24-h forecast error**
  - **Compare impact from AR RECON with North American Radiosondes**
  - **Compare impact from moisture, temperature and wind observations**

- **Data Denial Studies: Run DA-Forecast system with and without AR RECON observations**
  - **How is East Pacific analysis changed by RECON observations?**
  - **What is impact for forecasts over N. America?**

NAVGEM FSOI Studies

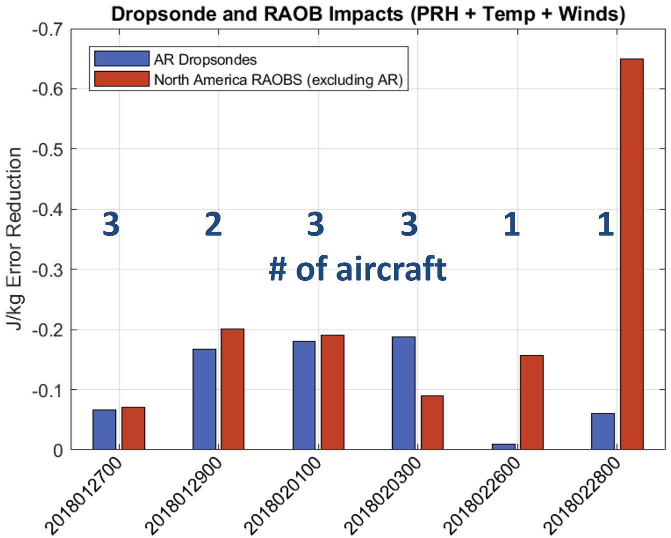


Wind ob impacts (10^{-3} J kg^{-1}) for IOP 2018020300
Size & color of spheres give FSOI value

FSOI for IOP 2018020300

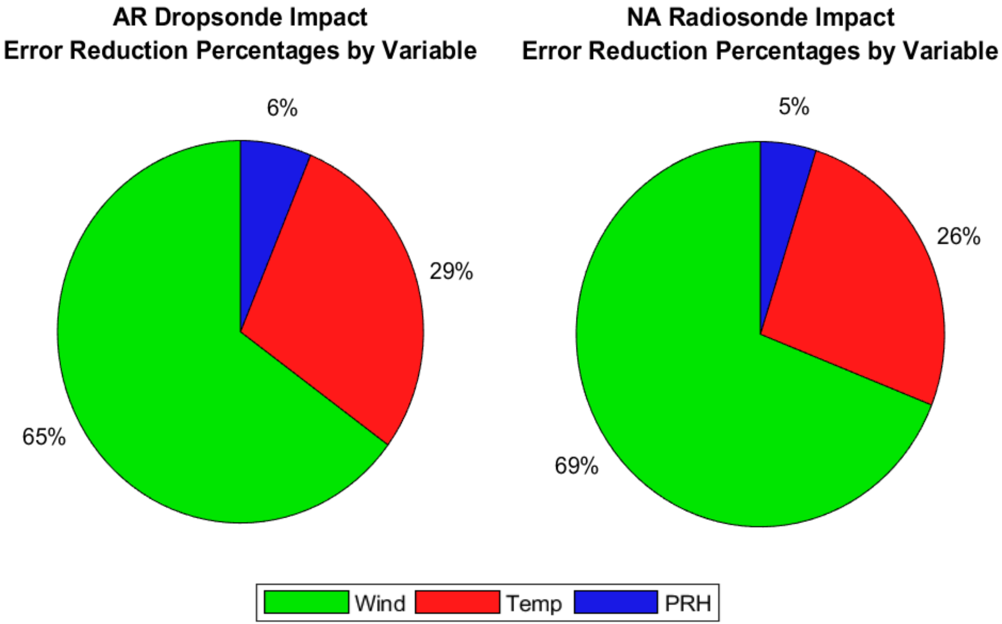
- **Forecast model resolution - T425 (31km); DA inner loop – T119 (110 km)**
- **Color/size of sphere correspond to ob impact on 24-h global moist total energy error**
- **More color (bigger impact) for EPAC dropsondes and Hawaii radiosondes than N. American radiosondes (larger impact typical for more isolated obs)**
- **Obs can be beneficial or non-beneficial; aggregate impact on next slide**

NAVGEM FSOI Studies



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

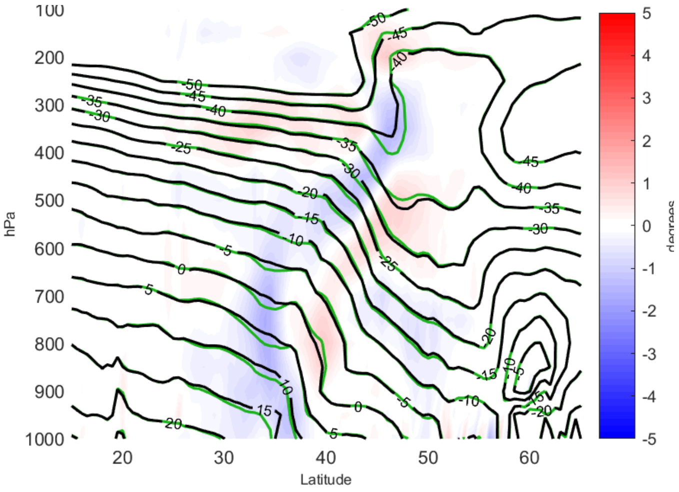
Aggregate impact of AR RECON comparable to NA Radiosondes given 2-3 flights (per ob impact much higher)

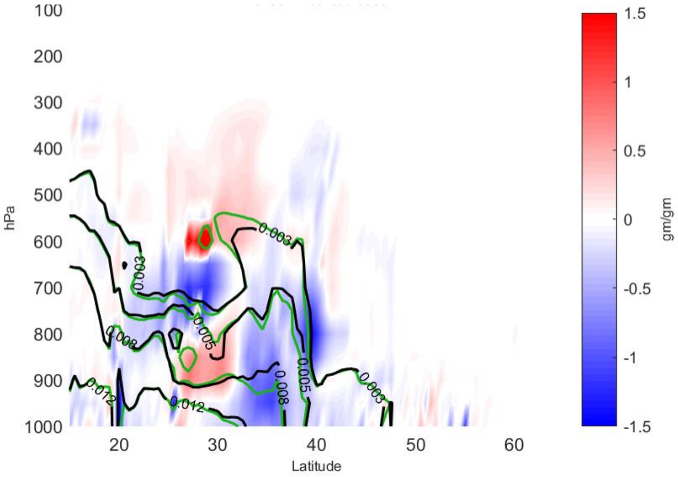


Impact of moisture obs smaller than winds or temperature impact; specified error variance may be too small (rejecting too many moisture obs)

NAVGEM Data Denial Studies

27JAN Case: Temp. analysis (left) and moisture analysis (right) at 155W for control (black), RECON (green). Difference field shaded.



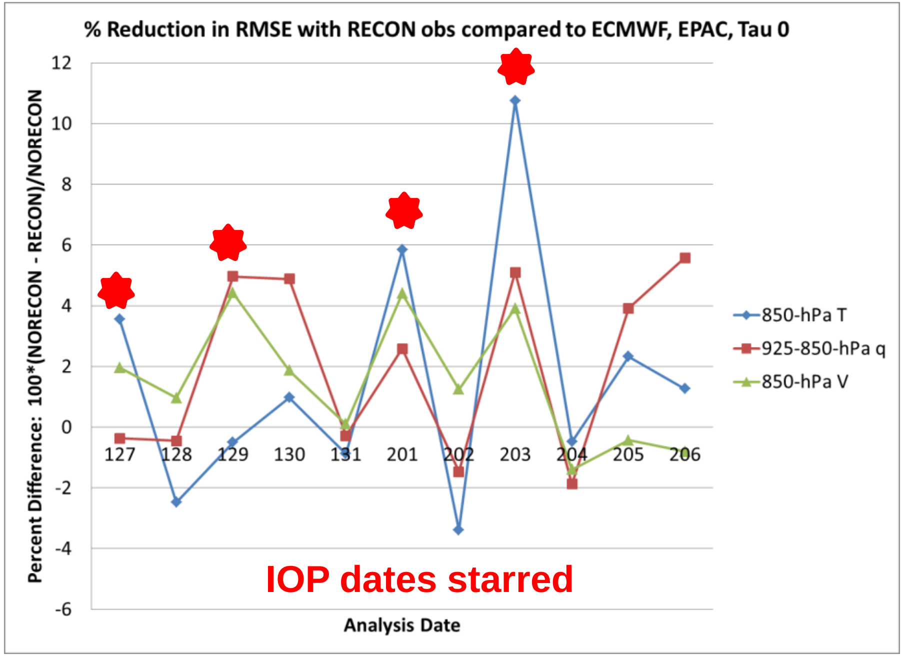


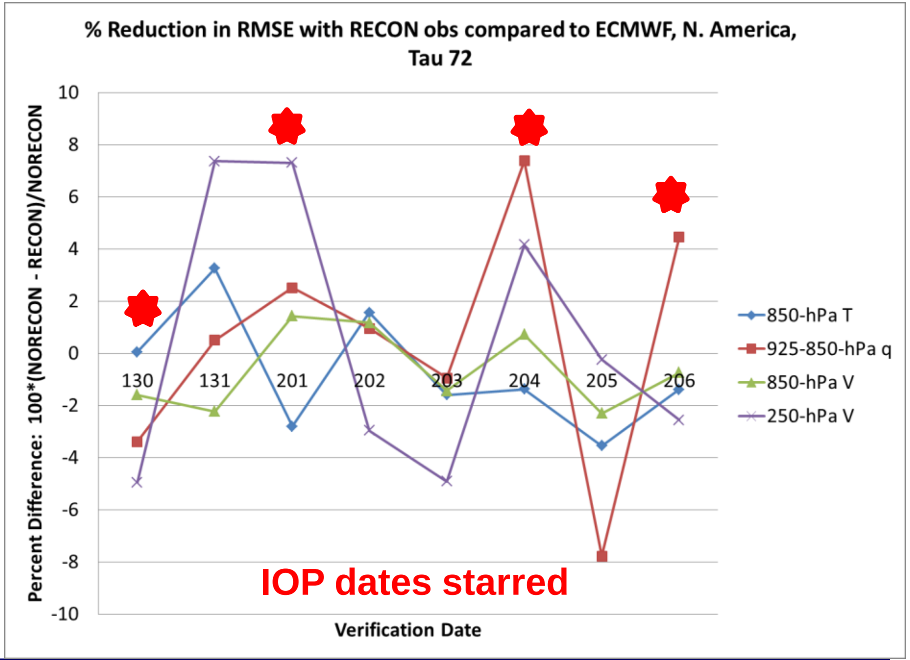
- Temperature increments related to physical fields (i.e., front)
- Moisture increments more complex

Can we get more impact from moisture observations?

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

NAVGEM Data Denial Studies





As expected, difference between NAVGEM and ECMWF analyses in Eastern Pacific tends to be smaller during IOP cases

- Standard forecast error metrics do not show uniform improvement over N. America
- To Do: Evaluate impact on west-coast precip.

Summary Part II

- NAVGEM FSOI
  - With 2 or 3 RECON flights, total forecast error reduction from AR RECON similar to NA RAOBS
  - Relatively small impact from moisture compared to other obs (bias, representativeness error?)
  - More moisture observations rejected (extra slide), will revisit error assumptions in DA

- NAVGEM Data Denial Studies:
  - Physically-relatable changes in temperature, but complex changes in moisture (representativeness?)
  - Dropsondes reduce EPAC (Navy-ECMWF) analysis differences by up to 11%, but standard forecast error metrics do not show uniform improvement over N. America.

- Future Work:
  - Quantify NA forecast skill changes due to dropsondes for impact metrics (e.g., precipitation)
  - Consider 2019 and 2020 IOPs, impact of buoy surface pressure
  - Look at model representation of upper level jet
  - Perform similar experiments with COAMPS

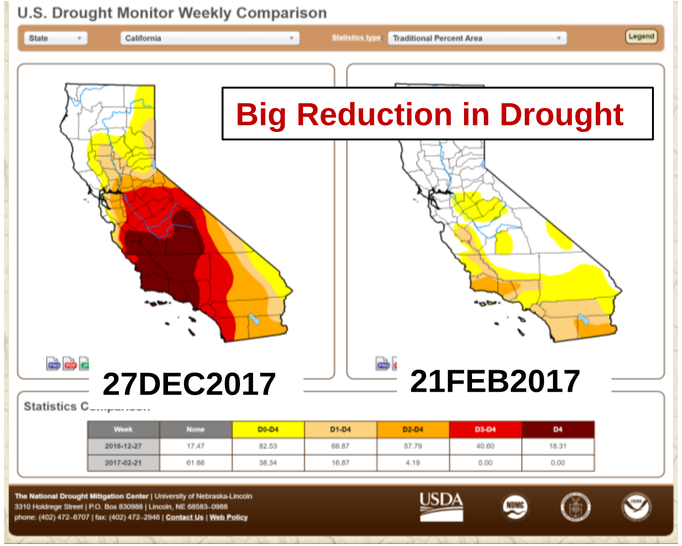
Extra Slides

California Rainfall
January-February 2017

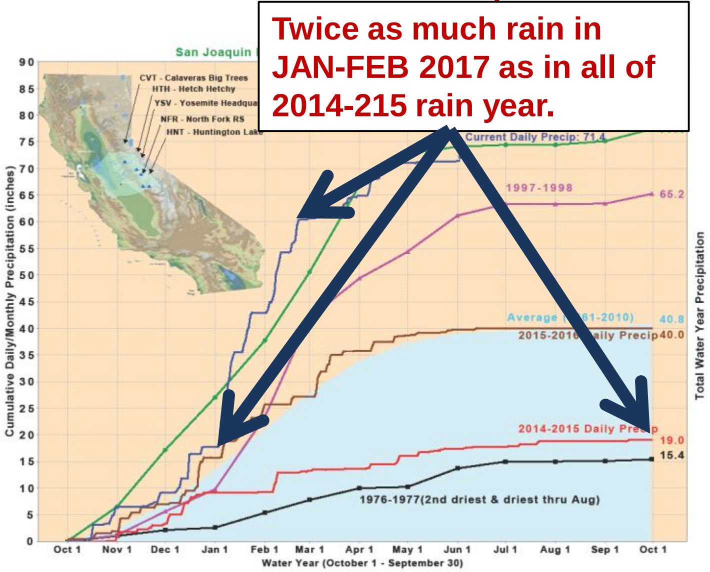
From the RENO NWS Forecast Discussion, 9 January 2017:

BOTTOM LINE: DO NOT TRAVEL IN THE EASTERN SIERRA. LIFE THREATENING BLIZZARD CONDITIONS ARE OCCURING in places and will continue through Wednesday morning.

This second storm and AR is wreaking havoc in the Sierra at this time. Highway 395 is shut down in portions of Mono County due to blizzard conditions with **visibility 10 feet** ………. **Sierra ridge gusts will reach or exceed 150 mph tonight. Total snow accumulations up to 10 feet** in the higher elevations and several feet in the lower elevations …. **Drifts up to 20 feet are possible.**



Week	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
2016-12-27	17.47	82.53	68.87	57.79	40.60	18.31
2017-02-21	61.66	38.34	16.87	4.19	0.00	0.00



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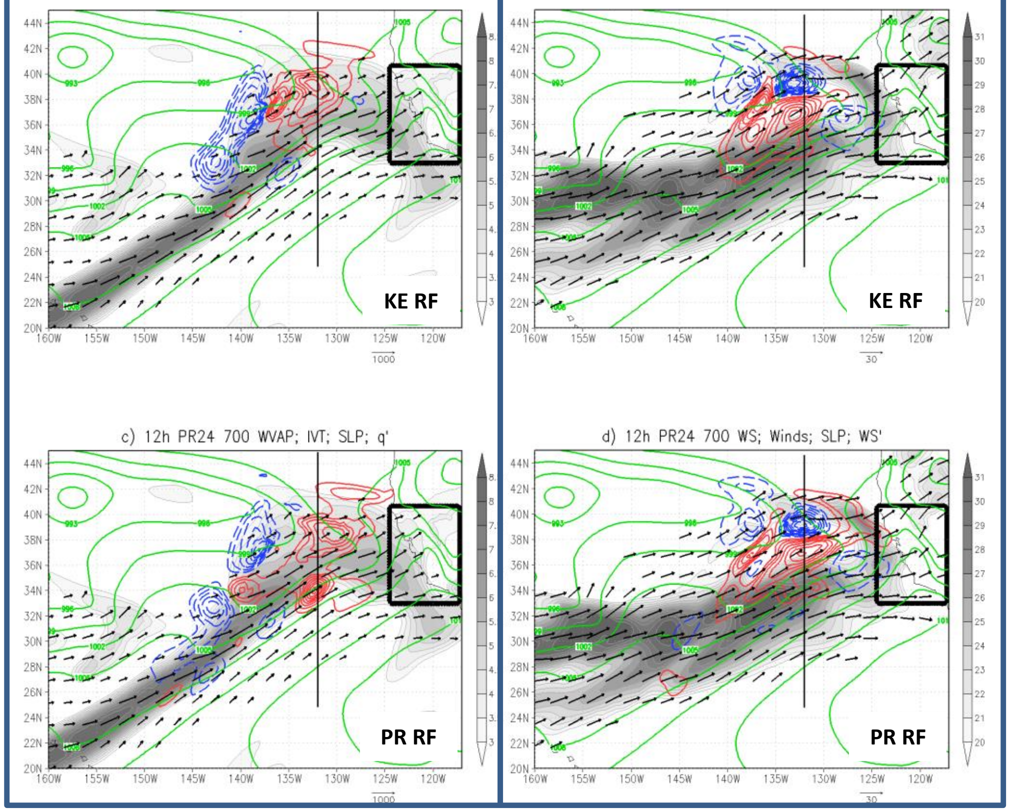
Optimal Perturbation Case Study

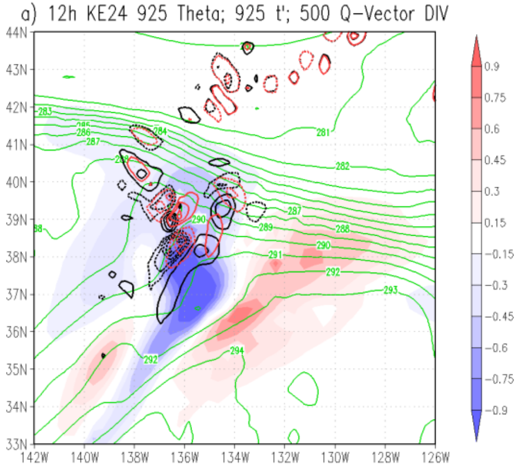
700-hPa Water Vapor (gray scale), IVT (vectors), SLP (green), 700-hPa q opt. pert.

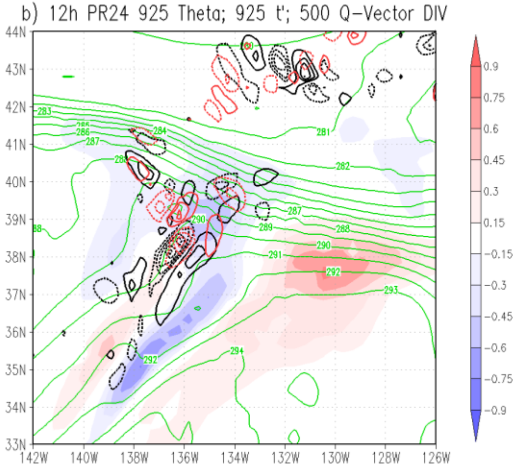
700-hPa wind speed (gray scale), winds (vectors), SLP (green), 700-hPa wind speed opt. pert.



Perturbations evolve to impact the flow at the intersection of the warm and cold fronts.

Optimal Perturbation Case Study

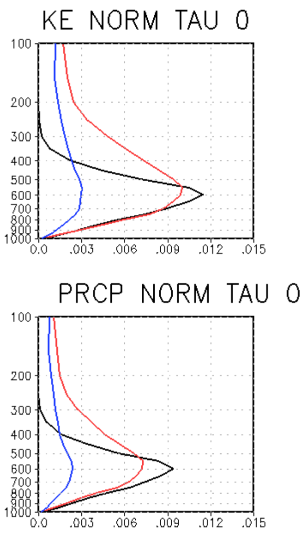




Perturbations have a first order impact on Q-vector forcing

Vertical Profiles of Initial Sensitivity

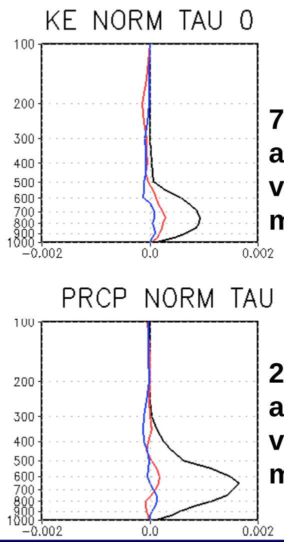
Initial-time mean of absolute value of optimal perturbation



Dominated by low-level moisture and temperature.

Moisture (g/kg)
Temperature (k)
Zonal Wind (m/s)

Initial-time mean of optimal perturbation



7% of absolute value max

20% of absolute value max

Near zero for winds and temperature, positive for moisture.

Note that the initial perturbation values are very small. Precipitation and winds are enhanced through enhancement of the dynamics, not just increased moisture advection.

Latitude averaged Absolute Values of Optimal Perturbation (normalized by maximum value)

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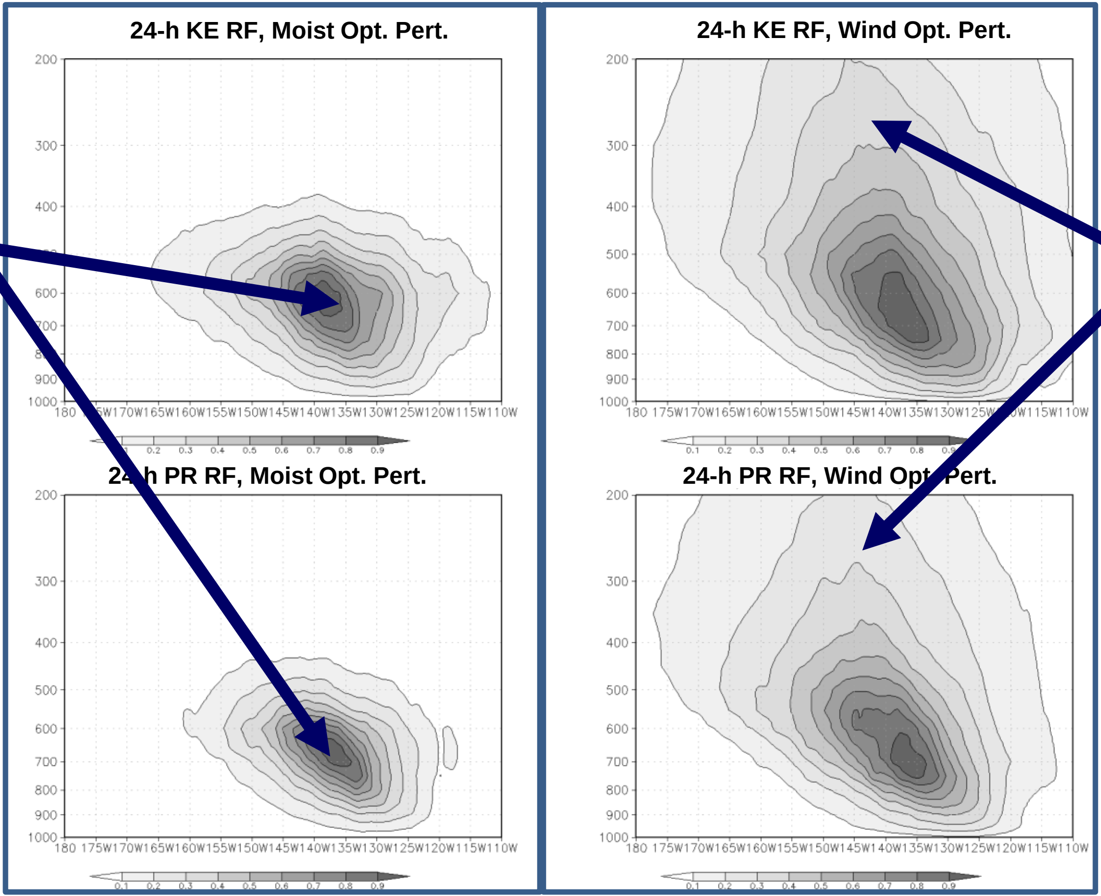
Most of the moisture sensitivity occurs below 500-hPa: slightly lower for PR RF than for KE RF

Perturbation growth mechanisms explored in Demirdjian et al., 2020, JAS

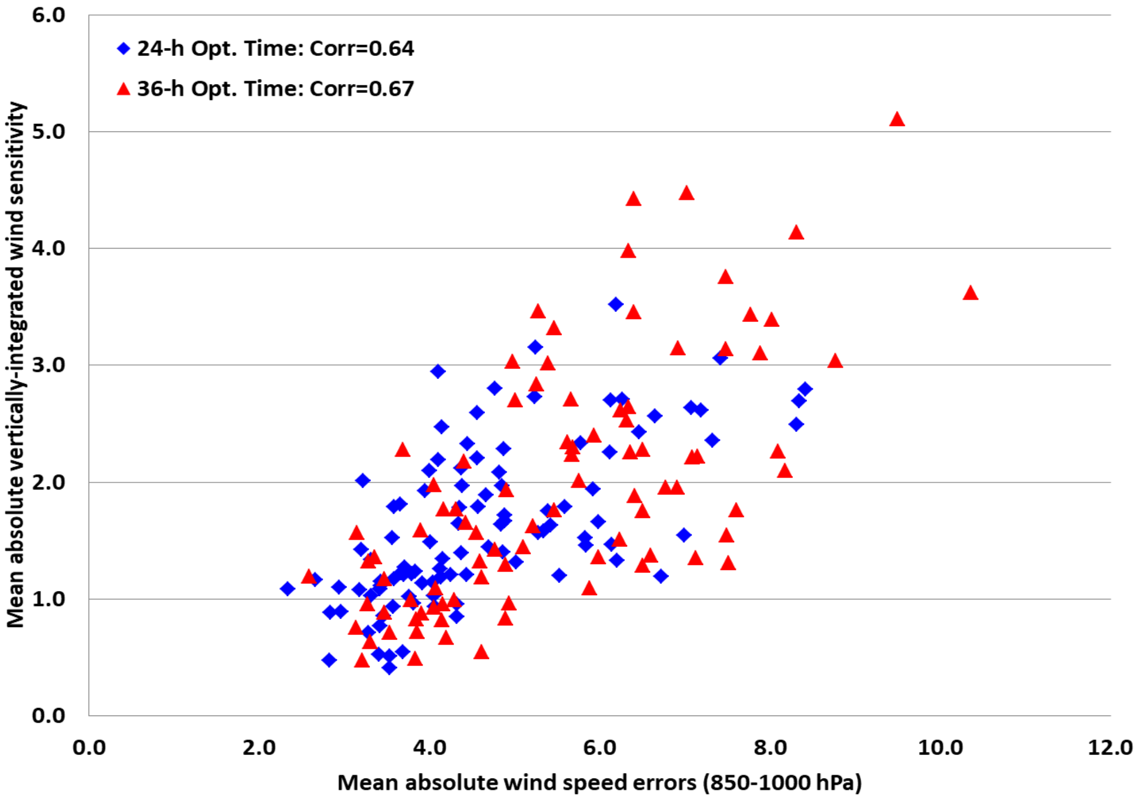


Wind perturbations extend further vertically and longitudinally than the moisture perturbations

Moisture perturbations confined to vicinity of AR while wind perturbations associated with both lower and mid-level dynamics

Sensitivity vs Error

Final-time wind speed RMSE in RF box vs. domain-averaged sensitivity magnitude



Positive correlation between error and sensitivity supports use of adjoint for predictability studies

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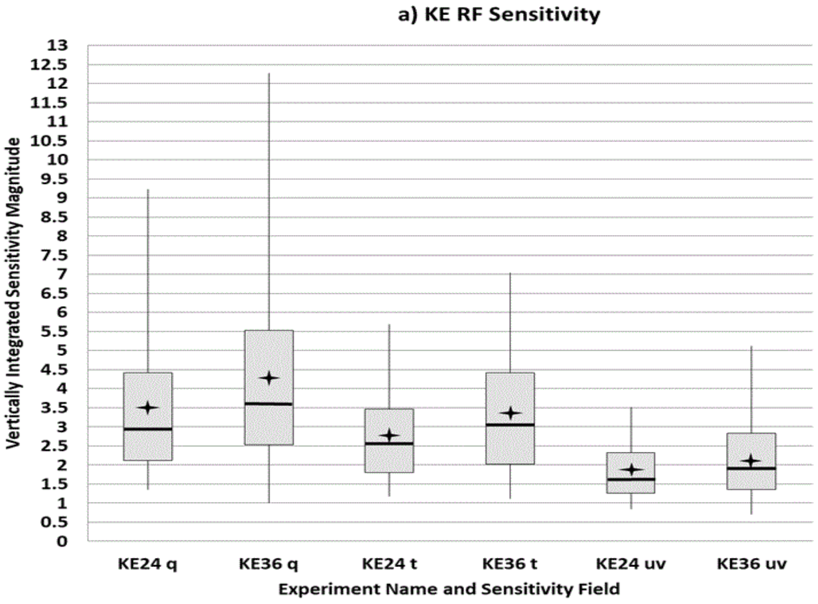
Linear and Nonlinear Perturbation Growth

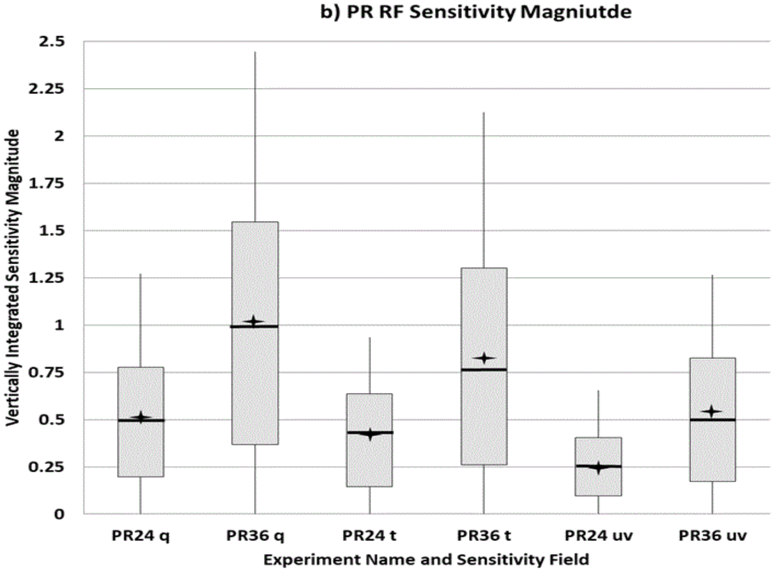
Linear and nonlinear perturbation wind speed (m s^{-1}) and precipitation (mm) averaged over the response function domain.

	24-h KE RF	24-h PR RF	36-h KE RF	36-h PR RF
Linear Wind Pert.	1.15	0.55	1.36	0.66
Nonlinear Wind Pert.	0.95	0.47	1.06	0.54
Linear Precip. Pert.	0.35	0.71	0.60	1.19
Nonlinear Precip. Pert.	0.28	0.73	0.42	1.12

- KE RF about twice as effective as PR RF in enhancing wind speeds
- PR RF about twice as effective as KE RF in enhancing precip
- NL wind perturbations about 75-85% as large as linear wind perturbations
- For KE RF: NL precip perturbations 70-80% as large as linear precip perturbations
- For PR RF: NL precip perturbations comparable to linear precipitation perturbations

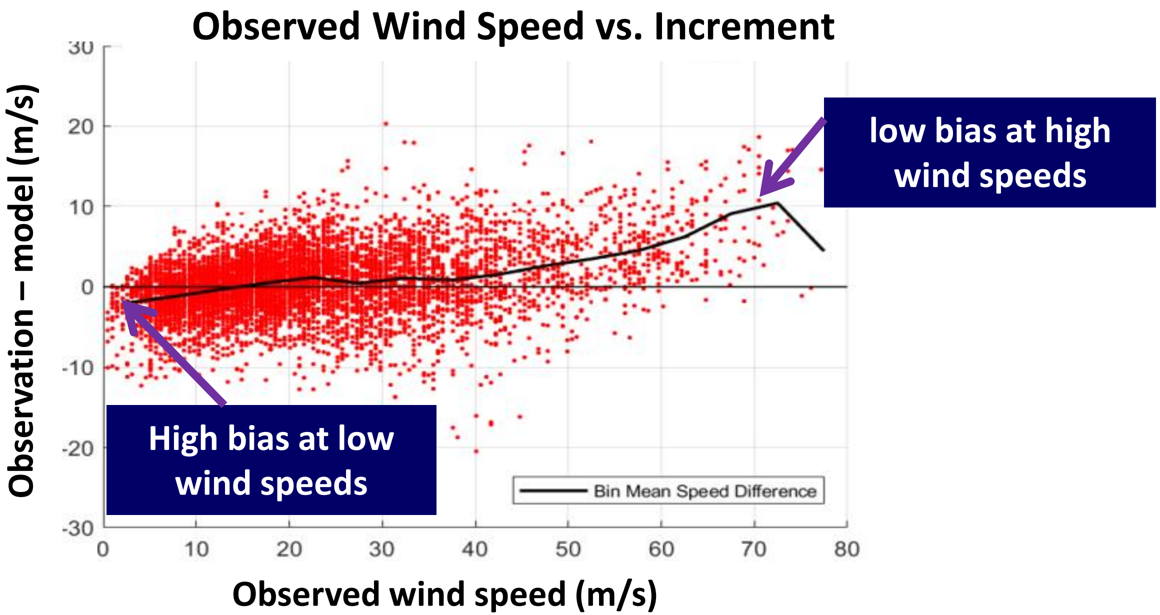
Sensitivity to Winds, Temperature and Humidity





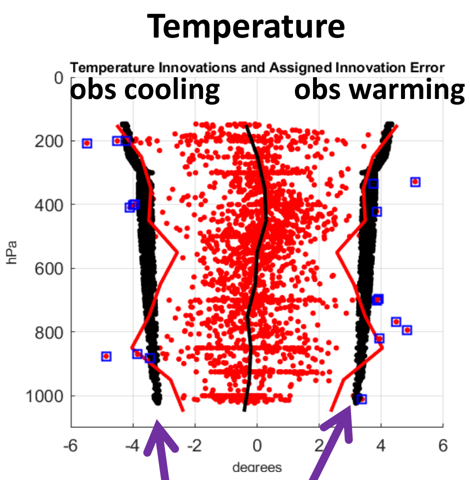
For both response functions, largest sensitivity is to moisture, followed by winds and temperature.

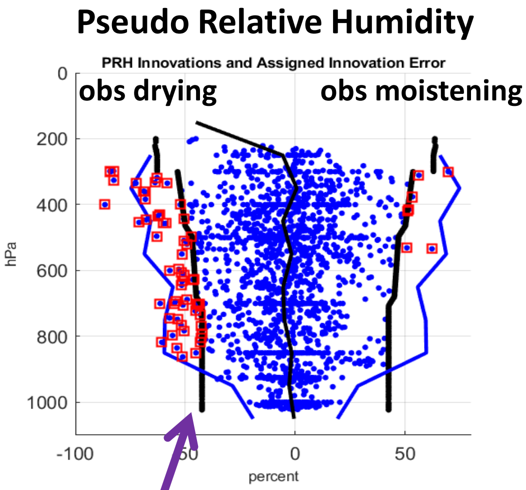
NAVGEM FSOI Studies



- High wind speed bias at low wind speeds and low wind-speed bias at high wind speeds expected due to fairly coarse resolution
- Impacts integrated water vapor advection and forecasts critical for precipitation

NAVGEM FSOI Studies



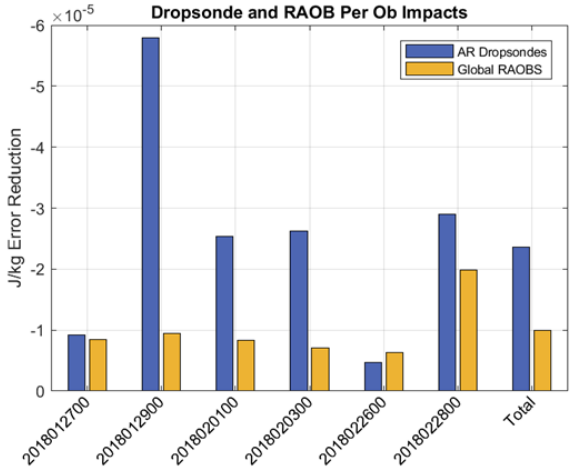


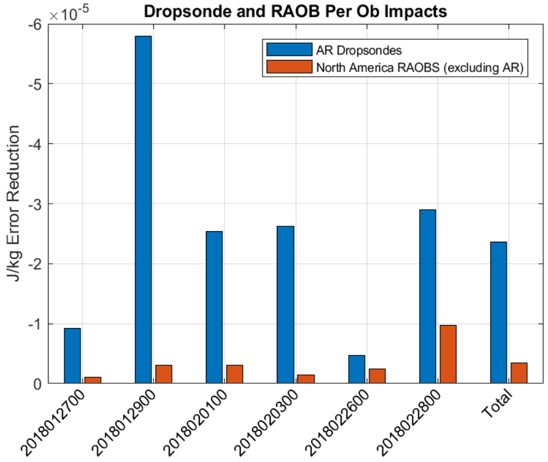
Innovations (dots), mean assimilated obs (thin black line), 3*specified error standard deviation, used in departure check (black marks), 3-sigma of actual observation set (color lines), rejected innovations (squares).

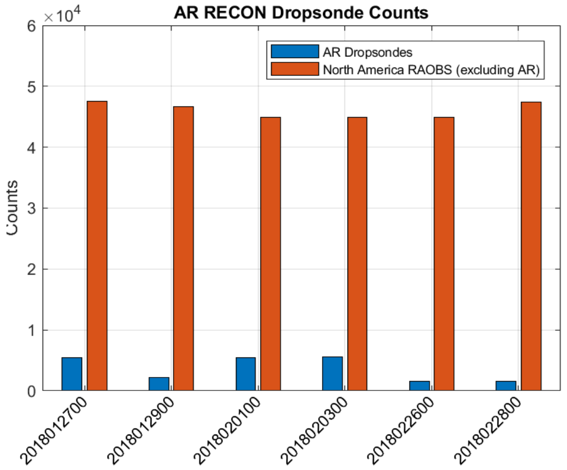
Good statistics match for temperature

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

NAVGEM FSOI Studies







Per ob RECON impact comparable to or greater than global RAOBS per ob impact

Per Ob RECON impact usually substantially greater than NA RAOB per ob impact

Per Ob RECON impact not obviously a function of total dropsonde count

AR Perturbation Growth Mechanism Study (with UCSD)
Demirdjian et al. 2020, JAS

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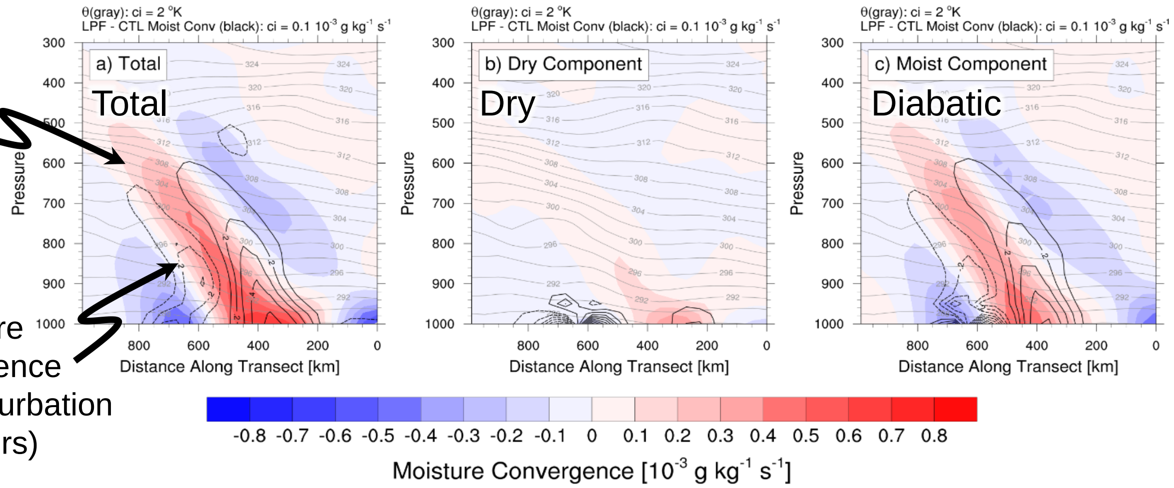
Atmospheric Rivers

Sawyer-Eliassen Derived Moisture Convergence Adjoint Optimal Perturbation

F+ 30 hr, Initialized: 2017010700, Valid: 0600 UTC 8 Jan 2017

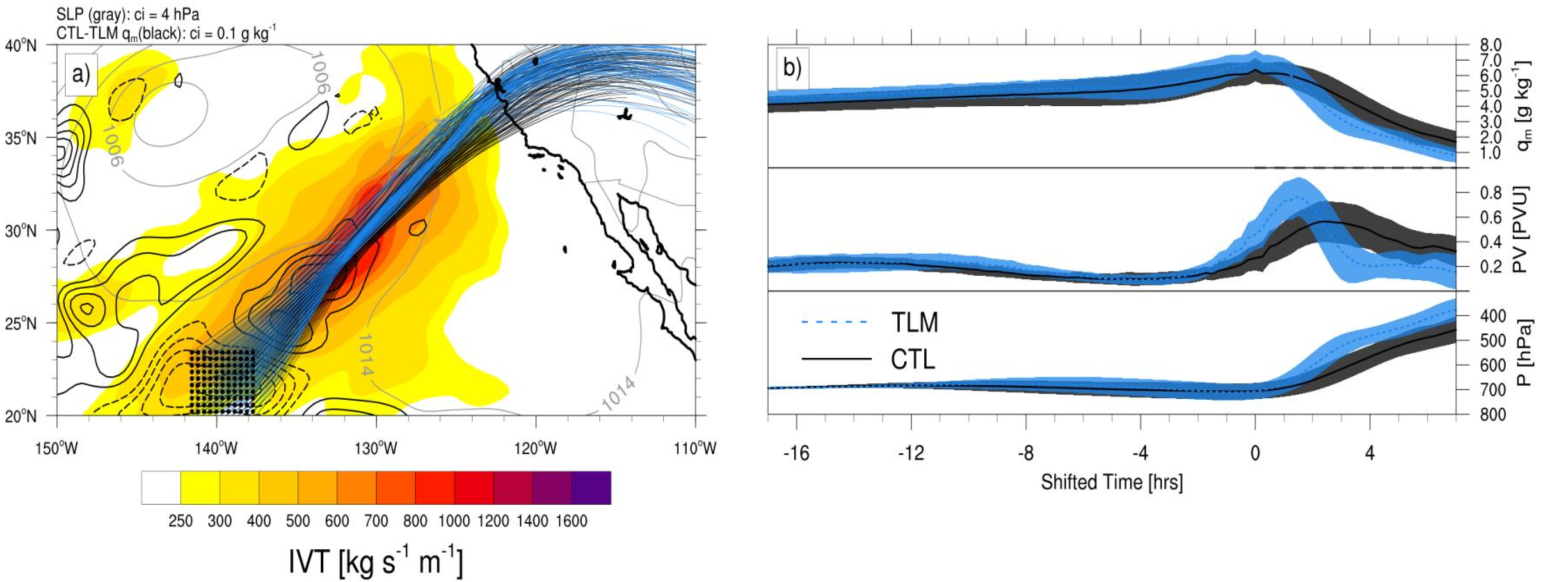
Moisture Convergence Nonlinear Fcst (fill)



Moisture Convergence Optimal Perturbation (contours)

- **Regions of large moisture sensitivity enhance moisture convergence and diabatic heating.**
- **Diabatic heating reinforces a secondary circulation that enhances the moisture convergence**

AR Perturbation Growth Mechanism Study (with UCSD)
Demirdjian et al. 2020, JAS



- Sawyer-Eliassen derived moisture convergence shows that vertical velocity enhancement primarily due to diabatic processes
- Using trajectory analysis to examine changes to parcels in Lagrangian framework
- The moisture perturbation is fed downstream into a region of moisture convergence leading to a stronger transverse circulation due to greater LH production, greater vertical velocity, greater rainout