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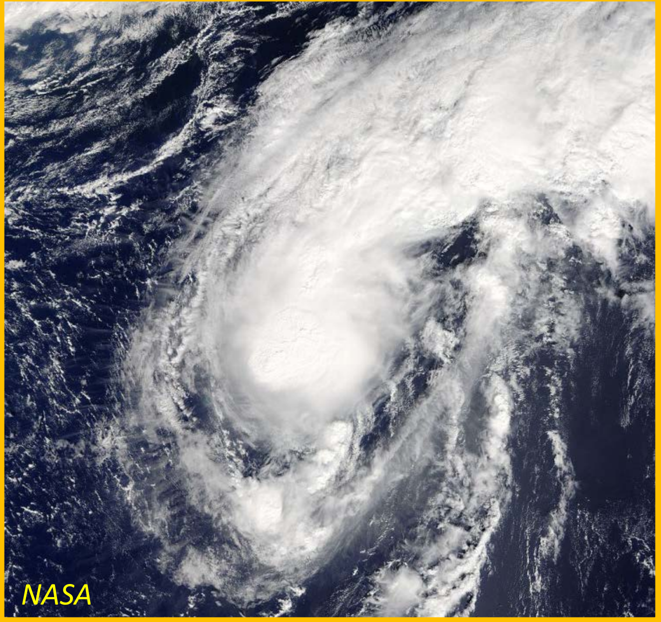
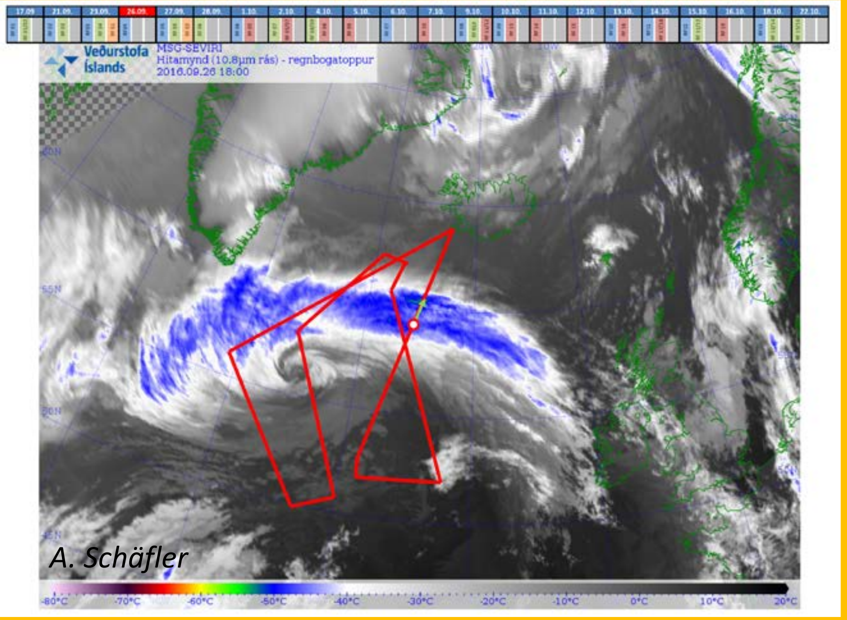
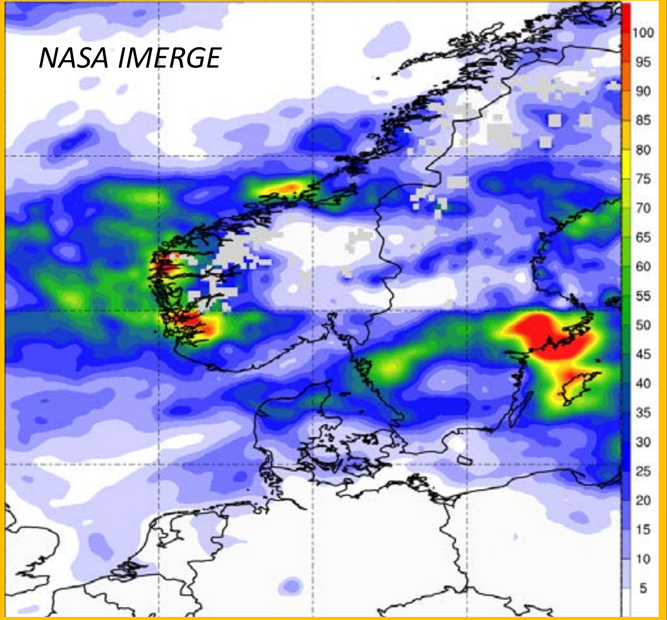
Influence of Warm Conveyor Belts on the Predictability of Downstream High-Impact Weather







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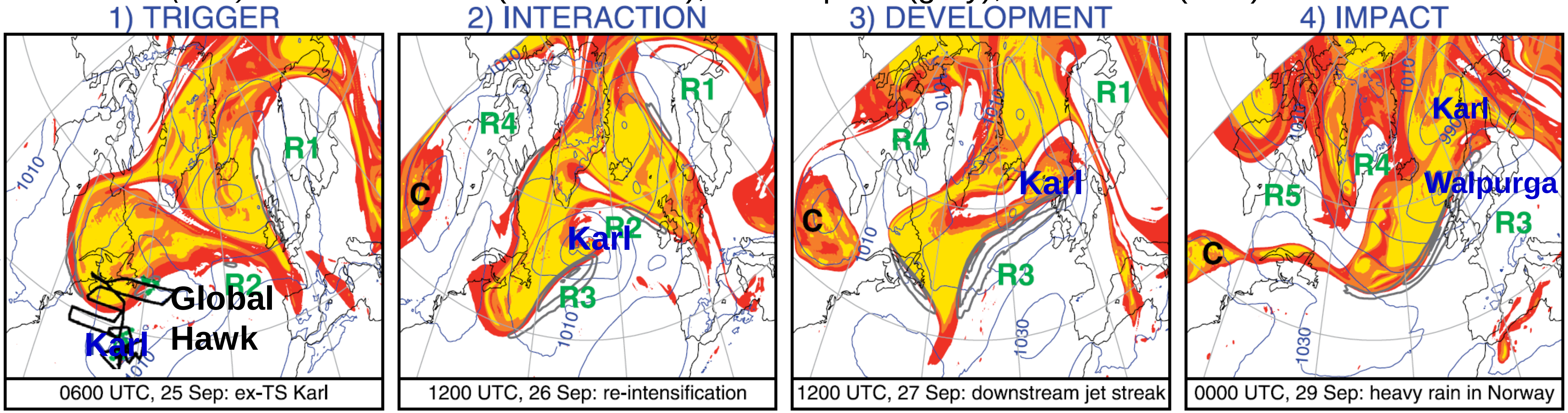
Acknowledgements: NAWDEX team, NRL and ONR

NAWDEX PIs: A. Schäfler, G. Craig, H. Wernli, J. Methven, G. Rivière

Background

- High-impact weather forecasts often are sensitive to the initial state (Zhang et al. 2003) with warm conveyor belts (WCBs) (Wernli et al 2002) and atmospheric rivers (ARs) (Ralph et al. 2019) acting as predictability barriers (Berman & Torn 2019)
- Waveguide disturbances, such as extratropical transition (ET) of TCs, initiate Rossby wave packets (Keller et al. 2019), with diabatic processes acting as 'seeds' that impact downstream weather (Grams & Blumer 2015) & predictability
- 2016 Field Programs: NAWDEX (EU HALO GV) (Schäfler et al. 2018); SHOUT (NASA Global Hawk)
- How do warm conveyor belts influence the predictability of downstream high-impact weather?

Schäfler et al. (2018) PV at 325K (PV > 2 PVU), Wind Speed (gray), and MSLP (blue)



- Ex-TS Karl (observed in *NAWDEX* and *SHOUT*) strongly re-intensified after ET and featured WCBs, strong moisture transport ("Walpurga") and high-impact event (Scandinavia)
- NRL COAMPS® mesoscale model and moist adjoint system
  - Adjoint Sensitivity of response function (*J*) at time t_n to the state at time t_0:

$$\frac{\partial J}{\partial \mathbf{x}(t_0)} = \mathbf{M}^T \frac{\partial J}{\partial \mathbf{x}(t_n)}$$

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Extratropical Transition Sensitivity

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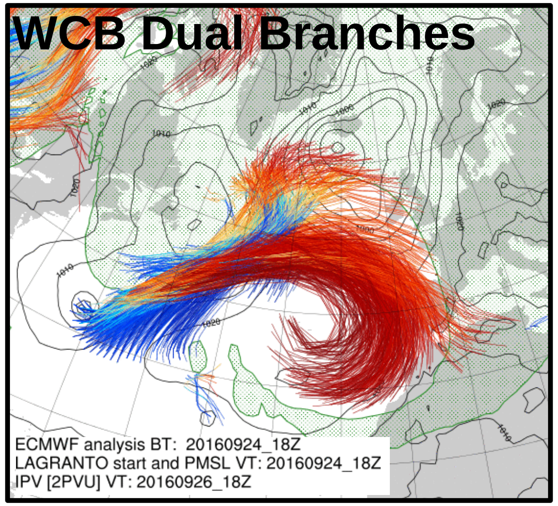
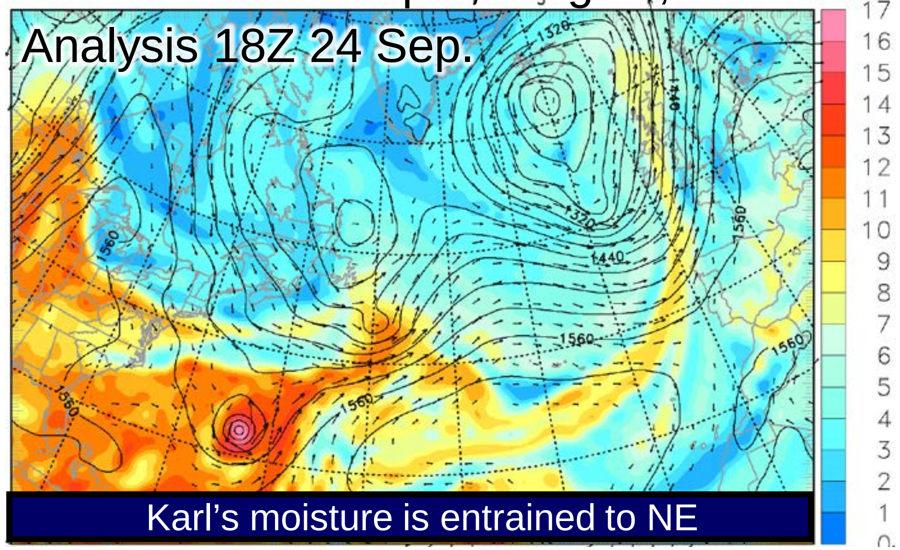
Ex-Karl ET

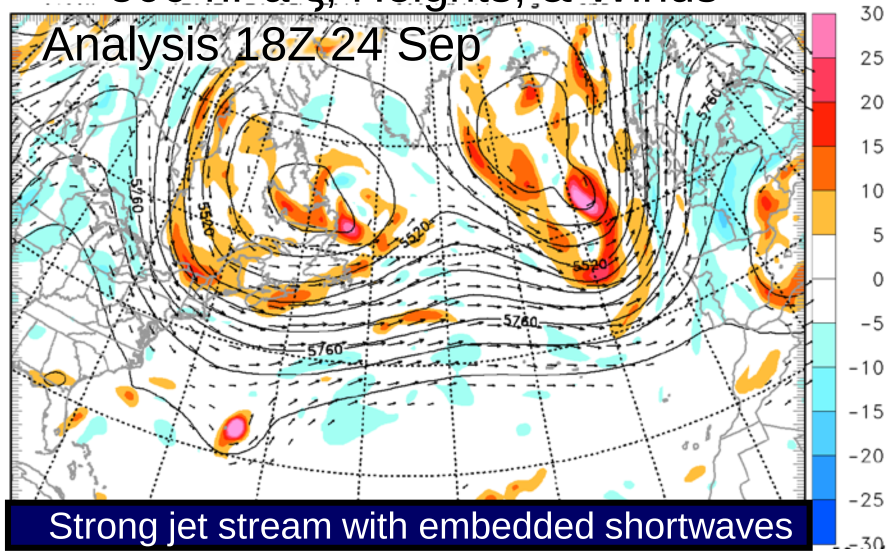
- Ex-TS Karl (observed in *NAWDEX* and *SHOUT*) recurved to NE and strongly intensified during ET
- WCB with 2 branches
- Integrated vapor transport (IVT) used as response function (RF) and RF box placed over LLJ & IVT max



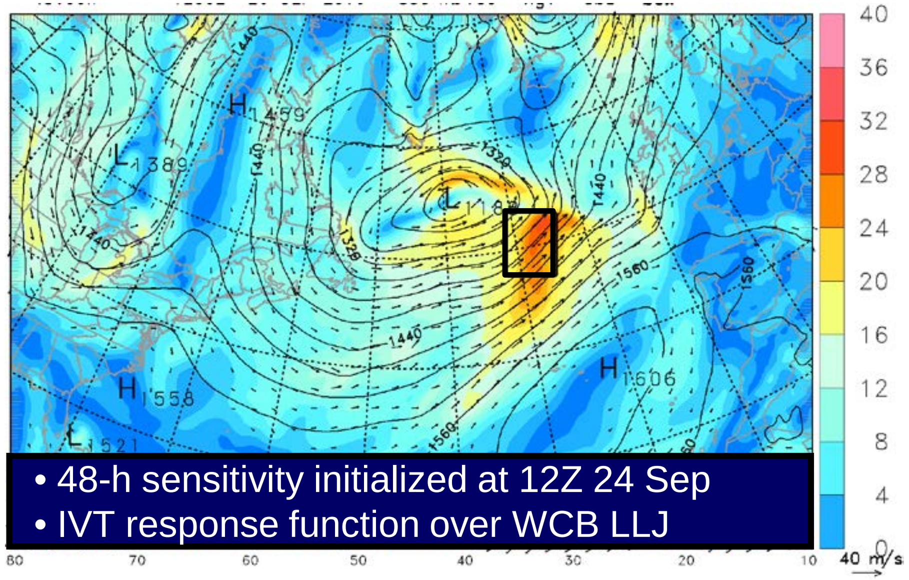
850-hPa Water Vapor, Heights, & Winds



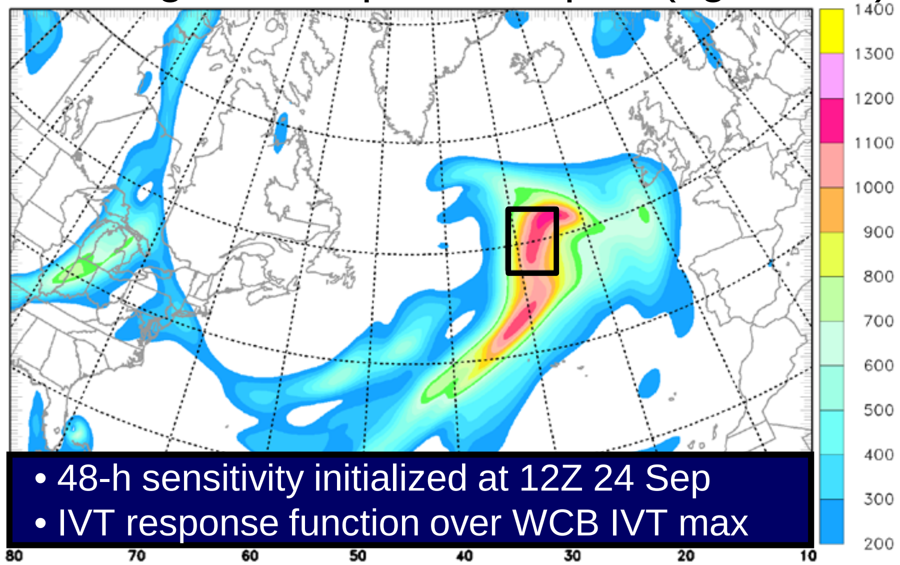
500-hPa ζ, Heights, & Winds



COAMPS 48-h 850-hPa Heights & Winds



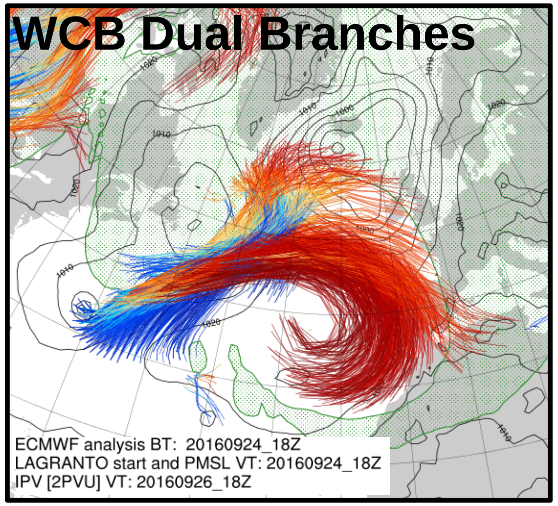
48-h Integrated Vapor Transport (kg m^{-1} s^{-1})



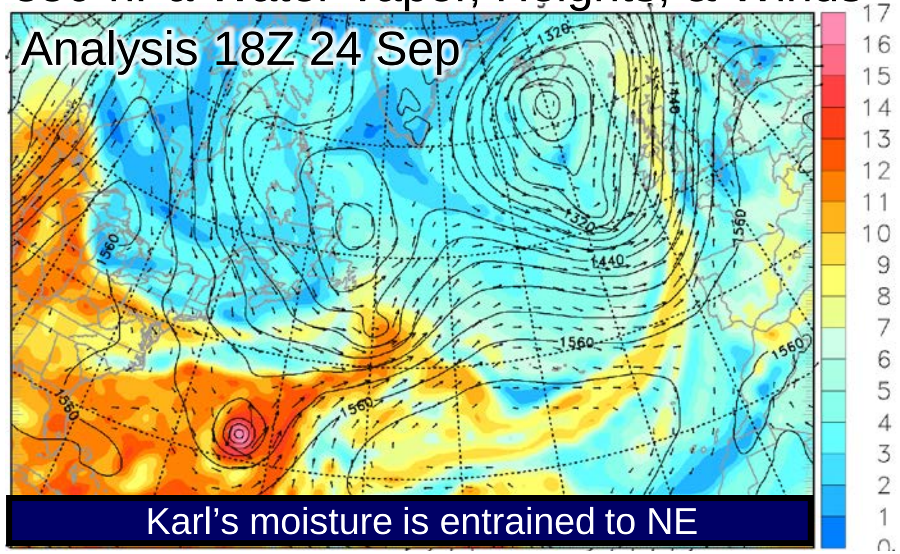
Extratropical Transition Sensitivity

WCB/ET Sensitivity (48h)

- WCB (IVT) sensitivity to moisture NE of Karl and along a corridor to the NE prior to ET
- Sensitivity of IVT to relative vorticity is located in the upstream trough and east of Karl

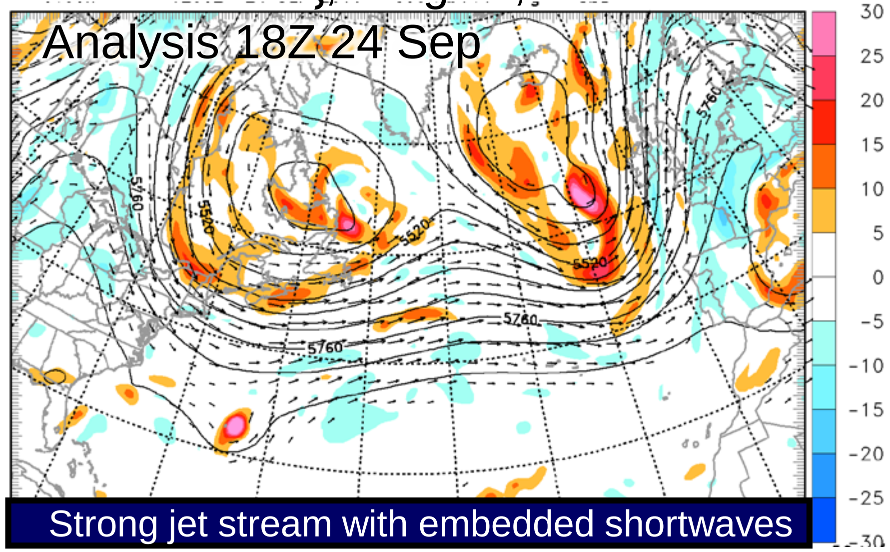


850-hPa Water Vapor, Heights, & Winds



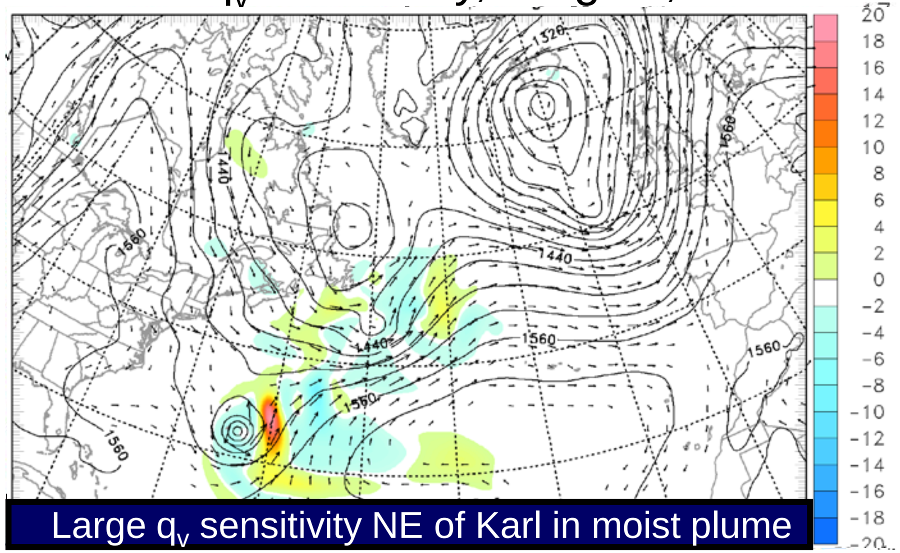
Karl's moisture is entrained to NE

500-hPa ζ, Heights, & Winds

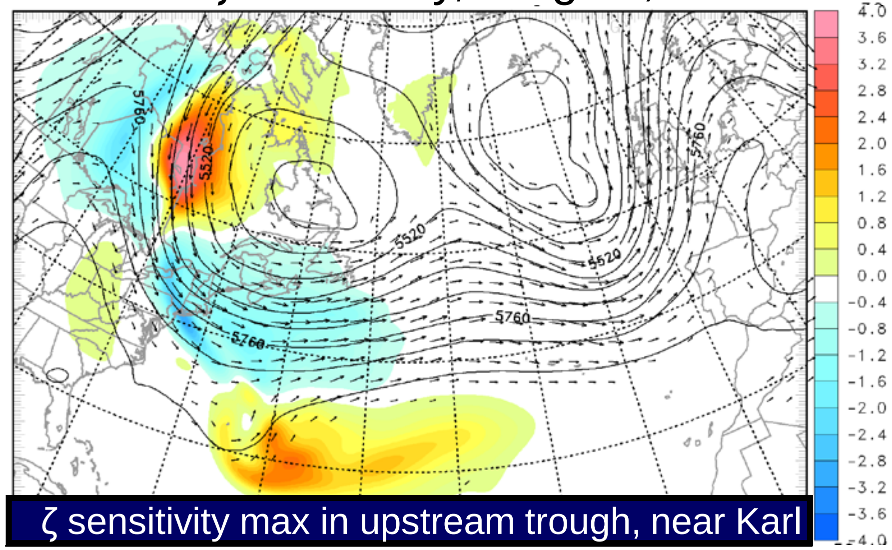


Strong jet stream with embedded shortwaves

850-hPa q_v Sensitivity, Heights, & Winds


Large q_v sensitivity NE of Karl in moist plume

500-hPa ζ Sensitivity, Heights, & Winds


ζ sensitivity max in upstream trough, near Karl

Extratropical Transition Sensitivity

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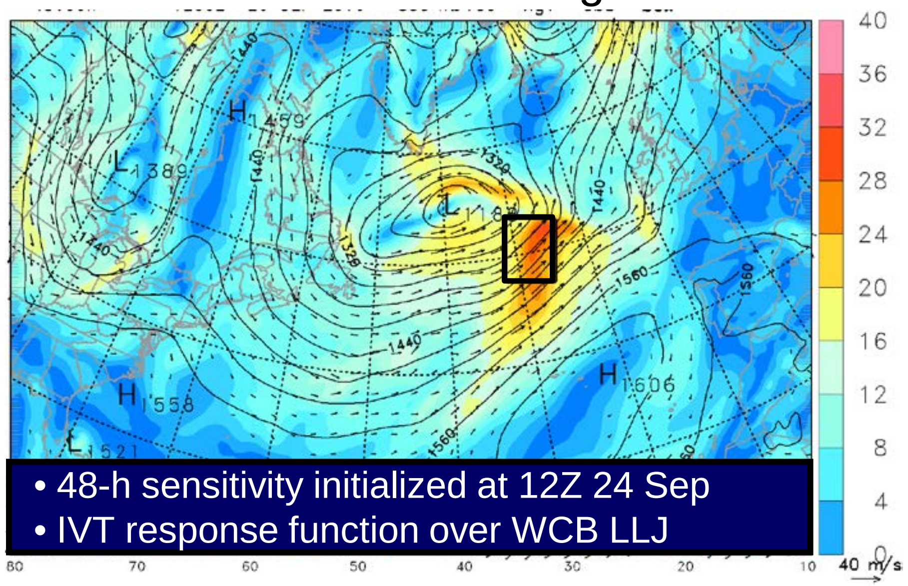
Adjoint Perturbations

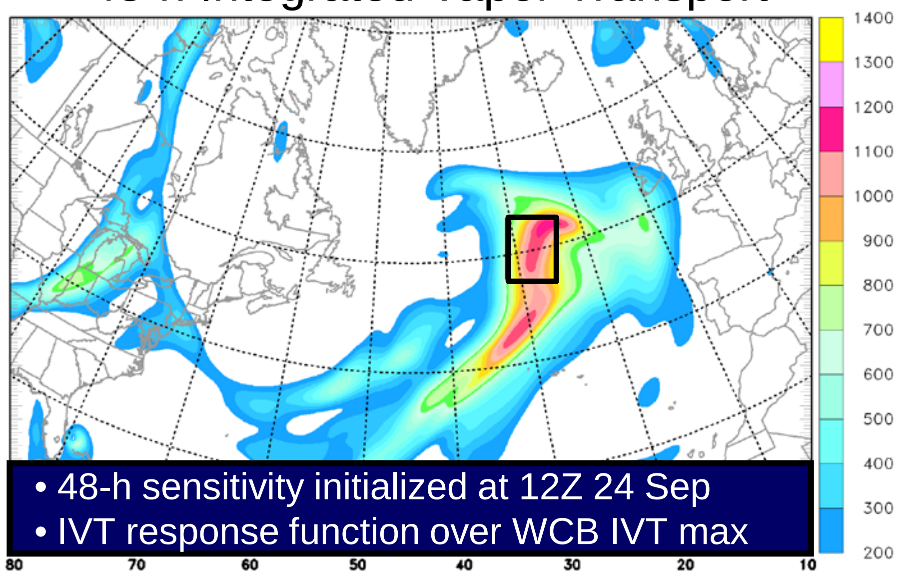
- Optimal perturbations derived from sensitivity
- Perturbations introduced in NL and TL models
- Strengthen WCB by 20 ms^{-1} & increases IVT by 500 kg $m^{-1}s^{-1}$
- Perturbations increase the WCB outflow; irrotational winds increase by >50% (9 to 15 m s^{-1})
- Enhances diabatic heating in WCB
- Enhances downstream ridge building

COAMPS 48-h 850-hPa Heights & Winds



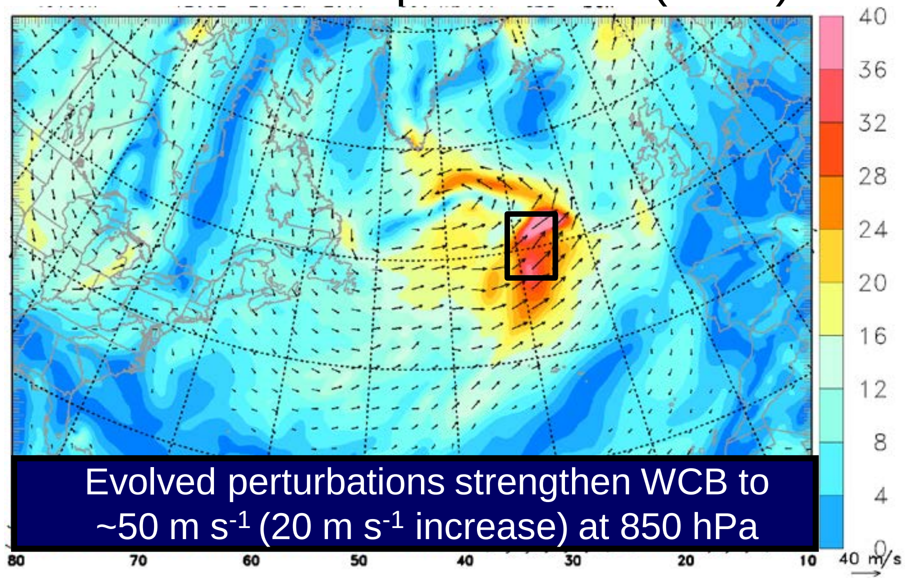
- 48-h sensitivity initialized at 12Z 24 Sep
- IVT response function over WCB LLJ

48-h Integrated Vapor Transport



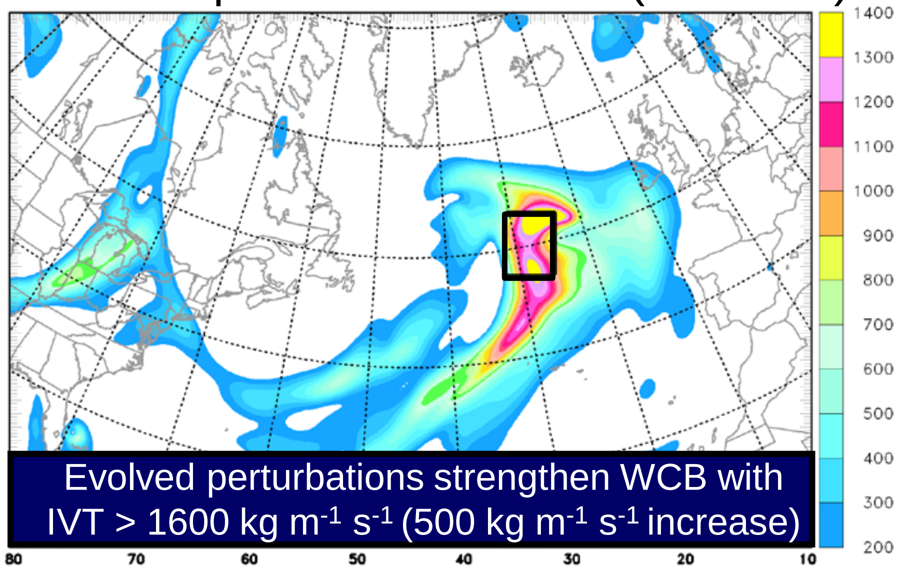
- 48-h sensitivity initialized at 12Z 24 Sep
- IVT response function over WCB IVT max

48-h 850-hPa Optimal Pert. (U'+U)



Evolved perturbations strengthen WCB to ~50 m s^{-1} (20 m s^{-1} increase) at 850 hPa

48-h IVT Optimal Perturbation (IVT+IVT')



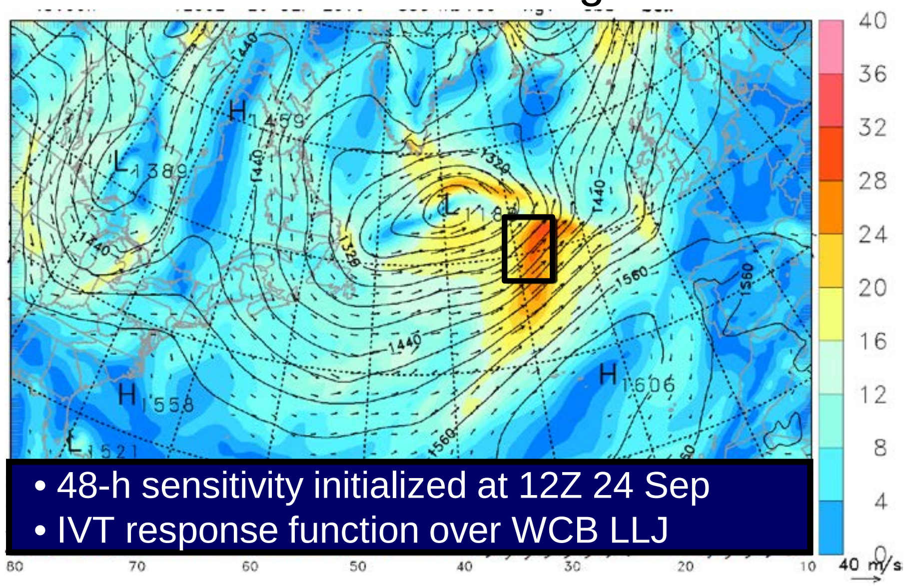
Evolved perturbations strengthen WCB with IVT > 1600 kg m^{-1} s^{-1} (500 kg m^{-1} s^{-1} increase)

Extratropical Transition Sensitivity

Adjoint Perturbations

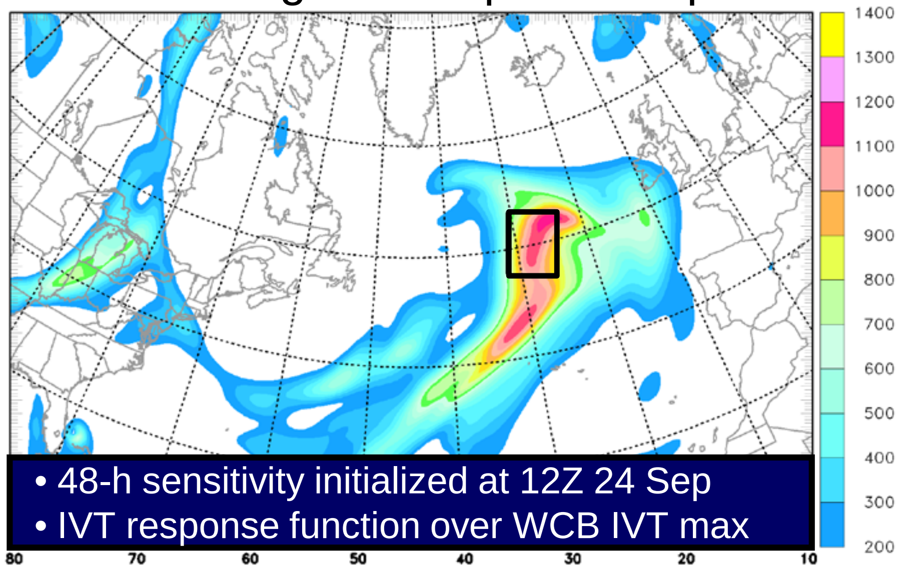
- Moist perturbations only increase winds in WCB by 11 m s^{-1} to 41 m s^{-1}
- Still enhances diabatic heating in WCB
- WCB acts as “valve”, regulating energy and error transport downstream

COAMPS 48-h 850-hPa Heights & Winds



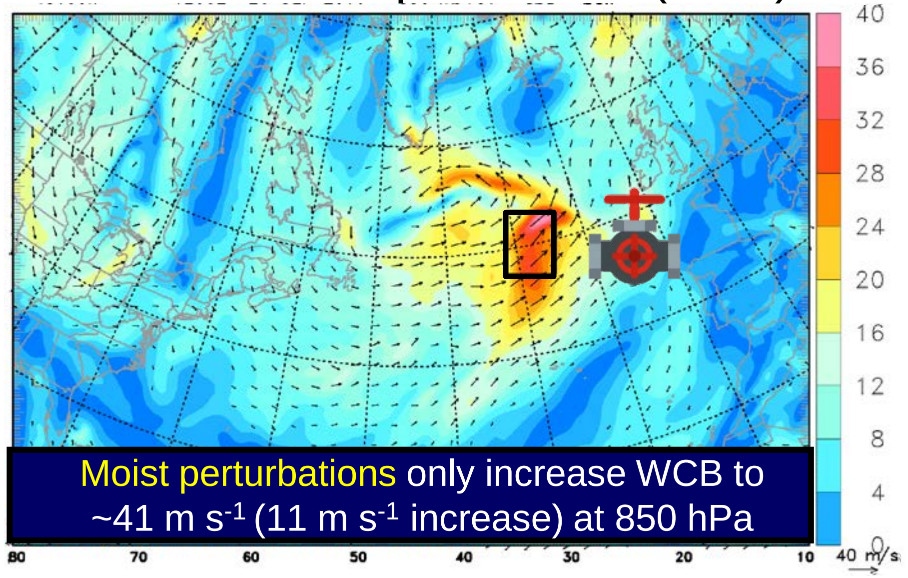
- 48-h sensitivity initialized at 12Z 24 Sep
- IVT response function over WCB LLJ

48-h Integrated Vapor Transport



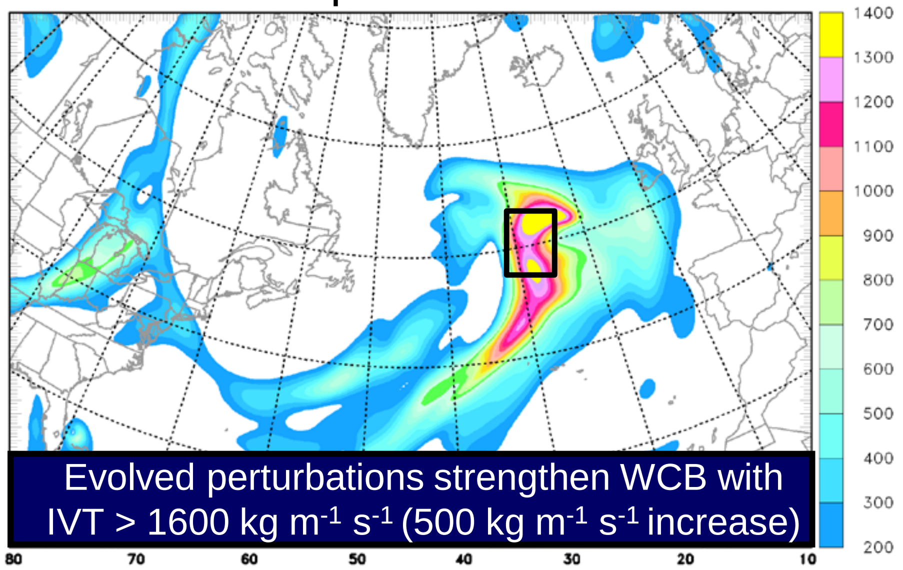
- 48-h sensitivity initialized at 12Z 24 Sep
- IVT response function over WCB IVT max

48-h 850-hPa Optimal Pert. (U’+U)



Moist perturbations only increase WCB to ~41 m s^{-1} (11 m s^{-1} increase) at 850 hPa

48-h IVT Optimal Perturbation

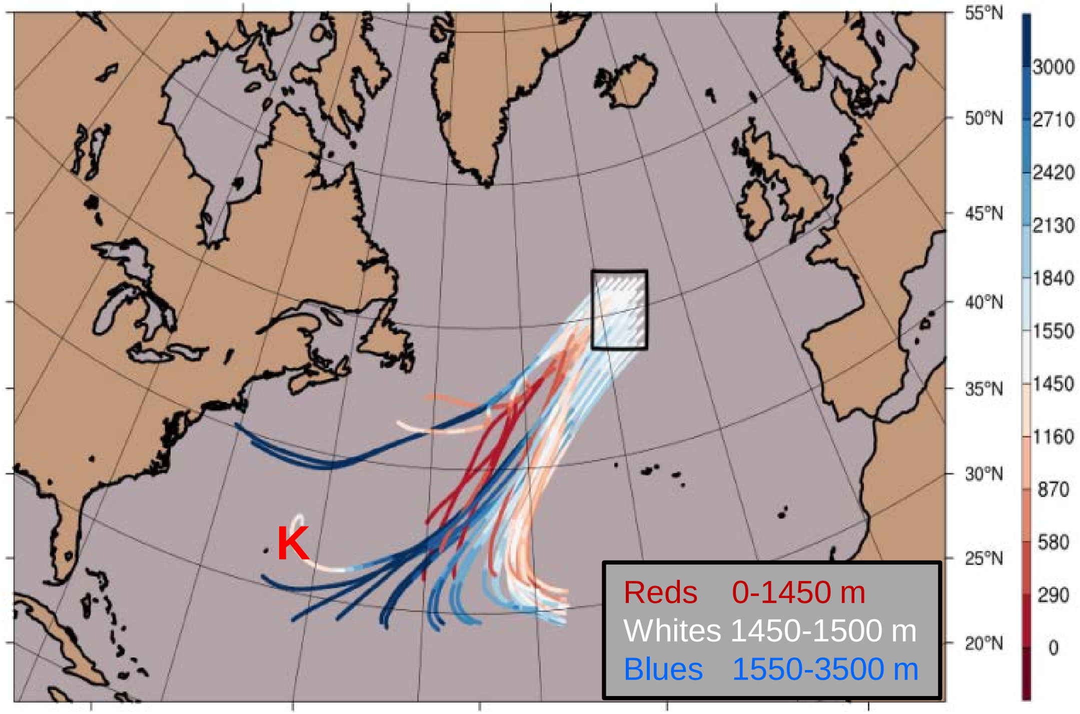


Evolved perturbations strengthen WCB with IVT > 1600 kg m^{-1} s^{-1} (500 kg m^{-1} s^{-1} increase)

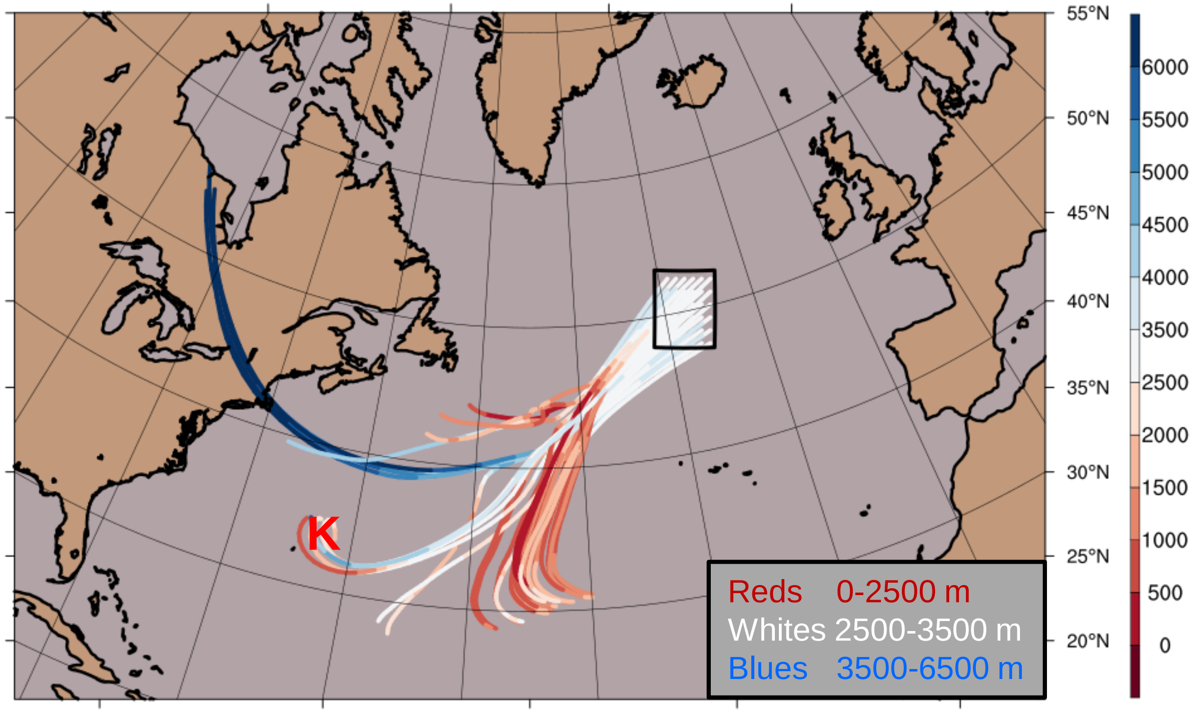
Trajectory Analysis

48-h back trajectories (LAGRANTO) Initialized in WCB (RF Box)

850 h Pa



700 h Pa

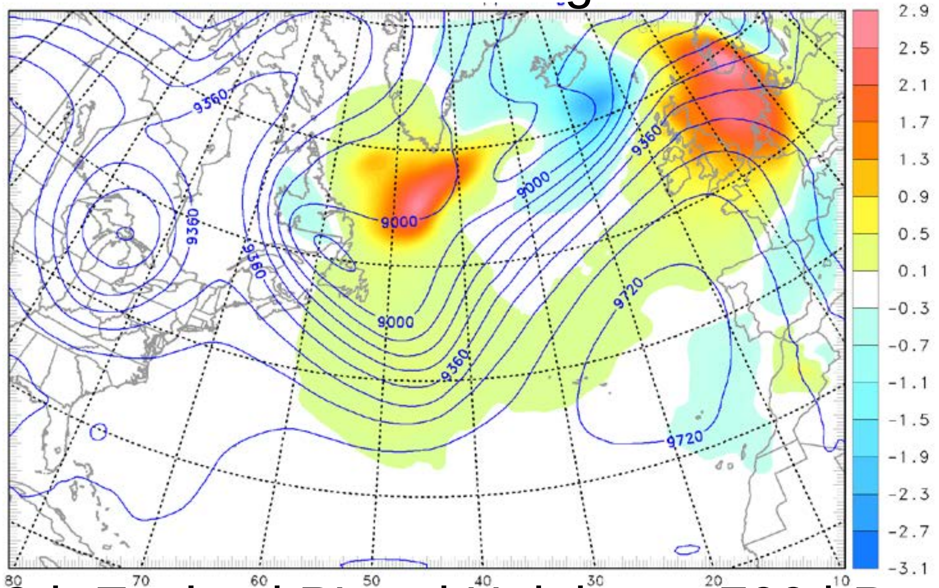


- Low-level trajectories originate in the sub-tropics, and only a few near Karl (unlike moisture sensitivity)
- Sensitivity is broadly similar to trajectory sources, however sensitivity propagates at group speeds
- Not all trajectories are of equal importance for the predictability

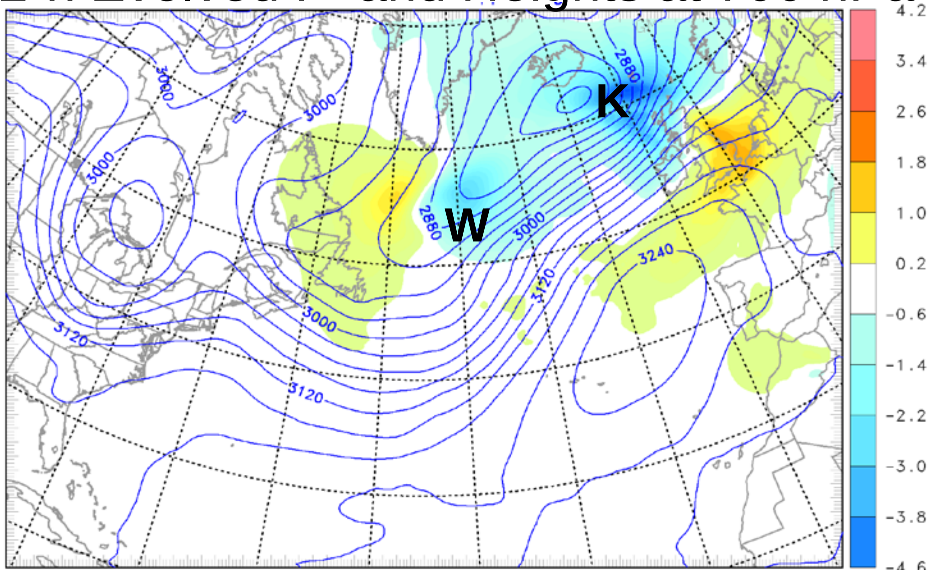
<u>LAGRANTO</u>: Michael Sprenger and Heini Wernli (ETH)

Downstream Impact of Perturbations

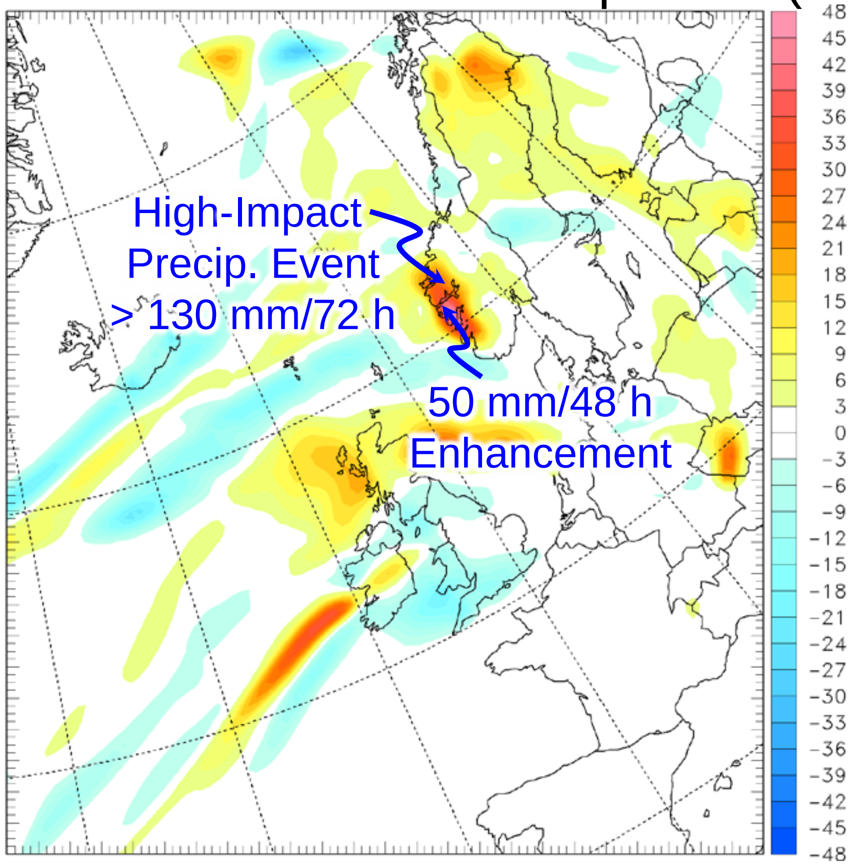
72-h Evolved P' and Heights at 300 hPa



72-h Evolved P' and Heights at 700 hPa



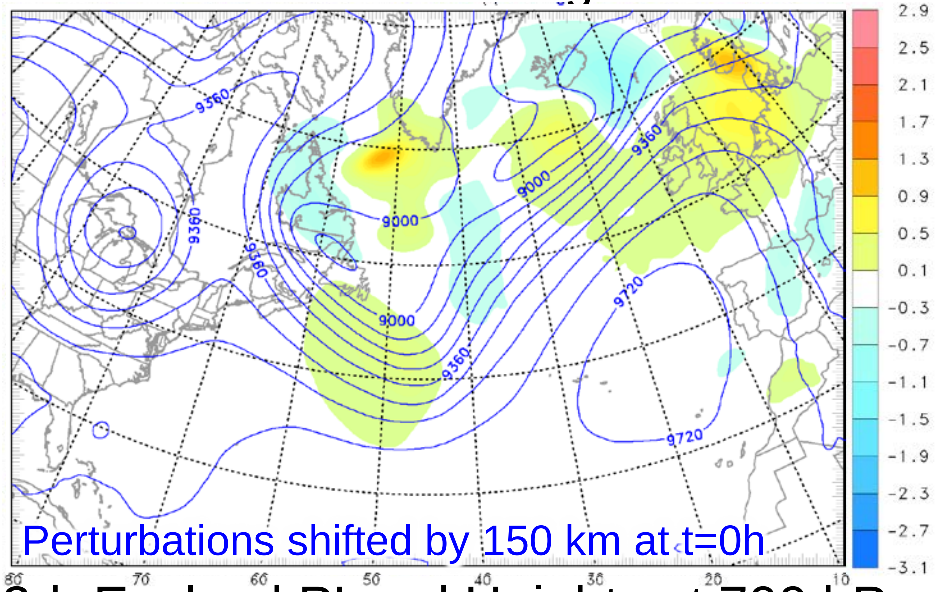
60-108-h Perturbation Precipitation (mm)



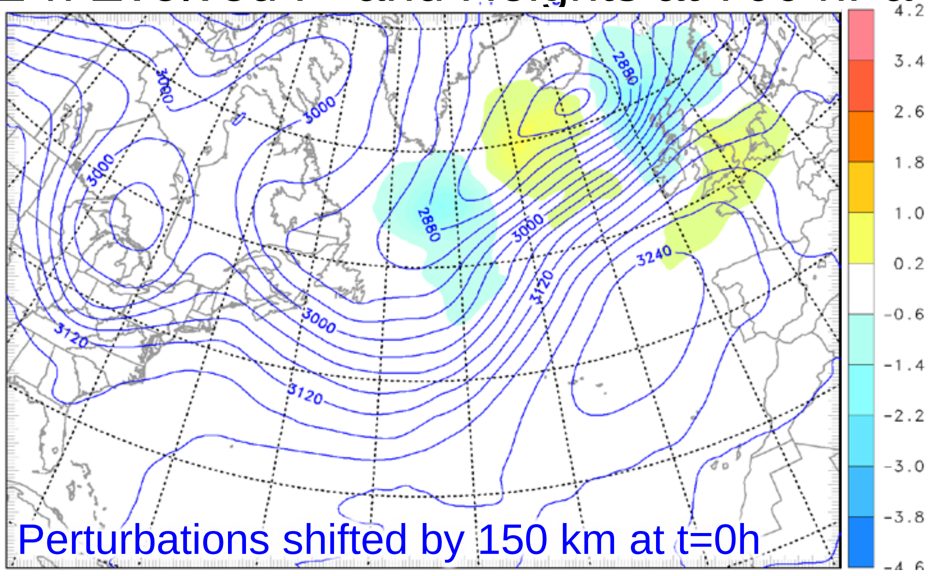
- 72-h evolved pressure perturbations (+24 h adjoint time) show ridge building downstream over NW Europe and enhancement of ex-Karl and Walpurga troughs at 700 hPa
- 48-h accumulated precipitation max (+108 h adjoint time) enhances high-impact precipitation event along Nor. coast
- Connects moisture sensitivity in Karl to high-impact event!

Downstream Impact of Perturbations

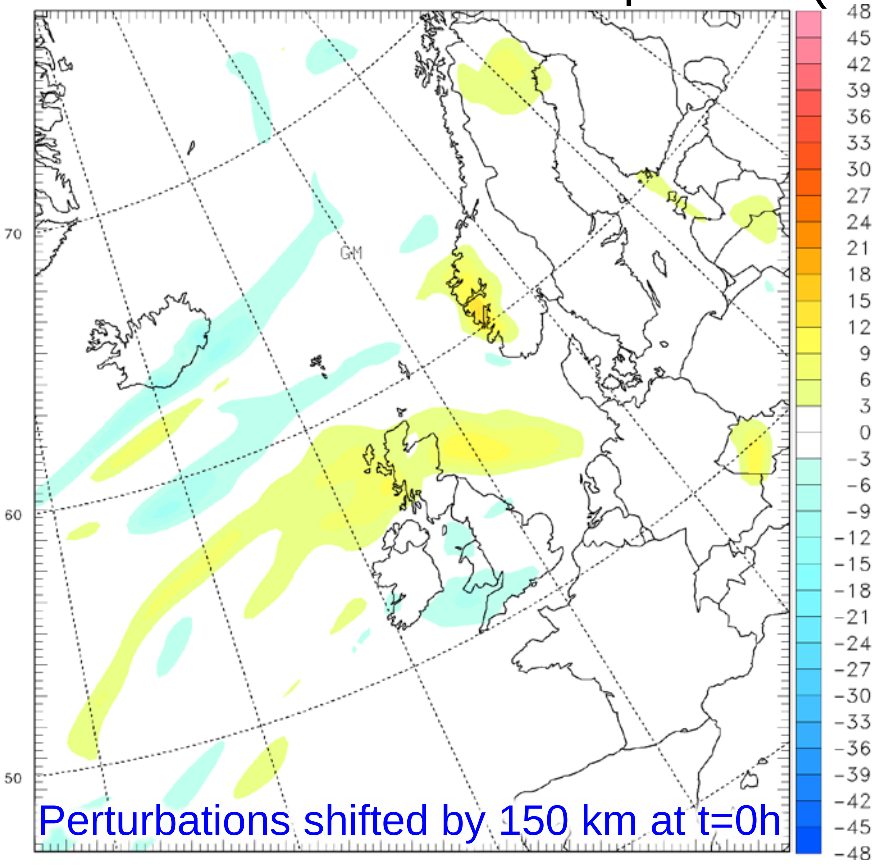
72-h Evolved P' and Heights at 300 hPa



72-h Evolved P' and Heights at 700 hPa



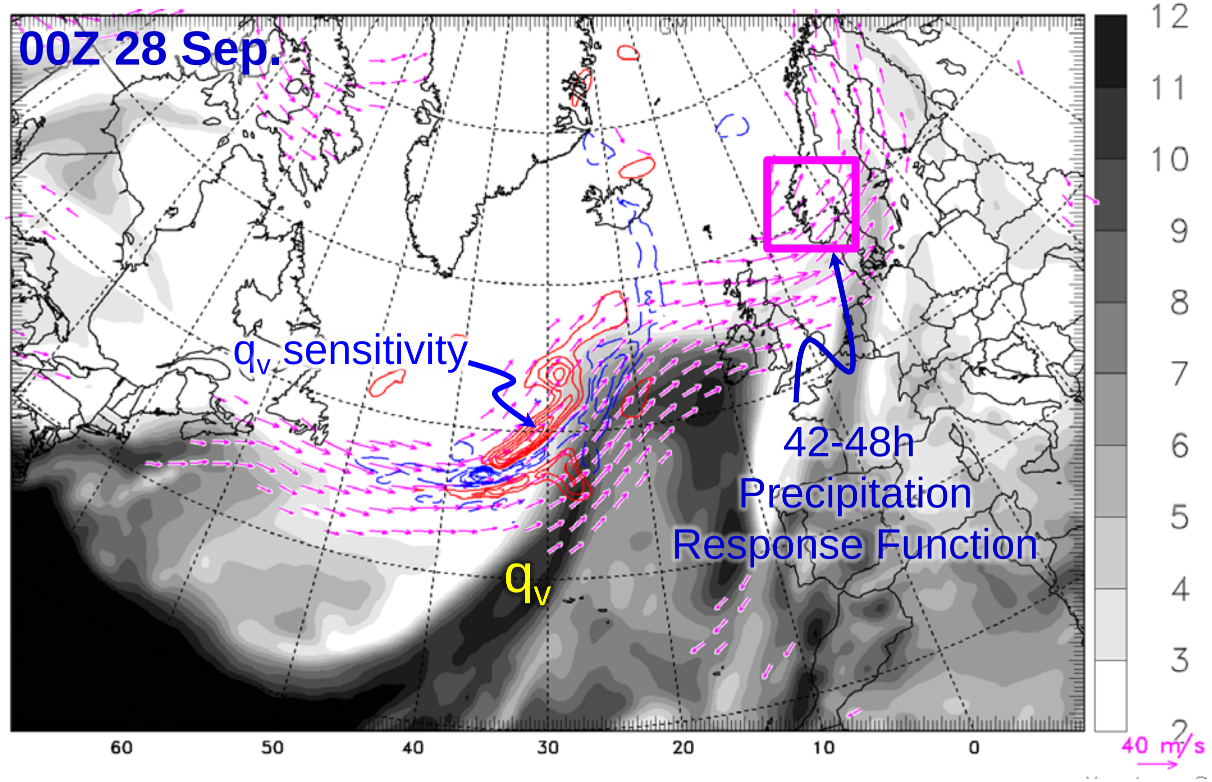
60-108-h Perturbation Precipitation (mm)



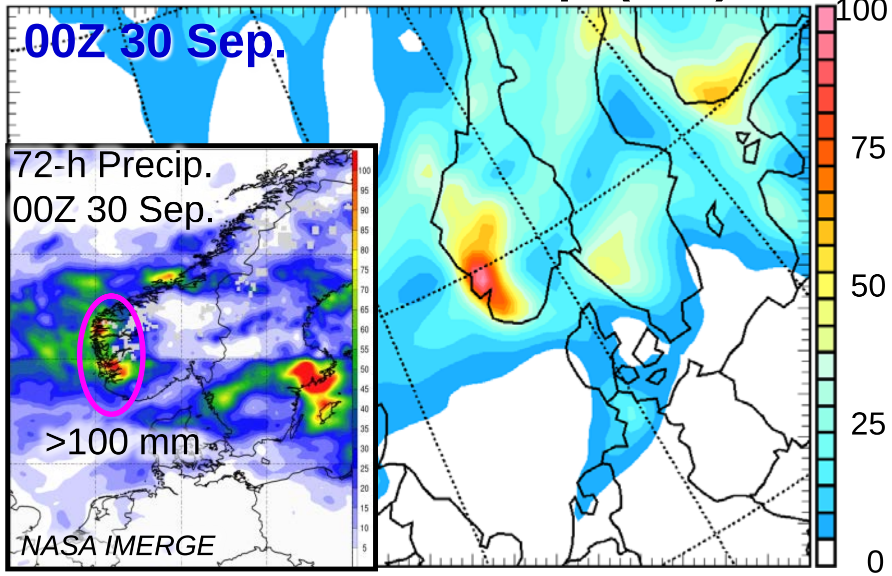
72-h evolved pressure perturbations (+24 h adjoint time) using sub-optimal perturbations show considerably smaller downstream impact (partially closing the valve)

Moisture Transport Cyclone (Walpurga)

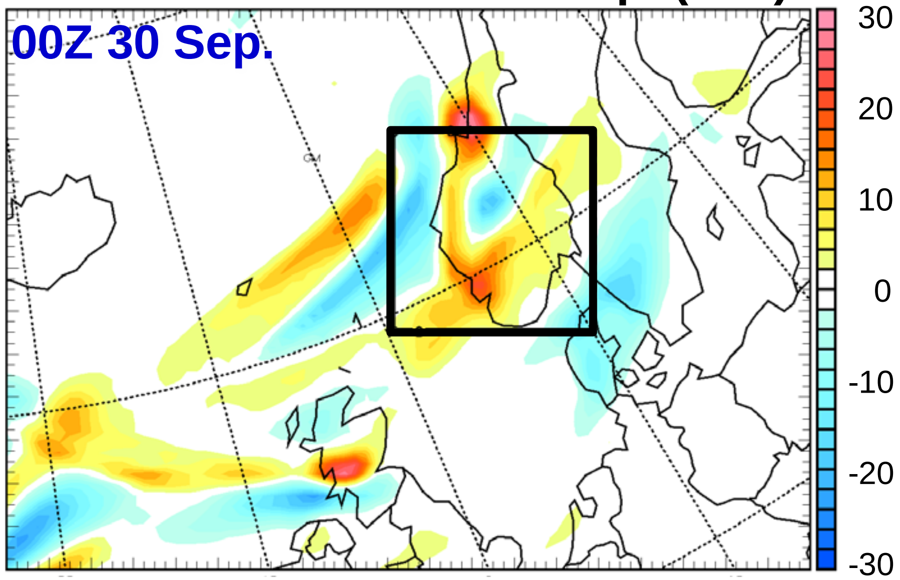
300K q_v (gray); SLP; Winds; 48-h q_v and θ Sensitivity



Nonlinear 48-h Precip. (mm)



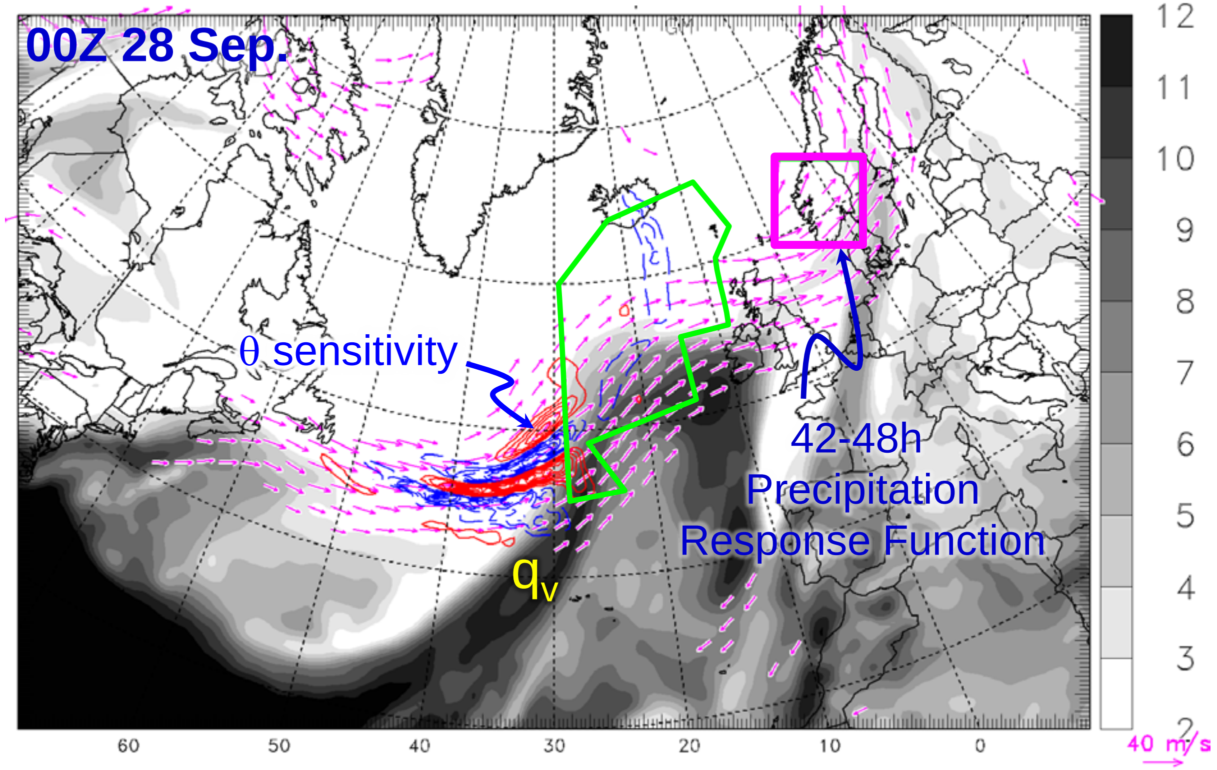
42-48h Perturbation Precip. (mm)



- Sensitivity maxima of q_v and θ in *WCB inflow* near edges (horizontal & vertical) of *moisture gradients*
- Sensitivity to diabatic heating along the WCB
- Over 100 mm/72-h over precipitation over Norway; Optimal perturbations increase precip. >25 mm/6h

Moisture Transport Cyclone (Walpurga)

300K q_v (gray); SLP; Winds; 48-h q_v and θ Sensitivity



- Sensitivity maxima of q_v and θ in *WCB inflow* near edges (horizontal & vertical) of *moisture gradients*
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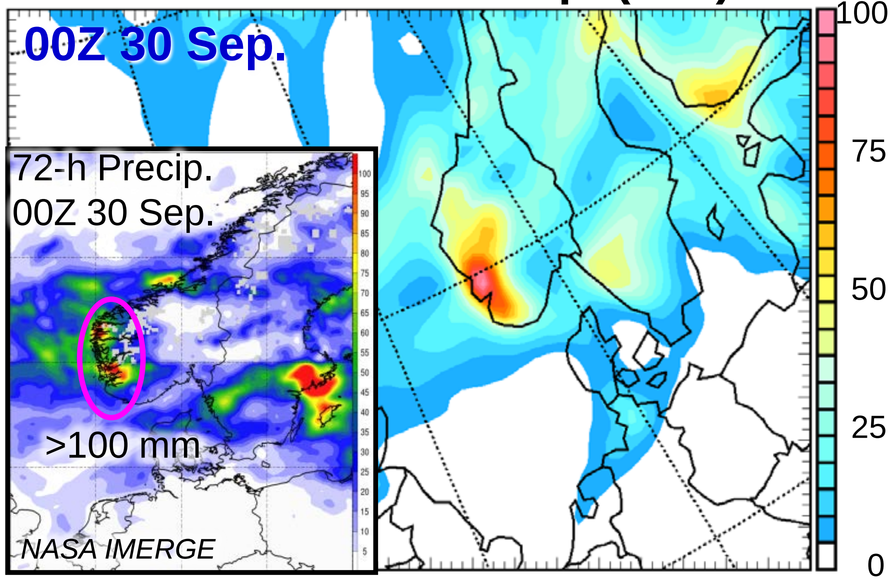
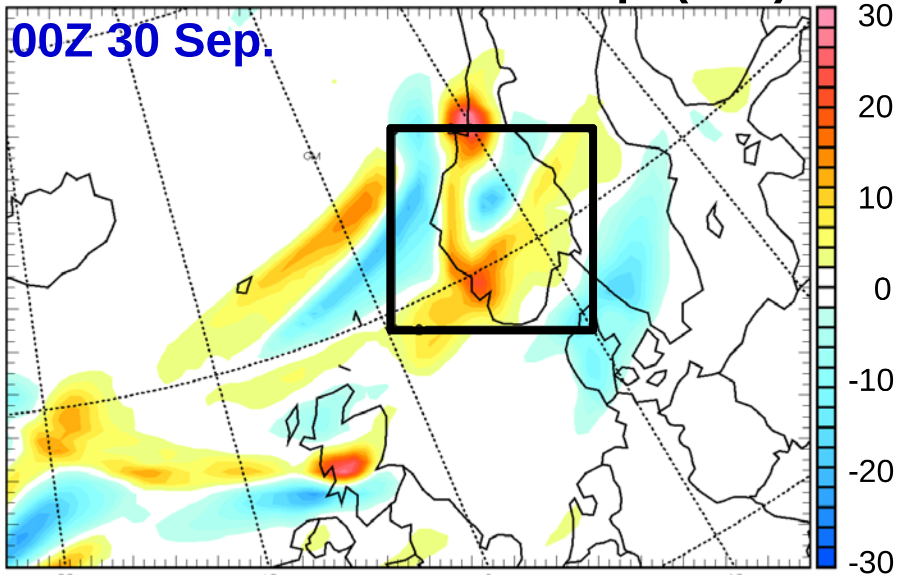
Nonlinear 48-h Precip. (mm)

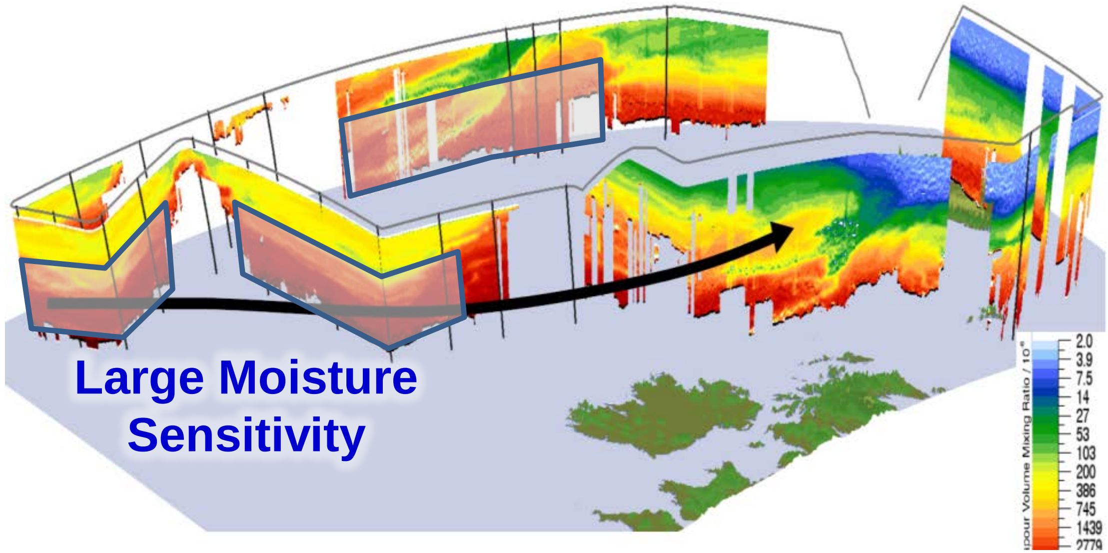


42-48h Perturbation Precip. (mm)

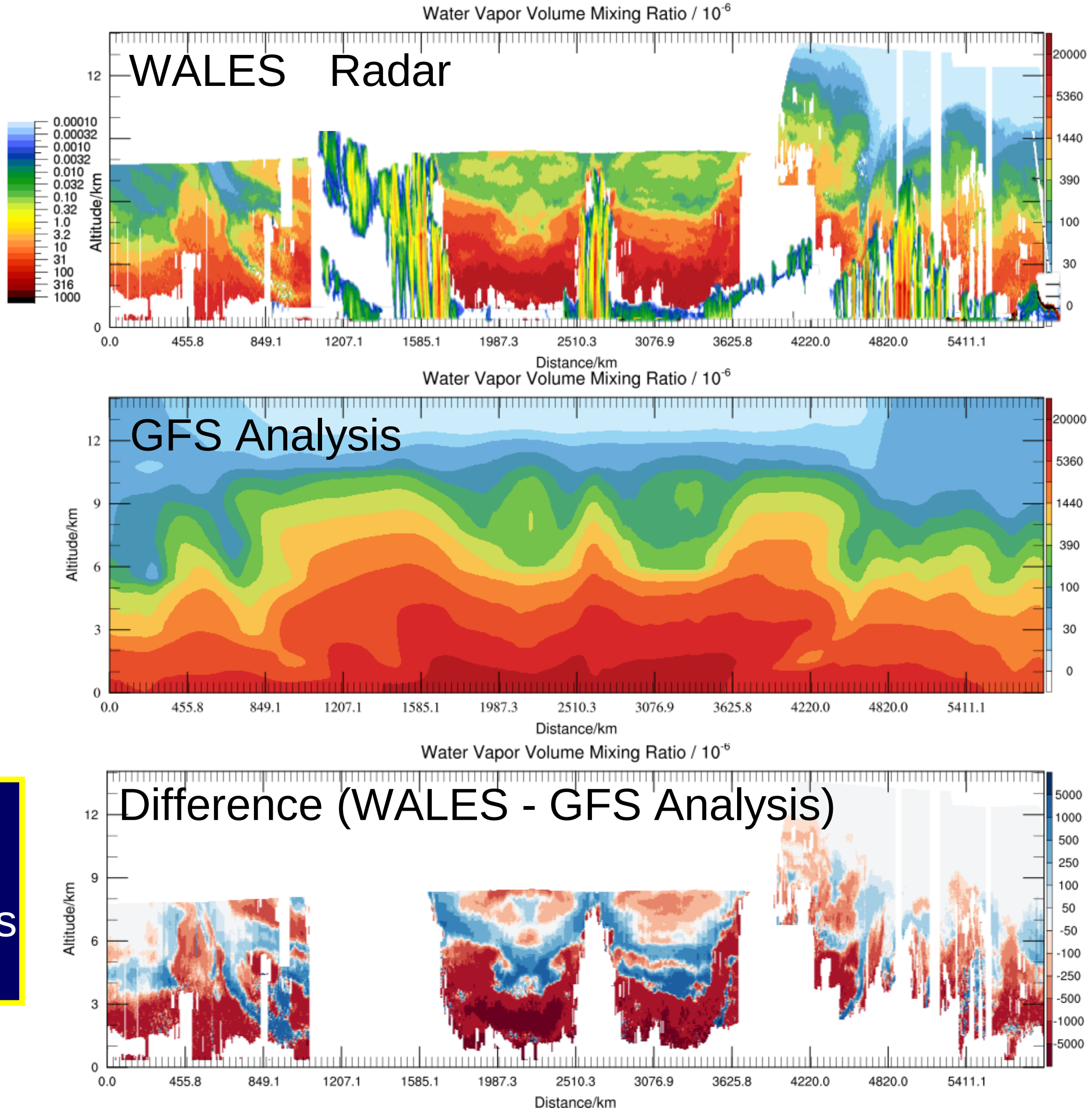


Moisture Transport: WALES Lidar

HALO WALES Lidar Water Vapor Volume Mixing Ratio (10^3 g kg^{-1})



Martin Wirth (DLR)

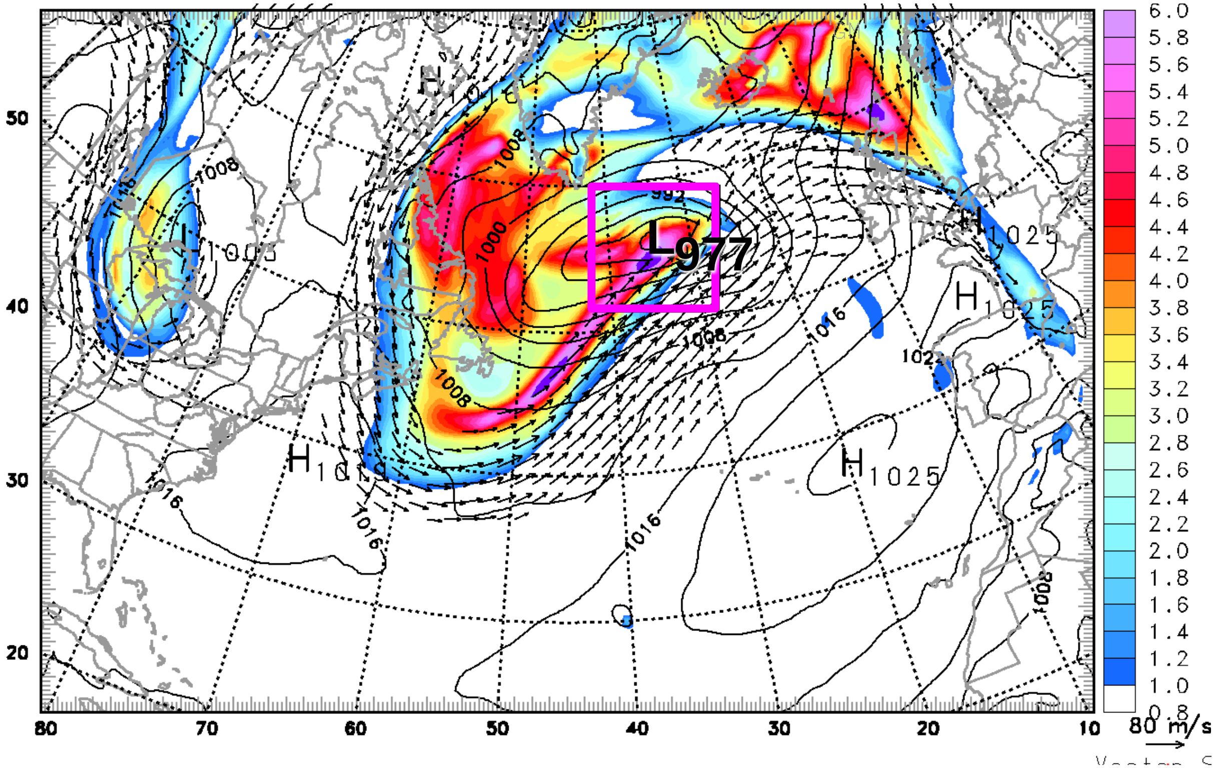


- DLR WALES Lidar measured deep moisture and fine-scale water vapor structure in AR and WCB
- Large differences in structure between the observations and GFS analysis in sensitive regions

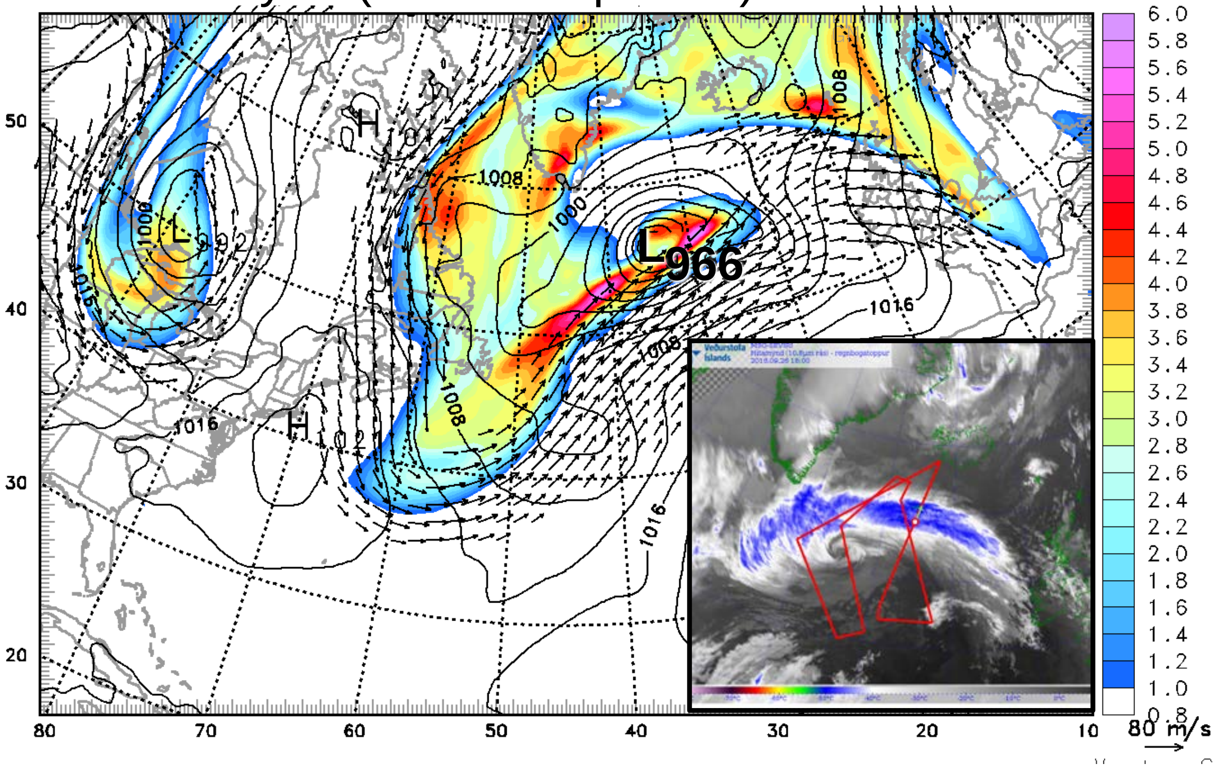
Forecast Error Sensitivity

1. PV Rollup During Rapid Intensification of Ex-Karl

325K PV and Winds; sea level pressure
48-h Forecast (18Z 26 Sep 2016)



325K PV and Winds; sea level pressure
GFS Analysis (18Z 26 Sep 2016)



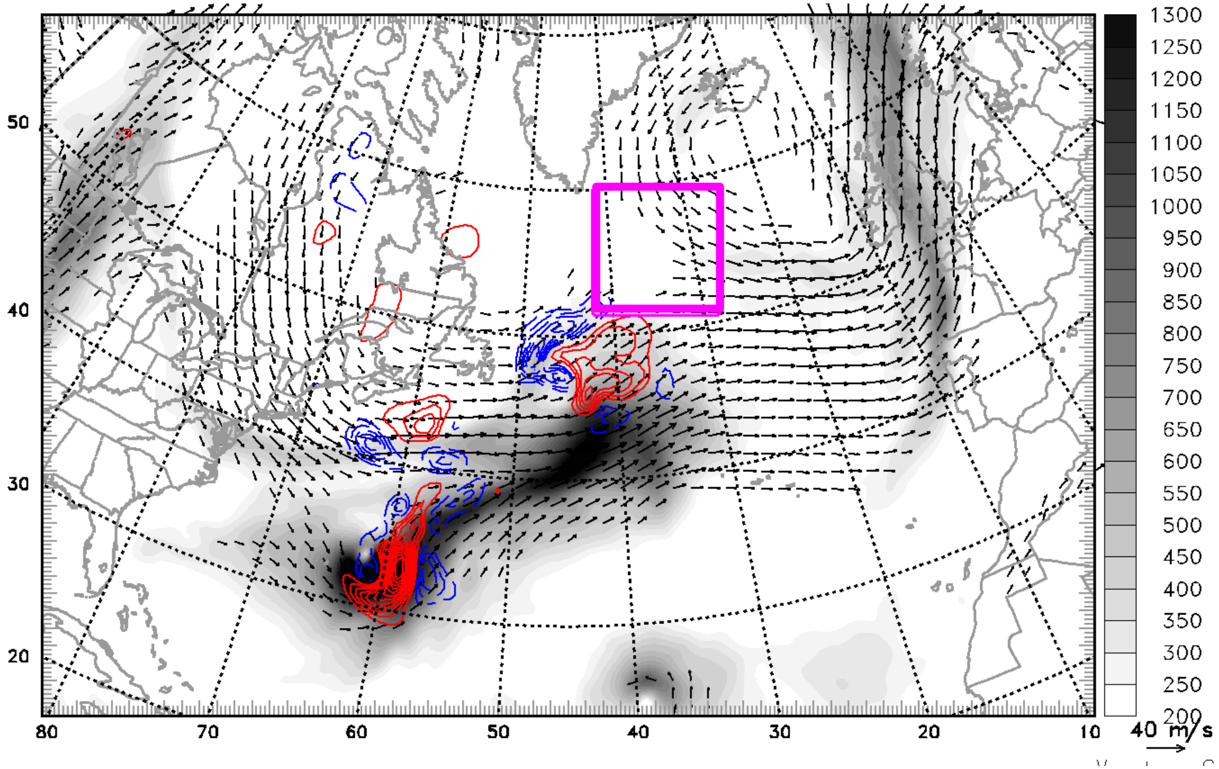
- Response function is the *Forecast Error* of the 6-10 km PV aloft over ex-Karl near the PV "roll up"
- PV forecast errors: PV filament lacks a maximum to east of cyclone; too weak of a PV "clear slot"
- SLP forecast errors: Central pressure is 11 hPa too shallow; "inner core" of cyclone is much weaker

Acknowledgements: Marlene Baumgart and Michael Riemer

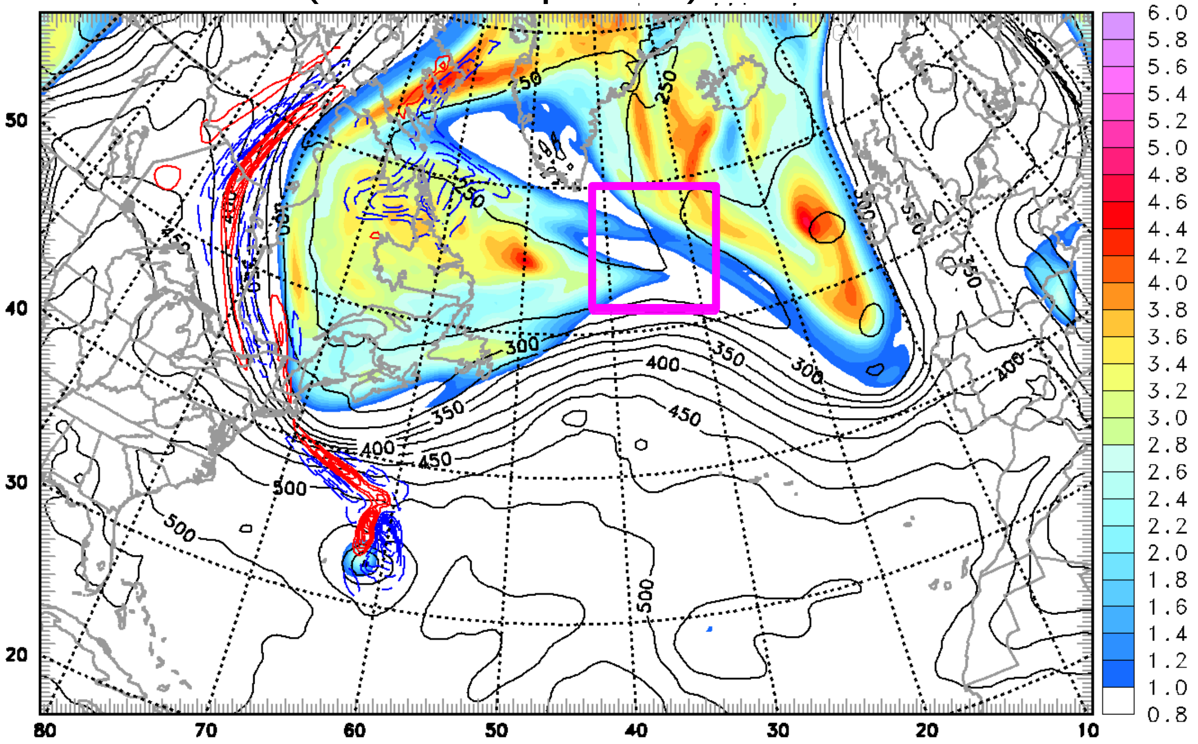
Forecast Error Sensitivity

1. PV Rollup During Rapid Intensification of Ex-Karl

700-mb IVT (gray); Winds; q_v Sensitivity (blue/red)
Initial State (18Z 24 Sep 2016)



325K PV (color); SLP; PV Adjoint Pert. (blue/red)
Initial State (18Z 24 Sep 2016)

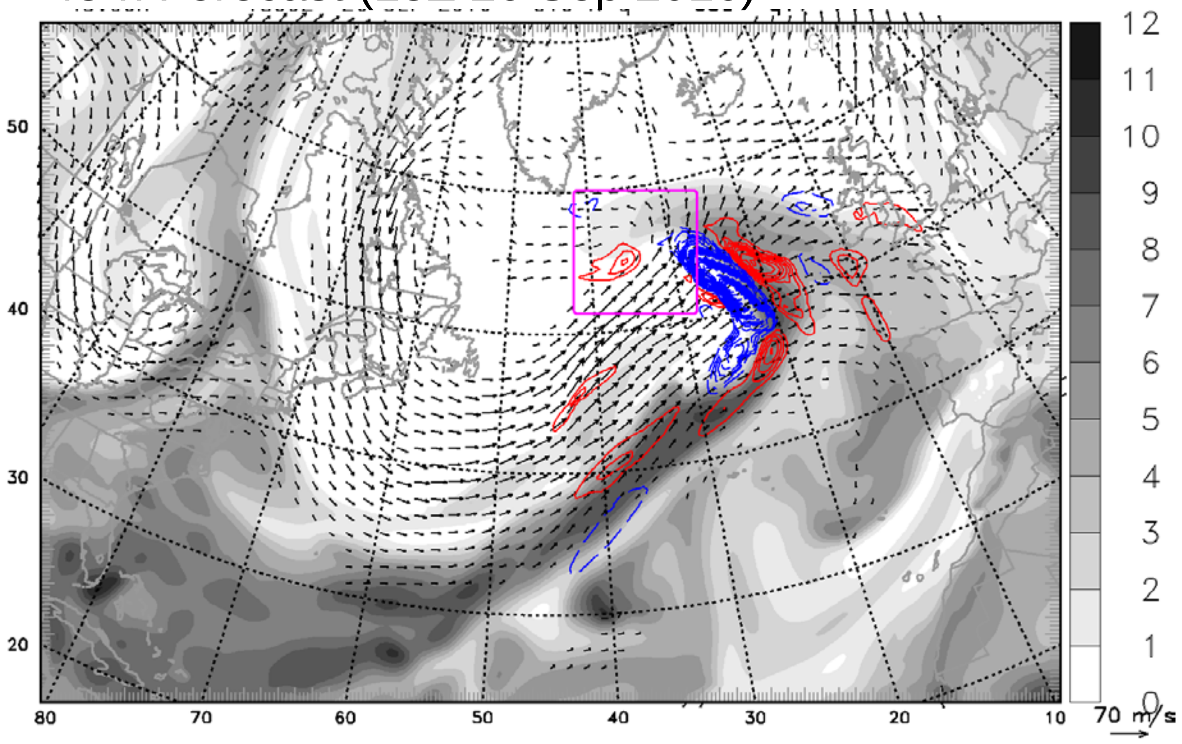


- Water vapor sensitivity (0 h) is maximized to the east of Karl in the WCB inflow along IVT corridor
- Strong 325K PV sensitivity (PV adjoint pert.) extending from Karl to NW curving along the tropopause
- Water vapor errors east of Karl and upstream tropopause PV displacement errors lead to large 48-h forecast errors in the waveguide PV and ex-Karl cyclone intensity

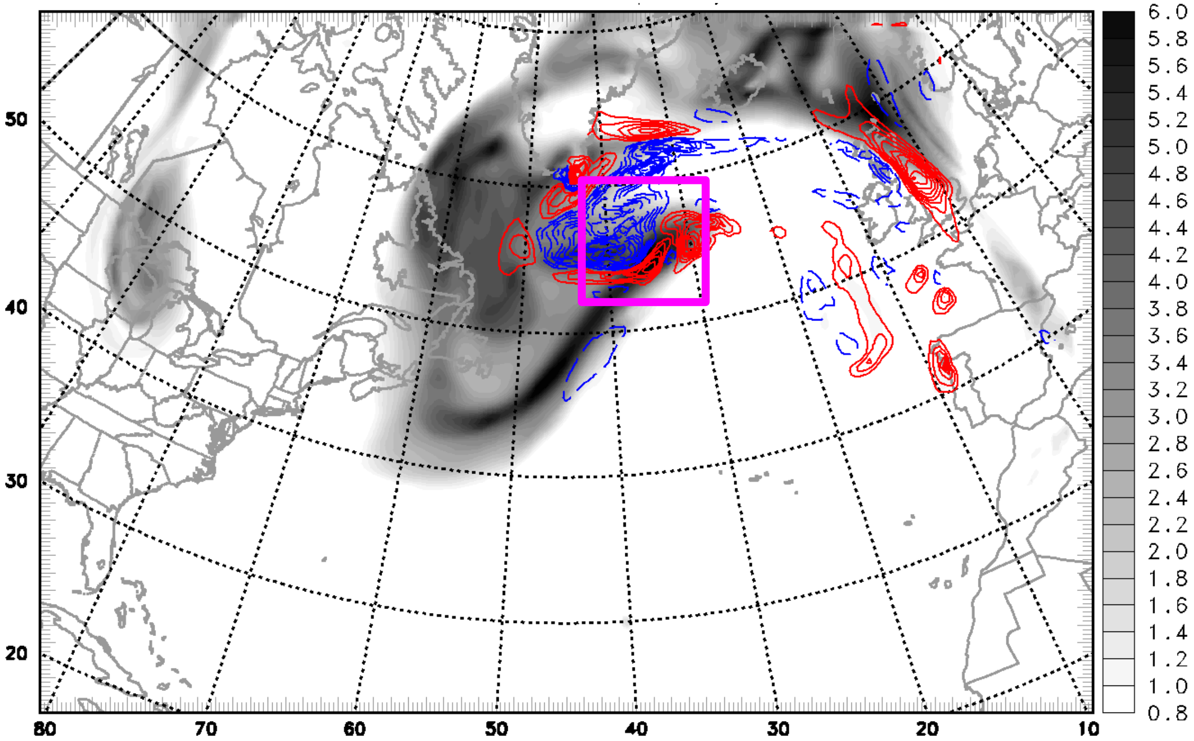
Forecast Error Sensitivity

1. PV Rollup During Rapid Intensification of Ex-Karl

310K q_v (gray); Winds; 310K q_v Perturbation (blue/red)
48-h Forecast (18Z 26 Sep 2016)



325K PV (gray); PV Evolved Perturbation (blue/red)
48-h Forecast (18Z 26 Sep 2016)

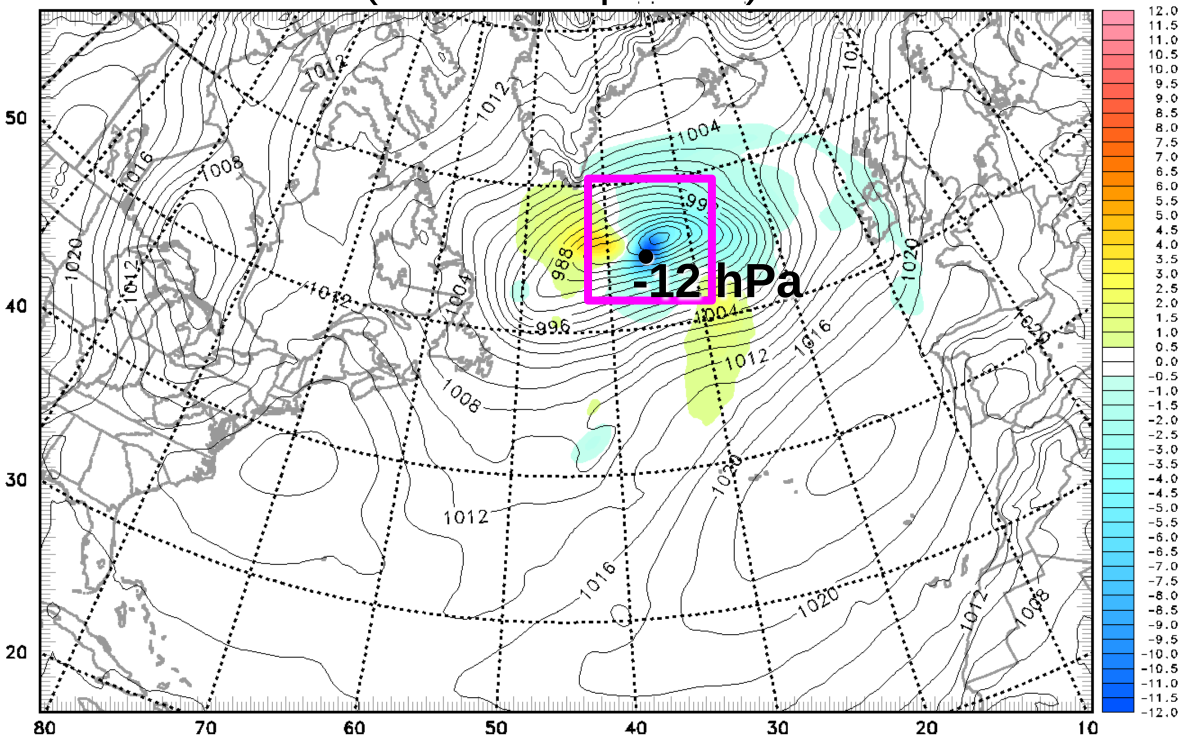


- Evolved adjoint perturbations (48-h) lead to:
  - Redistribution of water vapor in the WCB
  - More intense PV roll-up over ex-Karl and PV clear slot in agrees with the analysis

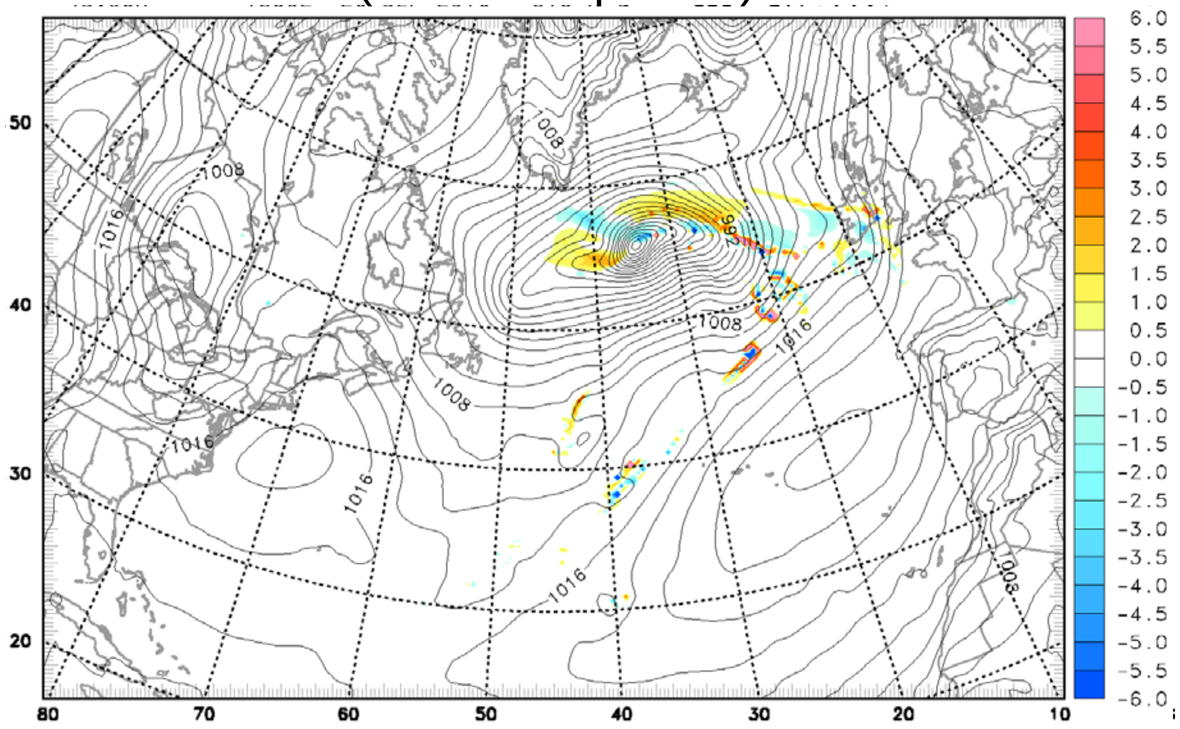
Forecast Error Sensitivity

1. PV Rollup During Rapid Intensification of Ex-Karl

Sea level pressure (contours); Pressure Pert. (blue/red)
48-h Forecast (18Z 26 Sep 2016)



Perturbation Sea Level Pressure; $\dot{Q}$'(K/hr) (fill)
48-h Forecast (18Z 26 Sep 2016)

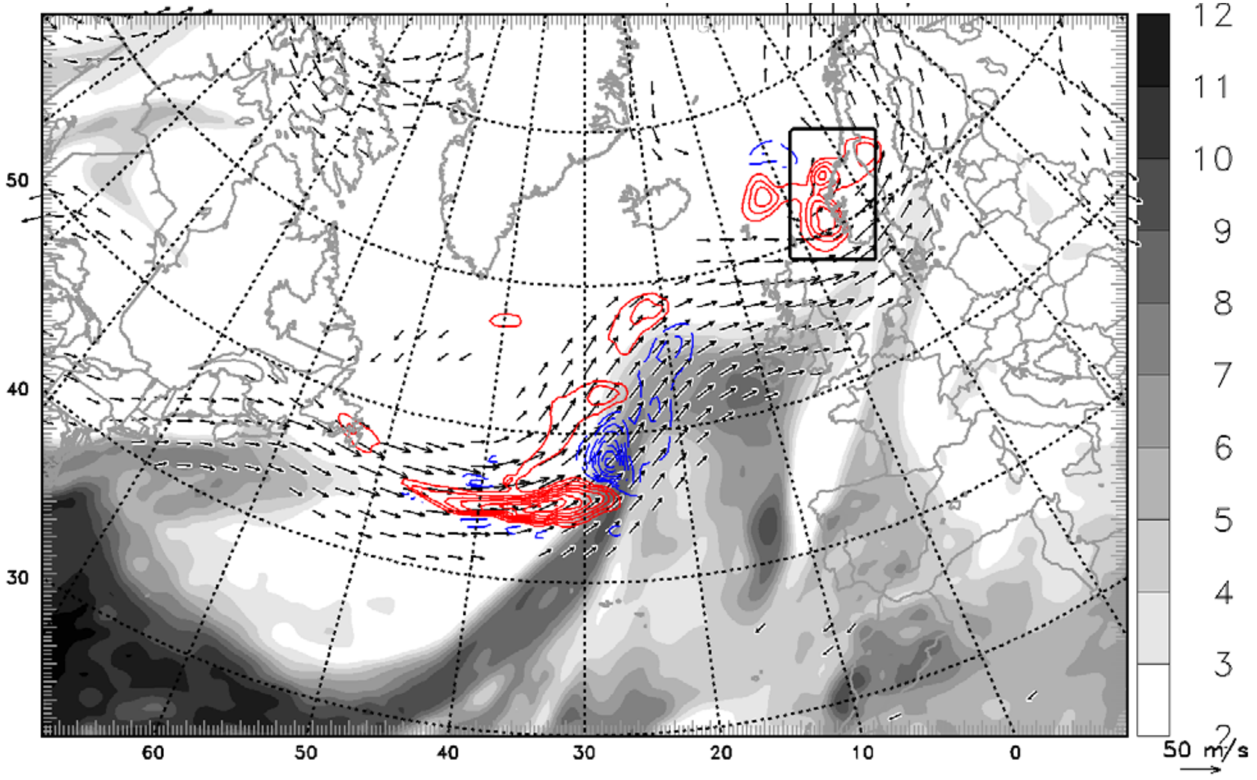


- Evolved adjoint perturbations (48-h) lead to:
  - ~10 hPa deeper cyclone (close to analyzed 966 hPa); reduction of erroneous trough to the west
- Key factors: i) water vapor inflow into WCB; ii) upstream tropopause PV gradients
- Perturbation growth enhances diabatic heating within frontal ascent
- Perturbations below 6 km lead to ~60% of P' minimum (-12 hPa), and ~40% above 6 km.

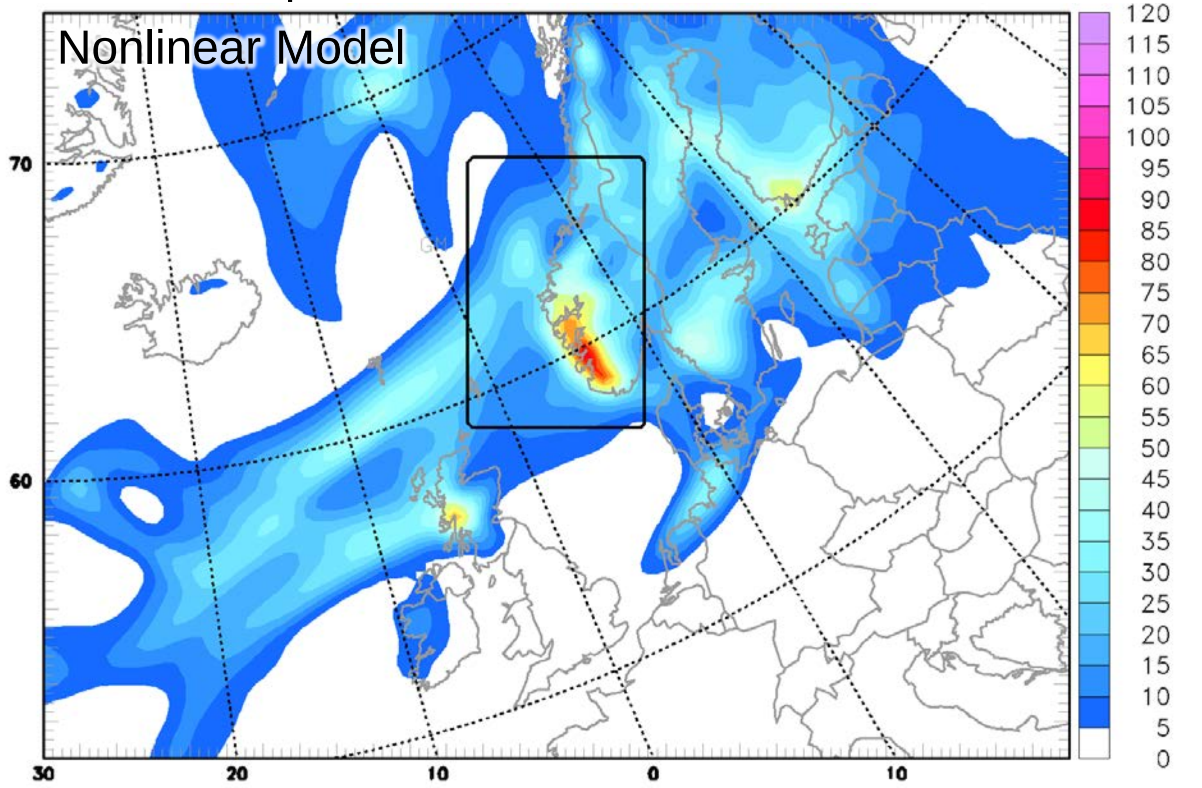
Forecast Error Sensitivity

2. High-Impact Precipitation Downstream of Ex-Karl

305K q_v (gray); Winds; q_v Sensitivity (blue/red)
Initial State (00Z 28 Sep 2016)



48-h Accumulated Precipitation (mm)
00Z 30 Sep 2016

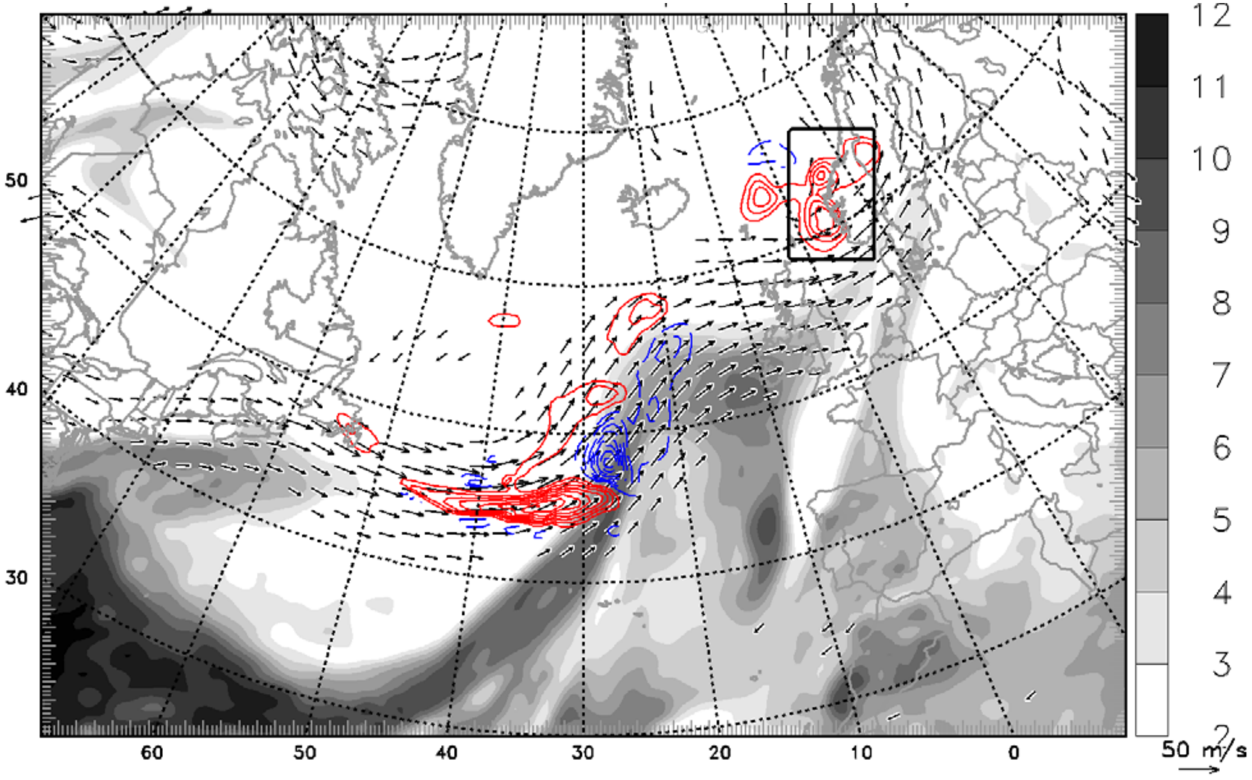


- Response function is the *Forecast 48-h Accumulated Precipitation Error* associated with the high-impact event over Norway
- Precipitation errors are especially sensitive to moisture and temperature inflow to WCB

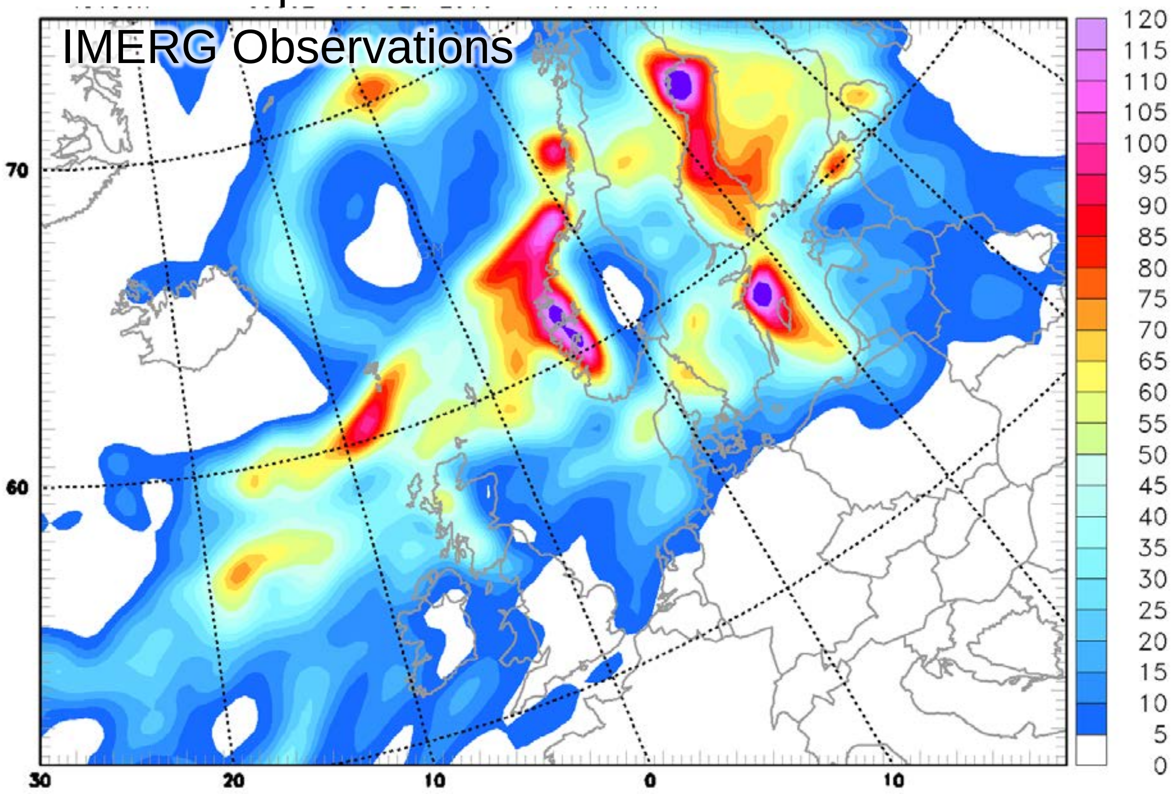
Forecast Error Sensitivity

2. High-Impact Precipitation Downstream of Ex-Karl

305K q_v (gray); Winds; q_v Sensitivity (blue/red)
Initial State (00Z 28 Sep 2016)



48-h Accumulated Precipitation (mm)
00Z 30 Sep 2016

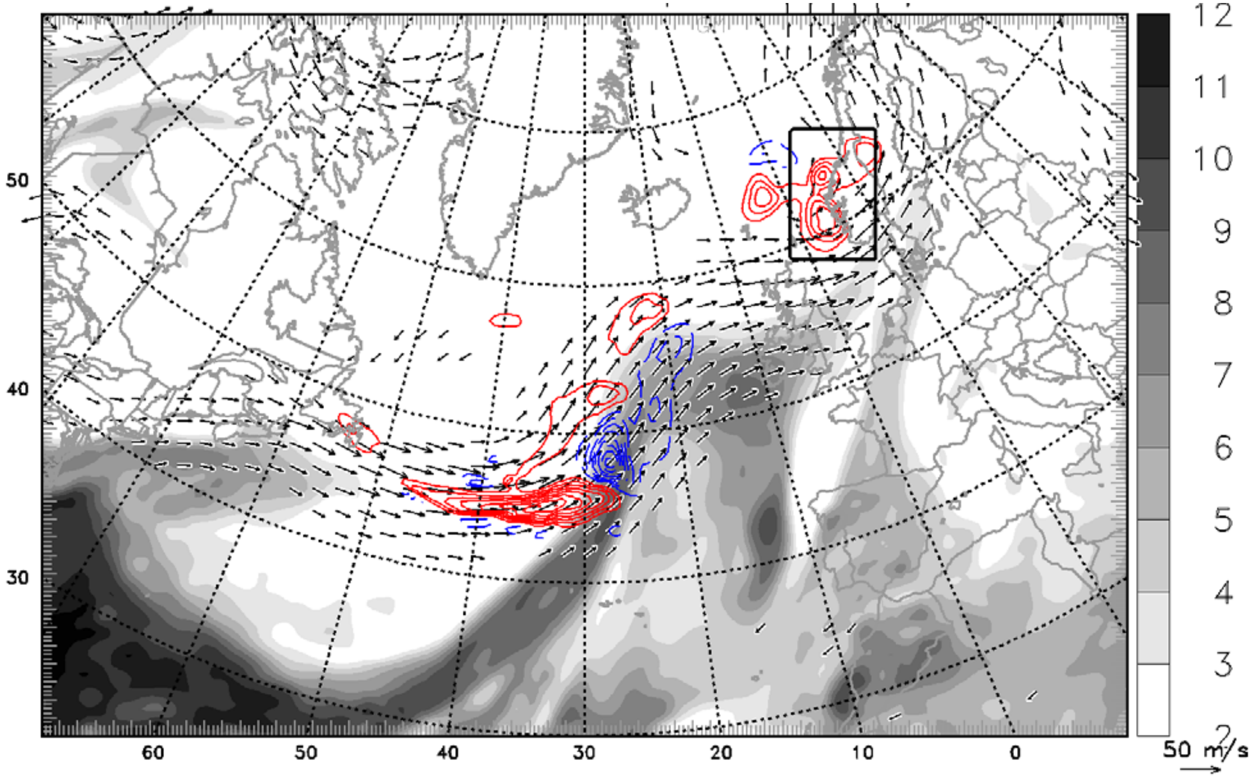


- Response function is the *Forecast 48-h Accumulated Precipitation Error* associated with the high-impact event over Norway
- Precipitation errors are especially sensitive to moisture and temperature inflow to WCB

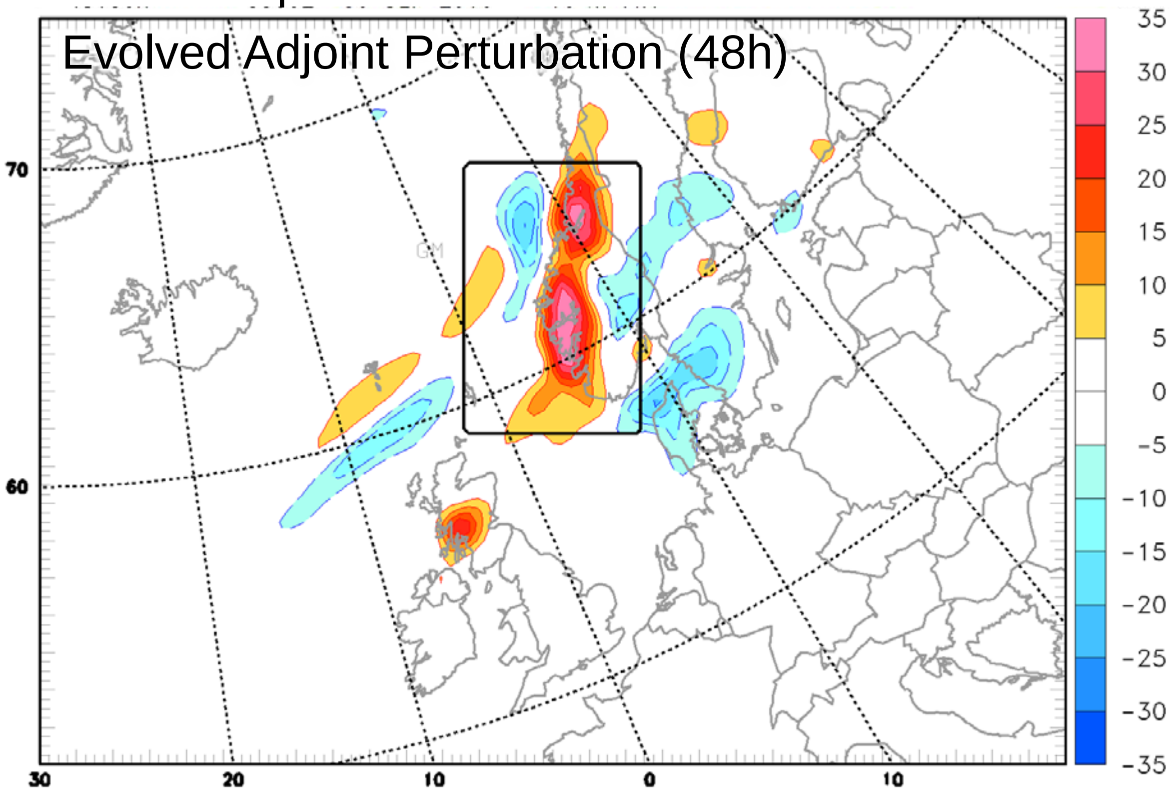
Forecast Error Sensitivity

2. High-Impact Precipitation Downstream of Ex-Karl

305K q_v (gray); Winds; q_v Sensitivity (blue/red)
Initial State (00Z 28 Sep 2016)



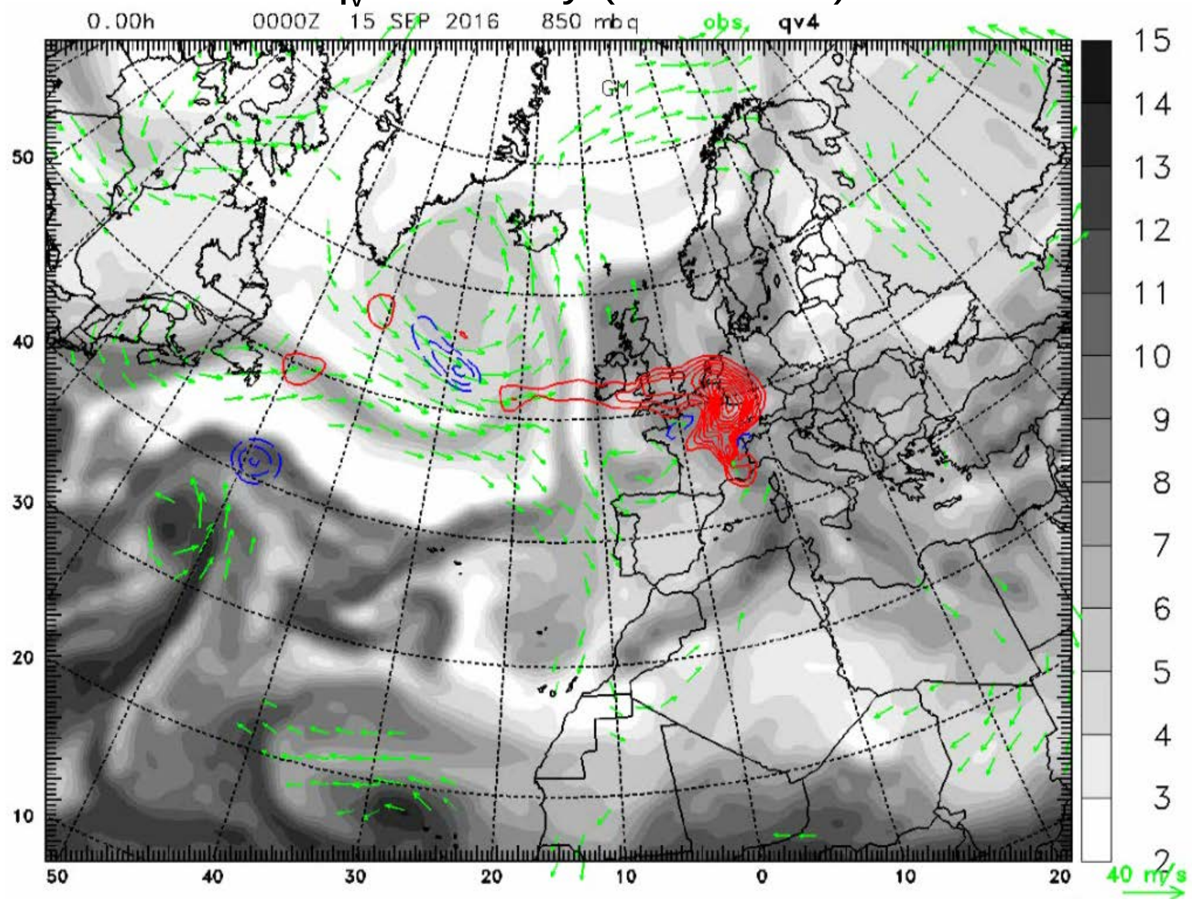
48-h Accumulated Precipitation (mm)
00Z 30 Sep 2016



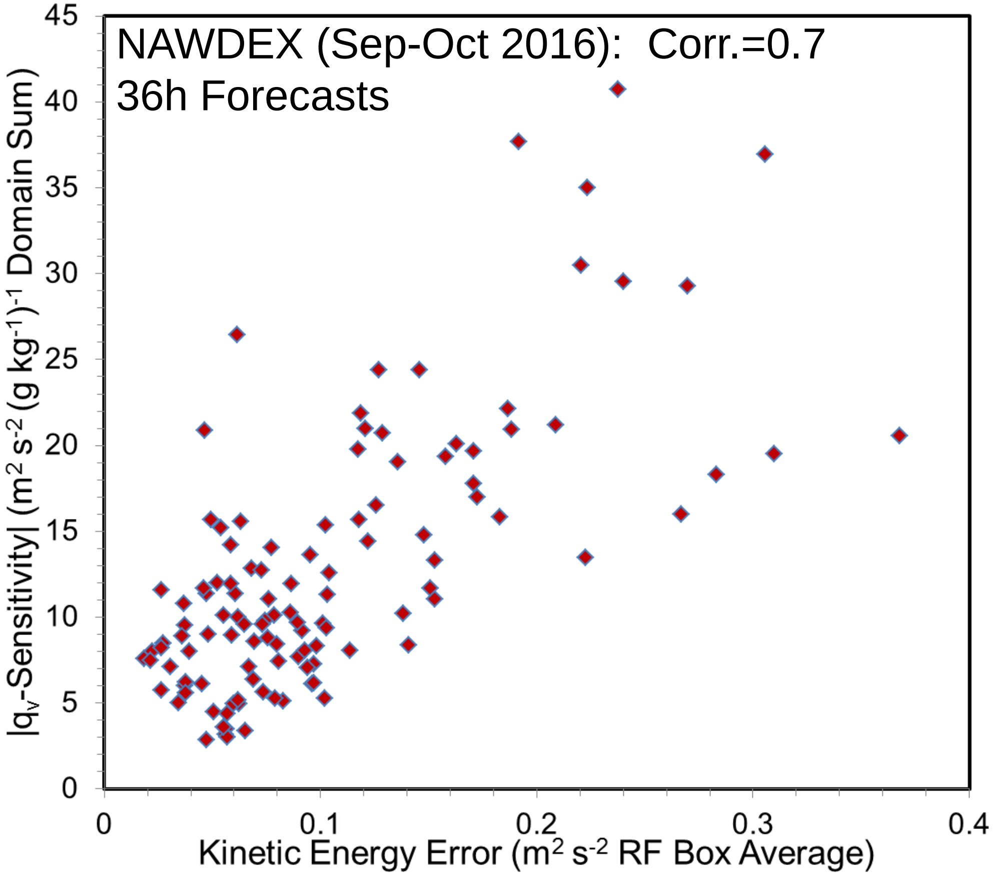
- Response function is the *Forecast 48-h Accumulated Precipitation Error* associated with the high-impact event over Norway
- Precipitation errors are especially sensitive to moisture and temperature inflow to WCB

Waveguide Seeds and Error Growth

850-hPa q_v (gray), winds (green vectors)
36-h q_v sensitivity (red & blue)



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



- Response function is the 0-1.5 km KE over the UK
- Episodic periods of strong moisture sensitivity shows peaks corresponding to strong NAWDEX events
- Moisture sensitivity magnitude & forecast error are well correlated (Reynolds et al. 2019; Doyle et al. 2019)

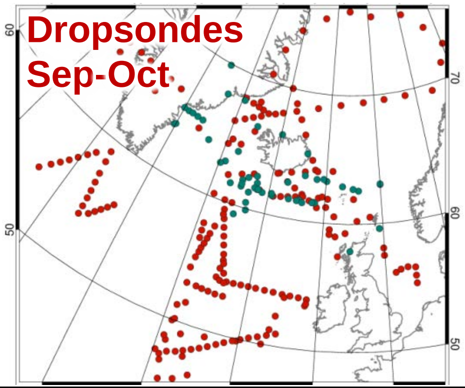
Conclusions

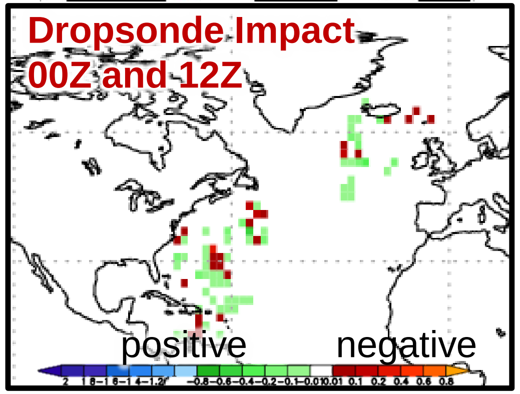
- How do WCBs influence the predictability of downstream high-impact weather?
  - Highly sensitive regions of mid-level moisture in WCBs (e.g., ex-Karl) and PV sensitivity along the upstream tropopause that "seed" waveguide, grow rapidly, and impact downstream high-impact weather

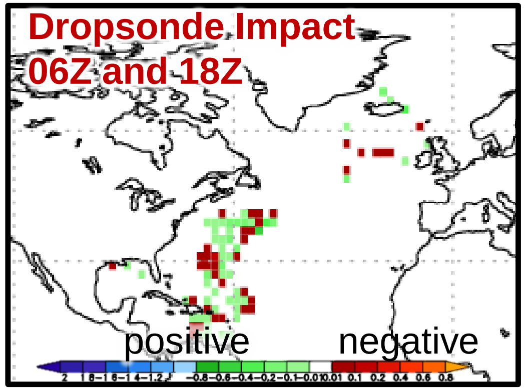
- Why are downstream extreme weather events difficult to predict?
  - High sensitivity to moisture, often in WCBs, and challenging to observe & assimilate (all-sky radiances)
  - Sensitivity magnitudes are well correlated with forecast error
  - Fast perturbation growth in diabatically active regions (WCB valve), which are seeds for error growth

- Future Directions:
  - Mesoscale predictability drivers over the N. Atlantic (NAWDEX) and Arctic
  - Predictability of heavy rainfall & atmos. rivers on U.S. West Coast (AR-Recon, Marty Ralph, Scripps)
  - Adjoint-based tool (SVs, Ob impact) development

Impact of Dropsondes in Navy NAVGEM



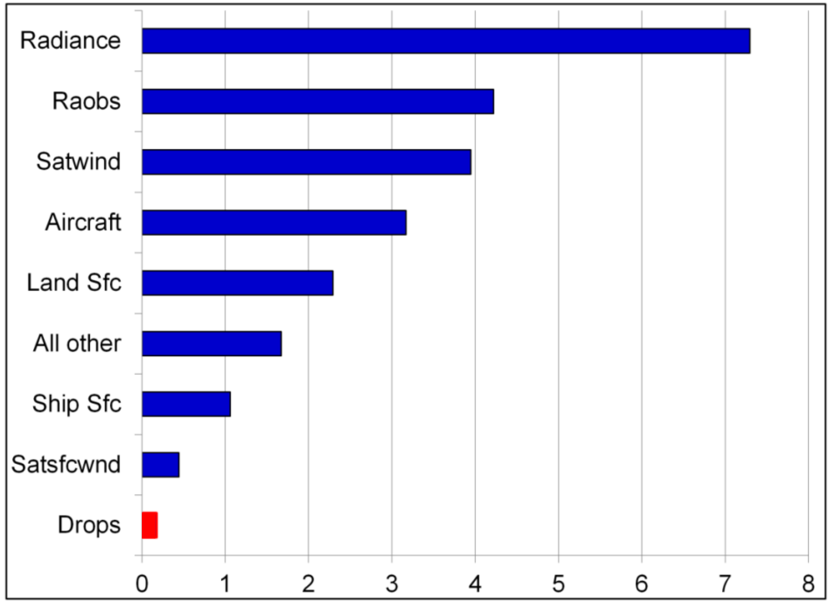




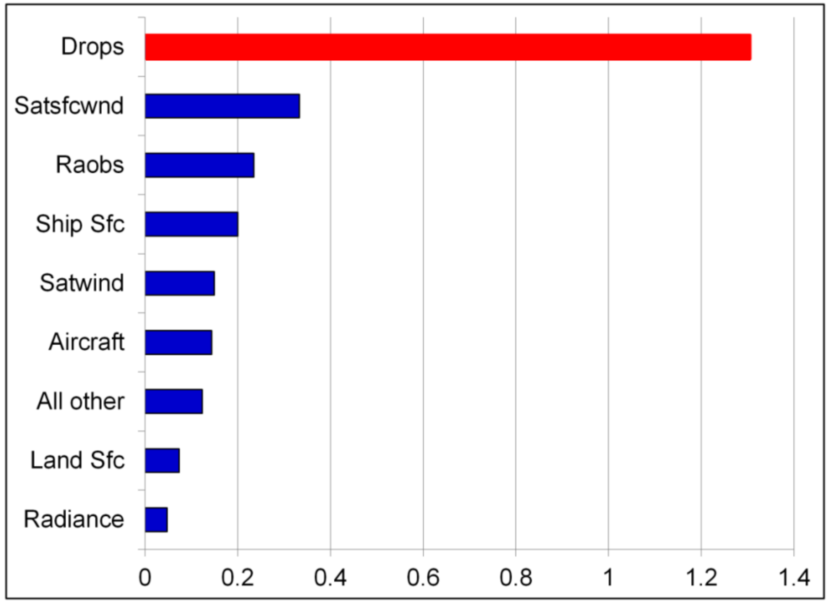
Navy NAVGEM Forecast Sensitivity Observation Impact (FSOI) (24h)

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 Ob.



- During NAWDEX, 289 dropsondes were deployed
- Forecast Sensitivity/Observation Impact (FSOI): Adjoint of NAVGEM (31 km) & hybrid 4-D VAR DA to calculate impact of each ob. on 24-h forecast error
- NAWDEX (& SHOUT) dropsondes during Sept. were most impactful (per ob.)

In collaboration with Rolf Langland (NRL)