Sensitivity of High-Impact Extratropical Cyclones to Water Vapor in Atmospheric Rivers

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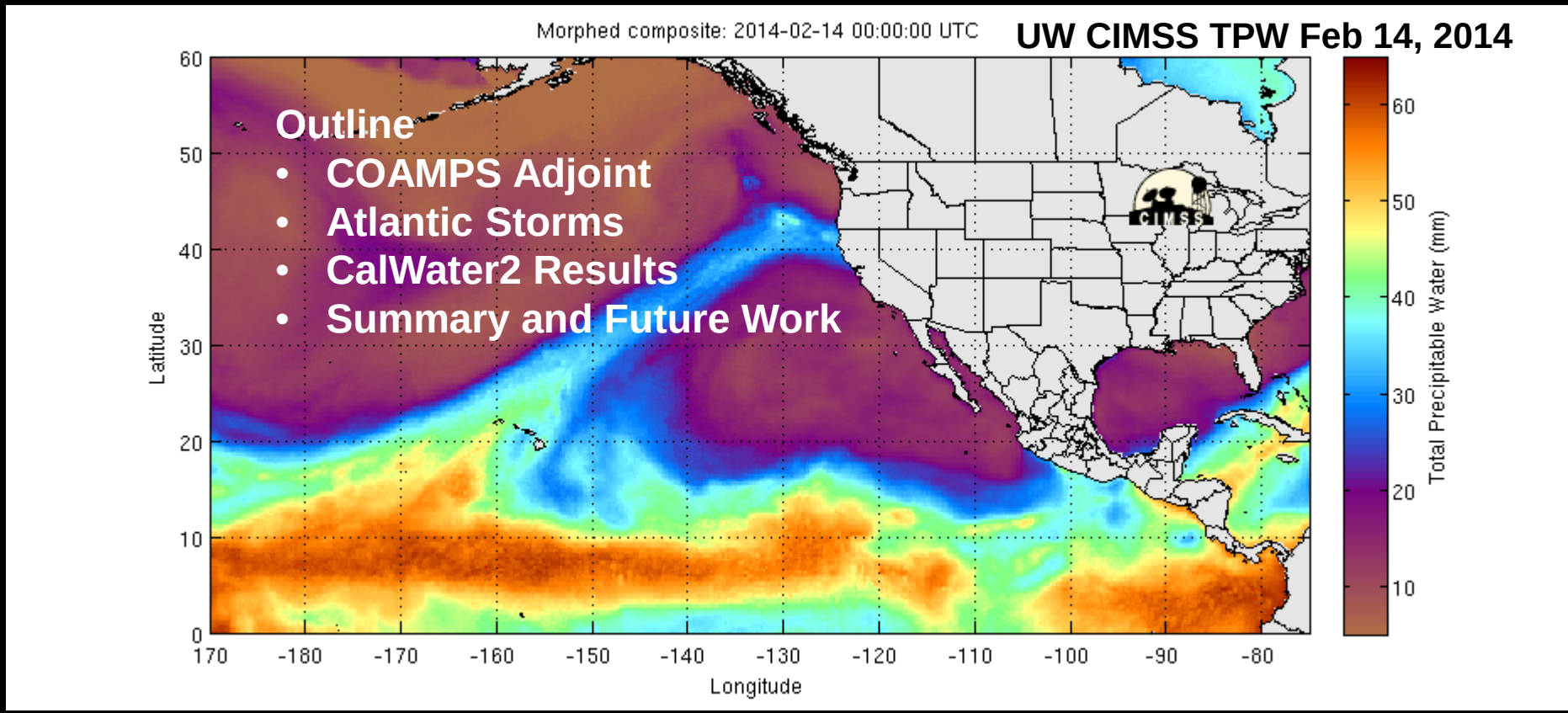


COAMPS Adjoint Model

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

Sensitivity of response function (***J***)
at time t_n to the state at time t_0

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

$\mathbf{M}^T$ is the adjoint or transpose of the tangent linear model

COAMPS® Moist Adjoint Model

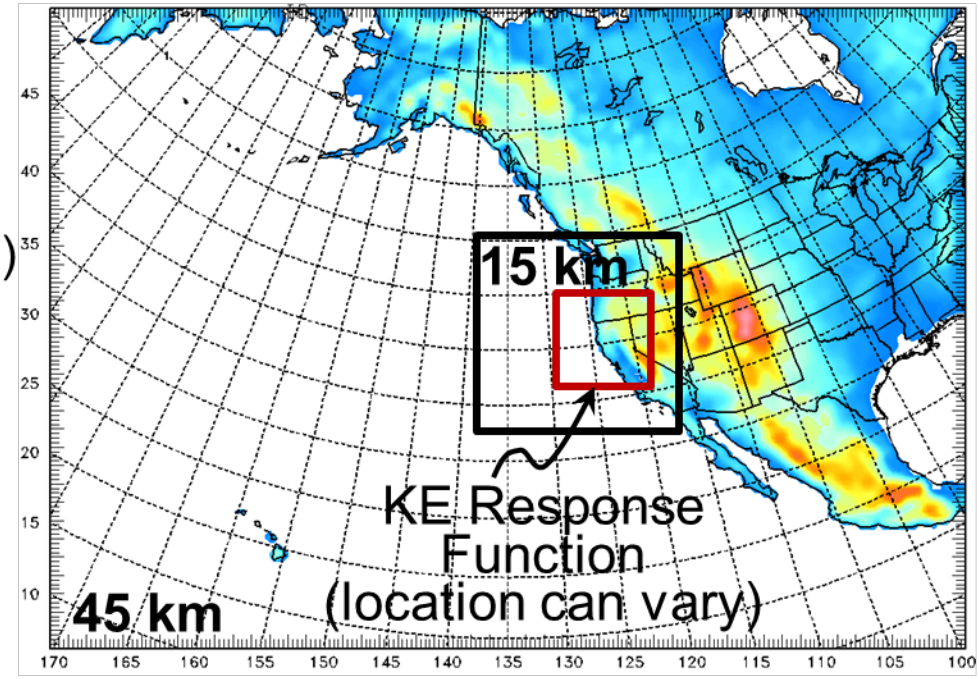
- **Dynamics:** nonhydrostatic, nested
- **Physics:** PBL, surface flux, microphysics
- **Response Function, *J*:**
  - kinetic energy in a box (1 km deep)
- **Resolution:** Δx=45 km, 15 km (36 & 24h)

Atlantic Cases

Xynthia (Feb 2010), winter 2013-14

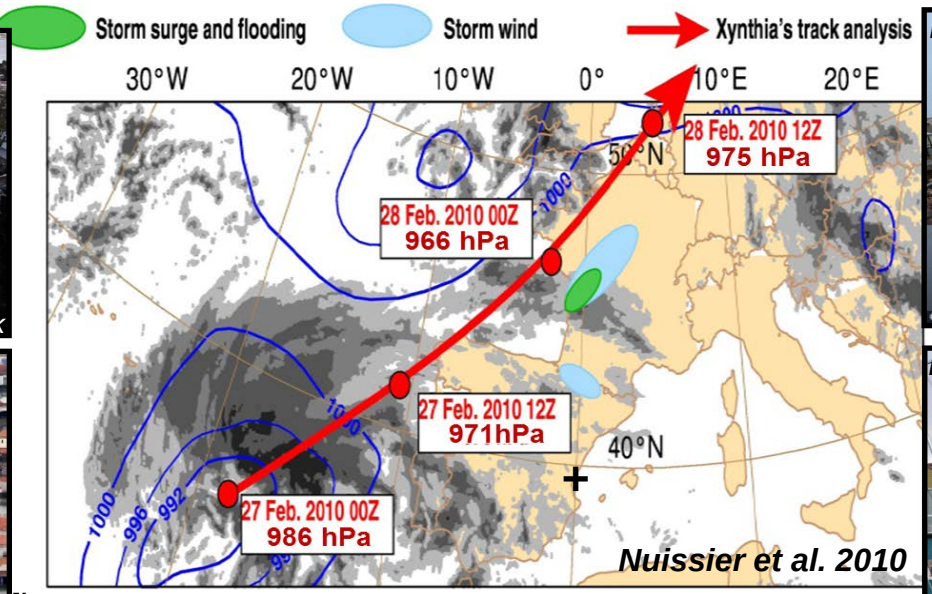
CalWater2 Demonstration Cases

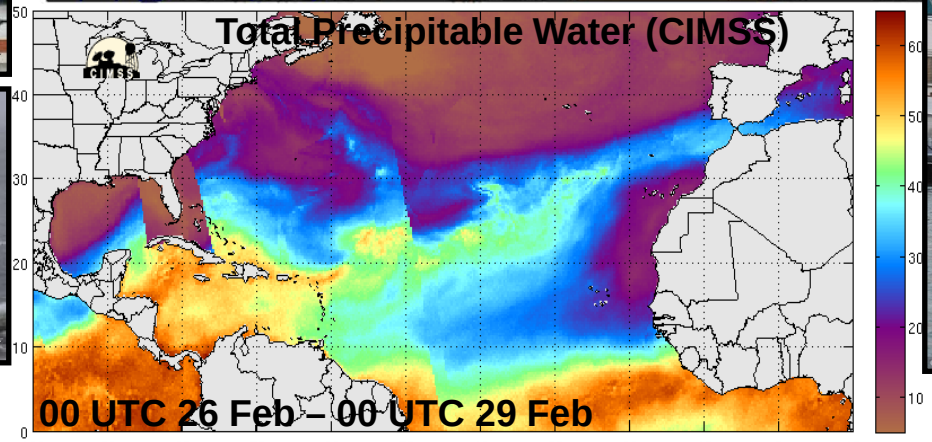
8-10 Feb 2014, 13-14 Feb 2014



Atlantic Cases: Xynthia

- Largest impact on Europe in a decade with insured losses of $2-4B
- 63 fatalities; storm surge in France (> 7.5 m); Damaging winds (150 mph)
- Synoptic-scale was well predicted (ECMWF, GFS); mesoscale not as well
- Developed along a plume of high precipitable water (atmospheric river)

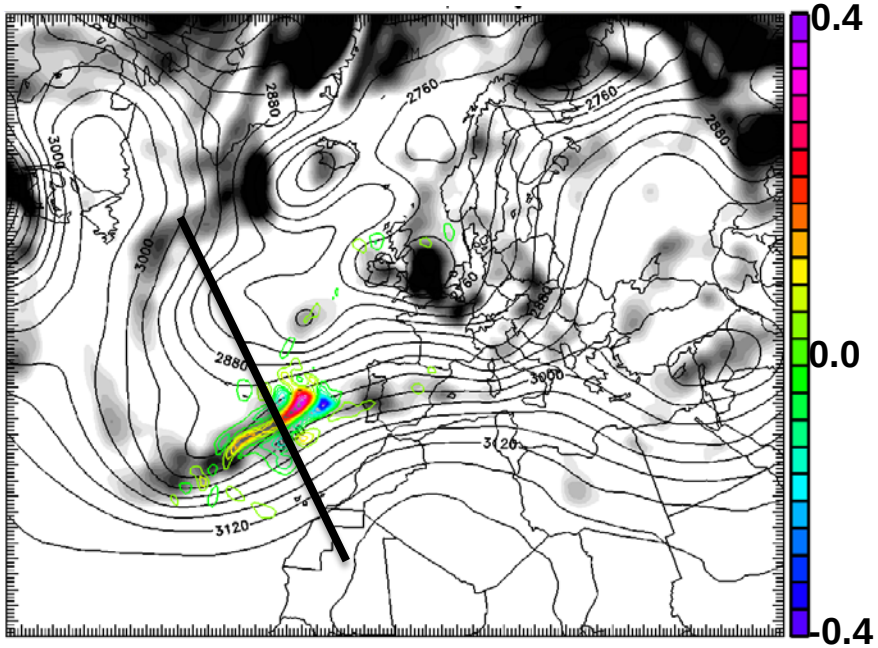




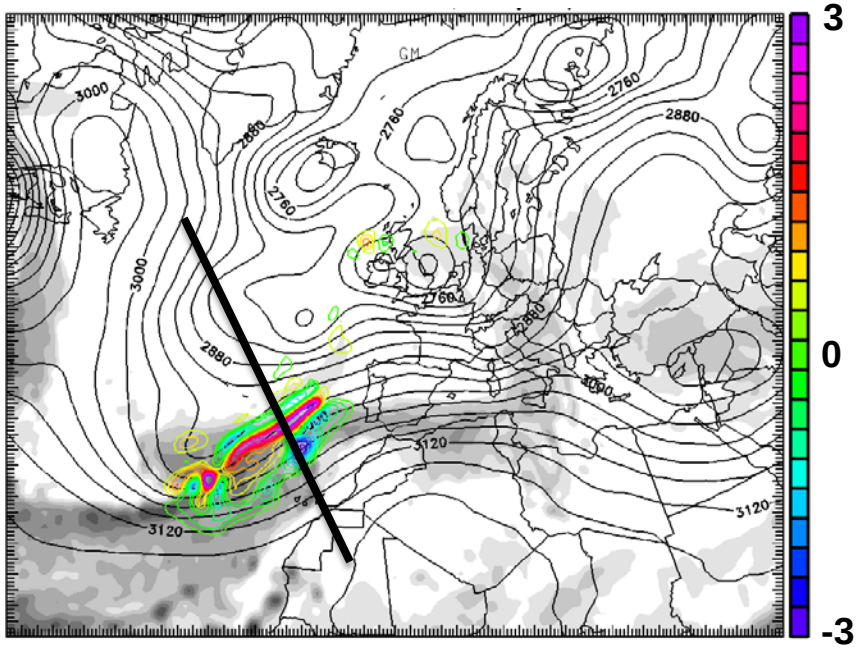
Atlantic Cases: Xynthia

PV and Moisture Sensitivity (Δx=45 km)
1200 UTC 26 February 2010 (Analysis)

700-hPa PV and PV Sensitivity



700-hPa q_v and Sensitivity to q_v

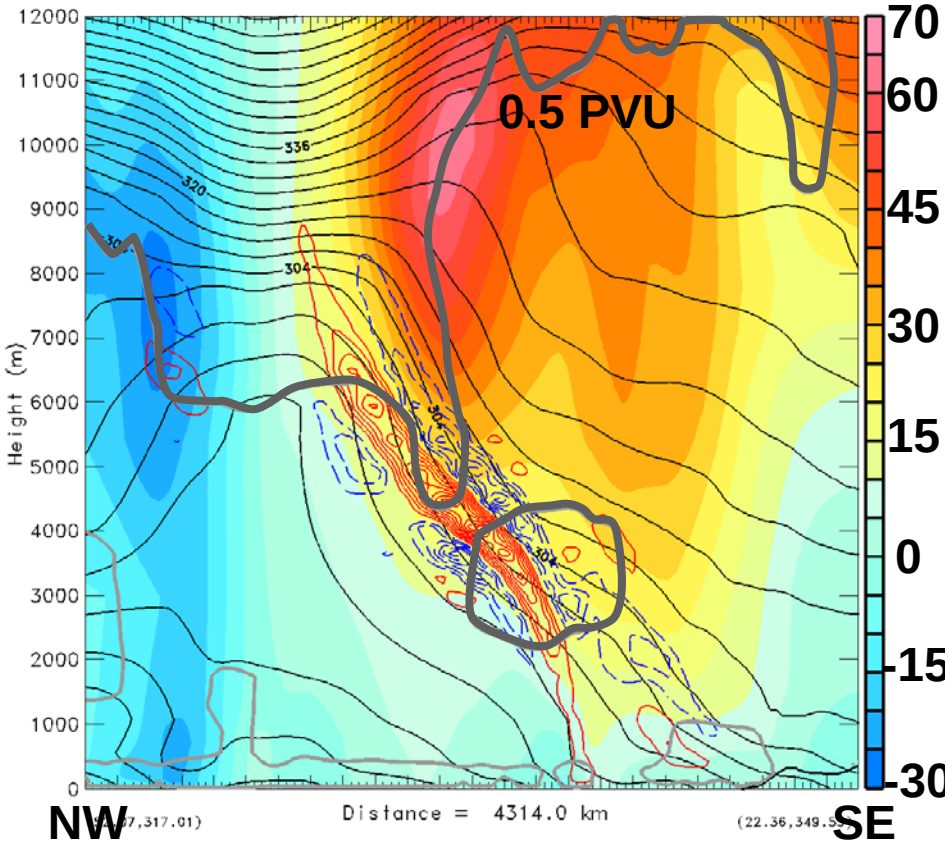


- **Low-level PV filament coincident with a moist low-level jet.**
- **Adjoint sensitivities (PV, u, T, q_v) are maximized along shortwave.**
- **Moisture sensitivity along AR is 5x greater than wind sensitivity (and 2x larger than T).**
- **Sensitive regions collocated with analysis uncertainties**

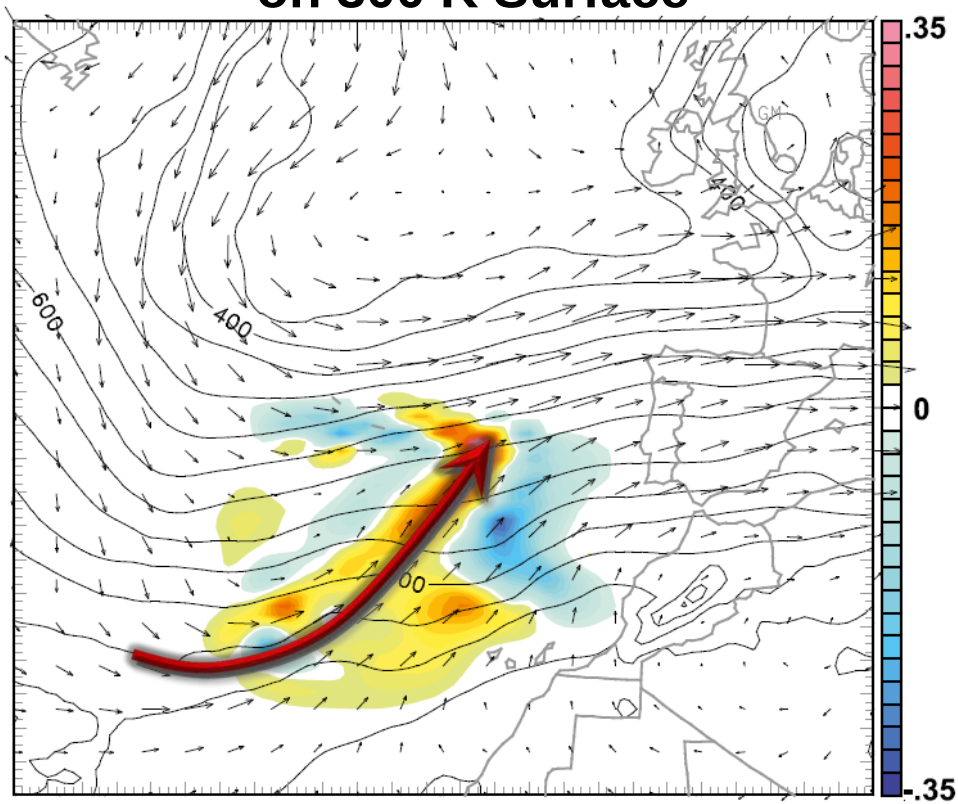
Atlantic Cases: Xynthia

PV and Moisture Sensitivity (Δx=45 km) (Analysis)

θ, U (normal), and PV Sensitivity



Sensitivity to q_v, winds, pressure on 300 K Surface

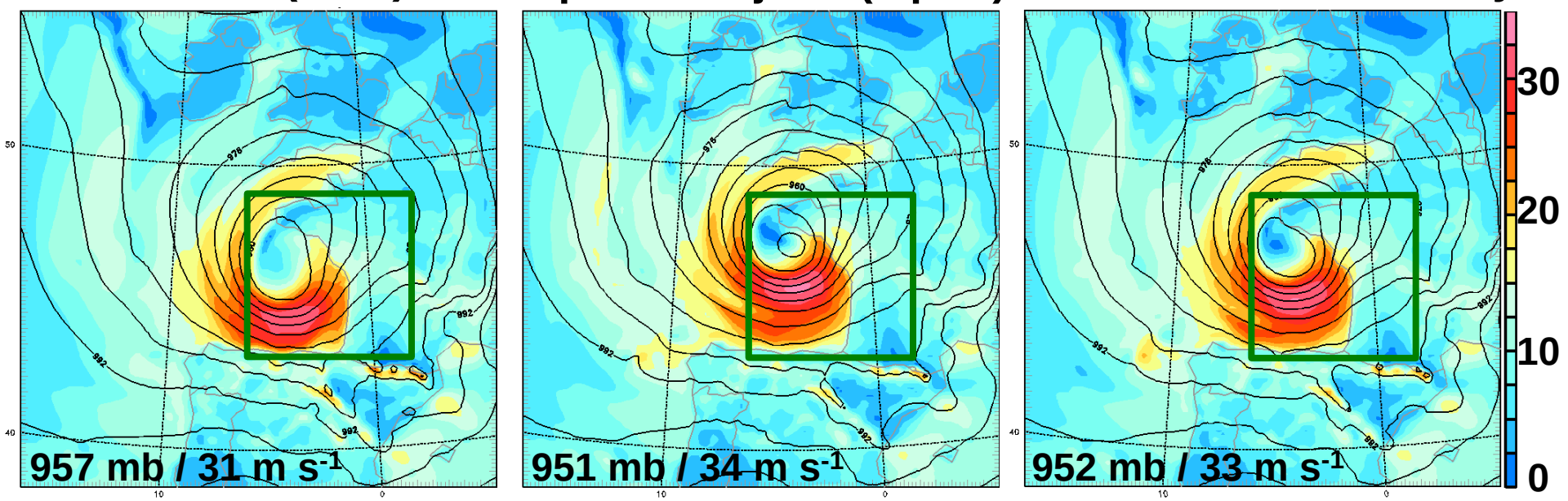


- Restructuring of PV (connection of anomalies) leads to intensification.
- Sloping PV and q_v sensitivity are maximized along mid-level front.
- Moisture sensitivity is a maximum along the ascending warm conveyor belt.
- "Unshielding" of PV and rapid growth of tilted perturbations (Orr mechanism).

Xynthia Evolved Optimal Perturbations

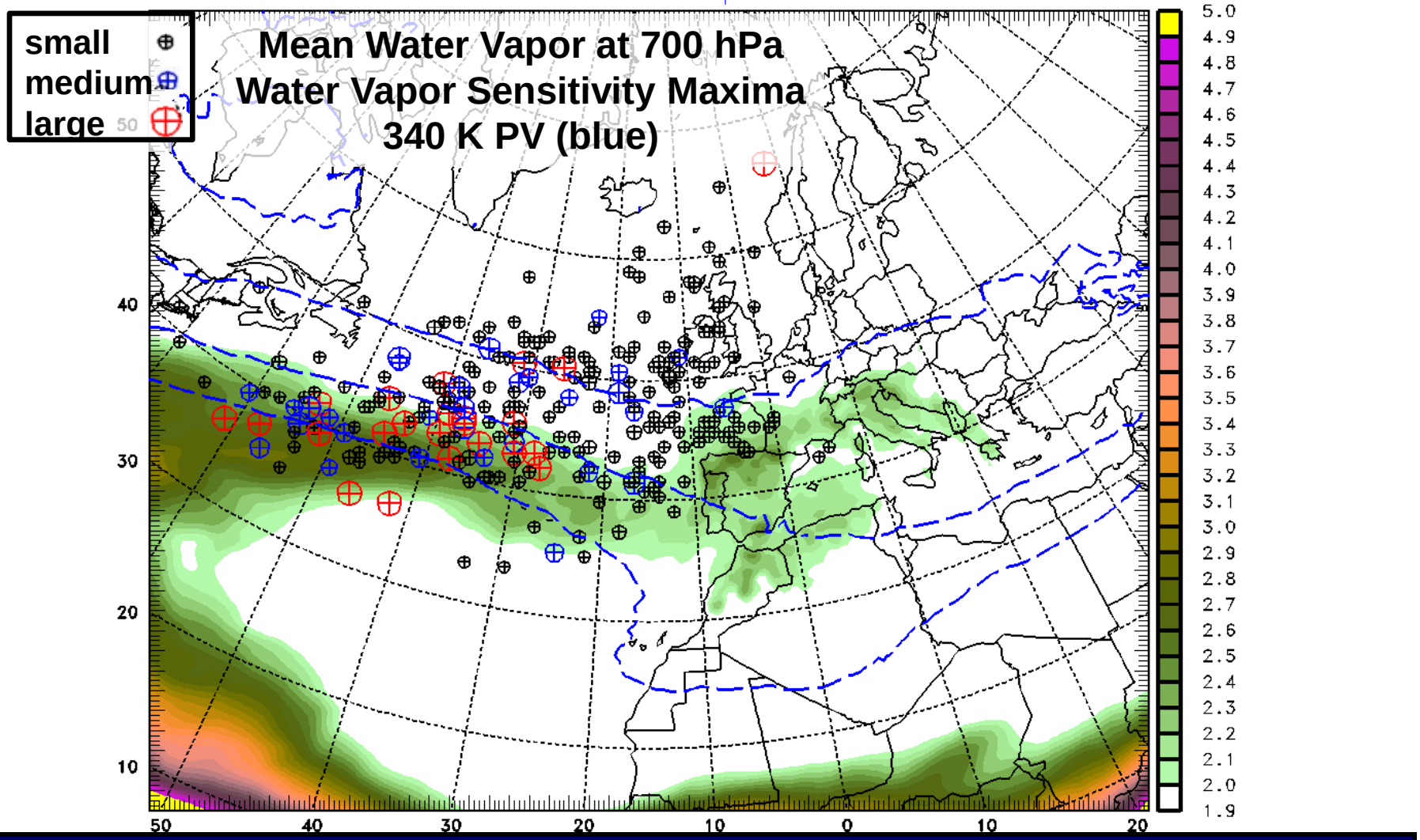
Sea-Level Pressure, 10-m Winds (Nest 2 Δx=15 km)
00Z 28 Feb (36 h)

Control (NLM) | **Optimal Adjoint (+ pert)** | **Moist Perturbation Only**



- **The structure and intensity of the cyclone, low-level jet, and front change markedly with the evolved perturbations (negative and positive).**
- **Moisture perturbations in the NLM grow much faster than temperature and wind perturbations.**

UK and Europe Winter Storms 2013-14



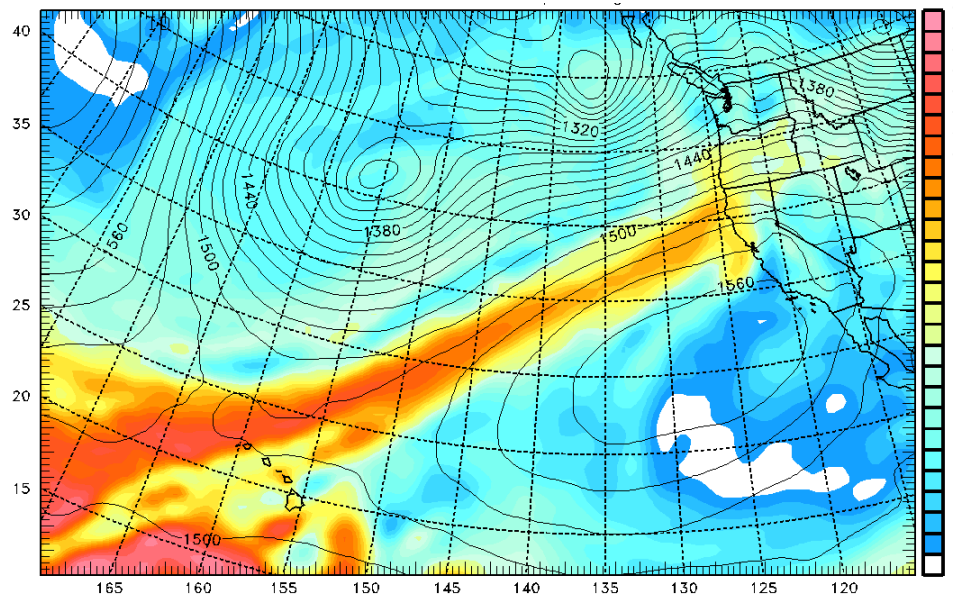
- **Strong jet and wave guide during Dec-Feb; 25 m/s zonal wind anomaly.**
- **Largest moisture sensitivity located along mean moist plume at 700 hPa, and beneath the southern portion of the wave guide (PV gradient).**

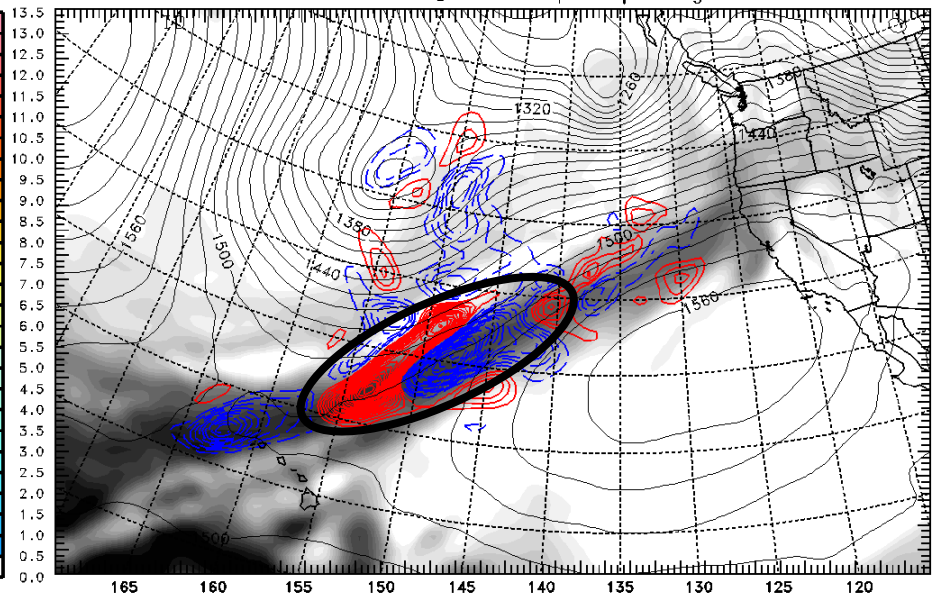
CalWater2

36-h Sensitivity (Analysis)

00Z 13 February 2014 (Final Time 12Z 14 February)

Geopotential Heights and Water Vapor
850 hPa





36-h Water Vapor Sensitivity
850 hPa (q_v shown in gray)

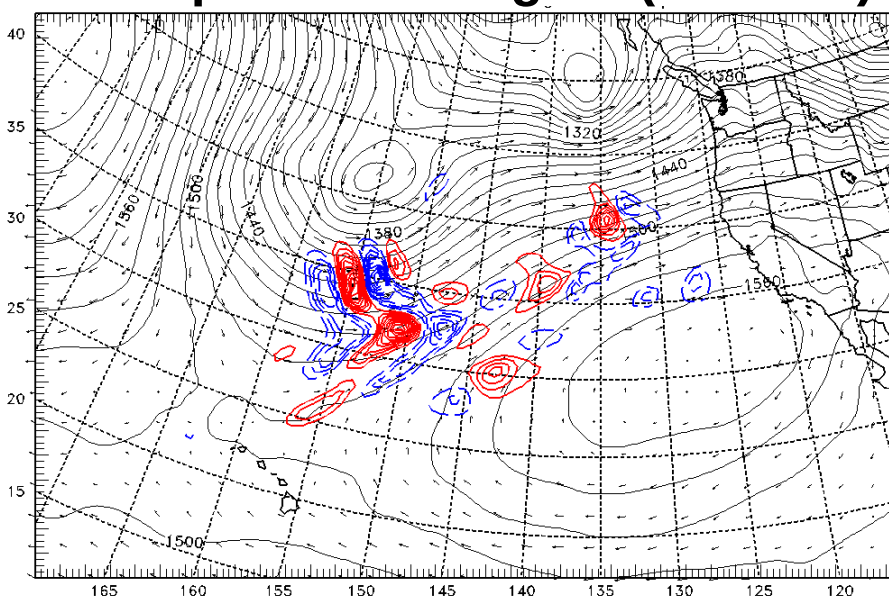
- **36-h forecast sensitivity calculations for 00Z 13 Feb. (valid at 00Z 14 Feb.)**
- **Moisture sensitivity is strongest along AR axis; located > 2000 km upstream**
- **Moisture sensitivity substantially larger than temp. or wind sensitivity.**

CalWater2

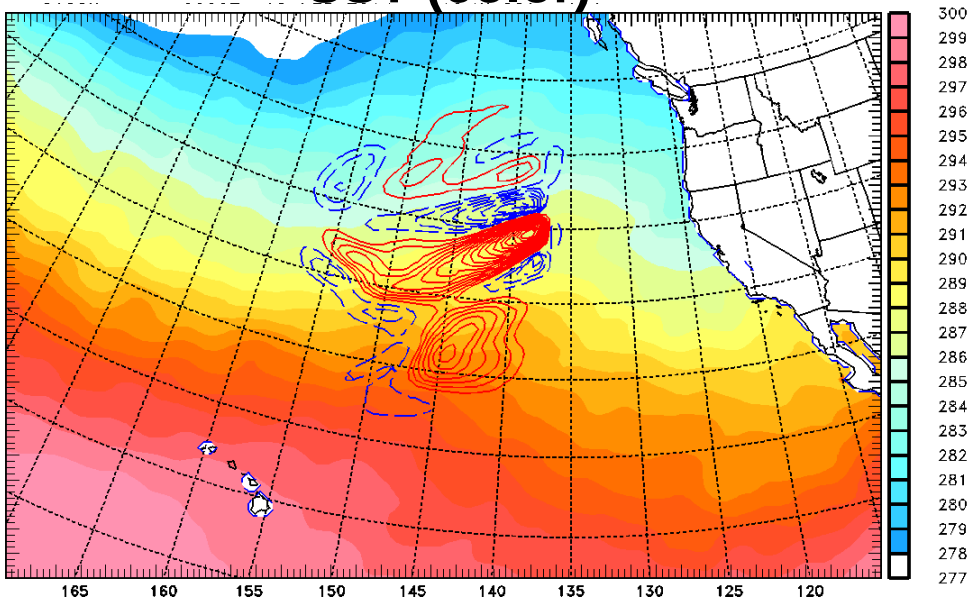
36-h Sensitivity (Analysis)

00Z 13 February 2014 (Final Time 12Z 14 February)

PV Sensitivity (Adjoint Optimal Pert.)
Geopotential Heights (850 hPa)



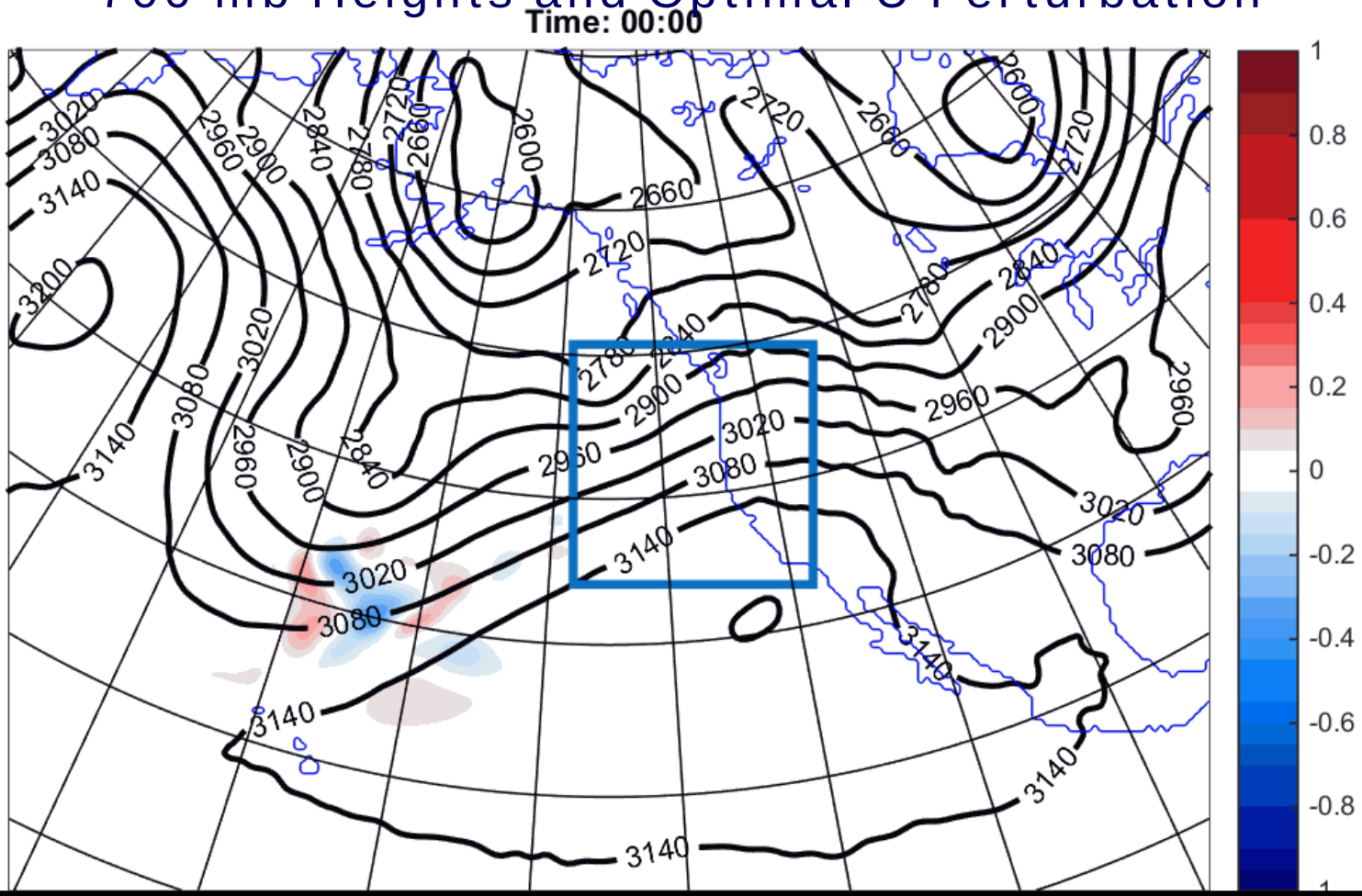
36-h SST Sensitivity
SST (color)



- **PV adjoint optimal perturbation maxima near 850-hPa shortwave trough**
- **Sea surface temperature sensitivity is a maximum north of the AR.**
- **Sensitivity is larger for the 13 Feb case than for 8 Feb (extra slides).**

CalWater2

36-h Evolved Optimal Perturbations (Grid 2)
700-mb Heights and Optimal U Perturbation



- **Evolved u-wind component and qv optimal perturbations grow rapidly; after 36 h, u-wind component grows from 1 to 20 m s^{-1}.**
- **Analysis errors that project on to the initial sensitivity regions will rapidly contaminate the forecast.**

Summary and Future Plans

- **Initial moisture: key factor for Atlantic and Pacific storm intensification:**
  - **Sensitivity to moisture is most important for many of the cyclones, despite substantial differences in structure & evolution of the storms.**
  - **Rapid growth (via PV unshielding) and downstream propagation.**
  - **Optimal perturbations for moisture grow faster than other variables.**
  - **Moisture sensitivity maximum in ARs and along WCB.**

- **Mesoscale predictability of these storms is limited by very rapid growth:**
  - **Moist processes in the presence of PV introduce inherent uncertainty.**
  - **Diabatic processes act to perturb wave guide in fast growth regions.**
  - **Motivates the use of ensembles for these high-impact weather events.**

- **Future plans:**
  - **Perform data denial and observation impact experiments using CalWater2 and ENRR observations.**
  - **Test predictability and sensitivity hypotheses in NAWDEX.**
  - **Examine COAMPS and NAVGEM ensemble behavior for case studies.**
  - **Proposal to study AR sensitivity and extended-range predictability.**

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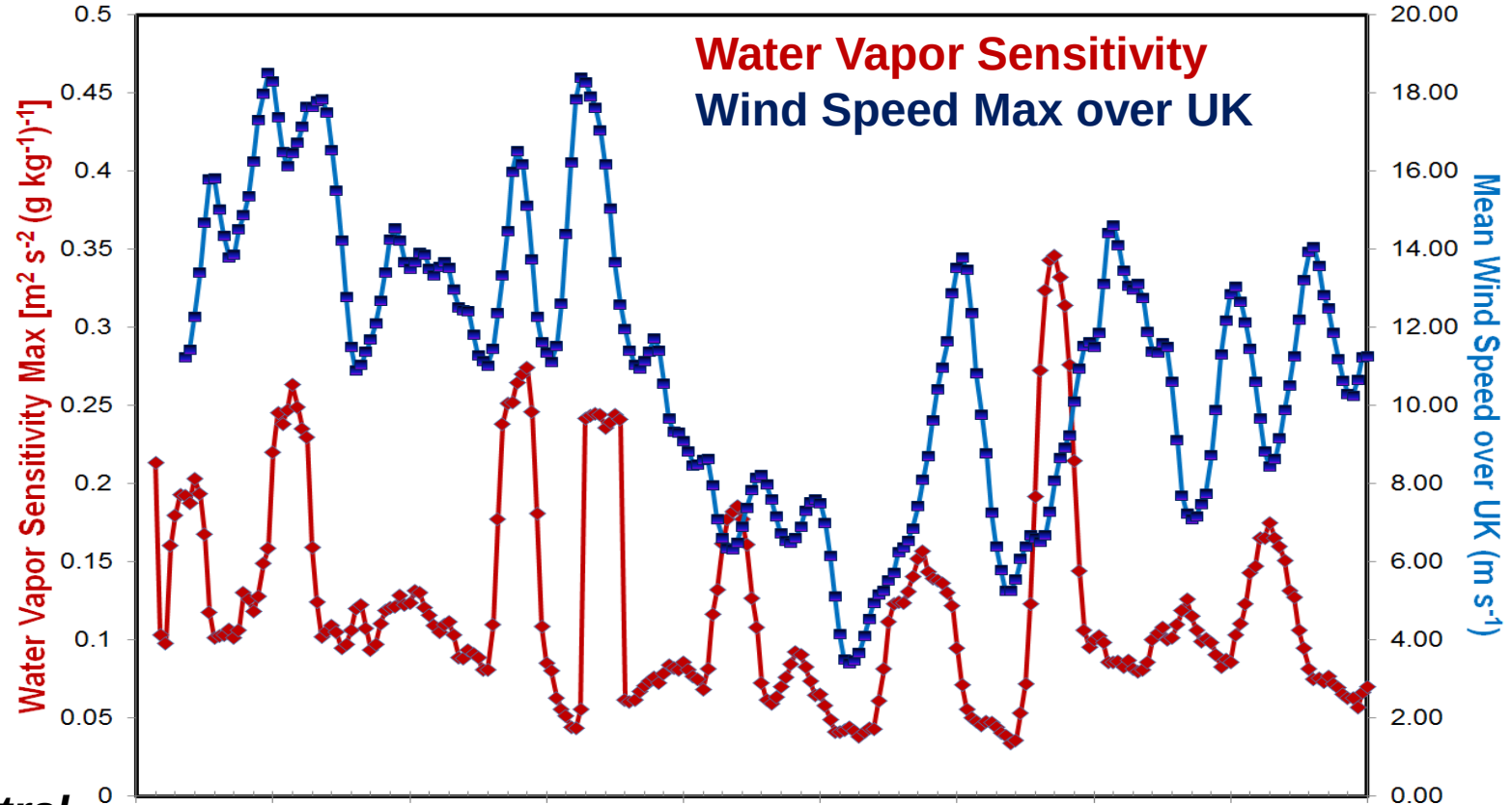
UK and Europe Winter Storms 2013-14

- **Dec – Feb 2013/14 featured an exceptional period of strong and damaging extratropical cyclones (12+) that impacted the UK and Europe.**
- **Unusually strong jet stream and polar vortex; storm track displaced south.**
- **Widespread flooding, damaging high winds.**
- **Adjoint model 36-h forecasts (45 km), for 15 Dec-15 Feb 2013/14 every 6 h.**



Central Pressure (hPa)

947 944 945 950 975 985

927 970 940 945 945 960