Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

Investigating the Impact of Numerical Model Uncertainty in the Marine Boundary Layer on the Predictability of Atmospheric Rivers and Onshore Precipitation

Center for Western Weather and Water Extremes (CW3E) at
University of California San Diego/Scripps Institution of Oceanography

2026 AR Recon Workshop
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Presented by: **Kevin Lupo**
Coauthors: Sawyer Smith, Nora Mascioli, Ryan Torn, Luca Delle Monache, and F. Martin Ralph

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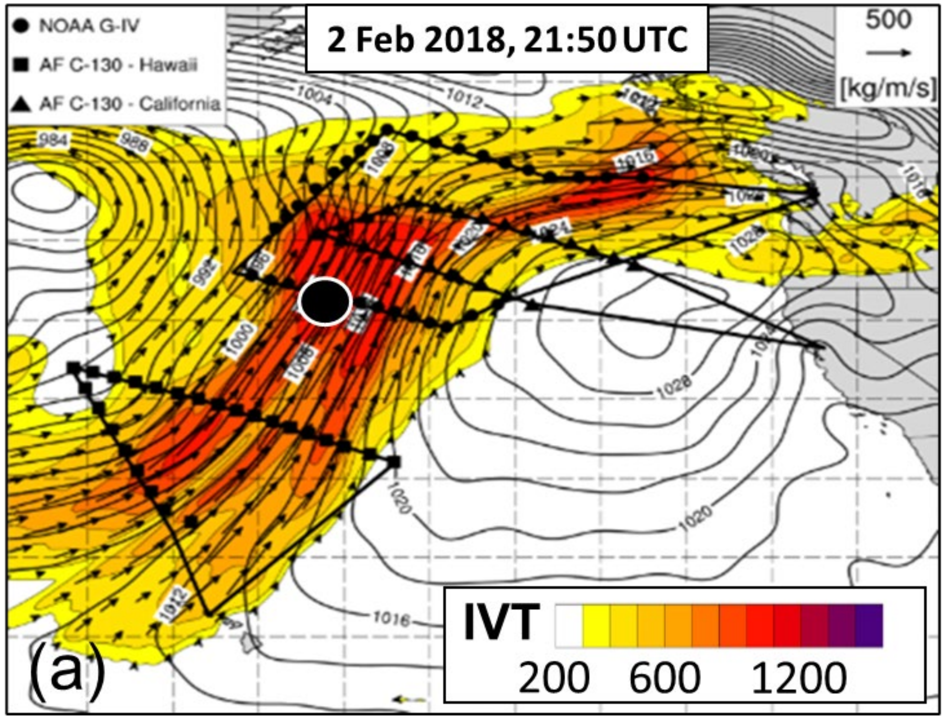
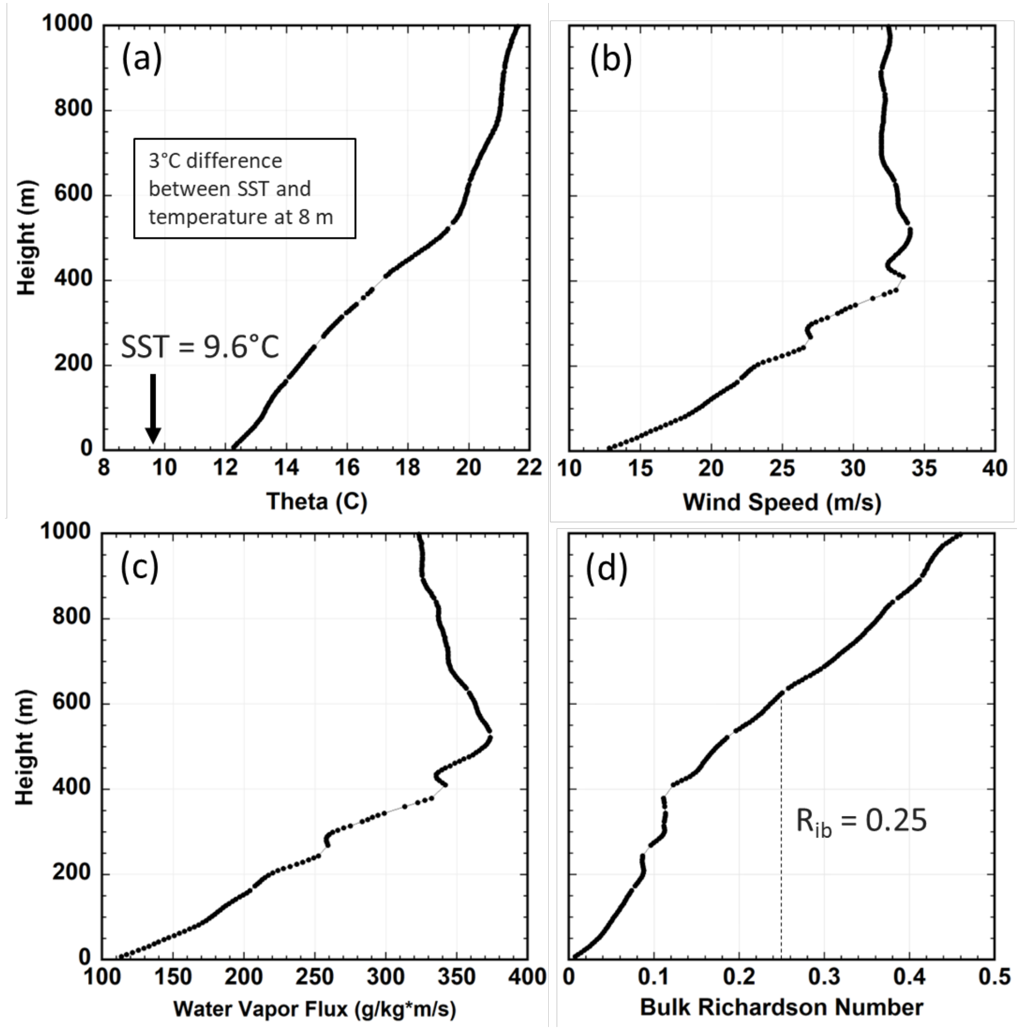
Research support provided by ONR grant number N000142412752

Motivation for Marine Boundary Layer Research

- **Goal:** Improve forecasts of atmospheric rivers and their associated precipitation through better understanding and model representations of the MBL.
  - **Dropsonde observations** provide a visualization of complex physical processes and interactions occurring in the lower atmosphere including the marine boundary layer (MBL)





Figures adapted Ralph, F. M., M. Simpson, S. Iacobellis, J. M. Cordeira, F. Cannon, A. Cobb, A. C. Michaelis, and L. Delle Monache, 2024: Dropsonde Observations of the Stable Marine Boundary Layer beneath Atmospheric Rivers. Mon. Wea. Rev., ***152****, 2735–2751, https://doi.org/10.1175/MWR-D-23-0207.1.*

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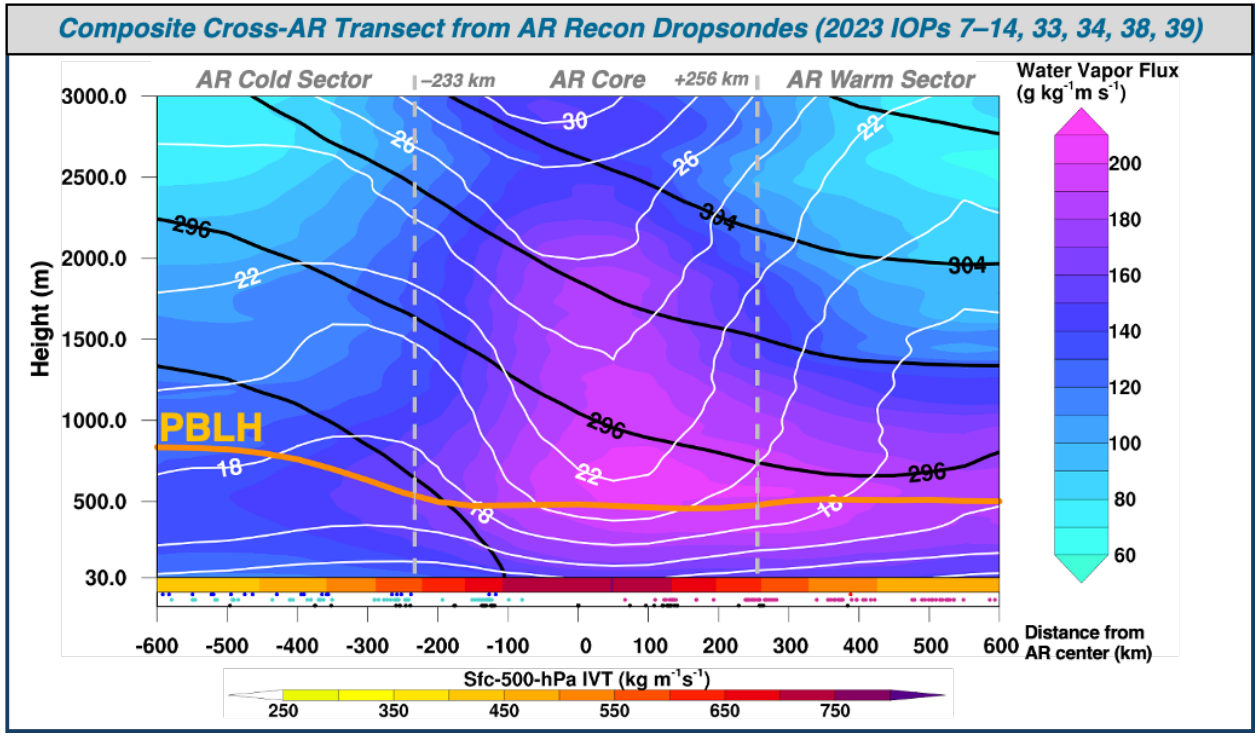

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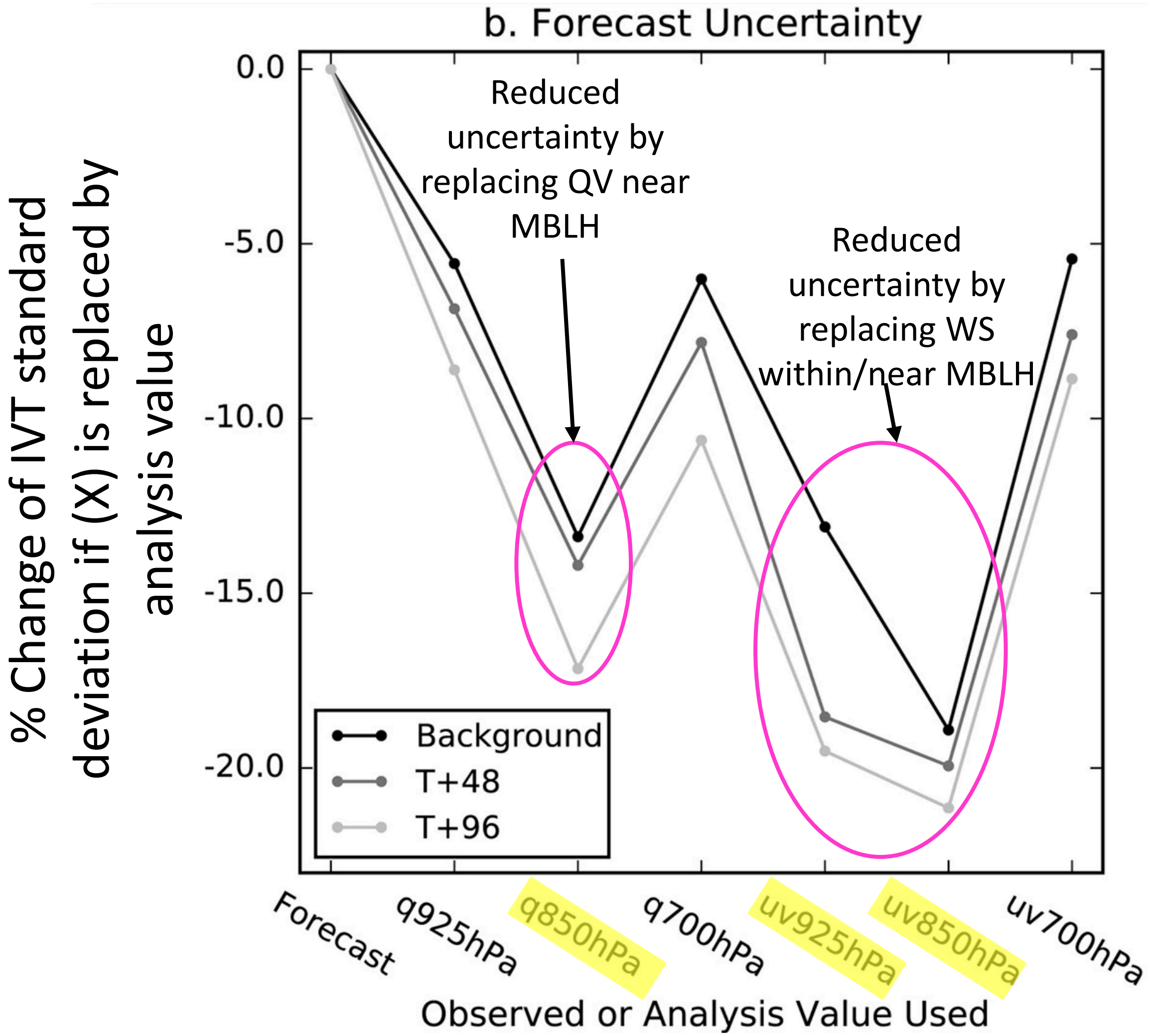

Figures adapted from Lavers, D. A., and Coauthors, 2018: The gauging and modeling of rivers in the sky. Geophys. Res. Lett., ***45,*** *7828–7834, https://doi.org/10.1029/2018GL079019.*

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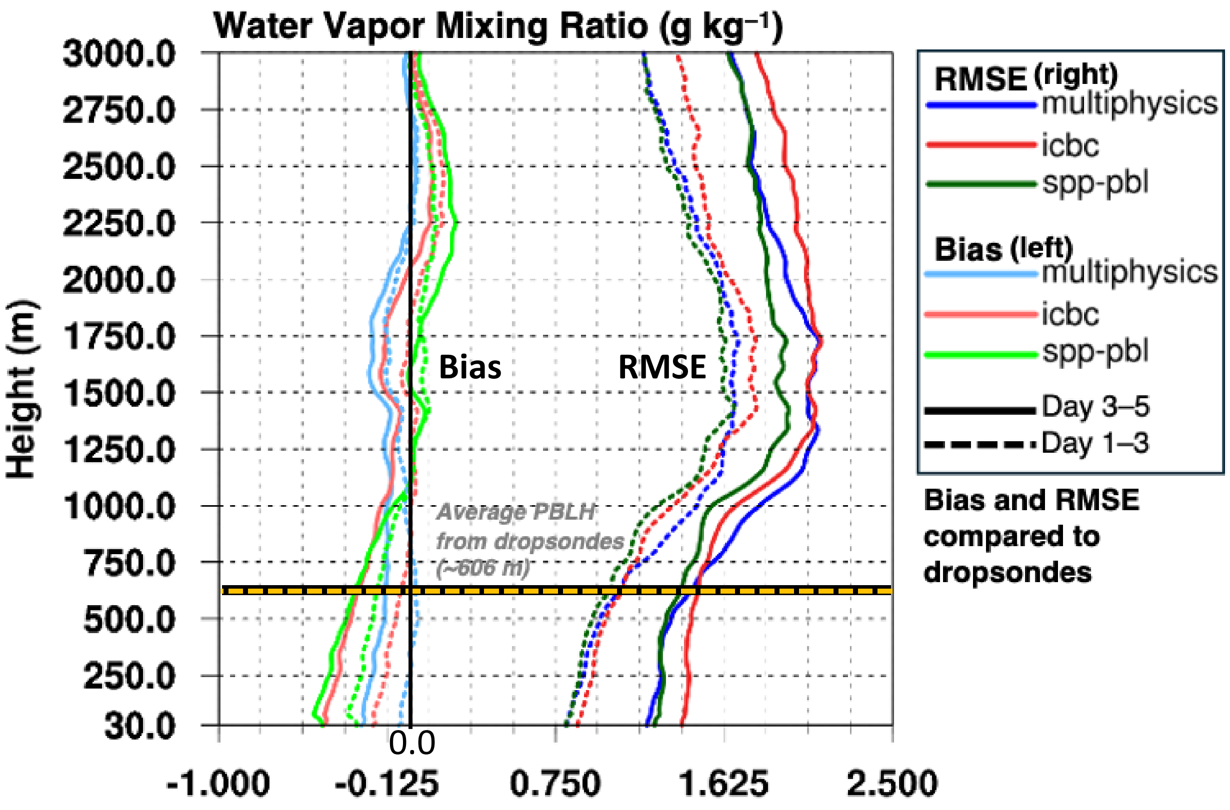

Ensemble mean errors (RMSE, bias) computed with respect to dropsonde observations during 5 case studies during WY2023

WRF *ensembles generated using (1) 11 PBL/SL combinations, (2) GEFS ICBCs, and (3) stochastic perturbed parameters (MYNN PBL/SL)*

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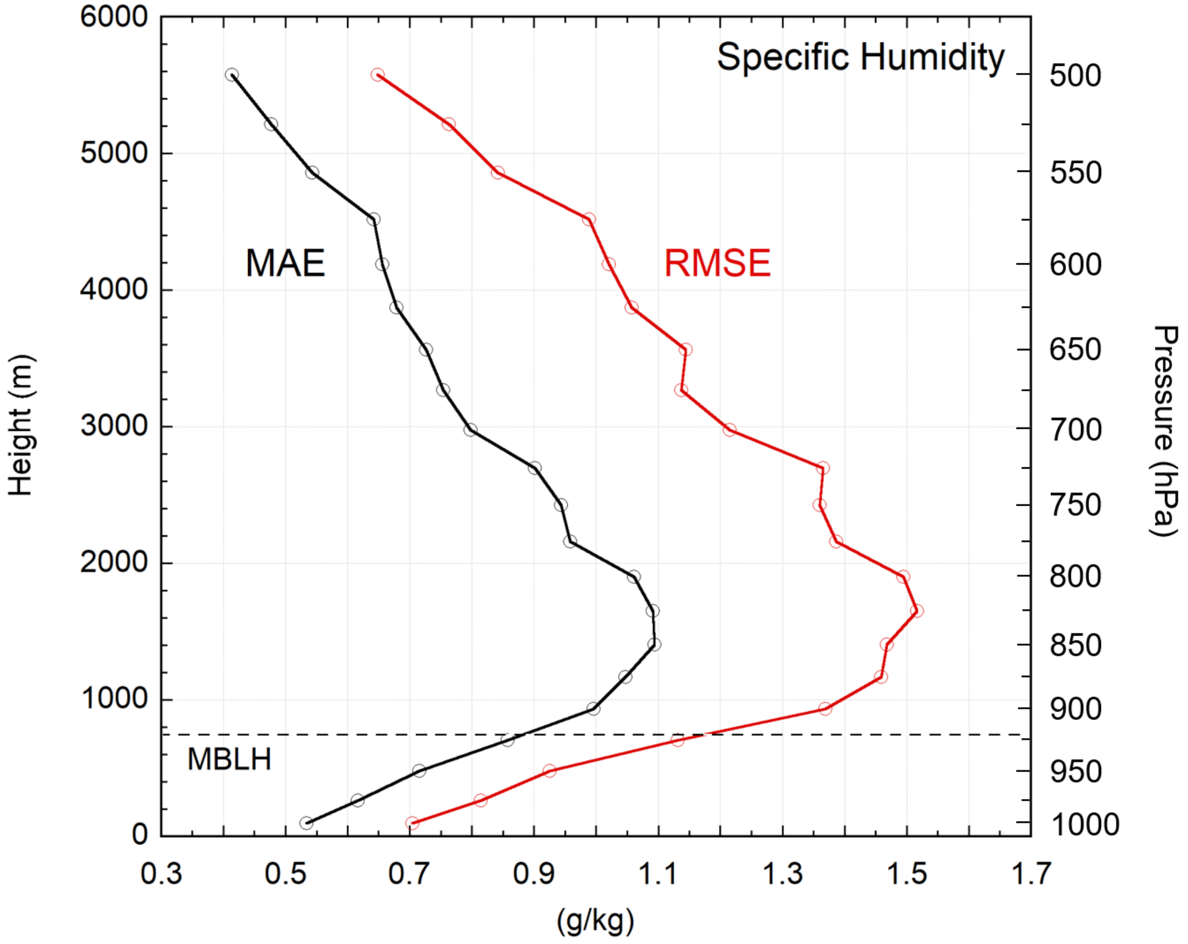

UFS-AR *model errors (RMSE, MAE) computed with respect to dropsonde observations during 6 case studies during WY2023*

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Research hypothesis: The MBL plays an important role in AR precipitation, and the propagation of MBL error and uncertainty can influence onshore precipitation forecast skill

Targeted MBL Uncertainty Representation Using a Modified Stochastic Perturbed Parameter Approach

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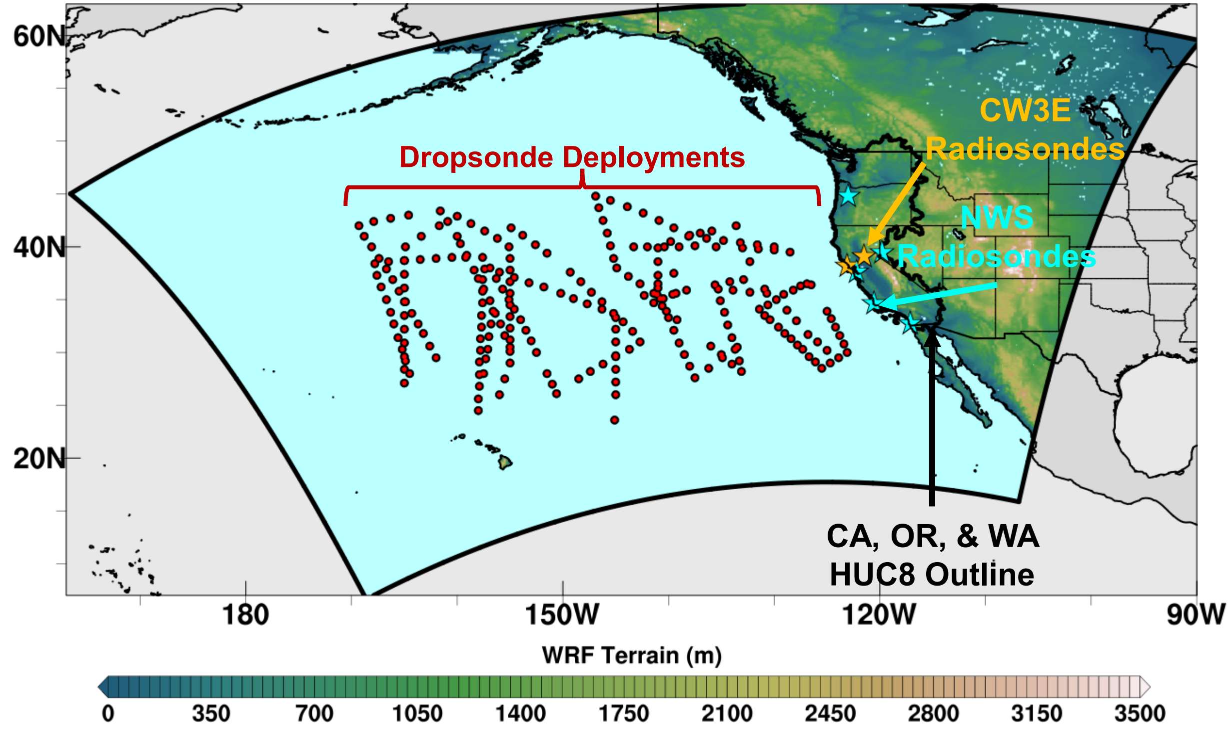
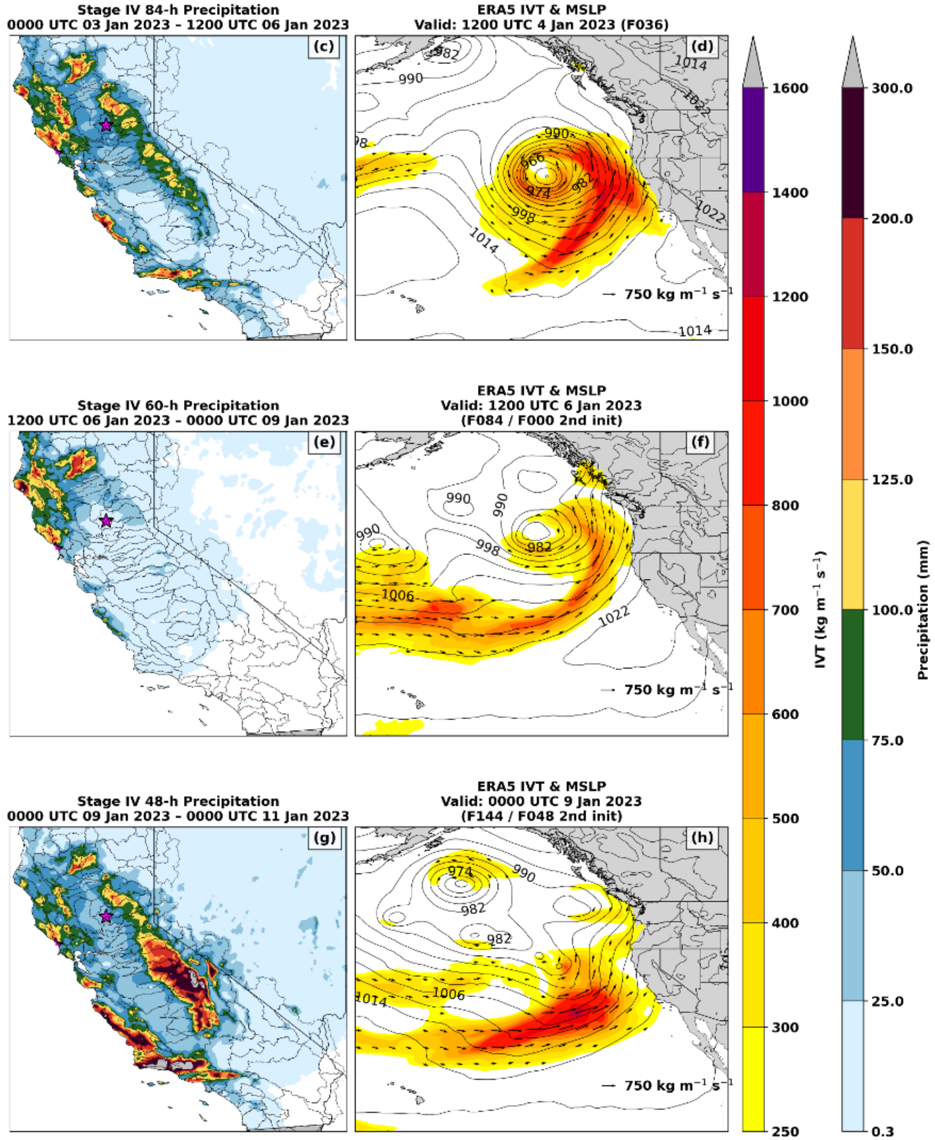
Case Selection

- **3–11 January 2023** [252 dropsondes during AR Recon IOPs 06–11; 39 USBOD, 35 USYUB radiosondes]





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Experiment Design

- WRF version 4.5.1; Initialized at **00 UTC 3 Jan** & **12 UTC 6 Jan**
  - MYNN-2.6 PBL & SL parameterization
- 2 initial time x 3 configurations x 31-member ensemble experiments
  - **Config. 1: PBL physics uncertainty only (SPP isolated to the MBL)**
  - **Config. 2: ICBC uncertainty only (GEFS)**
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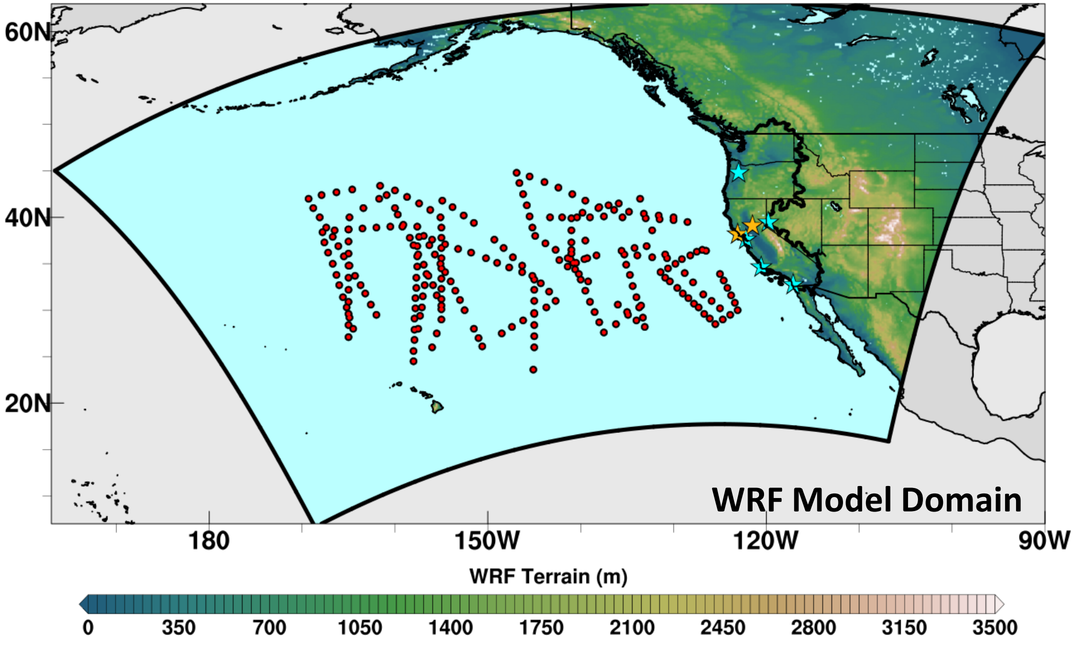
Physics Category	Scheme		Single Domain Configuration	Value
Microphysics	Thompson		**dx**	9000 m
PBL	MYNN-2.6		**ny x nx**	570 x 828
Radiation	RRTMG		**nz**	140 levels with constant dz (50 m) in the lowest 1.5 km
Cumulus	Grell-Freitas			
Surface Layer	MYNN		**IC/BCs**	GEFS
Land Surface	Noah-MP		**dt**	10 s
Model Error Representation: *Modified* Stochastic Perturbed Parameter (SPP) Scheme				



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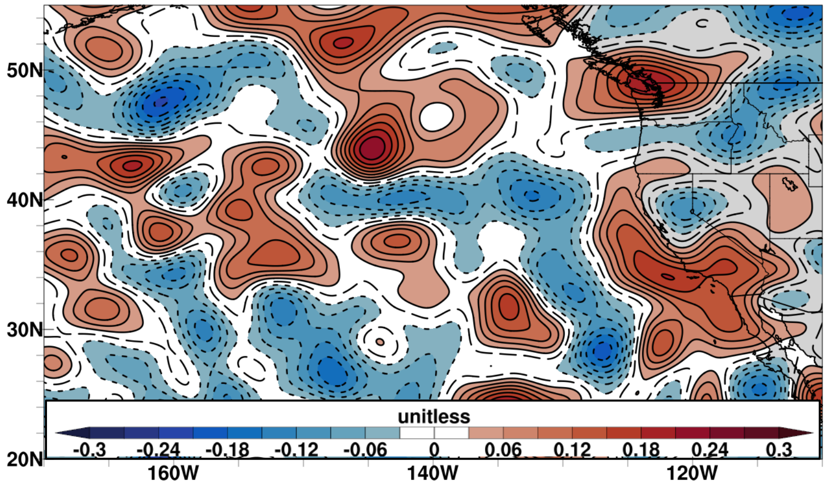
Targeted PBL Physics Uncertainty – Stochastic Perturbed Parameters (SPP)

- Represent uncertainty associated with specific parameterized processes using a spatially and temporally evolving random noise field (e.g., Jankov et al. 2017, 2019, 2020).
- In MYNN PBL & SL schemes, perturbations are applied as **multiplicative noise (a scaling)** to the **thermal and momentum diffusivity coefficients, entrainment coefficient, total water vapor, and thermal/moisture/aero roughness lengths.**

Example of the multiplicative SPP perturbation field



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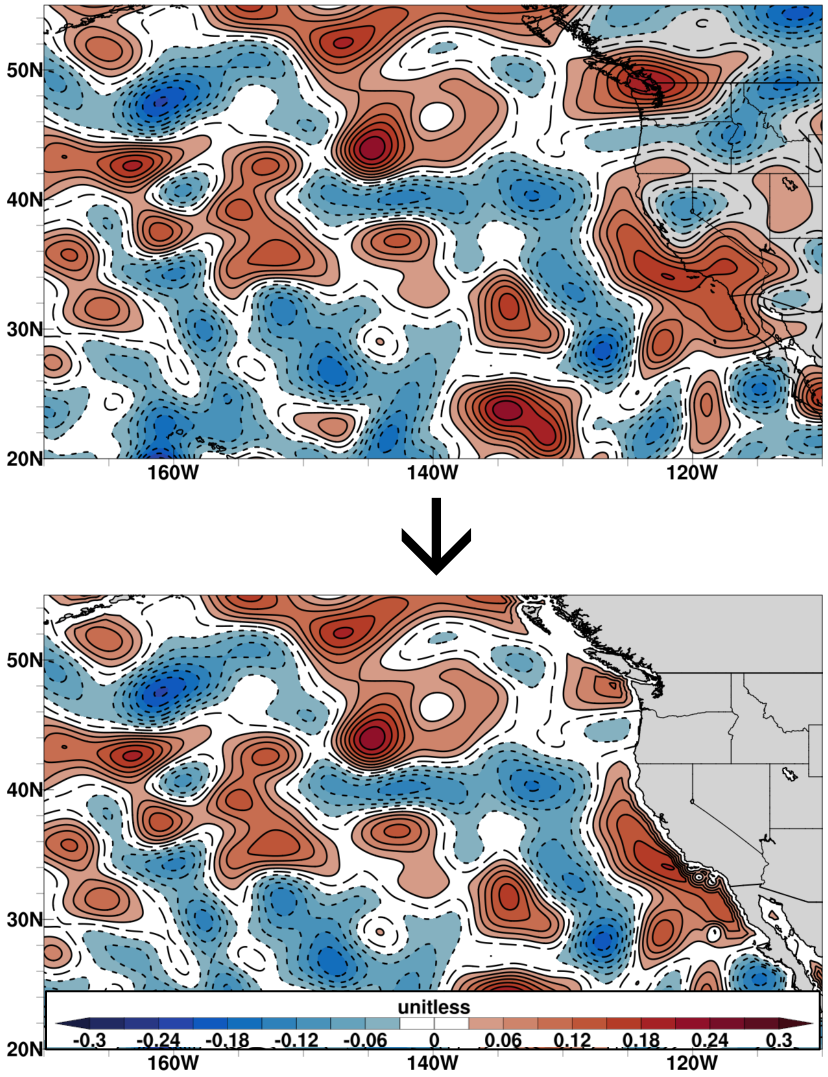
Isolating Uncertainty within the MBL

- To directly represent model error in the MBL, only – Modified WRF code to enable (1) horizontal tapering of the perturbations to **zero over non-ocean grid points (100–10 km taper)** and…

Horizontal Tapering of SPP Perturbations



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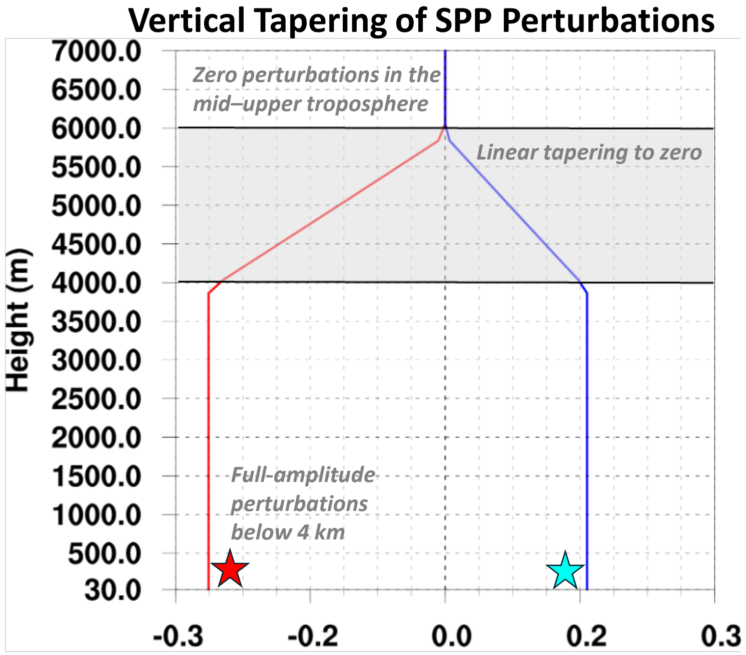
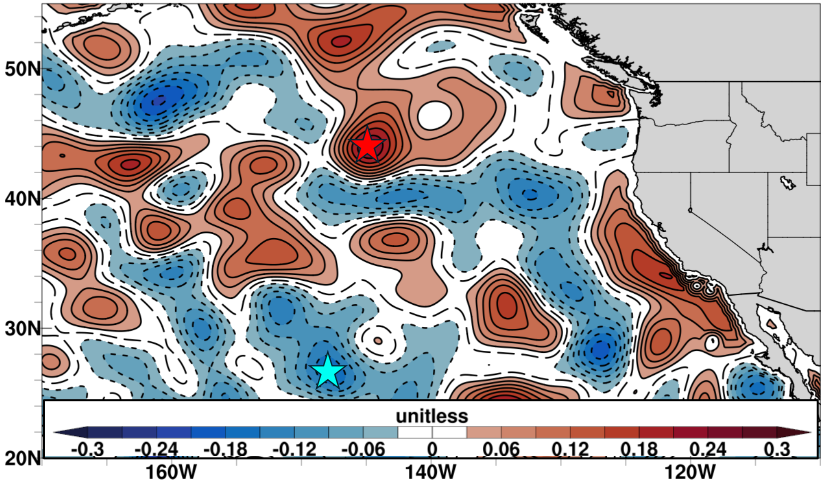
Isolating Uncertainty within the MBL

- To directly represent model error in the MBL, only – Modified WRF code to enable (1) horizontal tapering of the perturbations to **zero over non-ocean grid points (100–10 km taper)** and (2) **zero in the mid–upper troposphere (4–6 km taper)**





Results 1: Comparison of SPP-MBL, ICBC, and Combined SPP-MBL+ICBC Ensemble Configurations

N=31 members | 100–10 km horizontal masking | 4–6 km vertical masking | A=0.3, T=72 h, L = 150 km

Results 1: Comparison of SPP-MBL, ICBC, and Combined SPP-MBL+ICBC Ensemble Configurations

Ensemble Standard Deviation at Dropsonde Locations

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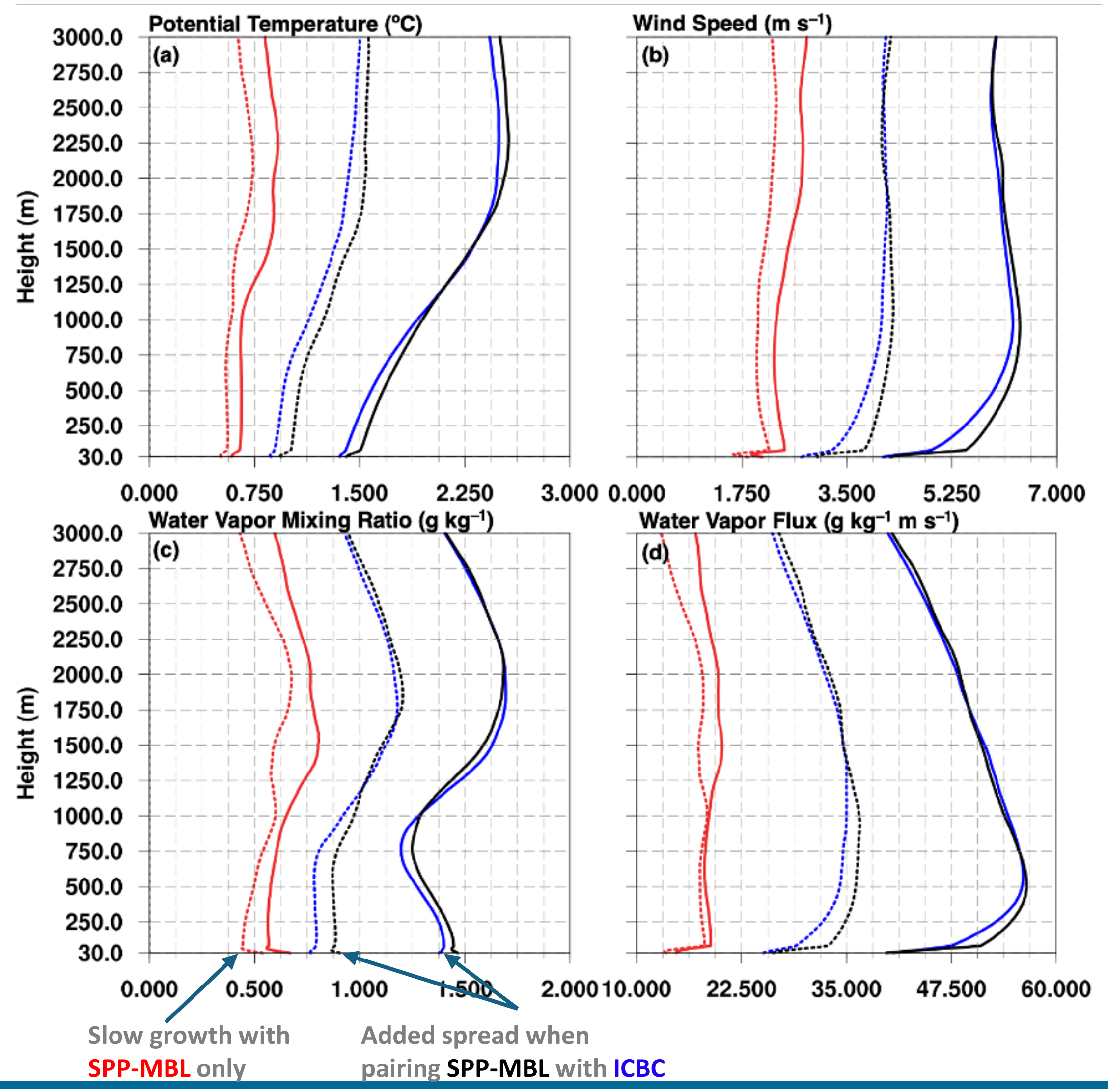
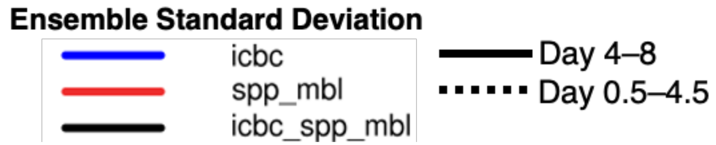


- Little growth in ensemble variability beyond day 4 for SPP-MBL
- SPP-MBL *increases* ensemble standard deviation at dropsonde locations when paired with ICBC variability



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RMSE (right lines) and Bias (left lines) Compared to Dropsonde Observations

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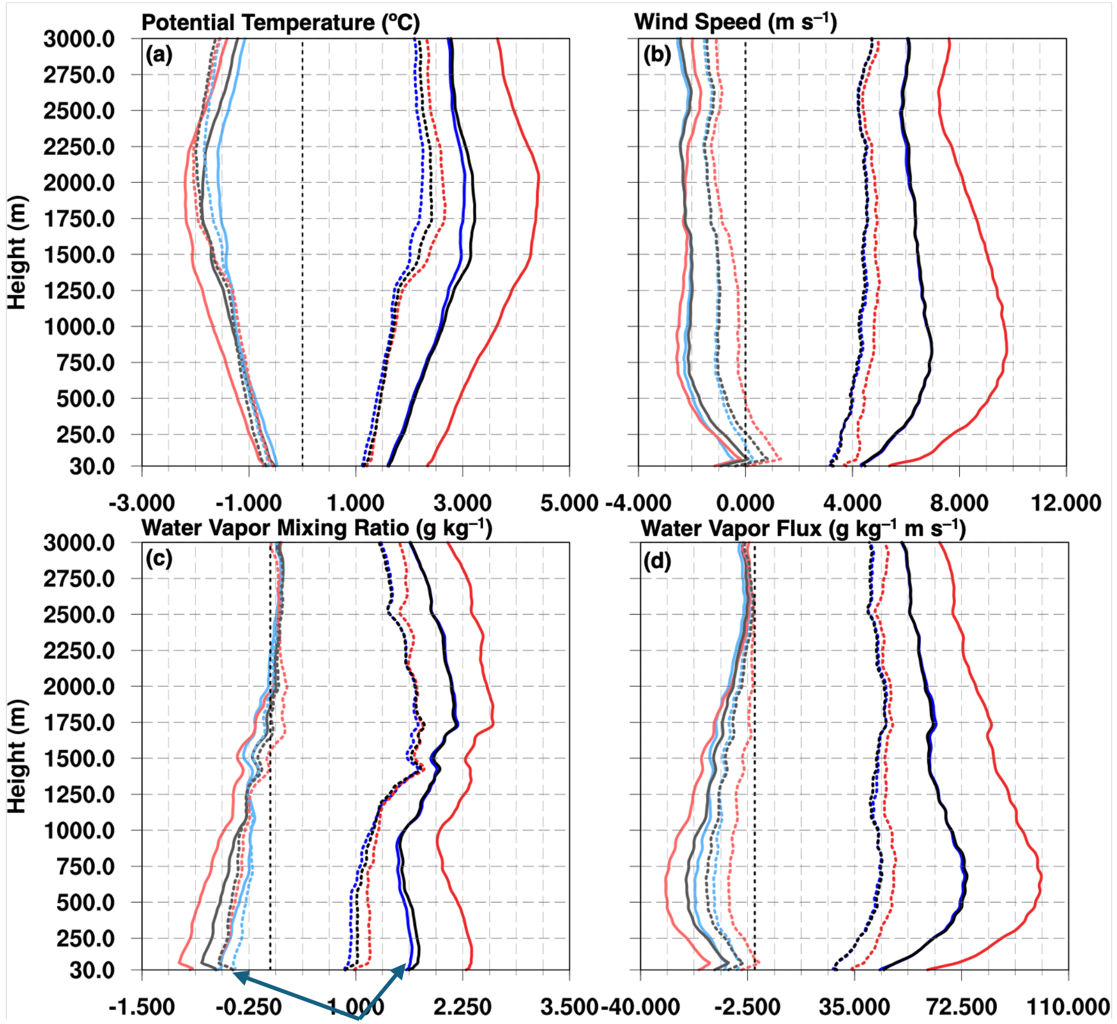
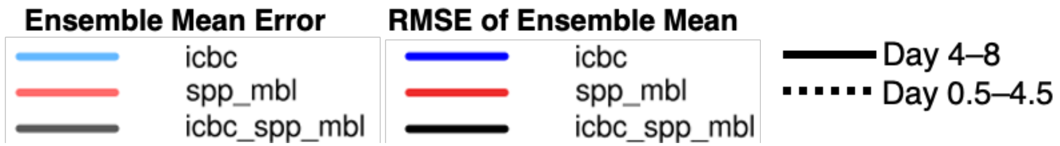


Increased water vapor RMSE and bias when pairing **SPP-MBL** with **ICBC**

- Ensemble mean errors are larger for SPP-MBL (less spread)
- SPP-MBL *increases* RMSE for temperature (above MBL) and water vapor mixing ration (within the MBL) at medium and long forecast lead times.
- SPP-MBL increases a dry bias in the MBL (all perturbed members have a larger dry bias than an unperturbed control), and increases a negative water vapor flux bias near the MBL top



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Results 1: Comparison of SPP-MBL, ICBC, and Combined SPP-MBL+ICBC Ensemble Configurations

Bias Compared to Dropsonde Observations (31-member spp-mbl experiment)

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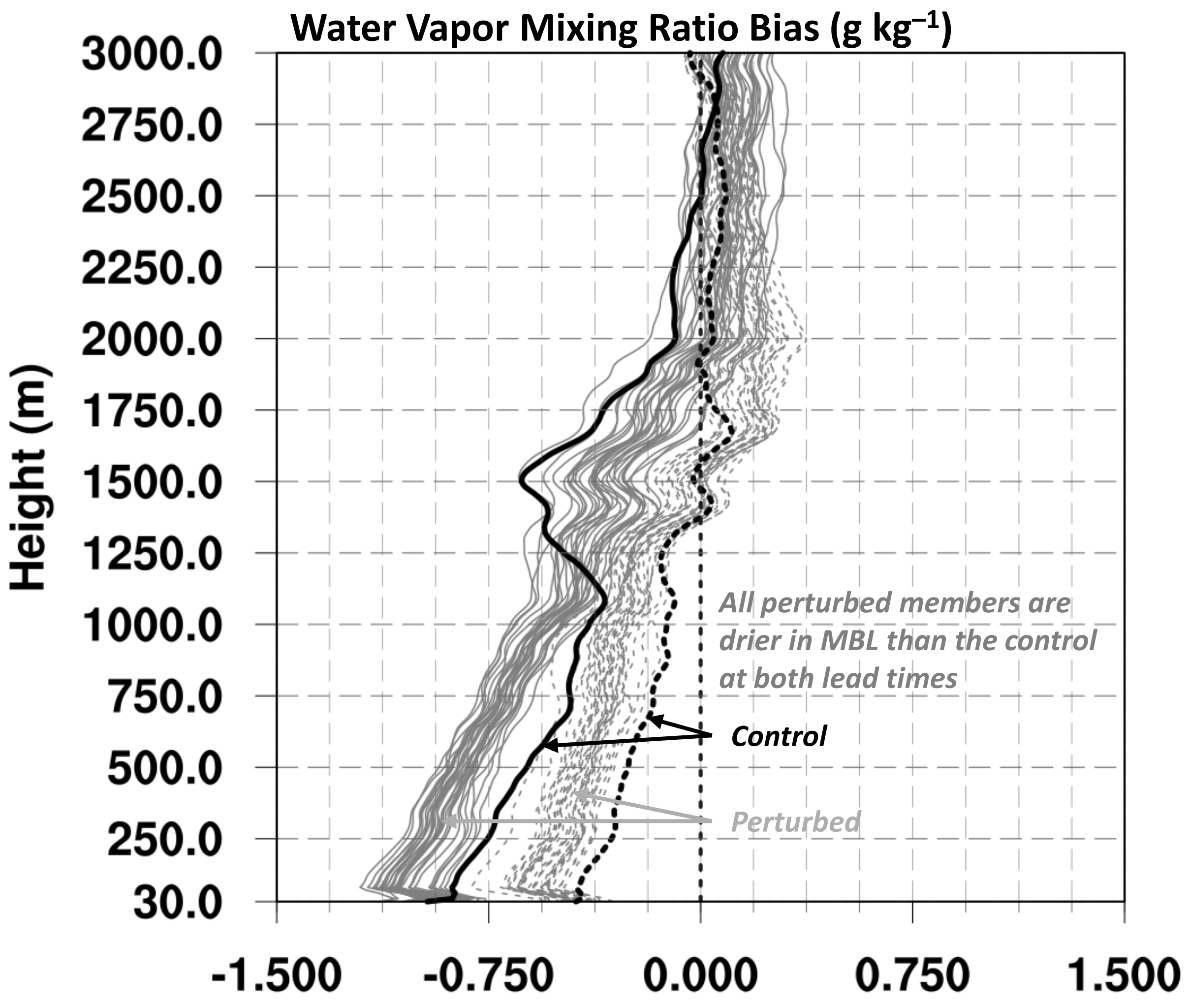

- Ensemble mean errors are larger for SPP-MBL (less spread)
- SPP-MBL *increases* RMSE for temperature (above MBL) and water vapor mixing ration (within the MBL) at medium and long forecast lead times.
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Mean Error of Ensemble Members

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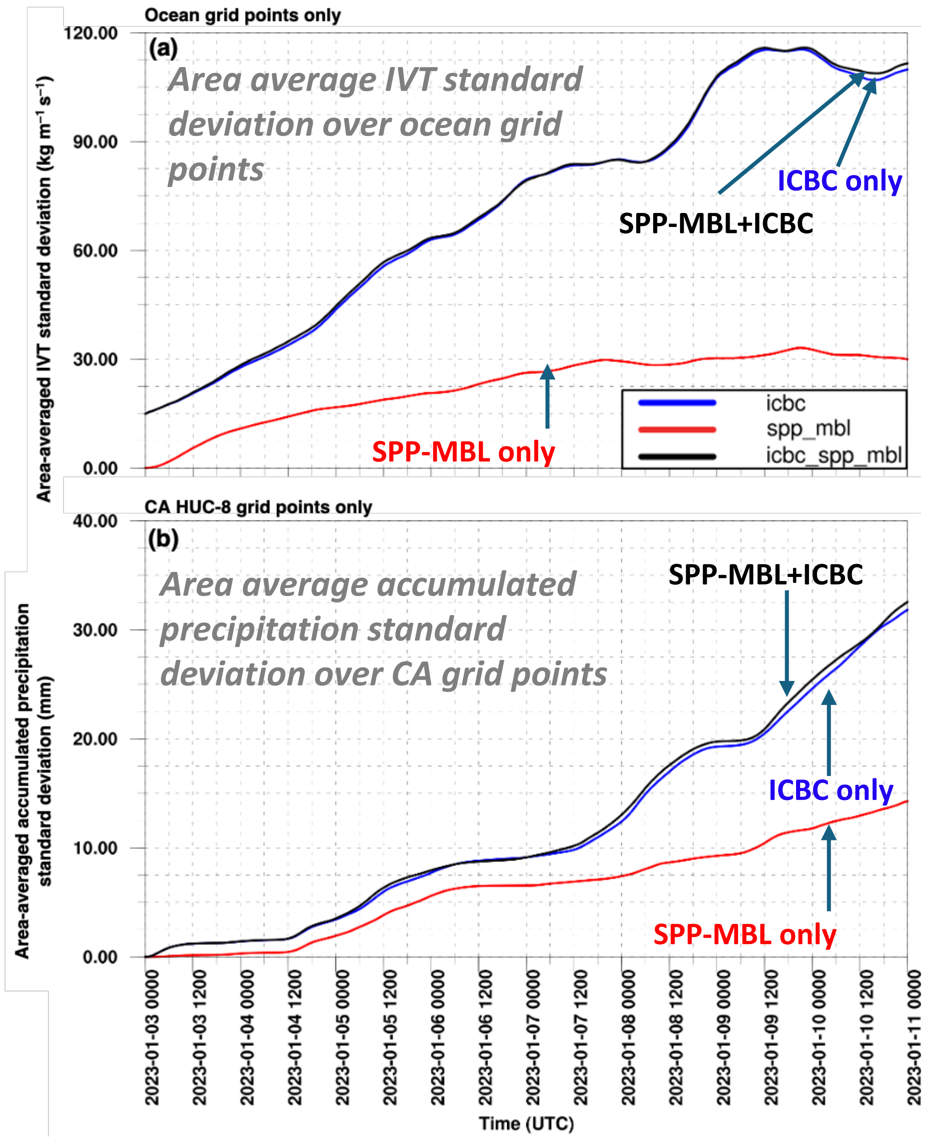

- Applied in isolation, SPP-MBL introduces variability in IVT over the ocean and onshore precipitation.
- SPP-MBL spread is small compared to that associated with ICBC variability (expected result).
- SPP-MBL adds a small amount of spread when paired with ICBC variability.

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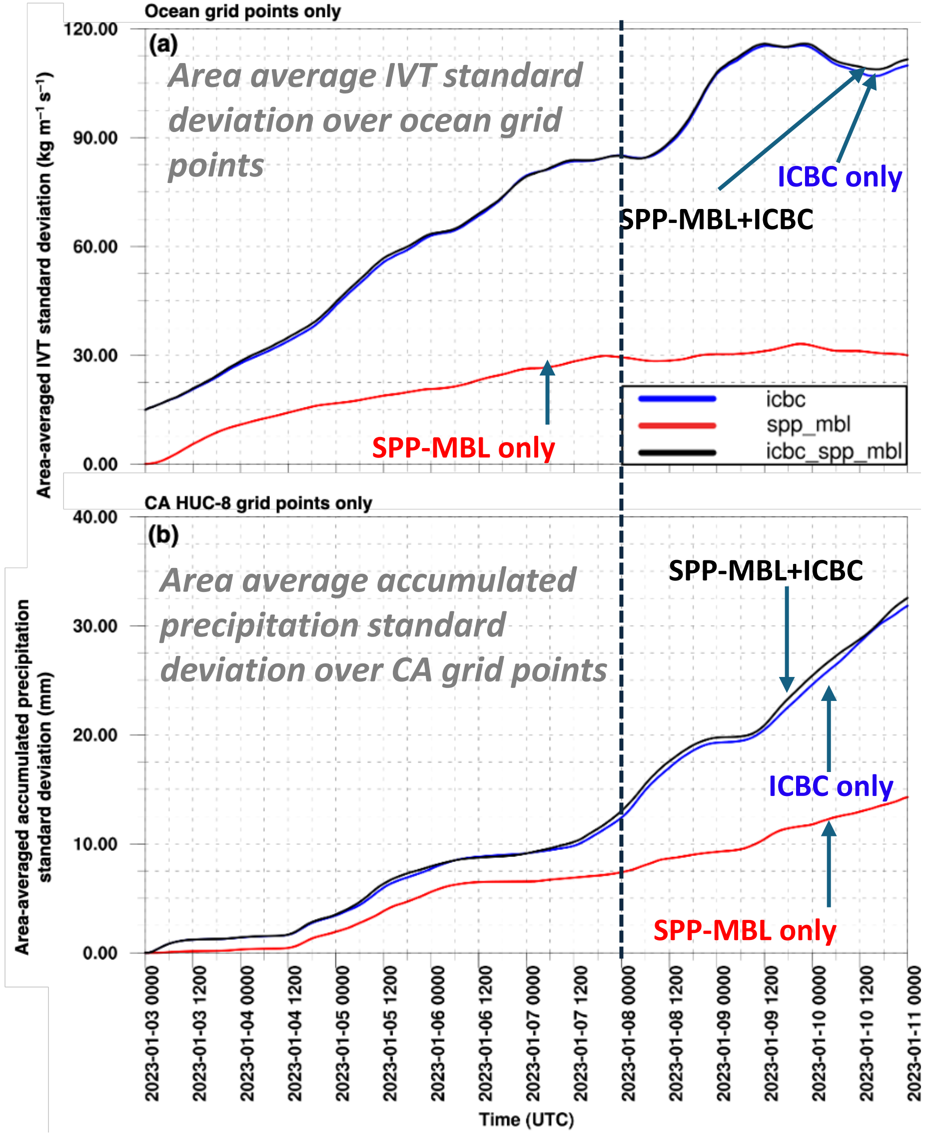

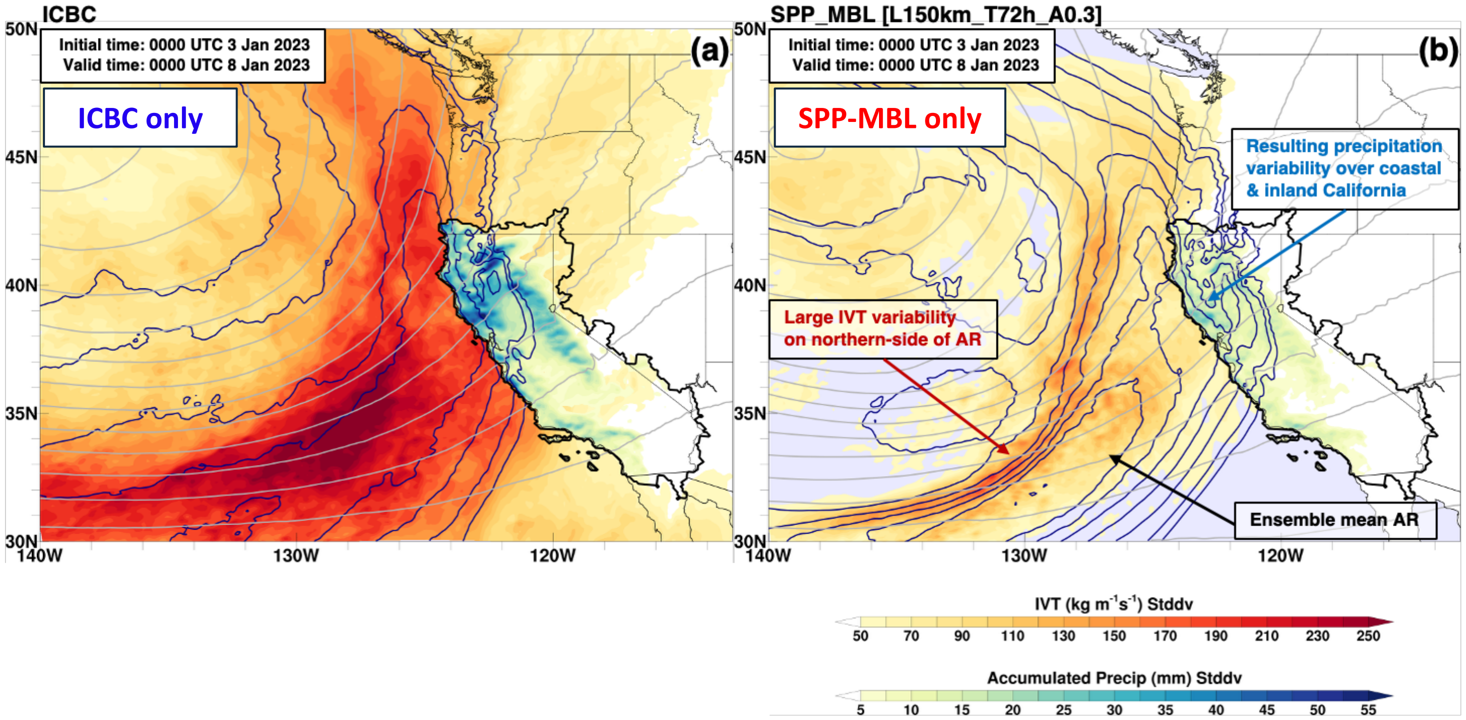

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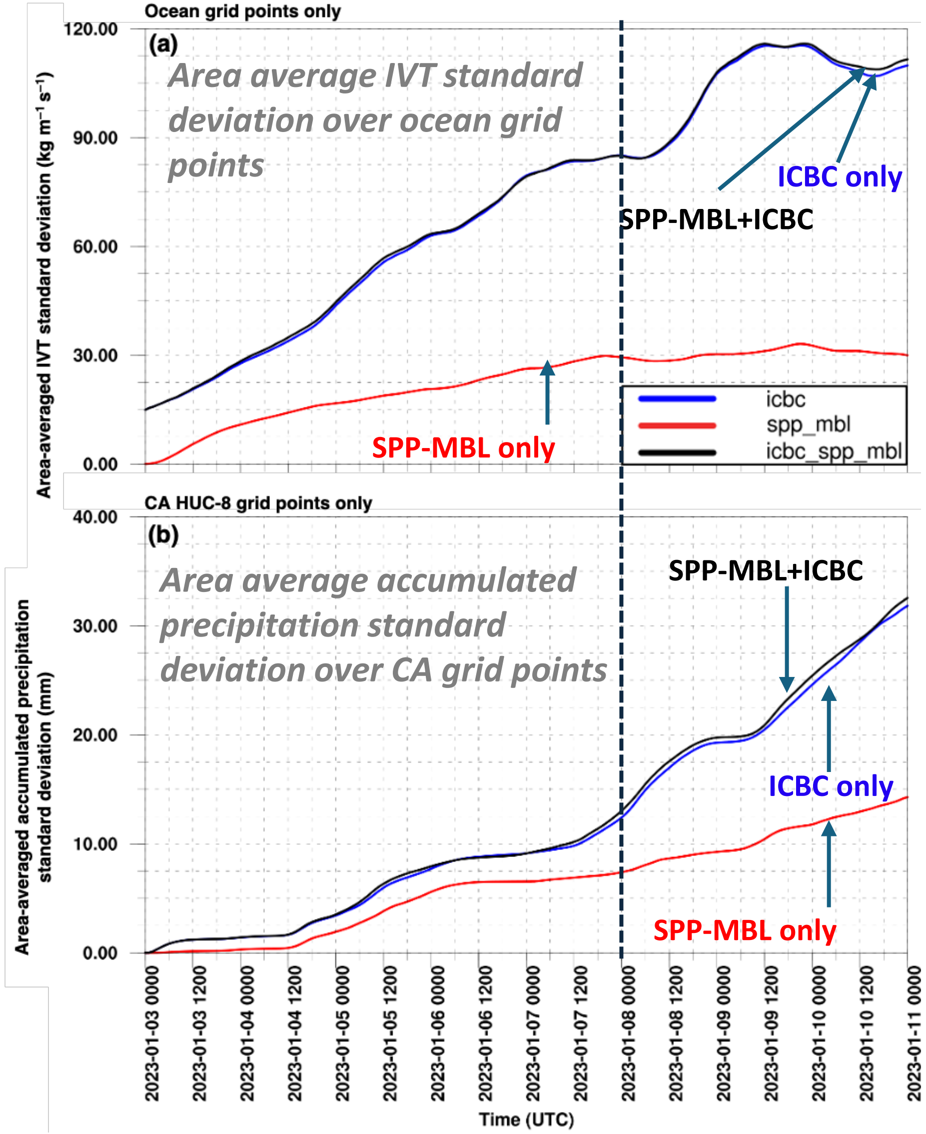

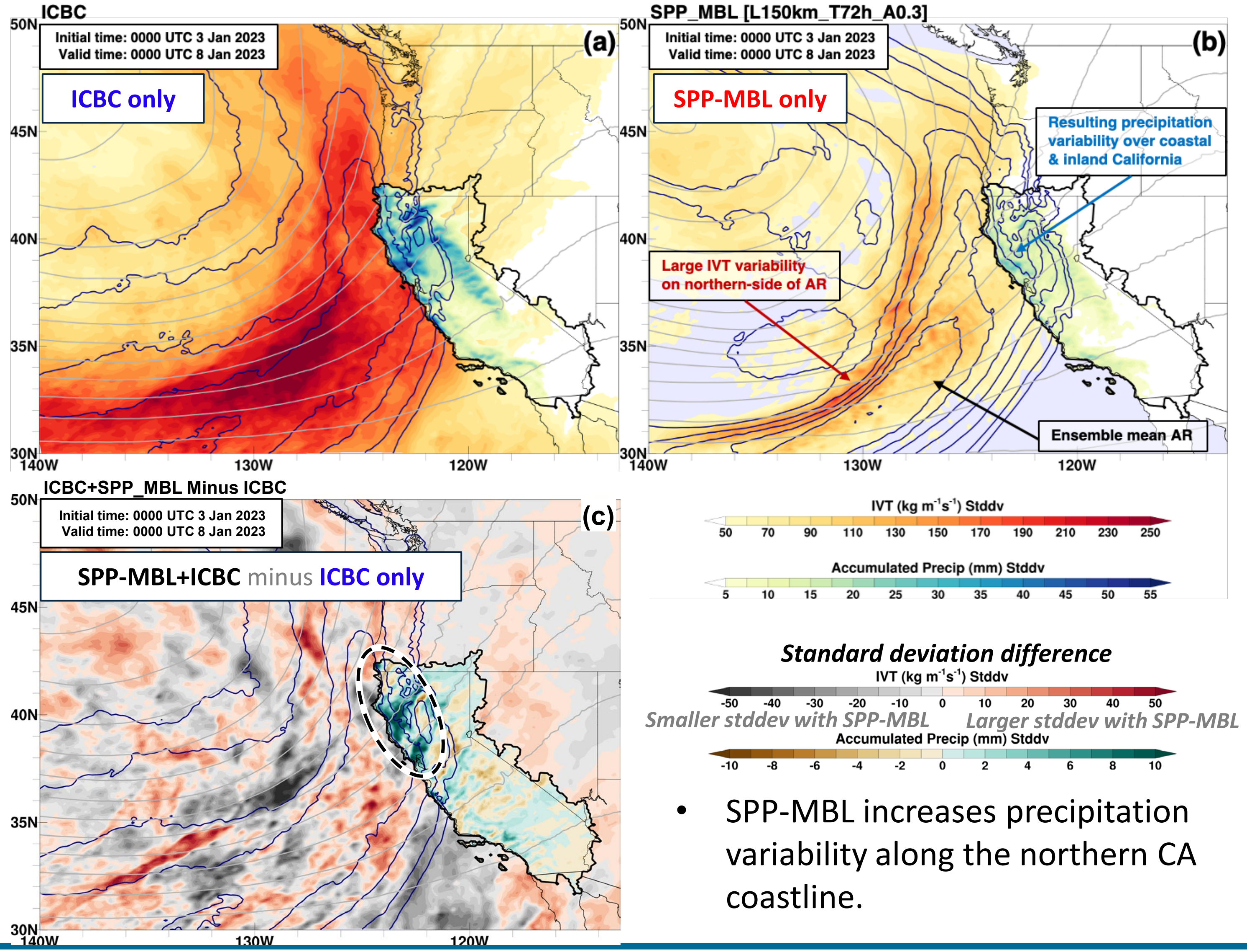

- SPP-MBL increases precipitation variability along the northern CA coastline.

Results 2: SPP-MBL Processes

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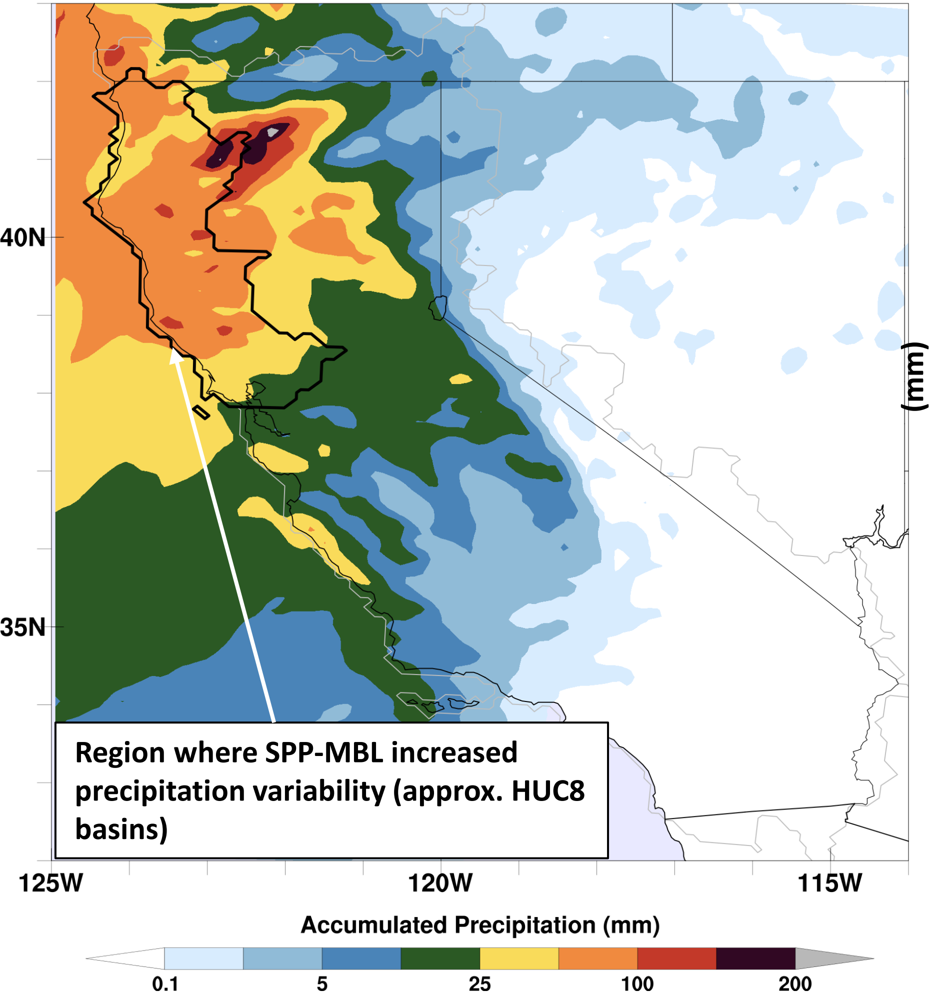
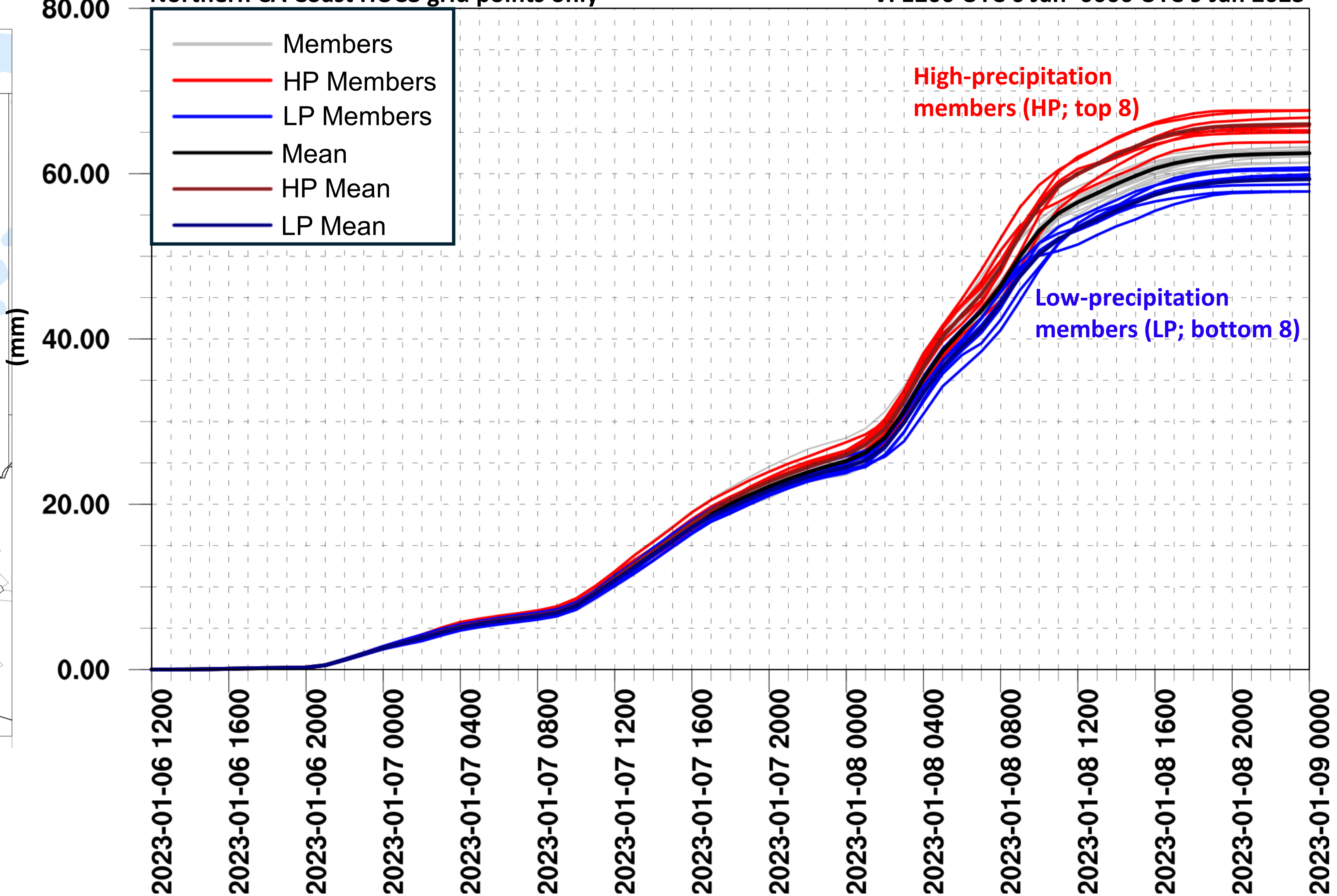
SPP-MBL Ensemble Mean Accumulated Precip
1200 UTC 6 Jan – 0000 UTC 9 Jan 2023





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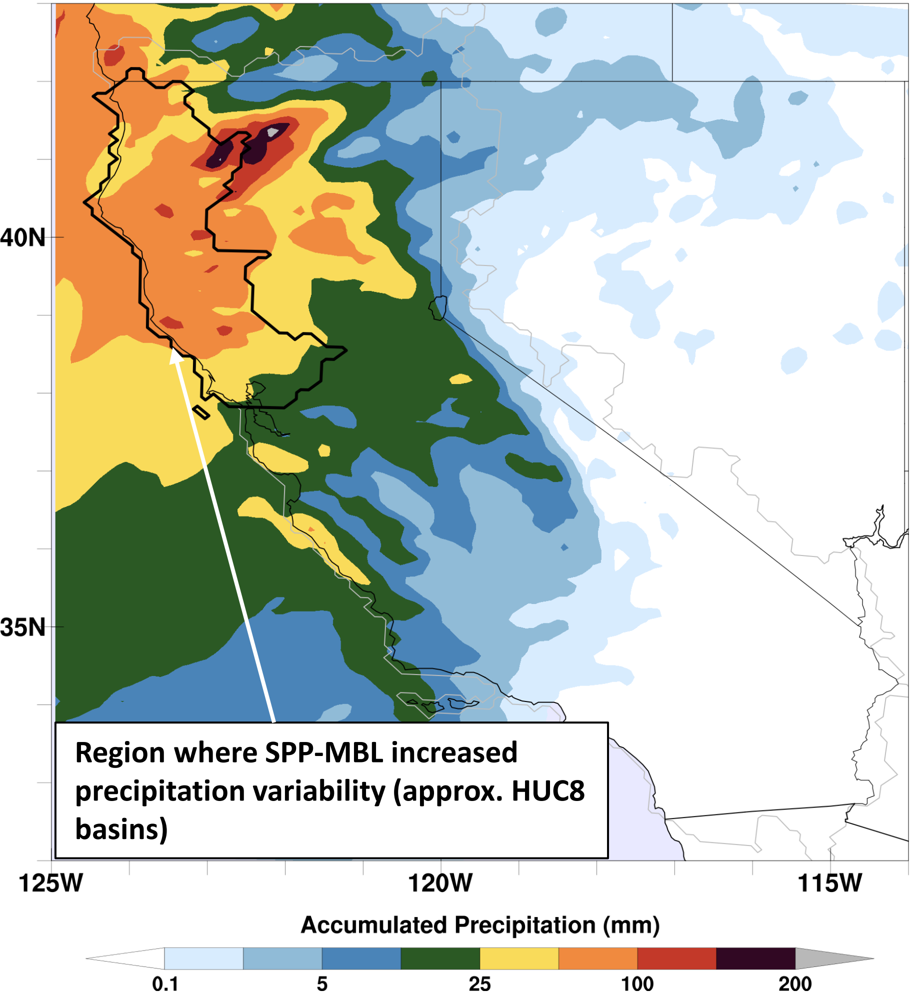

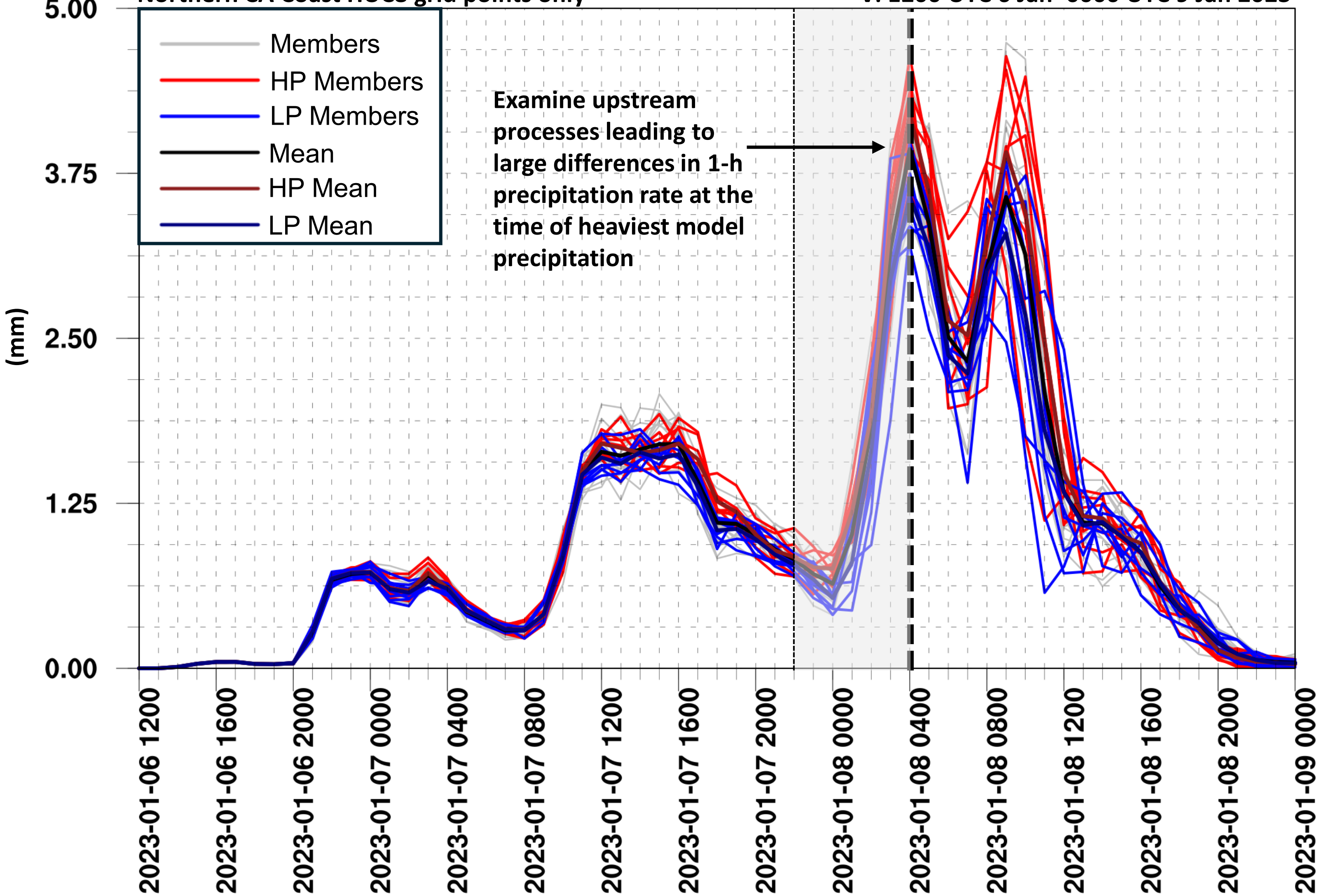

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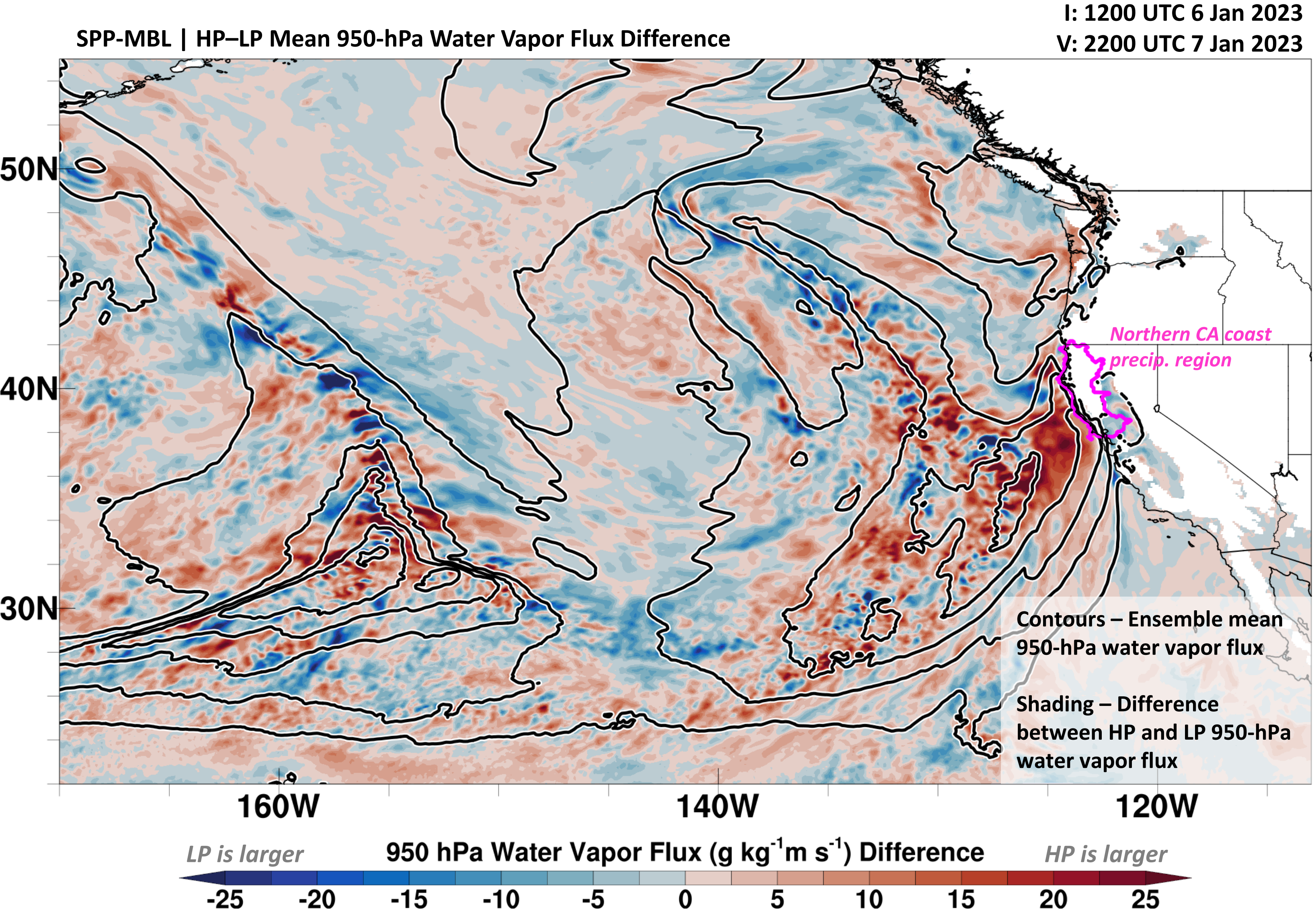
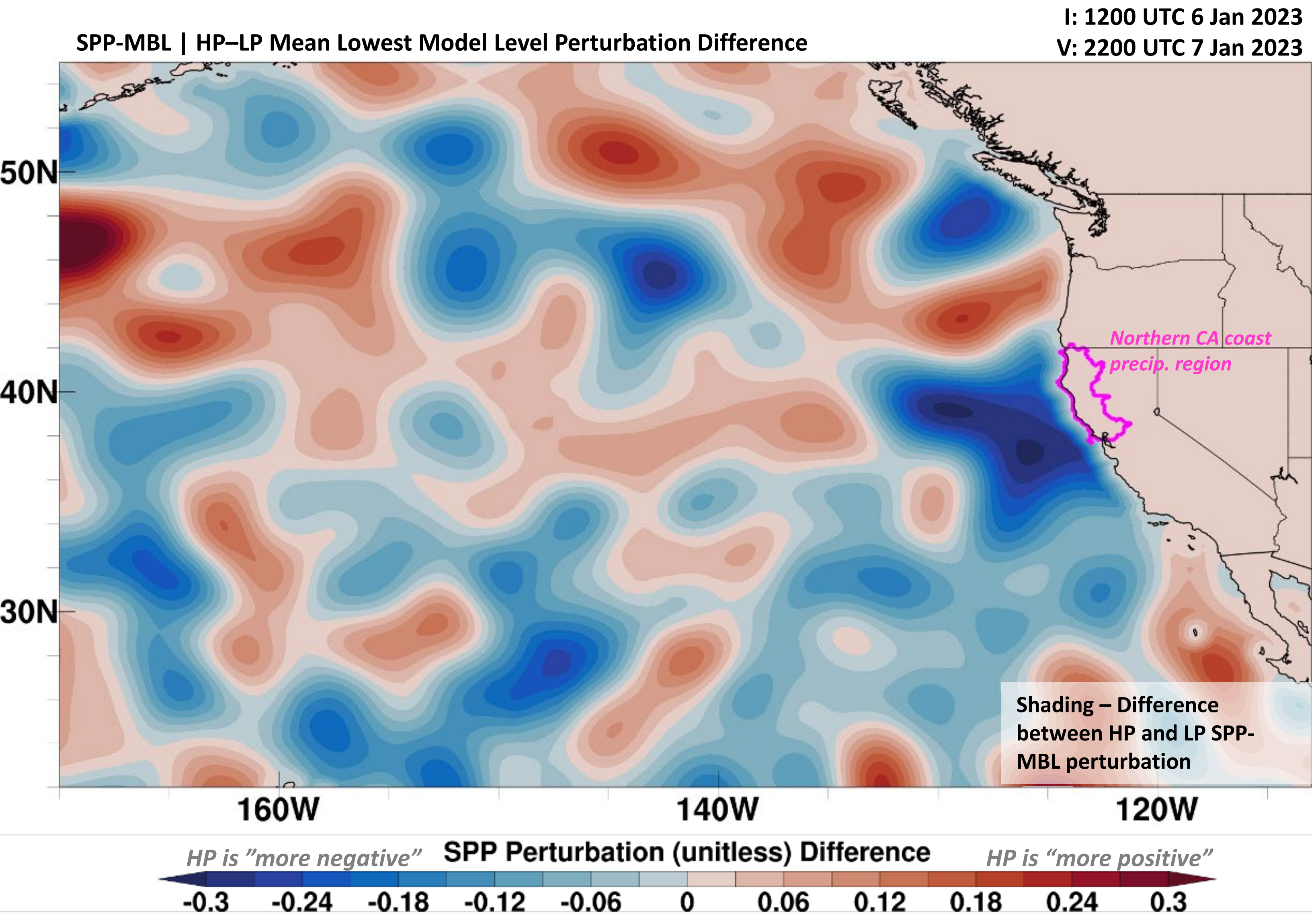


(1) Water Vapor Flux Near MBLH

- Higher-precipitation members have larger horizontal water vapor flux within the MBL

Results 2: SPP-MBL Processes



(1) Water Vapor Flux Near MBLH

- Higher-precipitation members have larger horizontal water vapor flux within the MBL.

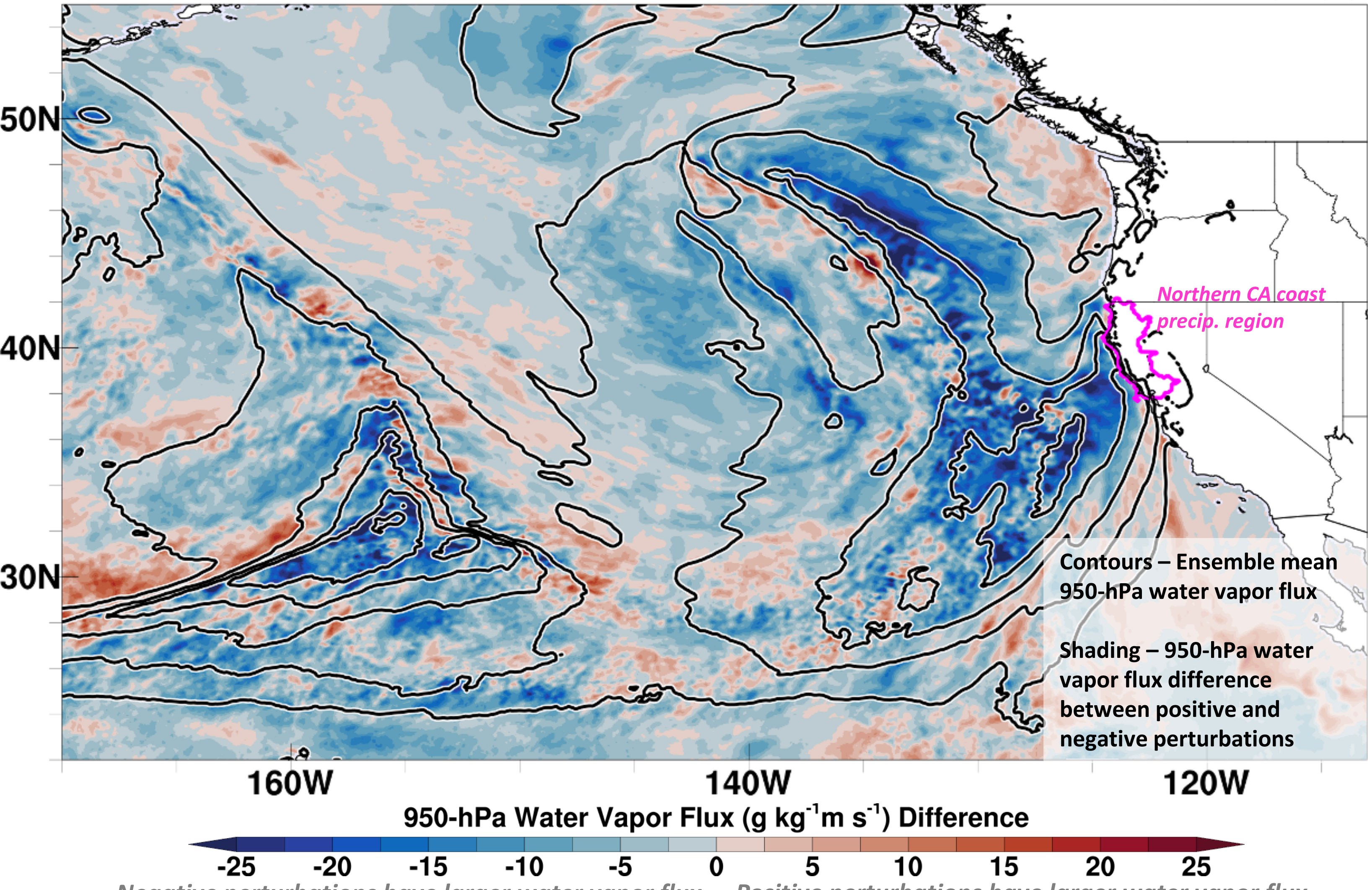
(2) Differences in Instantaneous Perturbation Field

- Higher-precipitation members have larger-negative MBL parameter perturbations along the coast compared to low-precipitation members.

Results 2: SPP-MBL Processes

SPP-MBL | Mean Positive–Mean Negative Perturbed Grid Point
950-hPa Water Vapor Flux Difference

I: 1200 UTC 6 Jan 2023
V: 2200 UTC 7 Jan 2023



Negative perturbations have larger water vapor flux *Positive perturbations have larger water vapor flux*

(1) Water Vapor Flux Near MBLH

- Higher-precipitation members have larger horizontal water vapor flux within the MBL.

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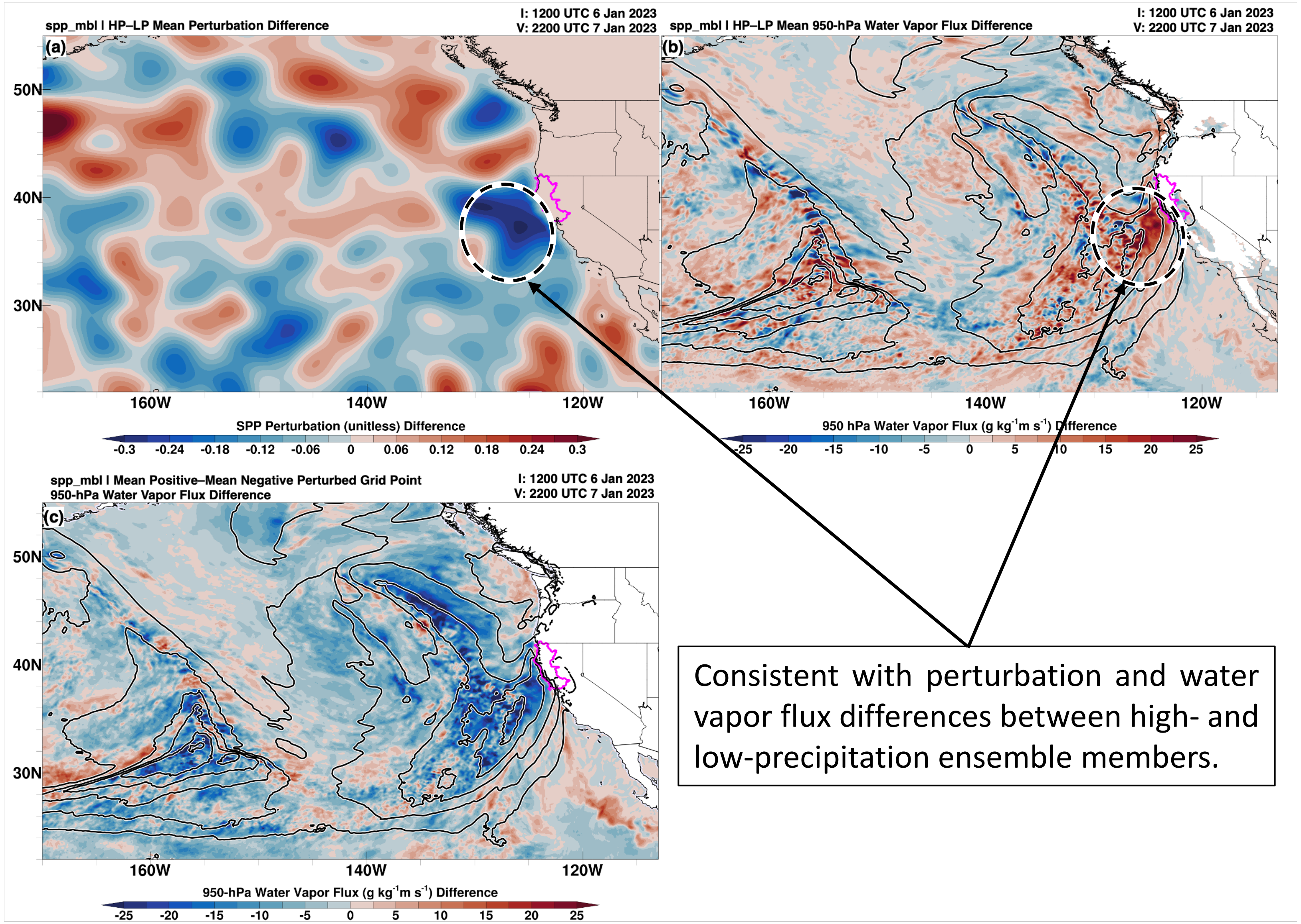
- Higher-precipitation members have larger-negative MBL parameter perturbations along the coast compared to low-precipitation members.

(3) Direct Impact of Perturbations on Water Vapor Flux

- Compute the ensemble mean over (a) only positively-perturbed grid points and (b) only negatively-perturbed grid points. Subtracting (a) – (b) …
  - Negative parameter perturbations (i.e., suppressed diffusivity coefficients / water vapor / entrainment / roughness lengths), results in greater near-surface horizontal water vapor flux.

Results 2: SPP-MBL Processes



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Summary and Next Steps

- **Goal:** Improve forecasts of atmospheric rivers and their associated precipitation through better understanding and model representations of the MBL.

- **Research hypothesis:** The MBL plays an important role in AR precipitation, and the propagation of MBL error and uncertainty can influence onshore precipitation forecast skill

- From prior and ongoing research, model error generally increases with height in the MBL, and is maximized near the MBLH.

- When paired with initial and boundary condition variability, MBL parameter uncertainty can increase ensemble dispersion, but can also asymmetrically drive biases.

- Targeted representation of MBL uncertainty using a modified stochastic perturbed parameter approach can increase ensemble dispersion via indirect (but systematic) modulation of precipitation processes (e.g., near-surface water vapor flux).

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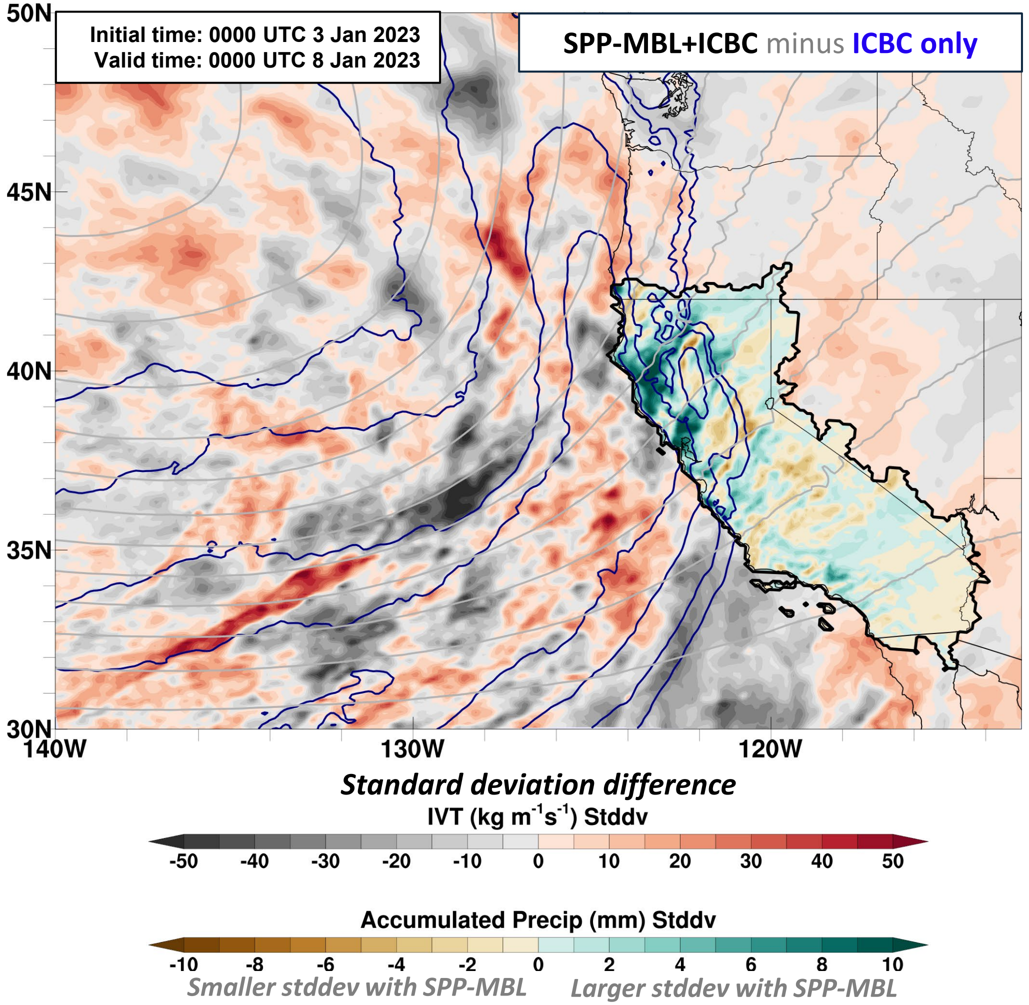
- **Work is ongoing** to quantify the impact of targeted MBL perturbations on precipitation forecast skill as a function of forecast lead time and geographic location.



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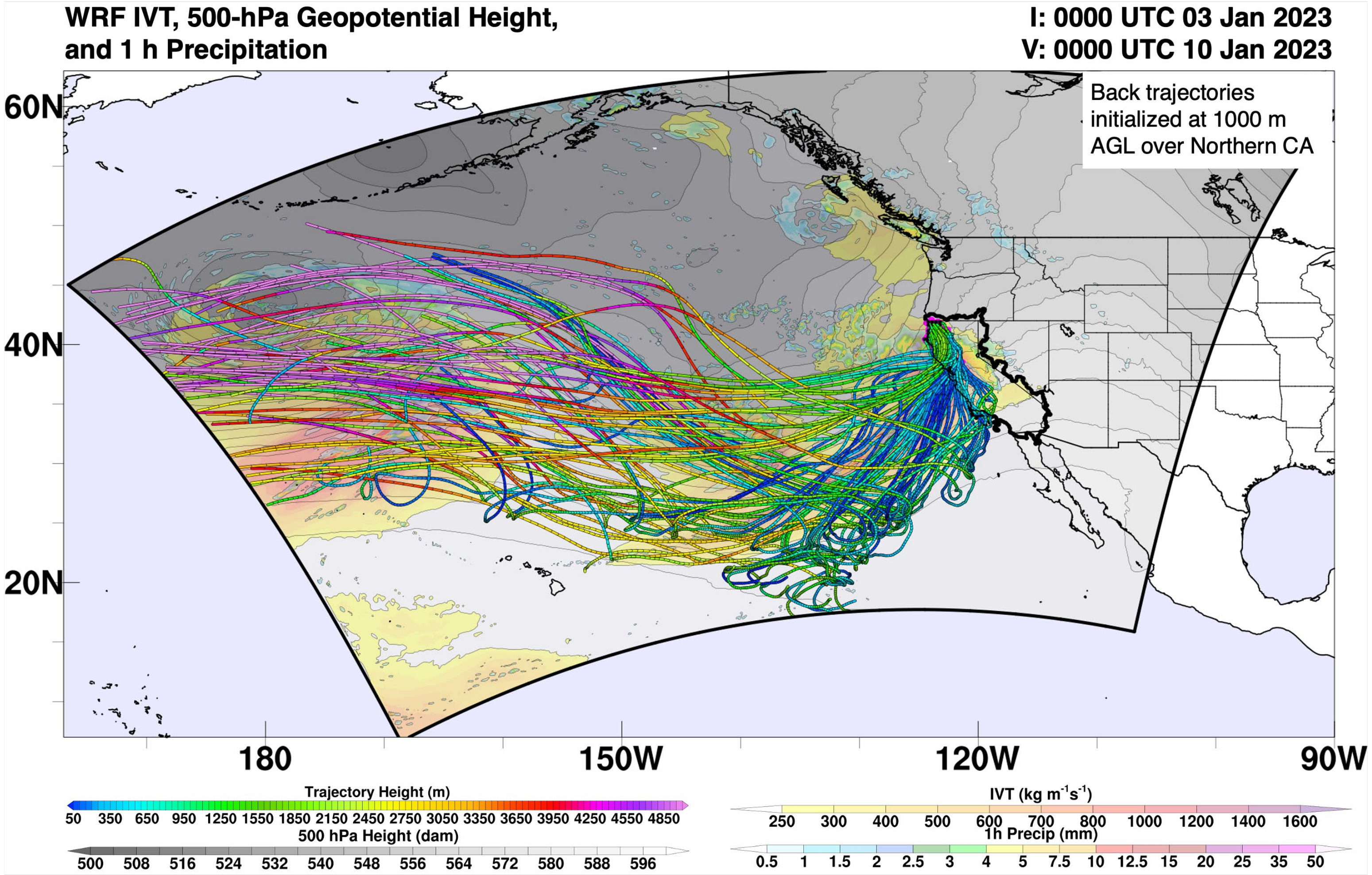
- **Work is ongoing** to quantify the impact of targeted MBL perturbations on precipitation forecast skill as a function of forecast lead time and geographic location.

- **Work is ongoing** to document the impact of more-distant perturbations on onshore precipitation.



Summary and Next Steps

Contact: klupo@ucsd.edu

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- How do stochastic parameter perturbations impact model bias?

- What is the impact of SST uncertainty and the model representation of surface fluxes on MBL structure?

- Can PBL and surface layer parameterizations be better optimized for AR forecasting?

Extra Slides: SPP in WRF

Extra Slides: Multiphysics Differences relative to Ensemble Mean

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Evaluation of 5 AR Cases During WY2023

Average IVT of ensemble mean

Member mean – Ens. Mean

- **Upper-left:** Average ensemble mean IVT from forecast hour 0–120, hourly, for all cases.
- **Other panels:** Difference between average member mean and ensemble mean.
- **Inset text:** Water vapor flux bias (compared to dropsondes) at the observed PBLH

- Larger IVT → smaller negative QVF bias at MBLH
- Smaller IVT → larger negative QVF bias at MBLH

Member has smaller IVT

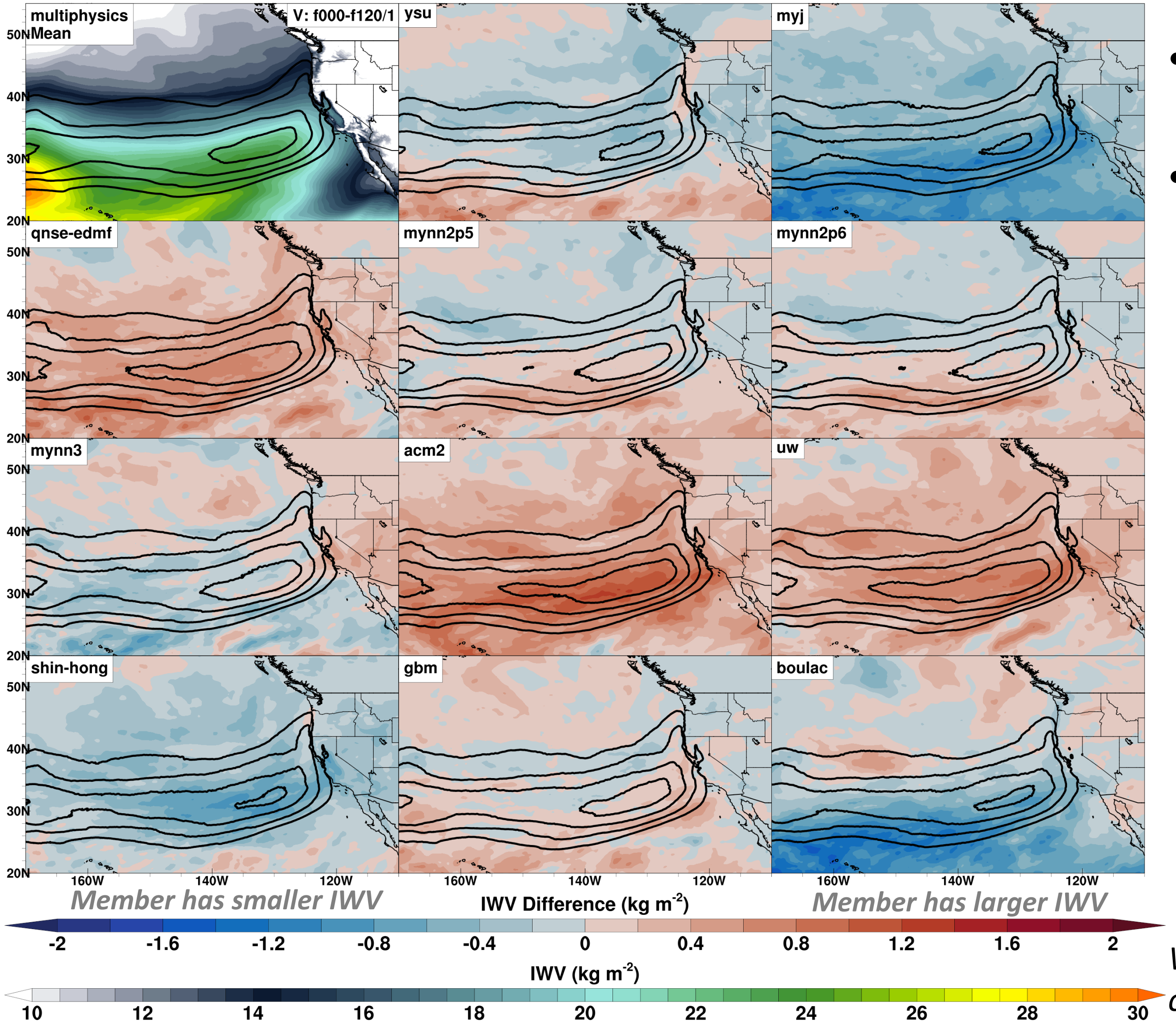
Member has larger IVT

WRF ”multiphysics” ensemble generated using 11 PBL/SL combinations over 5 case studies

Figures adapted from “Verification of Marine Boundary Layer Forecasts in Atmospheric River Environments using Dropsonde Observations” (Lupo et al. in review)

Extra Slides: Multiphysics Differences relative to Ensemble Mean

Evaluation of 5 AR Cases During WY2023



- **Upper-left:** Average ensemble mean IWV from forecast hour 0–120, hourly, for all cases.
- **Other panels:** Difference between average member mean and ensemble mean.

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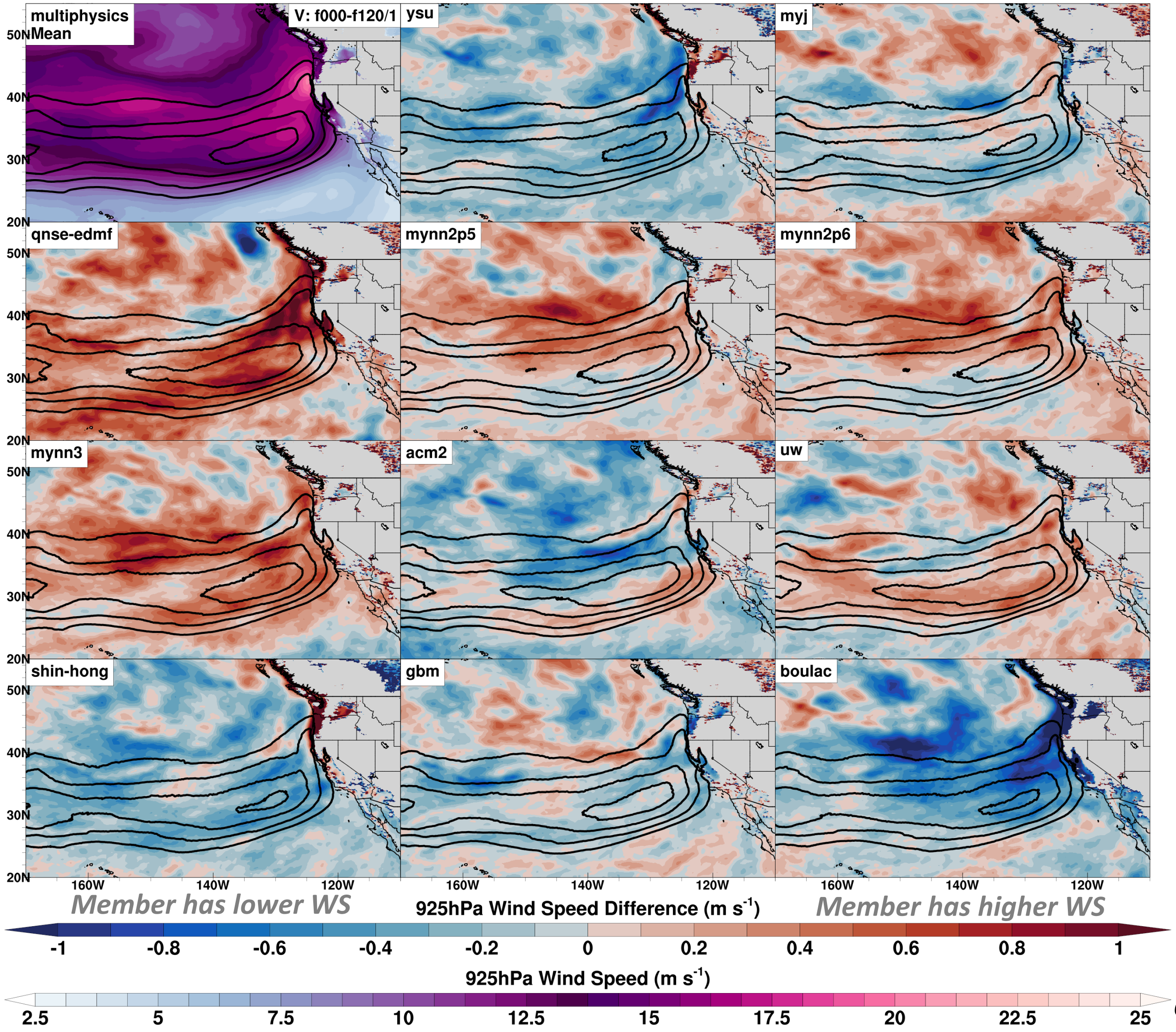

- **Upper-left:** Average ensemble mean 925 hPa wind speed from forecast hour 0–120, hourly, for all cases.
- **Other panels:** Difference between average member mean and ensemble mean.

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Extra Slides: Multiphysics Differences relative to Ensemble Mean

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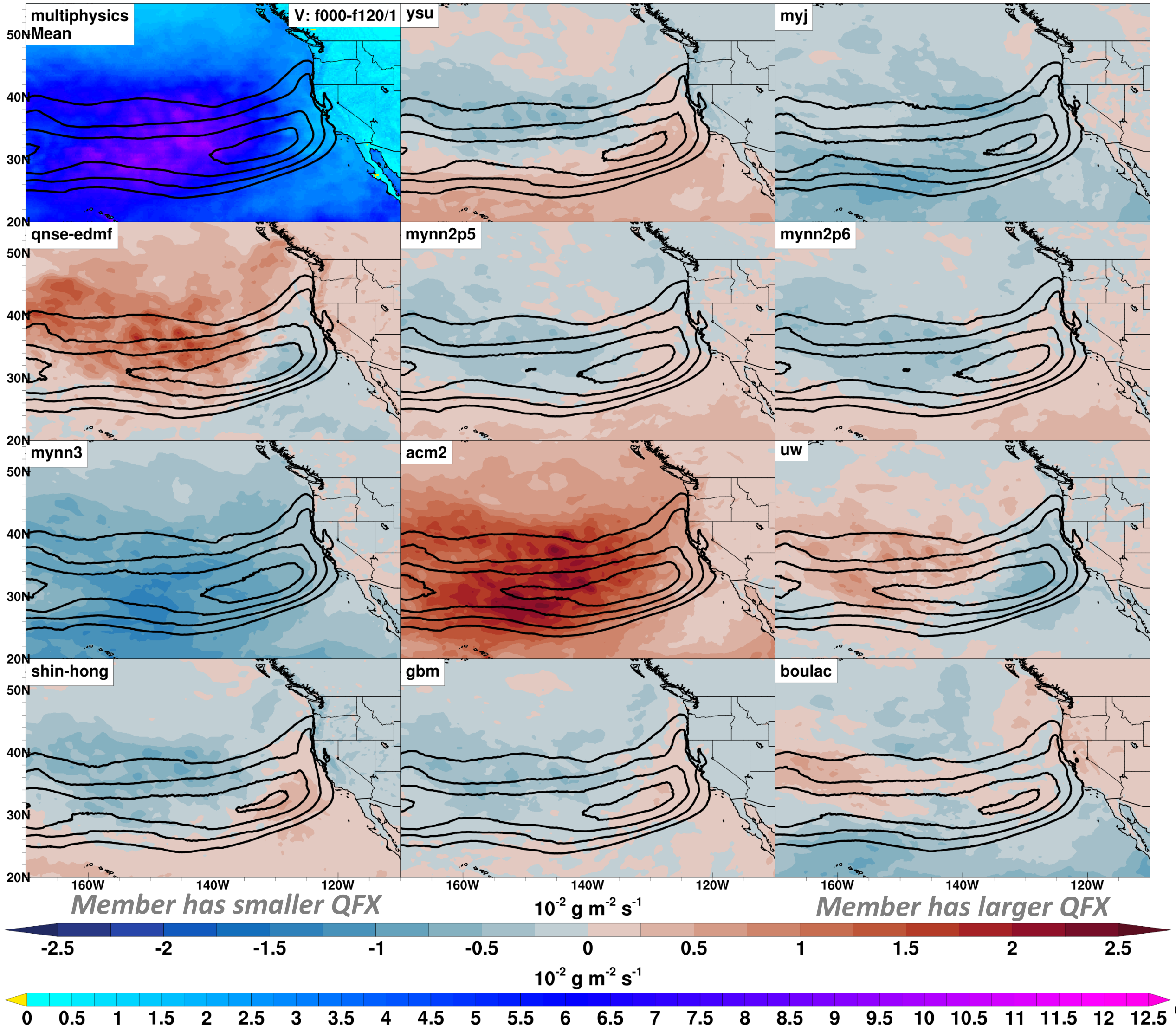

- **Upper-left:** Average ensemble mean QFX from forecast hour 0–120, hourly, for all cases.
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WRF "multiphysics" ensemble generated using 11 PBL/SL combinations over 5 case studies

Extra Slides: Multiphysics Differences relative to Ensemble Mean

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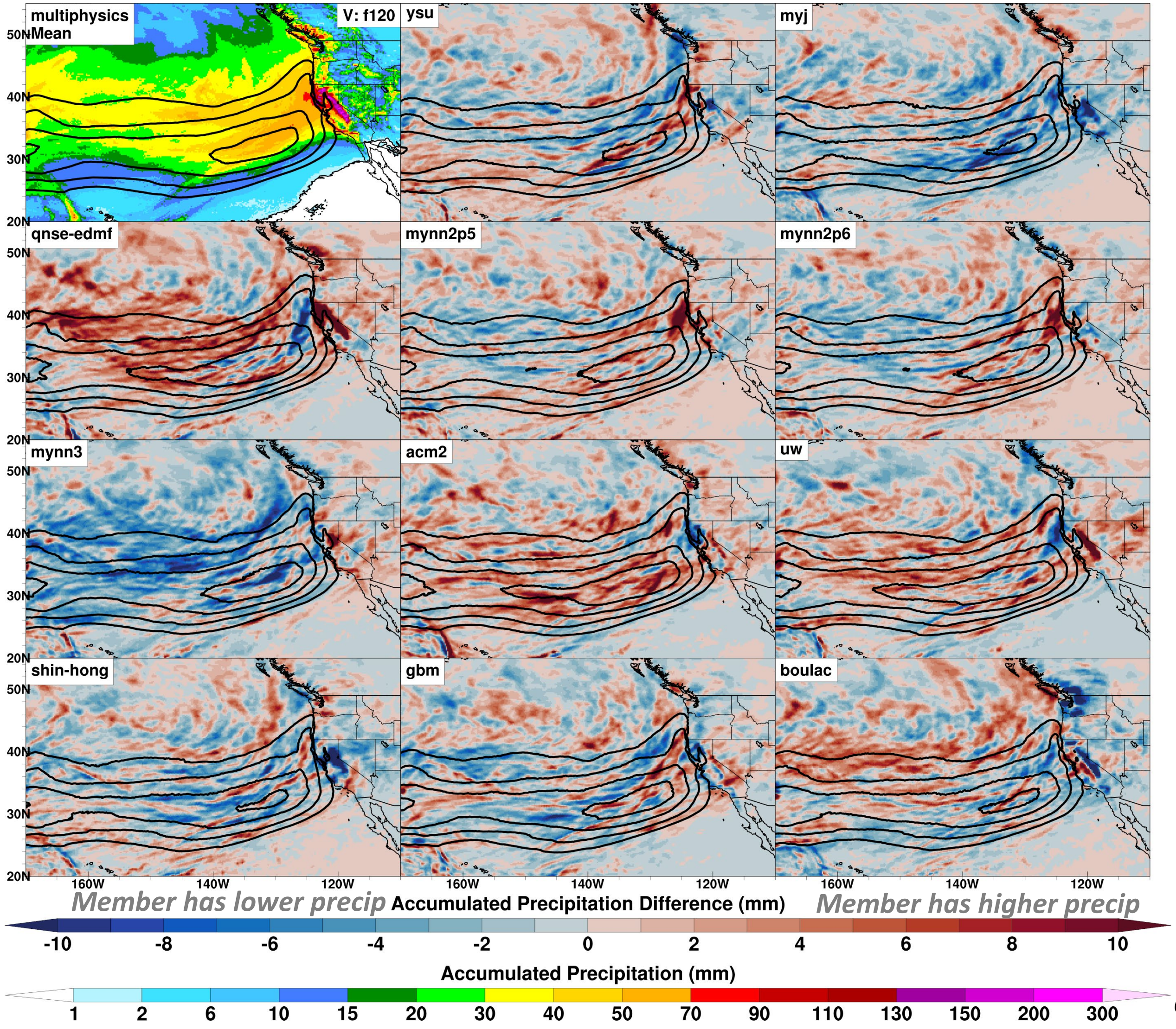

- **Upper-left:** Average ensemble mean 925 hPa PACC from forecast hour 0–120, hourly, for all cases.
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Center for Western Weather and Water Extremes

Extra Slides: SPP in WRF

Initial Case Selection

- 3–11 January 2023
  - Offshore verification using dropsondes during 2023 AR Recon IOPs 06–11 [252 dropsondes]
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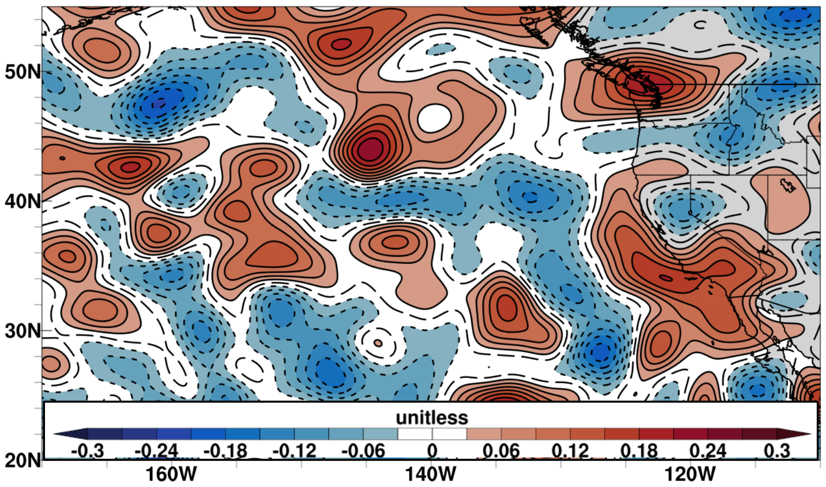
Targeted PBL Physics Uncertainty – Stochastic Perturbed Parameters (SPP)

- Represent uncertainty associated with specific parameterized processes using a spatially and temporally evolving random noise field (e.g., Jankov et al. 2017, 2019, 2020).
- In MYNN PBL & SL schemes, perturbations are applied as **multiplicative noise** to the **thermal and moisture diffusivity coefficients, entrainment coefficient, total water vapor, and thermal/moisture/aero roughness lengths.**

Example of the multiplicative SPP perturbation field



Pseudocode example of diffusivity coefficient perturbations

```
dfm(k) = dfm(k) + dfm(k) * rstoch_col(k) * 1.5 *
MAX(exp(-MAX(zw(k)-8000.,0.0)/2000.),0.001)

dfh(k)  = dfh(k) + dfh(k)   * rstoch_col(k) * 1.5 *
MAX(exp(-MAX(zw(k)-8000.,0.0)/2000.),0.001)
```

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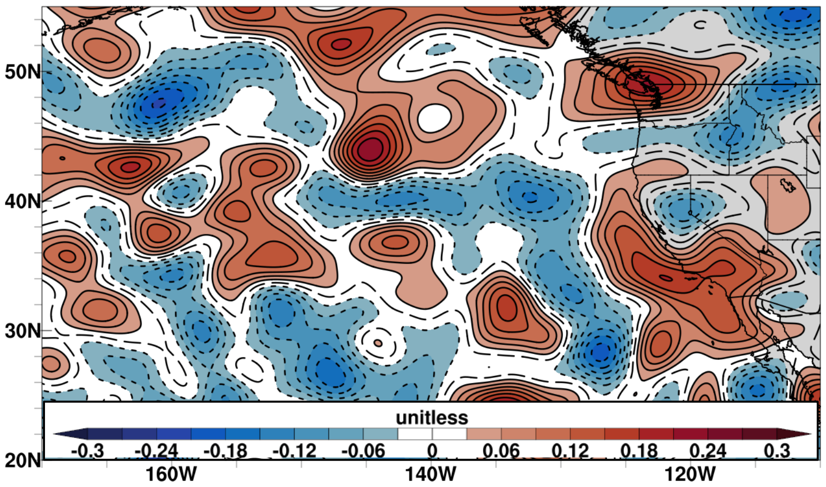

Pseudocode example of total water vapor perturbations

qw_pert = qw(k) + qw(k)*0.5***rstoch_col(k)***real(spp-pbl)

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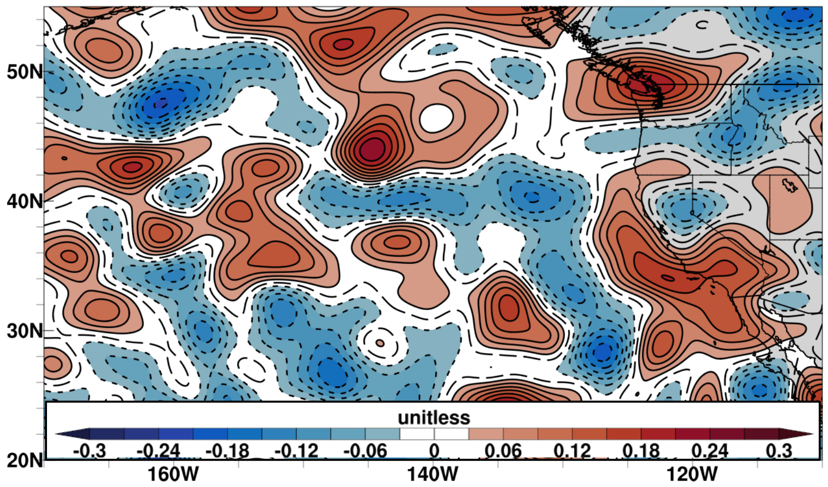

Pseudocode example of entrainment perturbations

ENT(k,i) = ENT(k,i) * (1.0 - **rstoch_col(k)**)

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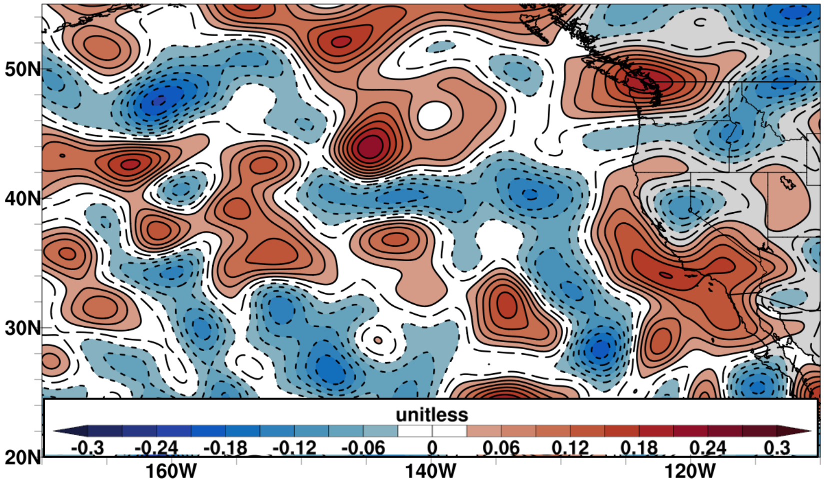


Pseudocode example of roughness length perturbations

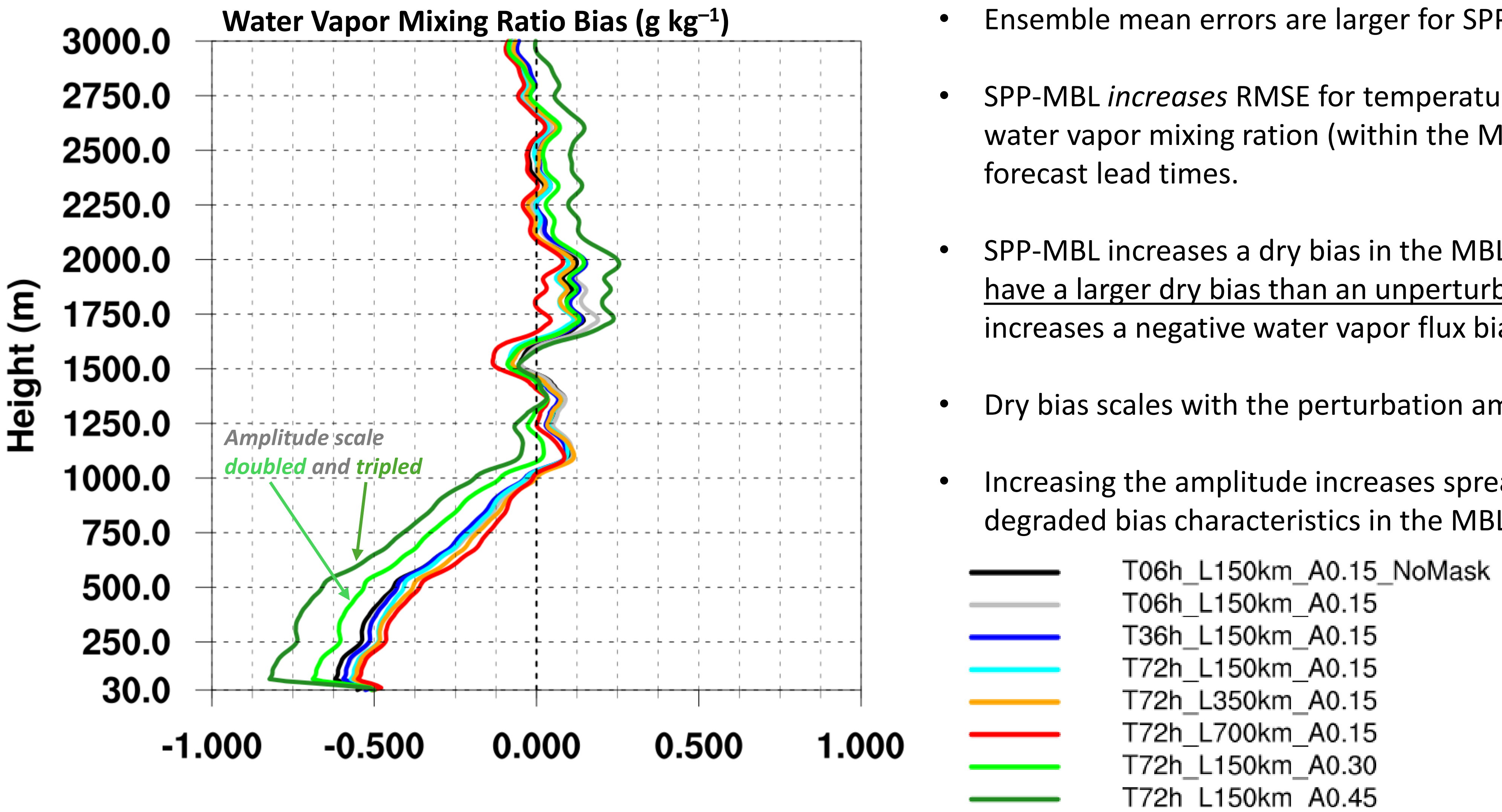
```
if (spp-pbl==1) then
  ZNTstoch(I)  = MAX(ZNT(I) + ZNT(I)*1.0*rstoch1D(i), 1e-6)
else
  ZNTstoch(I)  = ZNT(I)
endif
```

```
if (spp-pbl==1) then
  Zt = Zt + Zt * 0.5 * rstoch
  Zt = MAX(Zt, 0.0001)
  Zq = Zt
endif
```

Results 1: Comparison of SPP-MBL, ICBC, and Combined SPP-MBL+ICBC Ensemble Configurations

Bias Compared to Dropsonde Observations (11-member tuning experiments)

N=31 members | 100–10 km horizontal masking | 4–6 km vertical masking | A=0.3, T=72 h, L = 150 km



- Ensemble mean errors are larger for SPP-MBL (less spread)
- SPP-MBL *increases* RMSE for temperature (above MBL) and water vapor mixing ration (within the MBL) at medium and long forecast lead times.
- SPP-MBL increases a dry bias in the MBL (all perturbed members have a larger dry bias than an unperturbed control), and increases a negative water vapor flux bias near the MBL top
- Dry bias scales with the perturbation amplitude
- Increasing the amplitude increases spread, but at the expense of degraded bias characteristics in the MBL

Extra Slides: Perturbation Masking

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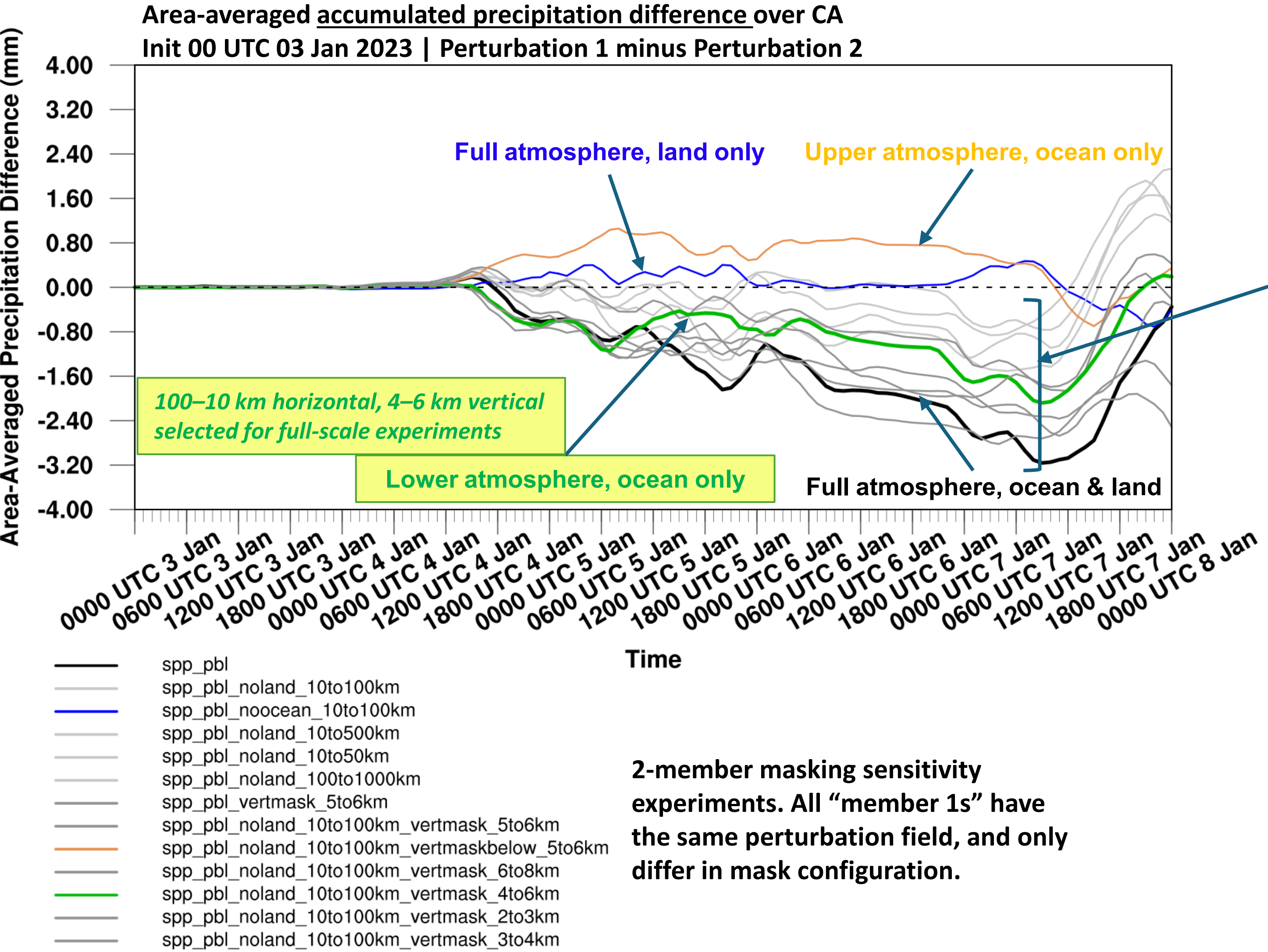
Perturbation Masking *(13, 2-member sensitivity experiments)*



2-member masking sensitivity experiments. All "member 1s" have the same perturbation field, and only differ in mask configuration.

- No spurious errors – accumulated rainfall difference for masking experiments (gray and **green**) is generally similar to non-masked perturbations (**black**).
- Some sensitivity to land / lower atmosphere masking lengths – member-to-member accumulated precipitation difference timeseries vary, but follow a similar trajectory (i.e., Perturbation 1 trending towards lower precipitation totals through ~12 UTC 7 Jan, then increasing afterwards.

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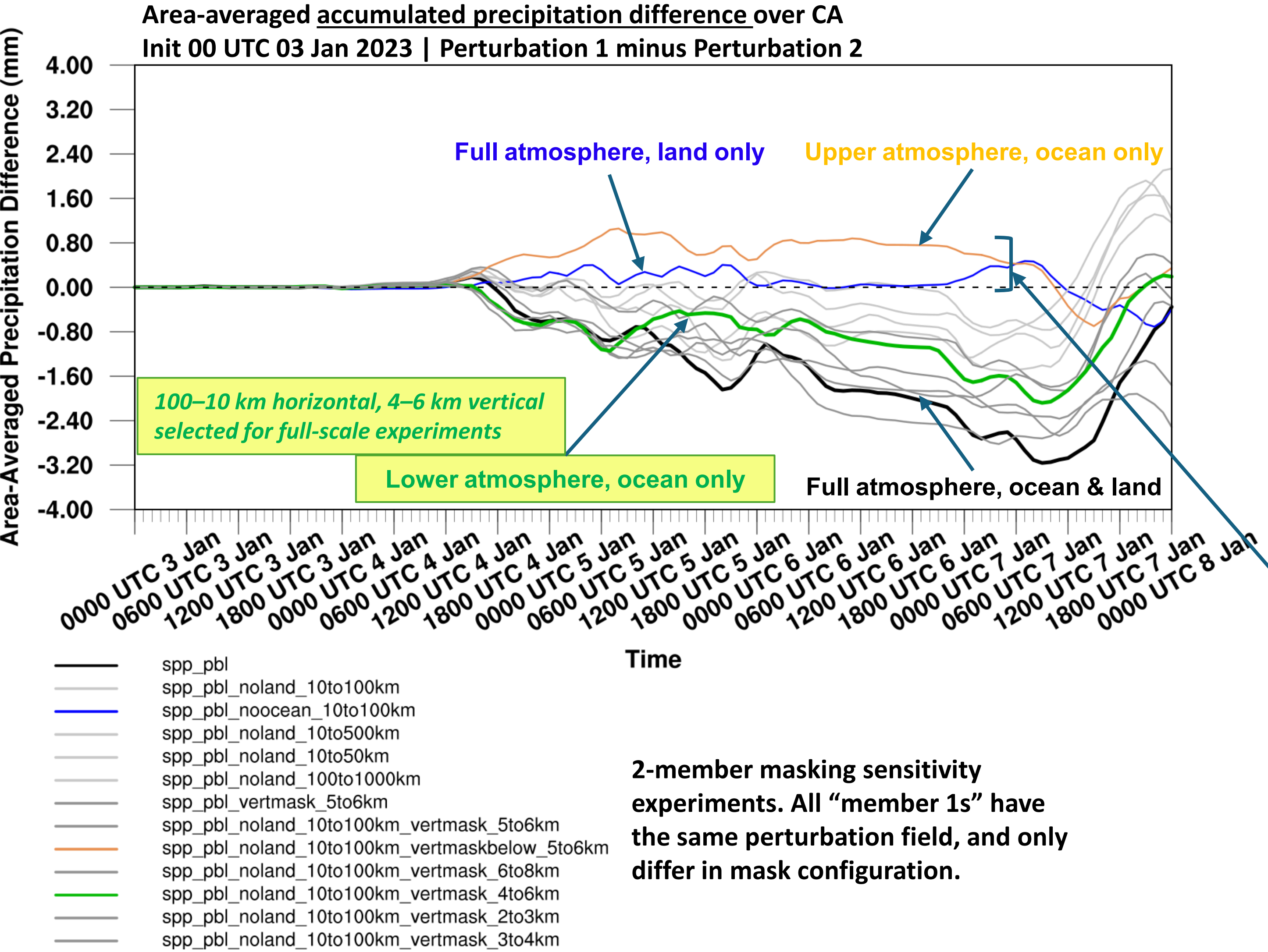

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- *Omitting* lower atmosphere and ocean perturbations (**blue** and **orange**) fundamentally changes the member-to-member difference timeseries compared to the full perturbation field – *That is, precipitation differences driven by the full perturbation field are most directly associated with uncertainty (1) over the ocean surface and (2) below 4–6 km.*

Extra Slides: Perturbation Tuning

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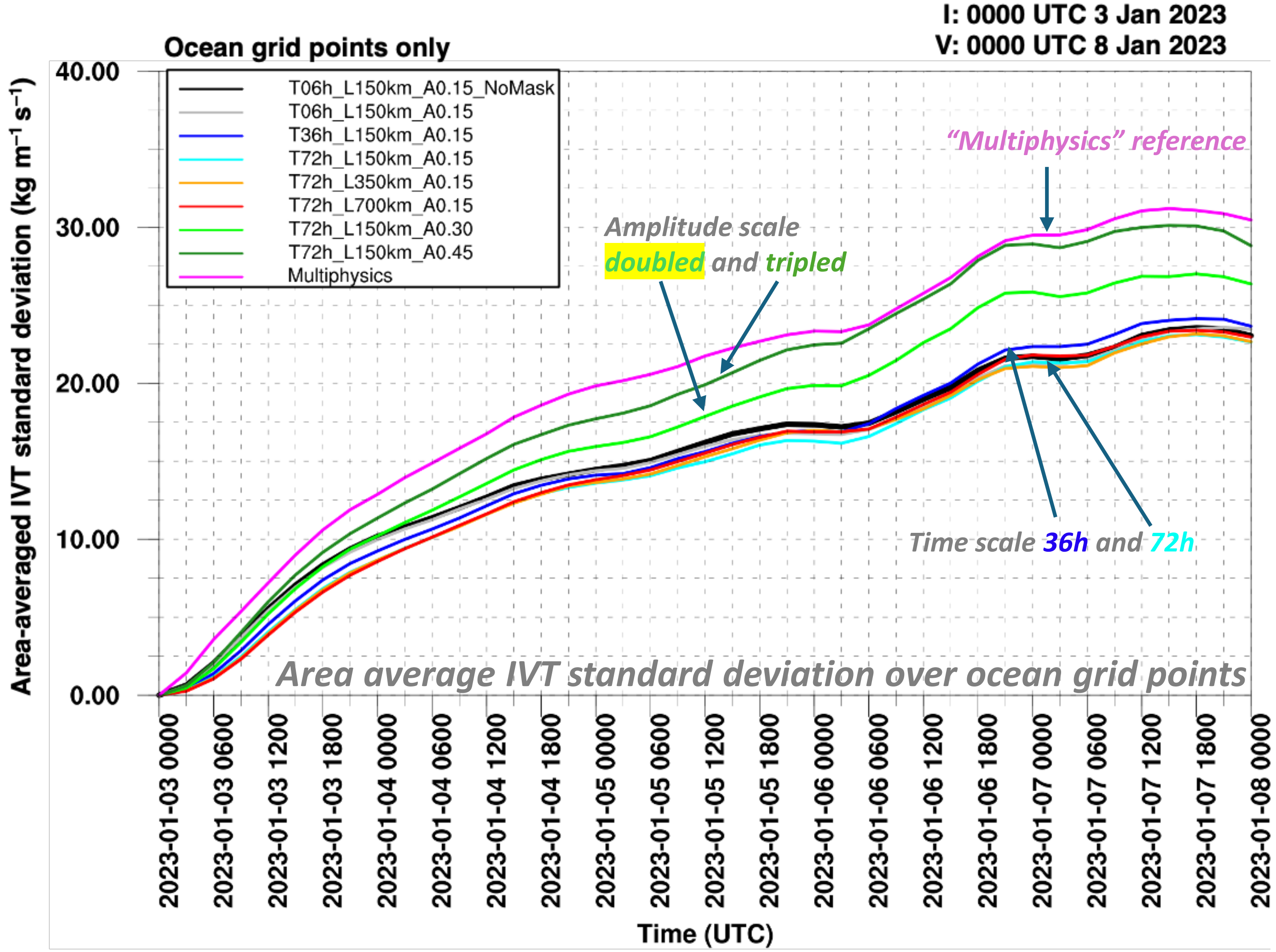
Perturbation Tuning *(9, 11-member sensitivity experiments)*

100–10 km horizontal masking | 4–6 km vertical masking



- Largest sensitivity to perturbation amplitude – larger perturbation amplitude, larger ensemble standard deviation of IVT. **Tripling** the amplitude scale approaches the spread of a **mixed physics** approach, but worsens biases (later slides).
- Some sensitivity to perturbation time scale – The slowest evolving perturbations (**72 h**) generally yield less IVT spread than the default (**6 h**) and medium-time scales (**36 h**). Longer time scales are slower to saturate to their maximum amplitude
- Little sensitivity to the perturbation length scale

T 72h, L 150km, A 0.3 Configuration selected for full-scale experiments. Consistent with an increased-amplitude version of the final HRRRE configuration (see Bartolini and Minder 2025; https://doi.org/10.1175/WAF-D-24-0141.1)

Extra Slides: Perturbation Tuning

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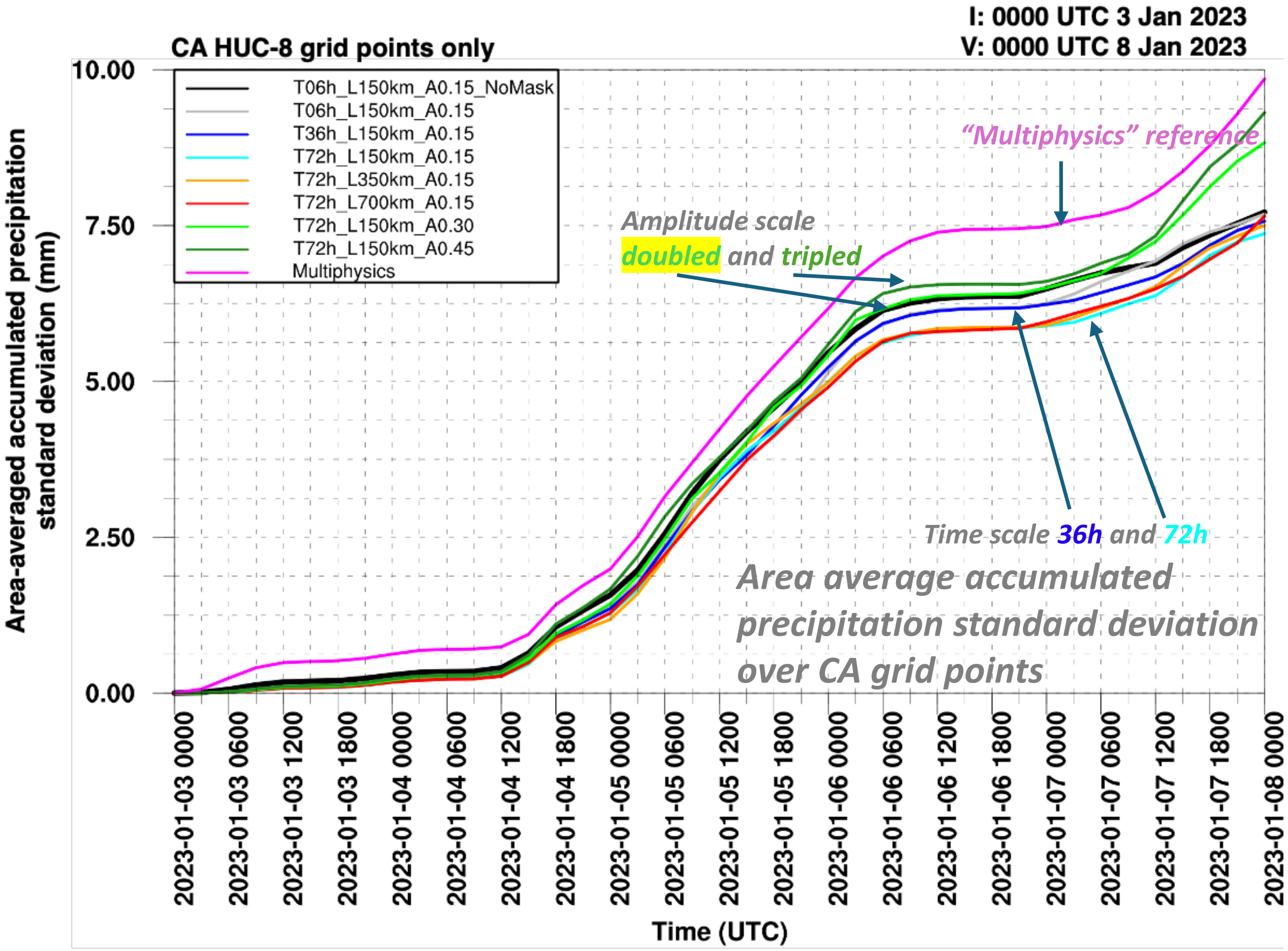

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- Similar results for accumulated precipitation

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Perturbation Tuning *(9 11-member sensitivity experiments)*

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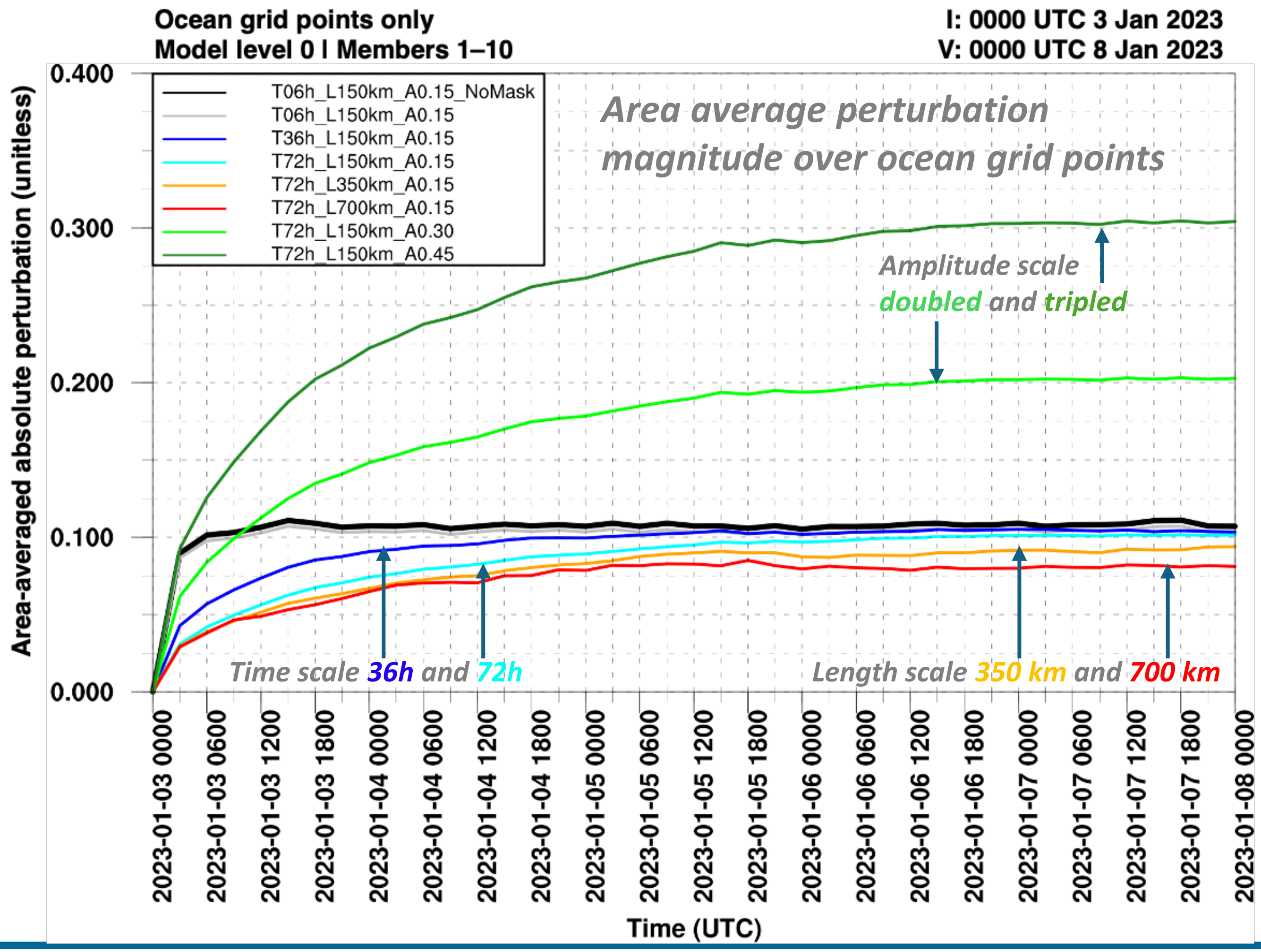
Why the reduced spread for longer perturbation time scales?



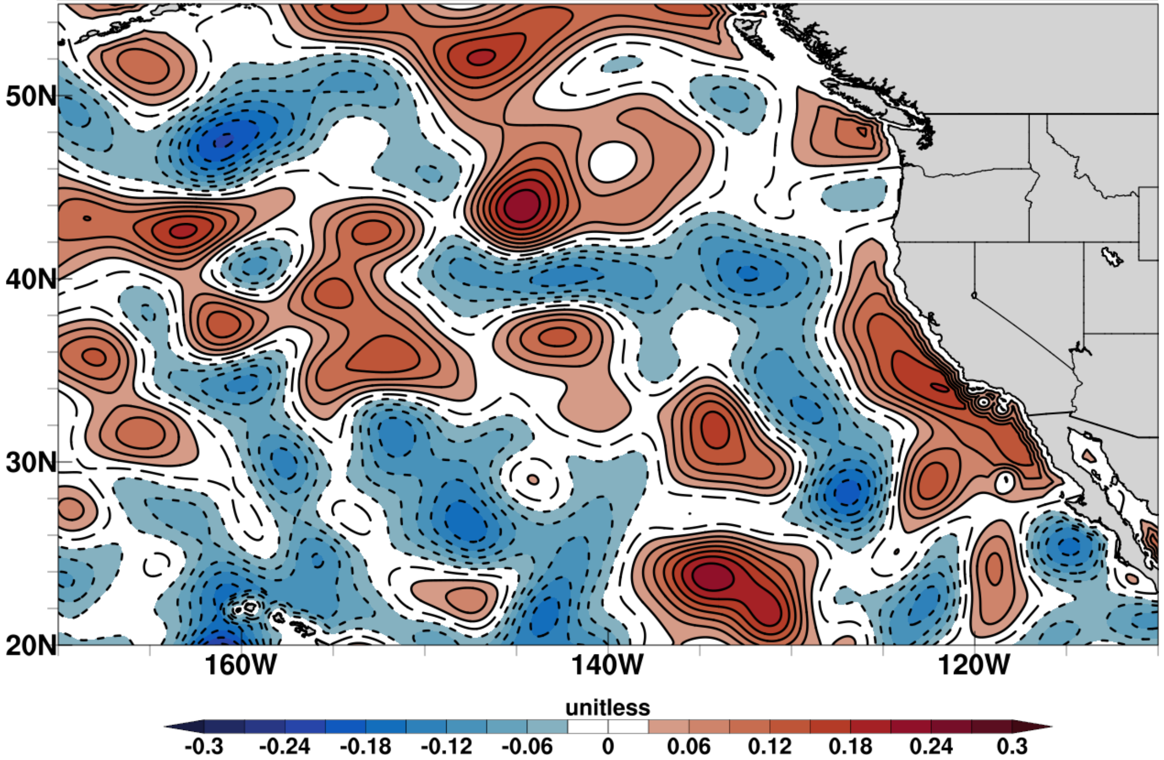
- Longer perturbation time scales take longer to reach their maximum value – lower amplitude perturbations persist for a longer time over the domain

- Larger amplitude perturbations – likely have a larger fraction of the domain in "gradients" between larger amplitude perturbations. Overall, a smaller average perturbation absolute value over the domain.

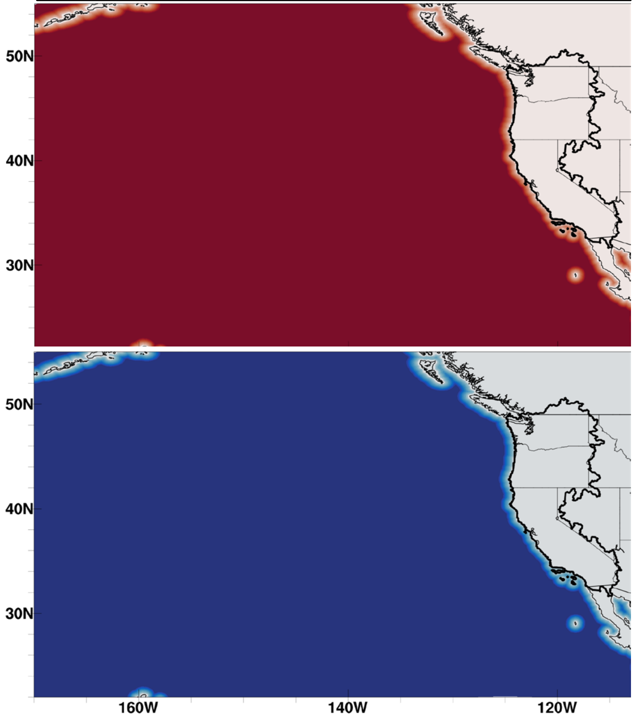
Extra Slides – Fixed Parameter Perturbations in the SPP Framework

- Additional options added to examine the **direct impact of parameter perturbations** on the model state – fixed perturbed parameter experiment that retains the mathematical implementation of SPP.

Masked Perturbation Field



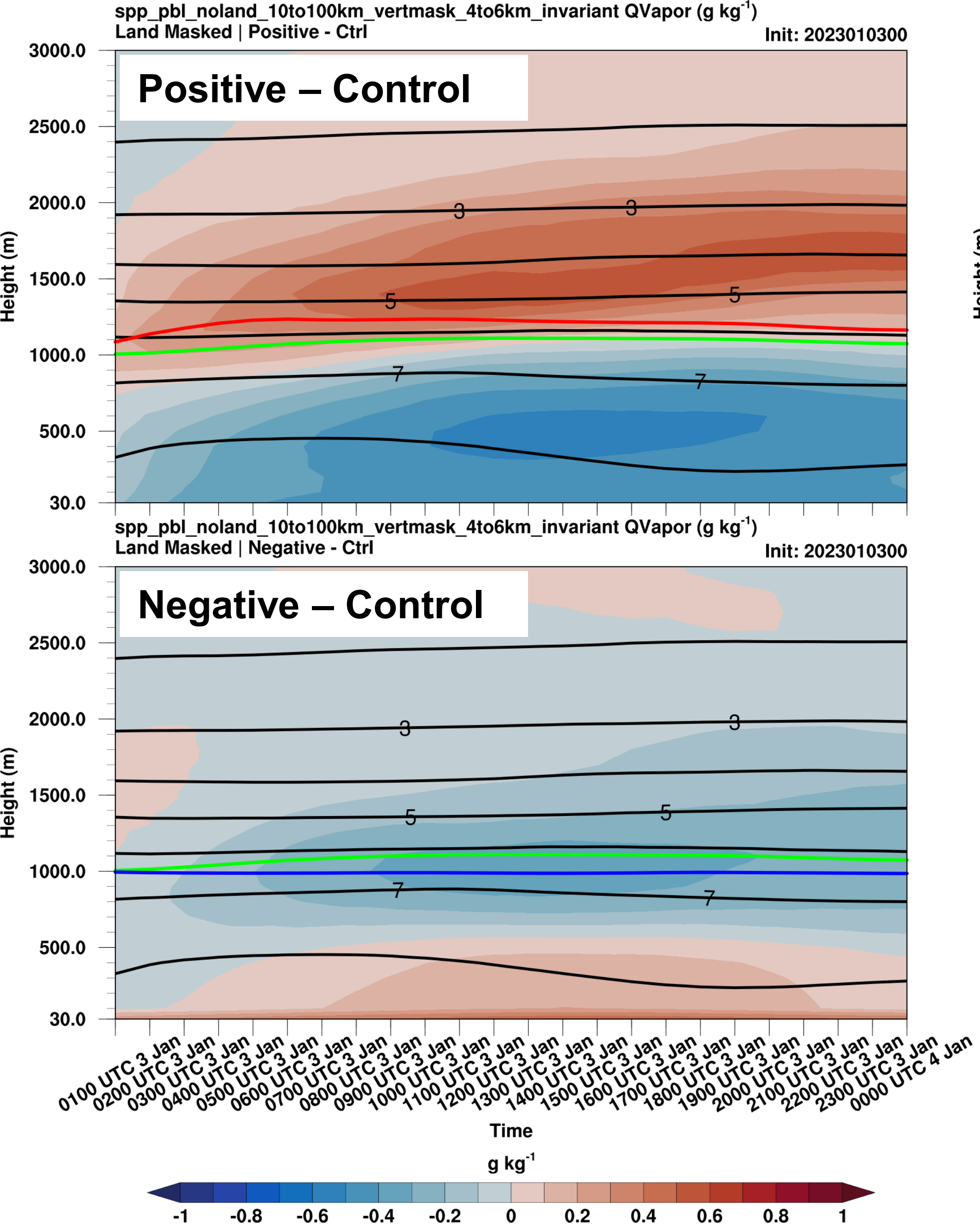
Masked & Invariant Perturbation

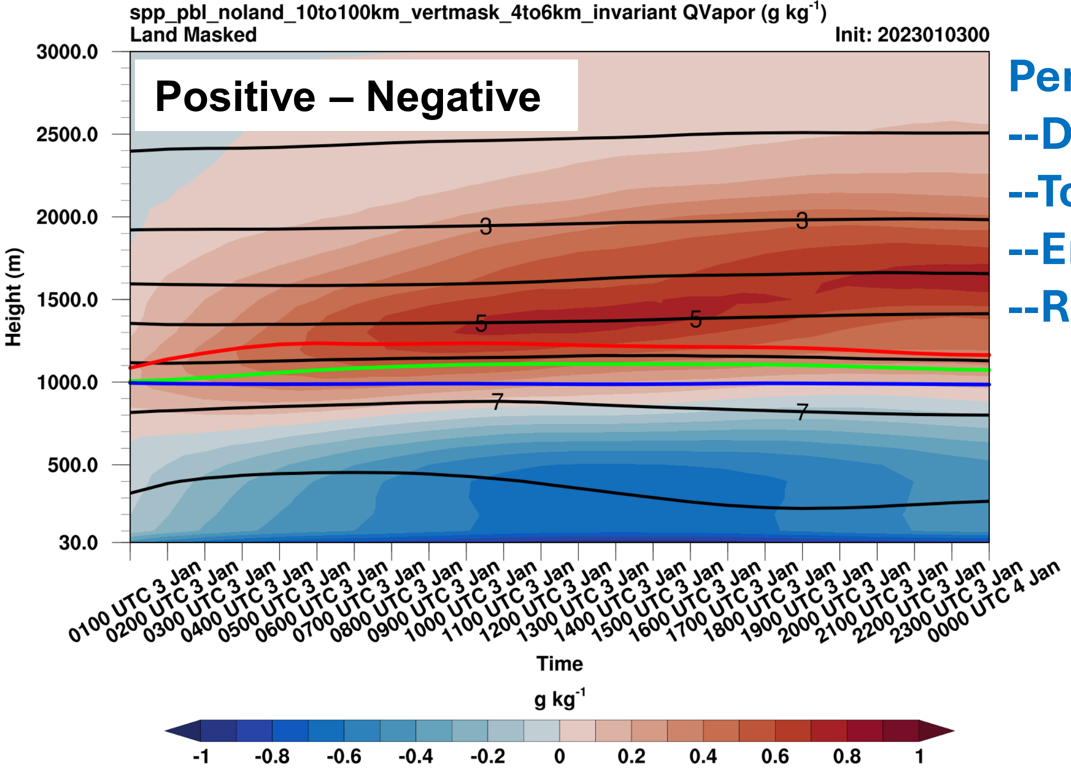



```
&cstoch
clobber_spp_pbl = 1, ! Replace pert.
spp_pbl_replace = 0.3, ! Replacement value.

spp_pbl_diff = 1, ! Diffusivity perts. on/off
spp_pbl_qwpert = 1, ! Water vapor perts. on/off
spp_pbl_ent = 1, ! Entrainment perts. on/off
spp_pbl_rough = 1, ! Roughness perts. on/off
/
```

- Further code modifications made to allow the user to (1) overwrite the existing perturbation field and/or (2) specify which components of spp_pbl to activate via WRF namelist.





Perturbed –

--Diffusivity Coeffs.

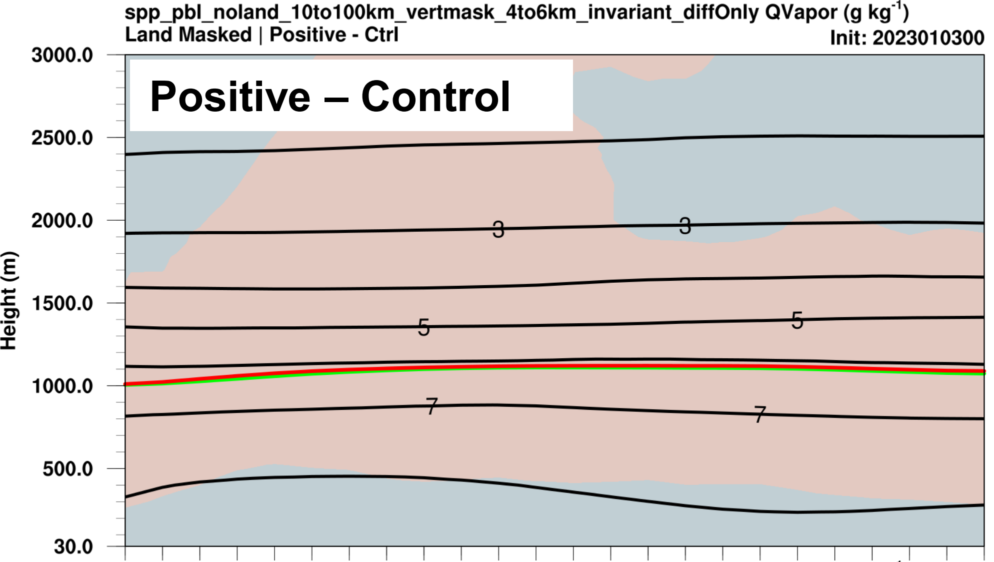
--Total Water Content

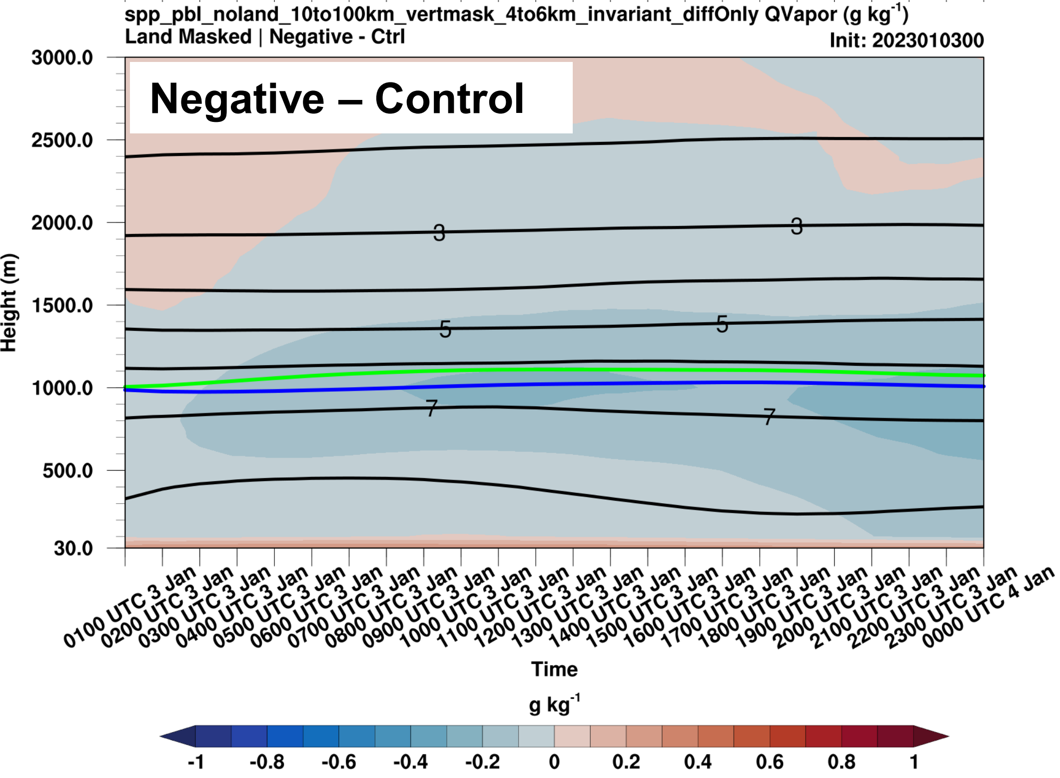
--Entrainment Coeff.

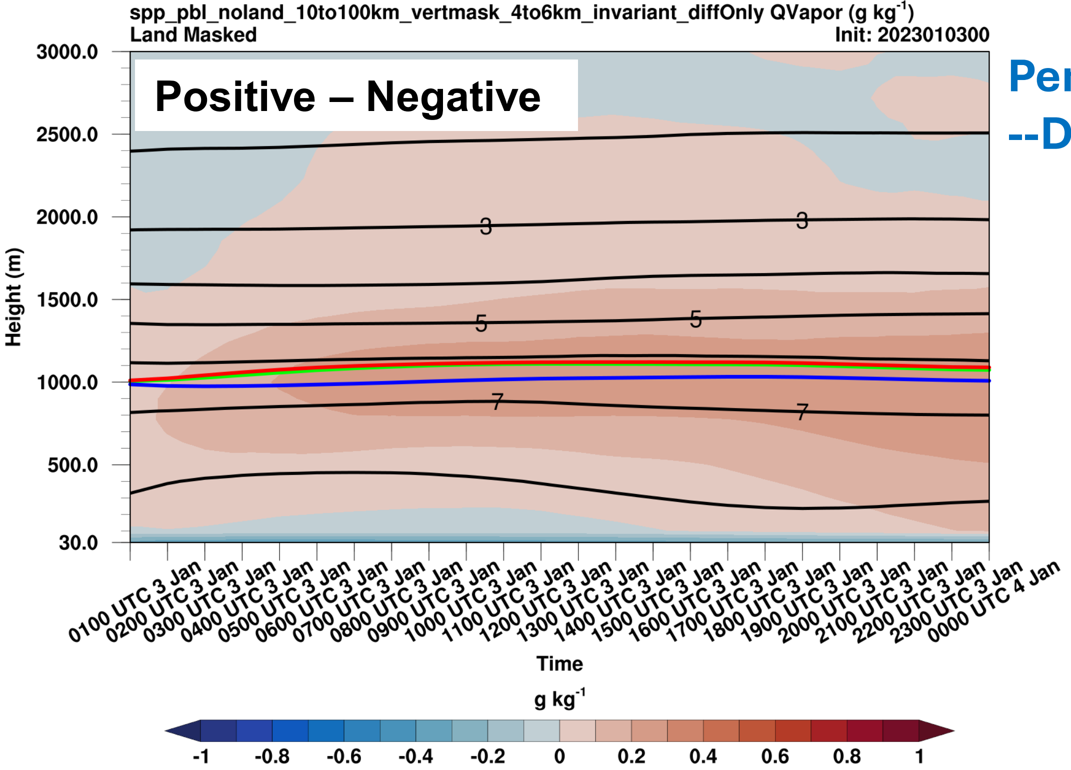
--Roughness Lengths

Area averaged water vapor mixing ratio difference (shaded) among mem001 (invariant +0.3 perturbation) and mem002 (invariant –0.3 perturbation) and control (0 perturbation). Black contours refer to the control forecast. Area averages are computed over ocean grid points only. Area averaged PBLH for control, mem001, and mem002 are in green, red, and blue, respectively. All experiments use a perturbation fields that is tapered to zero above 4 km (4-6km tapering zone) and over land (100–10km tapering zone), but is otherwise invariant for mem001 (+0.3) and mem002 (–0.3).

- Larger magnitude differences between positive perturbation and control than between negative and control. In the same direction as the dry bias noted with respect to dropsonde obs.







Perturbed Only–
--Diffusivity Coeffs.

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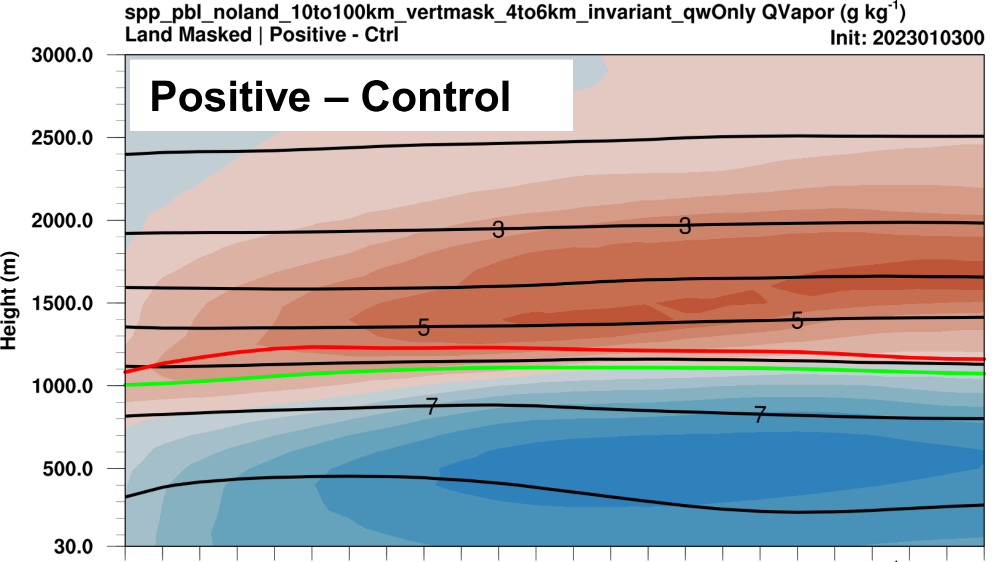
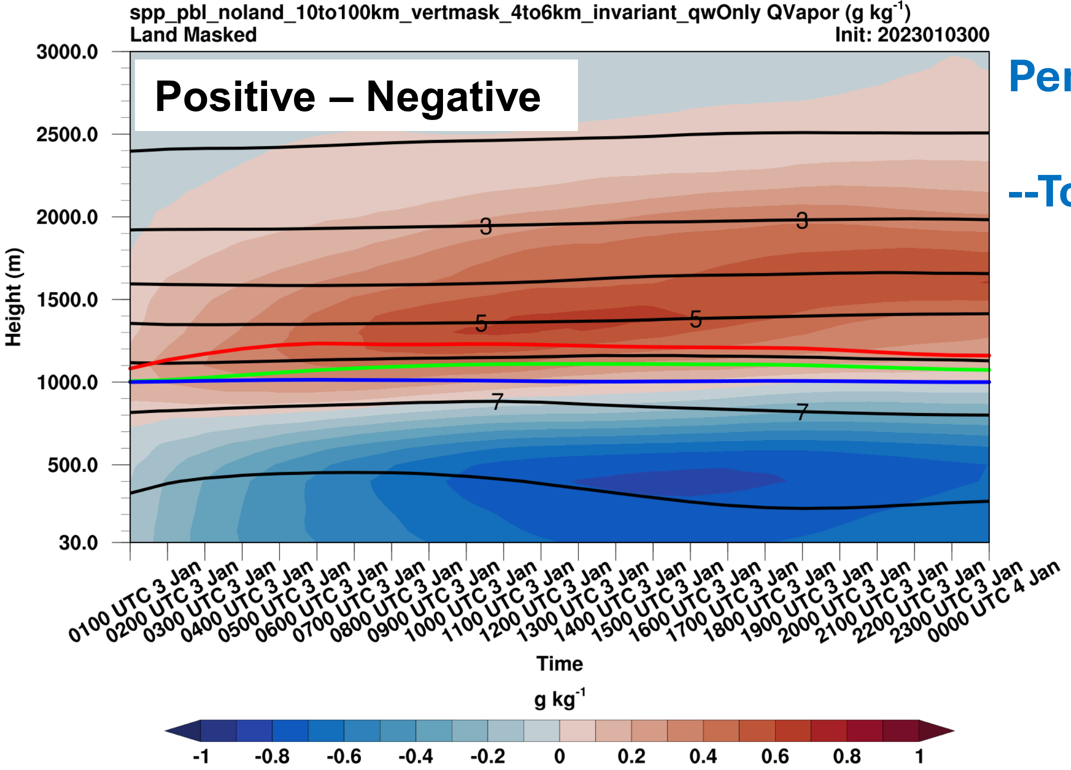
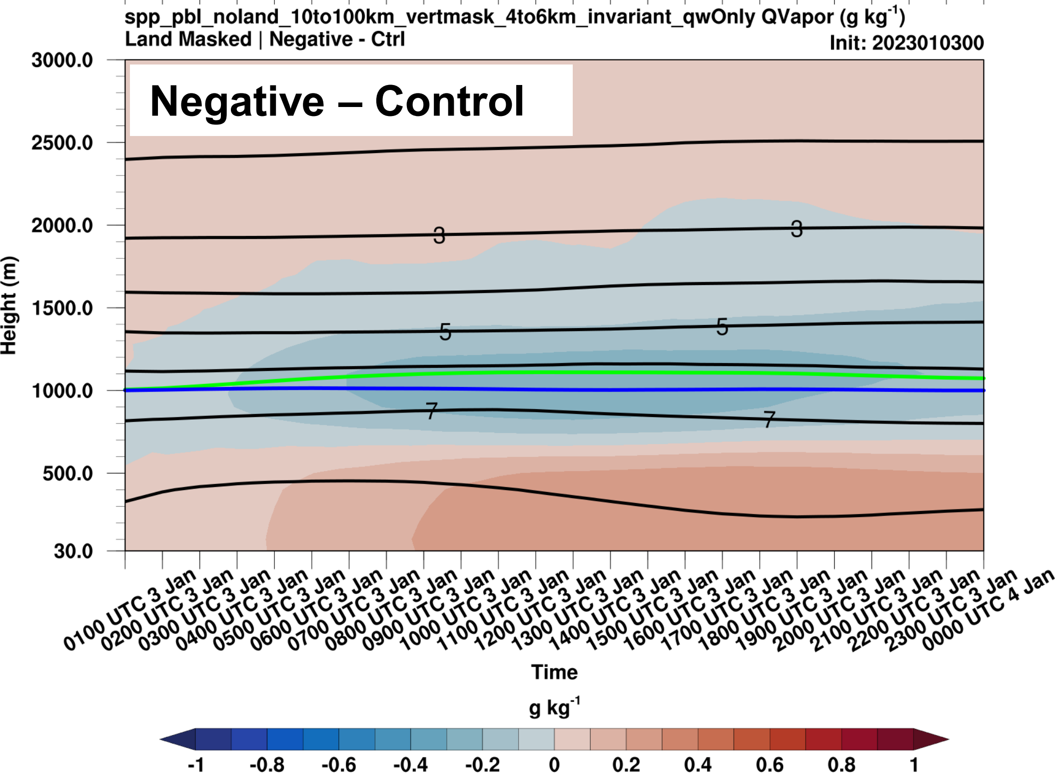
- Smaller magnitude differences when applying perturbations to diffusivity, only; however, negative perturbation has larger difference to the control





Perturbed Only–

--Total Water Content



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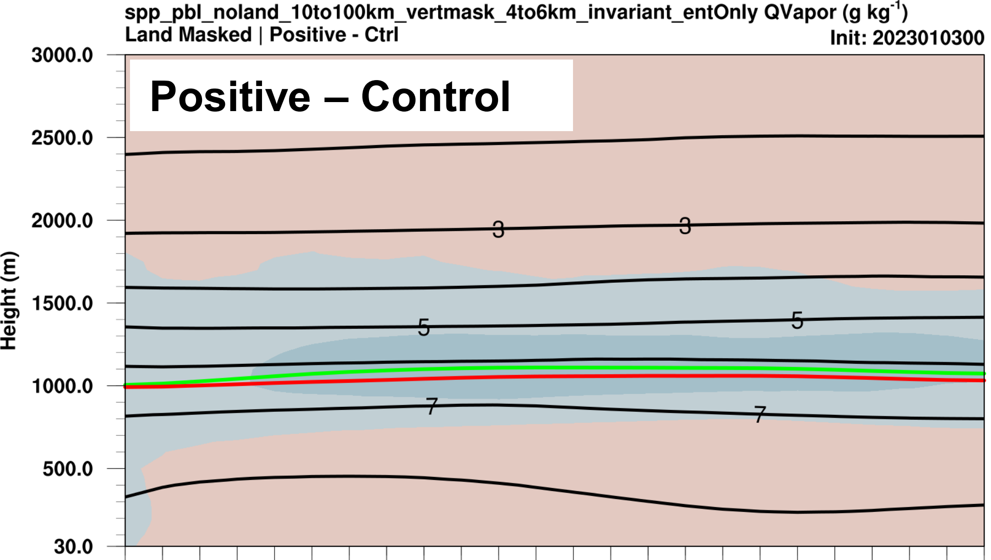
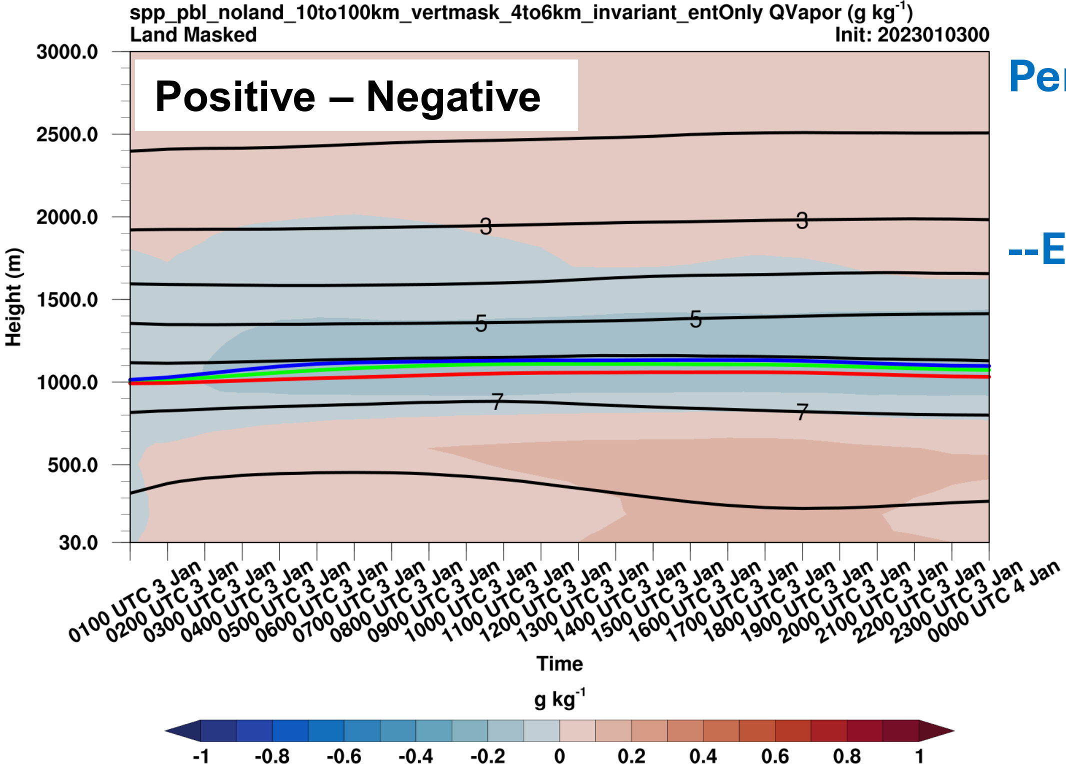
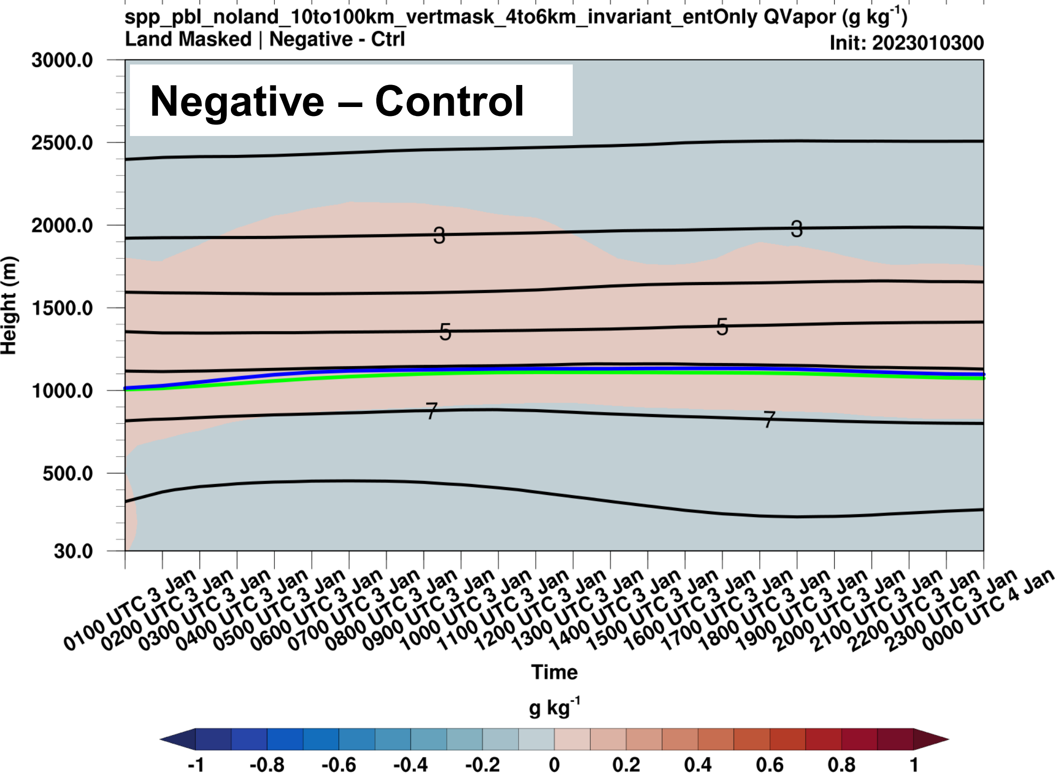
- Perturbations to the total water content (only) yield differences nearly identical to perturbing *all* parameters

Perturbed Only–

--Entrainment Coeff.







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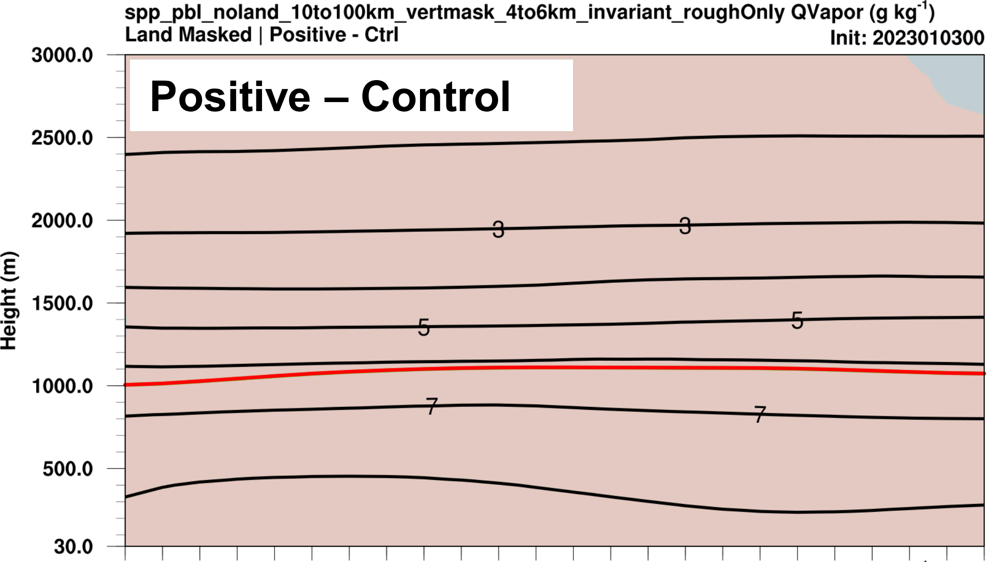
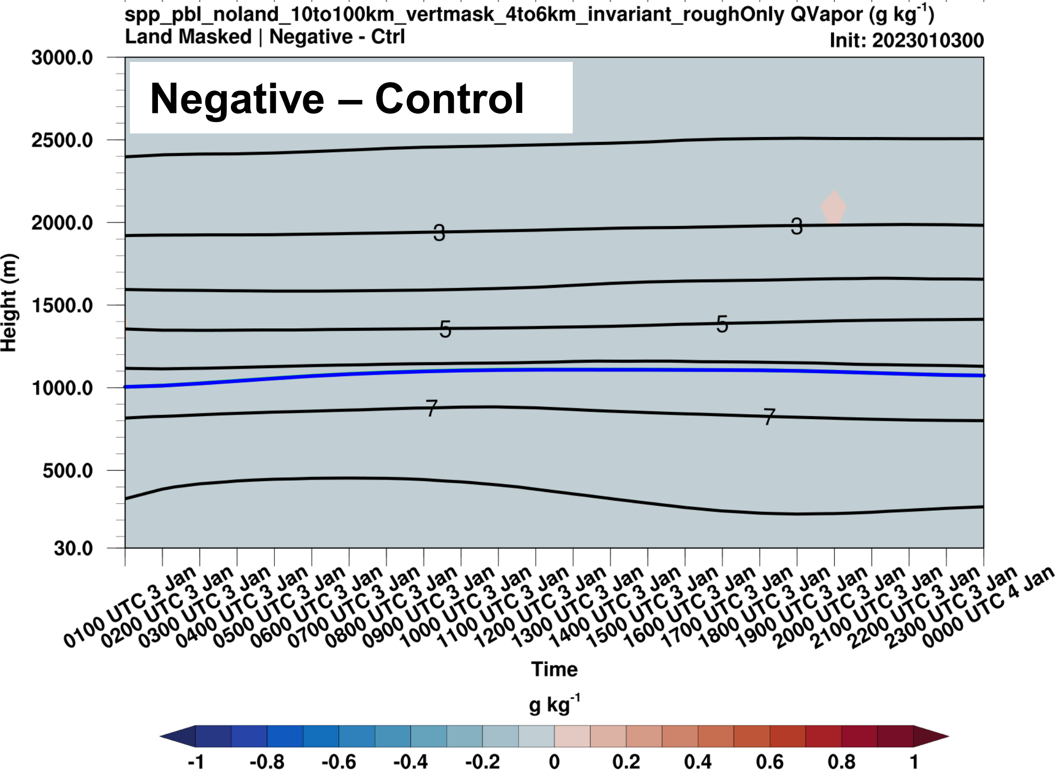
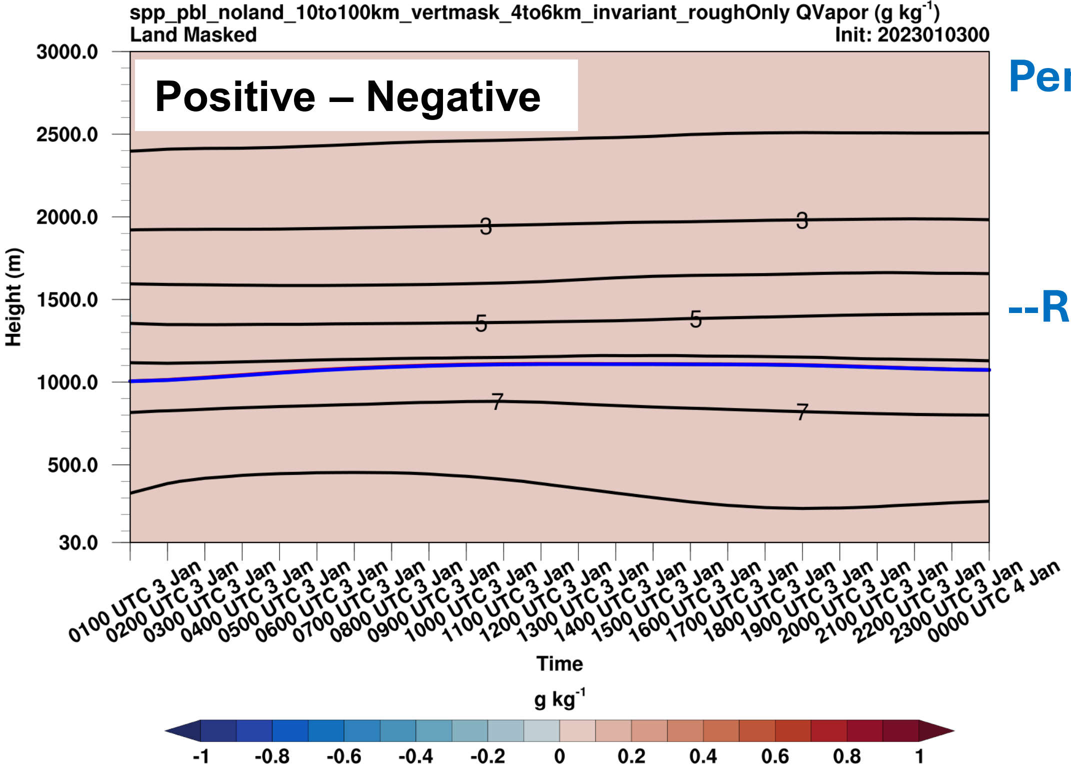
- Smaller magnitude differences when applying perturbations to entrainment, only; however, positive perturbation has larger difference to the control







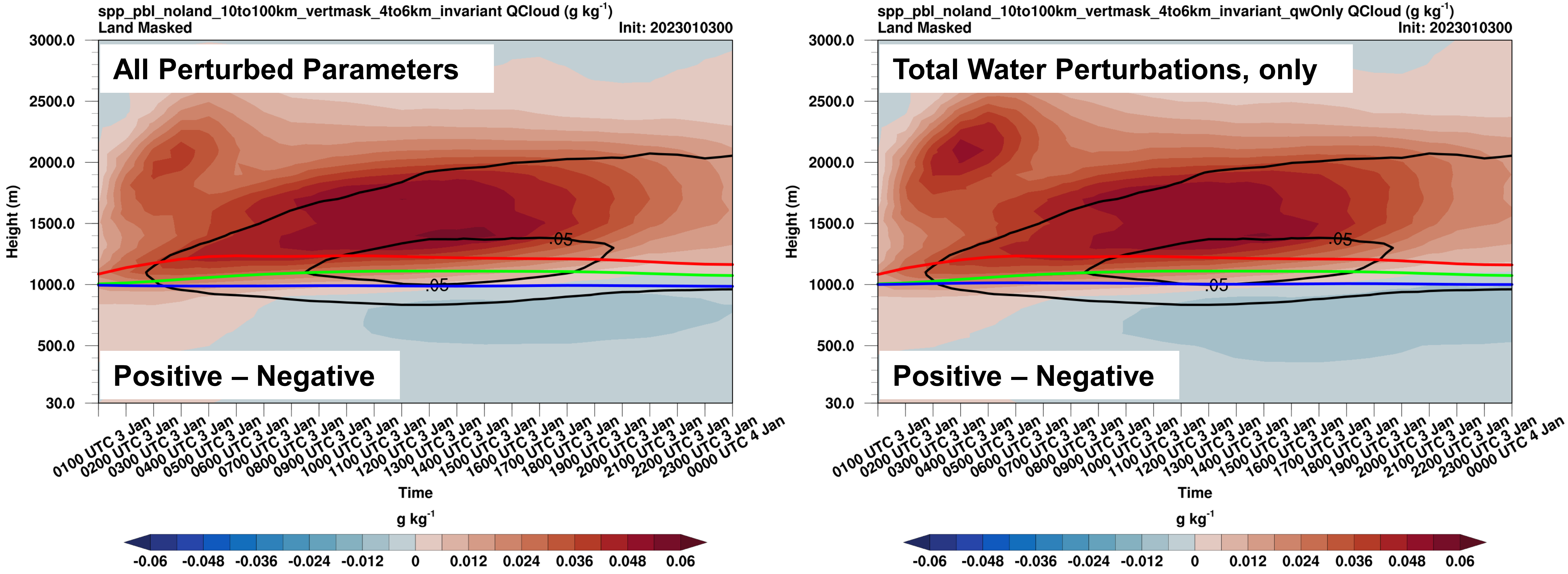
Perturbed Only–

--Roughness Lengths

Area averaged water vapor mixing ratio difference (shaded) among mem001 (invariant +0.3 perturbation) and mem002 (invariant –0.3 perturbation) and control (0 perturbation). Black contours refer to the control forecast. Area averages are computed over ocean grid points only. Area averaged PBLH for control, mem001, and mem002 are in green, red, and blue, respectively. All experiments use a perturbation fields that is tapered to zero above 4 km (4-6km tapering zone) and over land (100–10km tapering zone), but is otherwise invariant for mem001 (+0.3) and mem002 (–0.3).

- Nearly zero impact from perturbing thermal, moisture, and aerodynamic roughness lengths

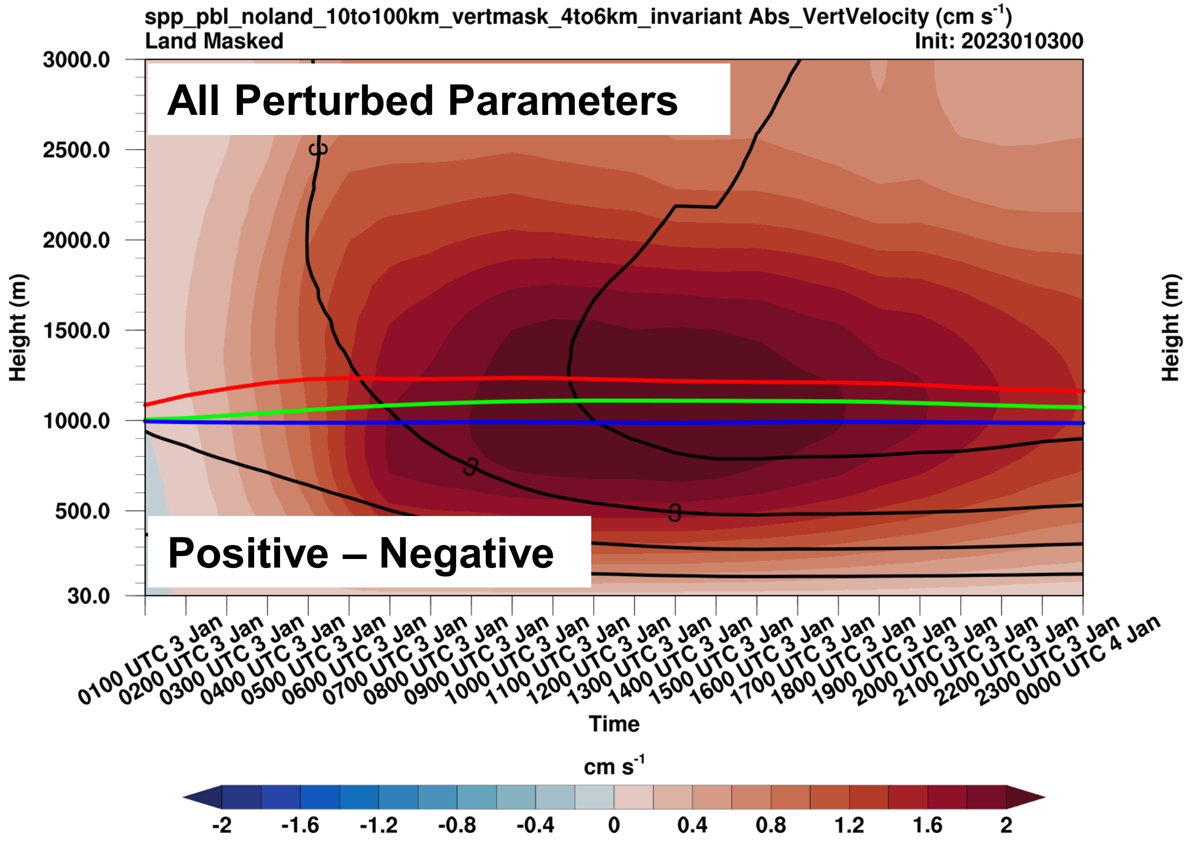
QCloud differences

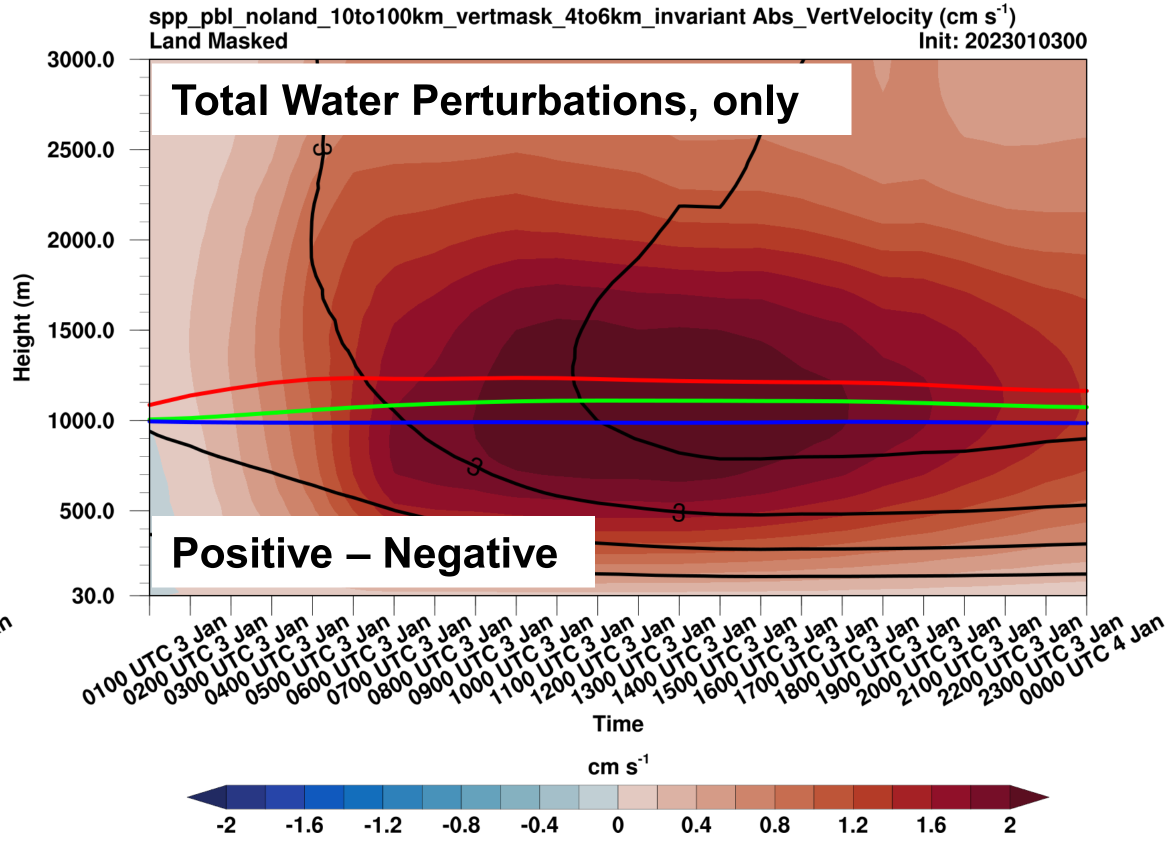


Area averaged cloud water mixing ratio difference (shaded) among mem001 (invariant +0.3 perturbation) and mem002 (invariant –0.3 perturbation) and control (0 perturbation). Black contours refer to the control forecast. Area averages are computed over ocean grid points only. Area averaged PBLH for control, mem001, and mem002 are in green, red, and blue, respectively. All experiments use a perturbation fields that is tapered to zero above 4 km (4-6km tapering zone) and over land (100–10km tapering zone), but is otherwise invariant for mem001 (+0.3) and mem002 (–0.3).

- Qcloud differences are nearly entirely due to total water content perturbations

Absolute value of vertical velocity differences



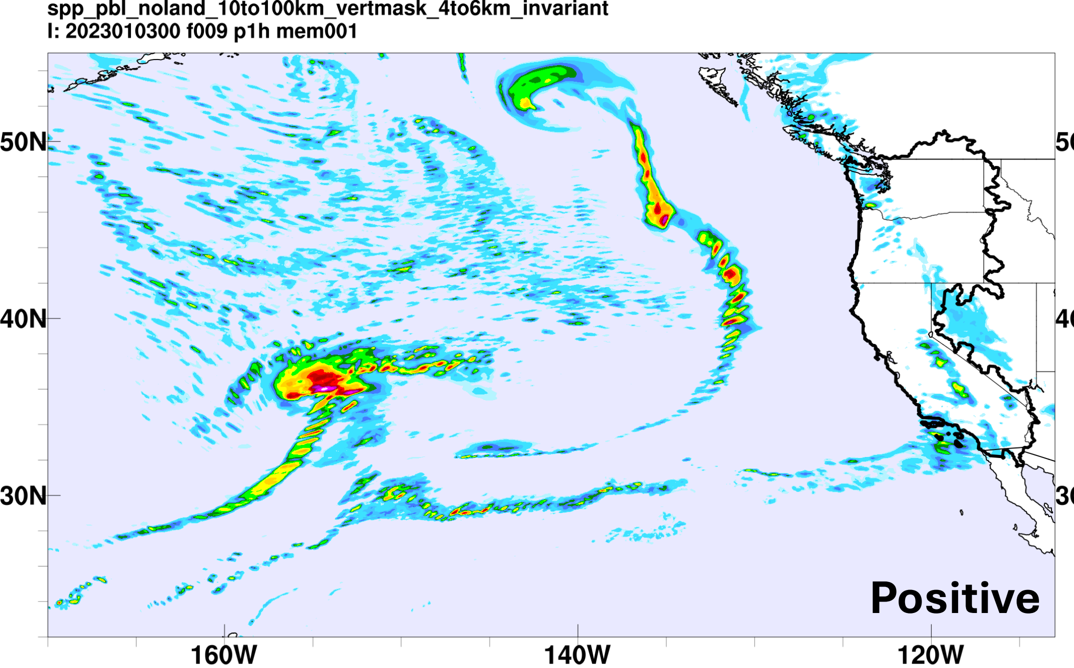


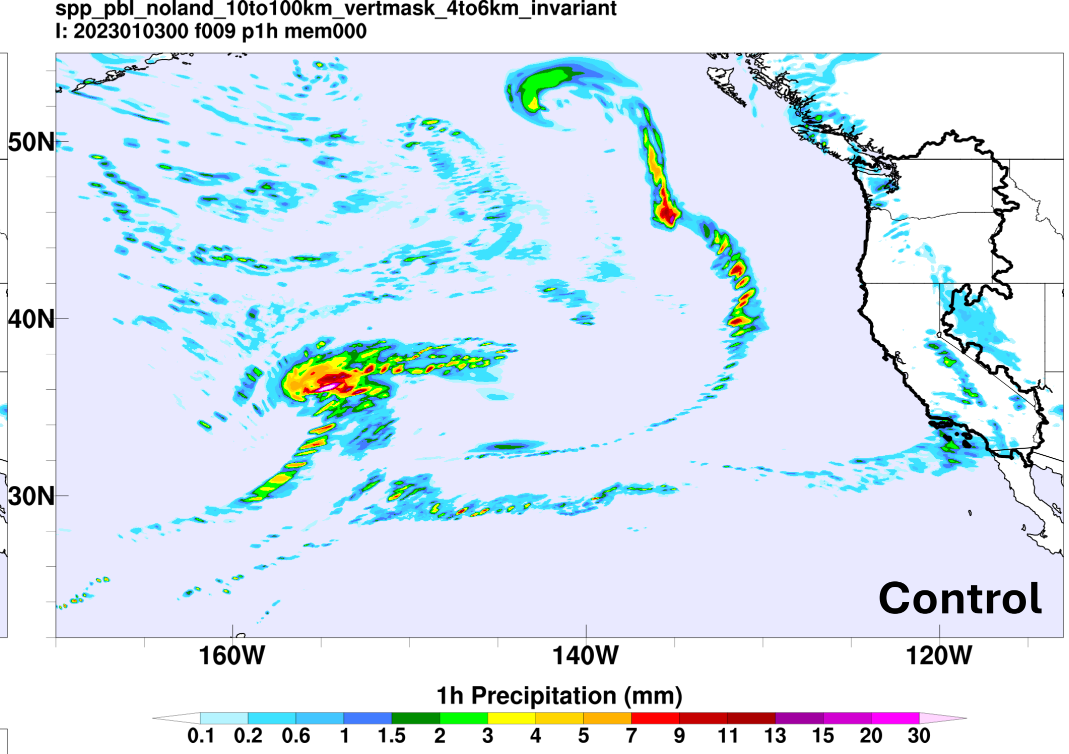
Area averaged absolute values of vertical velocity difference (shaded) among mem001 (invariant +0.3 perturbation) and mem002 (invariant –0.3 perturbation) and control (0 perturbation). Black contours refer to the control forecast. Area averages are computed over ocean grid points only. Area averaged PBLH for control, mem001, and mem002 are in green, red, and blue, respectively. All experiments use a perturbation fields that is tapered to zero above 4 km (4-6km tapering zone) and over land (100–10km tapering zone), but is otherwise invariant for mem001 (+0.3) and mem002 (–0.3).

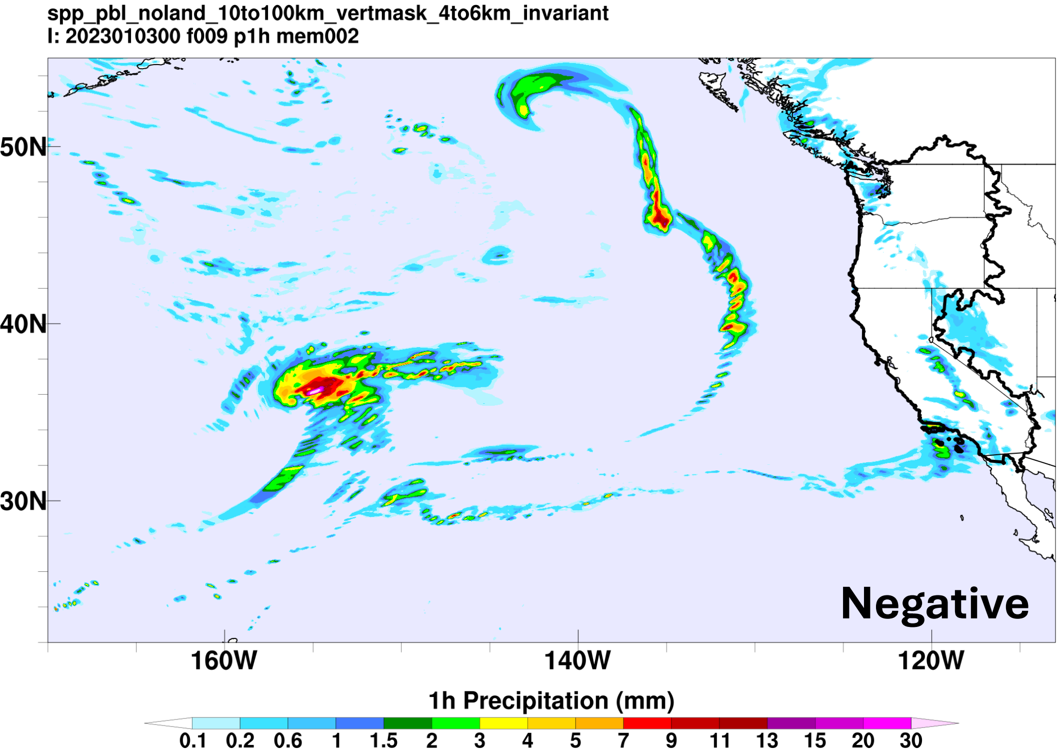
- Absolute vertical velocity differences are nearly entirely due to total water content perturbations
- Greater grid-scale mixing of heat, moisture and momentum?

1-h Precipitation Differences at F009

F009







Perturbed –

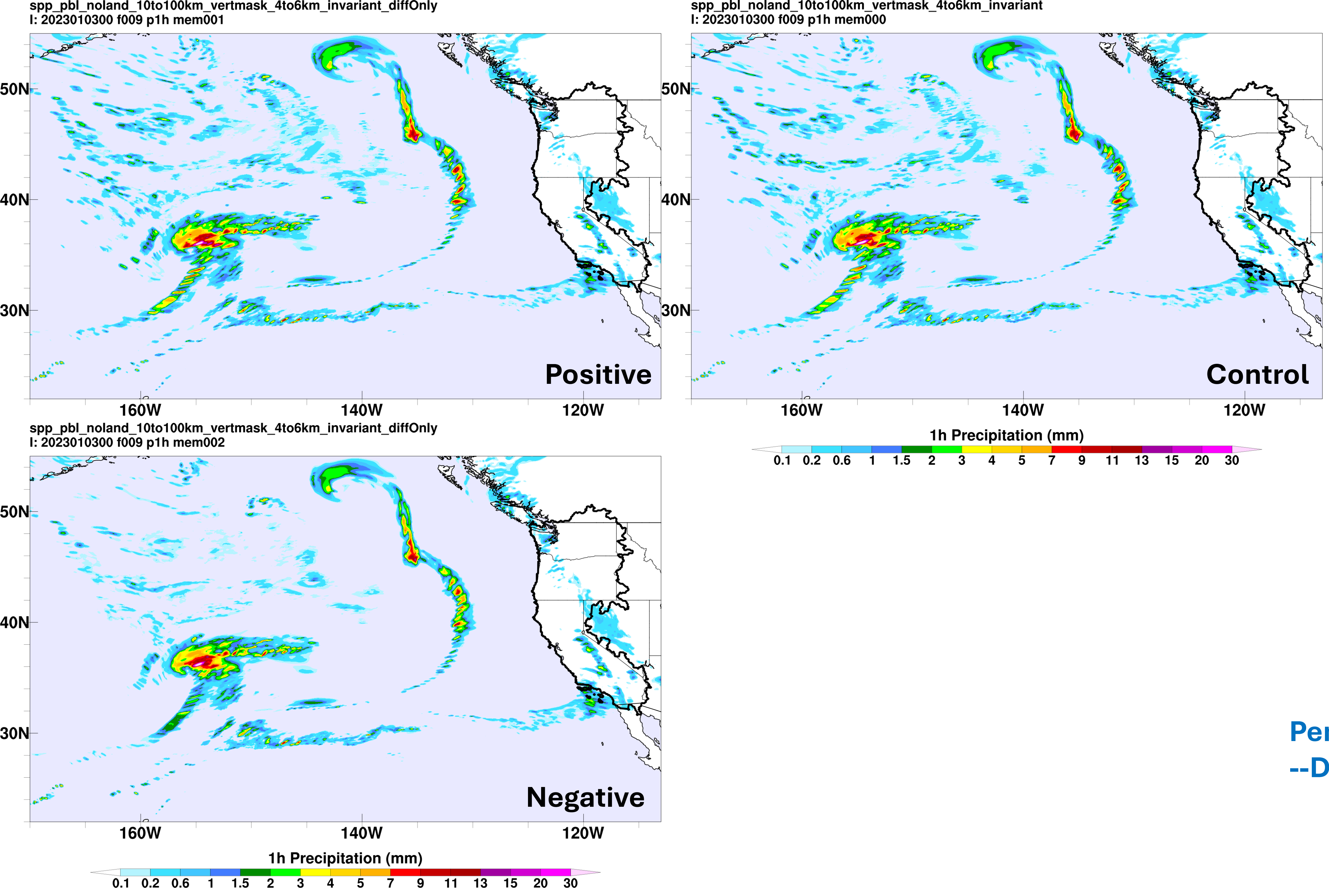
--Diffusivity Coeffs.

--Total Water Content

--Entrainment Coeff.

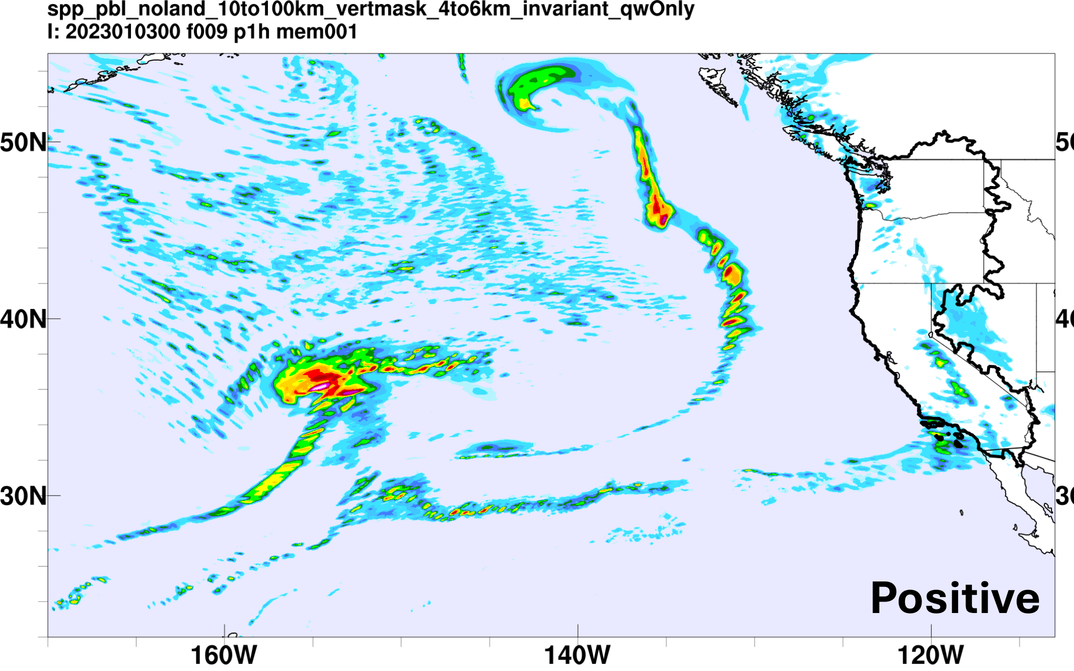
--Roughness Lengths

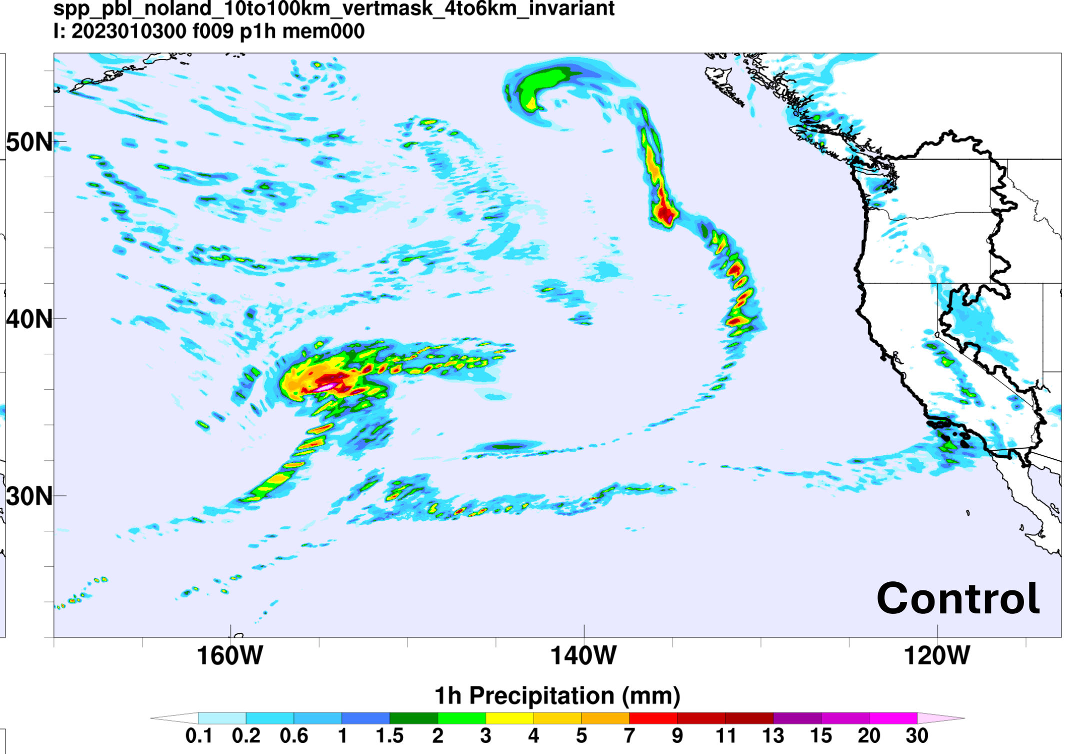
F009

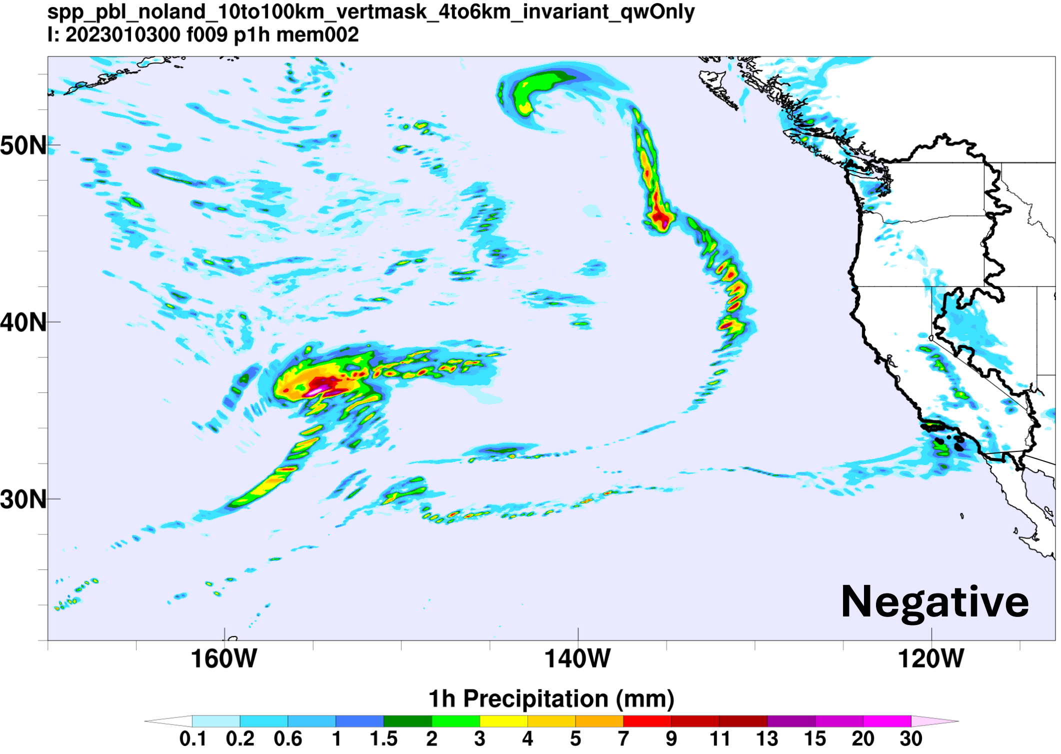


Perturbed Only –
--Diffusivity Coeffs.

F009



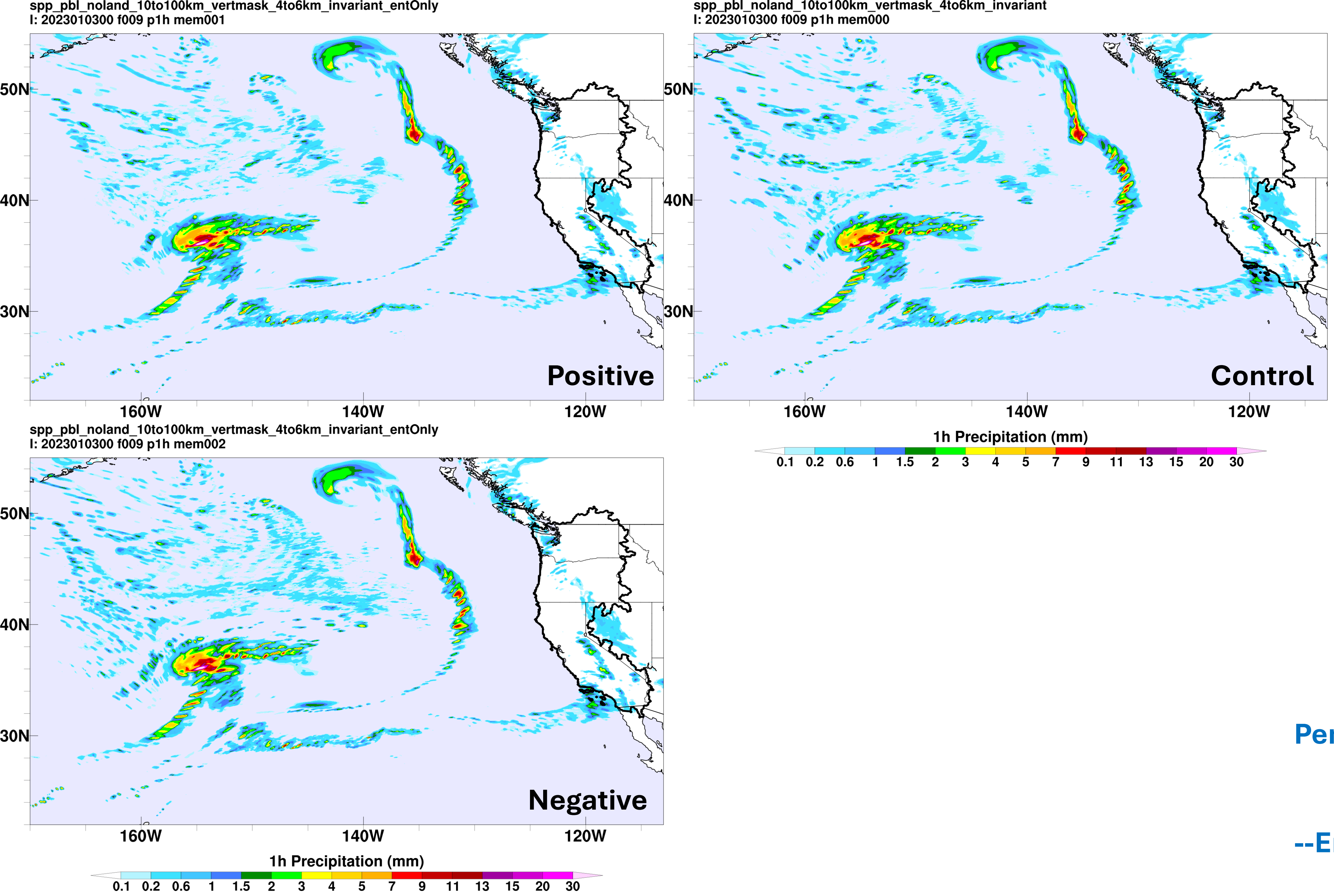




Perturbed Only –

--Total Water Content

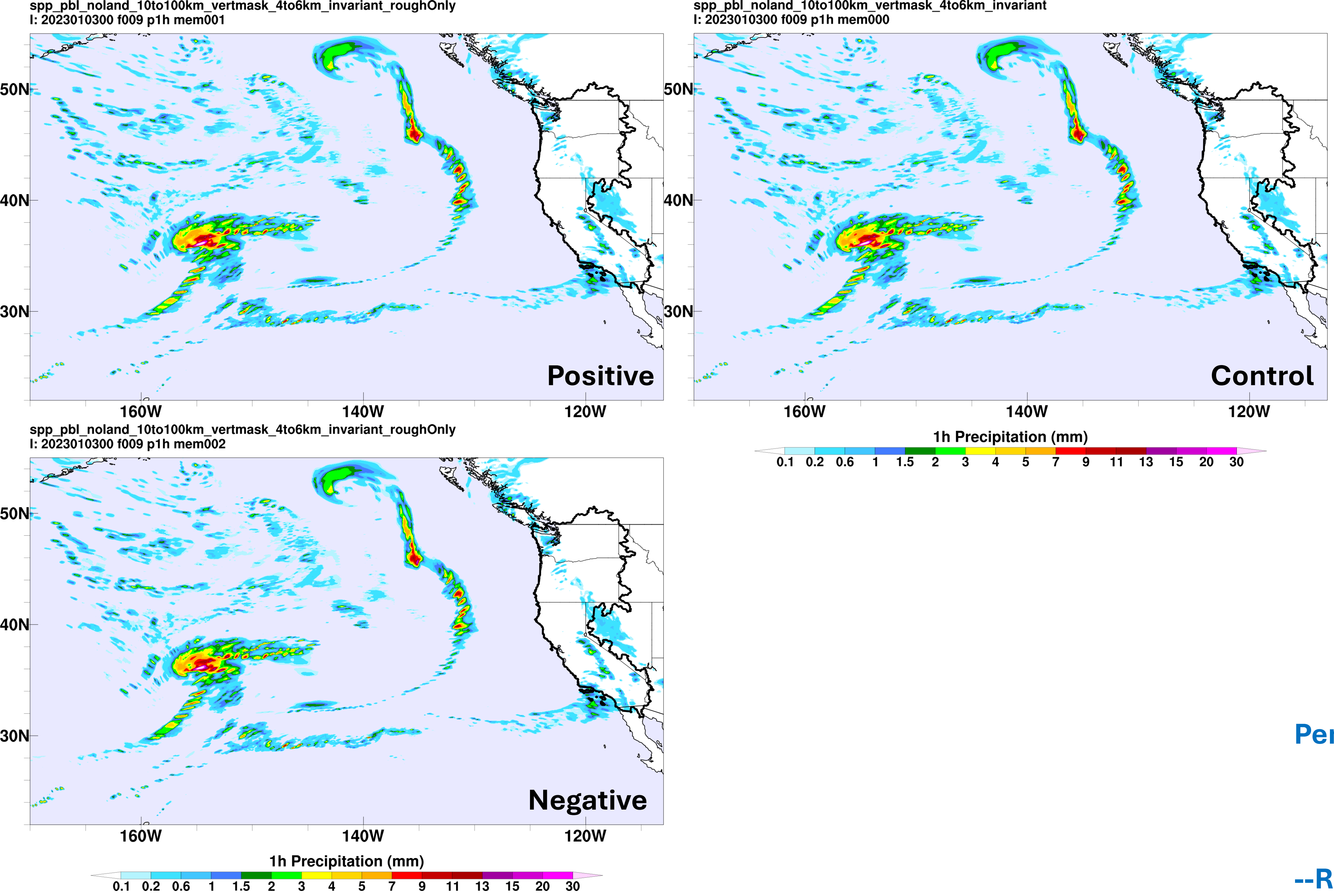
F009



Perturbed Only –

--Entrainment Coeff.

F009



Perturbed Only –

--Roughness Lengths

1-h Precipitation Over Ocean Grid Points