Was the February 2021 cold air outbreak over the central U.S. a subseasonal forecast of opportunity?

John R. Albers[1,2]

Matthew Newman[1,2], Andrew Hoell[2], Sam Lillo[1,2], Melissa Breeden[1,2]

[1]Cooperative Institute for Research in the Environmental Sciences
University of Colorado Boulder
[2]NOAA - Physical Sciences Laboratory

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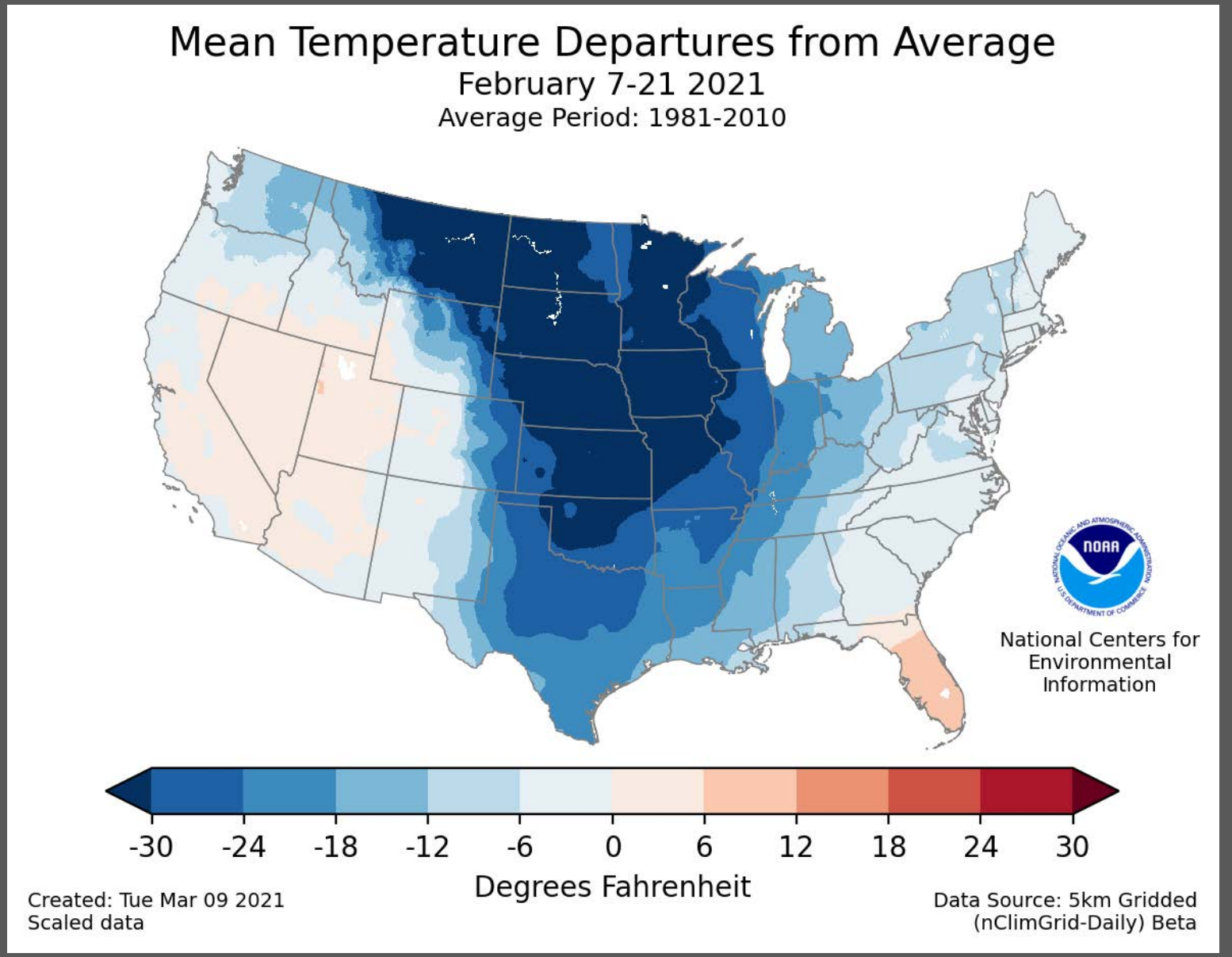
February 2021
North American cold air outbreak

- Central United States 30° F below normal Feb. 7-21
- Shreveport, LA breaks record low by 19° F (low of 1° F)
- Northern Texas receives 18-22" of snow
- Widespread power and water outages
- More than 100 deaths and $200-300 billion in damages



(sources: NOAA NWS and NCEI, AP, CBS)

Outstanding questions, models, and forecast data:

Did operational forecast models predict the 2021 CAO?

2021 CAO real-time forecasts

- NOAA CPC/PSL linear inverse model (LIM)
  (DJF 1979-2017 training period with out-of-sample forecasts)

- ECMWF IFS CY47R1 operational 2021 (bias corrected)
  (S2S prediction database, Vitart et al 2017)

What dynamical processes contributed to the 2021 CAO?

Ensemble reforecasts and climate simulations:

- 5,000 ensemble member LIM data denial experiments (initialized during Dec./Jan. 2020/2021)
  - ➤ How did La Nina, the January SSW, and the MJO contribute to the probability of the CAO?

- 3000-year LIM climate simulation
  - ➤ What is the return time for a similar CAO?

What is a linear inverse model (LIM)?

- Empirical model, where here, the forecast operator (L) is constructed from 5-day lag covariances of 7-day running mean anomalies of observational data (here Japanese Reanalysis JRA-55)

$$\frac{dx}{dt} = Lx + \xi$$

$$L = \tau_0^{-1} \ln \frac{\left\langle x(t+\tau_0)x(t)^T \right\rangle}{\left\langle x(t)x(t)^T \right\rangle}$$

$$\tau_0 \equiv \text{5-day lag}$$

Forecasted variables:

$$x = \begin{bmatrix} p \\ \Phi \\ H \\ \psi_T \\ \psi_S \\ SST \\ T_{2m} \end{bmatrix}$$

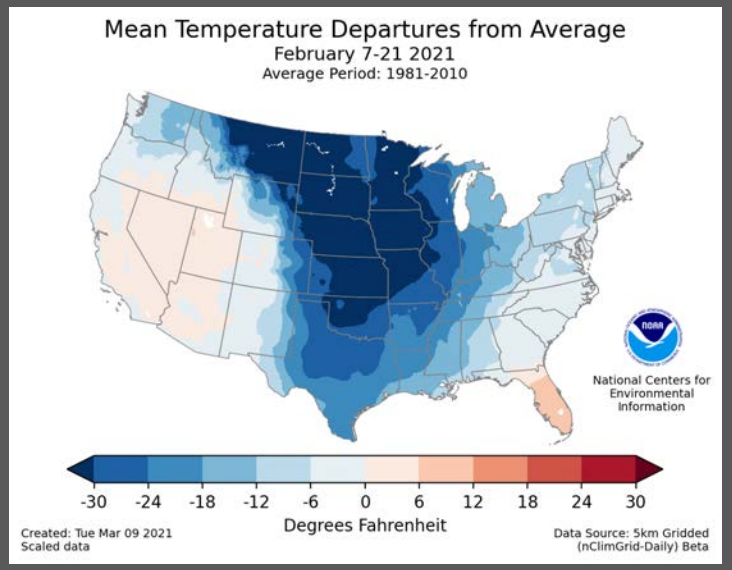
- Mean sea-level pressure (0˚-90˚N)
- Geopotential (500 hPa, 0˚-90˚N)
- Tropical heating (-15˚S-15˚N)
- Tropospheric stream function (750 hPa, 0˚-90˚N)
- Stratospheric stream function (combined 5 and 100 hPa, 30˚-90˚N)
- Tropical sea surface temperature (-15˚S-15˚N)
- 2m temperature (North America-land only)

State independent white noise

$$\xi$$

- Derived from fluctuation-dissipation relationship
- Function of L, x

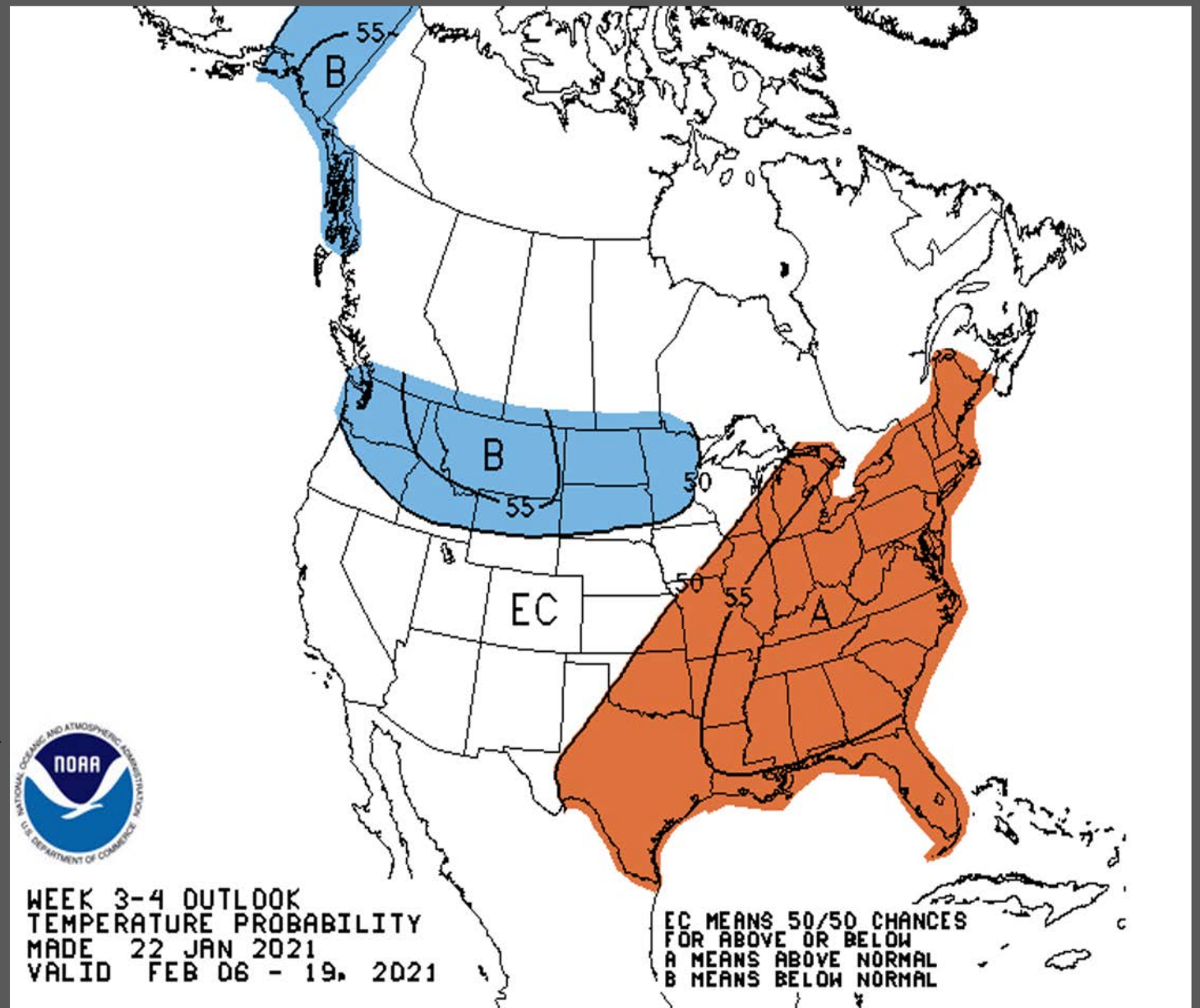
How successful was the weeks 3/4 2m temperature forecast?



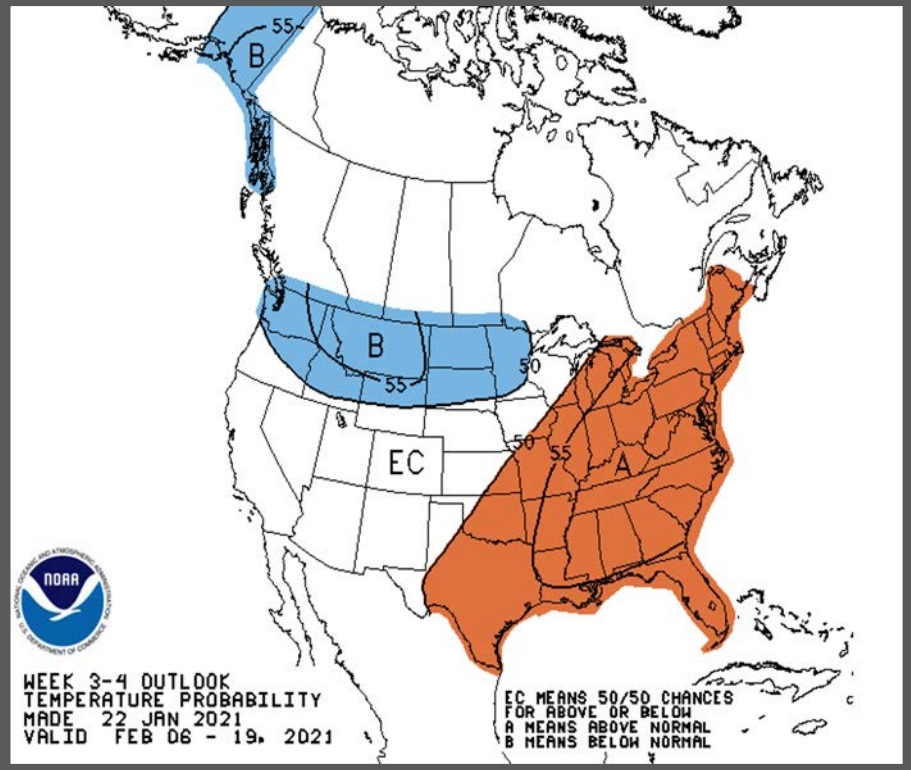
Verification

Official NOAA CPC forecast guidance →

- Issued – Jan. 22
- Verification period – Feb. 6-19



Reasonable forecast? Yes.



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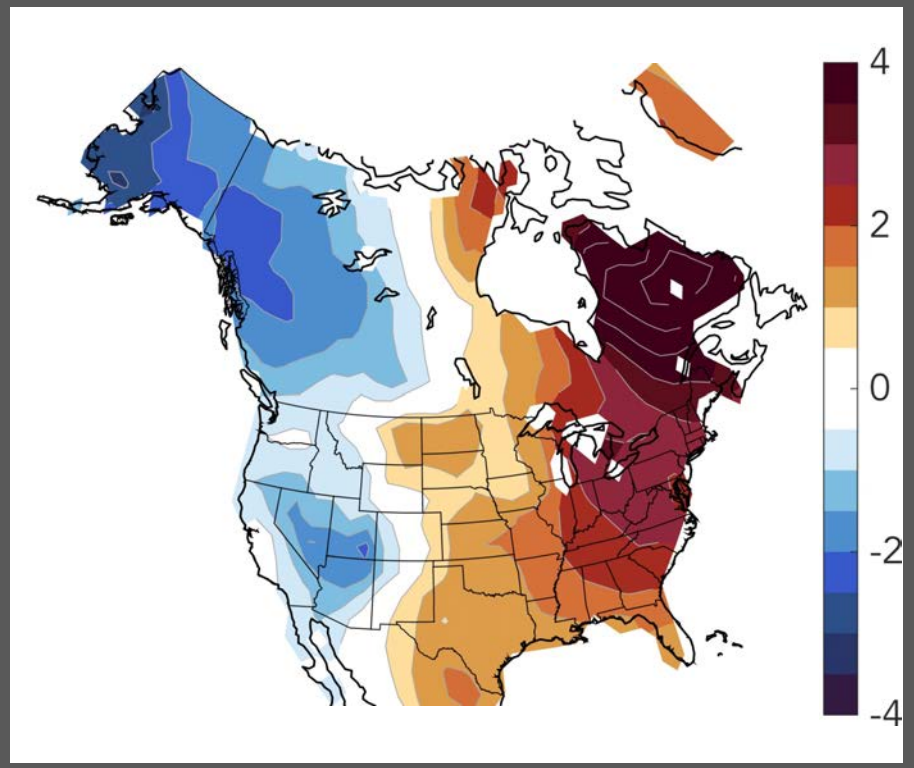
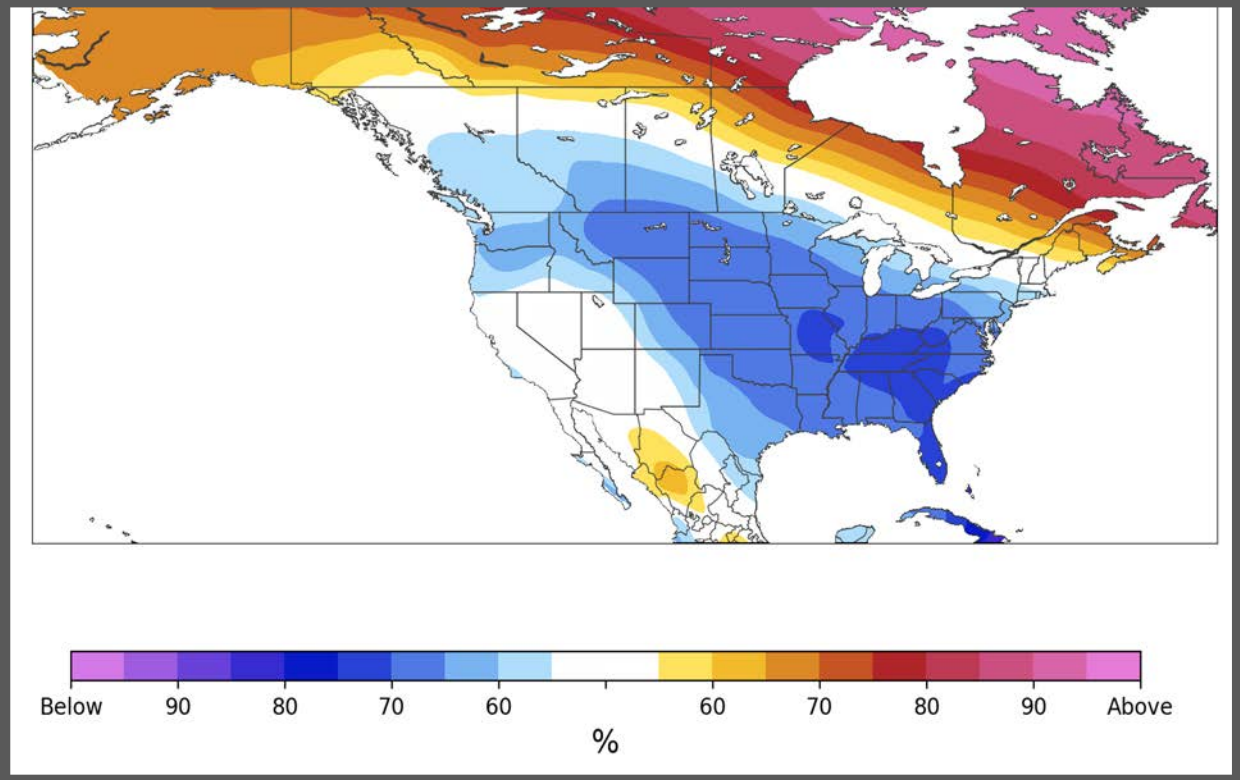


ECMWF IFS forecast

- Forecast initialized – Jan. 21
- Verification period – Feb. 5-18
- CFSv2 looked similar, JMA was even warmer

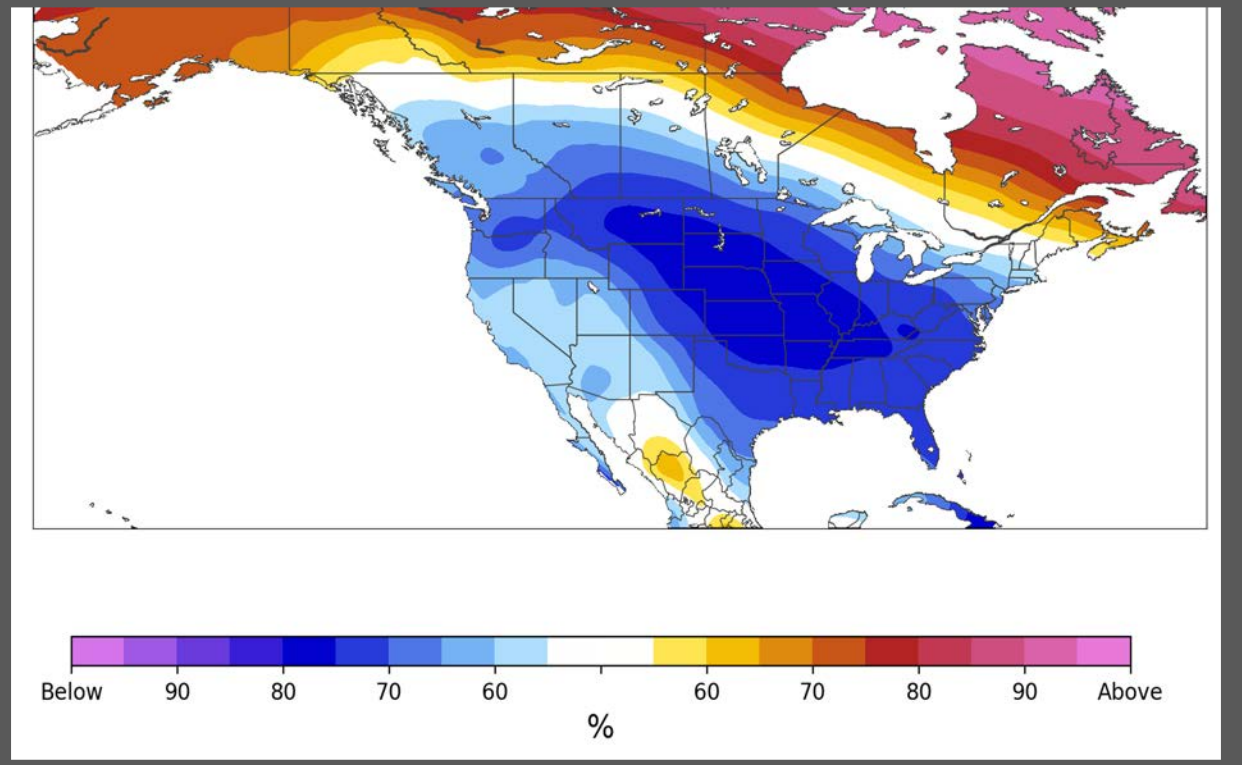
How did the LIM forecast compare?

NOAA CPC/PSL LIM probabilistic
2m temperature forecasts



Weeks 3/4 forecast

- Forecast initialized – Jan. 19
- Verification period – Feb. 3-16



Week 4 forecast

- Forecast initialized – Jan. 19
- Verification period – Feb. 10-16

Verification

Feb. 8 - 21

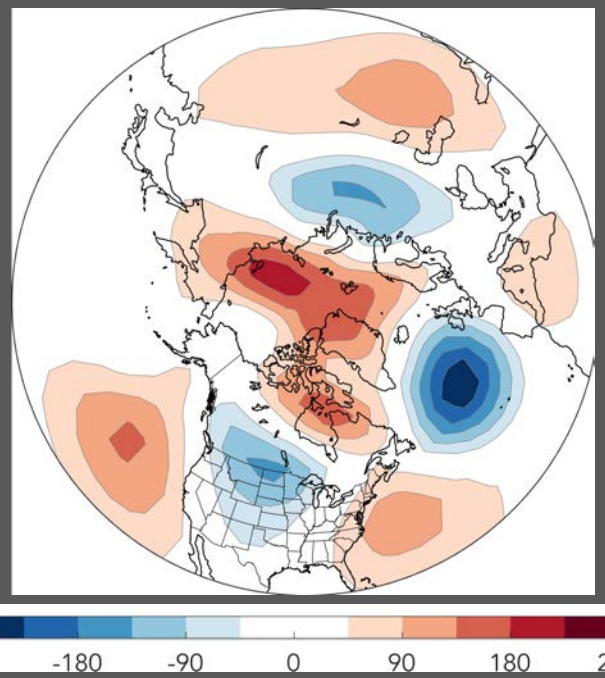
LIM forecast

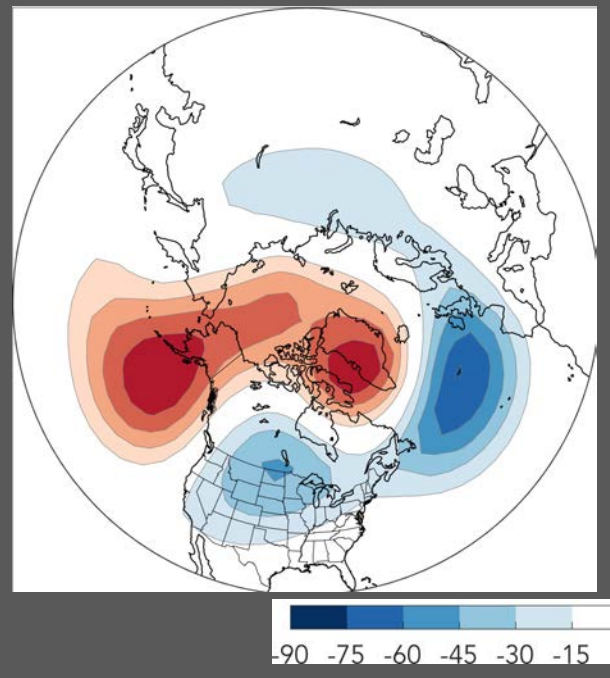
Forecast initialized – Jan. 24
Forecast verified – Feb. 8 - 21

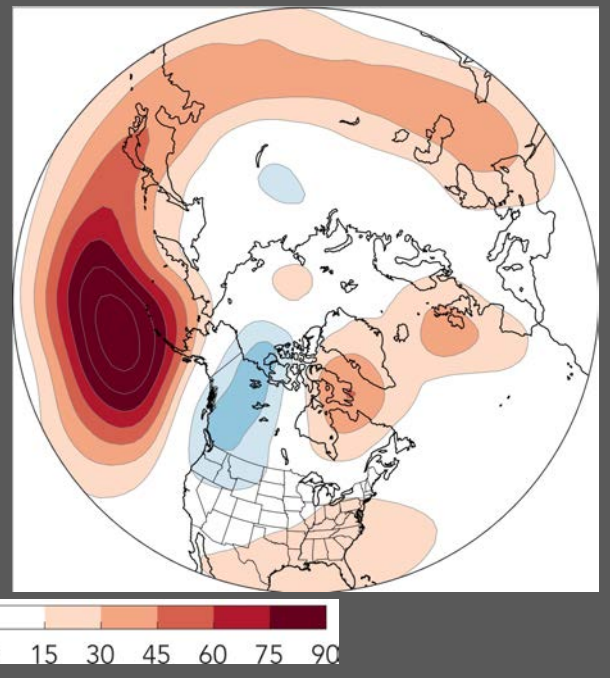
IFS forecast

Forecast initialized – Jan. 25
Forecast verified – Feb. 9 - 22

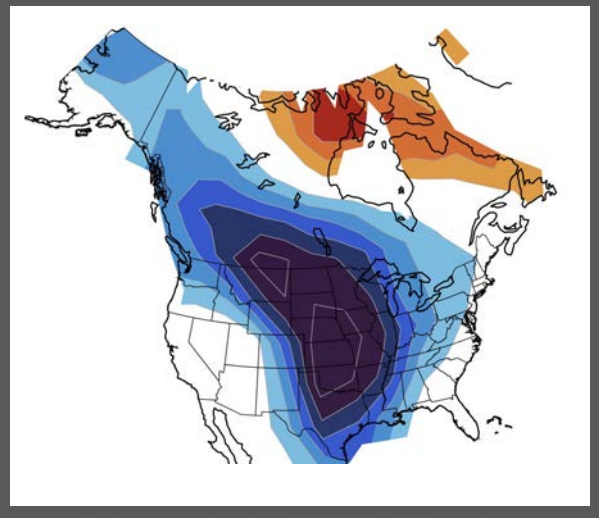
500 hPa geopotential height

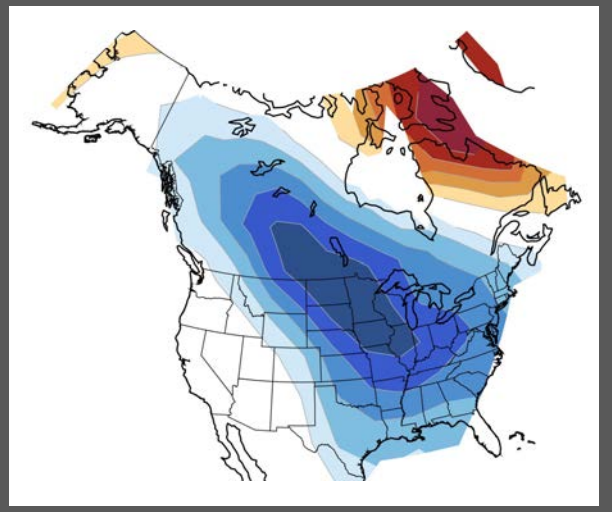


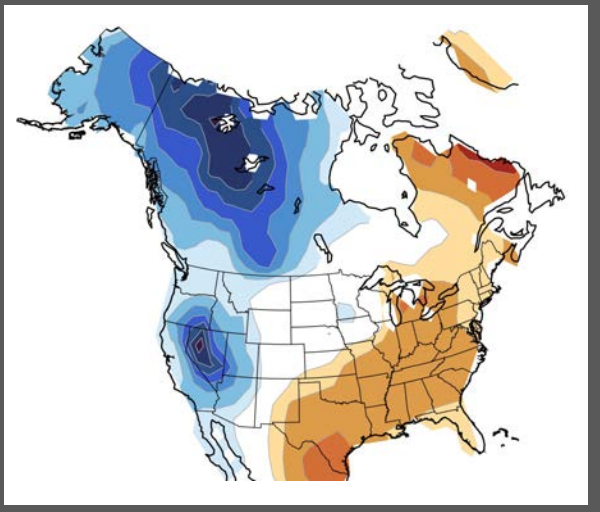




2m temperature







What dynamical processes caused the CAO?

LIM-based 'nonnormal' filter:

$$\frac{dx}{dt} = Lx + \xi$$

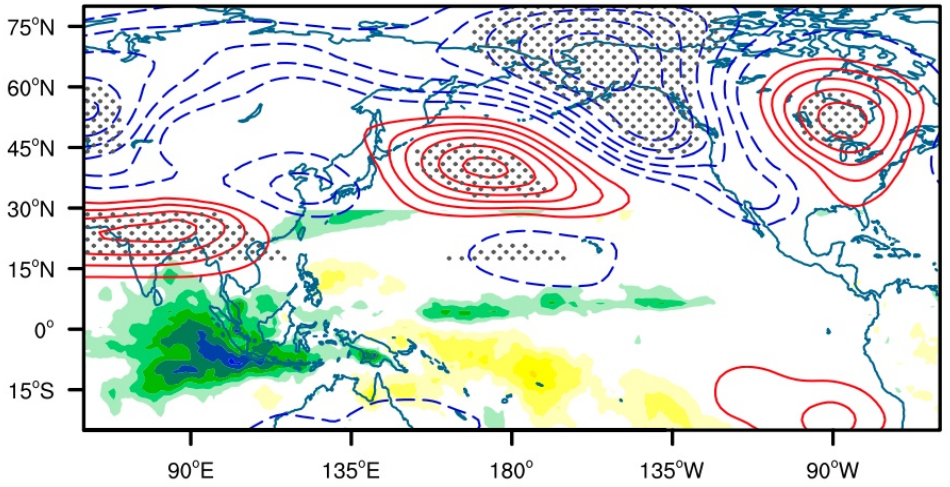
Eigendecomposition of L yields eigenmodes with 3 important characteristics:

1. Period/frequency of oscillation
2. e-folding decay time
3. Relative amplitude in each LIM state vector (x) variable

(e.g., Penland and Matrasova 2006, Albers and Newman 2021)

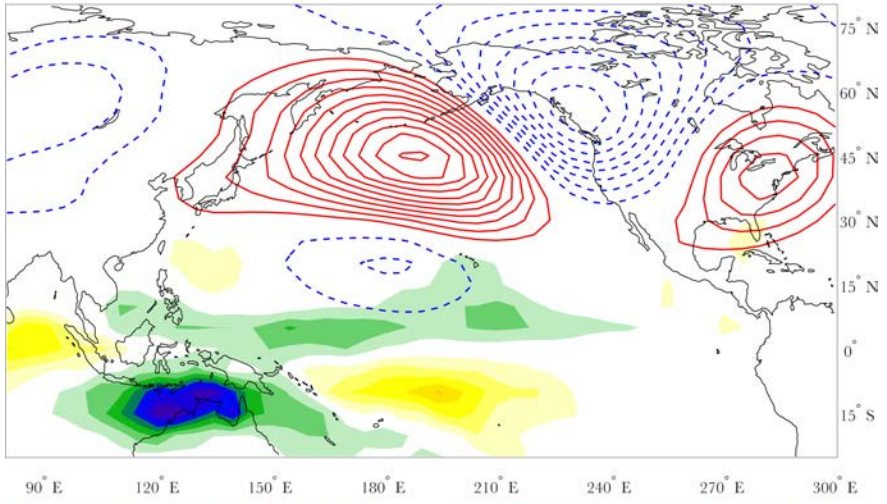
Example: LIM MJO eigenmode

MJO phase 3



- ERA-Interim 250 hPa geopotential heights (contours)
- GPCP precipitation (filled contours)

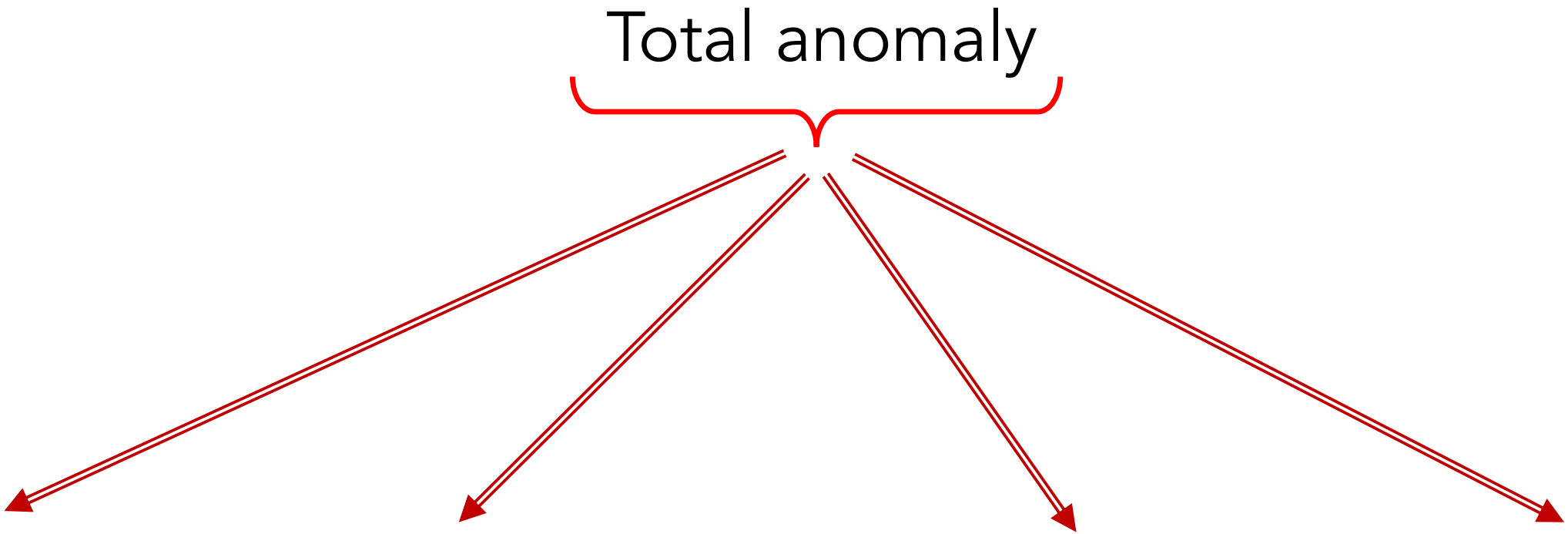
(Hendersen et al. J.Clim. 2017)



LIM-based MJO eigenmode:

- 500 hPa geopotential heights (contours)
- tropical heating (filled contours)
- e-folding time = 21 days
- oscillation period = 52 days

Dynamical processes from LIM filter:



Internal variability

MJO

Joint SST-stratosphere modes

- Teleconnections through upper troposphere-lower stratosphere

Stratospheric mode

- Captures downward SSW influence
- No SST component

(References: SST-stratosphere-SSW modes → Albers and Newman 2021 – MJO-ENSO → Henderson et al. 2020)

Dynamical processes from LIM filter:

LIM ‘nonnormal filter’ allow us to …

1. Isolate dynamical processes in forecasts AND verifications

2. Conduct dynamical process-based data denial reforecasts

troposphere-lower stratosphere

influence

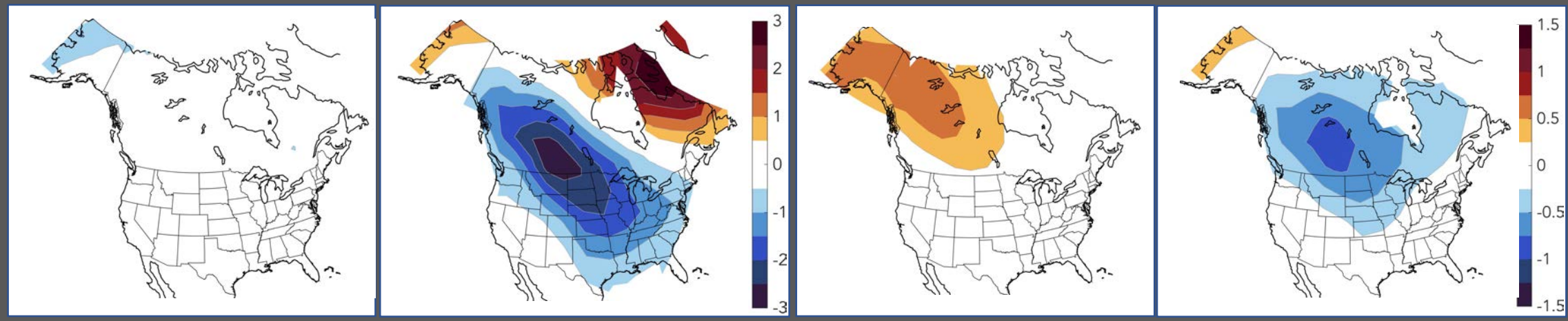
- No SST component

(References: SST-stratosphere-SSW modes → Albers and Newman 2021 – MJO-ENSO → Henderson et al. 2020)

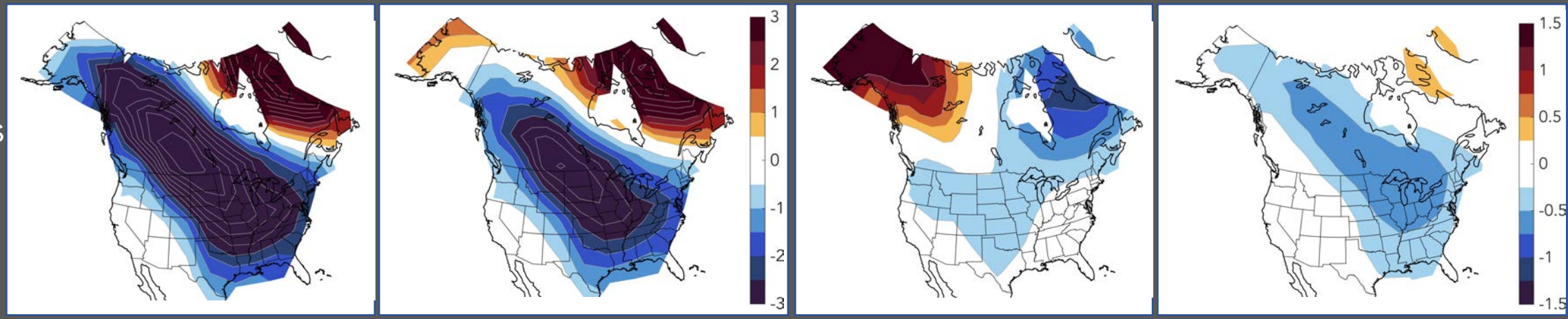
2m temperature Forecast initialized – Jan. 24 Forecast verified – Feb. 8 - 21

Total anomaly = Internal variability + SST-stratosphere (La Niña) + MJO + Stratospheric mode (SSW)

LIM forecasts



Verifications



Data denial experiments:

- LIM reforecasts using nonnormally filtered initial conditions…

Example:

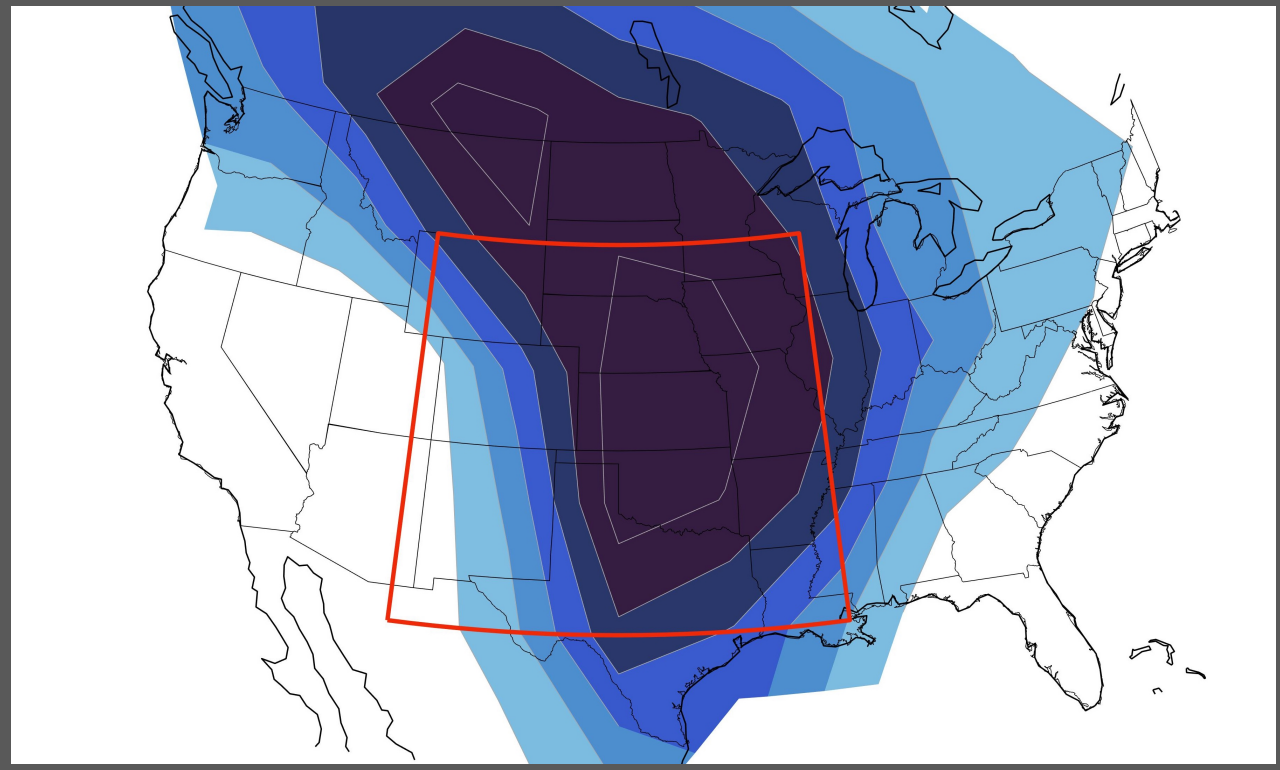
$$\boldsymbol{x}(t) = \sum_{i \in internal} \boldsymbol{x}_i(t) + \sum_{i \in \text{MJO}} \boldsymbol{x}_i(t) + \sum_{i \in \text{SST/stratosphere}} \boldsymbol{x}_i(t) + \sum_{i \in stratosphere/\text{SSW}} \boldsymbol{x}_i(t)$$

zero

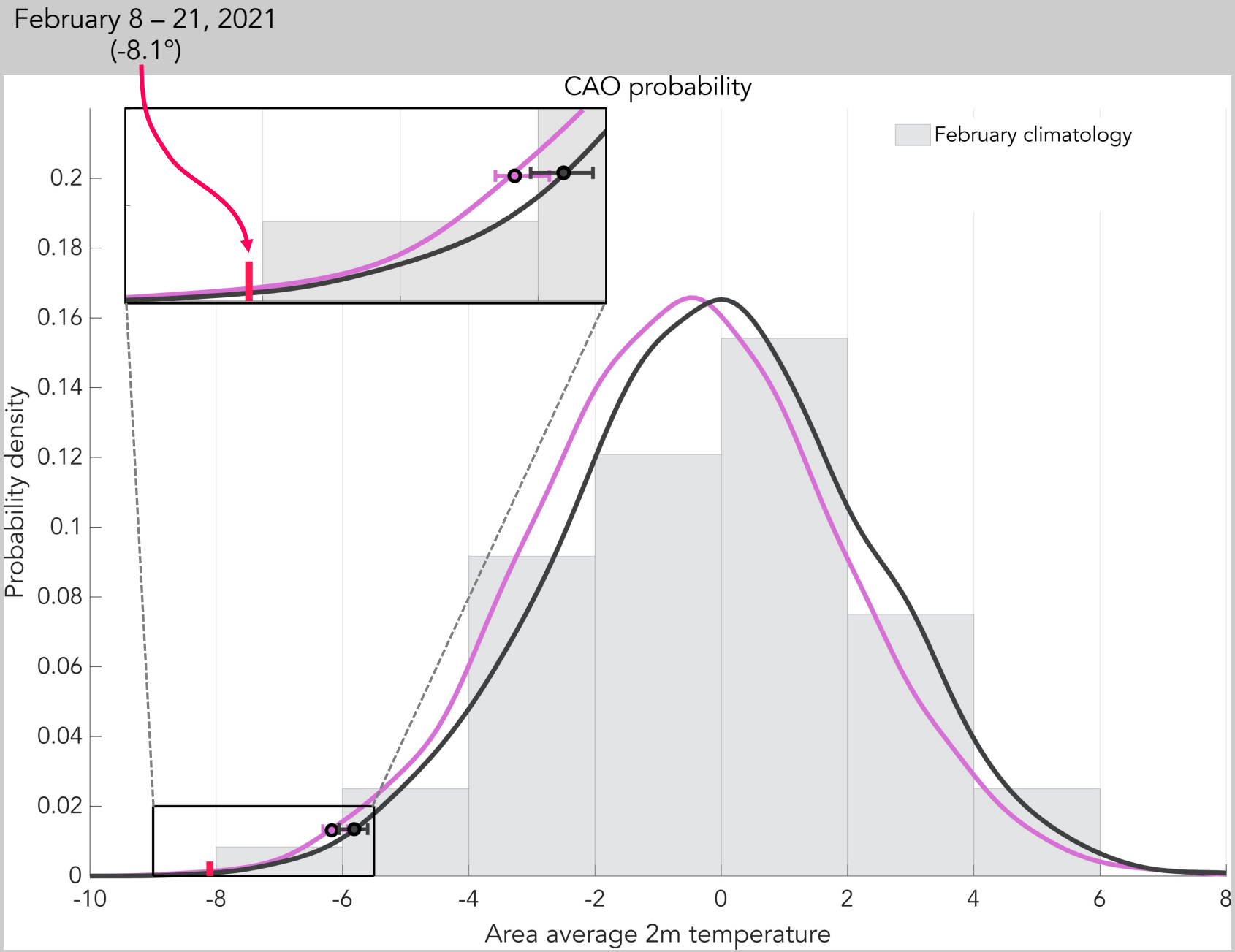
⟹ Isolates 'stratosphere/SST' (La Niña) contribution to CAO

LIM data denial ensemble reforecasts:

- 5000 ensemble members per experiment
- Initialize either Dec. 1, 2020 or Jan. 24, 2021
- All verify February 8-21, 2021
- Consider PDFs of 2m temperature area-averaged (250°-270°E - 30°-45°N)



5000 ensemble member reforecasts – verified Feb. 8 – 21, 2021



Experiment type

SSTs suppressed (ENSO neutral conditions)

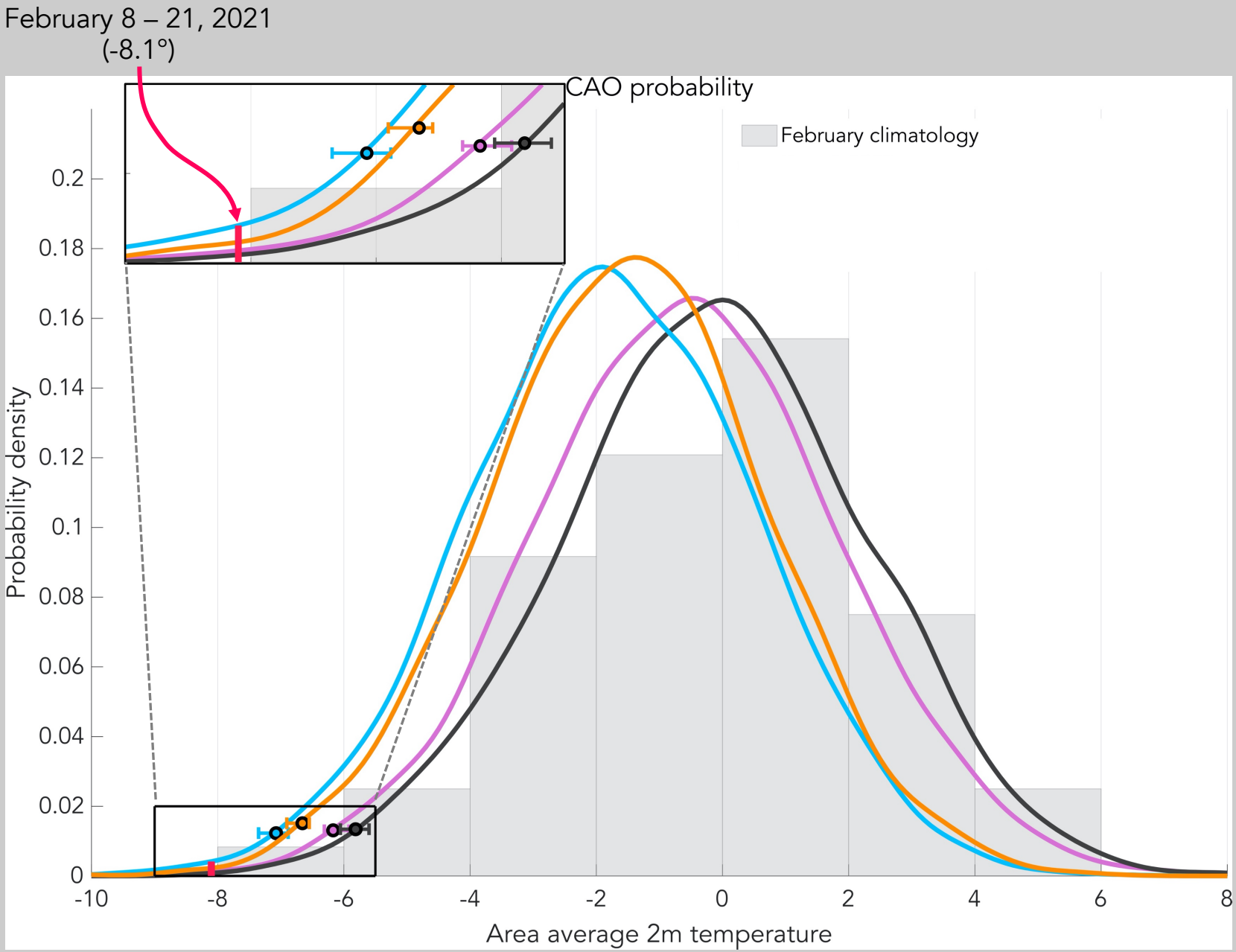
- Forecasts initialized Dec. 1, 2020

Full initial conditions

- Forecasts initialized Dec. 1, 2020

– Distributions significantly different according to two-tailed Kolmogorov–Smirnov test
– Bootstrap confidence intervals shown as whiskers for 1st percentile of each PDF

5000 ensemble member reforecasts – verified Feb. 8 – 21, 2021



Experiment type

SSTs suppressed (ENSO neutral conditions)

- Forecasts initialized Dec. 1, 2020

Full initial conditions

- Forecasts initialized Dec. 1, 2020

Full initial conditions

- Forecasts initialized Jan. 24, 2021

Stratospheric mode suppressed (no SSW effect)

- Forecasts initialized Jan. 24, 2021

– Distributions significantly different according to two-tailed Kolmogorov–Smirnov test
– Bootstrap confidence intervals shown as whiskers for 1st percentile of each PDF

$$Risk\ ratio = \frac{Probability\ of\ CAO\ for\ one\ of\ \left[\begin{matrix}\\ \\ \\ \end{matrix}\right]}{Probability\ of\ CAO\ for\ ENSO\ neutral}$$

Experiment type

Full initial conditions

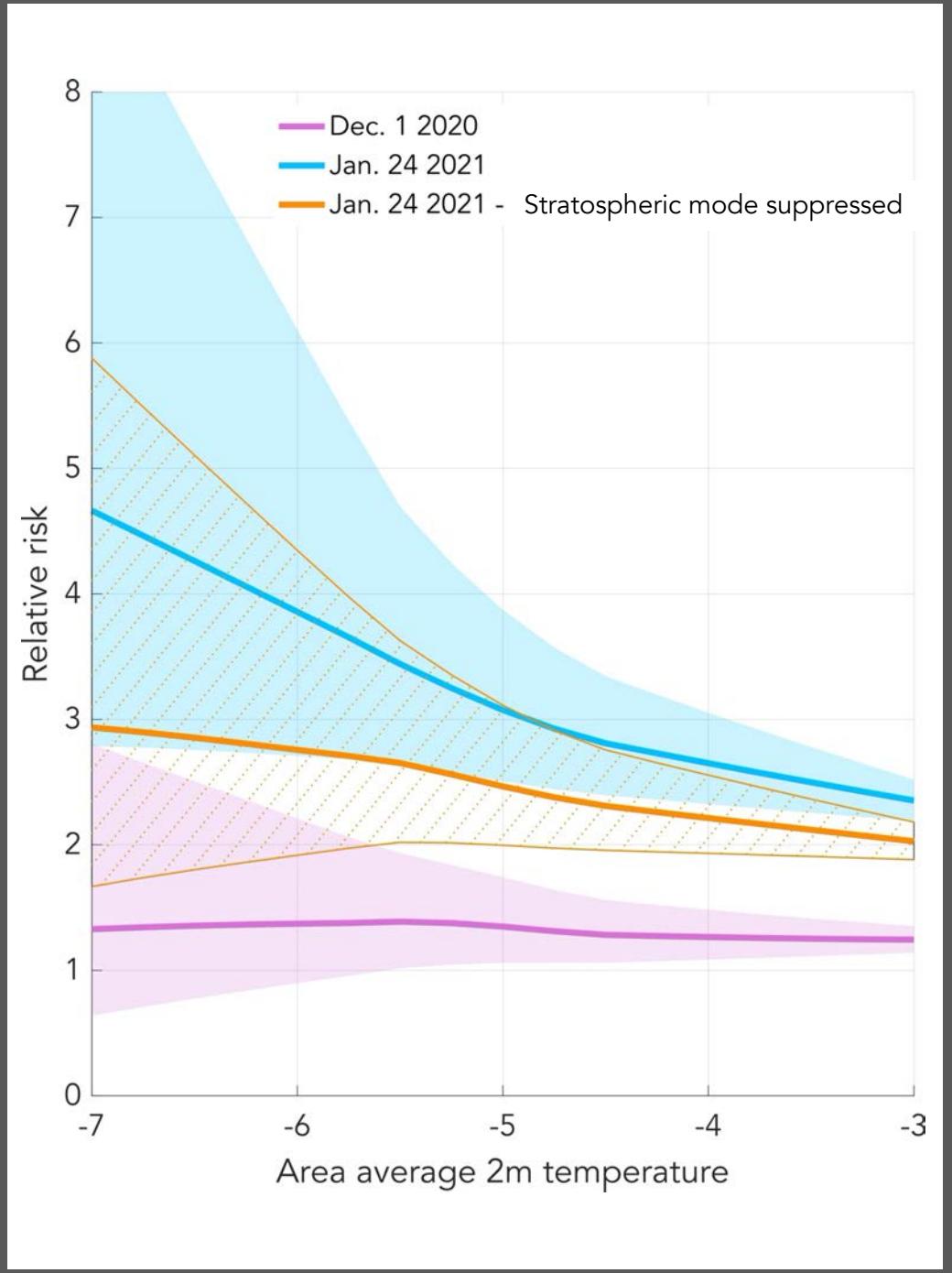
- Forecasts initialized Dec. 1, 2020
- Forecasts verified Feb. 8 – 21 , 2021

Full initial conditions

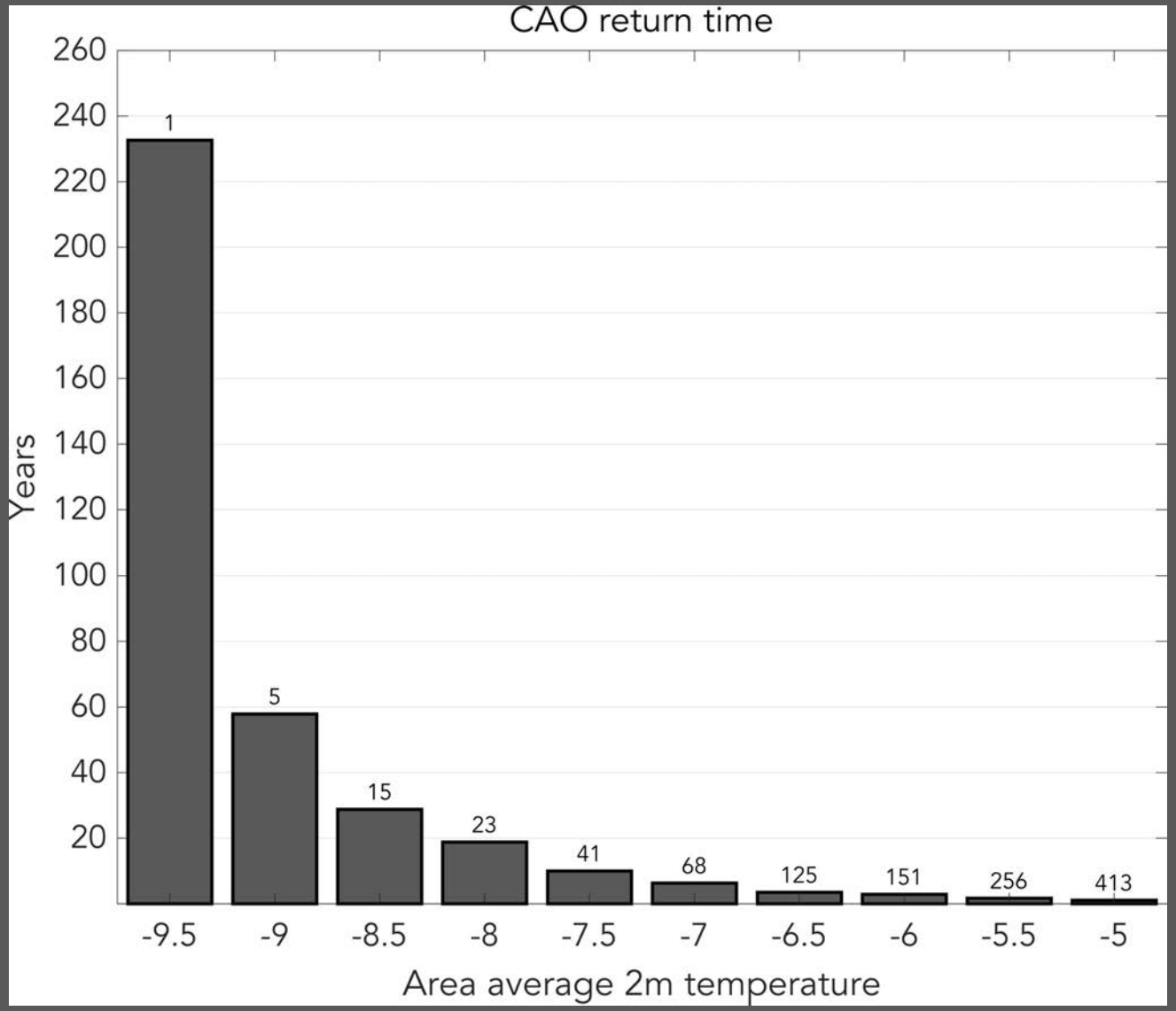
- Forecasts initialized Jan. 24, 2021
- Forecasts verified Feb. 8 – 21 , 2021

Stratospheric mode suppressed (no SSW effect)

- Forecasts initialized Jan. 24, 2021
- Forecasts verified Feb. 8 – 21 , 2021



3000-year LIM climate simulation :



- February 2021 CAO ~ 20-30 year return time (area average 2m temperature -8.1°F)
- Can get moderate CAOs caused individually by La Niña, SSWs, internal variability, etc.

BUT,

- Most severe CAOs (like Feb. 2021) require additive contributions from internal variability, La Niña, SSW, MJO

Conclusions:

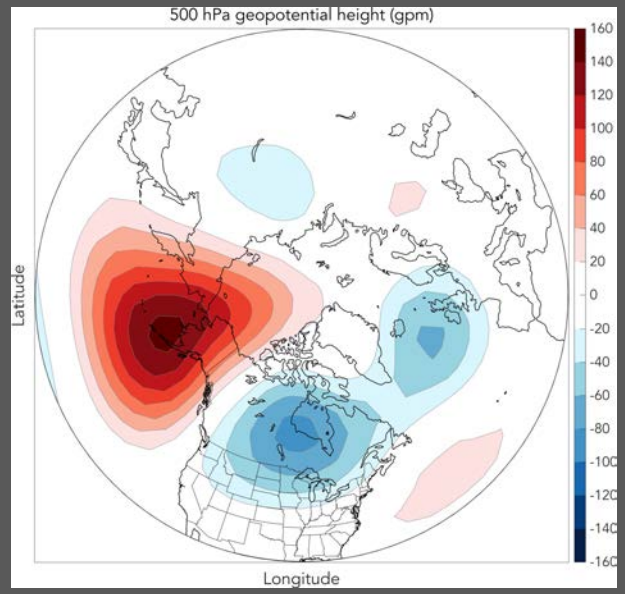
- Dynamical models suggested warm North American 2m temperatures until 2 weeks before CAO
- LIM suggested CAO at least 4 weeks in advance
- Predictable portion of 2021 North American CAO was due to SST-stratosphere modes (La Niña), with small contributions from January SSW and MJO
- Risk of strong CAO was mildly increased on Dec. 1, 2020 because of La Niña
- Risk of strong CAO was 3-5 times as likely by Jan. 24 due to combined effects of La Niña and SSW
- Strong CAO similar to February 2021 event can be expected every 20-30 years

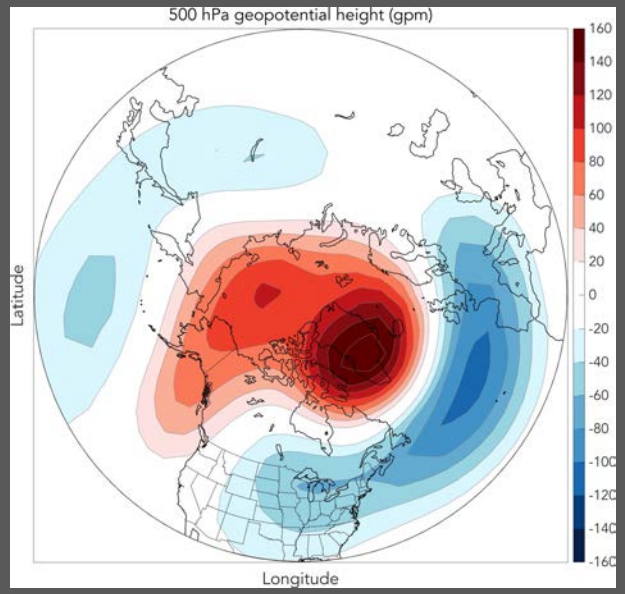
Internal variability

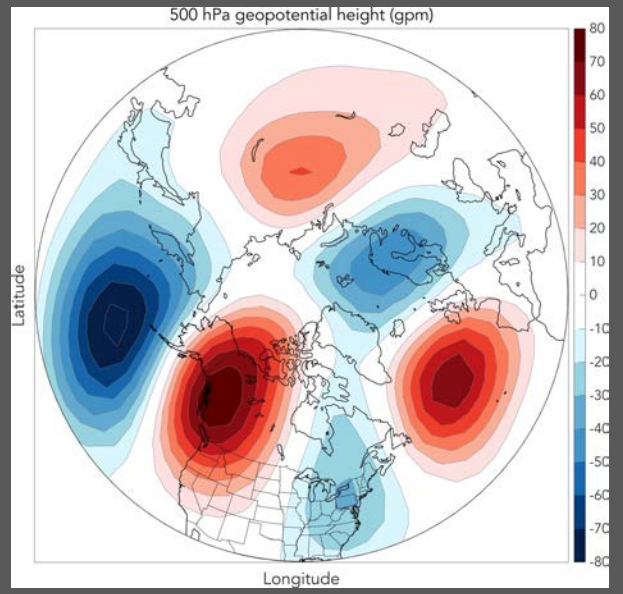
SST-stratosphere

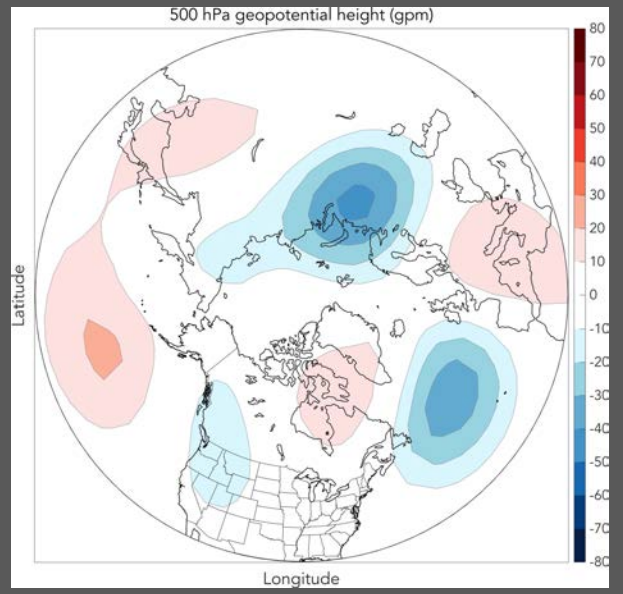
MJO

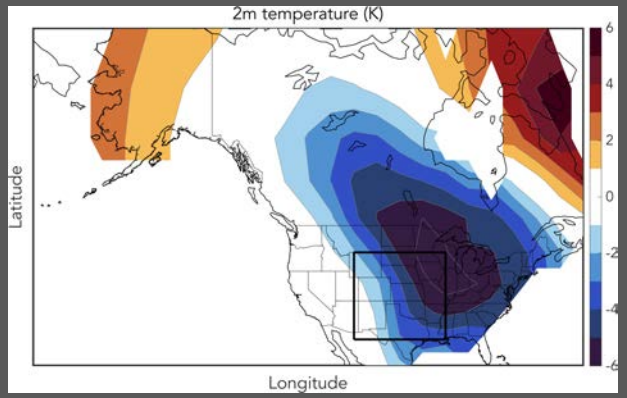
Stratospheric NAM

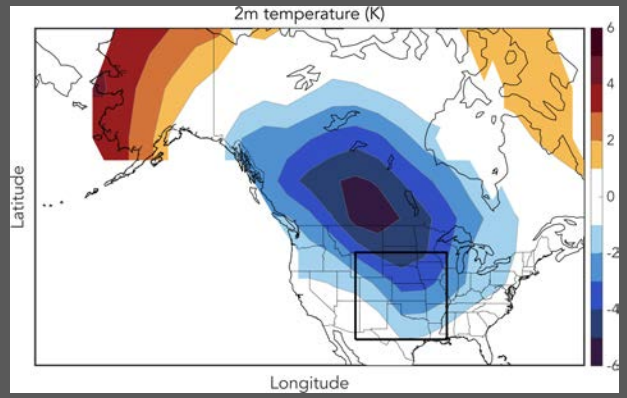


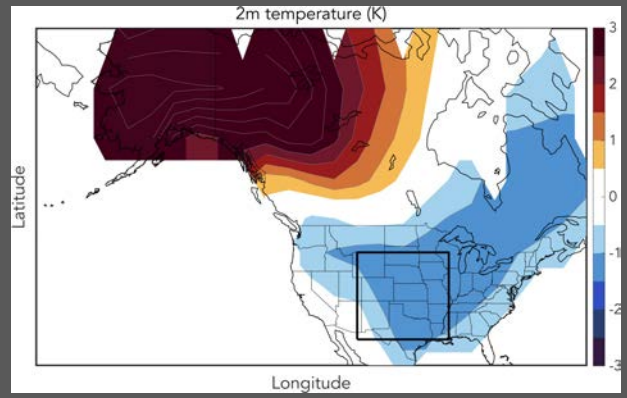


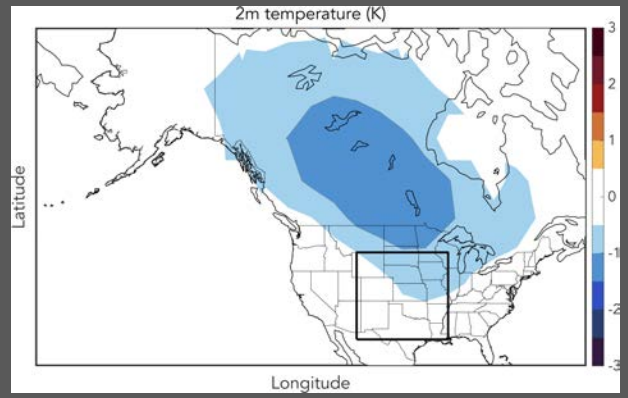


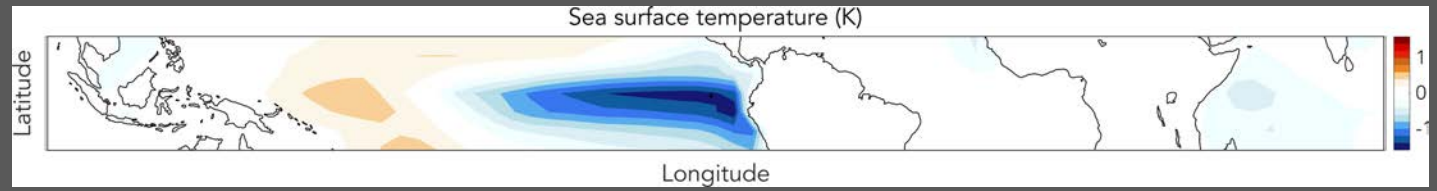












(LIM climate run)