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

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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)

\[
\frac{dx}{dt} = Lx + \xi
\]

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

\( \tau_0 \equiv 5\text{-day lag} \)

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?

Official NOAA CPC forecast guidance

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

Verification
Reasonable forecast? Yes.

Official NOAA CPC forecast guidance
- Issued – Jan. 22
- Verification period – Feb. 6-19

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)
What dynamical processes caused the CAO?

Eigendecomposition of $L$ yields eigenmodes with 3 important characteristics:
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LIM-based ‘nonnormal’ filter:

Example: MJO eigenmode

- Period (frequency) of oscillation = 52 days (0.02 days$^{-1}$)
- E-folding decay time = 21 days
- ERA-Interim 250 hPa geopotential heights (contours)
- GPCP precipitation (filled contours)


MJO phase 3

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:

- **Total anomaly**
  - **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

(References: SST-stratosphere-SSW modes → Albers and Newman 2021 – MJO-ENSO → Henderson et al. 2020)
Total anomaly = Internal variability + SST-stratosphere (La Niña) + MJO + Stratospheric mode (SSW)

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

LIM forecasts

Verifications
Data denial experiments:

- LIM reforecasts using nonnormally filtered initial conditions...

**Example:**

\[
x(t) = \sum_{i \in \text{internal}} x_i(t) + \sum_{i \in \text{MJO}} x_i(t) + \sum_{i \in \text{SST/stratosphere}} x_i(t) + \sum_{i \in \text{stratosphere/SSW}} x_i(t)
\]

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

February 8 – 21, 2021  
(-8.1 °)

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

Area average 2m temperature

Probability density

CAO probability

February climatology
Experiment type

- **SSTs suppressed (ENSO neutral conditions)**
  - Forecasts initialized Dec. 1, 2020

- **Full initial conditions**
  - Forecasts initialized Dec. 1, 2020

- **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

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

February 8 – 21, 2021

(-8.1 °)
Risk ratio = \frac{\text{Probability of CAO for one of } }{\text{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
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