Centennial Reanalysis

How the 20th Century Reanalysis (20CR) captures 200 years of weather using surface observations

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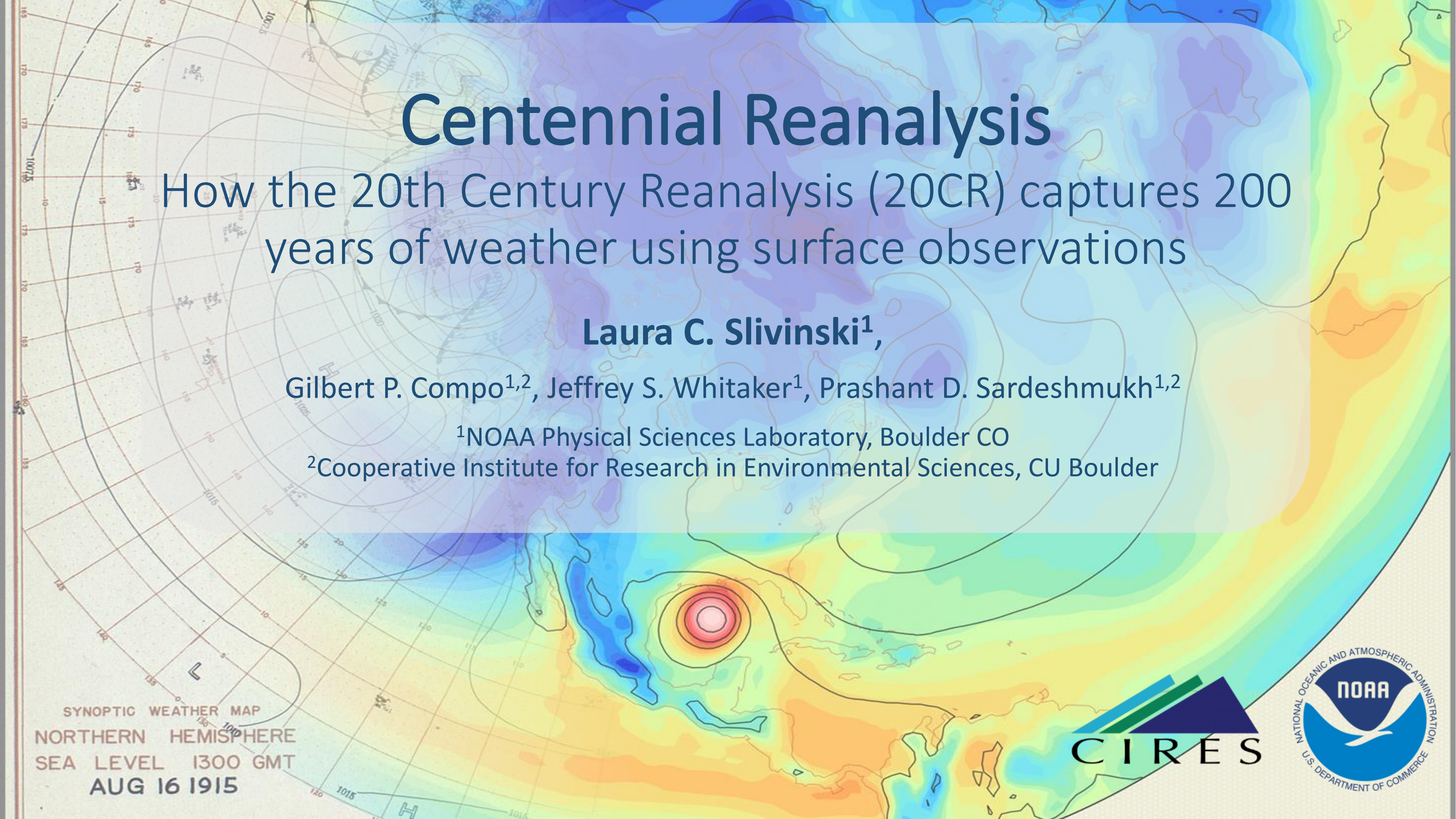

CIRES

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Outline

- Why centennial reanalysis?
- The challenge with centennial reanalysis
- Some solutions
- Performance
- Remaining challenges
- Outlook

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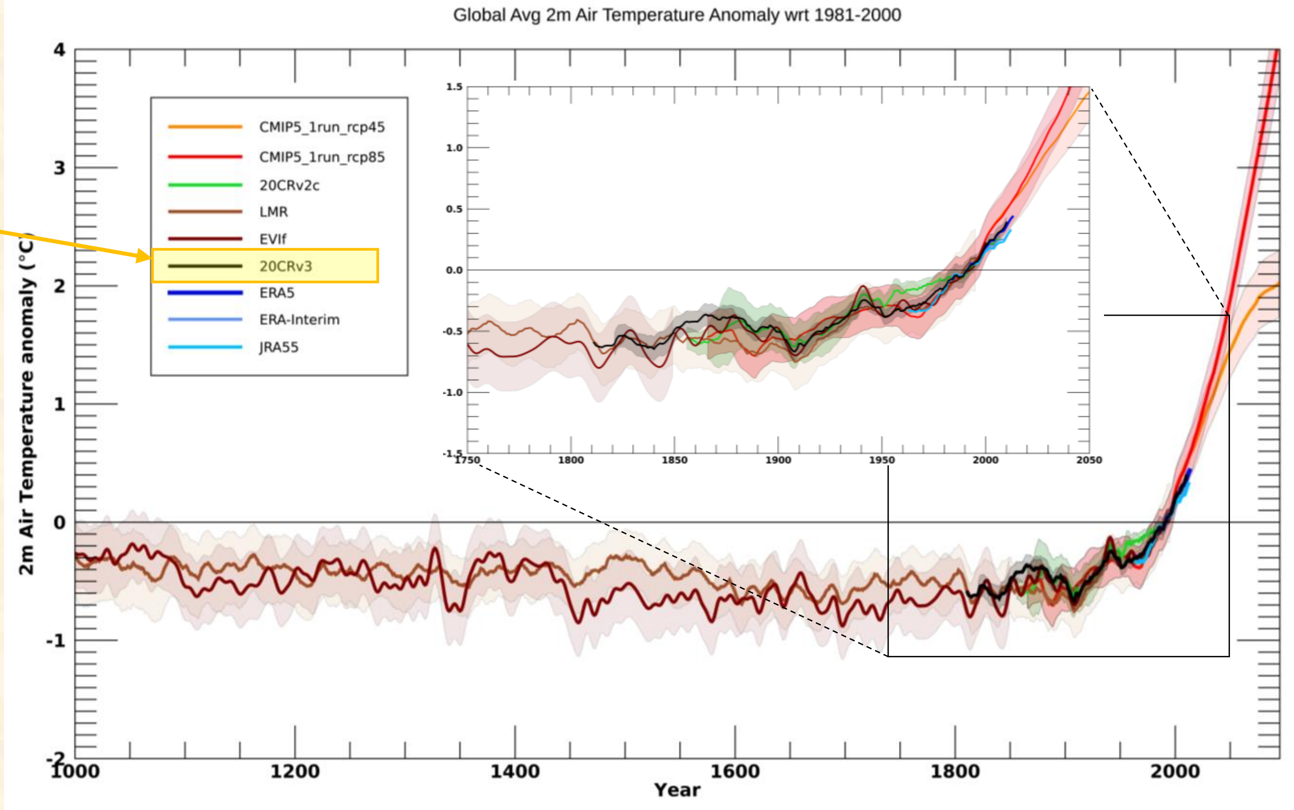
Why do we need reanalysis to span over a century?

- To bridge the gap between weather and climate
- To put recent extreme events in a consistent, long-term context
- To obtain a larger sample of extreme weather & climate events

- Risk assessment of extreme events for insurance and reinsurance
- Wind and solar droughts for renewable energy planning
- Coastal defense planning against sea-level rise and storm surges
- Trends in strength and frequency of hurricanes
- Historical risks of wildfires
- Variations in forest productivity
- Studying Greenland ice sheet melting
- Dust Bowl of the 1930s
- Arctic warming in the 1920s-1930s
- Droughts, floods, blizzards, wind storms, typhoons
- Discovering previously unknown hurricanes
- Irish potato famine of 1845
- 1815 eruption of Mt. Tambora and the following "Year Without a Summer"
- Weather and ocean conditions during the sinking of the Titanic
- Economic impacts of diseases spread by the TseTse fly in sub-Saharan Africa
- Probability of wind-assisted, cross-Atlantic bird species migration
- "The Long Winter" of 1880-1881 described in Laura Ingalls Wilder's books
- Validation & verification of paleo reconstructions and climate model projections

5-year averaged global **2m air temperature** anomalies from paleo reconstructions, reanalyses, and climate model projections

completely independent from *any* land surface temperature observations

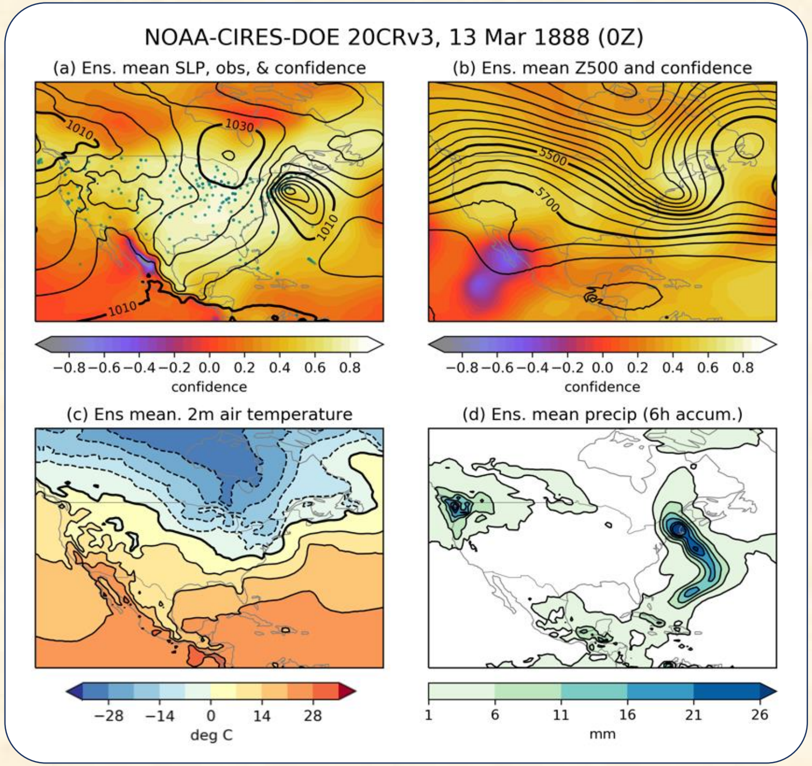


Reanalyses provide an instrument-based link between paleo reconstructions and climate model projections

Compo et. al. (2023)

The 20th Century Reanalysis (20CR) provides a global, 200-year history of sub-daily weather

by assimilating *only* surface pressure observations into a modern weather model



NOAA-CIRES-DOE 20th Century Reanalysis Version 3

- Estimates temperature, wind, precipitation, pressure, humidity, & other variables, from the ground to the top of the atmosphere
- Prescribed sea surface temperature, sea ice concentration, and radiative forcing
- Global 75km grid
- 3-hourly resolution
- Spans 1836-2015 [1806-1835 experimental]
- Data assimilation: Ensemble Kalman Filter with 80 ensemble members to quantify uncertainty
- Publicly available: https://go.usa.gov/XTd

Slivinski et. al. (2021)

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The challenge with centennial reanalysis

- Span 100+ years, including many significant changes in observing network

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Monthly Mean Global Precipitation

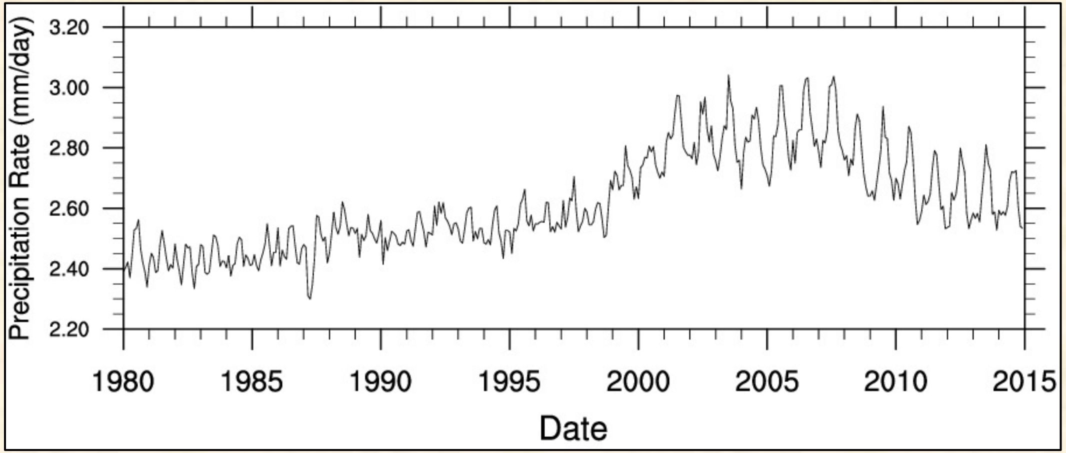

Image provided by the NOAA-ESRL Physical Sciences Laboratory from their website at https://psl.noaa.gov/data/writ

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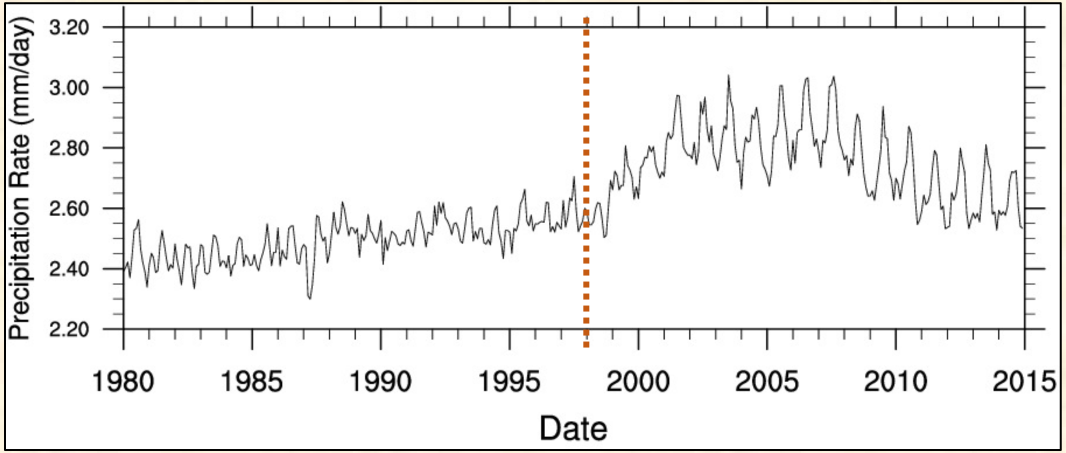

Example: spurious trend in MERRA global precipitation arising from observing network change

- ➢ Model may have dry bias that was corrected by water vapor sensitive radiances from AMSU, which came online in 1998

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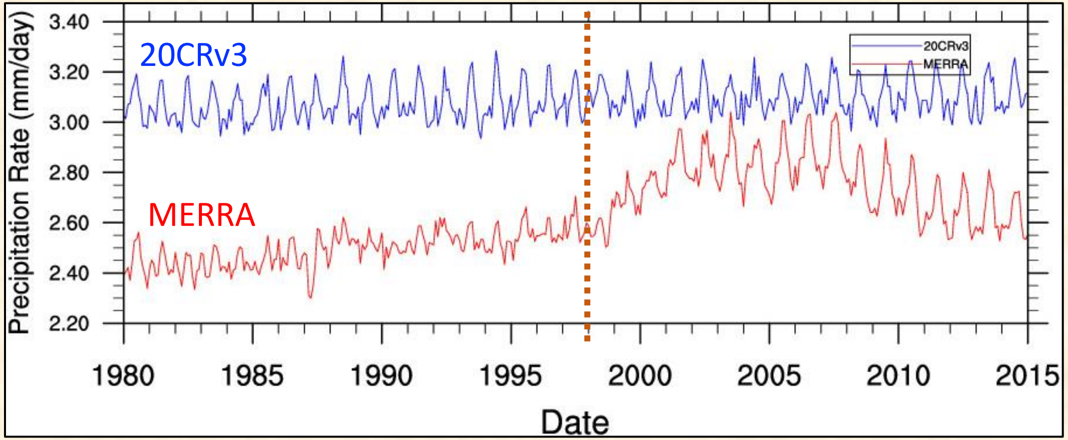


Example: spurious trend in MERRA global precipitation arising from observing network change

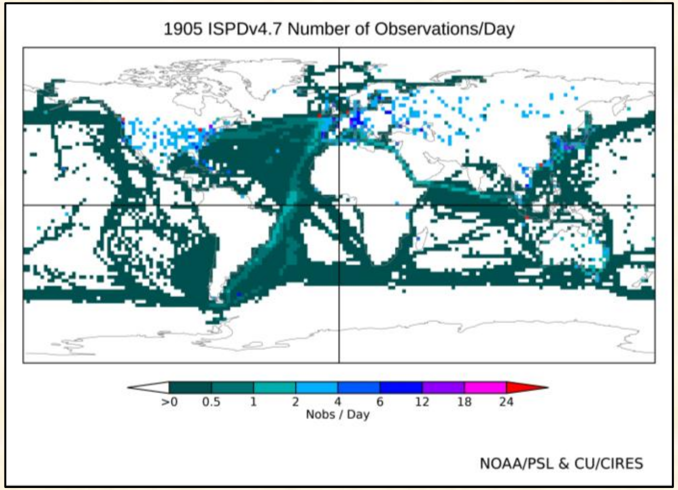
- ➢ Model may have dry bias that was corrected by water vapor sensitive radiances from AMSU, which came online in 1998
- ➢ 20CRv3 does not assimilate any radiances, therefore does not exhibit this discontinuity

Image provided by the NOAA-ESRL Physical Sciences Laboratory from their website at https://psl.noaa.gov/data/writ

The challenge with centennial reanalysis

- Span 100+ years, including many significant changes in observing network *(over 4 orders of magnitude)*

1905 sfc pres ob network



2005 sfc pres ob network

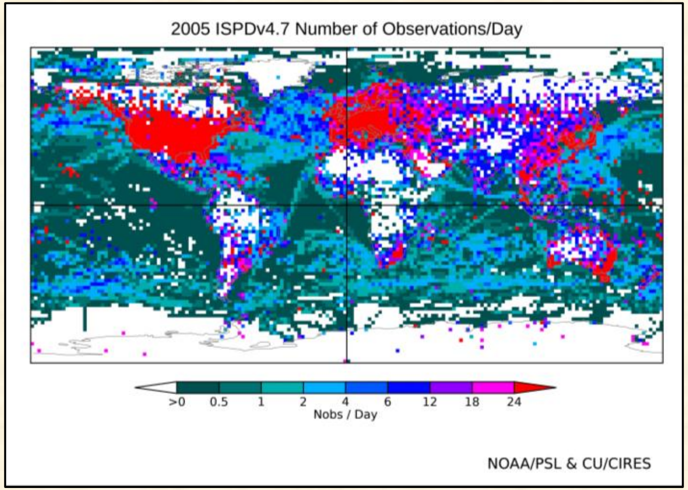


Image provided by the NOAA-ESRL Physical Sciences Laboratory from their website at https://psl.noaa.gov/data/20CRv3_ISPD_obscounts/

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- The challenge with centennial reanalysis
- **Some solutions:** Limit types of observations assimilated to those available for full time period
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Full input vs sparse input reanalysis

- **Full input**
  - ERA-interim, ERA5, MERRA, MERRA2, JRA-55
  - Assimilate most observations that are available *(in-situ, satellite, upper-air, aircraft)*
  - Cover latter half of 20th century to avoid spurious trends and signals arising from significant changes in the observing system
  - …Can still be impacted by instruments coming online
- **Sparse input**
  - 20th Century Reanalysis, ERA-20C, CERA-20C
  - Assimilate only certain types of observations (e.g. surface pressure)
  - Extend 100+ years into the past
  - Less impact from changes in observing network

Centennial reanalyses: a comparison

	Years spanned	Model	DA	Observations assimilated	Notes
20CRv3 *(NOAA/ CIRES/ DOE)*	1836 *(1806)* -2015	NOAA GFSv14 *(land/atmos)*	EnKF *(80 mem)*	sfc pres	Prescribed sea ice *(HadISST2.3)*, SSTs *(SODAsi.3/HadISST2.2)*
20CRv2c *(NOAA/ CIRES)*	1851-2012	NOAA GFS 2008ex *(land/atmos)*	EnKF *(56 mem)*	sfc pres	Prescribed sea ice *(COBE-SST2)*, SSTs *(SODAsi.2)*
CERA-20C *(ECMWF)*	1901-2010	IFS CY41R2 *(land/atmos/ ocean/wave/ice)*	4DVar EDA *(10 mem, outer loop coupling)*	*atmos:* sfc pres, marine winds *ocean:* temp & salinity profiles	SST relaxed to HadISST2
ERA-20C *(ECMWF)*	1900-2010	IFS CY38R1 *(land/atmos)*	4DVar	sfc pres, marine winds	Prescribed sea ice and SSTs *(HadISST2.1)*

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Solutions for centennial reanalysis

Allow for adaptive, time-varying DA techniques *(different from full-input reanalysis)*

- **Observation errors**
- **Background errors**
- **Confidence** (quantification of uncertainty)

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Solution: Observation errors

- ERA-20C, 20CR use constant observation errors
- CERA-20C uses time-varying observation errors

Observation type	ERA-20C	CERA-20C	20CRv3
Sfc pres from land stations	1.08 hPa	From 1.6 hPa in 1900 to 0.8 hPa in 2010	1.2 hPa *(2.0 hPa for dropsondes; 1.6 hPa for stations that only report SLP*
Sfc pres from ships	1.46 hPa	From 2.0 hPa in 1900 to 1.2 hPa in 2010	2.0 hPa
Sfc pres from TC bogus	1.56 hPa	2.0 hPa	2.5 hPa
Sfc pres from buoys	0.94 hPa	From 1.0 hPa in 1973 to 0.8 hPa in 2010	2.0 hPa
10m wind from ships	1.5 m/s	2.2 m/s	n/a
10m winds from buoys	1.33 m/s	From 1.7 m/s in 1973 to 1.4 m/s in 2010	n/a

Laloyaux et. al. (2018); Slivinski et. al. (2019)

Solutions for centennial reanalysis

Allow for adaptive, time-varying DA techniques *(different from full-input reanalysis)*

- **Observation errors**
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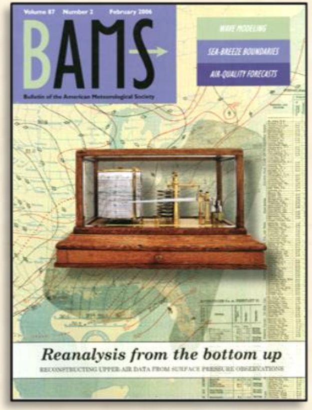
- **Confidence** (quantification of uncertainty)

Solution: Background errors

- 20CRv2c, 20CRv3 use ensemble Kalman filter for fully flow-dependent covariances
- ERA-20C, CERA-20C use hybrid background errors to incorporate flow-dependent covariances



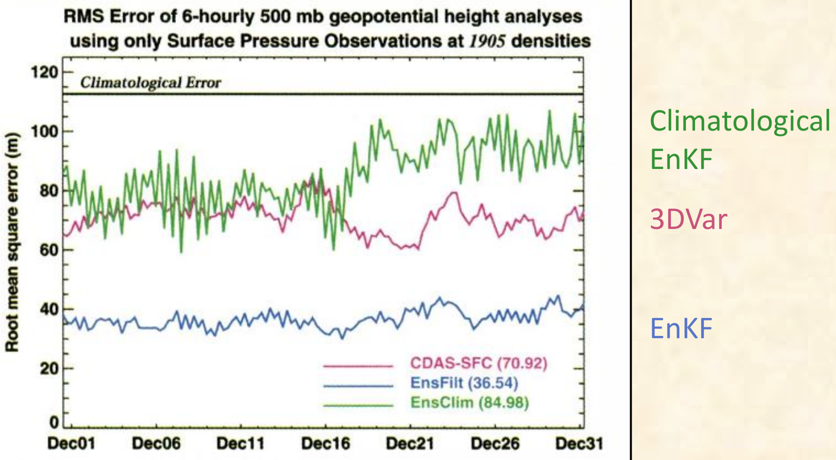


FIG. 5. Time series of the 500-hPa geopotential height rms difference between analyses of Dec 2001 from the full NCEP–NCAR reanalysis and from the assimilation experiments. The rms is averaged over the Northern Hemisphere (20°–90°N). Climatological std dev is indicated by the thick black line.

Compo et. al. (2006)

Solution: Background errors *(20CR)*

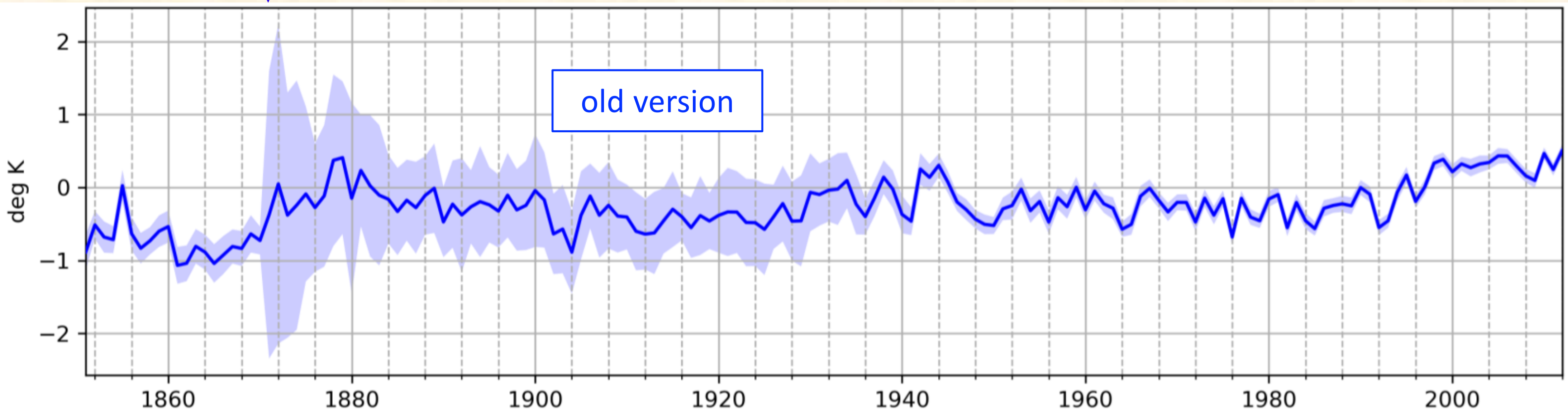
- Need techniques to mitigate sampling errors in EnKF
- **Inflation**: prevents "ensemble collapse" by artificially spreading out ensemble members
  - Simple example: multiply ensemble covariance by a tuned parameter larger than 1
- Need inflation factor(s) to work for 150+ years
  - *Adaptive inflation*: larger inflation when observations are dense, smaller inflation when observations are sparse

Simple “adaptive” inflation

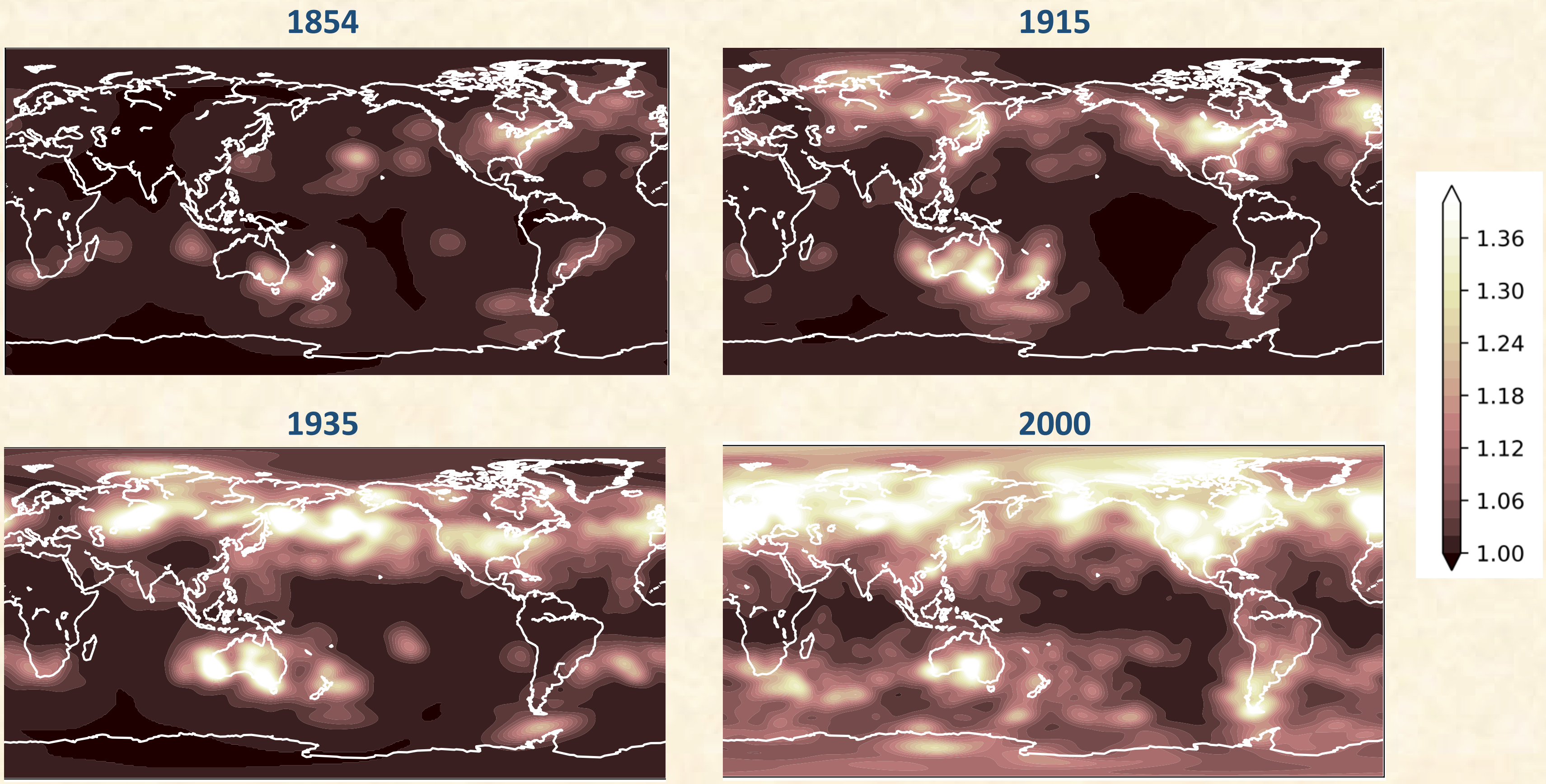
	Northern Hemisphere	Tropics	Southern Hemisphere
1851 – 1870	1.01	1.01	1.01
1871 – 1890	1.05	1.01	1.01
1891 – 1920	1.09	1.02	1.01
1921 – 1950	1.12	1.03	1.02
1951 – 2012	1.12	1.07	1.07

- Pre-defined multiplicative inflation factors based on year and location
- Unrealistic signals in uncertainty
- Inhibits accurate studies of significance of long-term trends

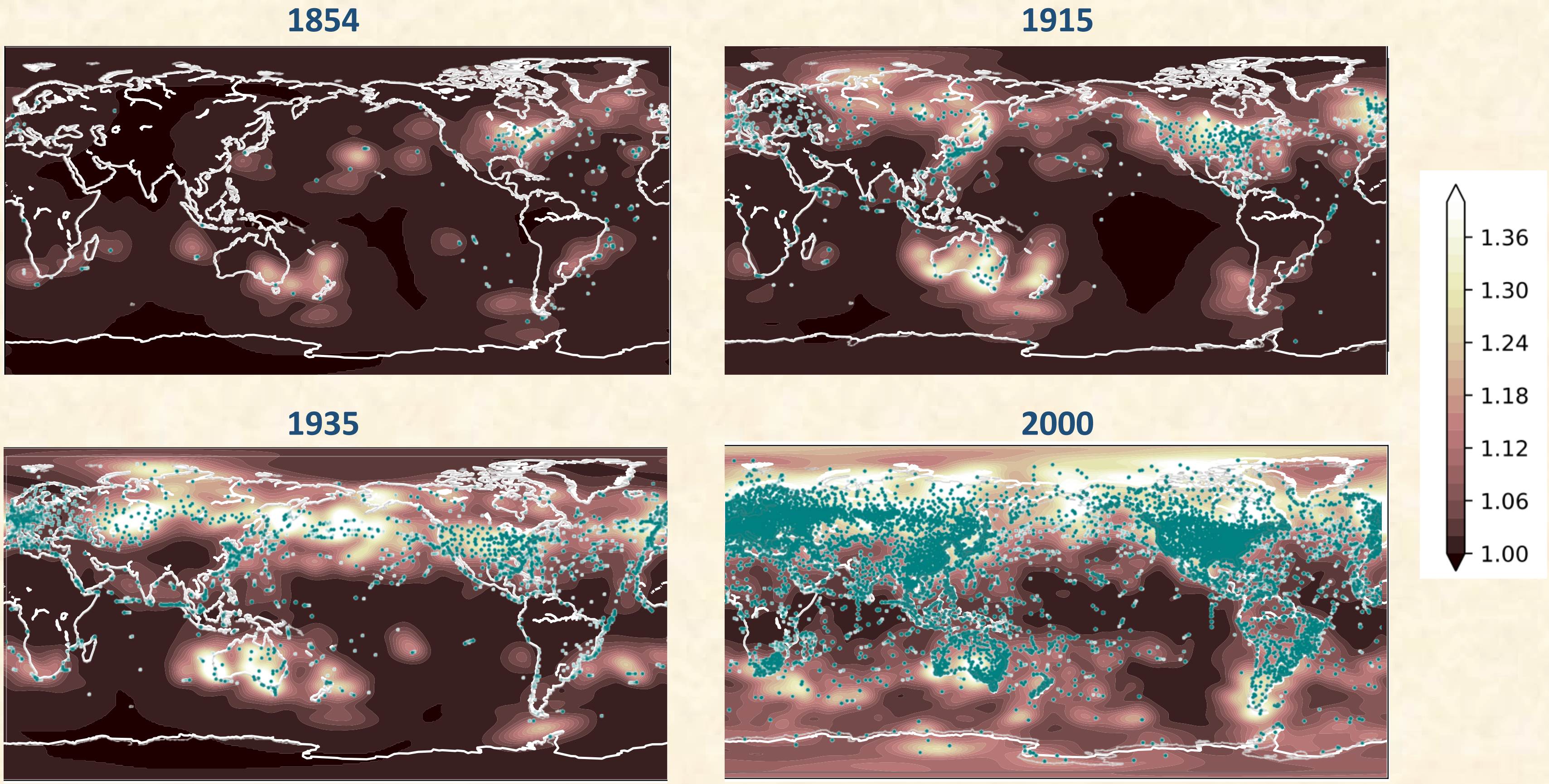
Atmospheric layer temperature anomalies, Northern Hemisphere



Sophisticated adaptive inflation



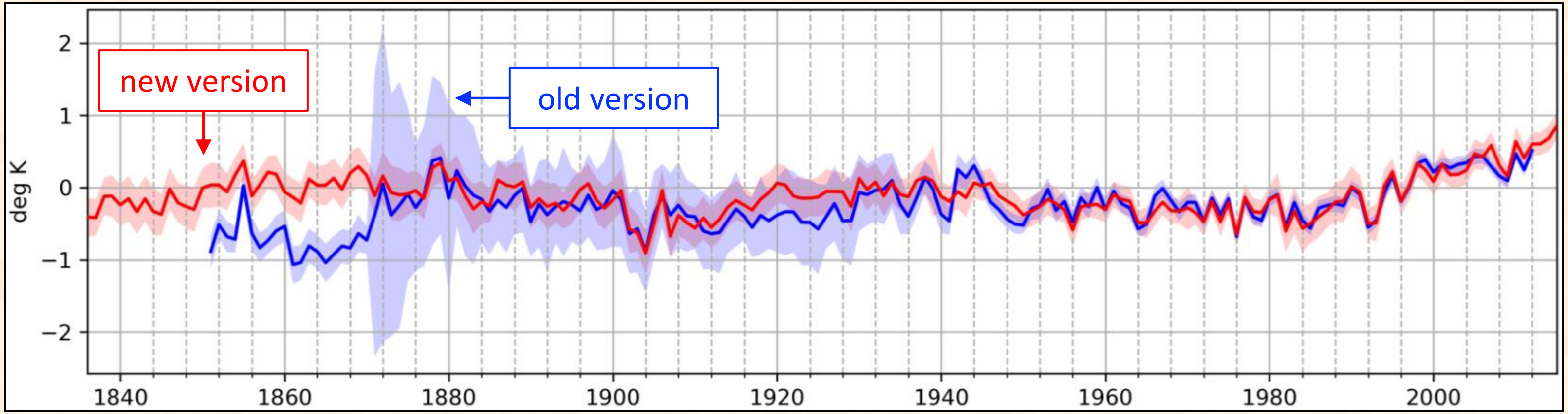
Sophisticated adaptive inflation



Sophisticated adaptive inflation

- More accurate, consistent estimates of uncertainty
- Can make stronger statements about trends

Atmospheric layer temperature anomalies, Northern Hemisphere



Solutions for centennial reanalysis

Allow for adaptive, time-varying DA techniques *(different from full-input reanalysis)*

- **Observation errors**
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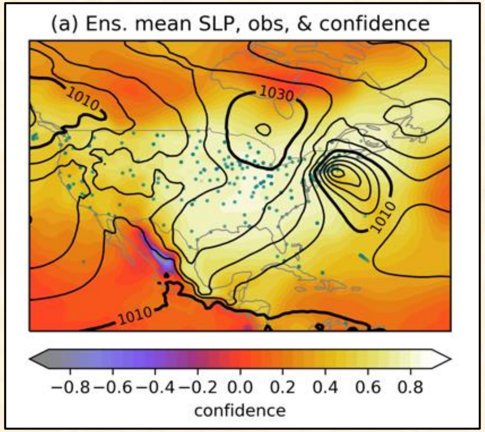
- **Confidence** (quantification of uncertainty)

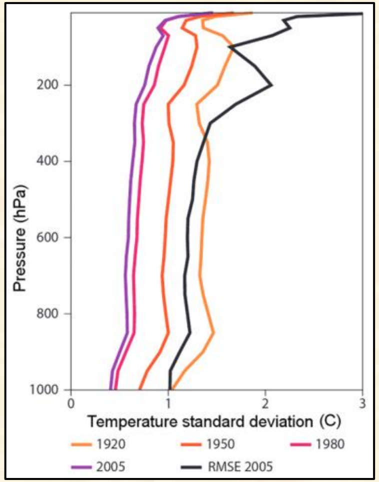
Solution: Confidence estimation

- Necessary to understand how centennial reanalyses can/should be used *(users should be aware that estimates from 1901 are less reliable than those from 2010)*
- 20CR, CERA-20C handle this by providing ensemble products

20CRv3:

- 80 ensemble members
- More accurate and reliable ensemble spread than 20CRv2c





CERA-20C:

- 10 ensemble members
- Captures spatial & temporal structure of uncertainty well, but is overconfident

Slivinski et. al. (2021) ; Laloyaux et. al. (2018)

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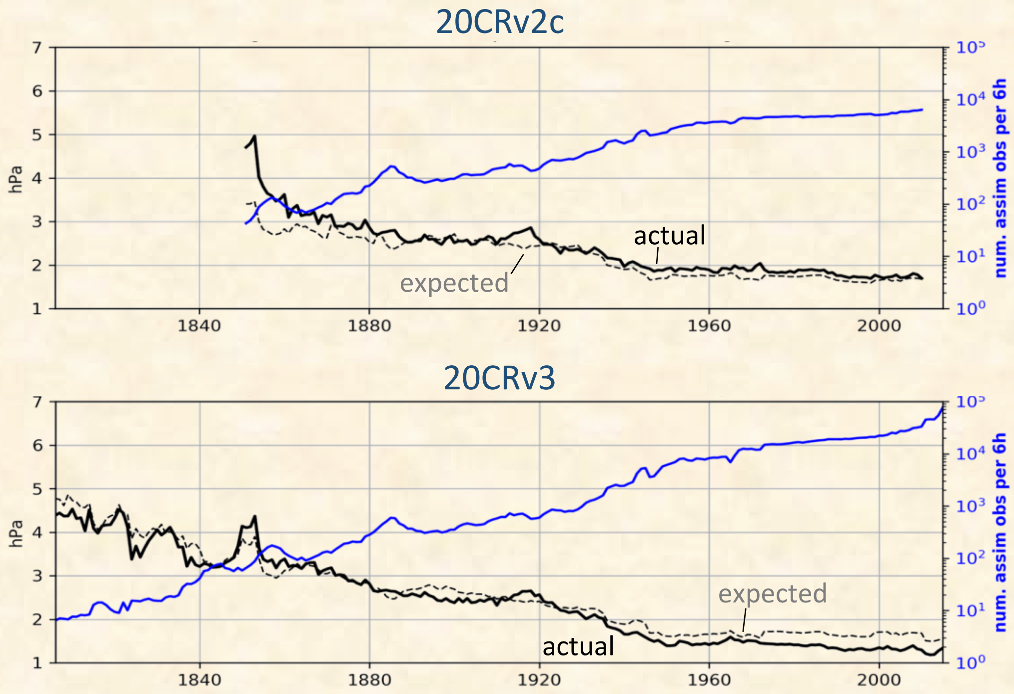
20CR performance:
fit to surface pressure obs

Global annual first-guess root mean squared errors in surface pressure



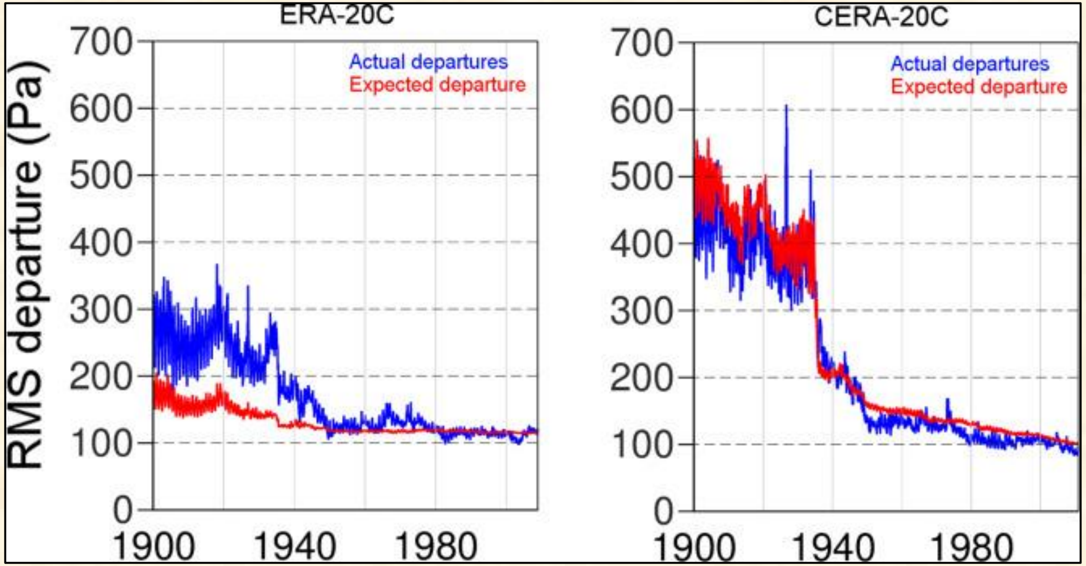
***Actual* error** is the RMSD between 6-hour forecasts and not-yet-assimilated observations: $\langle (ob - fg)^2 \rangle^{1/2}$

***Expected* error** is the root-mean of the sum of ob error variance and background ensemble covariance at ob time/location: $\left\langle ({\sigma^2}_{ob} + {\sigma^2}_{fg})^2 \right\rangle^{1/2}$

➢ **Actual errors are consistent with expected errors during entire 200 years** (despite significant changes *[4 orders of magnitude]* in observing network and constant ob errors)

Slivinski et. al. (2021)

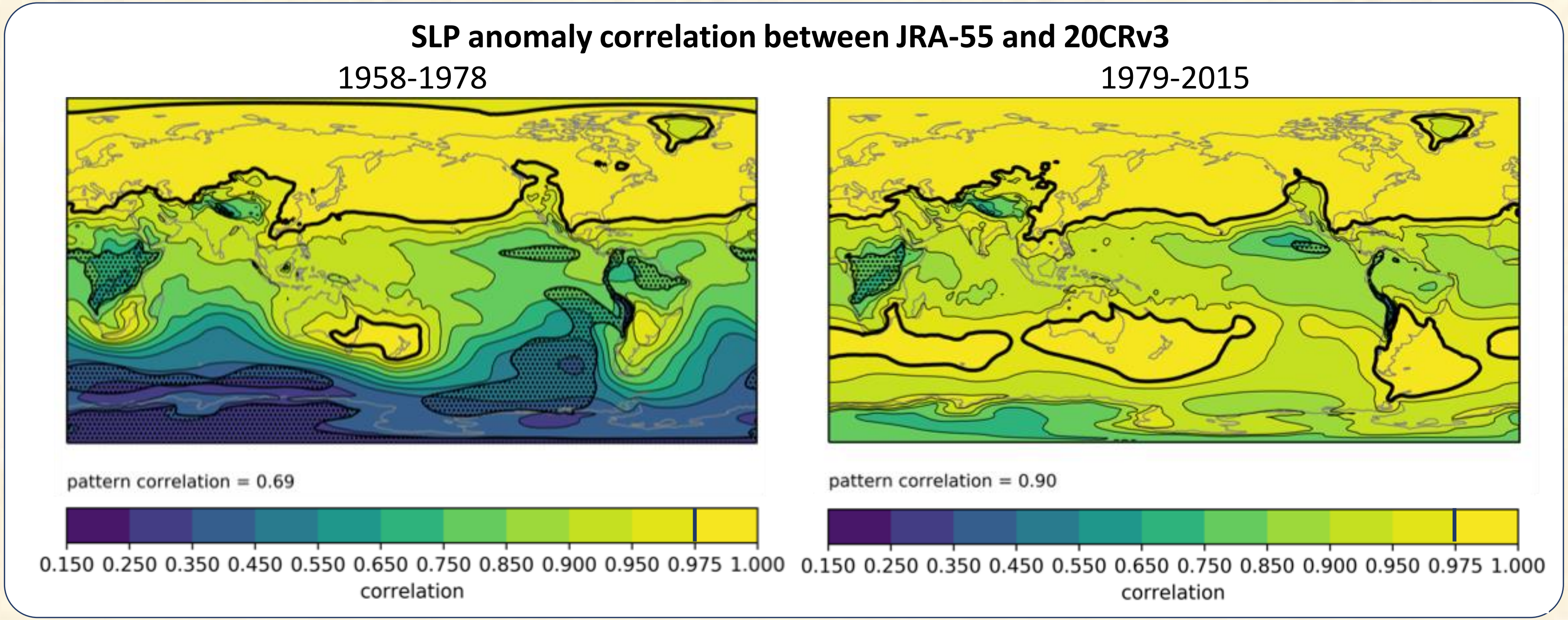
CERA-20C performance:
fit to surface pressure obs



- **CERA-20C errors more consistent with ensemble spread than ERA-20C** (due to time-varying ob errors and consistent flow-dependent background error covariance)
- **CERA-20C has larger errors in early period due to less confidence in observations**

Laloyaux et. al. (2018)

20CRv3 correlates well with other reanalyses, and can "predict" that correlation *(via confidence estimates)*

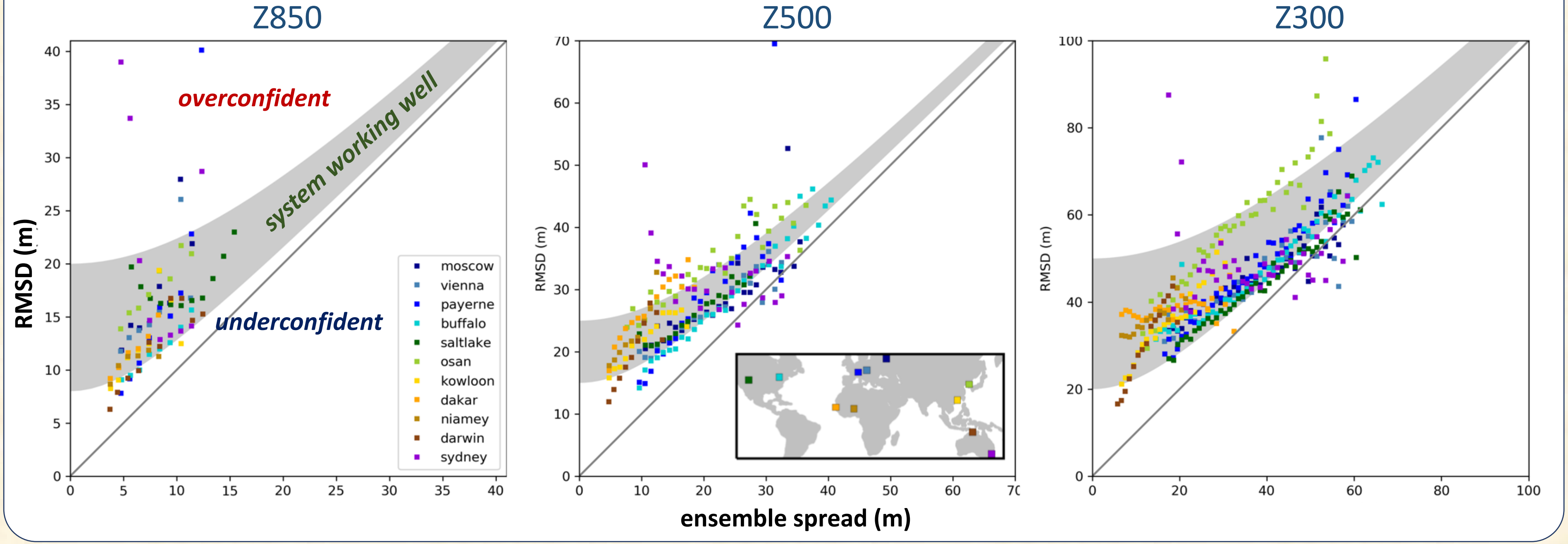


- Stippling indicates regions of low confidence (large ensemble spread) in 20CRv3
- Pattern correlation is given between confidence field and correlation field
- ➢ **20CRv3 uncertainty estimates are a good predictor of skill relative to JRA-55**

Slivinski et. al. (2021)

20CRv3 performs well relative to indep. upper air obs

Difference between observed and analyzed values, as function of 20CRv3 ensemble spread; 1943-2015



- If obs were perfect (zero error), then RMSDs should fall on diagonal.
- If ob error range estimated accurately and system works well, RMSDs ideally fall in gray swath.
- Above swath: 20CRv3 is overconfident. Below swath: underconfident.
- **20CRv3 geopot. height analysis performs well globally at several vertical levels**

Slivinski et. al. (2021)

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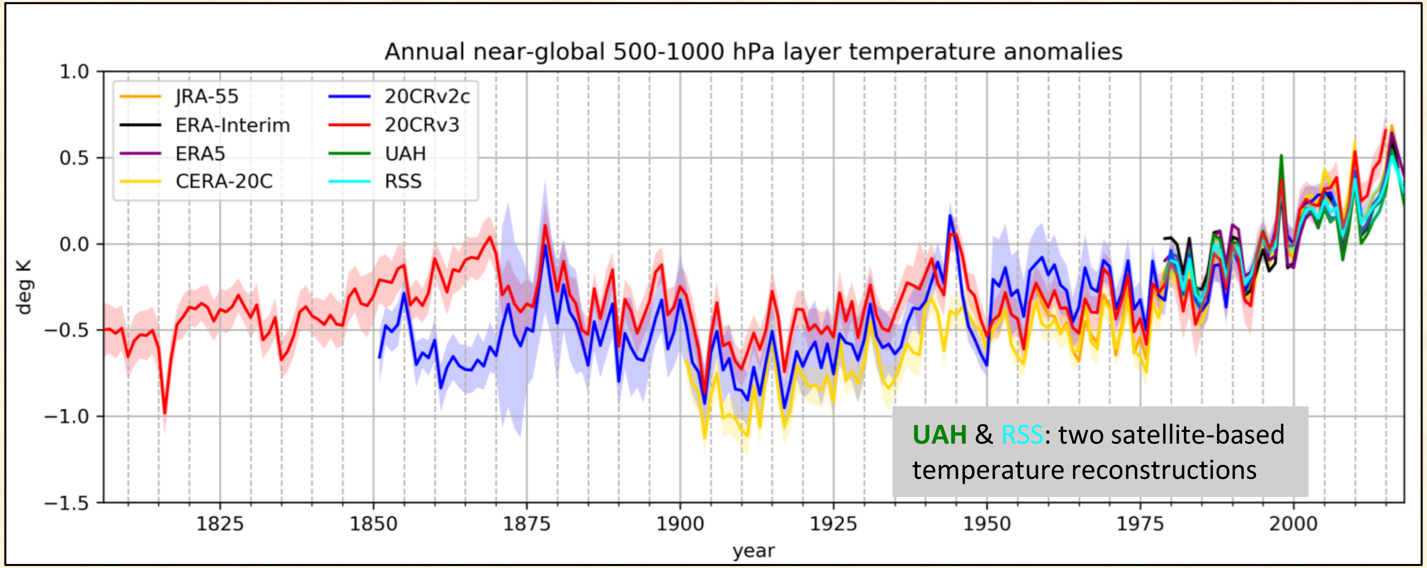
Challenge: evaluating long-term trends and variability



- 20CR, CERA-20C agree with ERA5, JRA-55, and satellite-based reconstructions in modern time period
- General agreement in early 20th century
- How to evaluate the accuracy of 200-year trends?
- Accurate confidence estimates are important

Slivinski et. al. (2021)

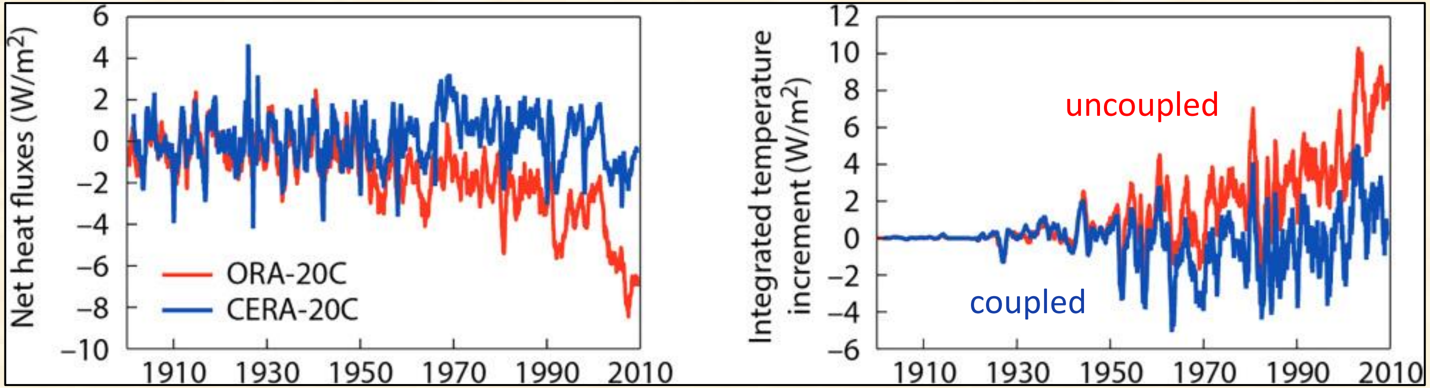
Challenge: estimating the ocean

- ERA-20C used prescribed SSTs
- 20CRv2c & 20CRv3 use "iteratively coupled" SSTs
- CERA-20C assimilates ocean obs into a coupled ocean-atmosphere model, and also nudges to prescribed SSTs

➢ How do we produce a consistent estimate of the ocean-atmosphere system for 200 years?

Why do we need coupled ocean-atmosphere?

- Produce consistent air-sea heat fluxes and energy balance

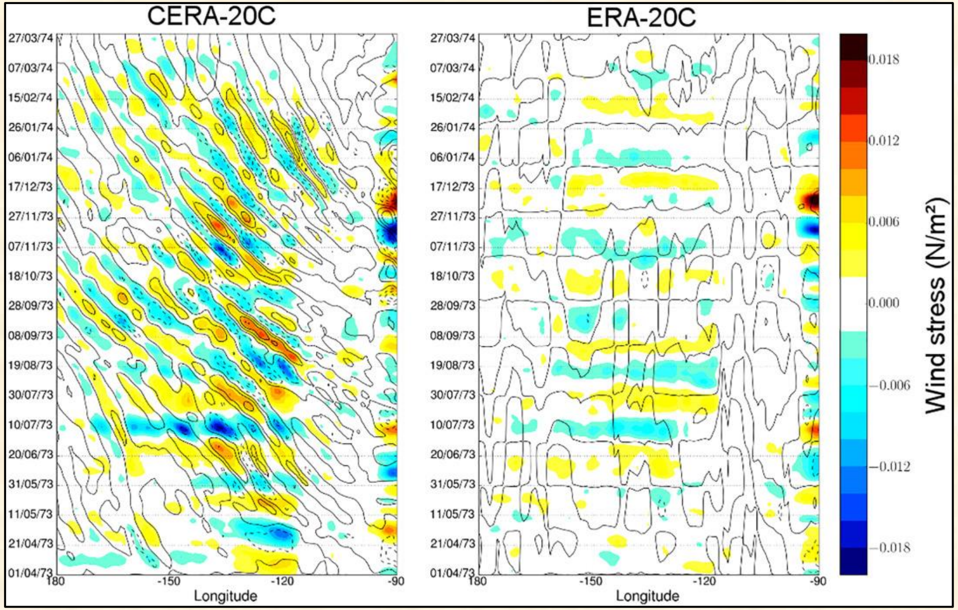


Laloyaux et. al. (2018)

Why do we need coupled ocean-atmosphere?

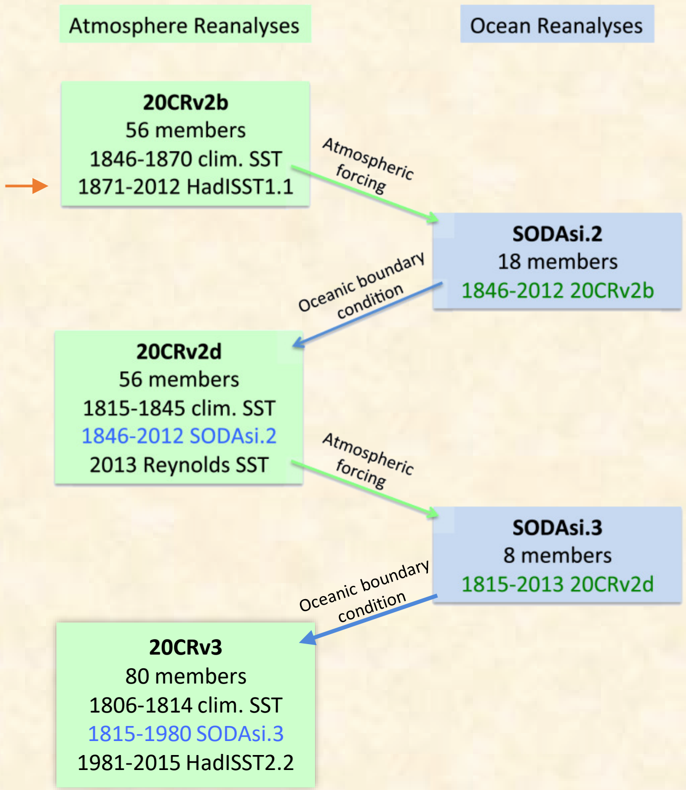
- Represent tropical instability waves, which impact ENSO variability & predictability

Hovmoller time series of high-pass filtered SST and wind stress at 1N in eastern Pacific



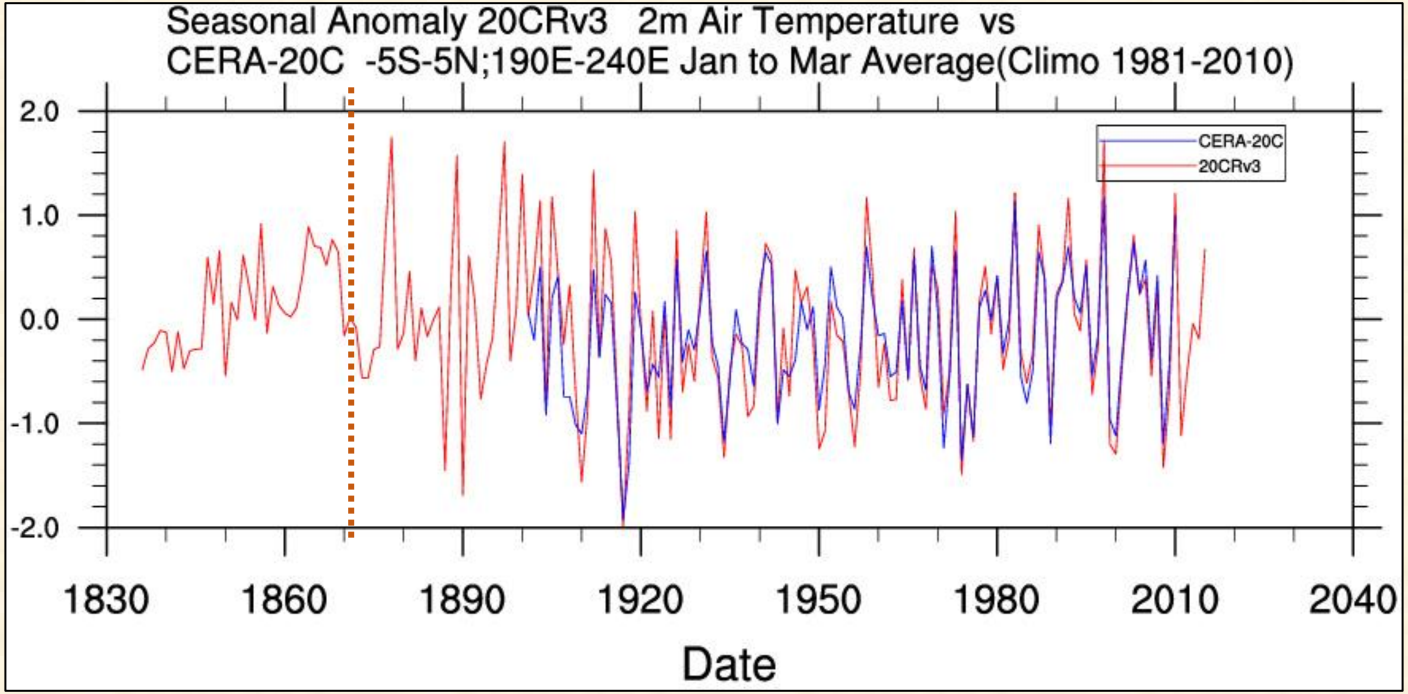
Laloyaux et. al. (2018)

20CR: Iteratively coupled ocean-atmosphere



Giese et. al. (2016)

20CRv3 struggles to represent ENSO prior to 1871



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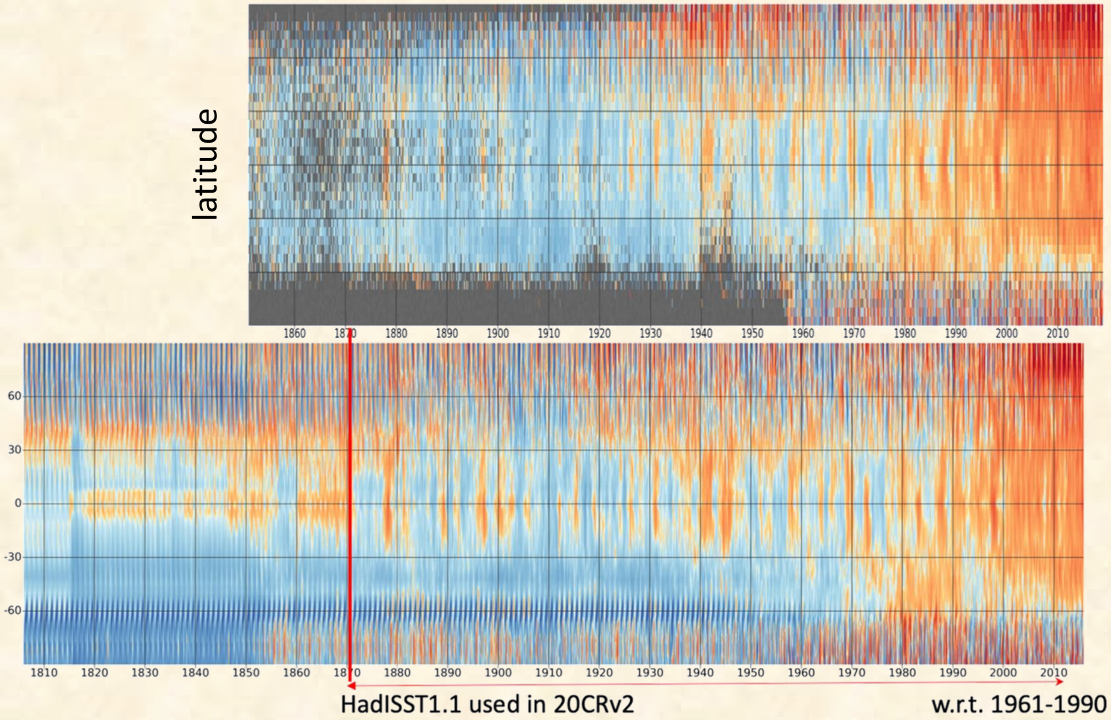
20CRv3 struggles to represent ENSO prior to 1871

Air and Sea Surface Temperature anomalies averaged over longitude

HadCRUT5

20CRv3



Slide courtesy P. Brohan (UKMO) & G. Compo

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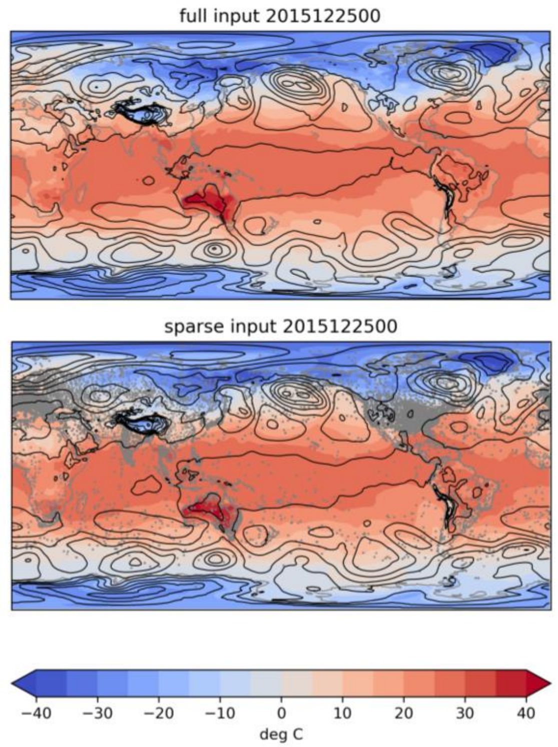
Future of 20CR – Possibilities

- ✔ Larger set of available observations *(smaller errors, greater confidence, maybe extend further back in time)*
- ? Coupled ocean-atmosphere
- ? Additional observation types *(SST, wind direction)*
- ? Data-driven models *(incorporate Linear Inverse Model [LIM] for ocean)*
- ? Machine learning-based bias correction algorithms



- Centennial reanalyses span at least 100 years into the past by only assimilating observation types available for the entire time period
- Traditional techniques need to be modified to handle sparse observing networks that can change drastically over 100+ years
- More information:

  - Compo, G. P., J. S. Whitaker, and P. D. Sardeshmukh, 2006: Feasibility of a 100-Year Reanalysis Using Only Surface Pressure Data. *Bull. Amer. Meteor. Soc.*, **87**, 175-190 https://doi.org/10.1175/BAMS-87-2-175.
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  - Slivinski, L.C., et. al. (2021) An Evaluation of the Performance of the Twentieth Century Reanalysis Version 3. *Journal of Climate*, 34(4): 1417-1438. https://doi.org/10.1175/JCLI-D-20-0505.1

For data access, visualization tools, and references, please visit https://go.usa.gov/XTd

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