Developing 20th Century Reanalysis version 3 (1850-2014)

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Review Article
The Twentieth Century Reanalysis Project

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Compo et al. 2011
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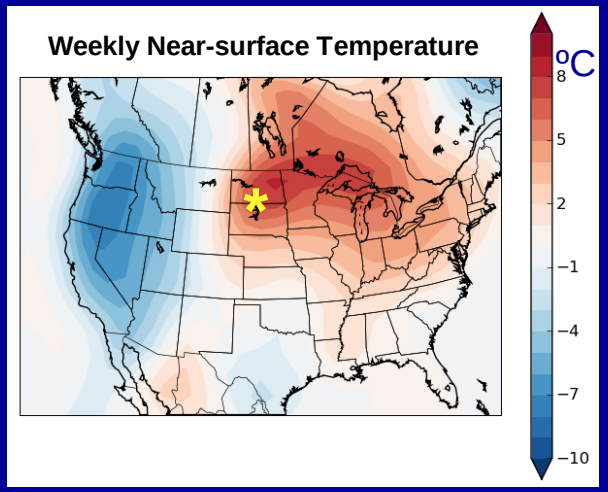
Special thanks to Chesley McColl, NCEP/EMC, NCDC, Hadley Centre, ACRE partners

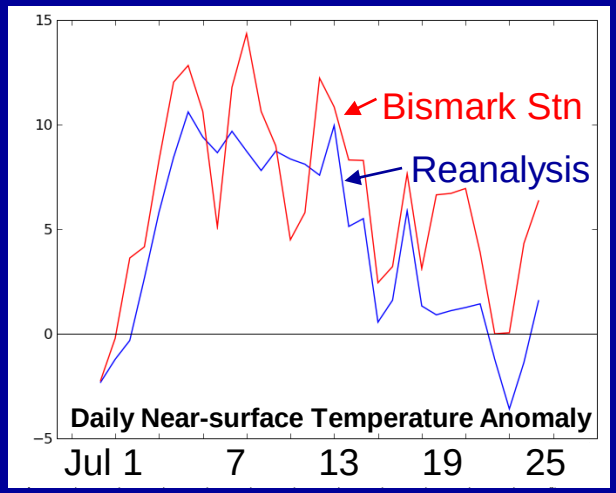
The 20th Century Reanalysis Project (1871-2011)

Summary: An international project led by NOAA and CIRES to produce *4-dimensional* reanalysis datasets for climate applications extending back to the 19th century using an Ensemble Kalman Filter and *only surface pressure observations.*

Example: Weekly-averaged anomaly during July 1936 United States Heat Wave (997 dead during 10-day span)

Daily variations compare well with in-situ data.





The reanalyses provide:

-First-ever estimates of near-surface to tropopause 6-hourly fields extending back to the beginning of the 20th century;

-Estimates of uncertainties in the basic reanalyses and derived quantities (e.g., storm tracks).

Examples of uses (see reanalyses.org for more examples):

•Validating climate models.

•Determining storminess and storm track variations over the last 150 years.

•Understanding historical climate variations (e.g., 1930s Dust Bowl, 1920-1940s Arctic warming).

•Estimating risks of extreme events

Compo et al. 2011

Support provided by
US Dept of Energy
Office of Science (BER),
NOAA Climate Program

Ensemble Filter Algorithm (Whitaker and Hamill, 2002)

Ensemble mean

$$\overline{\mathbf{x}}_j^{\mathrm{a}} = \overline{\mathbf{x}}_j^{\mathrm{b}} + \mathrm{K}\left(y^{\mathrm{o}} - \overline{y}_j^{\mathrm{b}}\right),$$

Ensemble deviations

$$\mathbf{x}_j'^{\mathrm{a}} = \mathbf{x}_j'^{\mathrm{b}} - \tilde{\mathrm{K}}\left(y_j'^{\mathrm{b}}\right),$$

Sample Kalman Gain

$$\mathrm{K} = \mathrm{P}^{\mathrm{b}}\mathrm{H}^{\mathrm{T}}(\mathrm{H}\mathrm{P}^{\mathrm{b}}\mathrm{H}^{\mathrm{T}} + R)^{-1}$$
$$= \frac{1}{n-1}\sum_{j=1}^{n}\mathbf{x}_j'^{\mathrm{b}}y_j'^{\mathrm{b}}\left(\frac{1}{n-1}\sum_{j=1}^{n}y_j'^{\mathrm{b}}y_j'^{\mathrm{b}} + R\right)^{-1}$$

Sample Modified Kalman Gain

$$\tilde{\mathrm{K}} = \left(1 + \sqrt{\frac{R}{\mathrm{H}\mathrm{P}^{\mathrm{b}}\mathrm{H}^{\mathrm{T}} + R}}\right)^{-1}\mathrm{K},$$

$\mathbf{x}_j = \bar{\mathbf{x}} + \mathbf{x}'_j$ is pressure, air temperature, winds, humidity, etc. at all levels and gridpoints, every six hours.

y^{o} is only observations of hourly and synoptic **surface pressure**,

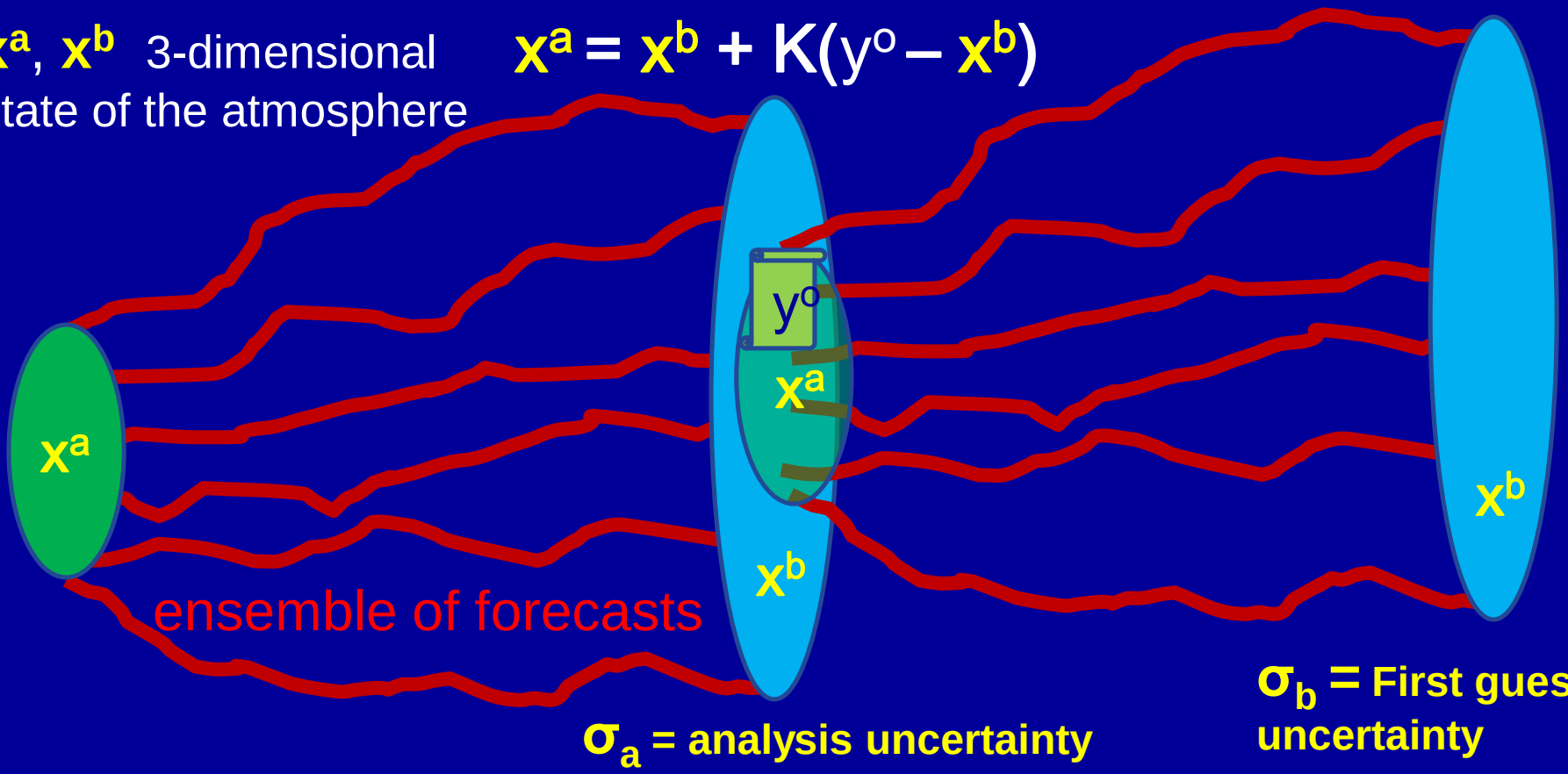
$\mathbf{y}^{\mathbf{b}} = \mathbf{H}\mathbf{x}^{\mathbf{b}}$ is guess surface pressure

Ensemble Data Assimilation (Whitaker and Hamill, 2002)

20CR analysis is a weighted average of the first guess x^b and pressure observation y^o. Each observation is assimilated serially.

x^a, x^b 3-dimensional state of the atmosphere

$$x^a = x^b + K(y^o - x^b)$$



the weight **K** varies with the atmospheric flow and the observation network

analysis time **analysis time** **analysis time**

20th Century Reanalysis implementation of Ensemble Filter Algorithm

(Whitaker et al. 2004, Compo et al. 2006, Compo et al. 2011)

Algorithm uses an ensemble of GCM runs to produce the weight **K** that varies with the atmospheric flow and the observation network every 6 hours

Using 56 member ensemble, HadISST1.1 prescribed SST and sea ice monthly boundary conditions (*Rayner et al. 2003*)

1871-2011: T62, 28 level NCEP GFS08ex atmosphere/land model

9 hour forecasts for 6 hour centered analysis window

- time-varying CO_2, solar and volcanic radiative forcing

Sampling and Model error parameterizations:

-Covariance localization (4000 km, 4 scale heights) and

-Latitude and time dependent multiplicative covariance inflation (alpha = 1.01 to 1.12) [*Anderson and Anderson, 1999*; *Houtekamer and Mitchell, 2001; Hamill et al. 2001; Whitaker et al., 2004*]

Every 5 years produced in parallel: 1871-1875,…, 1881-1885, …,1996-2000, except 1945-1951, 2001-2011 after 14 month spin-up

http://go.usa.gov/XTd Compo et al. 2011, doi:10.1002/qj.776

International Surface Pressure Databank version 2 (ISPD)

Synoptic and hourly observations assembled in partnership with

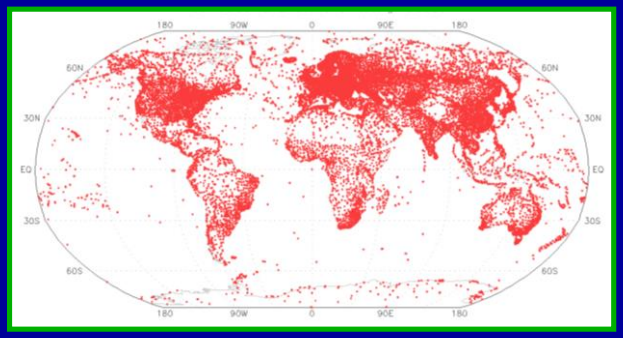
GCOS AOPC/OOPC Working Group on Surface Pressure

GCOS/WCRP Working Group on Observational Data Sets for Reanalysis

Atmospheric Circulation Reconstructions over the Earth (ACRE)

Land data Component: merged by NOAA NCDC, NOAA ESRL, and CU/CIRES

- **33 data sources**
- **33,653 stations**
- **1.7 billion obs**
- **1768-2010**



Marine data component: **ICOADSv2.4,2.5** merged by NOAA ESRL, NCDC, and NCAR

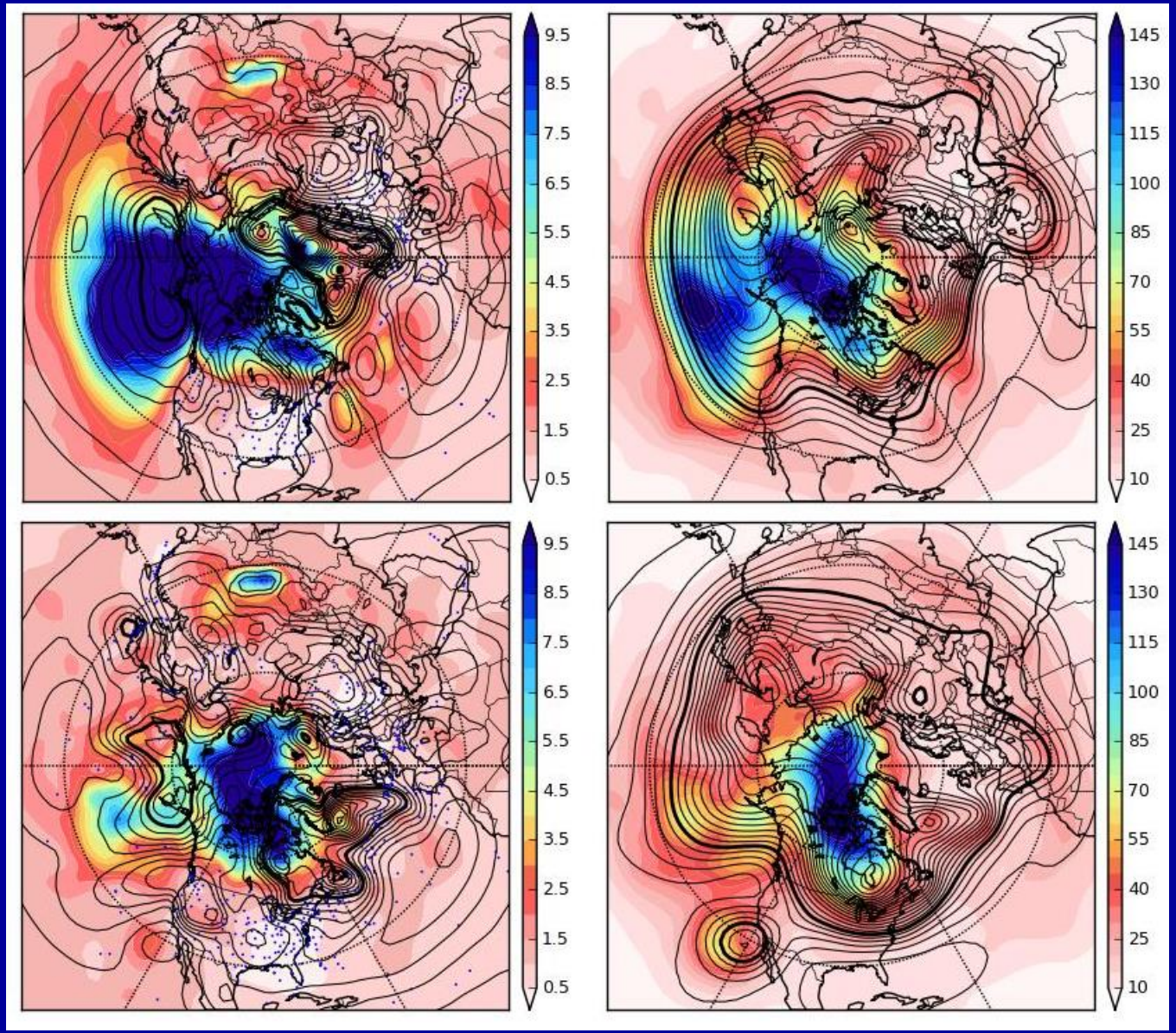
Tropical Cyclone Best Track data component: **IBTrACS** merged by NOAA NCDC

DATA ACCESS rda.ucar.edu/datasets/ds132.0 (T. Cram, NCAR DSS; C. McColl CIRES)
reanalyses.org/observations/surface

Analyses for selected dates in 1894 and 1914

1894

1914



Sea Level Pressure

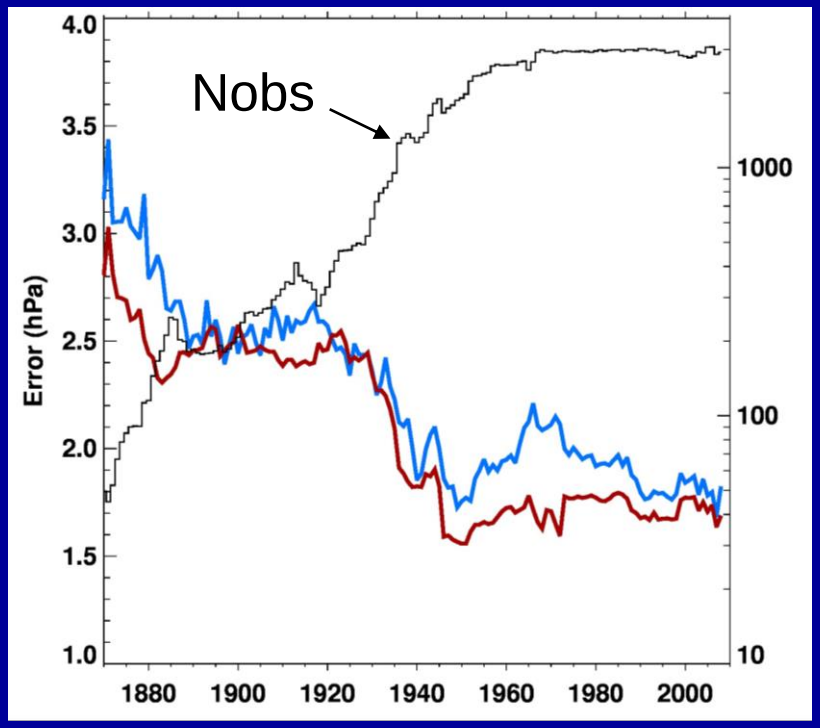
500 hPa Geopotential Height

Contours- ensemble mean

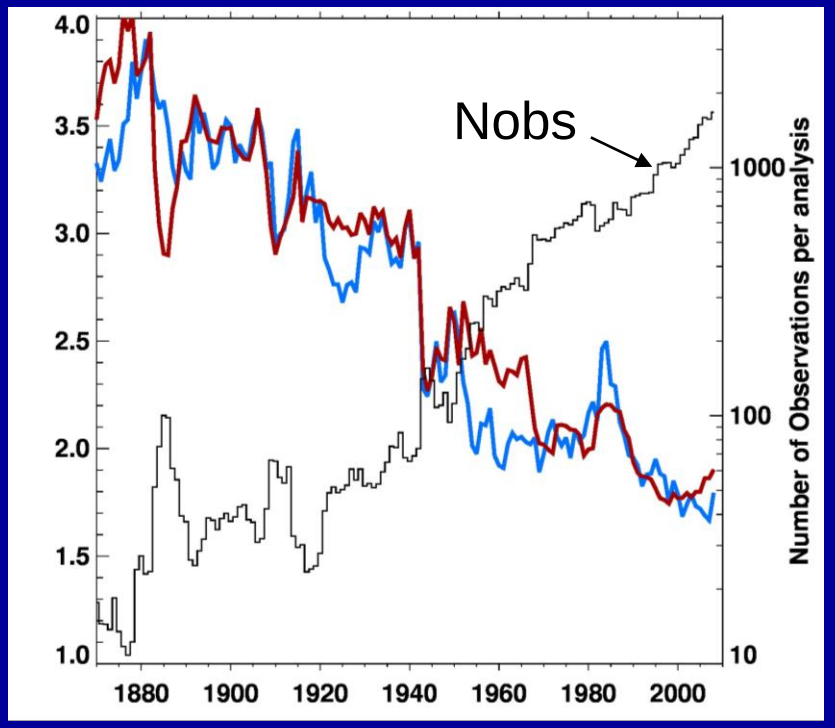
Shading- blue: more uncertain, white: more certain

Surface Pressure uncertainty estimate poleward of 20(S,N)
blue actual RMS difference
red expected RMS difference

Northern Hemisphere



Southern Hemisphere

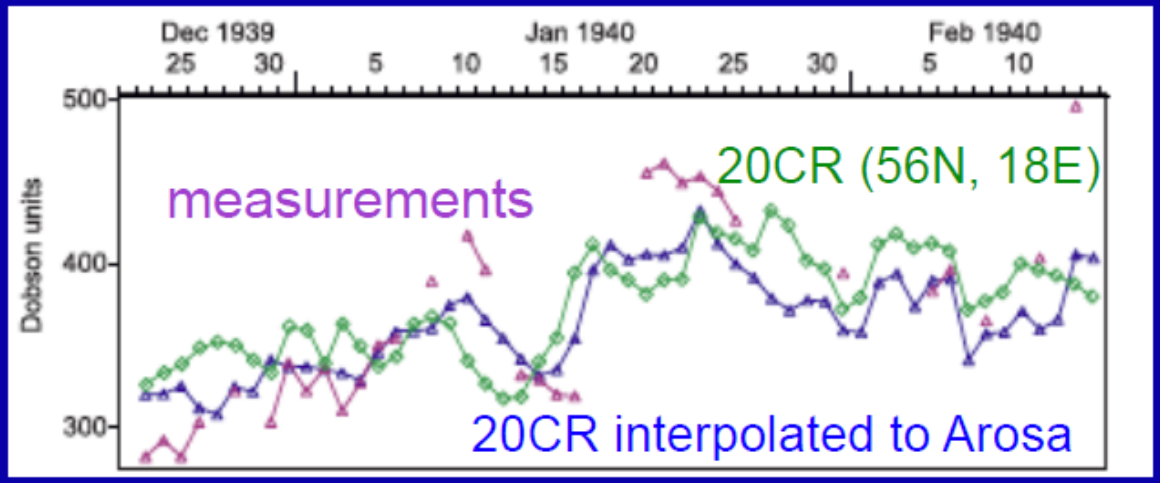


Uncertainty estimates are consistent with actual differences between first guess and pressure observations even as the network changes over more than 100 years!

Compo et al. 2011

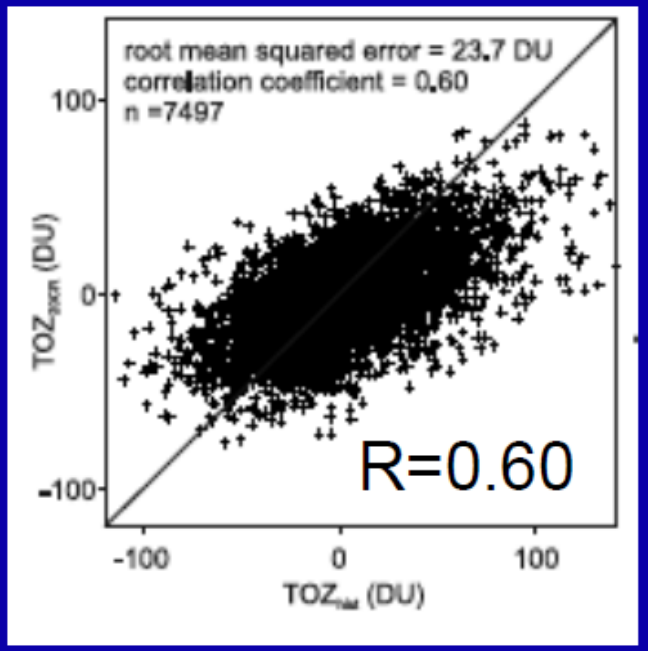
Daily column ozone measurements and 20CR daily ozone at Arosa, Switzerland (46.8N, 9.7E)

20CR has prognostic ozone from partial CHEM2D-OPP: production and loss depends on ozone mixing ratio and includes seasonal and spatial variation. Only gas phase chemistry.



Dec 1939 Feb 1940

Anomaly comparison spanning 1924 to 1963



20CR ozone field has large scale fluctuations that reflect ozone Highs associated with weather extremes, e.g., cold air outbreaks

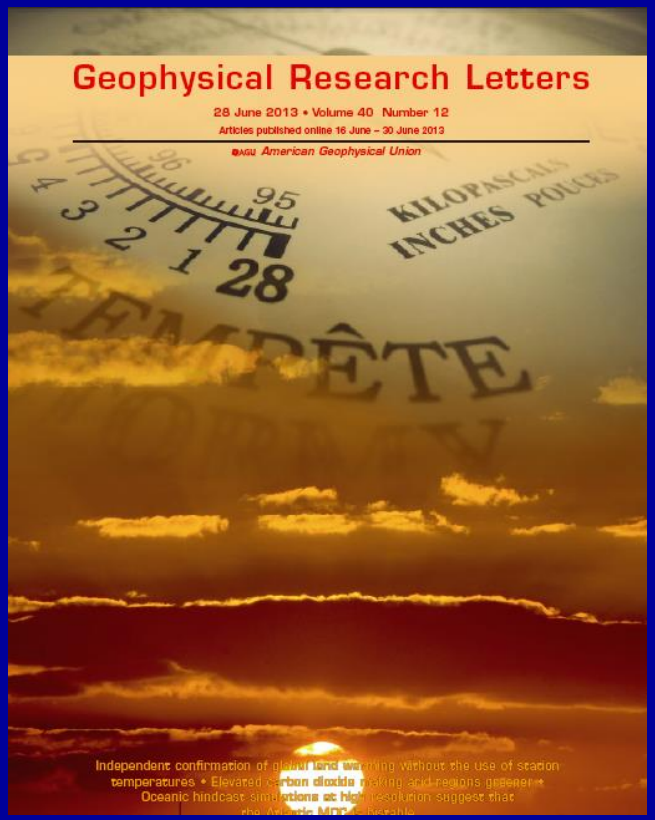
(Bronnimann and Compo 2012)

Climate application: Global warming over land

The observed increase in near-surface air temperature over land (2 m air temperature, hereafter TL_{2m}) is a core indicator of global warming (e.g., *IPCC AR4, Trenberth et al. 2007*).

Accuracy of datasets documenting the increase continues to be debated (e.g, *Pielke et al. 2007, Fall et al 2011, Montandon 2011, Jones and Wigley 2012*) -including before the US Congress (*Christy 2012*)

Why? The record of TL_{2m} consists of observations taken irregularly in space and time using a variety of instruments and measurement techniques (e.g., *Karl et al. 1986, Peterson et al. 1998, Pielke et al. 2007, Brohan et al. 2006, Jones and Wigley 2010, Hansen et al. 2010, Parker 2011, Christy 2012, Vose et al. 2012*).



Compo et al. 2013
dx.doi.org/10.1002/grl.50425

- Centers producing datasets of near-surface air temperature over land have addressed these issues [e.g., *Jones and Wigley 2010, Karl et al. 1986, Karl and Williams 1987, Peterson et al. 1998, Brohan et al. 2006, Hansen et al. 2010, Vose et al. 2012, Jones et al. 2012*]

- Plus, estimated the associated uncertainty. [e.g., CRUTEM3: *Brohan et al. 2006*, CRUTEM4: *Jones et al. 2012*, NOAA MLOST: *Vose et al. 2012*]

- But, debate continues [e.g., *Pielke et al. 2007, Jones and Wigley 2010 Fall et al. 2011, Montandon et al. 2011, Christy 2012*]

- Take completely different approach: ignore all TL_{2m} observations and look at 20CR, which assimilates only pressure observations over land!

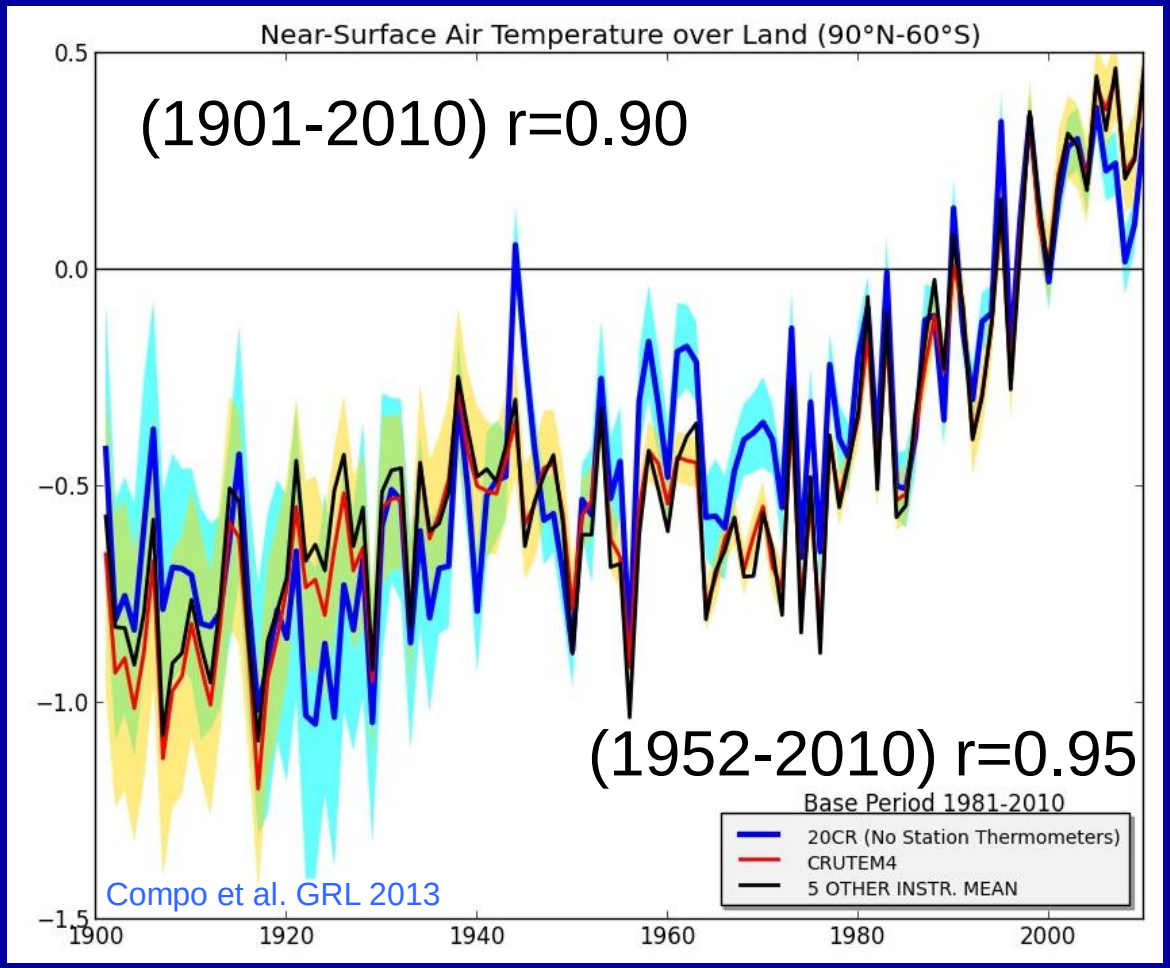
Annual anomalies of TL_{2m} from 20CR, CRUTEM4, average of 5 other instrumental datasets (1901-2010)

Other TL_{2m} datasets

1901-2010:
r=0.84 to 0.92

1952-2010:
r=0.95 to 0.96

Shading:
95% confidence interval



1901 2010

TL_{2m} from stations and 20CR has consistent large-scale annual, decadal, and centennial TL_{2m} variations

Advances and Improvements towards
Sparse Input Reanalyses
spanning 19th-21st centuries over the next 2-10 years

1. More land and marine observations back to early 19th century, especially Southern Hemisphere and Arctic.
2. User requirements for, and applications of, reanalyses (take survey)
3. Higher resolution, improved Quality Control methods, possibly other surface variables (e.g., wind, T, Tropical Cyclone position)
4. Uncertainty in forcings (e.g, CO2, solar, SST)
5. Possibly Multi-model (e.g., NASA, NCAR, NCEP, GFDL, ESRL)

Available 2015 – 20CRv3 (*1850-2014*)

Available 2018 – NOAA Climate Reanalyses, suite spanning (*1850-2018*)

Requires international cooperation, e.g.,

Atmospheric Circulation Reconstruction over the Earth initiative

http://www.met-acre.org

Developing 20CRv3:
Higher resolution testing 1999

20CRv2 system but with

GFS2013 T126L64: about 1 degree and better resolved stratosphere (top at 0.64 hPa, up from 5.6 hPa in 20CRv2)

Improved covariance inflation and localization: accounts for spatial inhomogeneity of observations

Incremental analysis update: should reduce shocks from observations

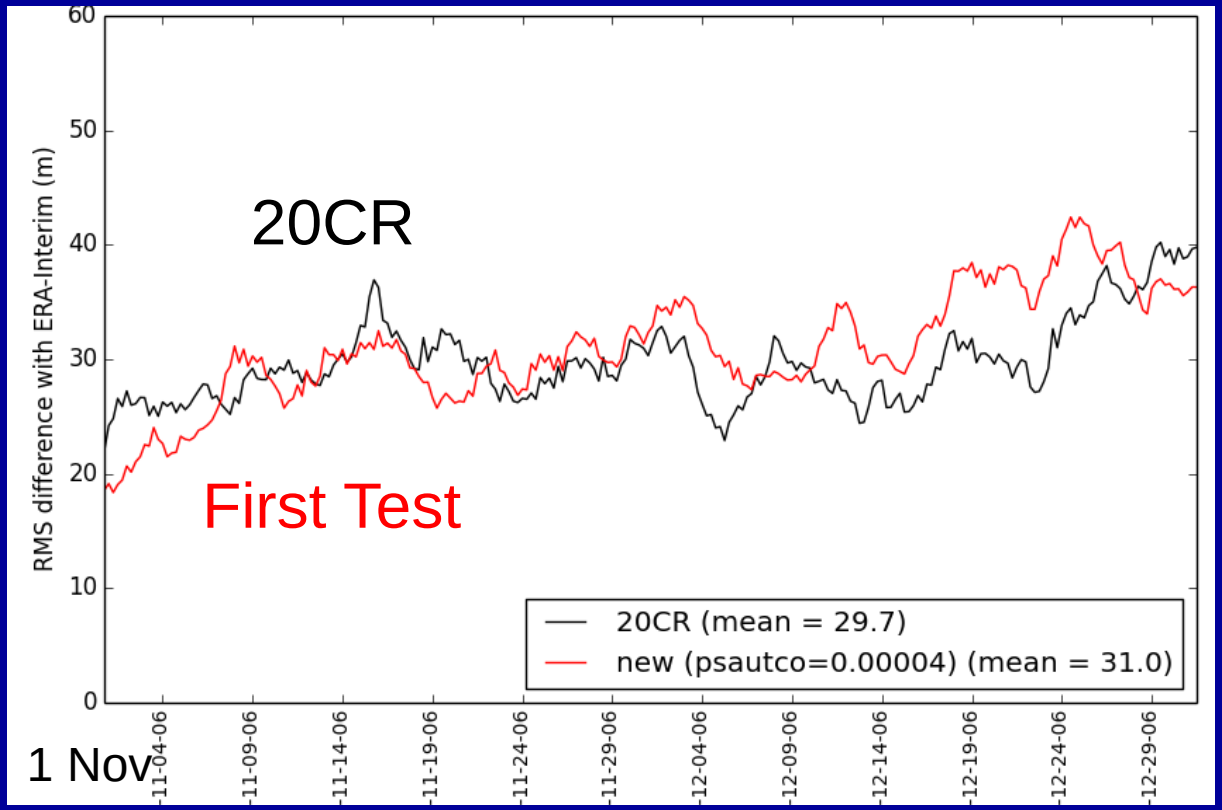
Testing:

- New GCM
- Better use of observations

After 2 month spin-up, 12 months produced

First try using default GFS parameters

Northern Hemisphere 500 hPa Geopotential Height
Root mean square difference with ERA-Interim



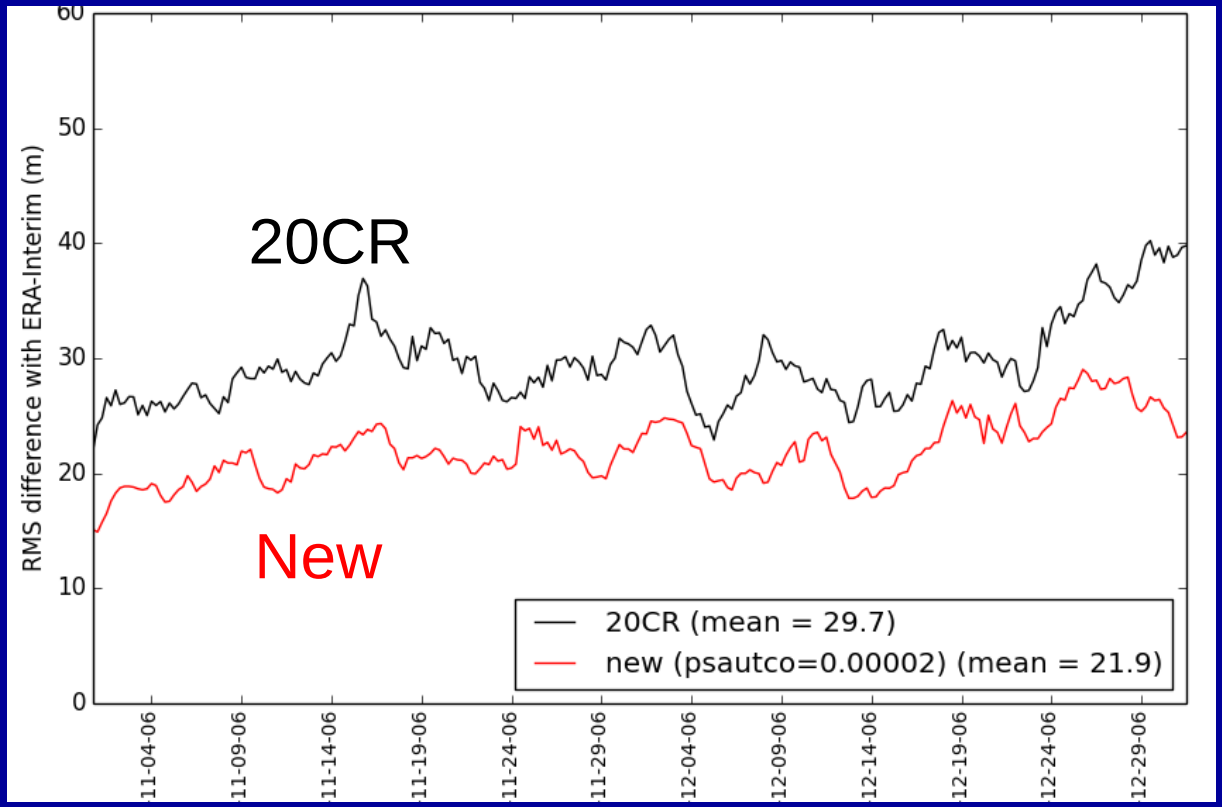
Worse than original 20CR. Mid-upper tropospheric cold bias.

Cause: Not enough high cloud.

Solution: Reduce ice to snow auto-conversion rate in Zhao-Carr microphysics.

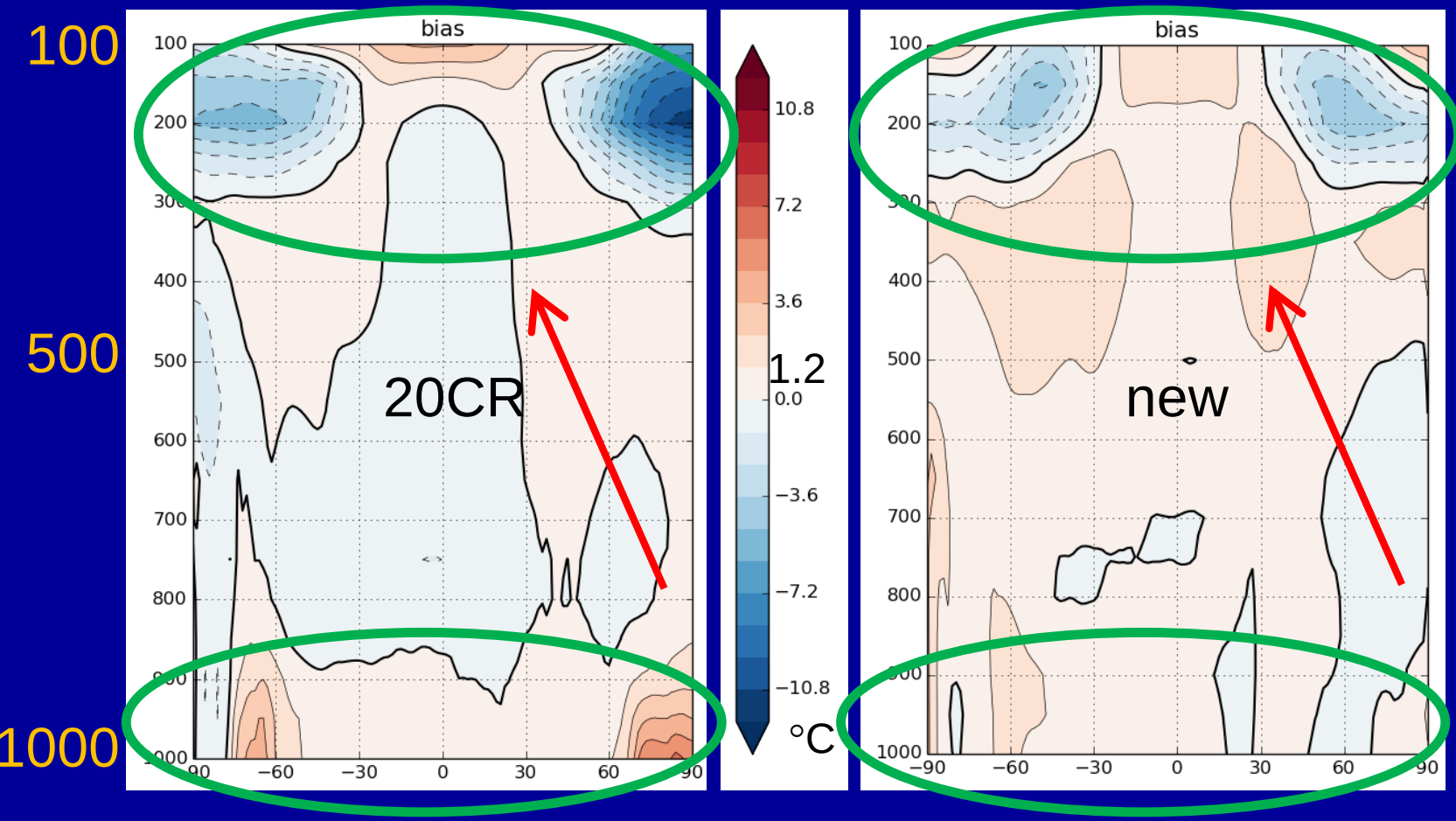
Halve the ice to snow autoconvergence rate

Northern Hemisphere 500 hPa Geopotential Height
Root mean square difference with ERA-Interim



Changing default GFS ice to snow autoconvergenc rate significantly improves the New data assimilation compared to 20CR. Almost a 25% reduction in error.

Zonal mean temperature bias (2000)



Upper tropospheric warm bias in new system
(too much high cloud?)

Near surface temperature bias due to ice problem fixed.

Stratospheric cold bias reduced, but not eliminated.

Developing 20CRv3:
Scout v3.3.8 testing 1831-1986

20CRv2 system but with

Simple Ocean Data Assimilation with Sparse Input v2 (SODAsi.2): 18 member ensemble of daily SSTs (1846-2011)

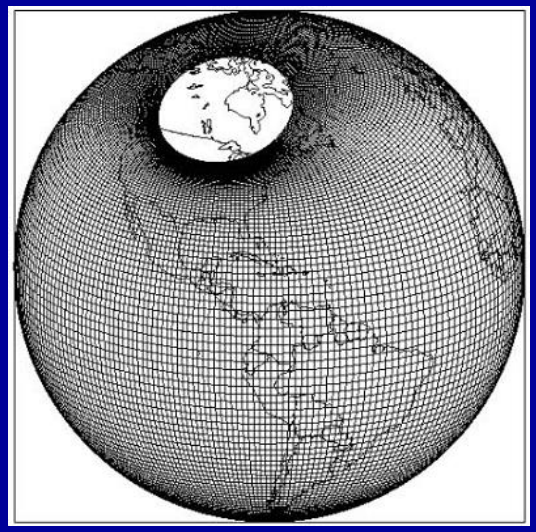
ISPDv3.2.8: International effort to recover 100s of new stations, new marine observations from OIdweather.org, ACRE data rescue, over 33 new organizations contributing

Testing:

- Effect of some accounting for uncertainty in SST
- Utility of increased density observations

After 14 month spin-up, 6 months produced for every 5th year of test years.

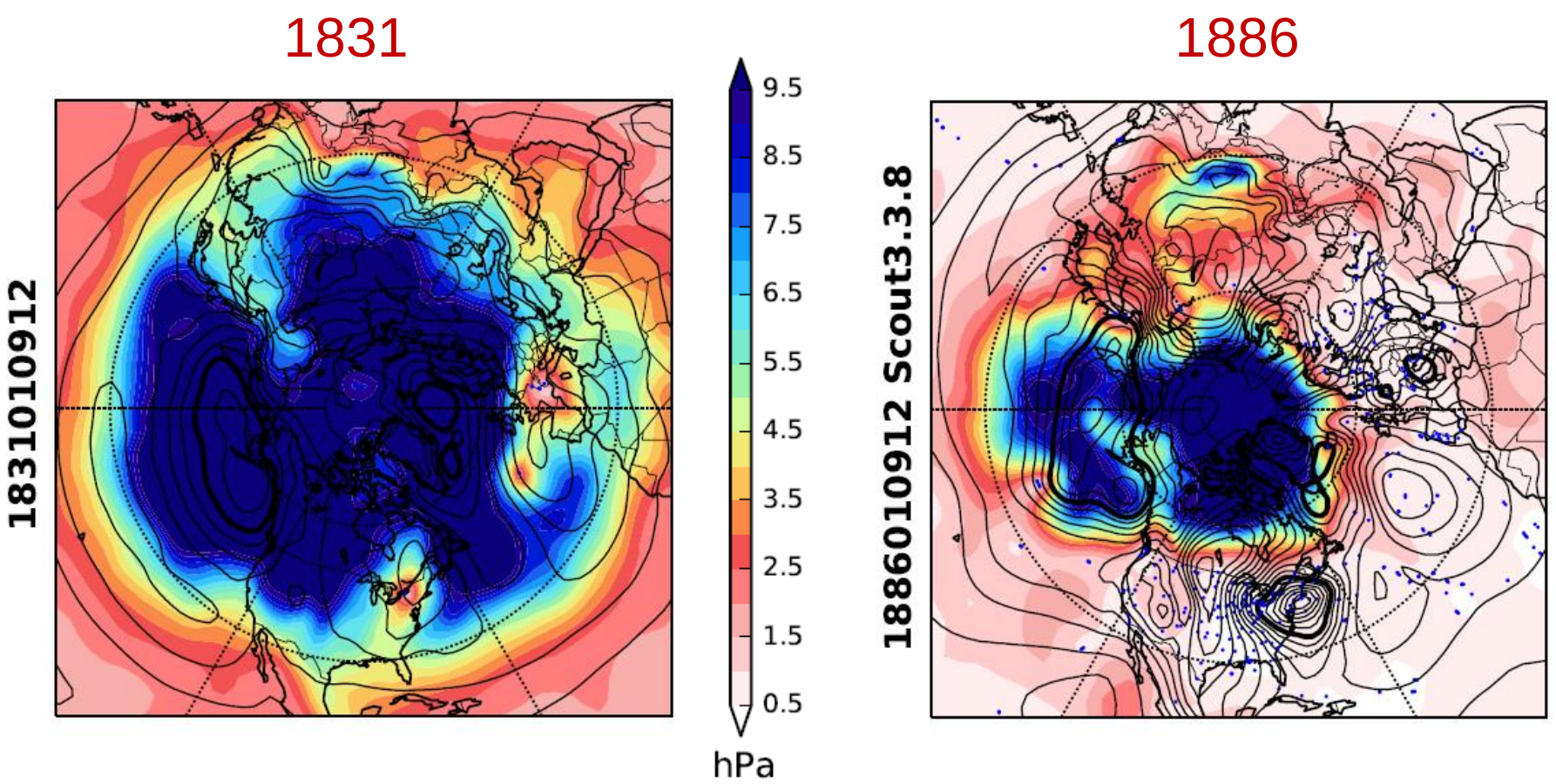
SODA Sparse Input 2 (1846-2011)



- **18 Ensemble Members**
- **Parallel Ocean Program v2.0.1**
  - **0.4° longitude x 0.25 ° to 0.4 ° latitude with 40 levels**
- **Winds**
  - 20CRv2 ensemble member daily stress (1949 – 2011)
  - 20CRv2 system with ISPDv3.2.4 and HadISST1.1 (1871-1948)
  - with ISPDv3.2.4 and climatological SST (1846-1870)
- **Heat and Salt fluxes**
  - Bulk formulae using 20CR daily variables
- **Observations**
  - Only ICOADS 2.5 SST data with Hadley Bucket Correction

Giese et al. 2014

Analyses of Sea Level Pressure for selected dates in 1831 and 1886

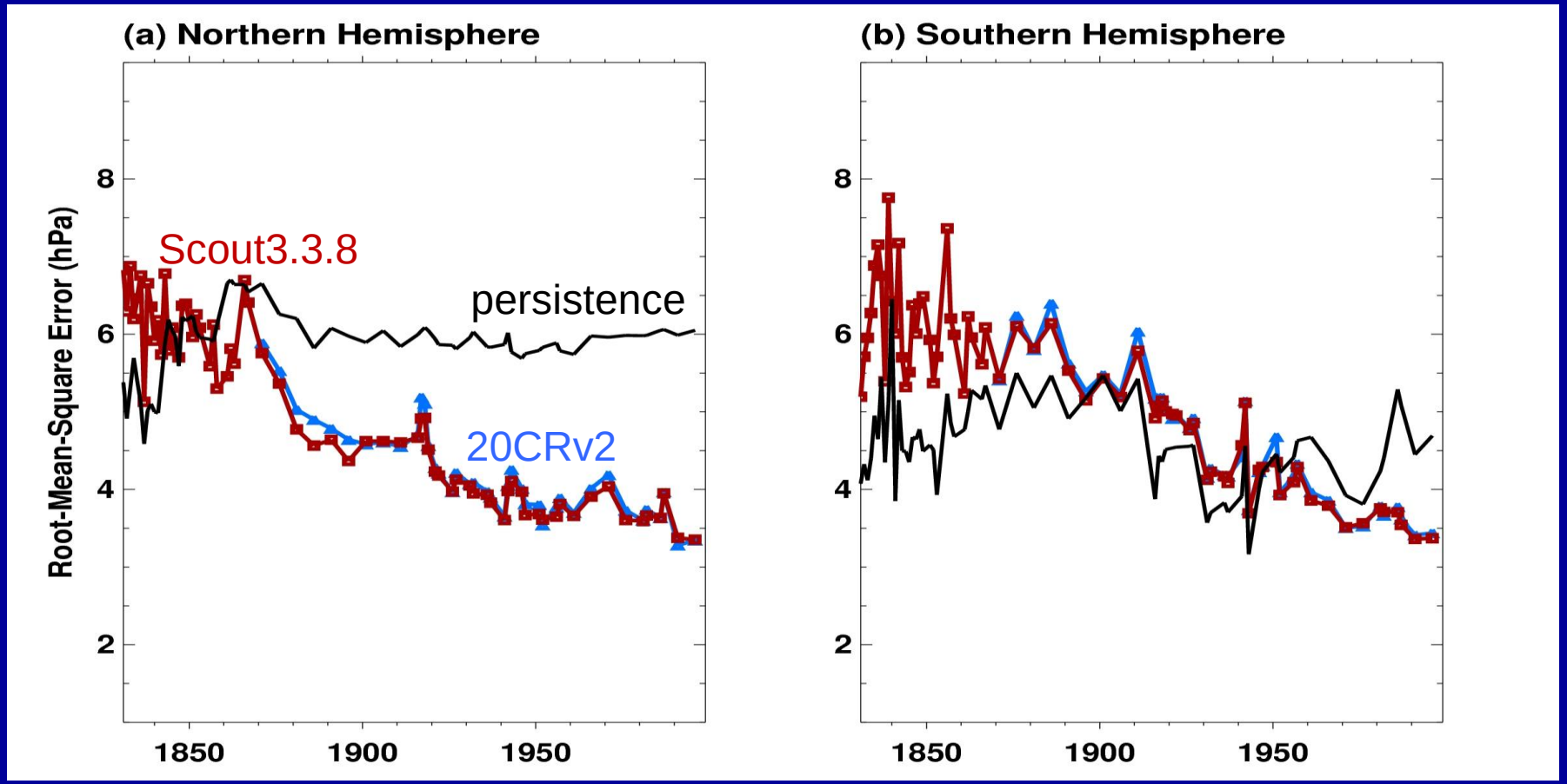


Contours-ensemble mean analysis (ci: 4 hPa, 1000 hPa thickened)
Shading- blue: more uncertain, white: more certain

Early analyses need more observations to advance.

Testing quality of Analyses

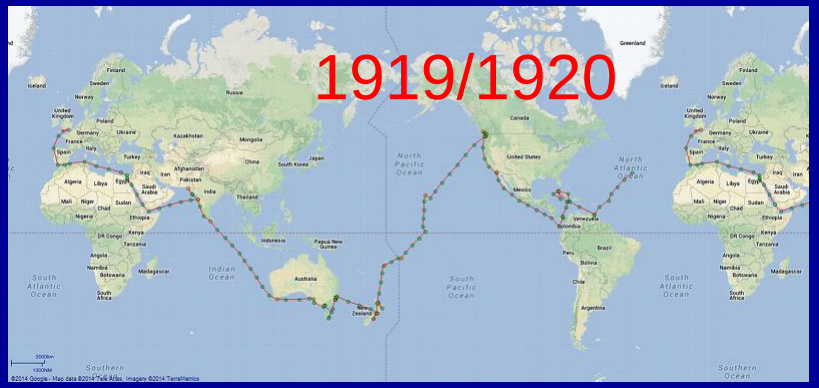
Root Mean Square difference of Surface and Sea Level Pressure Observations and 24 hour Forecasts from 20CRv2 and Scout3.3.8 (*Jan-Jun*)



Northern Hemisphere 24 hr forecasts beat persistence even in 1860s!
Southern Hemisphere has an analysis that produces forecasts comparable to persistence starting in 1950s.

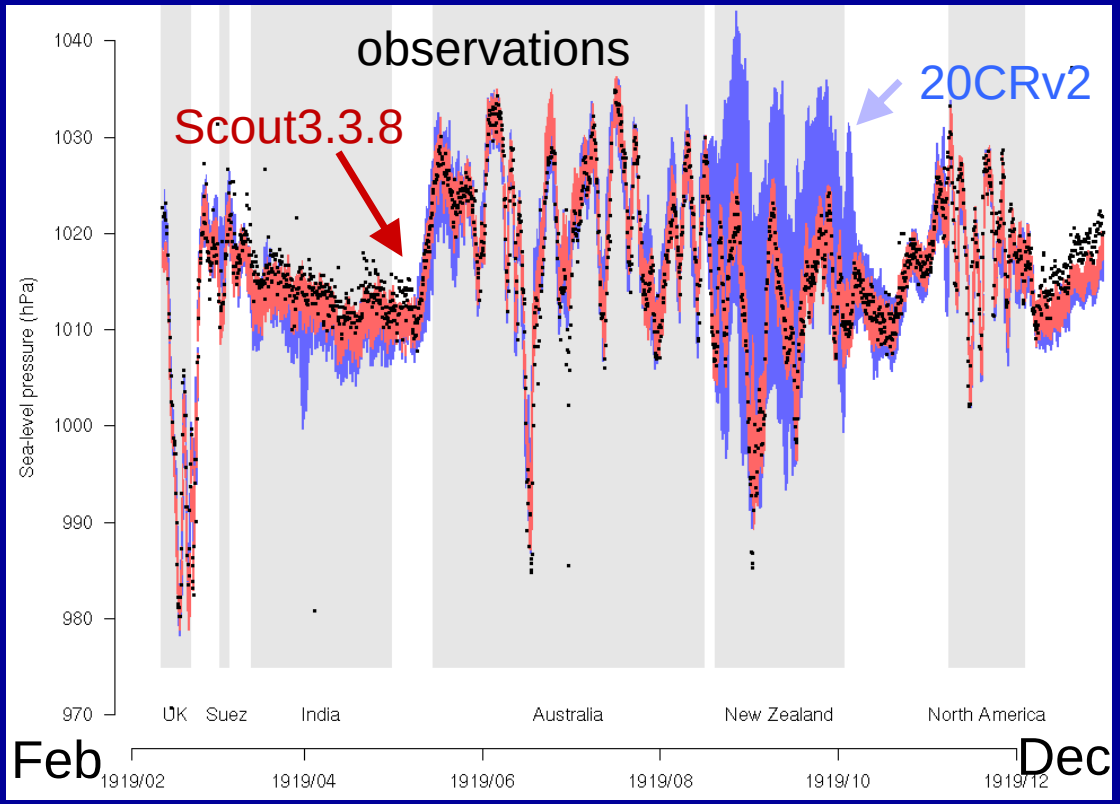
Sea Level Pressure obs from Oldweather.org HMS *New Zealand*

Mobile Weather platform



1040

970

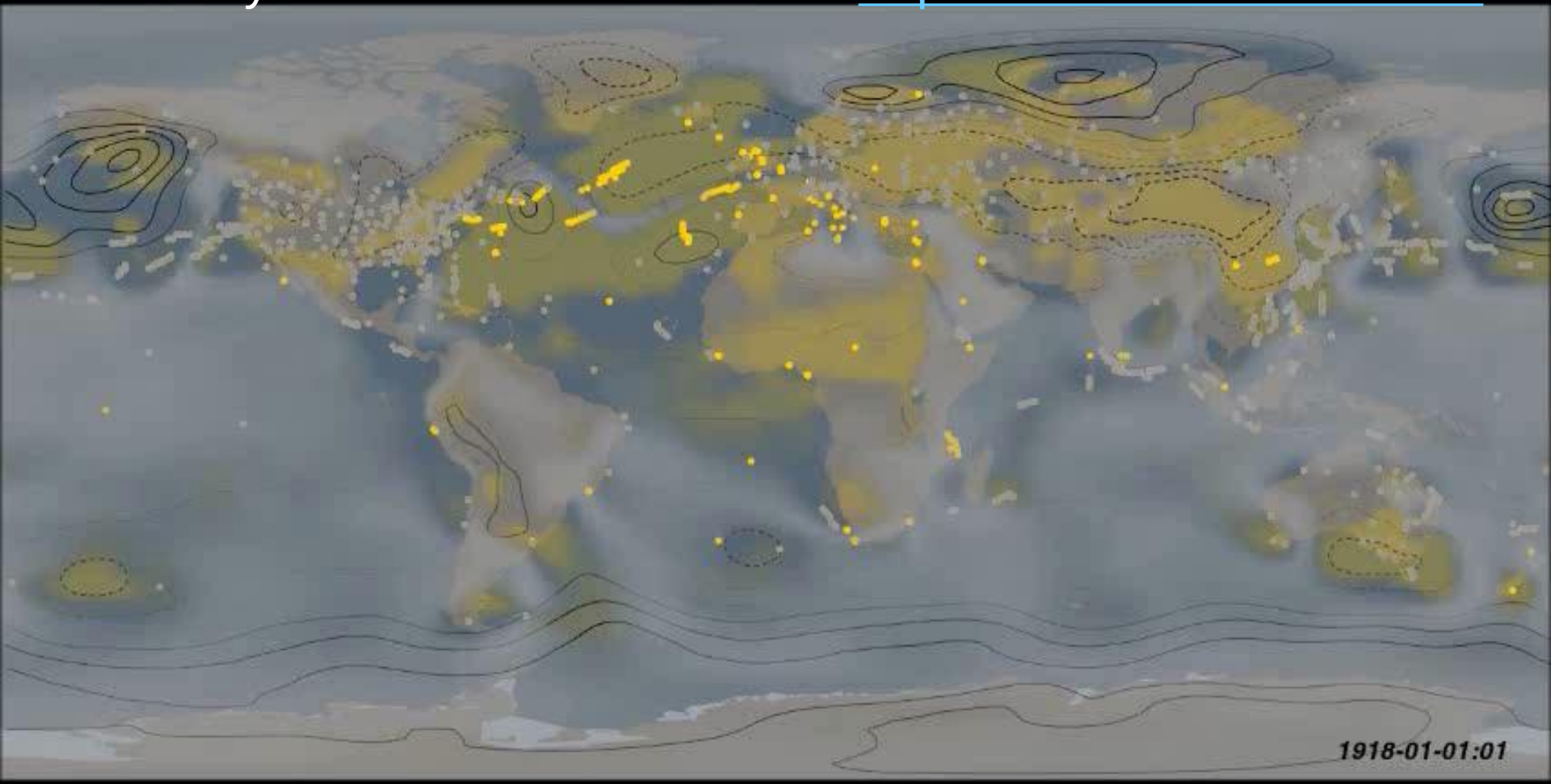


Shaded blue and red bars show ±2 σ from reanalyses

Demonstrable improvement in data-sparse area of New Zealand!

1918 Fog of Ignorance (Scout pdf compared to climatology) and Glow of Discovery (Scout pdf improves upon 20CR)

1 January 1918 Full Movie at http://vimeo.com/79549694



Grey dots=observations in 20CRv2

Gold dots=New observations used in Scout3.3.8 from ACRE partners

Black contours = Sea Level pressure

P. Brohan, UK Met Office

Historical Reanalysis Status and Plans

http://go.usa.gov/XTd

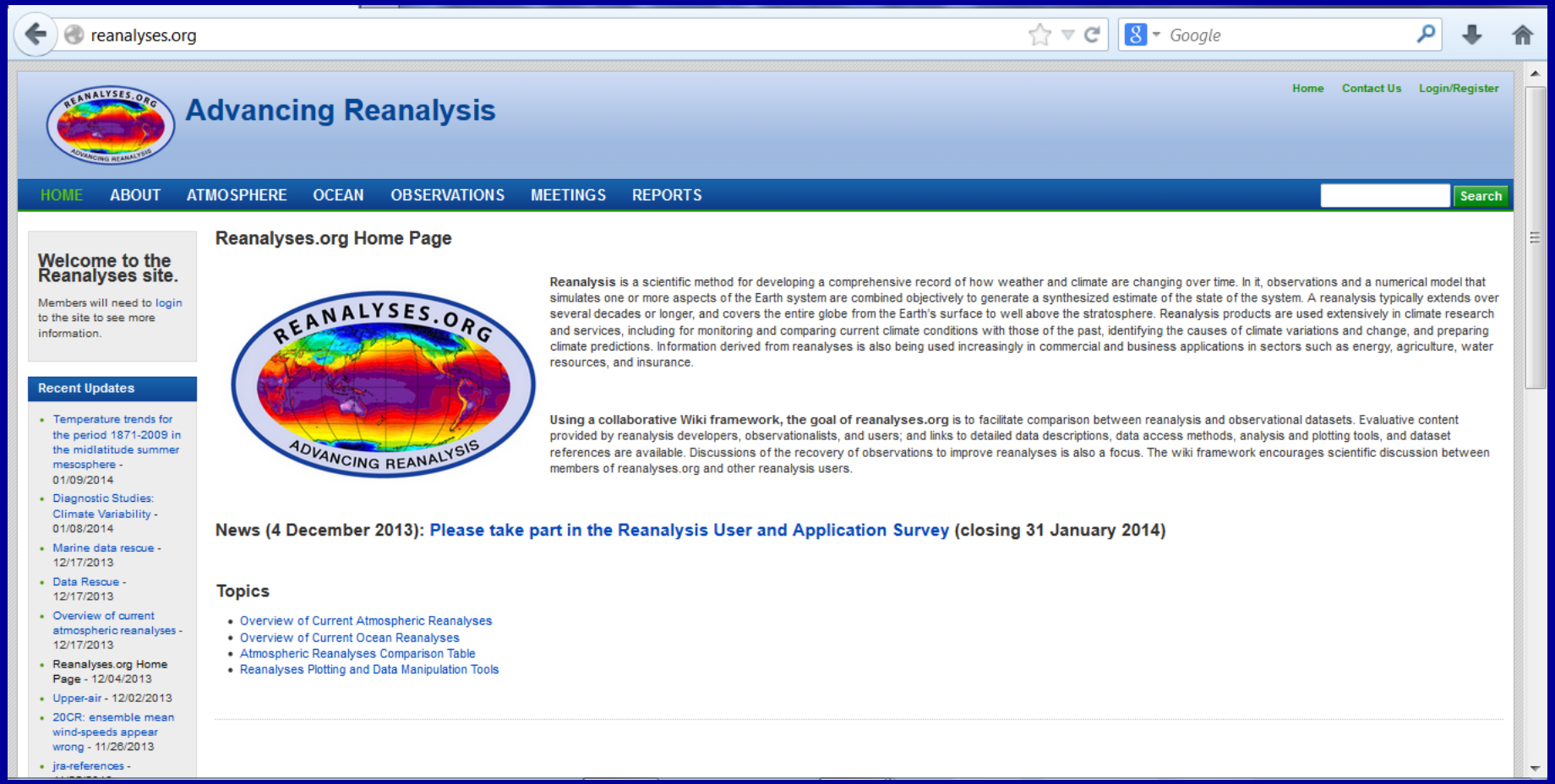
- Data Access: Analyses and ISPD (with feedback) freely available from NCAR, analyses from NOAA/ESRL, DOE NERSC, ESGF, and BADC.
- **Fall 2013**: 1871-2011 (includes time-varying CO2, volcanic aerosols, GFS from NCEP). **Ensemble mean and spread, and selected individual member variables online now**.
  - http://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2.html (NOAA ESRL)
  - http://dss.ucar.edu/datasets/ds131.1 (NCAR)
  - http://portal.nersc.gov/20C_Reanalysis **Every member** (US Dept of Energy, NERSC)

    NERSC High Performance Storage System direct-from-tape distribution
  - Earth System Grid Federation ana4MIPS distribution and validation for IPCC AR5 and CMIP5
  - British Atmospheric Data Center **Every member**
    - http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__DE_6ae84cbc-177b-11e2-9c9c-00163e251233

Summary

- **Demonstrated that surface-based reanalyses *throughout the troposphere* are feasible using advanced data assimilation and surface pressure observations.**
- **Effectively doubling the reanalysis record length from ~60 year to more than 150 years, allowing current atmospheric circulation patterns to be placed in a broader historical context.** ☺
- **Increasing vertical levels not a panacea to resolve all stratosphere bias issues.**
- **Higher resolution and additional observations will further improve these reanalyses.**
- For status updates, email
  - jeffrey.s.whitaker@noaa.gov,
  - compo@colorado.edu

Reanalyses.org: A collaborative website for research and questions about atmospheric, oceanic, and land reanalyses

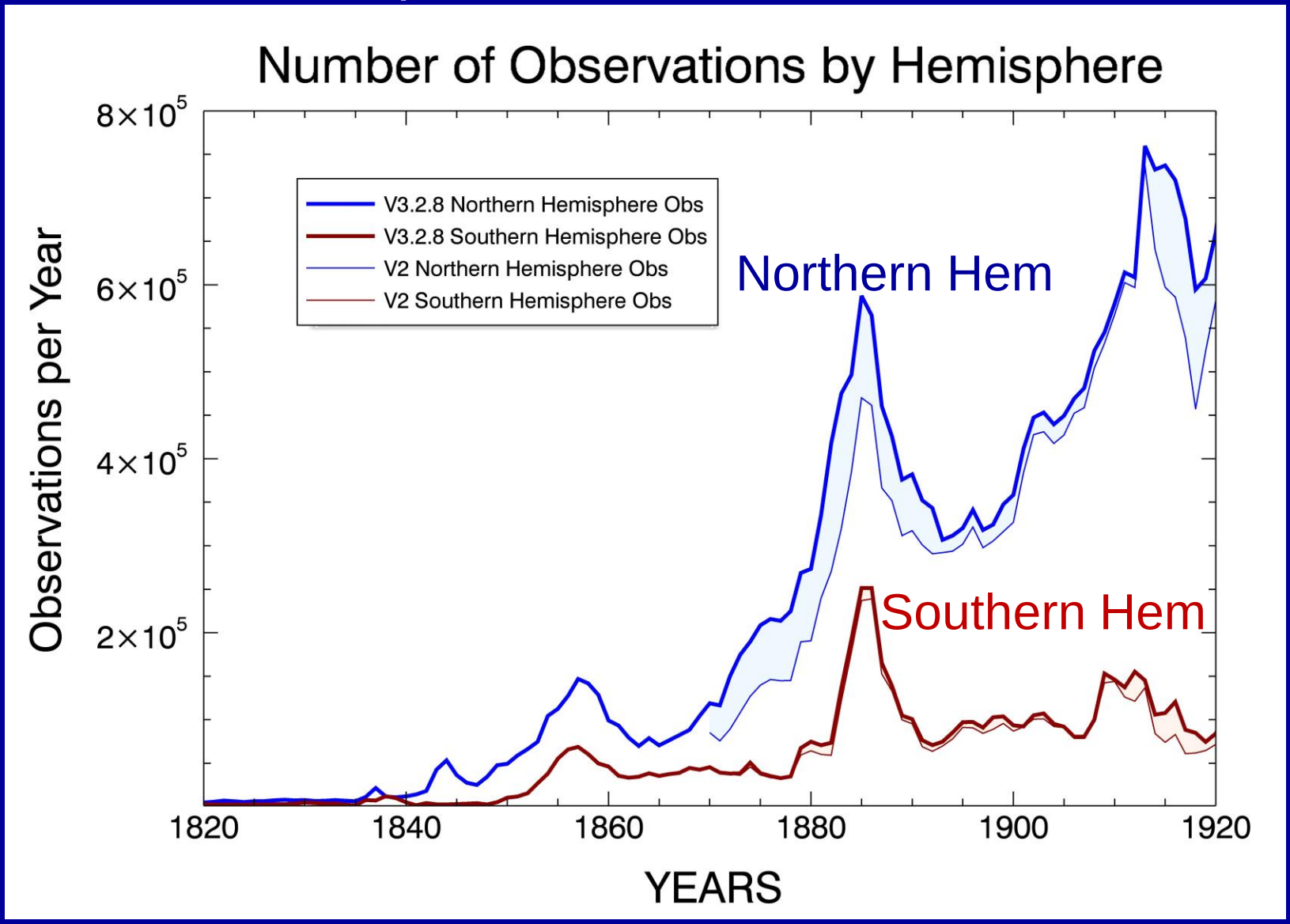


Please take part in the Reanalysis User and Application Survey

Thank you to organizations contributing observations to ISPD:

All Russia Research Institute of Hydrometeorological Information WDC
Atmospheric Circulation Reconstructions over the Earth (ACRE)
Australian Bureau of Meteorology
Australian Meteorological Association, Todd Project Team
British Antarctic Survey
Cook Islands Met Service
Danish Meteorological Institute
Deutscher Wetterdienst
EMULATE
Environment Canada
ETH-Zurich
European Reanalysis and Obs for Monitoring
GCOS AOPC/OOPC WG on Surface Pressure
GCOS/WCRP WG on Obs Data Sets
Hong Kong Observatory
Icelandic Meteorological Office
IBTrACS
ICOADS
IEDRO
JAMSTEC
Japan Meteorological Agency
Jersey Met Dept.
Lamont-Doherty Earth Observatory
KNMI
MeteoFrance
MeteoFrance – Division of Climate
Meteorological and Hydrological Service, Croatia
National Center for Atmospheric Research
Nicolaus Copernicus University
Niue Met Service
NIWA
NOAA Climate Database Modernization Program
NOAA Earth System Research Laboratory
NOAA National Climatic Data Center
NOAA National Centers for Environmental Prediction
NOAA Northeast Regional Climate Center at Cornell U.
NOAA Midwest Regional Climate Center at UIUC
NOAA Pacific Marine Environmental Laboratory
Norwegian Meteorological Institute
Oldweather.org
Ohio State U. – Byrd Polar Research Center
Portuguese Meteorological Institute (IM)
Proudman Oceanographic Laboratory
SIGN - Signatures of environmental change in the observations of the Geophysical Institutes
South African Weather Service
UK Met Office Hadley Centre
U. of Bern, Switzerland
U. of Colorado-CIRES/Climate Diagnostics Center
U. of East Anglia-Climatic Research Unit
U. of Giessen –Dept. of Geography
U. of Lisbon-Instituto Geofisico do Infante D. Luiz
U. of Lisbon-Instituto de Meteorologia
U. of Mebourne
U. of Milan-Dept. of Physics
U. of Porto-Instituto Geofisca
U. Rovira i Virgili-Center for Climate Change
U. of South Carolina
U. of Toronto-Dept of Physics
U. of Washington
World Meteorological Organization - MEDARE
ZAMG (Austrian Weather Service)

Comparison of ISPD versions

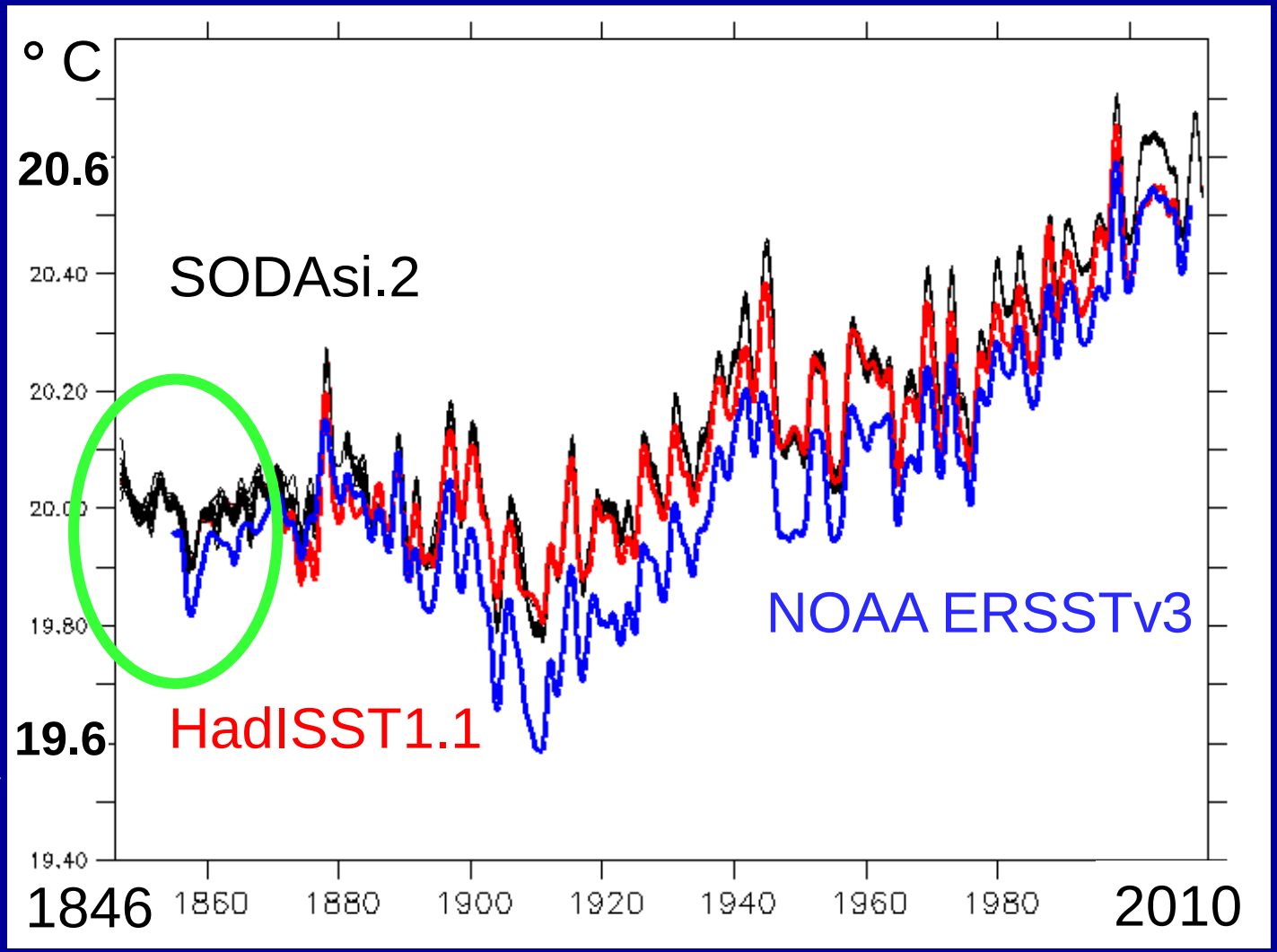


New ISPDv3.2.8 has considerably more observations than v2

Simple Ocean Data Assimilation si.2

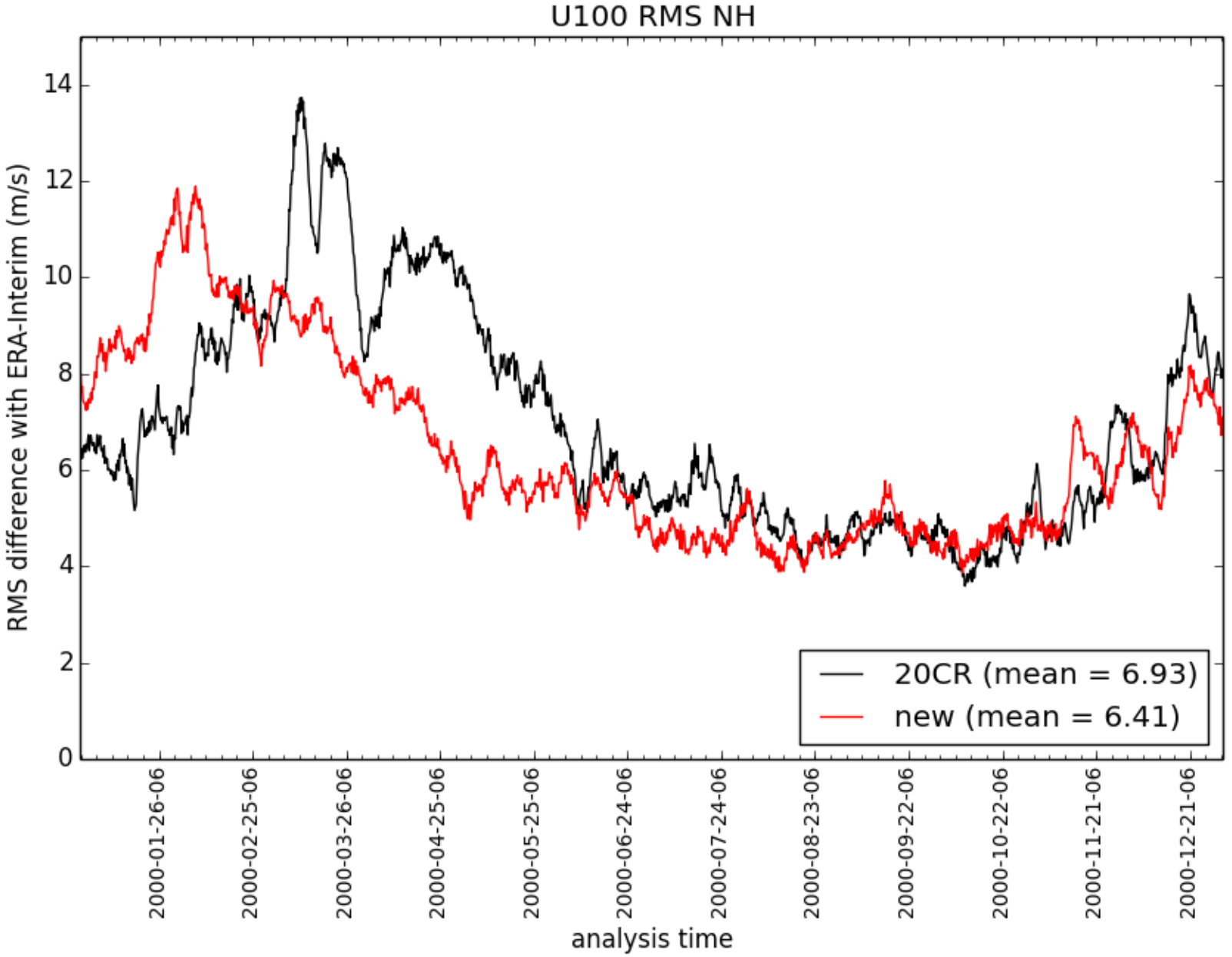
Global Ocean Annual Average (60N-60S)

Climo SST in 20CR 1846 to 1870 but variation in SODA



SODAsi.2 trends and decadal variability are consistent with statistical reconstructions. SODAsi Generates interannual variations in late 1850s even when 20CR forcing had climatological SST.

Giese et al. 2014

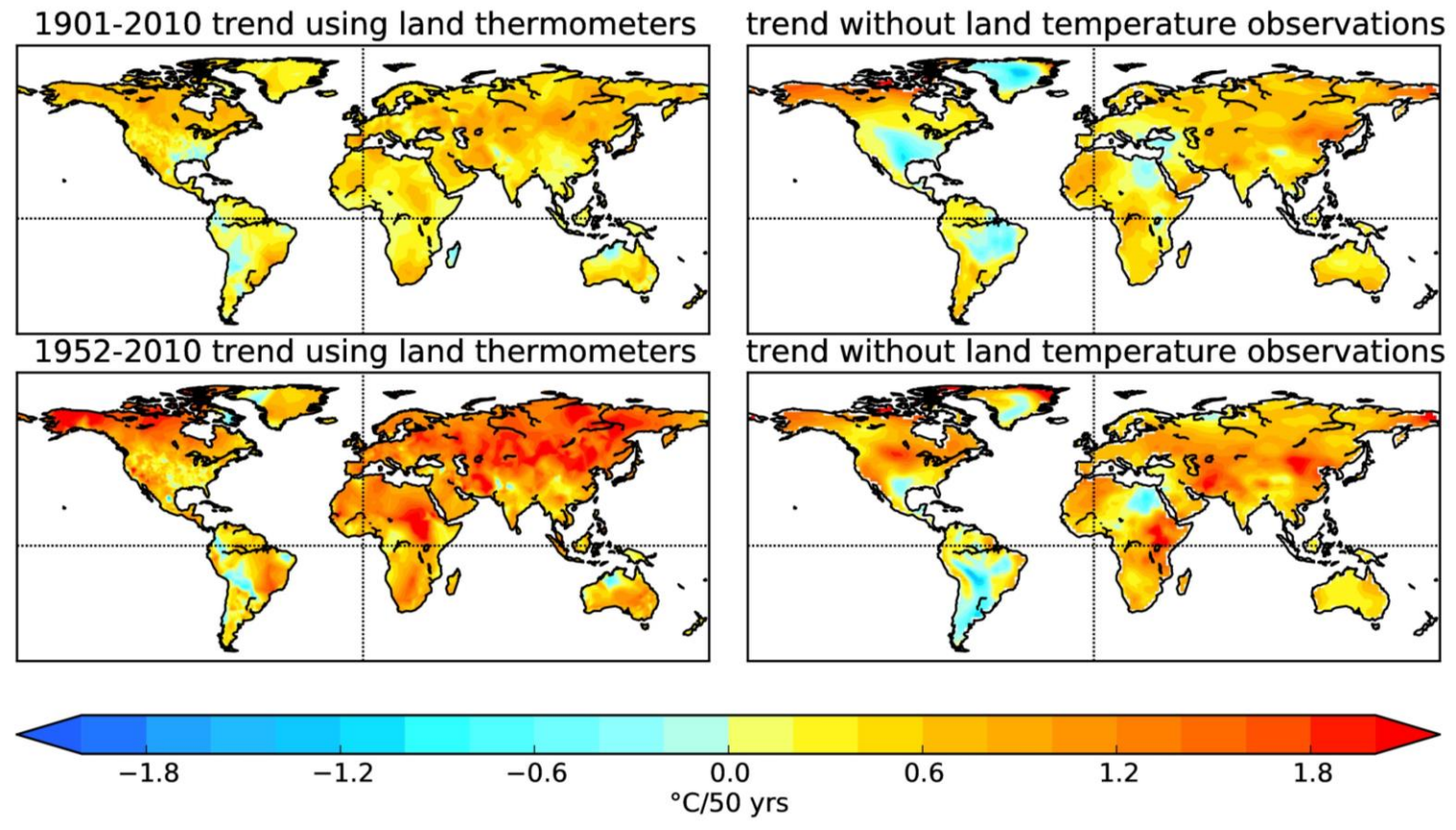

U100 RMS NH
RMS difference with ERA-Interim (m/s)
0
2
4
6
8
10
12
14
2000-01-26-06
2000-02-25-06
2000-03-26-06
2000-04-25-06
2000-05-25-06
2000-06-24-06
2000-07-24-06
2000-08-23-06
2000-09-22-06
2000-10-22-06
2000-11-21-06
2000-12-21-06
analysis time
20CR (mean = 6.93)
new (mean = 6.41)

Linear Trends of TL_{2m} are consistent

CRU_TS3.10 | 20CR

1901-2010

1952-2010

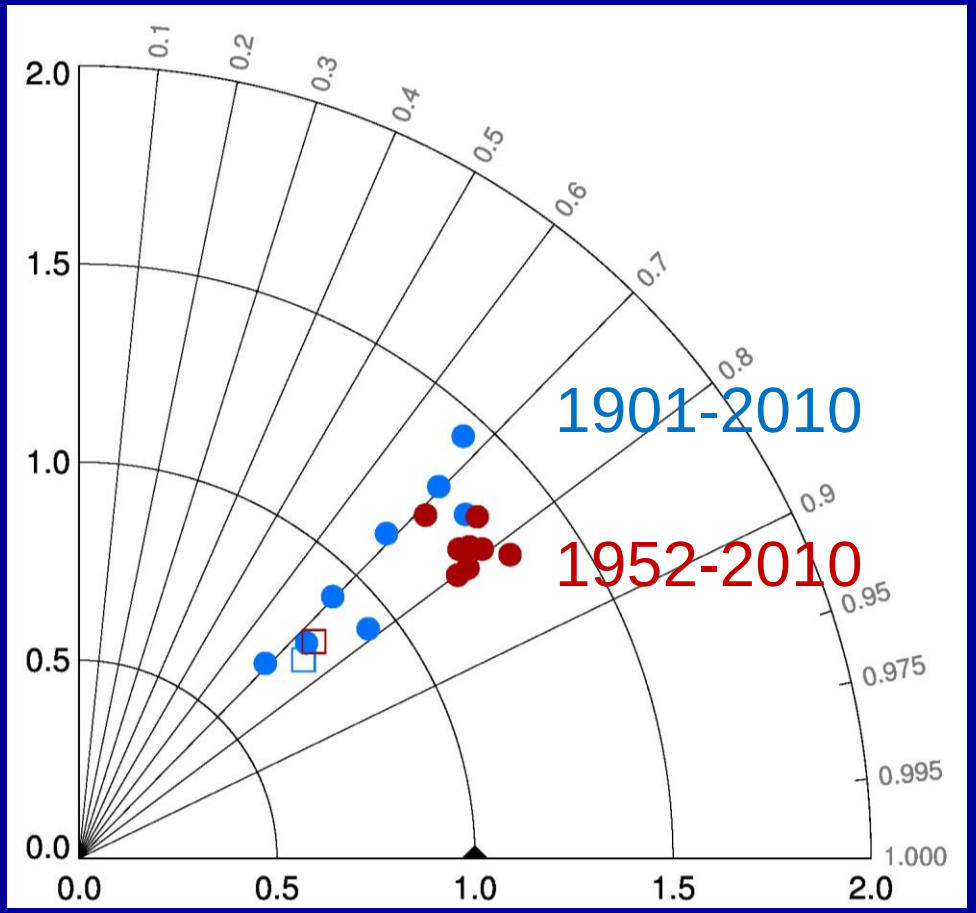


Trends are similar, with differences in detail,
over both 1901-2010 and more rapidly warming 1952-2010.

Comparing the spatial patterns and amplitudes of local trends of TL_{2m} from 20CR with (filled circles) eight observational datasets and from (open squares) SST-forced simulation AMIP20C

Cosine of angle is pattern correlation.

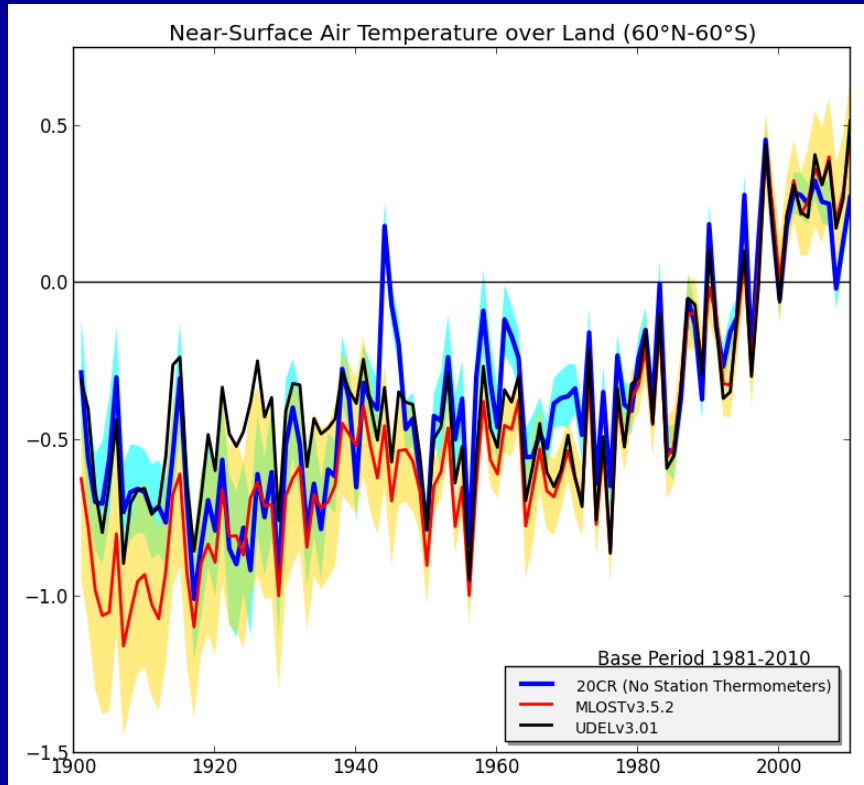
Radial distance is ratio of pattern amplitudes.



20CR compares better (r=0.69 to 0.81) to observed TL2m than to AMIP20C (squares), particularly in the recent period.

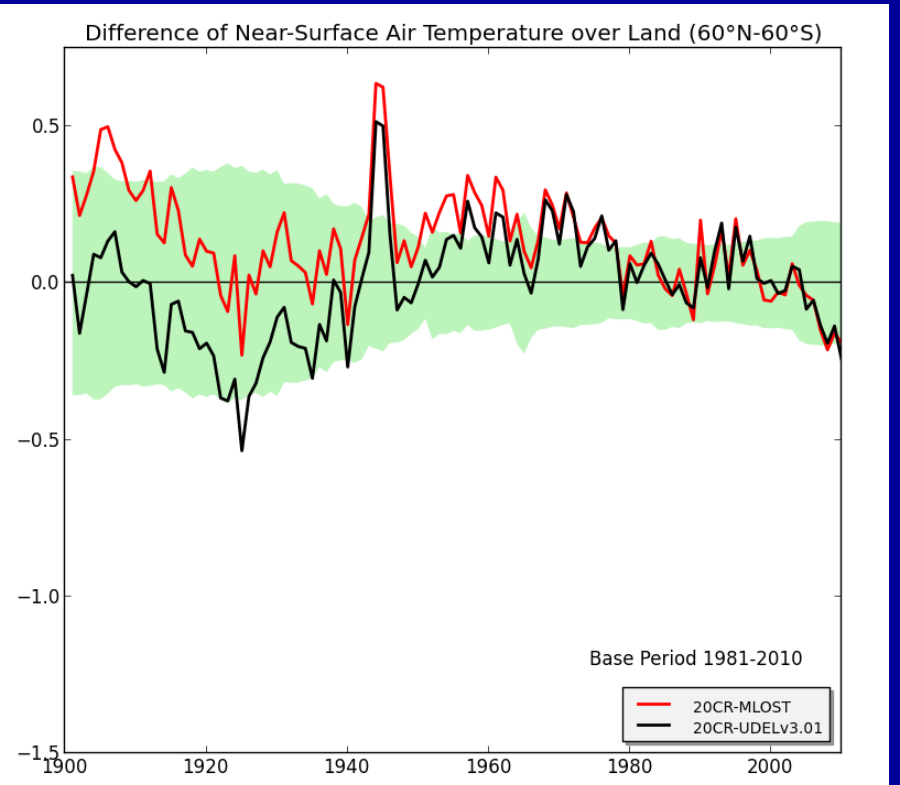
Annual anomalies of near-global TL_{2m} from 20CR, MLOST, UDEL (1901-2010)

TL2m



1901 2010

Difference



1901 2010

Uncertainty estimates are largely consistent.
Differences are not “urban warming”.

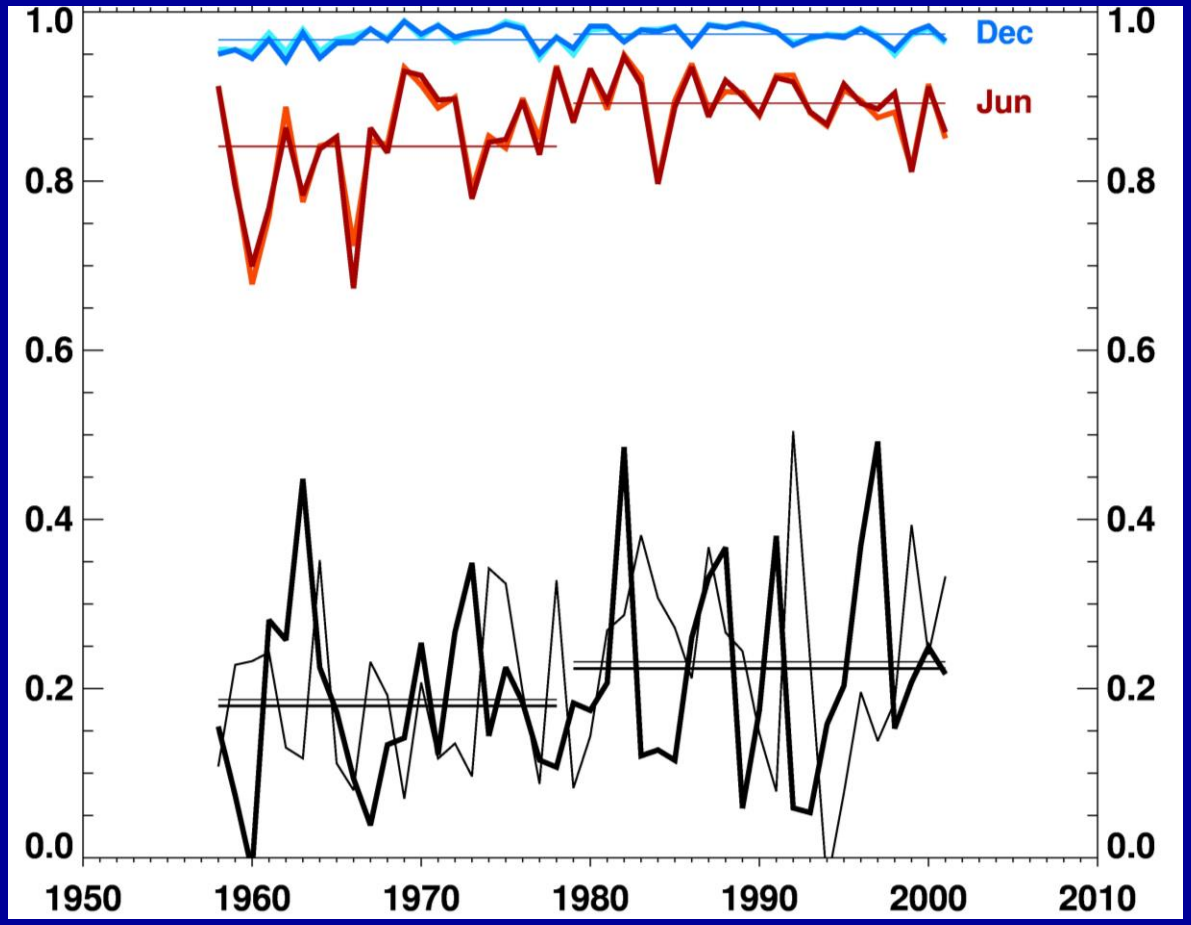
Conclusions

- Ignore near-surface air temperature observations (TL_{2m}) and instead infer them from global observations of subdaily barometric pressure using a physically-based data assimilation system called the 20th Century Reanalysis (20CR).
- Independent estimate of TL_{2m} from 20CR demonstrates that, in spite of recently published and public concerns with the station temperature record, **the temperature analyses** used by the IPCC and many others are ***reliable and robust estimates*** of large-scale TL_{2m} variability and change.
- The **20CR reproduces both TL_{2m} annual variations and centennial trends**, demonstrating the robustness of previous conclusions based on the temperature analyses regarding global warming (e.g., IPCC reports).

20CR data: http://go.usa.gov/XTd

Contact: compo@colorado.edu

Pattern correlation between 20CR and ERA40 and NCEP-NCAR Reanalyses of monthly anomalies of NH Tropospheric temperature (300 hPa geopotential height)



Correlation Between NNR and 20CR (and ERA-40 and 20CR)

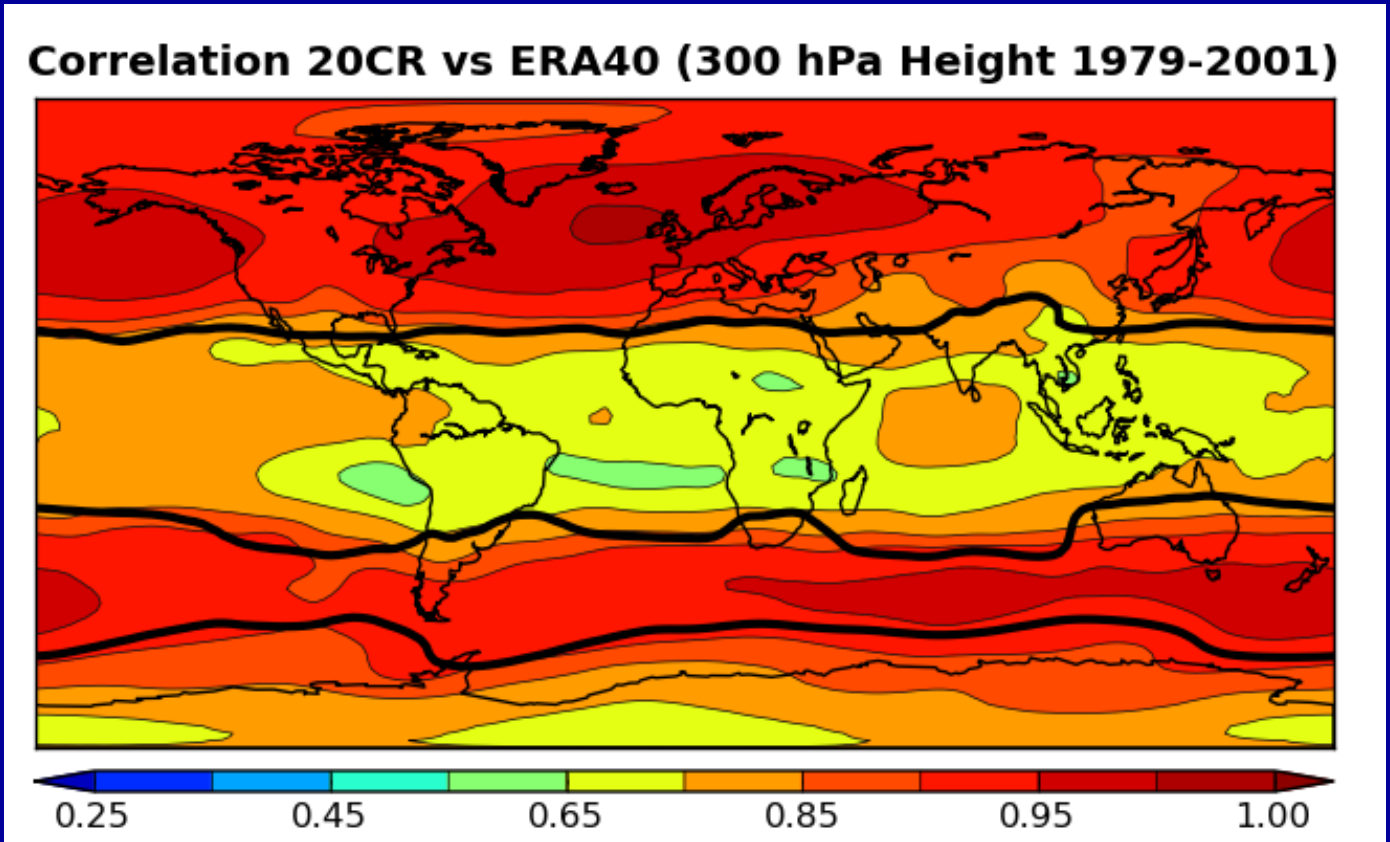
Correlation Between NNR and an SST-forced simulation

Reanalysis correlations are much higher than for SST-forced simulation.

20CR is more than an SST-forced simulation.

Local Anomaly Correlation of 300 hPa geopotential height anomalies from 20th Century Reanalysis (20CRv2) and ERA40 (1979 to 2001)

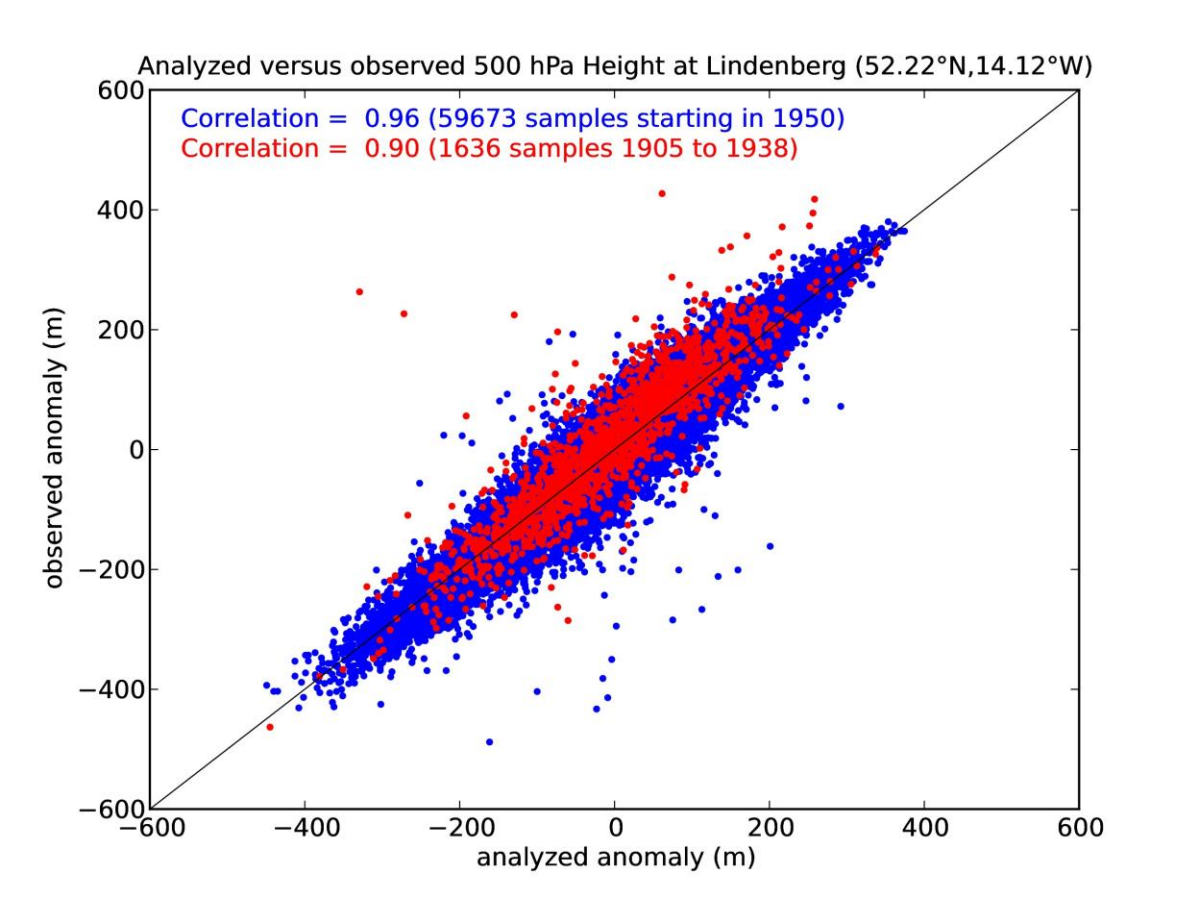
Black curves show where NCEP-NCAR and ERA40 correlate > 0.975



Northern and Southern Hemisphere agreement are excellent between 20CRv2 and ERA40 when ERA40 has satellite observations.

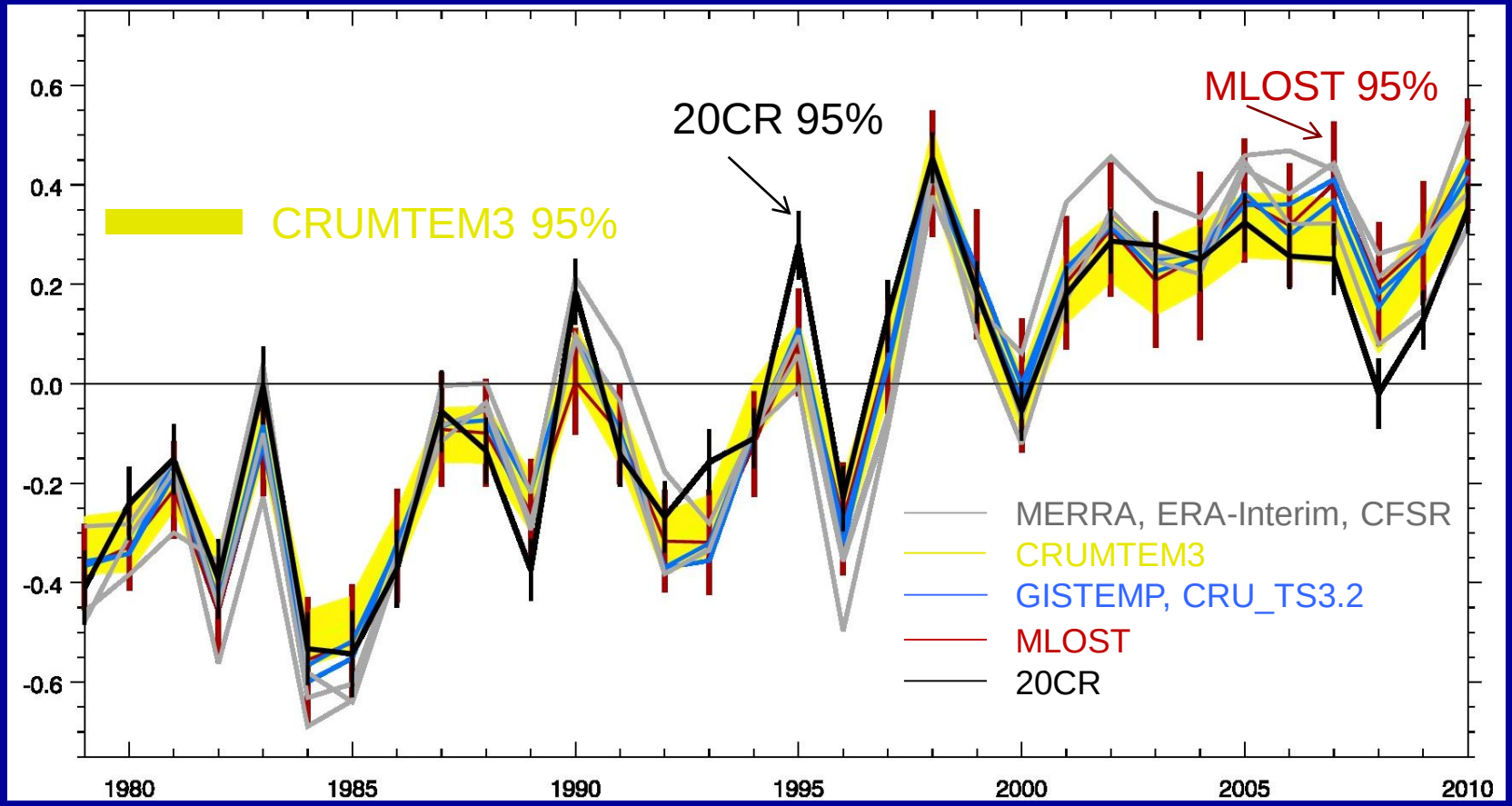
Subdaily 500 hPa Geopotential Height anomalies from observations and 20th Century Reanalysis compare well.

1905-2006 Measurements from kites, aircraft, registering balloon, and radiosondes at Lindenberg, Germany



Observations from CHUAN dataset (*Stickler et al. 2010*)

Near Surface
Annual Mean Temperature Anomalies
for Land only (60N to 60S) 1979 to 2010



Correlations between 20CR and thermometer-based estimates are relatively high (0.94 to 0.95) [see Parker 2011]. Correlations with upper-air and satellite-based reanalyses also high (0.91 to 0.94). 95% error ranges are largely consistent.

Compo, Sardeshmukh, Whitaker, Brohan , Jones, and McColl (2013)