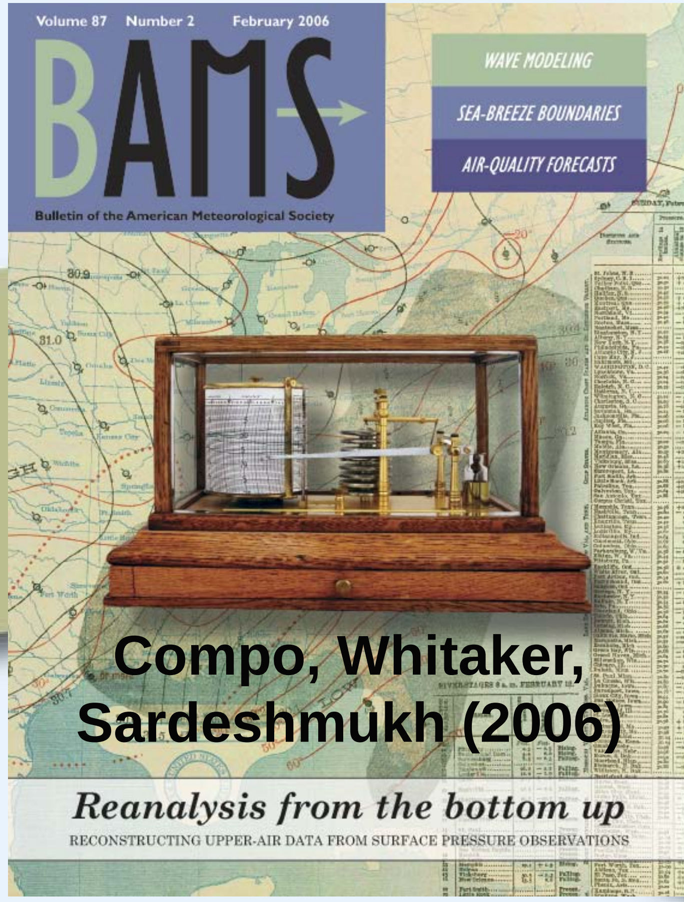
The Twentieth Century Reanalysis Project



Earth System Research Laboratory

Gilbert P. Compo, Jeffrey S. Whitaker, and Prashant D. Sardeshmukh

U. of Colorado/CIRES Climate Diagnostics Center & NOAA ESRL/ Physical Sciences Division

US and International calls for historical reanalyses

Reanalysis datasets "spanning the instrumental record"

(WCRP 3rd conference on reanalysis, Trenberth, EOS, 2008)

- Group on Earth Observations/GCOS Task CL-06-01 Sustained Reprocessing and Reanalysis Efforts

- U.S. GCRP Revised Strategic Plan (2008)

  Goal 3 Reduce uncertainty in projections of how the Earth's climate and environmental systems may change in the future

  Key research topics: Creating a Historical Reanalysis of the Atmosphere of the 20th Century

- NOAA Strategic plan (2006-2011) to meet NOAA and GCRP goals calls for integrated observations and analysis with "quantified uncertainties".

- Emphasis on reanalysis improvements for understanding multidecadal variability of weather extremes and variations

(eg., CCSP, 2008, Weather and Climate Extremes SAP3.3)

Some Uses of Historical Reanalyses

1. Effectively doubling the reanalysis record length ☺
2. Climate model validation dataset for large-scale synoptic anomalies during extreme periods, such as droughts (30’s, 50’s).
3. Better understand events such as the 1920-1940’s Arctic warming.
4. Determining storminess and storm track variations over last 100-150 years.
5. Developing new forecast products predicting changes in frequency and intensity of weather extremes, e.g., cold air outbreaks, severe storms.
6. Developing and improving forecasts of low-frequency (e.g., Pacific-North America pattern, North Atlantic Oscillation) atmospheric variations and their interannual to decadal variability.
7. Understanding changing atmospheric background state associated with interdecadal hurricane activity.
8. Homogenizing upper-air and other independent observations.
9. Offline forcing of models (e.g., ocean, land)
10. Estimating historical probability distributions for wind energy.
11. Estimating risks of extreme events for insurance and re-insurance.

Challenges to meeting National and International goals for Historical Reanalyses

- Satellite network only back to 1970’s,
  Upper-air network comprehensive only back to 1940’s, scant to non-existent in 19th century

- 3-D Var data assimilation systems such as used in NCEP-NCAR, NCEP-DOE, ERA-40 reanalyses depends on upper-air data for high quality upper-level fields (*Bengtsson et al.* 2004, *Kanamitsu and Hwang* 2005).

- However, studies using advanced data assimilation methods (e.g., 4D-Var, Ensemble Filter) suggest surface network, especially surface pressure observations, could be used to generate high-quality upper-air fields (*Bengtsson* 1980, *Thepaut and Simmons* 2003, *Thepaut* 2006, *Whitaker et al*. 2003, 2004, 2009, *Anderson et al.* 2005, *Compo et al.* 2006).

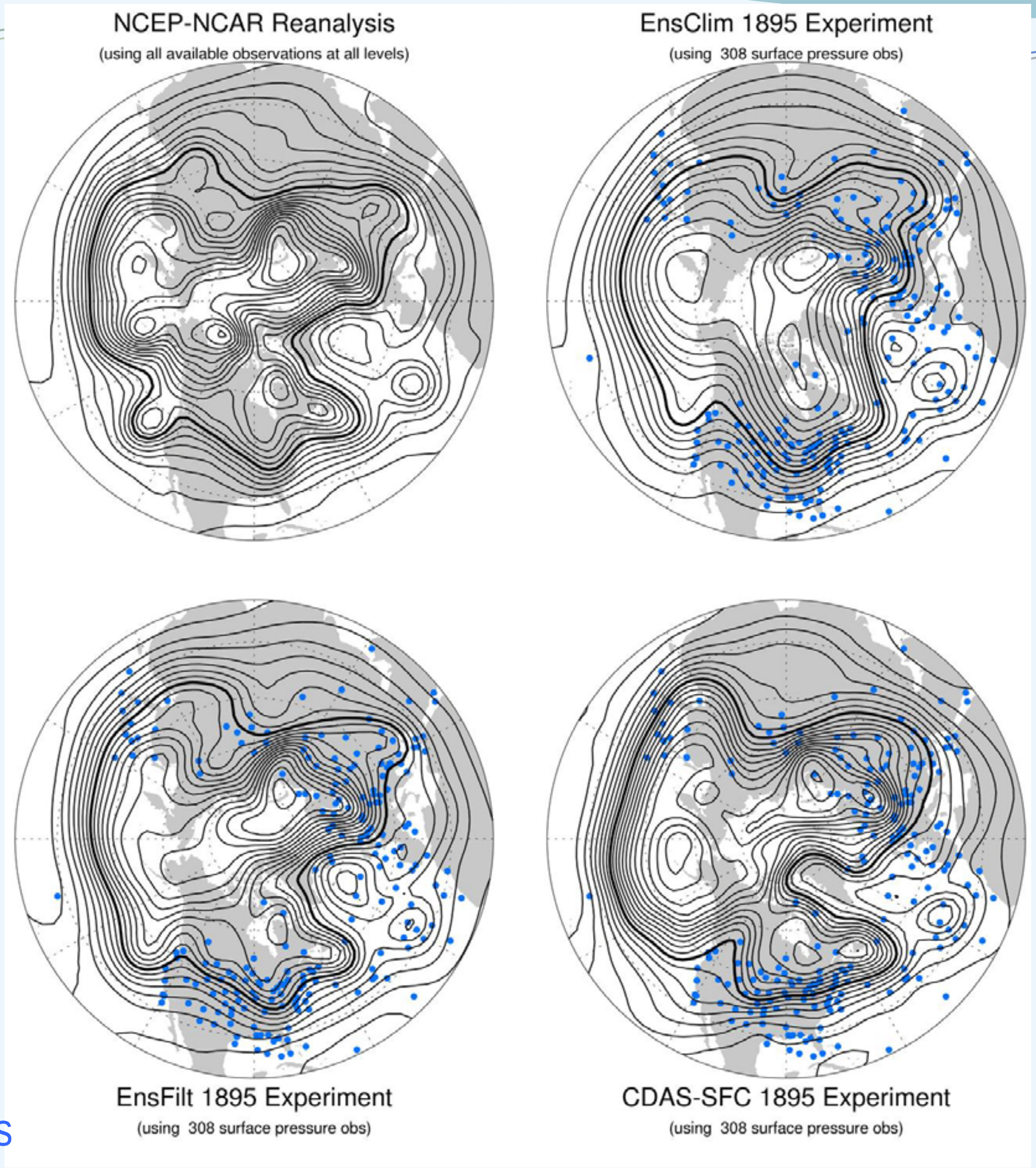
- Surface Pressure observations are consistent and reliable throughout 20th Century and provide dynamical information about the full atmospheric column.

500mb Height Analyses for 20 Dec 2001 0Z

Full CDAS
(120,000+ obs)

EnsFilt 1895
(308 surface pressure obs)
RMS = 49 m

Blue dots show surface pressure observation locations



EnsClim 1895
(308 surface pressure obs)
RMS = 96 m

CDAS-SFC 1895
(308 surface pressure obs)
RMS = 96 m

5500 m contour is thickened

Feasibility Observing System Experiment (Compo, Whitaker, Sardeshmukh 2006)

The Twentieth Century Reanalysis Project

Summary: An international collaborative project led by NOAA and CIRES to produce high-quality tropospheric reanalyses for the last 100+ years ***using only surface observations***.

The reanalyses will provide:

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

-Estimates of biases and uncertainties in the basic reanalyses;

-Estimates of biases and uncertainties in derived quantities (storm tracks, etc.)

Initial product will have higher quality in the Northern Hemisphere than in the Southern Hemisphere.

US Department of Energy INCITE computing award and NOAA Climate Goal support to complete *1871-2008* in 2010.

Initially produce 1908-1958.

Ensemble Filter Algorithm

Analysis x^a is a weighted average of the first guess x^b and observation y^o

$$x^a = (I-KH)x^b + Ky^o$$

Algorithm uses an ensemble to produce the weight K that varies with the atmospheric flow and the observation network

y^o is only surface pressure,

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

$\mathbf{x}$ is pressure, air temperature, winds, humidity, etc. at all levels and gridpoints.

Using 56 member Ensemble

T62 (about 2 degree), 28 level NCEP CFS03 model
HadISST monthly boundary conditions (*Rayner et al. 2003*)

International Surface Pressure Databank (ISPD)

Subdaily observations assembled by

GCOS AOPC/OOPC Working Group on Surface Pressure (co-convenors, R. Allan and G. Compo)

GCOS/WCRP Working Group on Observational Data Sets for Reanalysis (convenor R. Vose)

Atmospheric Circulation Reconstructions over the Earth (ACRE)

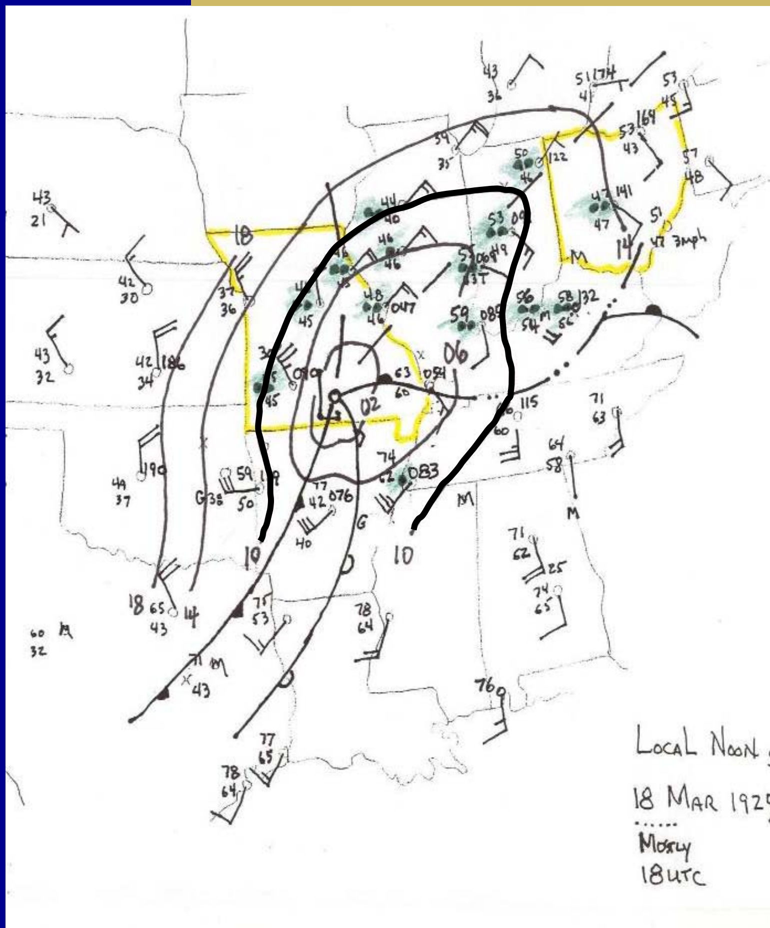
NOAA NCDC, NOAA ESRL, and CU/CIRES: merging station data

NOAA ESRL and NCAR (ICOADS): merging marine data

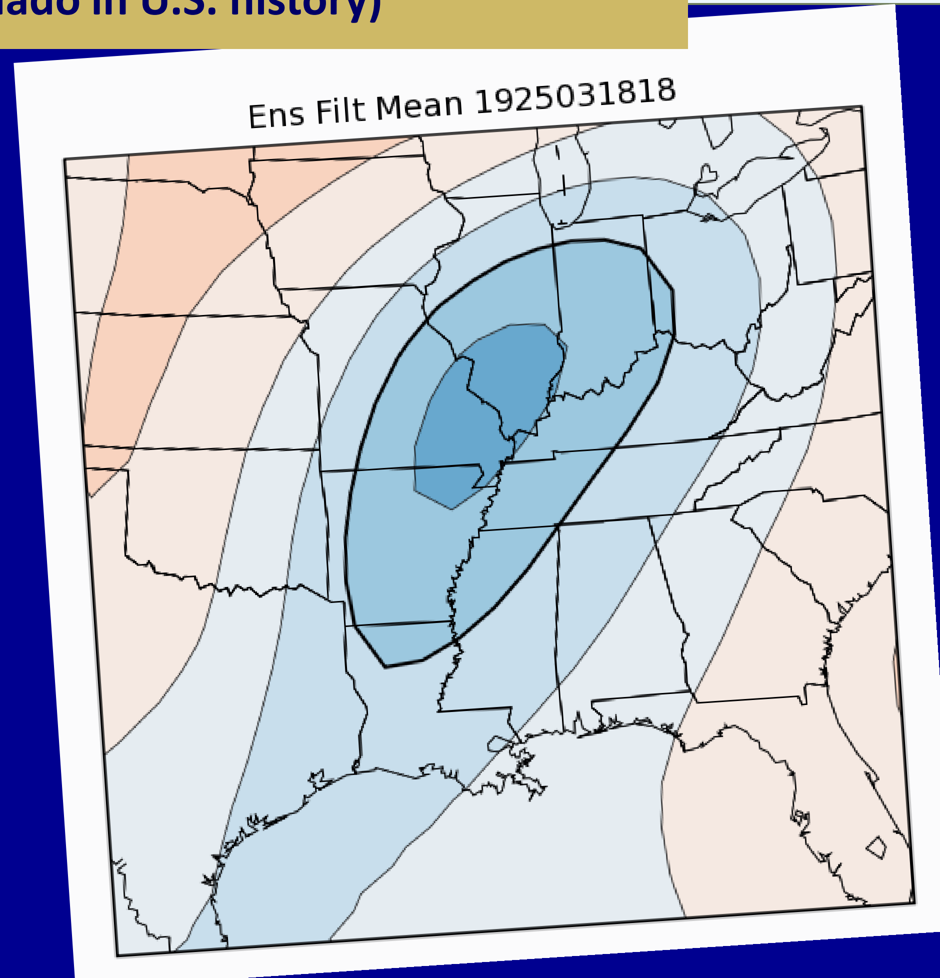
Thank you to organizations contributing observations:

All Union Research Institute of Hydrometeorological Information WDC
Atmospheric Circulation Reconstructions over the Earth (ACRE)
Australian Bureau of Meteorology
British Antarctic Survey
Danish Meteorological Institute
Deutscher Wetterdienst
EMULATE
Environment Canada
ETH-Zurich
GCOS AOPC/OOPC WG on Surface Pressure
Hong Kong Observatory
IBTRACS
ICOADS
Instituto Geofisico da Universidade do Porto
IEDRO
Japanese Meteorological Agency
Jersey Met Dept.
KNMI
MeteoFrance
MeteoFrance – Division of Climate
Meteorological and Hydrological Service, Croatia
National Center for Atmospheric Research
Nicolaus Copernicus University
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
Norwegian Meteorological Institute
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 Colorado-CIRES/Climate Diagnostics Center
U. of East Anglia-Climatic Research Unit
U. of Lisbon-Instituto Geofisico do Infante D. Luiz
U. of Milan-IFGA
U. Rovira i Virgili-CCRG
ZAMG

Sea Level Pressure analyses for Tri-State Tornado Outbreak of 18 March 1925 (deadliest tornado in U.S. history)



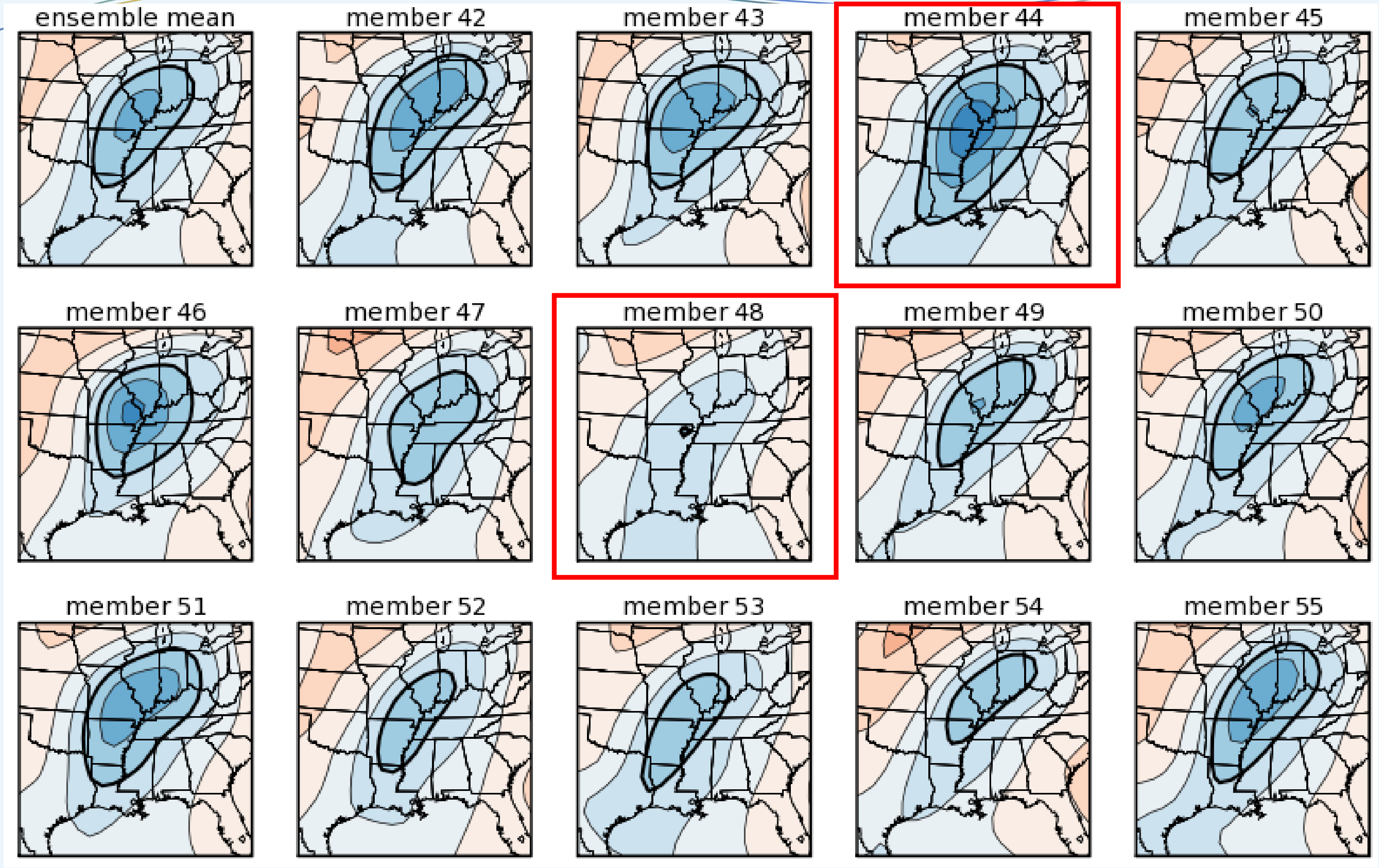
Manual Analysis, courtesy B. Maddox



Ensemble mean from Ensemble Filter (4 hPa interval, 1010 hPa thick)

NOTE!!! This analysis did not use ANY of the observations shown on the left.

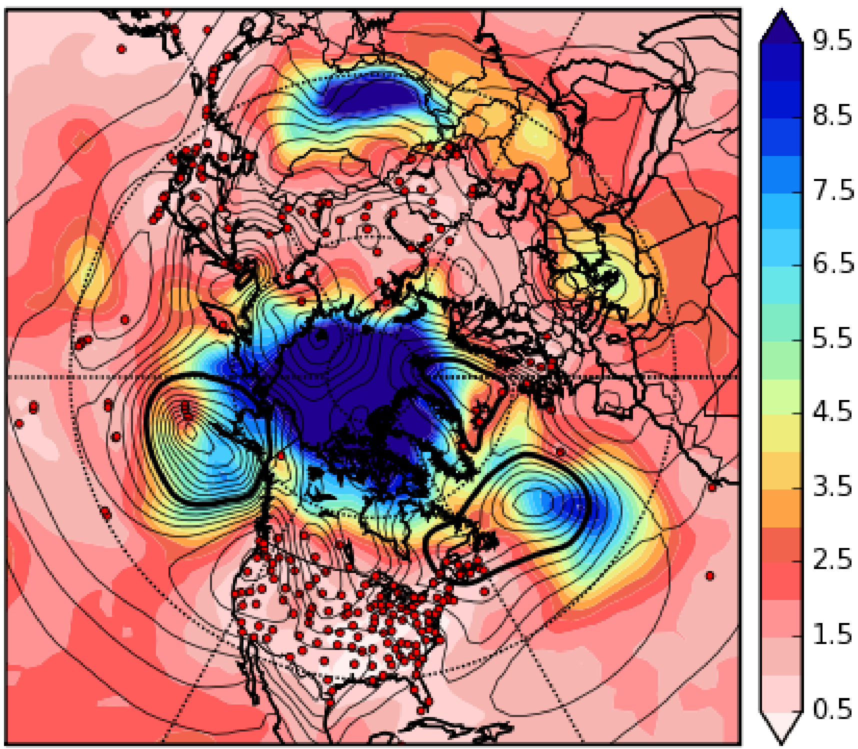
Range of possibilities for Sea Level Pressure 18 March 1925 18Z using 14 (of 56) members



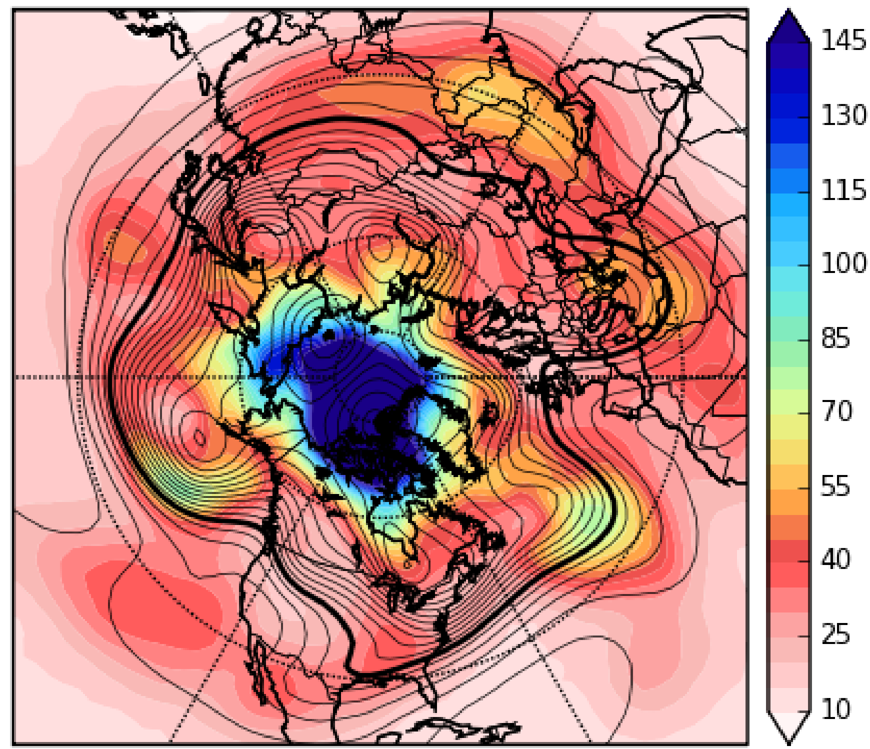
Ensemble of 56 possible realizations consistent with the observations

Analysis Ensemble Mean and Spread on 1 December 1918 00UTC

SLP



500 hPa GPH



Sea Level Pressure

500 hPa Geopotential Height

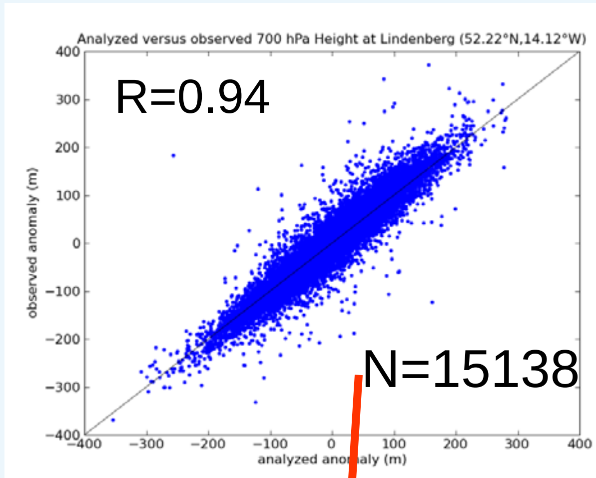
Contours- ensemble mean

Shading- blue: more uncertain, white: more certain

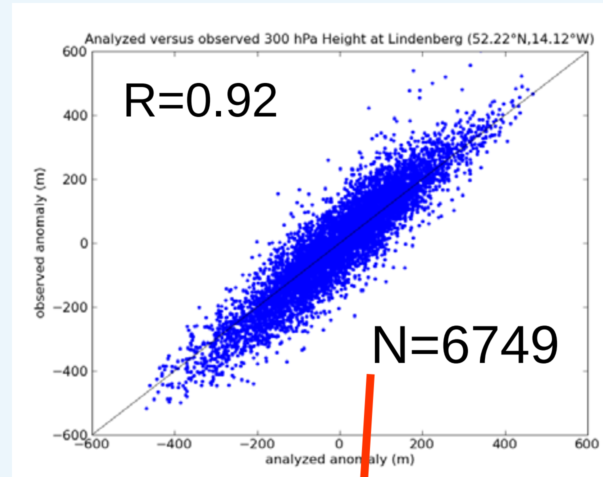
Local Anomaly Correlation of Twentieth Century Reanalysis and upper-air geopotential height observations from radiosondes and other platforms

1908-1958
data from kites, aircraft, radiosondes at Lindenberg, Germany

700 hPa

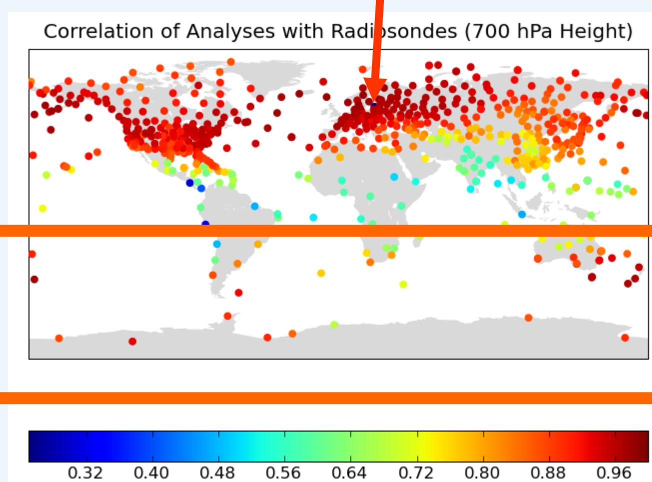


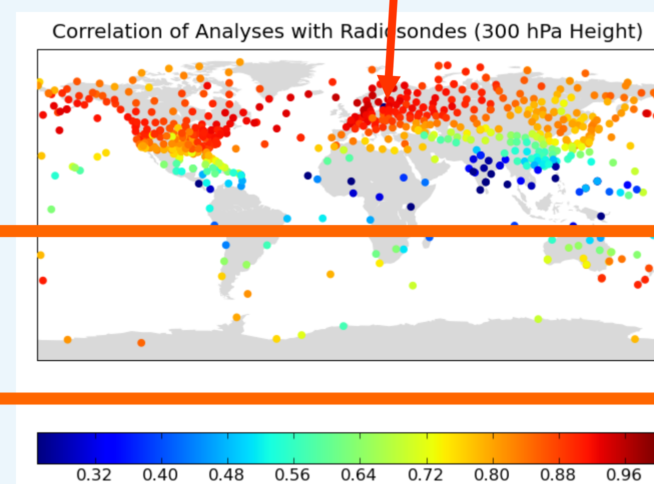
300 hPa



Upper-air observations with at least 730 ascents

Courtesy ETH Zurich





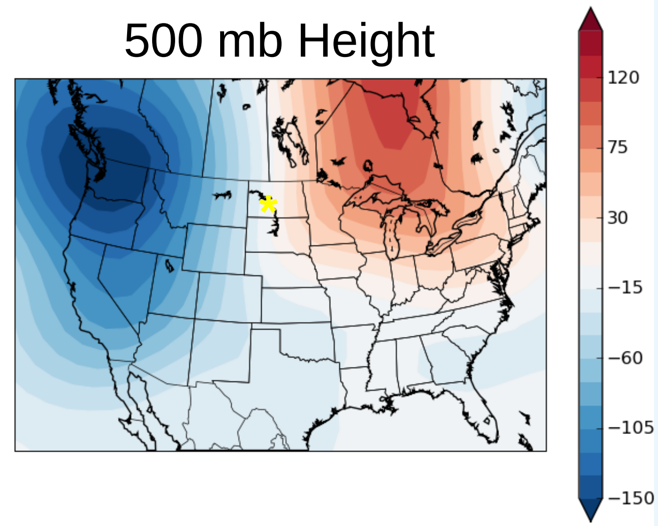
Agreement with Southern Hemisphere extratropics is good.

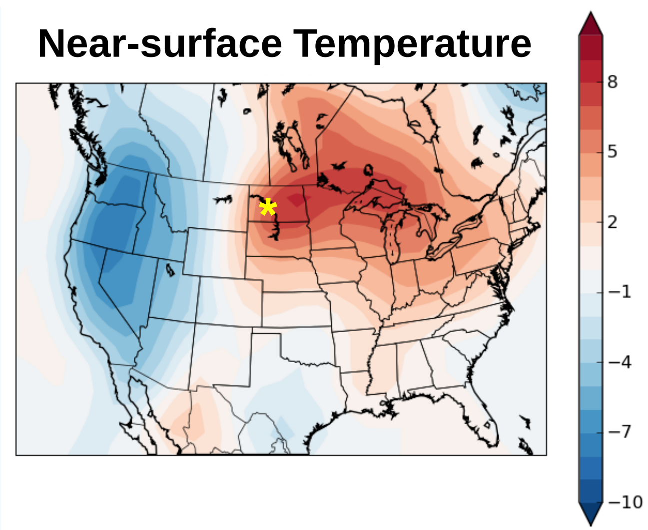
20th Century Reanalysis Version 2

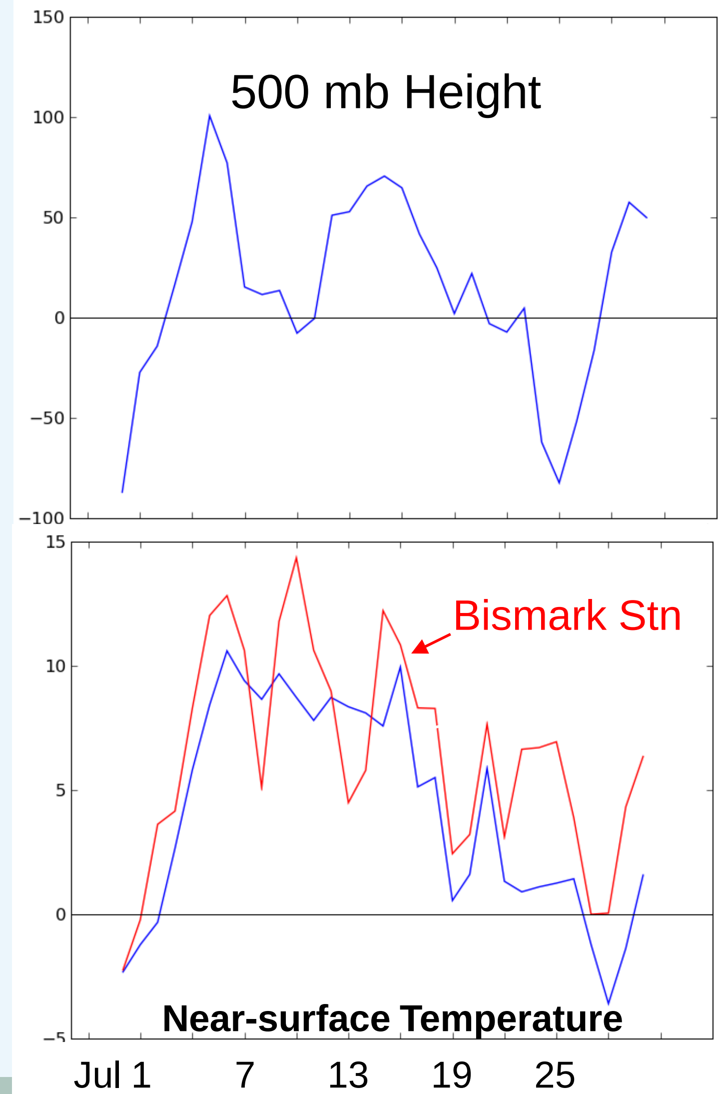
- Atmospheric model upgrade to experimental NCEP Global Forecast System (GFS2008ex), T62L28 (~2 degree latitude by longitude)
- GFS2008ex includes NOAH land model, and time-varying CO2, solar variability, and volcanic aerosols
- Additional surface and sea level pressure observations from ships and stations through ACRE, NOAA CDMP, and other partners
- All Australian observations at the correct time.
- Dataset will span 1871 to present when completed.

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

Anomalies averaged July 8 - 14



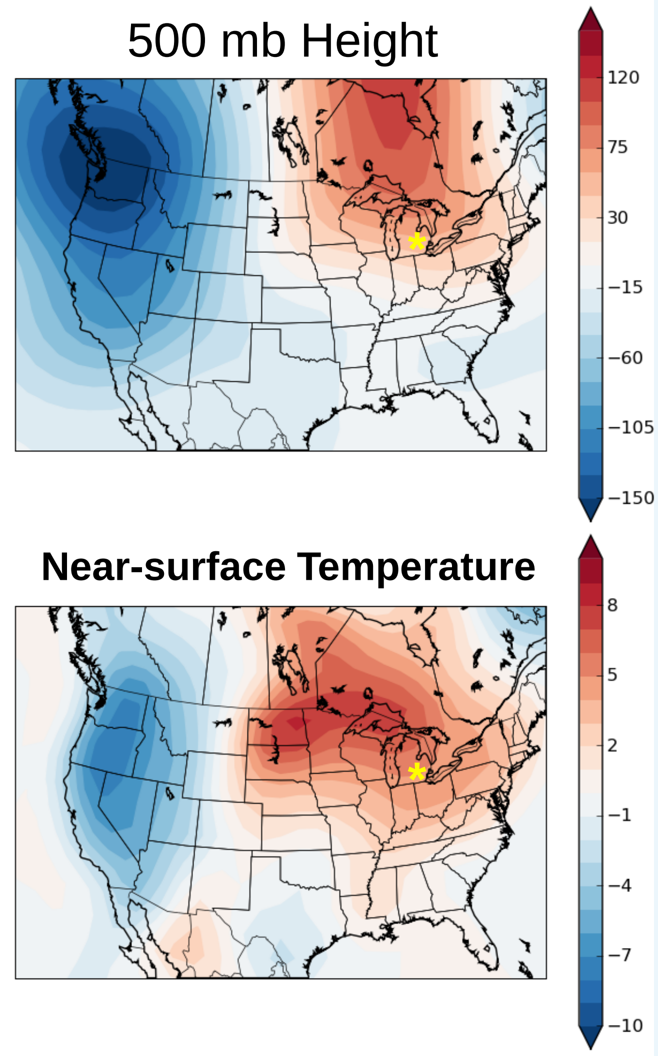


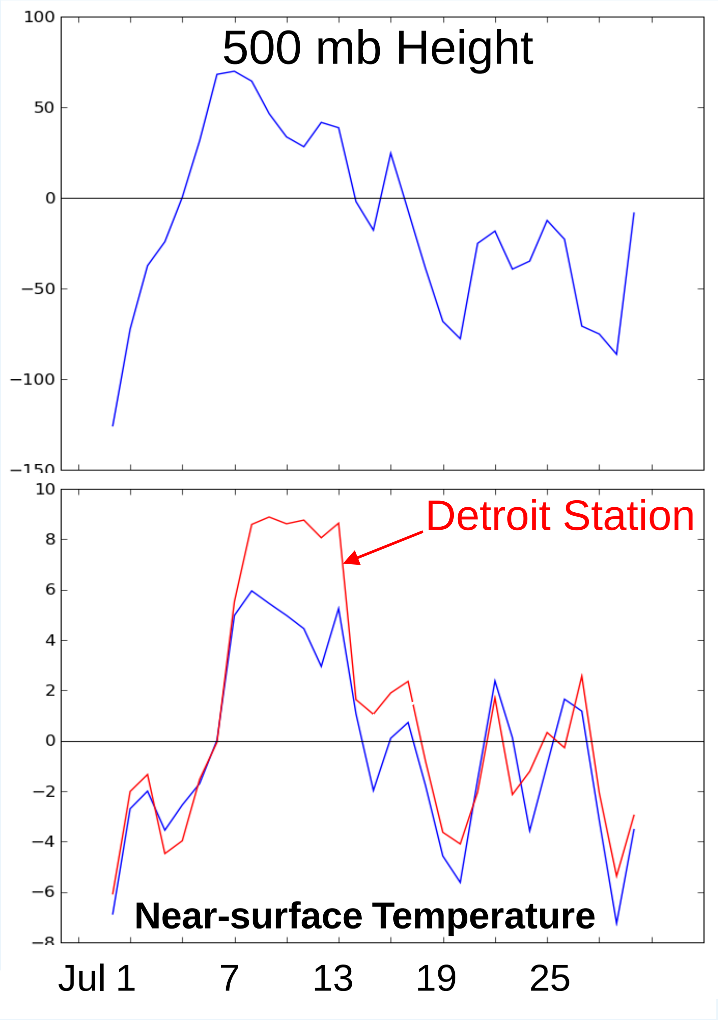


Reanalyses using only surface pressure observations

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

Anomalies averaged July 8 - 14

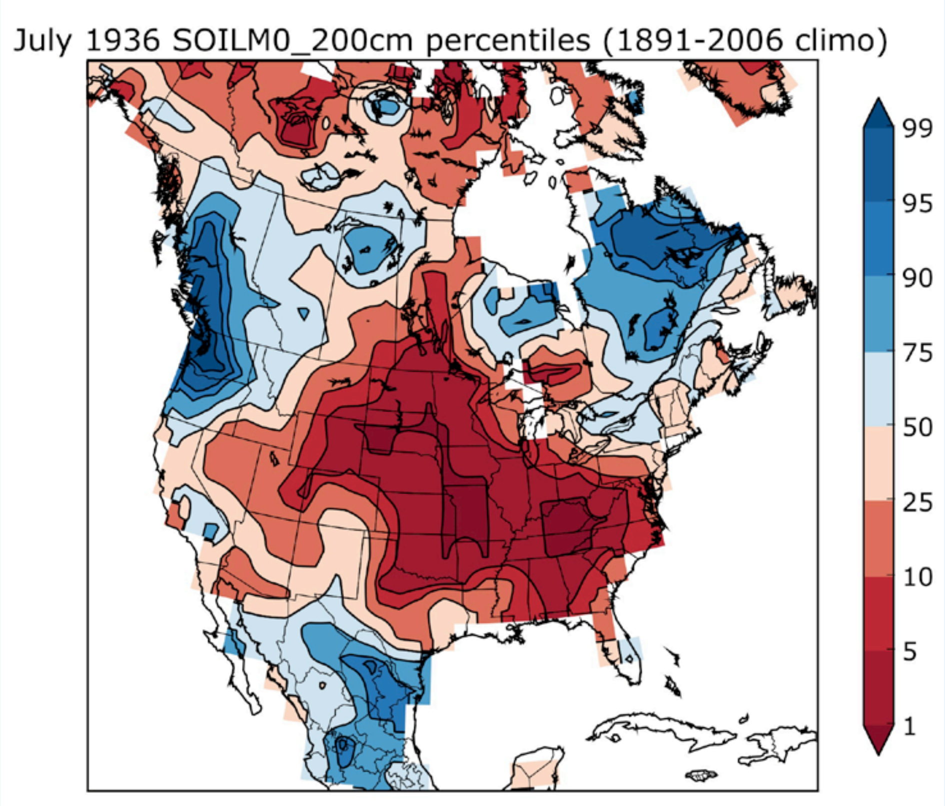




Reanalyses using only surface pressure observations

U.S Dust Bowl (July 1936)

Soil moisture from 0 to 200cm below the surface as a percentile of 1891-2006



Using only surface pressure, 20CR appears to capture expected features in derived quantities.

Historical Reanalysis Status and Plans

20th Century Reanalysis Project http://www.esrl.noaa.gov/psd/data/20thC_Rean

- Data Access: Analyses and ISPD (with feedback) will be freely available from NCAR, NOAA/ESRL and NOAA/NCDC.
- Spring 2009: Version 1, 1908-1958 (complete)
  - http://www.esrl.noaa.gov/psd/data/gridded/data.20thC_Rean.html (NOAA ESRL)
  - http://dss.ucar.edu/datasets/ds131.0 (NCAR)
- Spring 2010: Version 2, 1871-2008 (including time-varying CO2, aerosols, upgraded GFS from NCEP). **1891-2008 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://nomads.ncdc.noaa.gov (NOAA NCDC, coming soon)
  - Coordinate with PCMDI CMIP5 distribution and validation for IPCC AR5

ECMWF Reanalysis Archive-Climate (ERA-CLIM)

- Series of reanalyses, including Surface-observation based back to 1900 (ERA-P1).
- ERA-P1: T159 spectral (~125km grid spacing) 60 layers in the vertical, extending upward to 0.1 hPa (approximately 65km altitude)
- ERA-P1: Available 2012 (Contingent on EU funding)

Advances and Improvements towards *Surface Input Reanalysis for Climate Applications* (SIRCA) 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
3. Higher resolution, improved methods, other surface variables (e.g., wind, T, Tropical Cyclone position)

Requires international cooperation, e.g.,

Atmospheric Circulation Reconstruction over the Earth initiative

http://www.met-acre.org

Historical Reanalysis Status and Plans (con't)

Surface Input Reanalysis for Climate Applications (SIRCA)

SIRCA 1850-2013

- Higher resolution (T254 ~50km or higher)
- improved methods (e.g., Kalman Smoother)
- More input data (e.g., CDMP & ACRE, Zooniverse, maybe winds and T, storm position)
- latest model from NCEP (maybe multi-model, e.g., NASA, NCAR, GFDL, ESRL)
- Include uncertainty in forcings (e.g., ensemble of SSTs and Sea Ice, CO_2, solar)
- Available 2014

Chemical and Surface Input Reanalysis for Climate Applications

CSIRCA 1800-2016

- Higher resolution (T382 or higher)
- improved methods (e.g., include coupled Cryosphere-Ocean-Land-Atmosphere-Chemistry system, link with NOAA CarbonTracker advances)
- More input data (e.g., ACRE-facilitated, maybe winds and T, storm position, trace gases)
- latest model from NCEP, multi-model with other models (e.g., NASA, NCAR, GFDL, ESRL)
- Available 2017

- Summary: The Twentieth Century Reanalysis Project dataset could be used to place current atmospheric circulation patterns into a historical perspective.
- Challenges: Validating the dataset in regions of sparse observations and rapid change, e.g., the Arctic.
- Contact :
  - Jeffrey.S.Whitaker@noaa.gov
  - compo@colorado.edu

Extra Slides

Co-authors on 20th Century Reanalysis Project

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- **Russell S. Vose**, NOAA National Climatic Data Center
- **Glenn Rutledge**, NOAA National Climatic Data Center
- **Pierre Bessemoulin**, Meteo-France
- **Stefan Brönnimann**, ETH Zurich
- **Manola Brunet**, Centre on Climate Change (C3), Universitat Rovira i Virgili
- **Richard I. Crouthamel**, International Environmental Data Rescue Organization
- **Andrea N. Grant**, ETH Zurich
- **Pavel Y. Groisman**, University Corporation for Atmospheric Research & NOAA National Climatic Data Center
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- **Gareth J. Marshall**, British Antarctic Survey
- **Maurizio Maugeri**, Dipartimento di Fisica, Università delgi Studi di Milano
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- **Xiaolan L. Wang**, Environment Canada
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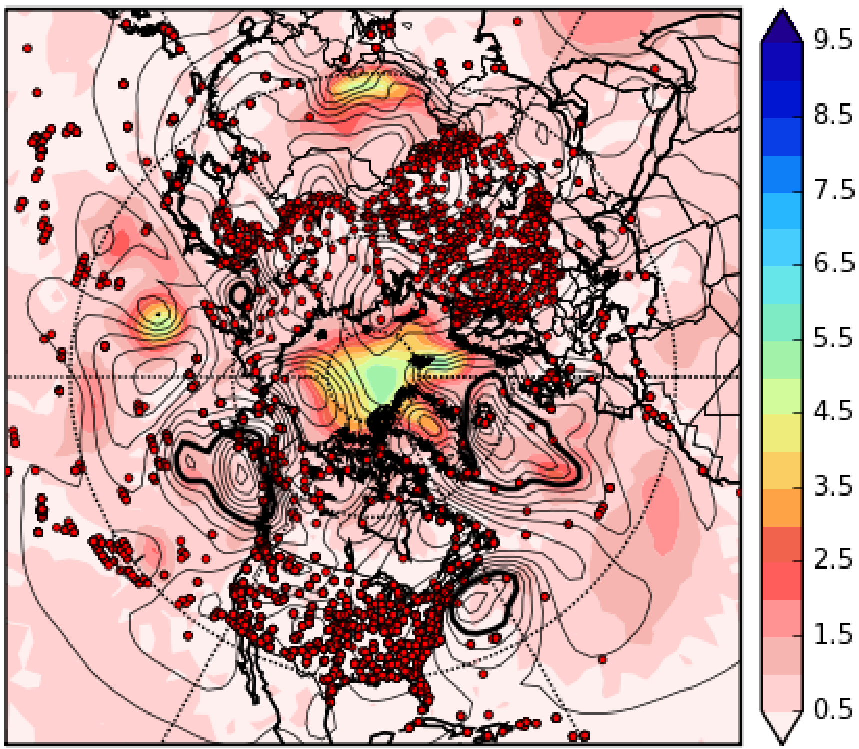
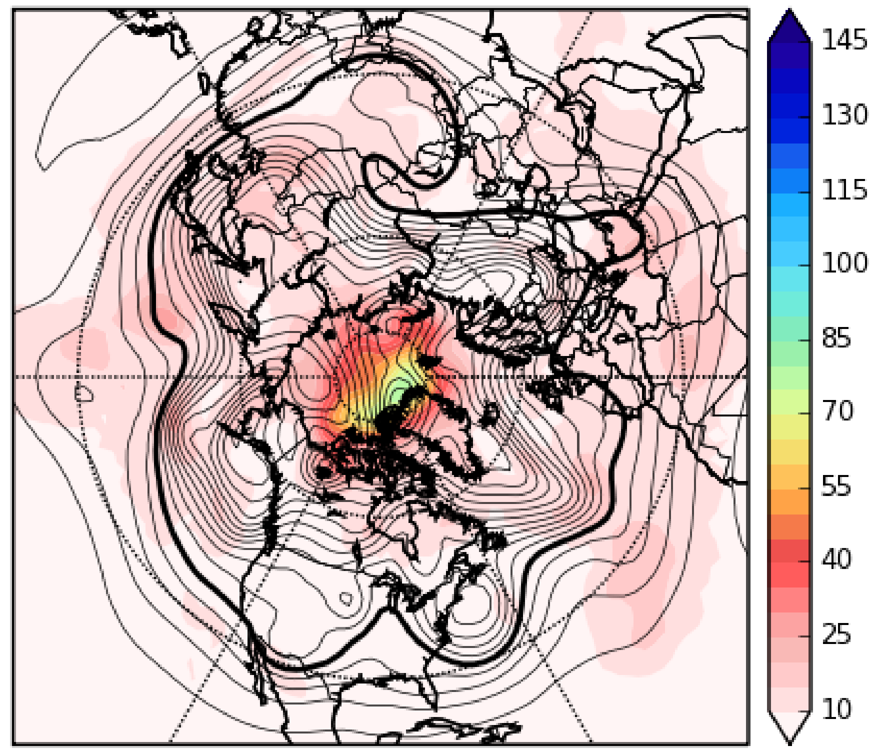
- **Steven J. Worley**, National Center for Atmospheric Research

Analysis Ensemble Mean and Spread on selected dates in the 1918-1945 reanalysis period

SLP 1 December 1945 500 hPa GPH





Sea Level Pressure

500 hPa Geopotential Height

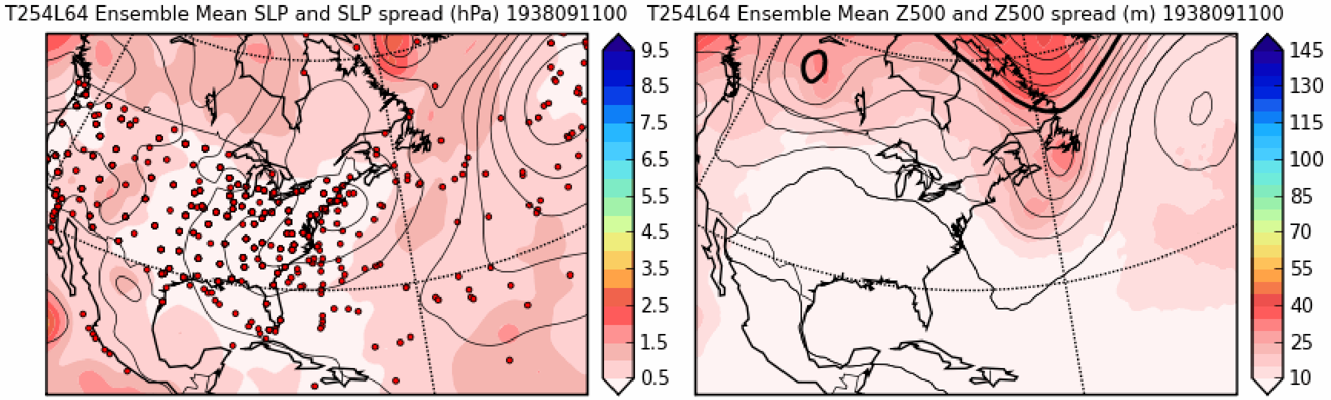
Contours- ensemble mean

Shading- blue: more uncertain, white: more certain

Higher resolution example of Surface Input Reanalyses for Climate Applications (SIRCA)

2008 NCEP GFS at ~50km resolution

September 1938 New England (movie)



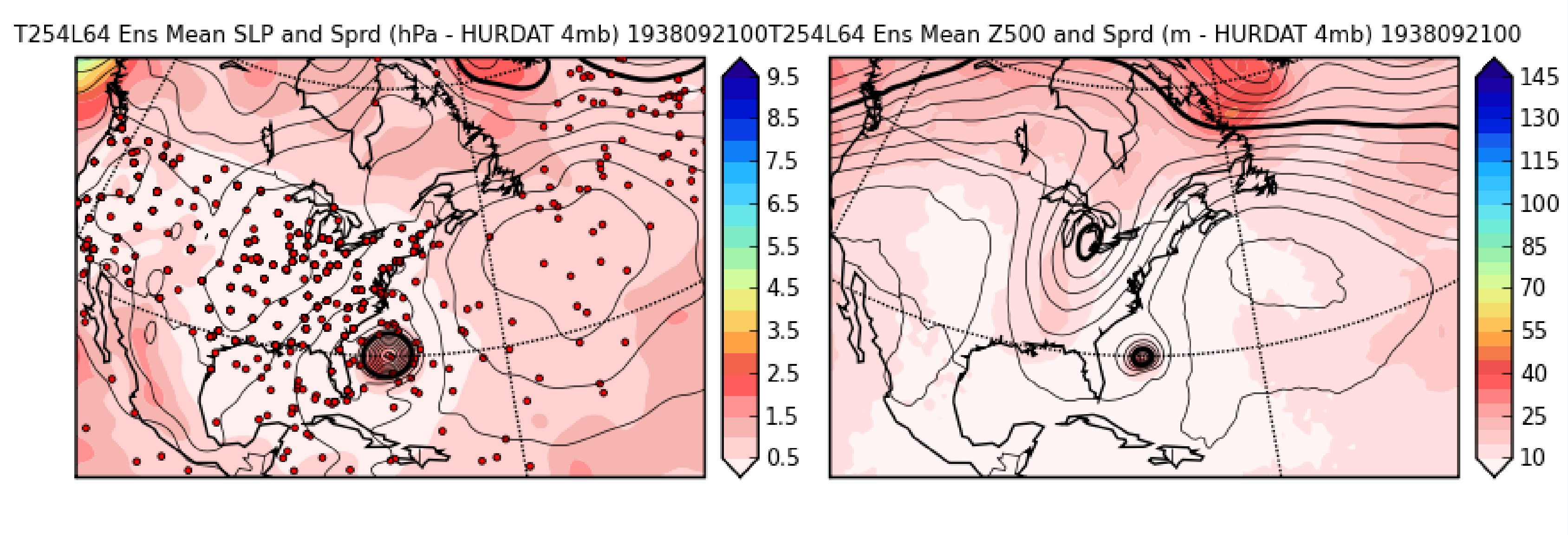
T254L64 (~50 km)

Is the extraordinary upper-level trough correct?

2008 NCEP GFS at ~50km resolution

21 September 1938 00 UTC

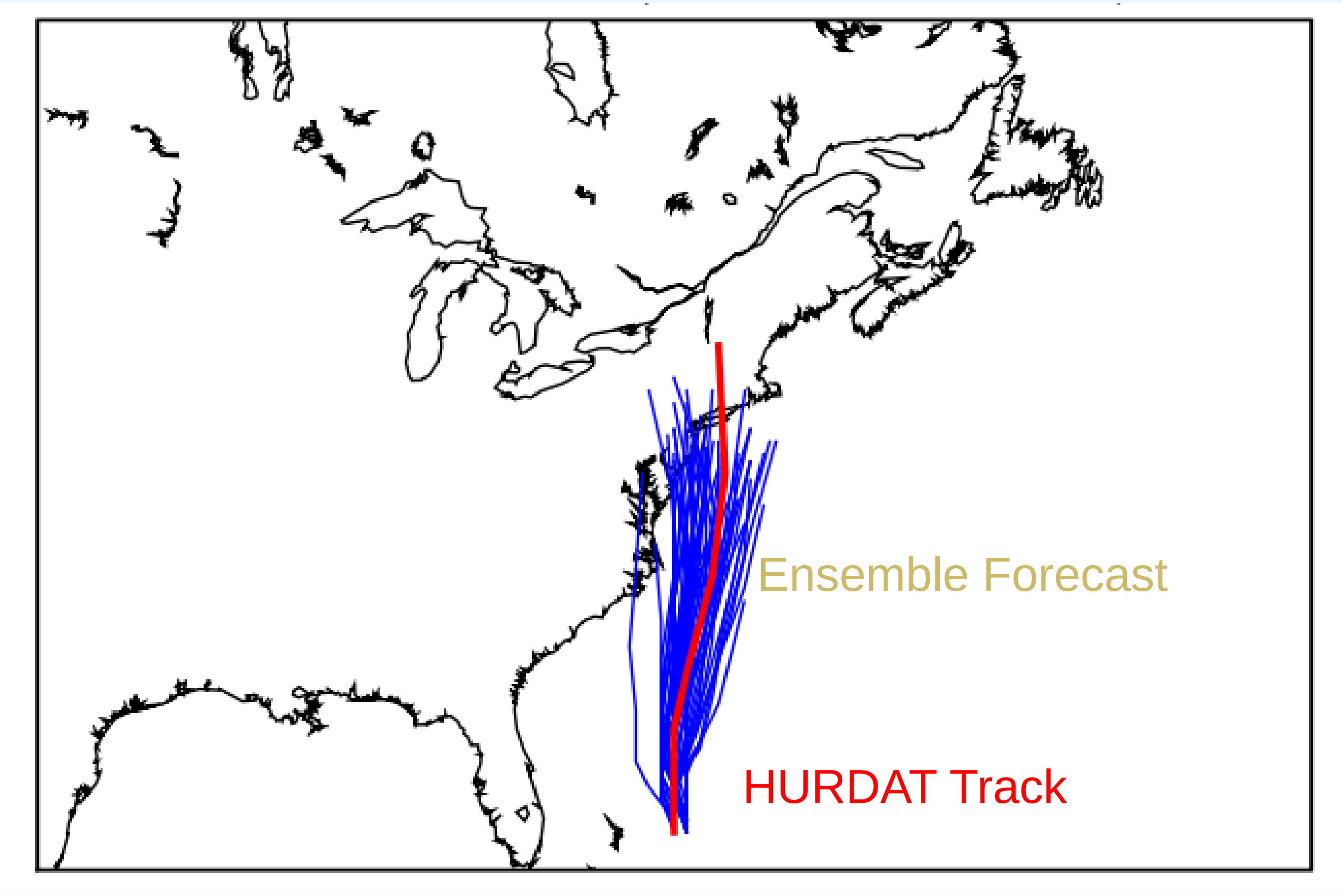
Sea Level Pressure | 500 hPa geopotential height



Is the extraordinary upper-level trough correct?

Any Skill Forecasting the Track?

36 hour forecast verifying 21 Sept 1938 18Z



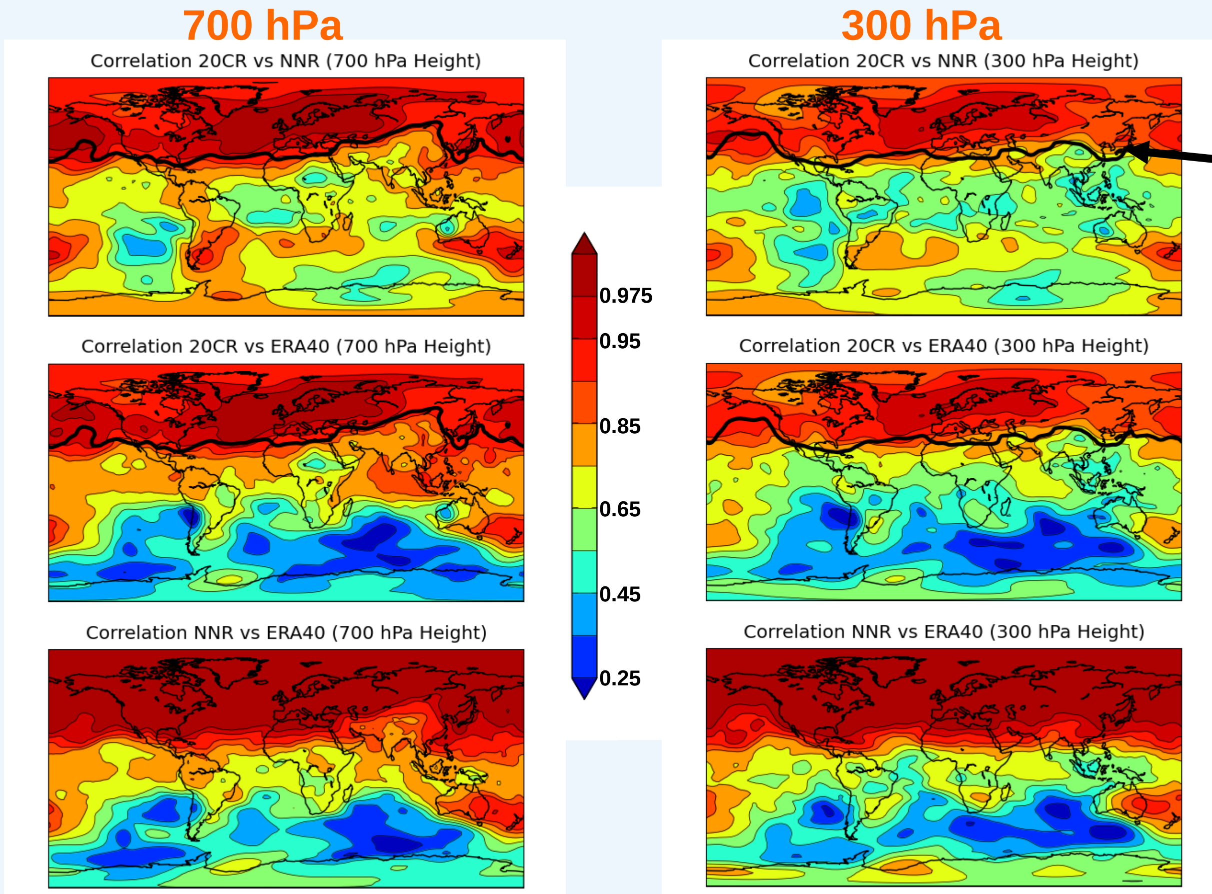
using 56 ensemble members T254L64 (about 0.5 degree)

Local Anomaly Correlation of Twentieth Century Reanalysis (20CR), NCEP-NCAR Reanalysis (NNR), and ERA40 twice-daily geopotential height anomalies (1958)

20CR vs. NNR

20CR vs. ERA40

NNR vs. ERA40



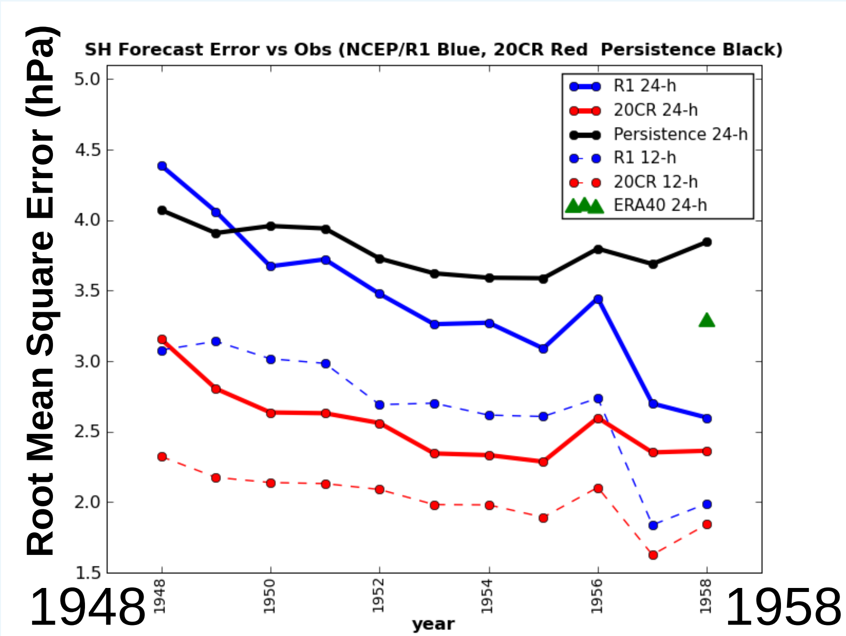
0.975 correlation between NNR and ERA40

Southern Hemisphere agreement with ERA40 is poor.

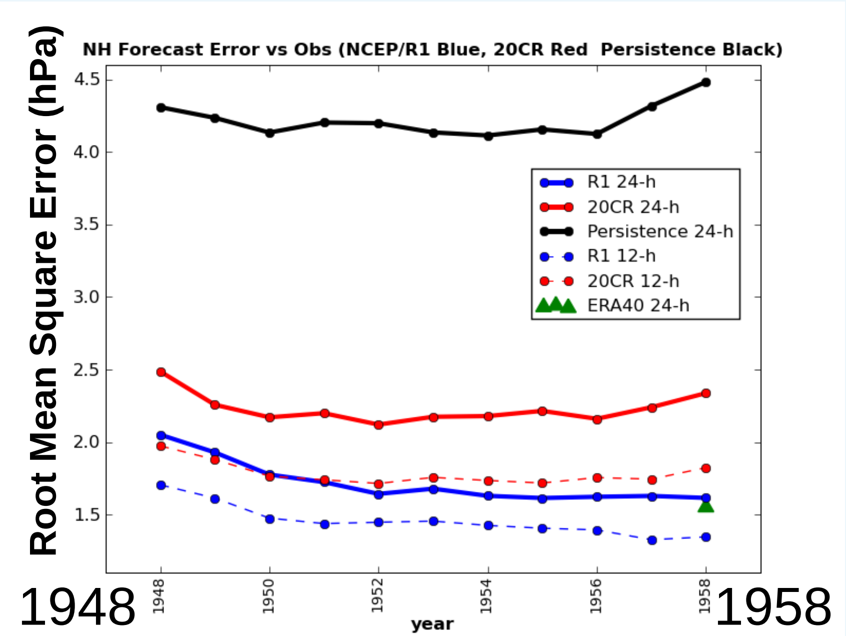
Northern Hemisphere agreement is excellent.
Southern Hemisphere agreement is moderate to poor.
Is 20CR useful in Southern Hemisphere?

12 and 24 hour Root Mean Square difference of Marine Observations and Forecasts from NCEP-NCAR Reanalysis, Twentieth Century Reanalysis, and ECMWF Reanalysis Archive 40 (1948-1958)

Southern Hemisphere



Northern Hemisphere



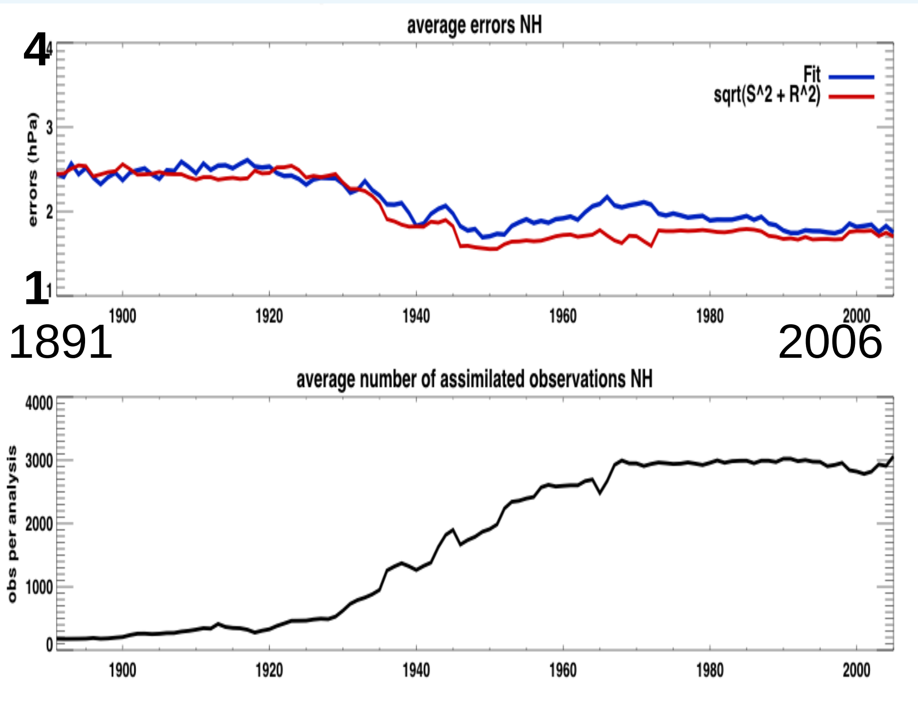
Substantially better skill for 20CR than for NCEP-NCAR Reanalysis or ERA40 in southern hemisphere despite the lack of upper-air observations.

Surface Pressure uncertainty estimate poleward of 20(S,N)

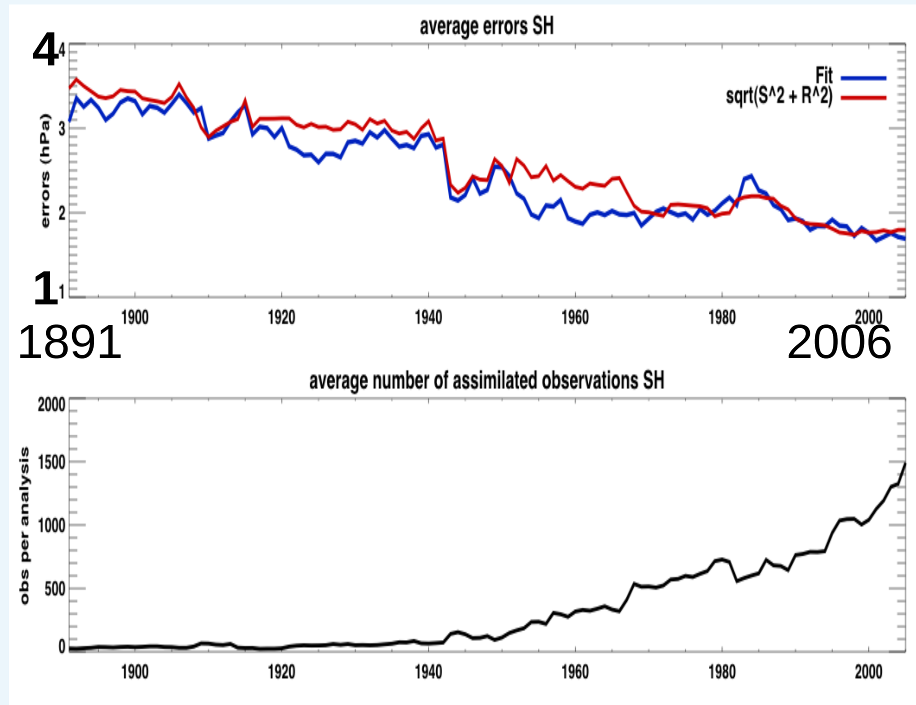
blue actual RMS difference between first guess and observations

red expected 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!

Publications using the Twentieth Century Reanalyses

Brönnimann, S., A. Stickler, T. Griesser, A. M. Fischer, A. Grant, T. Ewen, T. Zhou, M. Schraner, E. Rozanov, and T. Peter, 2009: Variability of large-scale atmospheric circulation indices for the Northern Hemisphere during the past 100 years. Meteorol. Z., 18, 365-368, DOI: 10.1127/0941-2948/2009/0392.

Giese B.S., G.P. Compo, N.C. Slowey, P.D. Sardeshmukh, J.A. Carton, S. Ray, and J.S. Whitaker, 2009:The 1918/1919 El Niño. Bull. Amer. Meteor. Soc., in press, DOI: 10.1175/2009BAMS2903.

Whitaker, J.S., G.P.Compo, and J.-N. Thepaut, 2009: A comparison of variational and ensemble-based data assimilation systems for reanalysis of sparse observations. Mon. Wea. Rev., 137, 1991-1999.

Wood, K. R., and J.E. Overland, 2009: Early 20th century Arctic warming in retrospect, Intl. J. Clim., in press, DOI: 10.1002/joc.1973.

Ensemble Filter Algorithm

$x_j^b = \langle x\rangle^b + x'^b_j$ = first guess jth ensemble member (j=1,…,56)

y^o = single observation with error variance R

First guess interpolated to observation location:
$\langle y\rangle^b = H \langle x\rangle^b$, $y'^b_j = H x'^b_j$

Form analysis ensemble $x_j^a = \langle x\rangle^a + x'^a_j$ from

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

$x'^a_j = x'^b_j + K^M (-y'^b_j)$ Note the different gain

$K = \Sigma_j x'^b_j y'^b_j (\Sigma_j y'^b_j y'^b_j + R)^{-1}$ Kalman Gain

$K^M = (1 + \{R/(\Sigma_j y'^b_j y'^b_j + R)\}^{-1/2})^{-1} K$ **Modified** Kalman Gain shrinks the ensemble

(1/(n-1)) is included in Σ_j

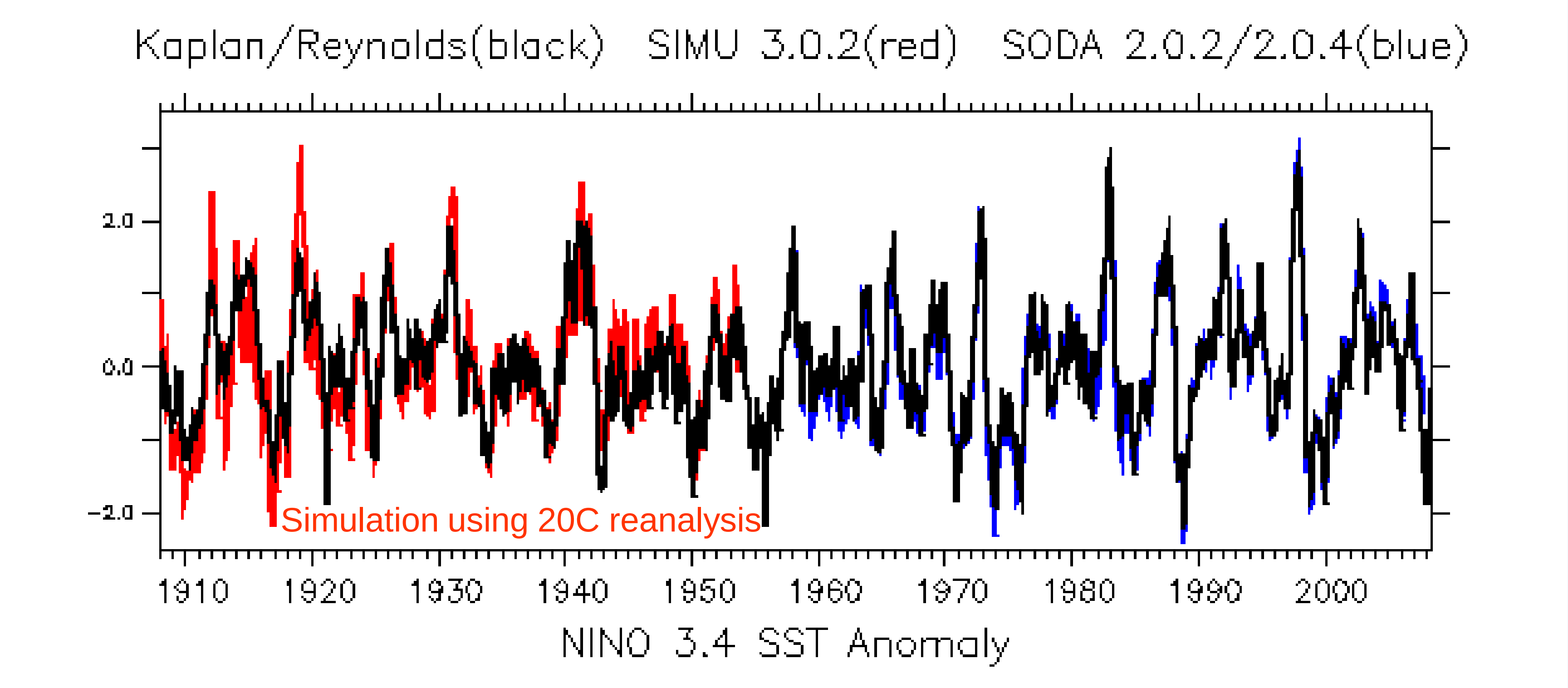
Analysis ensemble becomes first guess ensemble for next observation.

Tropical Validation

- Force global Parallel Ocean Program (POP) with daily 20th Century (1908-1956) reanalysis fields
    - 2m Air Temperature
    - 2m Specific Humidity
    - Downwelling Shortwave at Surface
    - Total cloud cover
    - 10 m Wind Speed
    - Precipitation
    - Zonal and Meridional Wind Stress

(*Giese et al. BAMS 2009)*

Nino3.4 Time series from Kaplan SST, POP Simulation, SODA Data Assimilation



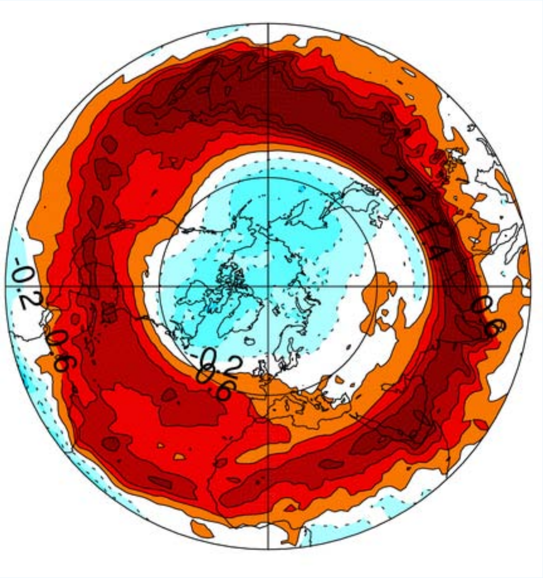
+20th Century reanalysis forcing fields with no adjustment generate realistic Nino3.4 variability in simulation

+Encouraging for Ocean and Coupled Data Assimilation.

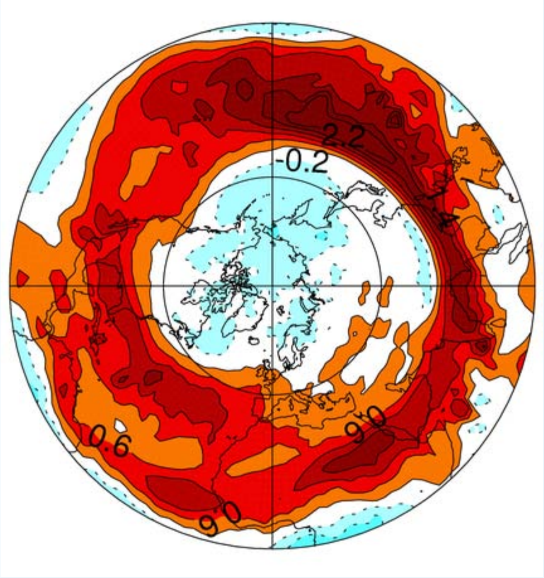
(*Giese et al. BAMS 2009*)

Storm Track

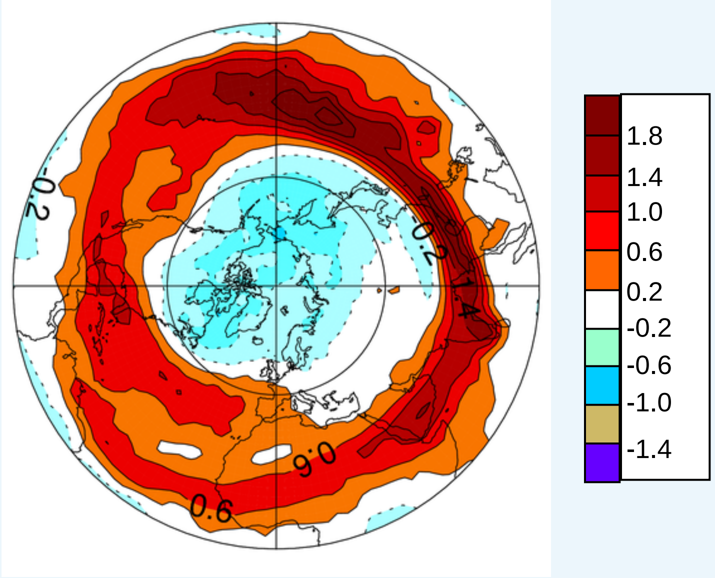
Skewness of Northern Hemisphere 250 hPa *daily* Vorticity (Dec-Feb) 1989/90-2005/06



ERA Interim (~50km)
Uses satellite data



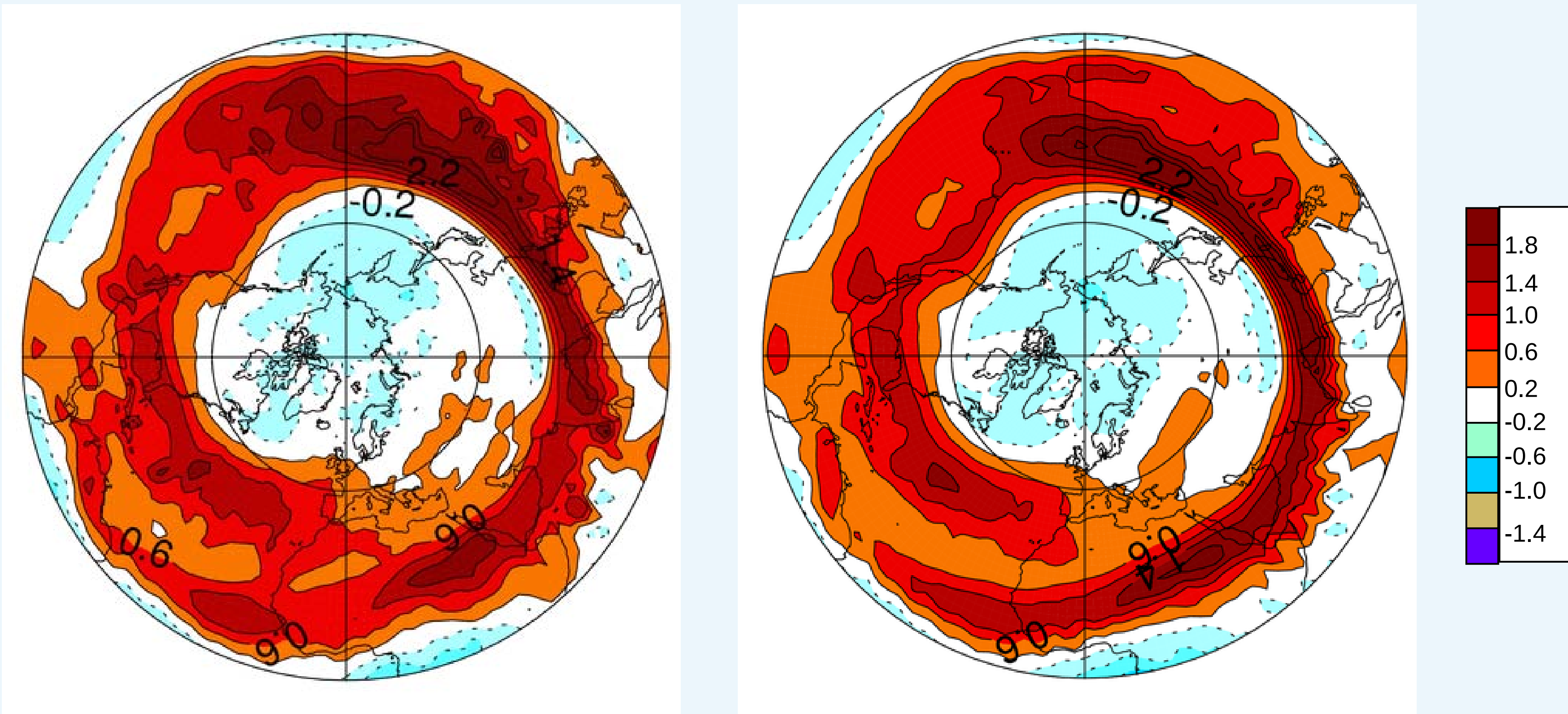
20CRv2 (~200km)
Surface pressure only



NCEP-NCAR (~200km)
Uses satellite data

Skewness of 250 hPa Vorticity from 20th Century Reanalyses

DJF 1989/90-2005/06 | DJF ***1891/92***-2005/06



Storm Track Features are remarkably robust