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Collaborative Research: Developing and Implementing Ocean-Atmosphere Reanalyses for Climate Applications (OARCA)

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As an important step toward a coupled data assimilation system for generating reanalysis fields needed to assess climate model projections, the Ocean Atmosphere Coupled Reanalysis for Climate Applications (OARCA) project assesses and improves the longest reanalyses currently available of the atmosphere and ocean: the 20th Century Reanalysis Project (20CR) and the Simple Ocean Data Assimilation with sparse observational input (SODAsi) system, respectively. In this project, we make off-line but coordinated improvements in the 20CR and SODAsi datasets, with improvements in one feeding into improvements of the other through an iterative generation of new versions. These datasets now span from the 19th to 21st centuries. We then study the extreme weather and variability from days to decades of the resulting datasets. A total of 24 publications have been produced in this project.

20CR is the first atmospheric reanalysis system that uses, together with a global numerical weather prediction (NWP) model developed at the National Centers for Environmental Prediction (NCEP) to provide background "first guess" fields, an Ensemble Kalman Filter data assimilation method. Only surface and sea level pressure observations are assimilated. This system directly yields a global analysis every 6 hours as the most likely state of the atmosphere, and also yields the uncertainty of that analysis. This uncertainty estimate is essential for making use of 20CR in evaluating climate simulations and assessing natural variations.

Toward the project goals, we extended 20CR version 2 (20CRv2) from its original 2008 end date to the year 2012. With more than 1300 citations in Web of Science and more than 1900 on Google scholar, it is clear that 20CRv2 is being widely used in climate model verification and other climate and weather applications, including discovering previously undocumented hurricanes. We completed a new version 20CRv "2c" extending back to 1851 that uses the SODAsi oceanic reanalysis ensemble, generated under this project, as its sea surface temperature boundary condition. From 20CRv2c and a further back extension to 1815, with our Texas A&M University collaborator Prof. Benjamin Giese, we have generated a new version of SODAsi (version 3, Giese et al. 2016). Figure 1 illustrates this accomplishment showing the global mean Sea Surface Temperature from SODAsi.3 back to 1815. The close correspondence between the new dataset and statistical reconstructions suggests that the OARCA iteration procedure is successful, while providing new information spanning 200 years.

We have continued to increase data availability and access to 20CRv2 and 20CRv2c via the Earth System Grid Federation and NERSC Science Gateway, via NCAR, and via NOAA Earth System Research Laboratory Physical Sciences Division (see Websites below); have enhanced the community portal website Reanalyses.org; and continued to develop the Web-based Reanalysis Intercomparison Tools (WRIT, Smith et al., 2014, https://reanalyses.org/atmosphere/web-based-reanalysis-intercomparison-tools-writ). In WRIT, users can compare reanalysis and reconstruction datasets in several ways, such as differencing user selected time ranges and plotting the results as, e.g., maps, cross-sections, and time series. Users can also plot trajectories from different reanalyses. In terms of data accesses, as one set of examples, in 2016, from the NERSC Science

Gateway, there were 3762 downloads per week from 385 unique IP addresses, and from the NERSC Tape Science Gateway, there were 4691 downloads per week from 119 unique IP addresses. In 2017, with 11 only weeks of monitoring data available because of a logging issue, there were 10 times more downloads than in 2016, with 55,272 downloads per week from the Science Gateway by 1033 unique IP addresses and 2008 downloads per week from the Tape Science Gateway by 66 unique IP addresses. As another example, spanning the period 2015 to 2017 from the NCAR Research Data Archive, more than 350 unique users accessed more than 70TB of 20CR data. From the plotting tools, such as the WRIT, more than 241,000 figures were generated in 2017 alone. These statistics suggest that the 20CR version 2c data are being widely used in the field for a variety of purposes.

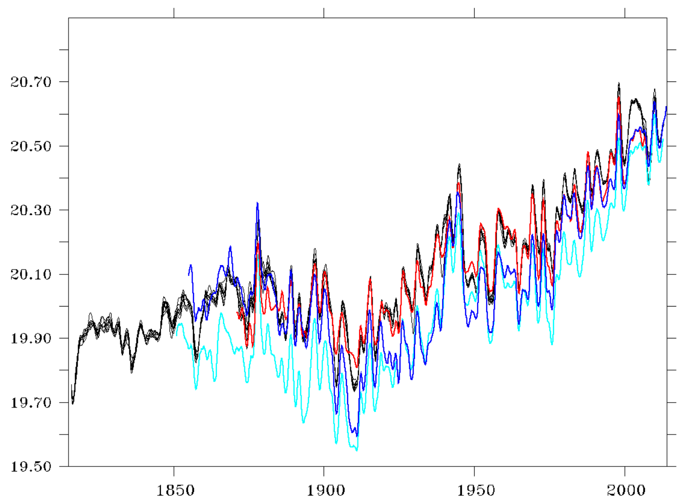

Figure 1. Global (60N-60S) sea surface temperature estimated from the 8 member ensemble of our new SODAsi.3 (black curves) generated under this project, and from HadISST 1.1 (red curve), ERSSTv4 (dark blue curve) and COBE v2 (cyan curve). The results illustrate the dramatic effect of the Tambora eruption in 1815, as well as the overall rise in global ocean temperatures since the 19th century (Giese et al. 2016).

With NCAR, we have made the observations in 20CRv2, the International Surface Pressure Databank (ISPD) version 2, including 20CRv2 feedback and quality control, publicly available at http://dx.doi.org/10.5065/D6SQ8XDW. We have also made the observations in 20CRv2c, ISPD version 3.2.9, publicly available at http://dx.doi.org/10.5065/D6D50K29.

We have demonstrated that global atmospheric reanalysis back to 1815 is now possible. We have shown that more observations are needed to improve the quality of reanalysis fields for the 19th and early 20th centuries. With these findings, we have encouraged data rescue partners under ACRE (www.met-acre.org), such as the UK Met Office Hadley Centre, Oldweather.org, and 61 other organizations (https://reanalyses.org/observations/international-surface-pressure-databank-contributing-organizations) to improve the quantity of digitally available surface meteorological observations, resulting in our production of ISPD versions 3 and 4. ISPDv3.2.6 has been used by the European Centre for Medium Range Weather Forecasts to generate a global atmospheric reanalysis entitled ERA-20C from 1900 onwards using their advanced 4D-Var system (http://apps.ecmwf.int/datasets/) and a coupled ocean-atmosphere global reanalysis entitled CERA-20C, also from 1900 onwards. These datasets were released in late 2014 and mid-2016 respectively. ISPDv3.2.9, which includes further additional contributions, has been used to generate 20CRv2c. We released 20CRv2c in 2016, spanning 1851 to 2012, with an experimental extension to 2014.

In a significant paper (Compo et al., 2013), we have shown that given barometric pressure, sea surface temperature, sea-ice concentration, and carbon dioxide, volcanic and solar variations, we were able to use the 20CR to infer the air temperatures over land across the globe back to 1900. These independently derived temperatures agreed both annually and centennially with those found by weather stations. The agreement confirms that deficiencies in land-based station temperatures have been corrected adequately. It also affirms that the conclusions based on large-area averages of land temperatures are robust, i.e., the climate can be shown to be warming over the past century, even without using land thermometers.

With our international collaborators, using 20CRv2 and 20CRv2c, we have made extensive studies of the decadal and interannual variability of Arctic land and ocean temperatures, the tropical Pacific Walker Circulation, the Hadley Circulation, historical ozone, extratropical storms, and mid-latitude extreme winds (see publications list below).

We have also conducted experiments using the 20CR system to reconstruct the global circulation following the eruption of Tambora in April 1815. These experiments suggest that the unusual weather of the "year without a summer" of 1816 in Europe can be attributed to the volcanic aerosols and provides an important check on climate model's abilities to correctly respond to a significant forcing (Brohan et al., 2016).

We have continued to improve the 20CR system and are now ready to produce 20CR version 3 at NERSC on the Cori Knight's Landing System. Several improvements have been made and are illustrated below. First, we have improved the ISPD (version 4.6) both by adding observations and better quality controlling the observations. The increased number of observations shown in **Figure 2** (note the log-scale) will allow better representation of the climate and of weather around the world. As an example, in the year 1850, 20CRv3 will have more than 99 000 observations to assimilate while 20CRv2c had close to only 59 000 observations.

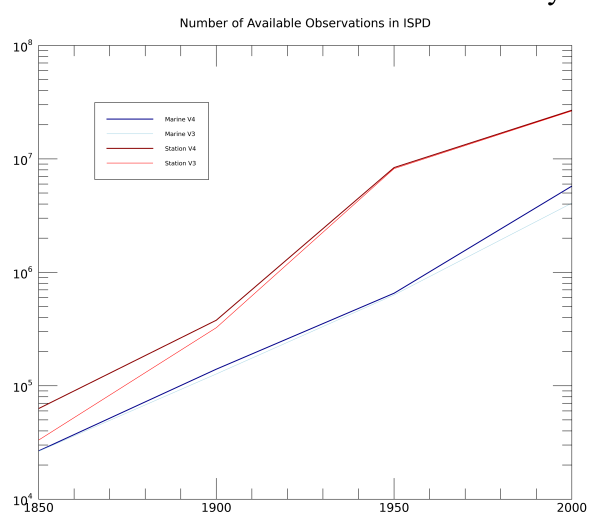

Figure 2. Number of observations per year in the International Surface Pressure Databank (ISPD) assembled at NERSC. Observations from ships and other marine platforms (blue curves) and from stations (red curves) have increased substantially in the new version 4.6 to be used in 20CR version 3 (thick curves) compared to the ISPD version 3.2.6 (thin curves) used in 20CRv2c.

Second, we have continued to develop the higher-resolution 20CR version 3 assimilation system, including implementing the new covariance inflation algorithm of Whitaker and Hamill (2012, Mon. Wea. Rev.). The advancements in the Ensemble Kalman Filter algorithm, combined with a higher resolution forecast model, will further improve the use of the enhanced observational network of ISPDv4.6, particularly during extreme weather events, and will generate better reanalysis fields (see, e.g., Project Description Figs. 2, 3, and 4).

We have investigated the combined effect of these improvements on the representation of extremes, such as the 1992 Hurricane Andrew (**Figure 3**), compared to full-input reanalyses that use all available satellite, conventional, and surface observations, and also compared to another surface-input based reanalyses: CERA-20C that extends back to 1901. No other reanalysis contains even a trace of Andrew's circulation that is captured in the 20CRv3 system (lower right panel).

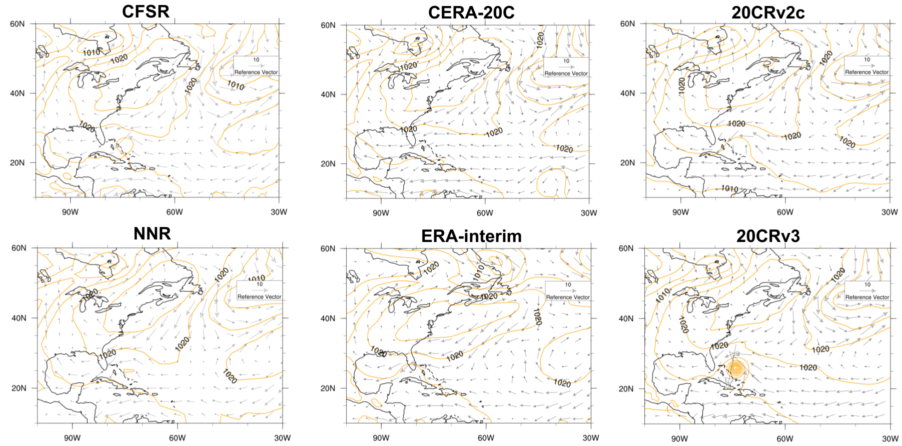

Figure 3. Synoptic maps for 12UTC 23 August 1992 during the track of Hurricane Andrew from 6 reanalyses: CFSR, CERA-20C, 20CRv2c, NCEP-NCAR reanalysis (NNR), ERA-Interim, and the new 20CRv3. Contours: sea level pressure in hPa (5 hPa interval). Vectors: 10m wind fields (m/s).

Additionally, we have incorporated a new representation of system errors using the "relaxation to prior" covariance inflation algorithm of Whitaker and Hamill (2012). This provides for a closer relationship between actual analysis error and the expected error deduced from the ensemble standard deviation (or spread). It also ameliorates 20CRv2's Arctic underconfidence, where the ensemble spread was larger than the climatological standard deviation, as shown in **Figure 4** for 1918. The overall "confidence" (= 1 minus the ratio of the ensemble spread to the climatological standard deviation) of 20CRv3 in our development is closer to CERA-20C than to 20CRv2c or v2 in most regions of the world. 20CRv3 will eliminate the underconfidence of 20CRv2 and v2c in the Arctic, a high-priority region for DOE/BER to understand climate, weather, and extremes. More broadly, the result of Figure 4 suggests the 20CRv3 will greatly expand the time-range of reliable estimates of historical weather and climate variability for comparison to climate model simulations.

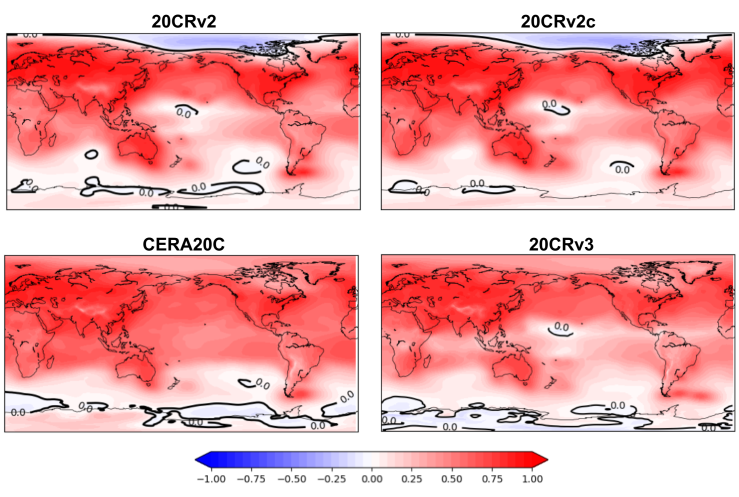

Figure 4. Maps of sea level pressure "confidence" from four ensemble-based reanalyses, averaged over the year 1918. Confidence is defined as 1 minus (ensemble spread)/ (climatological spread), where "ensemble spread" is the square root of time-averaged SLP analysis ensemble variance, and "climatological spread" is the temporal standard deviation of the 20CRv2c SLP analysis ensemble mean, over 1981-2010. A confidence value of zero (black contours) implies that the ensemble spread is equivalent to the climatological spread. Positive confidence (red) shows where the ensemble provides more information than climatology; negative confidence (blue) represents areas where the ensemble spread is larger than climatology. The higher the confidence, the narrower the ensemble spread. Except during periods when interannual variability from, e.g., ENSO, leads to larger spread, there should not be any blue.

We have contributed results from this project to the following 24 related publications:

Allan, R., P. Brohan, G.P. Compo, R. Stone, J. Luterbacher, and S. Brönnimann, 2011: The International Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative. Bull. Amer. Met. Soc., 92, 1421-1425. doi: 10.1175/2011BAMS3218.1.

Brönnimann, S., G.P. Compo, R. Spadin, R. Allan, and W. Adam, 2011: Early ship-based upper-air data and comparison with the Twentieth Century Reanalysis. Clim. Past, 7, 265-276, doi:10.5194/cp-7-265-2011.

Dee, D., P. Berrisford, M. G. Bosilovich, M. Chelliah , G. Compo, A. Ebita, P. D. Jones, S. Kobayashi, A. Kumar, G. Rutledge, S. Saha , H. Sato, A. Simmons, C. Smith, R. Vose, 2011: The use of reanalysis data for monitoring the state of the climate [in State of the Climate 2010]. Bull. Amer. Met. Soc., 92, S34-S35, doi: 10.1175/1520-0477-92.6.S1.

Brönnimann, S., A.N. Grant, G.P. Compo, T. Ewen, T. Griesser, A.M. Fischer, M. Schraner, and A. Stickler, 2012: A multi-data set comparison of the vertical structure of temperature variability and change over the Arctic during the past 100 years. Cli. Dyn., 39, 1577-1598, doi:10.1007/s00382-012-1291-6.

Brönnimann, S., O. Martius, H. von Waldow, C. Welker, J. Luterbacher, G.P. Compo, P.D. Sardeshmukh, and T. Usbeck, 2012: Extreme winds at northern mid-latitudes since 1871. Meteorol. Zeit., 21, 13-27, doi: 10.1127/0941-2948/2012/0337.

Brönnimann, S., and G.P. Compo, 2012: Ozone highs and associated flow features in the first half of the twentieth century in different data sets. Meteorol. Zeit., 21, 49-59, doi:10.1127/0941-2948/2012/0284 .

Wang, X.L., Y. Feng, G.P. Compo, V.R. Swail, F.W. Zwiers, R.J. Allan, and P.D. Sardeshmukh, 2013: Trends and low frequency variability of extra-tropical cyclone activity in the ensemble of Twentieth Century Reanalysis. Cli. Dyn., 40, 2775-2800, doi:10.1007/s00382-012-1450-9.

Compo, G.P., P.D. Sardeshmukh, J.S. Whitaker, P. Brohan, P.D. Jones, and C. McColl, 2013: Independent confirmation of global land warming without the use of station temperatures. Geophys. Res. Letters, 40, 3170-3174, doi:10.1002/grl.50425.

Wang, X.L., Y. Feng, G.P. Compo, F.W. Zwiers, R.J. Allan, V.R. Swail, and P.D. Sardeshmukh, 2014: Is the storminess in the Twentieth Century Reanalysis really inconsistent with observations? A reply to the comment by Krueger et al. (2013b). Cli. Dyn., 42, 1113-1125, doi:10.1007/s00382-013-1828-3.

Sandeep, S., F. Stordal, P.D. Sardeshmukh, and G.P. Compo, 2014: Pacific Walker Circulation variability in coupled and uncoupled climate models. Cli. Dyn., 43, 103-117, doi:10.1007/s00382-014-2135-3.

Smith, C.A., G.P. Compo, and D.K. Hooper, 2014: Web-based Reanalysis Intercomparison Tools (WRIT) for analysis and comparison of reanalyses and other datasets. Bull. Amer. Met. Soc., 95, 1671-1678, doi:10.1175/BAMS-D-13-00192.1.

Müller, W.A., D. Matei, M. Bersch, J.H. Jungclaus, H. Haak, K. Lohmann, G.P. Compo, P.D. Sardeshmukh, and J. Marotzke, 2015: A twentieth-century reanalysis forced ocean model to reconstruct the North Atlantic climate variation during the 1920s. Cli. Dyn., 44, 1935-1955, doi:10.1007/s00382-014-2267-5.

Stucki, P., S. Brönnimann, O. Martius, C. Welker, R. Rickli, S. Dierer, D. N. Bresch, G. P. Compo, P. D. Sardeshmukh, 2015: Dynamical downscaling and loss modeling for the reconstruction of historical weather extremes and their impacts - A severe foehn storm in 1925. Bull. Amer. Met. Soc., 96, 1233-1241, doi:10.1175/BAMS-D-14-00041.1.

Cram, T.A., G. P. Compo, X. Yin, R. J. Allan, C. McColl, R. S. Vose, J.S. Whitaker, N. Matsui, L. Ashcroft, R. Auchmann, P. Bessemoulin, T. Brandsma, P. Brohan, M. Brunet, J. Comeaux, R. Crouthamel, B. E. Gleason, Jr., P. Y. Groisman, H. Hersbach, P. D. Jones, T. Jonsson, S. Jourdain, G. Kelly, K. R. Knapp, A. Kruger, H. Kubota, G. Lentini, A. Lorrey, N. Lott, S. J. Lubker, J. Luterbacher, G. J. Marshall, M. Maugeri, C. J. Mock, H. Y. Mok, O. Nordli, M. J. Rodwell, T. F. Ross, D. Schuster, L. Srnec, M. A. Valente, Z. Vizi, X. L. Wang, N. Westcott, J. S. Woollen, S. J. Worley, 2015: The International Surface Pressure Databank version 2. Geoscience Data J., 2, 31-46. doi:10.1002/gdj3.25.

Stickler, A., S. Storz, R. Wartenburger, H. Hersbach, G.P. Compo, P. Poli, D. Dee, and S. Broennimann, 2015: Upper-air observations from the German Atlantic Expedition (1925-27) and comparison with the Twentieth Century and ERA-20C reanalyses. Meteorol. Zeit., 24, 525-544, doi:10.1127/metz/2015/0683.

Brugnara, Y., R. Auchmann, S. Brönnimann, R. J. Allan,I. Auer, M. Barriendos, H. Bergström, J. Bhend, R. Brázdil, G. P. Compo, R. C. Cornes, F. Dominguez-Castro, A. F. V. van Engelen,J. Filipiak, J. Holopainen, S. Jourdain, M. Kunz, M., J. Luterbacher, M. Maugeri, L. Mercalli, A. Moberg, C. J. Mock, G. Pichard,L. Řezníčková , G. van der Schrier, V. Slonosky, Z. Ustrnul, M. A. Valente, A. Wypych, and X. Yin, 2015: A collection of sub-daily pressure and temperature observations for the early instrumental period with a focus on the "year without a summer" 1816, Clim. Past, 11, 1027-1047, doi:10.5194/cp-11-1027-2015.

Sardeshmukh, P.D., G.P. Compo, and C. Penland, 2015: Need for caution in interpreting extreme weather statistics. J. Climate, 28, 9166-9187, doi:10.1175/JCLI-D-15-0020.1.

Brönnimann, S., A. M. Fischer, E. Rozanov, P. Poli, G. P. Compo, P. D. Sardeshmukh, 2015: Southward shift of the Northern tropical belt from 1945 to 1980. Nature Geoscience, 8, 969-974, doi: 10.1038/NGEO2568.

Turney, C.S.M., R.T. Jones, D. Lister, P. Jones, A.N. Williams, A. Hogg, Z. A. Thomas, G.P. Compo, X. Yin, C.J. Fogwill, 2016: Anomalous mid-twentieth century atmospheric circulation change over the South Atlantic compared to the last 6000 years. Env. Res. Lett., 11, 064009, doi:10.1088/1748-9326/11/6/064009.

Brohan, P., Compo, G. P., Brönnimann, S., Allan, R. J., Auchmann, R., Brugnara, Y., Sardeshmukh, P. D., and Whitaker, J. S., 2016: The 1816 ‘year without a summer’ in an atmospheric reanalysis, Clim. Past Discuss., doi:10.5194/cp-2016-78.

Giese, B., H. Seidel, G.P. Compo, and P.D. Sardeshmukh, 2016: An ensemble of ocean reanalyses for 1815-2013 with sparse observational input. J. Geophys. Res-Oceans, 121, 6891-6910, doi:10.1002/2016JC012079.

Wegmann, M., S. Brönnimann, and G.P. Compo, 2017: Tropospheric circulation during the early twentieth century Arctic warming. Cli. Dyn., 48, 2405-2418, doi:10.1007/s00382-016-3212-6.

Fujiwara, M., Wright, J. S., Manney, G. L., Gray, L. J., Anstey, J., Birner, T., Davis, S., Gerber, E. P., Harvey, V. L., Hegglin, M. I., Homeyer, C. R., Knox, J. A., Krüger, K., Lambert, A., Long, C. S., Martineau, P., Molod, A., Monge-Sanz, B. M., Santee, M. L., Tegtmeier, S., Chabrillat, S., Tan, D. G. H., Jackson, D. R., Polavarapu, S., Compo, G. P., Dragani, R., Ebisuzaki, W., Harada, Y., Kobayashi, C., McCarty, W., Onogi, K., Pawson, S., Simmons, A., Wargan, K., Whitaker, J. S., and Zou, C.-Z., 2017: Introduction to the SPARC Reanalysis Intercomparison Project (S-RIP) and overview of the reanalysis systems, Atmos. Chem. Phys., 17, 1417-1452, https://doi.org/10.5194/acp-17-1417-2017.

Rohrer, M., S. Brönnimann, O. Martius, C.C. Raible, M. Wild, and G.P. Compo, 2018: Representation of extratropical cyclones, blocking anticyclones, and alpine circulation types in multiple reanalyses and model simulations. J. Climate, 31, 3009-3031, doi:10.1175/JCLI-D-17-0350.1.

Under this project, the PI has received support, and we have mentored and provided support to postdoctoral scholar Laura Slivinski, researchers Antonietta Capotondi, Chesley McColl, Aaron Wang, Lawrence Spencer, computational support persons Cathy Smith, Barry McInnes, and Don Hopper, and also to high school student intern Elyssa Hofgard.

The high school student intern Elyssa Hofgard has presented the following posters, winning several awards:

- E. Hofgard, 2016: A Historical Analysis of the Current California Drought, poster presentation, Boulder Valley Regional Science Fair, Boulder, CO, 17 February 2016.
    - 1st place in the Senior Division for Earth and Space Sciences
    - American Meteorological Society Denver/Boulder Chapter for Outstanding Achievement

- E. Hofgard, 2016: A Historical Analysis of the Current California Drought, invited poster presentation, Colorado Science and Engineering Fair, Colorado State University, Fort Collins, CO, 7-9 April 2016.
    - 3rd place in the Senior Division for Earth and Space Sciences
    - American Institute of Professional Geologists Certificate of Excellence in the Geosciences
    - American Meteorological Society Denver/Boulder Chapter Award for Excellence in Atmospheric Science Research
    - Colorado Geographic Alliance Application of Geography Award
    - Colorado College merit scholarship
    - 4 yr engineering scholarship to University of Colorado at Boulder
    - American Meteorological Society National Chapter Outstanding Achievement in Atmospheric Sciences Award
    - National Oceanic and Atmospheric Administration Taking the Pulse of the Planet Award

DATASETS AND WEBSITES DEVELOPED:

Web-based Reanalysis Intercomparison Tools: https://reanalyses.org/atmosphere/writ
Advancing Reanalysis: http://reanalyses.org
International Surface Pressure Databank version 3.2.9: http://rda.ucar.edu/datasets/ds132.1
20th Century Reanalysis version 2c all 56 members available from
DOE NERSC Science Gateway: portal.nersc.gov
DOE NERSC Tape Science Gateway:
portal.nersc.gov/archive/home/projects/incite11/www/20C_Reanalysis_version_2c/
20th Century Reanalysis version 2c ensemble mean and standard deviation available from

NCAR: https://rda.ucar.edu/datasets/ds131.2/
NOAA: go.usa.gov/XTd

AWARDS
Other awards related to this project

Award Title : Great Long-Term Datasets
Sponsor : Wired magazine
Description : 20th Century Reanalysis Project described by Wired magazine as one of ten great long-term datasets in all of science. http://www.wired.com/wiredscience/2011/10/long-term-datasets/?pid=2267&pageid=81090&viewall=true

Award Title : High Performance Computing Innovation Excellence Award
Sponsor : International Data Corporation
Description : Awarded to Gilbert P. Compo and National Energy Research Scientific Computing Center with citation ' International study has enabled much more detailed and longer (100 years) record of past weather, to improve climate studies. '
Date : 2011