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Report on the SCAR/CliC/ICPM Workshop on High Latitude Reanalyses, British Antarctic Survey, 10-12 April 2006

The workshop was held at the Headquarters of the British Antarctic Survey, with the first two days being taken up with presentations and discussions. On the 12 April the participants visited ECMWF for discussions with the scientists there on the ECMWF reanalyses and IPY matters.

Attendees at the meeting were David Bromwich and Ryan Fogt (Byrd Polar Research Center, Ohio State University), Roy Jenne (NCAR), John Walsh (University of Alaska), Kevin Hodges (University of Reading), Phil Arkin (University of Maryland), Sakari Uppala (ECMWF), Mark Serreze (University of Colorado), Dave Carlson (IPY Office), Christophe Genthon (CNRS-LGGE, Grenoble), Lennart Bengtsson (University of Reading) and John Turner, William Connolley, Tom Bracegirdle, Zhaomin Wang, Helen Campbell, Todd Arbetter, Gareth Marshall, Steve Harangozo, John King (all BAS, Cambridge).

The meeting began with two assessments of the NCEP/NCAR and ECMWF reanalysis data sets by respectively Phil Arkin and Sakari Uppala. Reanalyses in the USA have a long history (Table 1 lists the analyses carried out), with several publications appearing in the 1980s. The NASA Data Assimilation Office carried out reanalyses from early 1985 to 1993, but these had modest impact as the NCEP/NCAR reanalysis came out soon after. The NCEP/NCAR reanalysis (NCEP 1) covered the period 1948 to date. The NCEP/DOE reanalysis (NCEP 2) starting in 1979 was produced to correct some errors in NCEP 1, although not all errors were corrected. The products have been widely disseminated and have had a huge impact. The North American Regional Analysis is based on the operational regional Eta model with a resolution of 32 km. This covers the period 1979-2003, and is currently being disseminated. The Climate Data Assimilation System (CDAS) reanalysis is ongoing and is an extension in real time of the NCEP/NCAR global reanalysis. These fields are still useful, although they are coarse and derived from outdated models. The current operational analysis is beginning to be used for many purposes. The regional Climate Data Assimilation System (R-CDAS) is an extension in real time of the North American Regional Reanalysis. It was noted that while all of these reanalyses were extremely valuable, they all had/have serious flaws. In addition, there is no overall national coordination/oversight and no coherent NOAA programme. There was a workshop on Ongoing Analysis of the Climate System held over 18-20 August 2003 in Boulder, Colorado. It concluded that given the continuing improvement in climate observations and the need for long time series, reprocessing is an essential element of every climate observing system. The workshop concluded that the U.S. must establish a national program for Ongoing Analysis of the Climate System to provide a retrospective and ongoing physically consistent synthesis of Earth observations in order to:

- Guide the design and operation of observing systems
- Produce and sustain the growing climate record
- Reconcile disparate climate observations and characterize analysis uncertainty
- Establish initial conditions for climate prediction
- Validate prediction and projection models on all time scales

- Provide long time series of global and regional climatic analyses for all types of prediction and projection verification

The Modern Era Reanalysis for Research and Applications (MERRA) system was described. This project supports NASA's Earth-Sun science interests by:

- utilizing the NASA global data assimilation system to produce long-term (1979-present) synthesis that places the current suite of research satellite Earth observations in a climate data context
- providing the science and applications communities with state-of-the-art global analyses, with emphasis on improved estimates of the hydrological cycle on a broad range of weather and climate time scales

The MERRA system will cover the satellite era of 1979 to the present, have a half degree resolution, have 72 levels to 1 hPa and use the NASA GCM. The production run will begin in July 2006.

Sakari Uppala described the ECMWF reanalysis systems. These have been ERA-15 covering 1979-93 and ERA-40 covering 1957-2002. ERA-15 had 31 levels, while ERA-40 had 60 levels. In addition ERA-40 made more use of satellite radiances, more comprehensive use of conventional data and had improved SST and sea ice data. Extensive information was presented on the data used. For example, in 1958 there were on average 1608 radiosonde soundings, while in 2001 this had dropped to 1189. It was pointed out that there was little snow cover data in the early part of the period. It was also noted that the radiosonde time series from some stations show jumps as a result of changes of radiosonde types. This pointed to a need to homogenize radiosonde biases in time. Extensive use has been made of the IGRA (Integrated Global Radiosonde Archive) data base of radiosonde data.

The greatest number of users of ERA-40 were from the USA, and then the UK. An atlas of ERA-40 products covering the period 1979-2001 is available at:

http://www.ecmwf.int/research/era/ERA-40_Atlas/docs/index.html

The ERA-40 reanalysis is described in Uppala, S.M., et al.. 2005: The ERA-40 re-analysis. Quart. J. R. Meteorol. Soc., 131, 2961-3012.doi:10.1256/qj.04.176

The ERA-Interim reanalysis covering 1989 to the present is to continue as with the CDAS reanalysis. It will make much better use of observations than ERA-40.

An ERA-70 reanalysis (possibly starting in 1940) is under consideration to start in 2010. Important components could be recovery of observations, variational technique aimed for reanalysis, comprehensive adaptive bias handling, handling of model bias and improved SST and ICE dataset.

Dave Bromwich and Ryan Fogt discussed significant differences in the mean atmospheric circulation and hydrologic cycle in the high southern latitudes of the ERA-40, NCEP, and the Japanese JRA-25 reanalyses. They had found that during the modern satellite era there were large differences in the various reanalyses. Two key regions were noted - the interior of the Antarctic continent and in the Southern Ocean off the East Antarctic coast. The NCEP2 reanalysis has a persistent low bias at 500 hPa until 1998 with the differences being most marked in summer and winter. JRA-25 displays a downward trend in 500 hPa heights prior to 1995, after which all three reanalyses align. The reasons for the changes in the reanalyses are currently not known.

The large increase in data from satellite soundings starting at 1979 creates a discontinuity in the total Antarctic precipitation fields resulting in a jump in ERA-40 total precipitation. The precipitation errors are generally confined to the Antarctic continent, with the largest values over the highest elevations. The precipitation jump is caused by ERA-40 adjusting to the longwave (Rossby wave) pattern in the Southern Ocean.

In addition, ERA-40 and NCEP2 produce accumulation trends of opposite sign from 1979-2001. The changes appear in the eddy term of the meridional moisture flux, particularly in the v-component of the wind. Comparing the trends with available observations does not provide a clear answer as to which is more accurate. However, the suggestion is that NCEP2 provides a better representation over the Southern Ocean while ERA-40 does better over Antarctica

Mark Serreze dealt with the Arctic heat budget and water cycle in the ERA-40 and NCEP reanalyses. The various terms in the heat budget and their trends were examined via reanalysis data. There are large differences in the ERA-40 and NCEP 2 m temperatures over the period 1982-99. A comparison with data from the North Pole Drifting Stations suggests that the ERA-40 temperatures are considerably warmer than the in-situ data.

Roy Jenne considered the available polar observations in the pre-satellite era. There are global radiosonde ascents and pilot balloon data from 1940 but it may not be possible to get these early reports. Antarctic radiosonde ascents only started in 1957/8. Some pilot balloon launches took place from about 1920 but these mostly started in the 1940s. Some early satellite sounder data are available over 1969-72 and could fill this gap.

Some surface pressure measurements are available from Russian Arctic ice islands for 1951-54 to 1991. These were used in the reanalyses.

The University of Wisconsin has a project to derive cloud track winds for the polar regions from 4 km resolution AVHRR data. These would start in November 1978.

Daily Southern Hemisphere charts were prepared in South Africa for 1950-57 (surface) and 500 hPa heights for 1957-58. Many of these were published in NOTOS. For a future reanalysis exercise there may be value in digitizing these and using the data in the same way as Australian pseudo observations (PAOBS). A general point noted was that care needs to be exercised in merging observations as errors can be re-introduced.

Dave Bromwich gave a talk prepared by Gill Compo on the feasibility of a 100 year reanalysis using only surface pressure data. The goal would be to produce 6 hourly fields extending back to the start of the Twentieth Century. The Northern Hemisphere fields are expected to be more accurate than those for the south. The plan is to carry out a proof of concept for 1938-48, initially testing 1947 and 1944. Simulated 5 year periods are being considered by degrading the 2001 observational data base. The number of observations was reduced from 150,000 per analysis to 2,000. The conclusions are that the 100 year NH reanalysis is feasible. Even upper-tropospheric errors would be similar to current 2-3 day forecast errors. In the Southern Hemisphere, the reanalysis performs better after 1935 in the austral summer (only), when larger quantities of data are available.

John Walsh examined the handling of Arctic clouds and radiation in reanalyses and climate models. Observational products, primarily in-situ measurements, were used to assess radiative flux and cloud fields in recent atmospheric reanalyses (ERA40, NARR, NCEP/NCAR) and to diagnose Arctic simulations by models used in the IPCC 4th Assessment. Ultimately the goal is to extend the work to assessment of candidate cloud/radiative schemes for Arctic regional reanalysis. Conclusions presented were that clouds are critical to surface radiative fluxes in the Arctic and that errors of >100 W/m^2 result from errors in cloud cover. Accordingly, a reanalysis' or GCM's surface energy budget will have large systematic errors if clouds are misrepresented. The NCEP reanalysis has too few clouds while the ERA-40 system has clouds that are too optically thin. Clouds represent a major challenge and a major opportunity for an Arctic Regional Reanalysis.

Phil Arkin gave a talk on the utility (or otherwise) of global precipitation analyses derived in high latitudes and plans for future developments. Projects such as the GPCP (Global Precipitation Climatology Project) and CMAP (CPC Merged Analysis of Precipitation) are combining snow gauge, radar and satellite estimates of precipitation. Both GPCP and CMAP suffer from inhomogeneities in input data sets, artifacts in the resulting analyses, records that are too short to identify trends and too heterogeneous to permit budget calculations. They also have particular problems with high latitude and orographic precipitation. Many of the problems are associated with observing system gaps/changes (passive microwave, radar, geostationary data). Others are related to fundamental physical limitations (e.g. snow/ice) and analysis shortcomings (limited physical model input). Phil considered what needed to be done and suggested a reanalysis of global precipitation for 1988 to the present. This should use the period of robust, relatively consistent data: SSM/I++, geostationary and make use of TRMM PR to pin down actual values. It should be extended back to 1979/1974 if possible by utilizing NOAA OLR dataset and earlier geostationary observations. Artifacts should be removed/reduced and it should use advanced products (GPROF for SSM/I, microwave/IR combinations), develop/use improved analysis procedures. In high latitudes it should make use of ERA-40, equal area grid.

A number of talks dealt with the high latitude applications of the reanalysis data sets. John Turner described the major winter season mid-tropospheric warming that has been identified over the Antarctic. The warming was identified by radiosonde ascents and is larger than any previously identified regional tropospheric warming on Earth. The radiosonde data show that regional mid-tropospheric temperatures have increased at a statistically significant rate of 0.5 to 0.7 deg Celsius per decade over the past 30 years. The warming is also apparent in the ERA-40 fields.

Christophe Genthon described Antarctic surface mass balance variability on various time scales. He had compared reanalysis estimates of mass balance with satellite data (altimeter) and in-situ measurements from ice cores, gauges and stake arrays. The satellite and ice core data covered years, while the field data was on time scales of days to years. The detrended surface elevation anomaly for Davis was compared with accumulation/precipitation anomaly from ERA4-40 and NCEP2. The 12-month running-means were in good agreement. Data from various weather sensors for precipitation had been compared with ECMWF precipitation and there was reasonable agreement. The CONCORDIASI IPY proposal was also described. This will involve operational meteorology via THORPEX and climate research. New/advanced tools for observation will be applied, such as satellite sounders, drift/drop sondes, weather sensors, etc. Data from the new plateau station at

Concordia will be used, along with advanced high-resolution assimilation/prediction models. The special observing period will be austral spring-summer 2008-09.

Kevin Hodges described his work on storm tracks derived from reanalysis fields. The reanalyses fields provide the current best 4D view of the atmosphere over short climate time scales and allow cyclone climatologies to be created that can be used to investigate variability. Amongst over things he discussed how the reanalyses inter-compared with respect to cyclones. He had used ERA-40, NCEP/NCAR and JRA-25. His conclusions were that there is greater uncertainty for small scale or low intensity systems in general. The reanalyses inter-compare well in the NH over the full 40+ year period for storm tracks, both for spatial distribution and direct matching. There is greater uncertainty in the SH for the period 1979-2002 and virtually no correspondence for the period 1958-78. Observing system experiments highlight the importance of the terrestrial observing system in the NH and satellite system in the SH. The surface system is very poor in both hemispheres (not optimal). There is little impact from humidity observations. The predictability of storm position is handled better than intensity. The relative importance of observing systems is similar to analyses. Future work will consider vertical structure. Preliminary work suggests terrestrial observations result in better storm tilts.

Gareth Marshall discussed the Southern Hemisphere Annular Mode (SAM) and its variability in recent decades. The SAM is the principal mode of variability in the atmospheric circulation of the Southern Hemisphere (SH) and contributes a significant proportion of SH climate variability from daily to inter-annual timescales. The SAM can be defined as the mean sea level pressure (MSLP) between 40 and 65 deg S, with the MSLP values either coming from station data or the reanalyses. Errors in the NCEP-NCAR reanalysis have led research using this dataset to overestimate the trend in the SAM by a factor of at least two. The ERA-40 reanalysis is significantly better than the NCEP-NCAR reanalysis for studies of the SAM.

Dave Bromwich indicated that there is a lower-mid tropospheric cold bias in ERA-40 over the central Arctic Ocean. During winter it starts in 1979 when HIRS data started to be assimilated and ended in early 1997 when the HIRS assimilation approach was modified. During summer, the onset and cessation cannot be confidently established. There is a similar cold bias in ERA-40 over the Antarctic sea ice of the South Pacific and Weddell Sea. There is not a strong seasonal cycle to this bias. It also stops in early 1997. The cessation is hardly evident in summer, but maximized in spring (the time of maximum sea-ice extent). He had not examined the onset because of the big adjustment in ERA-40 to the start of the modern satellite era in 1979.

Lennart Bengtsson briefly discussed the report on the ESSC workshop on reanalysis that had taken place in Reading. This had resulted in a paper on 'The Need for a Dynamical Climate Reanalysis'. He pointed out that the reanalyses suffer from a number of limitations that unfortunately restrict their general use, especially for climate applications, such as changes in the observing system. There was a consensus at the meeting that reanalyses are a most important contribution to climate research. It was felt that several of the problems found in present reanalyses will diminish with the implementation of more advanced methods to handle physical processes in the models as well as further improvements in the data-assimilation.

In the final discussion session it was noted that the reanalysis data sets are of great value in the polar regions and finding many applications in areas such as the investigation of climate trends, storm tracking, driving ocean models and investigating climate processes. However, there are a number of issues such as:

- Many of the fields are poor in the SH before 1979 when no satellite data are available. The output needs to be used with care, which is a question of education
- Before 1973 in the SH no actual sea ice data are used, only climatological values
- The reanalysis systems are not set up for data sparse areas
- Some early data are missing and still in hardcopy form
- The systems have poor snow cover
- Some of the polar parameterisation schemes are poor, such as the handling of Arctic shortwave radiation and polar clouds
- There are surface pressure trends and a poor SAM trend in the NCEP/NCAR reanalysis
- There is a lower tropospheric cold bias over the Arctic Ocean in ERA-40 reanalysis apparent in winter over 1979-97
- Polar precipitation is poor.
- There is no correlation between storms in the pre-satellite era in ERA and NCEP
- Trend differences between NCEP and ERA over the Southern Ocean and Antarctic.
- Energy budget residuals needed?
- Mass budget corrections required

Reanalyses are very expensive to run and require huge computer resources. However, they are essential for many studies. Some suggests for the future were:

- Since polar data are always so limited all efforts should be made to digitise those observations that are still in hardcopy form. This could involve digitising the NOTOS charts as PAOBs.
- Ensure that future reanalyses have good snow and sea ice data.
- There needs to be better assimilation of VTPR satellite data.
- There would be value in a high resolution, regional analysis for the Arctic since this is an area of rapid change. This could have a higher horizontal resolution for the satellite era of say 20 km and a time resolution of 3 h. A lower horizontal resolution could be used for the pre-satellite period. The Arctic reanalysis system could be optimised for high latitude processes. Such output could be of value for testing observing systems.
- At a later stage it could be useful to run a regional reanalysis for the Antarctic. At present it seems as though this would be useful covering the period from 1979. The Antarctic Peninsula is a key area of change where it would be useful to have fields with a horizontal resolution of around 20 km.
- The meeting felt that a Twentieth Century reanalysis based on surface data would be useful
- Care needs to be taken with the surface fluxes and other high latitude processes.
- Wherever possible there should be free access to the reanalysis products.
- Include validation data with the reanalysis fields

- In the future it may be possible to carry out coupled atmosphere-ocean reanalyses. However, care needs to be taken to ensure that the surface flux fields are not compromised by the coupling.
- Regarding the archiving of data, it would be useful to have access to more frequent forecast fields (3 hourly or better) for selected parameters. These would be of particular help for tracking small scale, short lived and possibly fast moving systems, such as polar lows. Also, forecasts at 3 hourly sampling out to 10 days for predictability studies would be useful.

There was some discussion of **priorities** for the polar aspects of the reanalyses and the following points were highlighted:

- Assess available data for future reanalyses
- One scientific priority is to understand the decadal timescale variability eg the 1930s in the Arctic
- Get Greenland right in terms of surface fluxes and surface melt
- Reliable precipitation fields
- Bring lake ice data together and get it into future reanalyses
- Have the best possible horizontal resolution for future reanalyses
- Ice and snow cover data are important in pre 1980 analysis (NSIDC). Access station data.
- Keep the systems up to date. ERA-40 finishes in 2002
- Make sure the observations get to the major reanalysis centres during IPY
- An Arctic high resolution reanalysis is the first priority, then the Antarctic later
- A mixed layer model for the reanalysis systems
- Good involvement of the community in the planning of future reanalyses, for example in determining the fields to store
- SH. Determine how to do reanalysis in the pre-satellite era. IGY could be a starting point. Possibly a cross between the Gil Compo approach and modern re-analysis.
- It would be good to have more data on how each observation was used (or whether it was rejected) in the reanalysis.

On the 12 April the group visited ECMWF for further discussion on high latitude re-analysis. Talks were given by Roy Jenne, John Walsh and Phil Arkin, and there was extensive discussion. A summary of the main points is:

- ECMWF are keen for additional polar observations to be digitised for future reanalyses. We will try and work with organisations such as SCAR and CliC to encourage the various nations to digitise early polar observations.
- John Turner agreed to work through CliC on trying to see what lake ice data are available for future reanalyses.
- There is also a need for high quality snow cover data for the reanalyses and CliC may also be able to help here.
- Specifying sea ice extent and concentration in the pre-satellite era is a major problem. To date climatological fields have been used, but this

is far from satisfactory. Some coastal observations and summer whaling observations could be used but large areas are devoid of observations. It is hard to see how this can be resolved.

- There was extensive discussion on how scientists might get access to ECMWF analyses and forecasts during (and after) IPY. We were told that the procedure with large projects such as IPY is to have one of the member states host a centre that would act as a distribution point for these fields. This would be discussed with David Carlson at the IPY office.
- The group stressed that many scientists from non-European countries are keen to have access to future ECMWF reanalysis fields. We were told that the policy on access to ECMWF products is determined by the ECMWF Council so access to new reanalysis fields cannot be guaranteed.
- John Turner gave a brief presentation on the Antarctic mid-tropospheric warming. The trends from 1979 were slightly larger in the reanalysis fields than from the radiosonde data. Adrian Simmons indicated that they were aware of a small cold bias in their data that may account for this.
- The visit was deemed very useful and we are grateful to the staff of the ECMWF for spending so much time with the group.

We are grateful to SCAR for providing support for the workshop.

John Turner
30 May 2005

Table 1. A summary of reanalyses carried out or planned

Centre	Reanalysis period	Period when work carried out	Notes
NASA Data Assimilation Office		Early 1985 to 1993	
NCEP/NCAR reanalysis (NCEP 1)*	1948 to 1997	1991- July 1998	Still updated each month by CDAS at NCAR (see below)
NCEP-DOE reanalysis (NCEP 2)*	1979 - 1997	Started May 1998	Corrected some errors in NCEP 1. Resolution T62, 208 km 28 levels. Still updated each month by CDAS at NCAR (see below)
North American Regional Analysis	1979-2003	1999-2004	Based on the regional Eta model with a resolution of 32 km
Climate Data Assimilation System (CDAS) reanalysis	1996-present	Current	An extension in real time of the NCEP 1 and 2 global reanalyses
Regional Climate Data Assimilation System (R-CDAS)*	2003 - present	Current	An extension in real time of the North American Regional Reanalysis
Modern Era Reanalysis for Research and Applications (MERRA)	1979-present		Will begin in July 2006
ERA-15	1979-93	June 1994 – Sep 1996	31 levels
ERA-40	1957-2002		60 levels
ERA-Interim	1989 onwards		91 levels
ERA-70?	1940 onwards	Possibly starting in 2010	
JRA-25	1979-2004	????	

* = routinely updated.