SHORT- TO MEDIUM-RANGE NUMERICAL WEATHER PREDICTION IN THE ARCTIC AND ANTARCTIC

BY JEFFREY S. TILLEY AND DAVID H. BROMWICH

The workshop on Short to Medium Range Numerical Weather Prediction in the Arctic and Antarctic fostered interaction among researchers and operational forecasters working in high-latitude numercial weather prediction (NWP) and promoted an effort toward an Arctic System Reanalysis (ASR), proposed at an earlier workshop (Overland et al. 2003). The attendees provided a variety of operational and research perspectives as well as energetic discussion on current results and the proposed ASR.

WORKSHOP ON SHORT- TO MEDIUM-RANGE NUMERICAL WEATHER PREDICTION IN THE ARCTIC AND ANTARCTIC

What: Forty forecasters, researchers, and others focused on high-latitude numerical modeling discuss recent results and prospects for an Arctic System Reanalysis
When: October 2003
Where: International Arctic Research Center, University of Alaska at Fairbanks, Fairbanks, Alaska

CURRENT REANALYSIS SYSTEMS. Mark Serreze (University of Colorado) and Pedro Viterbo [European Centre for Medium-Range Weather Forecasts (ECMWF)] discussed features, strengths, and weaknesses of the ECMWF 15-yr Re-Analysis (ERA-15), ECMWF 40-yr Re-Analysis (ERA-40), National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR)-1 reanalysis (NCAR-1), and NCEP–NCAR-2 reanalysis (NCAR-2) systems in representing the atmosphere over the polar regions. NCEP-1 and NCEP-2 tend to produce excessive downwelling solar radiation, convective precipitation, and evaporation during the summer over Arctic land areas. Because the precipitation (*P*) and evaporation (*E*) errors counterbalance each other, values of the commonly used (*P*–*E*) diagnostic appear reasonable, which is a misleading result. ERA-15 suffers from similar problems with simulated precipitation and evaporation rates. Further, NCEP-1/-2 and ERA-15 surface estimates of (*P*–*E*) are not in hydrologic balance with estimates that are computed from aerological variables, as they should be.

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Despite these shortcomings, ERA-15 outperforms the NCEP-1 and NCEP-2 systems in high latitudes, but maintains a cold bias in wintertime 2-m temperatures over boreal forests. Fortunately, data from the newer ERA-40 system, which includes improvements to soil, vegetation, snow, and ice physics, and utilizes a three-dimensional variational data assimilation (3DVAR) technique, are now available online (information available at http://data.ecmwf.int/data/d/era40/), and appear to be superior to the other reanalyses in several respects. For example, the ERA-40 mean annual cycles, monthly spatial patterns, and temporal correlation statistics of precipitation for the Ob, Lena, and Yenisey River basins are superior to those obtained from the satellite-derived estimates. The fields are better in winter than summer, highlighting problems in simulating summertime convection in the Arctic. While ERA-15 is too warm in winter, is too cold in summer over the Arctic Ocean, and lacks high-frequency variability, ERA-40 contains more short-term variability than ERA-15, and better depicts the sea ice concentration and surface heat flux in marginal ice zones.

Viterbo cautioned that trends in reanalysis fields might result as much from the effects of different data densities as from actual trends in the variables. He supported this assertion with ERA-40 verification data over the Mackenzie River basin—neighboring data-rich and data-poor regions within the basin produced different trends in terms of regional-scale atmospheric behavior.

SATELLITE DATA APPLICATIONS. Numerous products from geostationary and polar-orbiting satellite instruments are available for assimilation into NWP systems. Jeff Key [National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite, Data, and Information Service (NESDIS)] noted that some of these data products are only now beginning to be utilized, while other products have been in use for years. Operational NWP centers have primarily focused on assimilating radiances, though for cloudy conditions it may be more cost effective to assimilate retrieved quantities, including new ice surface temperature retrievals, which can be advantageously assimilated into NWP models.

Products that are available from the extended Advanced Very High Resolution Radiometer (AVHRR) Polar Pathfinder (APP-x) dataset include surface temperature and albedo, cloud optical depth, cloud radiative forcing, and cloud phase. Key illustrated the APP-x applications through a modeling study over Antarctica utilizing the Arctic Region Climate System Model (ARCSyM) (Lynch et al. 1997). Simulations with and without the APP-x cloud initialization indicated substantial differences in simulated cloud amount and downwelling longwave fluxes near the South Pole during austral summer. Detailed validation of the simulations indicated that inclusion of the APP-x cloud fields was overall beneficial.

Key, Chris Velden, and Dave Santek [both of University of Wisconsin (UW) Cooperative Institute for Mesoscale Meteorological Studies (CIMSS)] discussed the Moderate Resolution Imaging Spectroradiometer (MODIS) cloud-track wind algorithm, which utilizes an infrared (IR) and a water vapor (WV) channel, and is similar in concept to previous CIMSS cloud-track wind algorithms applied to geostationary platforms. Case studies using 1-km MODIS data from the *Terra* satellite to obtain winds at 2-km resolution suggest acceptable agreement with available radiosonde data, though only ~ 4% of MODIS winds can be verified against the relatively sparse radiosonde network. Extremely dry conditions, optically thin clouds, and surface temperature inversions near the poles make the height assignment of clouds and winds problematic because the surface is often detected instead of the clouds. Other challenges involve parallax, complex terrain, and changing cloud characteristics during the 100-min MODIS orbital period.

An archive of MODIS wind data (back to July 2002 for the *Terra* satellite, and back to December 2002 for the *Aqua* satellite) is available from CIMSS. Work is ongoing to provide this data in Binary Universal Form for Representation (BUFR) format.

Jaime Daniels (NOAA/NESDIS) discussed work to transition production and distribution of MODIS wind products to NESDIS from the National Aeronautics and Space Administration (NASA). Experimental production of MODIS winds from *Terra* at NOAA uses the NCEP Global Forecast System (GFS) and the Navy Operational Global Atmospheric Prediction System (NOGAPS) model output as first-guess fields. Examples of these experimental winds show large wind differences as a consequence of differences between the GFS and NOGAPS first-guess fields, with the largest differences occurring where no radiosonde data enter the analysis. To expedite the transition to operational application, NASA is developing a new 3DVAR system that is similar to the current NCEP system, allowing NOAA to rapidly adapt future MODIS wind research at NASA into NOAA operations.

In general, the use of MODIS wind data resulted in positive impacts to NWP forecasts for the Northern Hemisphere, especially over Europe, and improved NWP forecasts in experiments at operational centers. By contrast, impacts to the NWP forecasts were negative for the Southern Hemisphere and Antarctica. Lars Peter Riishojgaard (NASA Global Modeling and Assimilation Office), Lueder von Bremen (ECMWF), and Howard Berger (Met Office) all pointed to the greater utilization of winds from the *Aqua* satellite in the Southern Hemisphere as a potential source of the negative forecast impacts, though more work is needed to determine the exact nature of the problem. Consistent with this observation, ECMWF has used MODIS winds—from *Terra* only—operationally. Observations are thinned to 140-km resolution, and errors for MODIS winds are assumed to be characteristically larger than those for other sources. The MODIS investigators developed a plan to jointly investigate the Southern Hemisphere issues.

Berger discussed the use of aggregated "superobs" for MODIS winds, as opposed to thinning the observations. Berger's approach to creating a superob is to average the observation minus model background (*O–B*) values within a grid box, then add the background component back in at the location within the box, which is the average location of all observations within that box. Superobs can alleviate potential problems with observation errors due to the MODIS winds being spatially correlated. Early tests suggest that reduced errors result when superobs are utilized.

IMPROVING MODEL PHYSICS. Nicole Molders (University of Alaska, Fairbanks) described investigations into the interactions between gradients in soil moisture and soil temperature. These interactions, as well as diffusion and phase changes of soil water vapor, are often ignored in NWP models. However, if soil ice is present, all of these phenomena can be important in determining soil water content. Offline land surface modeling tests indicate, however, that the temperature gradient has little impact on soil moisture (Ludwig–Soret effect), except when soil is freezing and thawing. The opposite cross effect (Dufour effect) is more pronounced, with soil temperature changes up to 2 K resulting from altered volumetric soil water content.

Experiments incorporating these effects into the fifth-generation Pennsylvania State University (PSU)–NCAR Mesoscale Model (MM5) suggest that the improved treatment of snow, rather than frozen soil, has a greater impact on surface humidity and temperature fields, though impacts to winds are only seen if patchy snow cover is adequately treated. Molders stressed that NWP models that are applied to high latitudes need to consider organic soils, lateral runoff, and the lack of data for commonly prescribed soil parameters.

Amanda Adams (UW) discussed simulations of a strong late-winter wind case (46 m s^{-1}) over the Ross Sea in Antarctica, using the UW nonhydrostatic model, a quasi-compressible, enstrophy-conserving model with variable-step topography, such that the depth of the lowest grid box varies so that the bottom boundary matches the mean topography across the grid volume. Nested grids with resolutions of 90, 15, 5, and 1.25 km were used, and terrain in the variable-step topography was specified at 1-km resolution.

The results indicate that some localized flow features, including a wind maximum traversing Ross Island, can be produced on the coarser grid. However, the finest grid, with resolution nearly that of the step topography, is required to produce the most realistic simulation, including multiple vortices leeward of Ross Island.

Topographic effects around Svalbard often result in strong winds (~ 20 m s^{-1} at 10 m AGL) between the two main islands. Anne Dagrun Sandvik (Bjerknes Centre for Climate Research) discussed MM5 simulations with two-way-nested 6- and 2-km grids that produced structures similar to synthetic aperture radar estimates of the wind, though cross sections indicated that MM5 underestimates the wind speeds and the temporal variation that are associated with the 600-m-deep feature. Low speed biases in the cross-jet direction are less pronounced, and the cross-jet temporal variations in winds are well captured. Based on analysis of the simulation results plus several sensitivity experiments, Sandvik concluded that the wind increase is related to a barrier jet effect.

Strong winds also blow at Paulutuk, Northwest Territories, Canada, a community at the base of a steep 270-m escarpment along the Canadian Arctic coast. Ron Goodson of the Meteorological Service of Canada (MSC) used 2D Advanced Regional Prediction System (ARPS) (Xue et al. 2000) simulations with a 1-km horizontal grid and an 85-m vertical grid to investigate the possible presence of hydraulic jumps during the wind events. The Paulatuk topographic profile was inserted at initialization within the nearby Inuvik radiosonde profile.

The model reproduced much of the observed variation in the three simulated cases: a steady 50-kt flow gusting to 80 kt, a weaker wind with a 3-mb surface pressure jump, and a case where a small cyclone between Inuvik and Paulatuk was associated with a period of strong winds. Because the cases examined have large synoptic pressure gradients, drainage flow can be ignored as a contributor to the strong winds.

Currently, model upper boundary conditions are specified as either having a rigid lid, where upward-propagating wave energy is reflected; a radiative condition (Klemp and Durran 1983), where internal gravity waves can propagate through the model top; or a sponge condition, where upward-propagating waves are damped through filtering. David Bromwich [Ohio State University (OSU)] introduced a method where the upper boundary fields are nudged toward a specified synoptic analysis with an exponential decay downward from the model top. This methodology is similar to how lateral boundary conditions are specified in regional models.

Over land, the nudging upper boundary conditions fit better with observations than radiative upper boundary conditions for Antarctic tests, using both the Polar MM5 (e.g., Cassano et al. 2001) and the Antarctic Mesoscale Prediction System (AMPS; Powers et al. 2003). Experiments with a higher model top produced better results for all schemes. Over ocean points, all schemes seem to perform equivalently, suggesting that wave generation by Antarctic terrain is the main area of concern for the upper boundary conditions.

Wieslaw Maslowski [Naval Postgraduate School (NPS)] noted uncertainties in our knowledge of sea ice thickness and volume, freshwater export, and the magnitude of northward heat transport and atmosphere–surface energy exchanges. He described a new NPS 9-km coupled ice–ocean model that includes new bathymetry, new hydrographic climatology, freshwater from river runoff, and tracers for Pacific water, Atlantic water, and runoff. The sea ice submodel conserves energy and has five ice categories, four ice layers, a snow layer, elastic-viscous-plastic dynamics, and remapping schemes for horizontal ice transport and ice thickness distribution. A 70-yr simulation, including 48 yr of spinup with ERA-15, satisfactorily reproduces interannual and interdecadal patterns of Arctic Ocean and sea ice variability. Using snapshots of ice concentration for the Bering, Barents, and Chukchi Seas, he noted the importance of prognostic ice–ocean interactions in models, as opposed to time-varying climatologies, which cannot reproduce all of the observed interactions and variability. To further illustrate his point, Maslowski also showed the progress of ice thickness anomalies around the Arctic basin using synthetic aperature radar imagery and discussed the degree to which the simulations, including ice–ocean interactions, compared favorably with the imagery.

KEYNOTE ADDRESS. Dale Barker [NCAR Mesoscale and Microscale Meterology Division (MMM)] summarized the MM5 3D variational data assimilation system, employing analysis increments and cost–function minimization in model grid space. The analysis increments penalize background error covariances and observational errors according to predetermined weights for each observation or background field type. For the polar regions, the background error covariances should be ideally derived from a model with appropriate polar physics so that the lower-tropospheric covariances are correct.

Barker reviewed the observation types that can be utilized in the MM5 3DVAR system: in situ observations, satellite thermodynamic profiles, GPS total precipitable water (TPW) and refractivity, Special Sensor Microwave Imager (SSM/I) TPW and ocean surface wind speed, Special Sensor Microwave Temperature Profiler (SSM/T) 1 temperature, SSM/T2 relative humidity, scatterometer winds, and Next Generation Weather Radar (NEXRAD) radial velocities. Preliminary testing of MODIS winds has also been done.

Barker discussed operational results from the use of 3DVAR in both AMPS and the Air Force Weather Agency's MM5 system. In all cases, use of 3DVAR appears to improve forecast skill, though Barker noted that more improvement is possible with tuning. However, current 3DVAR systems assume little latitudinal variation in background velocity potential covariance eigenvectors, and, therefore, are not well suited for high latitudes. As evidence, he presented a brief analysis suggesting strong variations with latitude of these eigenvectors.

MODEL APPLICATIONS AND CASE STUDIES. Timothy Shy [NOAA/National Weather Service (NWS) Fairbanks] examined the skill of NCEP model output statistics (MOS) products for wintertime surface temperature forecasts during 1997–2000. Observed maximum temperatures from Fairbanks International Airport were compared to predictions from the medium-range MOS. MOS products showed a general trend for less skillful forecasts with increasing forecast range.

Shy noted that 65% of the MOS forecasts, but only 50% of the observed temperatures, are within 10°F of climatological values. Thus, MOS is too constrained by climatology, a factor that enters the MOS equations. Shy determined that there was a clear warm bias (greater than 5°F) in the MOS temperature forecasts for Fairbanks. To complicate matters, an analysis of the temperature errors suggests that they follow a random distribution after day 6, thus, making MOS difficult to use even as a statistical starting point beyond that point.

Jeff Tilley (University of North Dakota, Grand Forks) spoke on the University of Alaska's real-time forecast system, which executes three 48-h forecast cycles daily on five grids at horizontal grid resolutions of 45, 15, and 5 km using a modified version of the MM5 system.

Verification over an annual cycle conducted against analyses indicated that the system has a slight cold bias (< 0.6°C) in the 500-hPa temperature year-round; an annual cycle to the surface temperature biases and rmses, but with cold biases > 0.5°C year-round; and westerly and southerly wind biases through the year, with the southerly bias maximizing in early December. Different error characteristics occur in many fields on the finer grids compared to the coarse grid, which contains many ocean points.

Precipitation forecasts were verified against observations at thresholds from 0.01 to 0.5 in. While the outermost grid shows a drop of skill at all thresholds in all seasons, the 15-km domain skill was best for spring forecasts at the 0.5-in. threshold. Tilley implied that this indicates that the higher-resolution grid adds value in strongly forced situations.

The spatial distribution of biases for 12-h wintertime sea level pressure (SLP) forecasts shows significant negative biases over land and positive biases over water; this implies that there are problems with the land surface scheme. Compared to analyses, the pattern of 500-hPa wind and temperature bias fields is generally consistent with a northeastward shift in the average forecast synoptic pattern for the winter season.

Keith Hines (OSU) spoke on efforts to develop a polar version of the Weather Research and Forecasting (WRF) model for use in an Arctic reanalysis system. To argue the need for such a model, Hines compared Polar MM5 SLP and surface winds with observations at Barrow, Alaska. The forecast SLP anomaly correlations were quite high, while wind correlations were somewhat less. Hines pointed out that efforts are underway to develop a version of the WRF model for the polar regions because the model for an ASR could tie in with the International Polar Year (2007), which strives to take advantage of opportunities to integrate efforts in polar research.

OPERATIONAL FACILITIES AND ISSUES. In the restructuring of the Meteorological Service of Canada, a new MSC Arctic Laboratory in Edmonton, Alberta, Canada, will be collocated with a new Hydrometeorology Laboratory and Storm Prediction Centre. The new laboratories will provide MSC forecasters opportunities to research forecast problems and interact with university researchers. Projects are anticipated involving mesoscale modeling, PBL interactions, lightning detection, quantitative precipitation forecasting, warning criteria, field programs, technology transfer, and forecaster training. Collaborative research efforts will be ad hoc in nature and will be pursued by both Canadian and American researchers.

Gary Hufford (NWS Alaska Region) summarized plans for NCEP's model suite, operational NWP for Alaska, and new Alaskan observing sites. Hufford showed significant differences in mesoscale structure between forecasts of the 12-km Eta Model, the 10-km WRF, and the 10-km NCEP nonhydrostatic mesoscale model (NMM). Hufford also presented examples of 4-km 48-h NMM forecasts for Alaska that are used for fire weather support and other emergency response situations. All products are available from NCEP either by ftp or on the Web.

VALIDATION ISSUES. John Cassano (University of Colorado) discussed self-organizing maps (SOMs) as a tool for model validation. SOMs utilize an unsupervised neural network and cluster data into a user-specified number of nodes. Once the number of nodes is specified, the algorithm attempts to classify nodes that are most representative of the data. Cassano presented a sample SOM for SLP, created with a training dataset of ECMWF SLP analyses over a 3-month period. Each panel on the map is a node and nodes that are more similar are closer together on the map than less similar nodes.

SOMs can be used in model validation through pattern classification, determining the frequency of occurrence of patterns, and determining model errors for different patterns. Cassano presented an example illustrating the determination of the frequency of each model's prediction of a given SLP node. By comparing these frequencies with those from the training dataset, one can determine whether a given model over- or underpredicts certain nodes. To understand why a model predicts certain patterns poorly, one can consider all of the time periods in which the validating analyses and the model forecasts map to a particular node. Alternatively, one can isolate a given time and note which nodes the analysis and the model each map to at that time.

Ola Persson (NOAA/Environmental Technology Laboratory) argued that a priori knowledge derived from process studies, conceptual models, and physical relations can be useful in evaluating model simulations. As an illustration, MM5 simulations of January PBL structure over the Beaufort Sea were discussed, using data collected during the Surface Heat Budget of the Arctic (SHEBA) project for validation.

An MM5 simulation, using a single snow/ice layer, produced surface temperatures 4°C too warm. SHEBA lidar data were used to rule out poor cloud forecasts as a factor in the temperature bias, and solar fluxes could also be ignored. Biases in the simulated longwave flux were inconsistent with the temperature bias, implying that the primary problem was with the conductive flux formulation. Adding two additional snow layers to the model produced the best conductive fluxes but degraded the sensible heat and longwave fluxes. Ultimately, comparison of the observed winds and fluxes indicated that the conductive flux issue is related to excessively strong simulated winds due to excessively high simulated SLP over the Canadian archipelago.

ANTARCTIC MODELING AND POSTER SESSION. Jordan Powers (NCAR/MMM) focused on the AMPS system, configured with six domains, with horizontal resolutions of 90, 30, 10, and 3.3 km, and forecasts out to a maximum range of 72 h. AMPS products are available either by the Web or ftp.

Powers utilized spectral analysis for verification; at synoptic scales, a k^{-3} power-law relationship should be visible in spectra while a $k^{-5/3}$ power law should apply on the mesoscale. The 3.3- and 10-km AMPS wind spectra for the middle and upper troposphere exhibit both power laws, but with greater energy in the 3.3-km grid. The 9-km spectra show planetary scales as well as the k^{-3} regime, while the 30-km spectra show mostly the k^{-3} regime. Specific components of the spectra appear to be associated with waves near Ross Island and the Transantarctic Mountains. Powers noted that the amount of simulation time that is required to produce stable spectra statistics is a function of grid size, with finer scales requiring greater time.

The Australian Antarctic Limited Area Prediction System (ALAPS) is a hydrostatic model with a terrain-following vertical coordinate, a multivariate statistical interpolation scheme for data assimilation and modified surface temperatures, and albedos based on satellite estimates of sea ice concentration. Neil Adams (Australian Bureau of Meteorology) showed examples of ALAPS forecasts, including those from a higher-resolution domain (denoted HI-ALAPS) nested within the ALAPS domain, but noted that the validation of surface winds, pressure, and dewpoint does not give a clear advantage to HI-ALAPS.

Adams also believes that HI-ALAPS problems are related to topographic forcing combined with the upper boundary condition. The HI-ALAPS grid, with steeper terrain slopes than those of ALAPS, has a higher potential for gravity wave generation. A 96-h simulation with the upper boundary raised to 25 km indicated that noise that was apparent in the control run was eliminated, while a topographically forced cyclone near the Antarctic continent, not produced in the control simulation, was adequately reproduced.

In a poster session, the University of Wisconsin Antarctic Meteorological Research Center presented an overview of how their data are being utilized in various data assimilation efforts. The Byrd Polar Research Center presented two posters illustrating aspects of Polar MM5 simulations over Greenland and the Mackenzie River Basin, and proposed a dedicated initiative toward Greenland NWP using Polar MM5. The Icelandic Meteorological Office presented efforts to improve precipitation forecasts and analysis in Iceland using deterministic (MM5) and statistical modeling, while Oregon State University presented work examining MM5-based estimates of boundary layer structure and wind stress in the Nares Strait/Smith Sound region.

TOWARD AN ARCTIC SYSTEM REANALYSIS. A plenary session identified the needs and requirements for the ASR. Key needs included the following:

- better surface datasets for land, ocean, and ice properties (Possibilities for mining surface station and satellite datasets were discussed.),
- defining the period and resolution of the reanalysis (The group came to consensus on a 1957–present time frame and a spatial resolution of 25–30 km.),
- accelerated development of data assimilation techniques for polar-orbiting, satellite-retrieved quantities and radiances,
- a WRF version with improved cloud, radiation, boundary layer, and upper boundary condition formulations before a reanalysis is begun (The issue of pressure gradients over steep terrain in WRF needs to be investigated.),
- resolving computational aspects (Compromises ranging from utilizing multiple platforms to restricting resolution and data assimilation sophistication were considered as ways to reduce the computational burden.), and
- international participation in the project.

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