Investigation of the quality of reanalysis climate datasets via a vorticity equation model reforecast experiment

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Motivation

- Replicate the first numerical simulations of the atmosphere, as performed by Charney, Fjörtoft and von Neumann (Tellus, 1950), and repeat them with modern data
- Qualitatively determine the utility of a simple, limited-area quasi-geostrophic vorticity equation model when run with present-day observations as inputs
- Are there any notable improvements in the quality of the forecasts produced with modern data?

Numerical Method

- Quasi-geostrophic vorticity equation along divergence-free isohypse (~500 mb), as used by Charney, Fjörtoft and von Neumann:
  \[
  \frac{\partial}{\partial t} \left( \nabla^2 \phi \right) = \frac{\partial \eta}{\partial x} \frac{\partial \eta}{\partial y} - \frac{\partial \eta}{\partial y} \frac{\partial \eta}{\partial x} + \frac{\partial \xi}{\partial x} \frac{\partial \xi}{\partial y} - \frac{\partial \xi}{\partial y} \frac{\partial \xi}{\partial x} - \nabla^2 \zeta
  \]
- Set \( \zeta = \nabla^2 \phi \) as intermediate solution variable: model becomes the following coupled system of equations:
  \[
  \frac{\partial \xi}{\partial t} = \frac{\partial \eta}{\partial x} \frac{\partial \eta}{\partial y} - \frac{\partial \eta}{\partial y} \frac{\partial \eta}{\partial x} + \frac{\partial \xi}{\partial x} \frac{\partial \xi}{\partial y} - \frac{\partial \xi}{\partial y} \frac{\partial \xi}{\partial x} - \nabla^2 \zeta
  \]
- Solve system over North America:
  \[\phi = [10.5^\circ N - 80^\circ N] \quad \lambda = [2.5^\circ W - 180^\circ W]\]
- Grid is not equidistant in longitude: \( \Delta \phi = R \sin(\phi) \Delta \lambda = 2.5^\circ \)
- Use NCEP/NCAR Reanalysis 1 database (Kalnay et al., B. Am. Meteorol. Soc., 1996) for the initial conditions (geopotential height of 500 mb pressure surface at 00Z)
- Through-flow boundary conditions for outflow regions; Neumann boundary conditions for inflow regions; second-order central (spatial) and first-order forward (temporal) finite difference discretizations

- Modern-day simulations have smaller errors in the predicted geopotential height of the 500 mb pressure surface than simulations initialized with late-1940s data
- Is this improvement in the vorticity model's forecast skill a lucky coincidence, or is there an underlying trend in the accuracy of the initial conditions?

Initial Tests

Extended Simulations

- Repeat simulations with the same model for all dates in the Reanalysis 1 database (R1) and in version 2 of the NOAA/ESRL PSD 20th Century Reanalysis (20CR, Compo et al., Quarterly J. Roy. Meteorol. Soc., 2011)
  - Reanalysis 1: Jan. 1, 1948–December 31, 2010
  - 20th Century Reanalysis: Jan. 1, 1871–December 31, 2010
- Initialize simulations at 00Z and 12Z; run model to 36 hours, store results for +06, +12, +24, and +36 hours
- Quantify errors at each snapshot by using anomaly correlation coefficient (Saha and van den Dool, Mon. Wea. Rev., 1988) weighted by latitude:
  \[
  AC = \frac{\sum_i \sum_j \left( \tilde{z}'_m (\lambda_i, \phi_j) - \tilde{z} (\lambda_i, \phi_j) \right) \left( \tilde{z}'_o (\lambda_i, \phi_j) - \tilde{z} (\lambda_i, \phi_j) \right)}{\sqrt{\sum_i \sum_j \left( \tilde{z}'_m (\lambda_i, \phi_j) \right)^2 \cos (\phi_j) \sqrt{\sum_i \sum_j \left( \tilde{z}'_o (\lambda_i, \phi_j) \right)^2 \cos (\phi_j)}}
  \]
  - Where \( \tilde{z}'_m (\lambda_i, \phi_j) \equiv z_{model} (\lambda_i, \phi_j) - \bar{z} (\lambda_i, \phi_j) \) and \( \tilde{z}'_o (\lambda_i, \phi_j) \equiv z_{obs} (\lambda_i, \phi_j) - \bar{z} (\lambda_i, \phi_j) \)
  - \( \bar{z} \) is calculated by the average of the reanalysis observation data at a given forecast time (00Z, 06Z, etc.) for the same calendar day for the entire forecast period
- Future work: Perform more detailed analysis of spatial / seasonal dependence of anomaly correlation

Results / Conclusions

- Short-term forecasts using modern data are noticeably improved than those made with historical data
- Lower anomaly correlations in the first decade of R1, late 1920s and early 1930s in 20CR reflect lower quality of underlying observations
- Model runs using initial conditions from 20CR, on average, performed better than simulations that used R1 data