Uncertainties in Model Initial Conditions

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Outline of Presentation

Background

- Initial Condition (IC) uncertainty leads to forecast uncertainty.
- IC uncertainty is represented in models using ensemble IC perturbations.

Significant Advances

- Physical processes of non-linear IC error growth
- Modeling IC uncertainty in forecast models (i.e., ensemble methods)
- Unique considerations in certain situations or flow regimes

Remaining Issues and Challenges

- Linking knowledge from different fields in coupled/unified models
- Limits of practical predictability obtainable from IC uncertainty research, relative to model/physics
- Flow-dependent ensemble design
- Understanding interactions among Mid-latitudes, Tropics, Arctic

Needs for knowledge/tools/observations/models

- Coupled data assimilation, and multi-scale observation networks
- Realistic, quasi-operational computational experiments
- Design modeling software with adaptability and maintainability as priorities
- Continued research emphasis on connectedness of distant regions

Importance of IC Uncertainty

- IC uncertainty affects both practical and intrinsic predictability of model forecasts
  - →***Intrinsic predictability (theoretical)***: Irreducible, infinitesimal errors will grow until they completely contaminate forecast at some fixed lead time (Lorenz 1963).
  - →***Practical predictability (empirical)***: Given the constraints of a particular modeling system and its approximations, the user should only expect useful forecast skill out to some lead time.

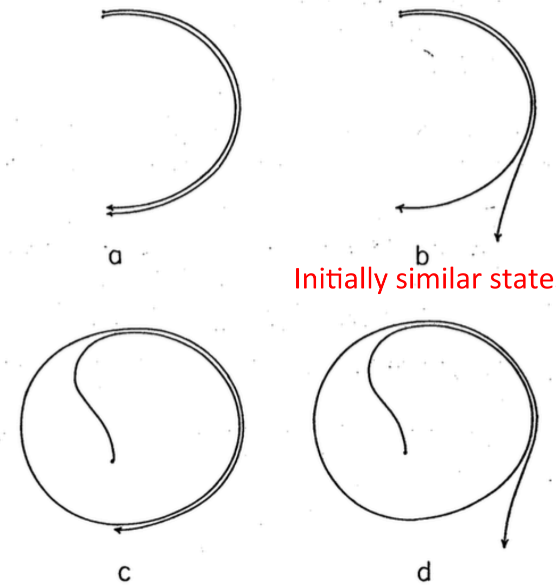
- Several ways to mitigate practical predictability limitations originating from IC uncertainty
  - → Assimilate more observations or better observations (e.g., more accurate, more frequent, optimally located, etc.)
  - → Advances in data assimilation techniques

- Some IC uncertainty will always exist: Ensemble methods can estimate the existing IC uncertainty in order to accurately quantify forecast uncertainty.
  - → This talk focuses primarily on mid-latitudes

IC errors grow during forecast

- Bifurcation point = Discrete event that dramatically changes the flow pattern
- Examples: Convective initiation (CI), Rossby Wave packets, establishment of blocking pattern, ice sheet collapse.

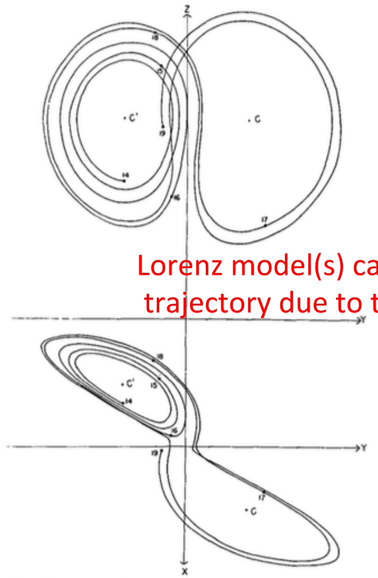
Lorenz, E., 1963: The predictability of hydrodynamic flow.
Trans. N.Y. Acad. Sci., **Ser. II, 25, No. 4**, 409-432.



Initially similar states can suddenly diverge

FIGURE 3. Schematic trajectories in phase space; (a) neighboring stable trajectories; (b) neighboring unstable trajectories; (c) stability implying periodicity (after the transient flow has died out); (d) nonperiodicity implying instability.

Lorenz, E., 1963: Deterministic nonperiodic flow. *J. Atmos. Sci*., **20**, 130-141.



Lorenz model(s) can follow completely different trajectory due to tiny IC differences

FIG. 2. Numerical solution of the convection equations. Projections on the *X*-*Y*-plane and the *Y*-*Z*-plane in phase space of the segment of the trajectory extending from iteration 1400 to iteration 1900. Numerals "14," "15," etc., denote positions at iterations 1400, 1500, etc. States of steady convection are denoted by *C* and *C′*.

Physical processes of IC uncertainty: Moist Convection

- CI is sensitive to small differences in low-level temperature and humidity that are within the range of IC uncertainty (e.g., Weckwerth 2000)
- IC uncertainty rapidly spreads throughout the model domain via sound and gravity waves (Hohenegger and Schar 2007).
- Error saturation within ~1hr on convective scales

Error propagation by sound waves

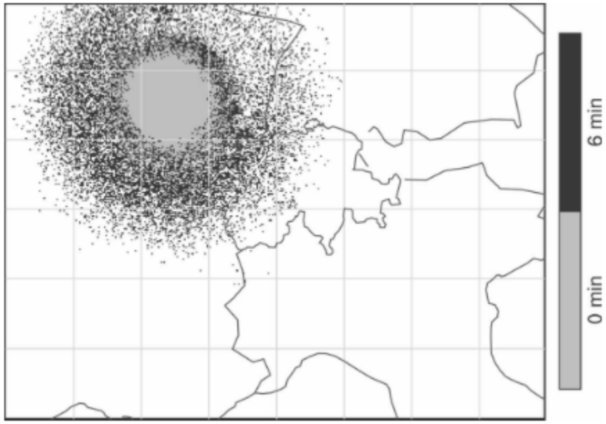


FIG. 5. Spatial distribution of temperature differences (GAUSS1–SHIFT6) after 0 and 6 min of integration. A grid point is shaded if the sum (in the vertical) of its absolute temperature differences is larger than 0.0075 K. Grid lines are drawn each 110 km.

Error propagation by gravity waves

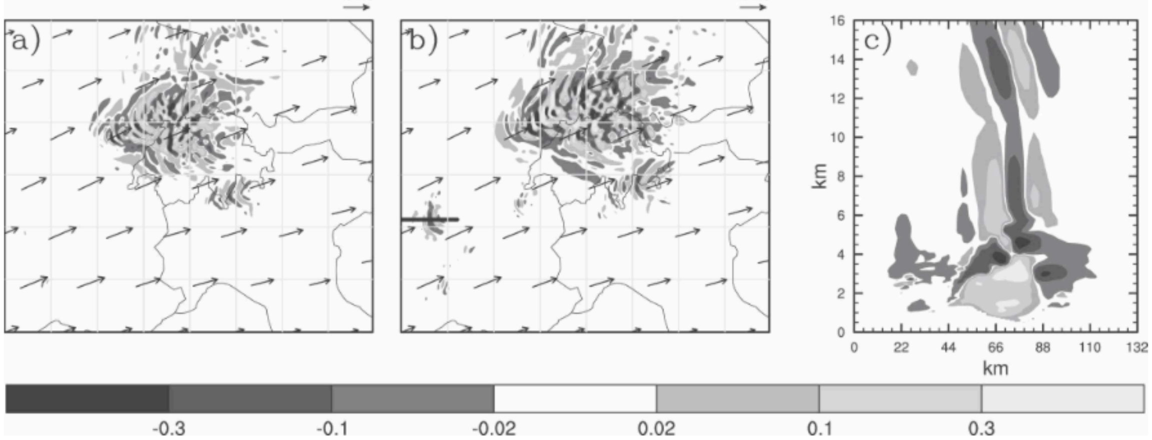


FIG. 6. Temperature differences obtained near the tropopause between GAUSS1 and SHIFT6 (K) after (a) 6 and (b) 7 h of integration with the wind field of SHIFT6 overlaid. (c) The corresponding cross section after 7 h with its location as indicated by the thick black horizontal line in (b).

Hohenegger, C. and C. Schar, 2007: Predictability and error growth dynamics in cloud-resolving models. *Jour. Atmos. Sci.*, **64**, 4467-4478.

Physical processes of IC uncertainty: Upscale error Propagation

- Initially small errors then become geostrophically balanced (e.g., Zhang et al. 2007; Selz and Craig 2015).
- Larger scale errors are transmitted through the domain via Rossby Wave Packets (Wirth et al. 2018).
- There is also a downscale error energy cascade that transmits errors from large to small scales (e.g., Durran and Weyn 2016).

Durran, D. R. and J. A. Weyn, 2016: Thunderstorms do not get butterflies. *Bull. Ameri. Meteor. Soc.*, **97**, 237-243

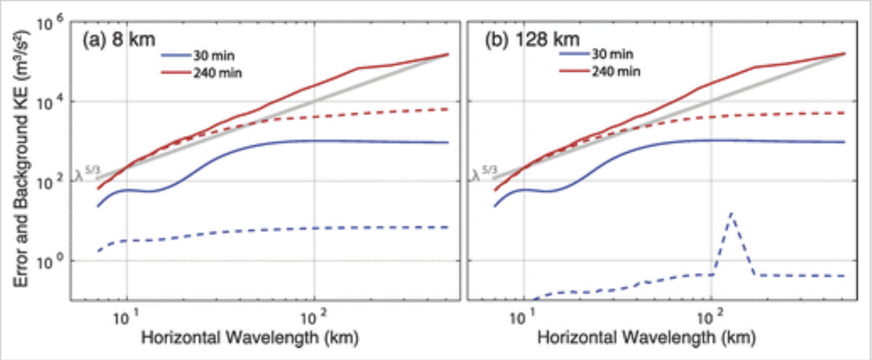
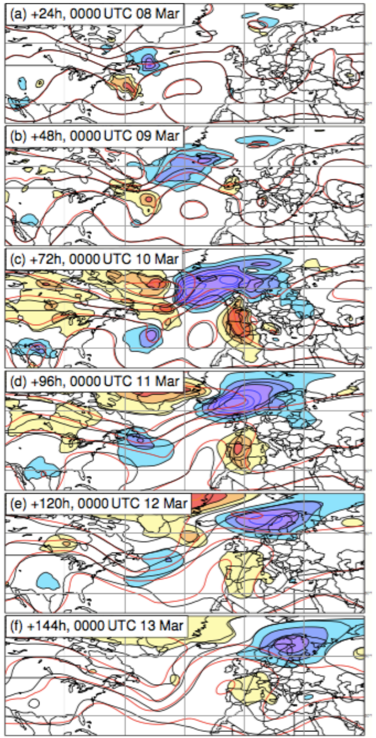


Fig. 3. Error amplitude (perturbation kinetic energy density) at a height of 10 km plotted as a function of horizontal wavelength from the squall-line simulations after 30 min (blue dashed line) and 4 h (red dashed line) for the ensemble with random initial temperature perturbations at scales of (a) 8 and (b) 128 km. Also plotted at the same times are the ensemble-mean kinetic energy density (solid blue and red lines) and a gray line with $\lambda^{5/3}$ slope approximating background kinetic energy spectrum observed in the atmosphere.

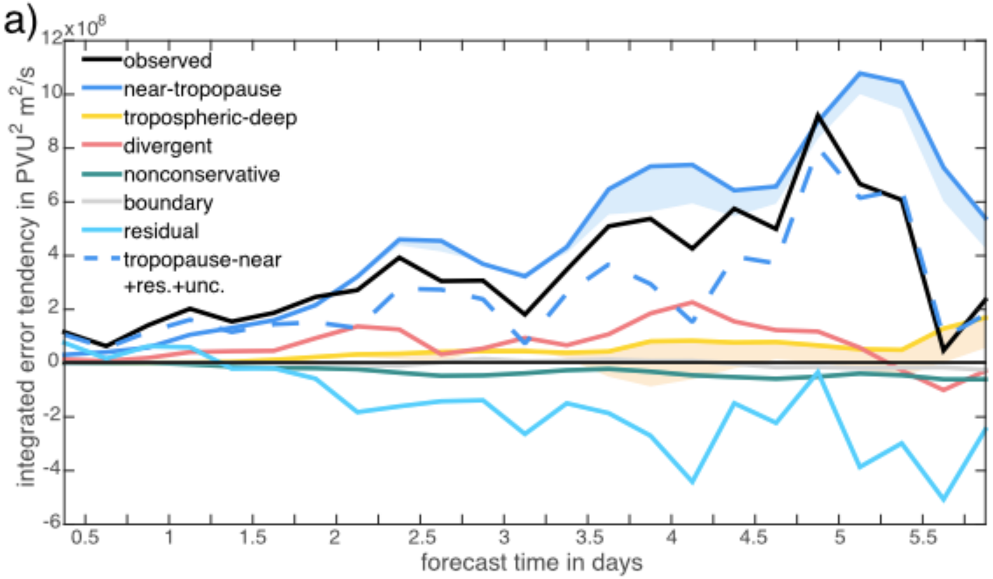


Grams, C. M. and coauthors, 2011: The key role of diabatic processes in modifying the upper-tropospheric wave guide: A North Atlantic case-study. *Quart. J. Roy. Meteor. Soc.*, **137**, 2174-2193.

Figure 2. Difference in 500 hPa geopotential height forecast (in m, shading) between the ensemble mean (absolute values shown with red contours every 200 m) and the analysis (black contours every 200 m) for the forecast initialised at 0000 UTC 7 March 2016 at different forecast lead times every 24 h. Adapted from Fig. 12 in Magnusson (2017).

Physical processes of IC uncertainty: Synoptic Scale

- Synoptic scale error growth may be more complex than baroclinically unstable growth of error pattern.
- Baumgart et al. (2018) case study found N. hemisphere integrated error growth was dominated by near-tropopause Rossby wave dynamics, with tropospheric-deep baroclinic processes actually being even smaller than upper level divergence contribution.
- Upper and lower level errors may need similar wavelength and favorable phase shift for them to grow baroclinically.



Baumgart M. and coauthors, 2018: Potential vorticity dynamics of forecast errors: A quantitative case study. *Mon. Wea. Rev.*, **146**, 1405-1425.

Modeling IC uncertainty in ensembles

- Breeding of Growing Modes (BGM; Toth and Kalnay 1993, 1997), Singular Vectors (SV; Buizza and Palmer 1995).
  - Focus on fastest growing IC errors since they will dominate forecast errors
  - **BGM**: rescale forecast perturbations every 6-24 hours to keep spatial pattern of growing error.
  - **SV**: Select modes of IC perturbation that explain most forecast error variance.

- Ensemble Kalman Filter (EnKF, Houtekamer 1996; ETKF, Wang and Bishop 2003, Wang et al. 2004), and its variants (ET, Wei et al. 2006, 2008), based perturbations for global models and synoptic scale systems of interest,
  - **EnKF**: Cycled ensemble DA inherently breeds growing modes and generates perturbations that sample the space relevant to the actual IC errors.
  - **ETKF** : Transform the background forecast perturbations to IC perturbations satisfying the analysis error covariance matrix from an optimal DA. Cheaper than EnKF and can maintain more modes than BGM.
  - **ET**: Use analysis error variance estimate to transform and constrain the bred modes.

- Other techniques for synoptic and mesoscale forecasts:
  - Regional models can borrow perturbations from global ensemble (**downscaling**; Marsigli et al. 2014).
  - Lagged Forecasting (**LAF**; Dalcher et al. 1988) makes an ensemble using forecasts initialized at slightly different times.

Modeling IC Uncertainty in ensembles: Multi-scale perturbations

Johnson et al. 2014

Johnson, A et al., 2014: Multiscale characteristics and evolution of perturbations for warm season convection-allowing precipitation forecasts: Dependence on background flow and method of perturbation. *Mon. Wea. Rev.*, **142**, 1053-1073.

- Rescaling frequency and amplitude determine modes that will dominate forecast error growth (Pena and Kalnay 2004).
- Small scale IC uncertainty can propagate upscale and generate comparable mesoscale uncertainty as direct mesoscale IC uncertainty (Johnson et al. 2014).
- Hypothesized that there are localized, flow-dependent convective scale IC uncertainties that can't be adequately captured by the downscale error energy propagation.

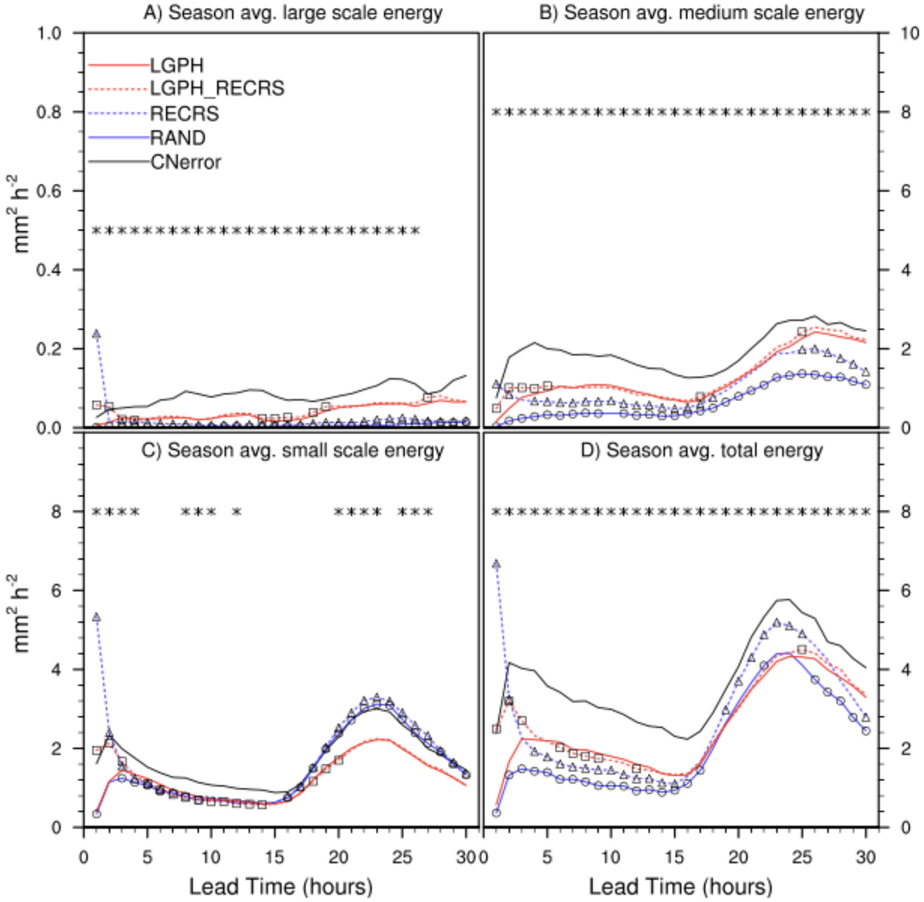


FIG. 11. As in Fig. 6, but averaged over the entire experiment period. Statistical significance at the 95% confidence level, based on permutation resampling, is indicated as follows. Markers on the RAND, RECRS, and LGPH_RECRS lines (circles, triangles, and squares, respectively) indicate a significant difference from the LGPH line. Markers (asterisks) above all the lines indicate a significant difference between RAND and RECRS.

Modeling IC Uncertainty in ensembles: OSSE Flow-dependence of Multi-scale perturbations

- Multi-scale IC perturbations from convective scale EnKF analyses generally outperformed coarser IC perturbations, when added to the same convective scale (4 km grid) mean analysis (Johnson and Wang 2018)
  - EnKF was first cycled every 3 hours (8 cycles) to breed synoptic scales of perturbation, then cycled every 5 minutes (36 cycles) to breed convective scales.
  - Difference between "MULTI" and "MULTI48" shows impact of the flow-dependent convective scale perturbations
  - Difference between "MULTI48" and "LARGE" shows impact of difference in how IC uncertainty is sampled with each set of perturbations *on commonly resolved scales*.
- Most of skill difference is explained by the commonly resolved mesoscale IC perturbations.
- Flow-dependent convective scale uncertainties may also be important at lead times out to at least 9 hours.

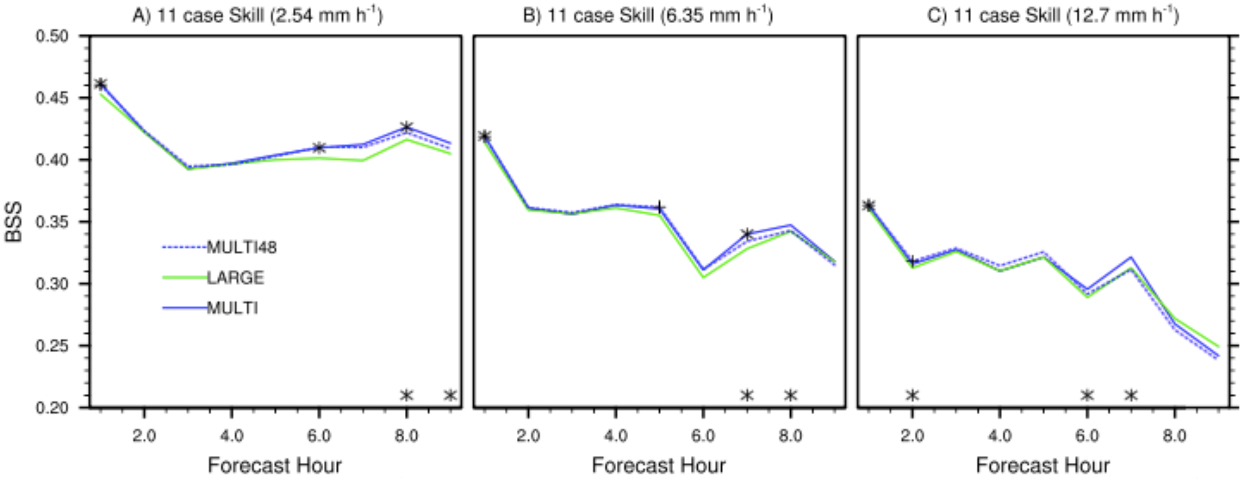


FIG. 4. Brier skill score (BSS) of the neighborhood ensemble probability (NEP) forecasts from all 11 cases for hourly accumulated precipitation thresholds of (a) 2.54, (b) 6.35, and (c) 12.7 mm h^{-1}. Statistical significance is plotted at the 80% confidence level, with significant differences between MULTI and LARGE, MULTI48 and LARGE, or MULTI and MULTI48 indicated by asterisks on the MULTI line, plus signs on the MULTI48 line, or asterisks along the horizontal axis, respectively. Also shown are the resolution component of the Brier score at the (d) 2.54, (e) 6.35, and (f) 12.7 mm h^{-1} thresholds and the reliability component of the Brier score at the (g) 2.54, (h) 6.35, and (i) 12.7 mm h^{-1} thresholds.

Johnson and Wang, 2016

Johnson, A., X. Wang, 2016: A study of multi-scale initial condition perturbation methods for convection-permitting ensemble forecasts. *Mon. Wea. Rev.*, **144**, 2579-2604.

Modeling IC Uncertainty in ensembles: Mesoscale IC uncertainty impact

- Near the MCS, mesoscales of the perturbation fields in MULTI48 were more consistent with the error fields than the perturbation fields in LARGE.

Johnson and Wang 2016

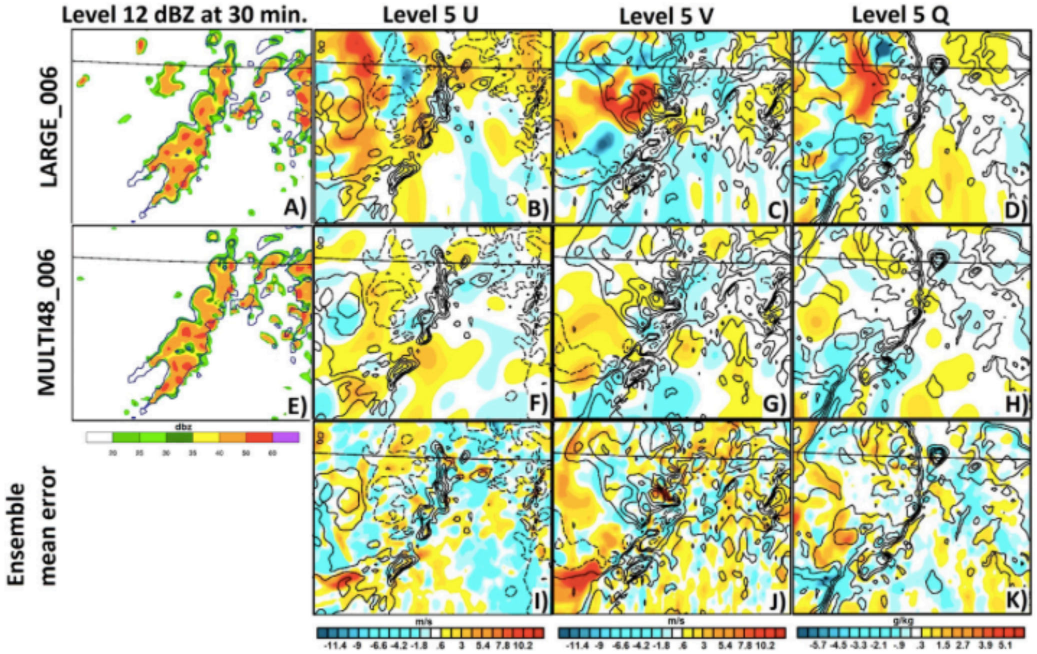


FIG. 14. Comparison of the 20 May case initial perturbations of member 006 from the LARGE and MULTI48 ensembles with the corresponding ensemble mean error. The 30-min reflectivity forecast at model level 12 for (a) LARGE_006 and (e) MULTI48_006. The LARGE_006 IC perturbation from the ensemble mean for the (b) u component of wind, (c) v component of wind, and (d) water vapor at model level 5. (f)–(h) As in (b)–(d), but for the MULTI48_006 IC perturbation. (i)–(k) The corresponding ensemble mean error (ensemble mean minus truth; note the IC ensemble mean is identical for all ensembles). Black contour overlays are the ensemble mean fields with contour intervals of 5 m s^{-1} for wind (negative values dashed) and 2 g kg^{-1} for water vapor.

Modeling IC Uncertainty in ensembles: Convective-scale IC uncertainty impact

- Explicitly including convective scales in IC perturbations can determine whether convective cell initiates or not.
- In this case, a bifurcation point was not captured by downscale propagation from the larger scale perturbation.

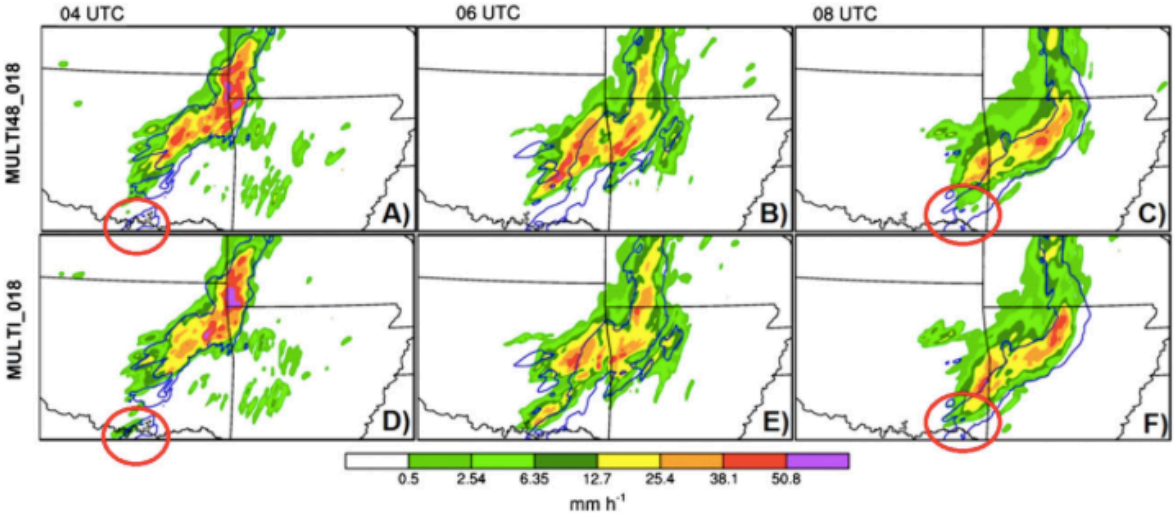
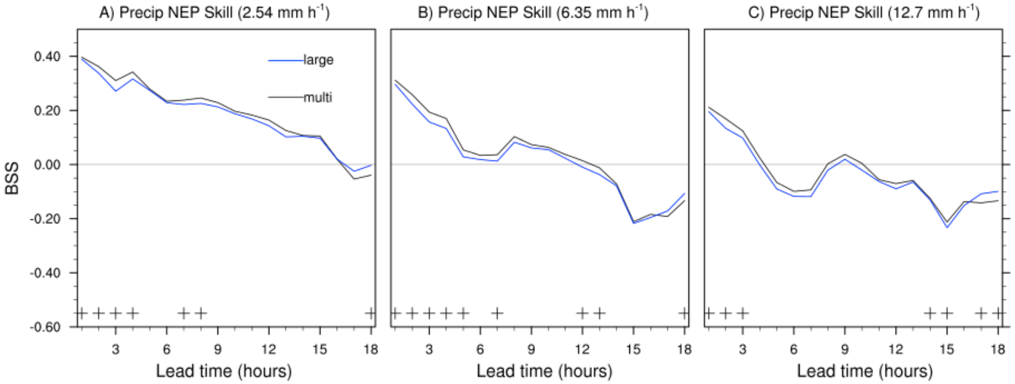


FIG. 16. Forecasts of hourly accumulated precipitation initialized at 0000 UTC 20 May and valid at (a),(d) 0400; (b),(e) 0600; and (c),(f) 0800 UTC for member 18 of the (a)–(c) MULTI48 and (d)–(f) MULTI ensemble. The observation contour at the 6.35 mm h^{-1} level is overlaid in blue.

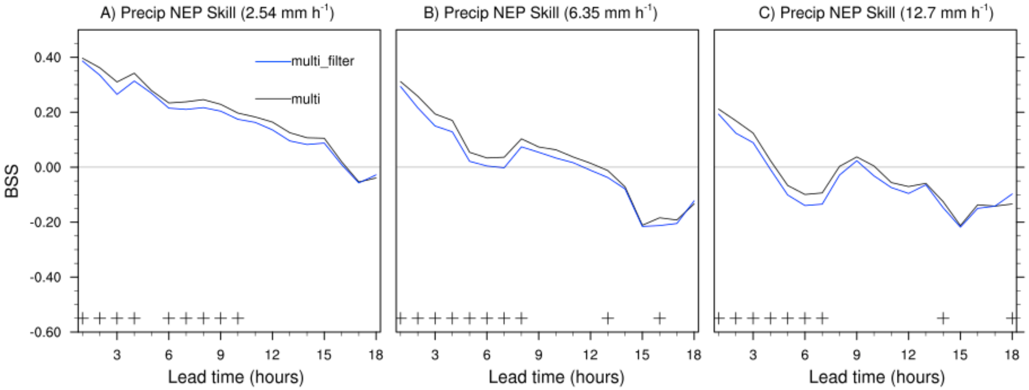
Johnson and Wang 2016

Modeling IC Uncertainty in ensembles: Real data experiments

- Real-data experiments using 10 cases (5 strongly forced, 5 weakly forced).
- IC perturbations from multi-scale EnKF (MULTI) lead to significantly (pvalue=0.1) better forecast than downscaled IC perturbations from GEFS (LARGE).



- Filtering the small scales out of MULTI (i.e., MULTI_FILTER) significantly reduces skill.

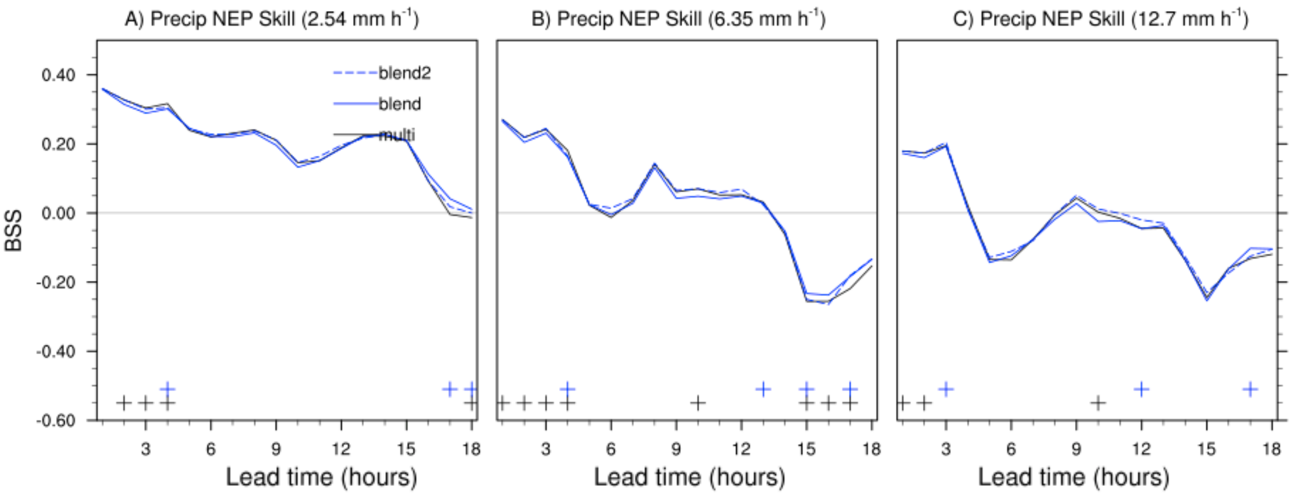


Johnson and Wang 2018, in preparation

Modeling IC Uncertainty in ensembles: Blending methods

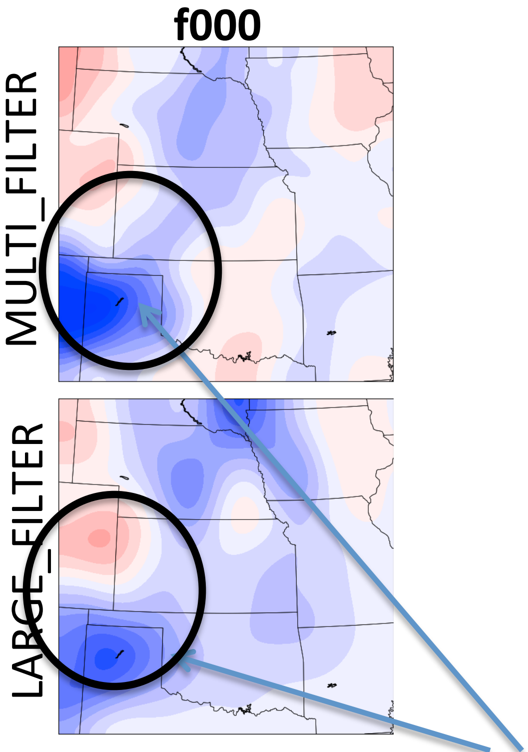
- Blending convective scale regional EnKF-based IC perturbations with coarser perturbations from global ensemble can maintain consistency between IC and LBC perturbations (Caron 2012; Wang et al. 2014).
- We find another advantage of blending may be that in cases with strong synoptic forcing the advantages of more realistic perturbation structures on convective and mesoscales in "MULTI" can be retained while also benefiting from the global ensemble perturbations.

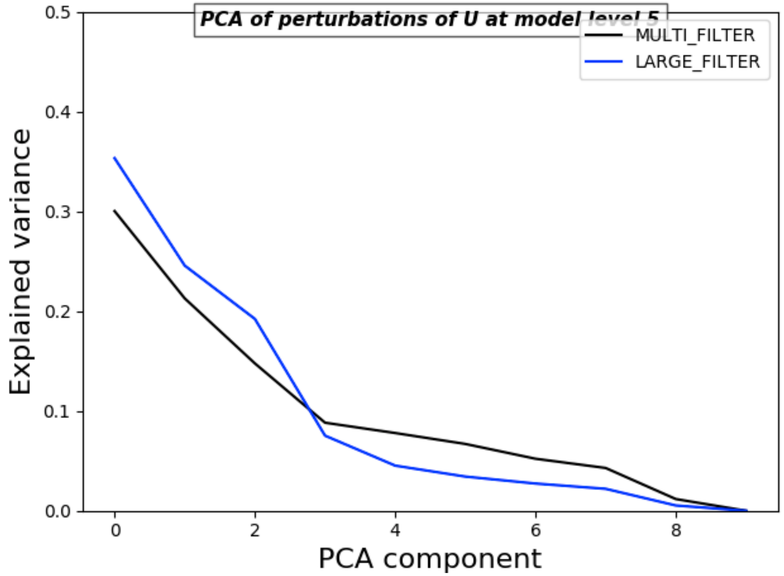
Verification over 5 strongly forced cases



Johnson and Wang 2018, in preparation

Modeling IC Uncertainty in ensembles: Blending methods





Eigenspectrum for U-wind on model level 5 for 2015051623 case

- Broad, synoptic scale mid-level vorticity and jet streak pattern upstream is the leading mode of IC variability in both ensembles.
- The LARGE_FILTER IC perturbations have (relatively) more energy in this leading mode than MULTI_FILTER which has a flatter eigenspectrum.
- This likely explains the skill advantage at some lead times for LARGE_FILTER and BLEND2 over MULTI_FILTER and MULTI, respectively, for the following reason:
  - LARGE_IC perturbations from GEFS are generated with DA cycling frequency of 6 hours that is most appropriate for synoptic scale error growth.
  - MULTI_IC perturbations from CAM ensemble are used a 10 minute cycling frequency that is most appropriate for convective scale error growth.
  - This would be most important for strongly forced cases where the synoptic scale forcing plays a more dominant role in the evolution of convective systems.

Case dependence of IC uncertainty impacts: Recent advances

- Hohenegger et al. (2006): Relative predictability of different events corresponds better to the residence time of perturbations in moist convective unstable regions than to stratiform vs. convection dominated cases.
- Johnson et al. (2014), Johnson and Wang 2016: Explicitly including convective scales in IC perturbations is more influential in cases characterized by upscale growing convection.
- Surcel et al. (2017): Enhanced predictability in cases of quasi-equlibrium convection.
- Flora et al. (2018): Practical predictability limit of supercells is very case-dependent. Further gains are possible in some cases.

- We don't have an over-arching theory of what controls variations in model predictability that can guide generation/selection of ensemble IC perturbations.

Remaining Issues

(1) How do we think of IC uncertainty in the context of coupled/unified modeling systems?

- IC perturbations must sample the relevant modes of IC uncertainty simultaneously for users interested in convective scale to global scale predictions.
- IC perturbations to slowly varying features (ocean circulations and SSTs, tropical teleconnections) and fast varying features (synoptic cold fronts, convective cold pools, etc.) all may need to realistically approximate the true expected IC errors, and their impacts on subsequent forecasts.

(2) How much practical predictability (i.e., ensemble probabilities that are better than climatology) can we buy with optimally sampled ensemble IC uncertainty in this context?

- Some forecast horizons may have potential gains limited by the dominance of other sources of forecast error.

(3) Can ensemble IC uncertainty be sampled differently for different flow regimes in a way that increases practical predictability?

- Adaptive ensemble design may be more optimal than a system that *on average* does better than any other configuration.

(4) How much more attention should we (modelers with mid-latitude focus) be paying to IC uncertainty in the Arctic and/or Tropics?

- Teleconnections are important.

Future challenges and their potential solutions

(1) Unified/coupled modeling

- Data assimilation should be developed as a multi-scale tool that consistently applies to all relevant coupled earth systems (atmosphere, ocean, ice, land surface).
- International coordination and consistent observation conventions to optimally assimilate observations sampling IC state from convective to global scales across different Earth systems.

(2) Continued basic research to understand processes of IC uncertainty growth

- If there are more degrees of freedom in a unified coupled modeling framework, larger ensemble sizes may be needed.
- 5~10 cases has been useful way to scale up conclusions from case studies, but experimental quasi-operational systems are still needed to guide future ensemble designs based on many more cases.
- Collaboration with HPC experts may help make research problems computationally tractable.

(3) Develop effective adaptive techniques

- Adaptively target certain regions or phenomena for observations to assimilate: Mixed results so far.
- Adaptively change the ensemble design based on what is known at analysis time: difficult to maintain multiple model configurations.
- Configurability of ensemble design should be "built in" to operational models and considered at the software design level for ease of maintainance.

(4) Better understanding and modeling of teleconnections

- Impacts of MJO, ENSO on longer range forecasts: need focus on multi-disciplinary projects
- Interactions with Arctic for medium range: emphasis on this previously under-explored aspect

Summary and Next Steps

IC Uncertainty grows during forecast and can be modeled via ensemble IC perturbations

→ Physical processes of error growth range from sound/gravity waves, through moist convection, to geostrophically balanced baroclinic errors and non-linear Rossby wave packets.

→ These processes have different characteristic time scales, error growth rates, and error amplitudes that need to be understood to properly sample the relevant modes of IC uncertainty in ensemble design.

Recent work has advanced our understanding of these processes and their modeling in ensembles

→At least in some cases, diabatic processes and Rossby wave dynamics explain as much or more synoptic scale error growth than baroclinic instability.

→ Ensemble flow-dependent sampling of small scales of IC uncertainty still can affect forecast performance out to ~9 hr.

→ Blending IC perturbations generated on regional domain and global domain may be an optimal design, at least in certain flow regimes.

Several challenges still remain to be addressed

→Unified/coupled modeling.

→Continued basic research to understand processes of IC uncertainty growth

→Develop effective adaptive techniques

→Better understanding and modeling of teleconnections