# **13A.1 INVESTIGATION OF NCEP GFS MODEL FORECAST SKILL "DROPOUT" CHARACTERISTICS**

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### **1. INTRODUCTION**

The NCEP Global Forecast System (GFS) model suffers from occasional forecast skill busts or "dropouts" possibly from problems with quality control (QC) and bias correction of conventional and non-conventional observations in the assimilation system along with possible model errors. Successful assimilation of multi-faceted observations requires intricate algorithms and techniques for QC and analysis. In a companion paper, Alpert et al. (2009b), we have conducted several sensitivity experiments assimilating the ECMWF gridded initial conditions (IC) as pseudoobservations (ECM runs), and using them as sole input into the NCEP Gridpoint Statistical Interpolation (GSI) analysis. These ECM 5-day forecasts alleviate several cases of Northern Hemisphere (NH) and Southern Hemisphere (SH) dropouts (Ballish et al. 2009 and Alpert et al. 2009a). Synoptically the IC errors impact the forecast most from areas that are dynamically active. ECM runs provide a methodology to make controlled experiments to study the interaction between different analysis systems. The interest is to study analysis errors in dynamically sensitive areas and their effect on forecasts.

One approach to investigating dynamically active regions is to use a relationship between the growth of mid-latitude baroclinic disturbances and model forecast errors. A suitable measure of the baroclinicity is the maximum growth rate of the most unstable mode as provided by the Eady Baroclinic Instability (EBI) index (Eady, 1949, Hoskins and Valdes (1990)). It is well known that forecast uncertainties arise from indeterminate observations that are assimilated to generate the initial state as well as the inadequacies of the model and the analysis system. To diagnose and understand the deficiencies of the analysed state of the atmosphere we use measures such as EBI, Rossby number, geostrophic, ageostrophic winds

Camp Springs, MD 20746; email: <u>Krishna.Kumar@noaa.gov</u> <sup>1</sup> Also at Perot Systems Government Solutions (PSGS), 8270 Willow Oaks Corporate Drive, Fairfax, VA 22031 and forecast error (forecast minus reference analysis) energy analysis and mass-wind balance relationship etc between the GFS, ECMWF and ECM models.

The EBI index and other measures are applied to NH and SH GFS dropouts, and the results are compared with the corresponding ECM and ECMWF forecasts. Overall, the GFS contains greater baroclinicity, by these measures, in the NH and SH mid-latitude regions compared to ECM and ECMWF 1-5 day forecasts. The evolution of the forecast error energy of GFS, ECMWF and ECM for a NH and SH dropout and the genesis of the forecast errors are investigated with a view to locate the sensitive regions.

The goal is to create detection algorithms to identify sensitive regions from which the GSI analysis errors grow with the potential for causing forecast skill dropouts. The motivation of this study is to understand these dropouts by comparing how different forecast systems treat similar situations. Dropouts are responsible for half of the skill difference between ECMWF and GFS operations alleviating them in the GFS would improve the model guidance.

## 2. NORTHERN AND SOUTHER HEMISPHERE FORECAST SKILL DROPOUT CASE STUDIES

Regardless of the steady improvements in the model and assimilation systems, various NWP centers are plagued with the occasional forecast busts, referred here as dropouts that taint the overall performance of the 5-day forecasts. These dropouts occur more frequently for the GFS model compared to the ECMWF model. The GFS and ECMWF models have several different characteristics in terms of resolution, physics, quality control procedures, the assimilation system and so forth which may cause the forecast differences. Divergence of forecast between two

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models may also occur by ingesting or not ingesting a certain class of observational data, by using different data time windows and cutoff times, data bias corrections, data QC, as well as analysis and forecast model differences

The GFS forecast skill dropouts occur both in the NH and SH regions and the spatial and temporal characteristics of forecast errors vary differently depending on dynamical and data QC related issues. We have chosen two GFS dropout cases specified by initial condition (IC) (described also as 0-h forecast (F00)) dates, one in the NH starting at 12Z on 21 October 2007, and the other in the SH starting at 00Z on 10 April 2009. The F00 as well as 5-day forecast error characteristics of both cases is described in detail for both cases in later sections. The 5-day forecast skill, as measured by the anomaly correlation (AC) score, of the 500 hPa geopotential height for 20-80 North for the GFS at 00, 06, 12, and 18Z cycles and ECMWF 00 and 12 Z cycles during October 2007 is shown in Fig. 1a. The red ellipse in Fig.1a shows a forecast skill dropout that occurred on 26 October 2007 (IC date is 21 October 2007) for all cycles of the GFS model but the ECMWF model does not have skill loss. Fig. 1b shows a similar significant 5-day forecast skill drop out for a SH case that occurred on 15 April 2009 (IC date is 10 April 2009). The ECMWF model analysis and forecasts are used as an independent verification source to compare GFS performance. Fig. 2 top panels show the 500 hPa geopotential height forecast errors (forecast-minus-verifying analysis) for the GFS at f00 (a), f48 (b), f72 (c) and f120 (d) starting from the IC at 12Z on 21 October 2007. The middle panels show the corresponding forecast errors for the ECMWF model and the bottom panels show the difference between GFS and ECMWF models. It is striking to note that the IC forecast errors emanate from North Pacific region shown as red color fill areas indicative of higher heights for the GFS (Fig. 2a bottom panel) and these forecast error structures propagate rapidly eastwards engulfing the eastern and North Atlantic regions by day 5 (Fig. 2d bottom panel). The trough in North Pacific shows substantial differences in the IC between GFS that had a dropout and ECMWF that had no dropout.

Figs. 3a,b,c,d show the 500 hPa geopotential height forecast errors for the SH dropout starting from the IC at 00Z on 10 April 2009. Positive height errors for the GFS model IC are distributed throughout the southern latitudinal band between

40-80 S as evident from Fig. 3a (bottom panel). The data coverage from satellite observations in the SH and the relative shortage of conventional data coverage, compared to the NH result in differences in the assimilation systems between GFS and ECMWF. Systematic height differences are shown between the GSI versus ECMWF analysis in Ballish et al. (2009). Further detailed investigation is necessary to understand the origin of the systematic higher height bias of the GSI analysis system. Ballish and Kumar (2008) has shown that large numbers of aircraft observations with warm temperature biases can warm the warm analysis has further analvsis. The ramifications affecting the satellite radiance bias corrections which may contribute to the existence of the systematic higher height bias.

Some of the key questions to address are: 1) are dropouts caused by poor ICs, 2) what role do dynamic instabilities play in interacting with observation errors and bias or 3) to what extent does the observation error, caused by QC problems or procedures, interact with areas of dynamical potential.

To address these questions, we use the ECMWF analysis as verification. The GFS analyses that are derived from the ECMWF gridded IC as pseudo-observations are referred here as ECM runs. Fig. 4 shows a schematic of how ECM analysis is created from the original ECMWF gridded analysis file containing 14 mandatory pressure levels on a 1x1 degree grid which is used for making ECM pseudo obs. Analysis/forecast experiments for a particular cycle hour (here, for example 00Z and 06Z are shown) are performed with the GSI analysis ingesting the pseudo ECM obs in conjunction with the GFS background (guess) to create the final ECM analysis valid for the cycle which is further used to generate the ECM 24h to 120-h forecasts. The analysis and forecasts from the NCEP's operational GFS, the operational ECMWF and the ECM models are used to compare the forecast skill and errors between different models. Fig. 5a shows the NH 5-day anomaly correlation scores at 500 hPa for several dropout IC dates of GFS, ECMWF, and ECM model runs. The dates shown on the bar graph span a time from 21 October 2007 at 12Z to 04 March 2008 at 12Z. The forecast skill corresponding to 21 October 2007 at 12Z case shows very low skill for the operational GFS (blue bars) compared to the ECMWF (red bars). The ECM run (yellow bar) for this particular

case shows poor forecast skill compared to the operational GFS. This low skill for this case is due to inherent problems in using the GFS analysis (output from GSI) valid at 12Z in combination with the pseudo ECM obs. This initial problem is shown to be corrected by cycling the ECM runs by using the 6-h forecast as the background guess as shown in Fig. 4. ECM runs show skill for several subsequent NH cases and prove to be a good representation for ECMWF analysis. The IC case for 22 October 2007 shows excellent forecast skill for both ECM and ECMWF compared to the GFS thereby enhancing the value of using the ECM runs as constructive tool to diagnose and understand the GFS forecast skill dropouts by conducting various controlled data impact, data QC experiments, etc. For SH dropouts, the skill of the ECM is better compared to the NH (Fig. 5b).

#### 3. CONNECTION BETWEEN FORECAST ERRORS AND EADY BAROCLINICITY INDEX

One of the rationales behind developing diagnostic dynamical tools is to assist the forecast busts/dropout analysis in order to understand and predict the location of sensitive regions from which the GSI analysis errors grow disproportionately and consequently degrade forecast skill of the GFS. These sensitive regions result because of dynamical reasons emanating from flow dependent characteristics and cause forecast amplification of analysis errors. There is a connection between baroclinic disturbances, growing model forecast errors, and synoptic activity in mid-latitudes (Klinker and Ferranti, 2001). The differences in GSI and ECMWF analyses are an estimate of analysis error between the two systems. The analysis errors from a model can be quantified by computing the forecast error, which is the difference between a model forecast and its corresponding verifying analysis.

A measure of the vertically averaged forecast error is computed by averaging the energy over the geographical domain, given by

$$E = \frac{1}{2A(p_b - p_t)} \int_{p_t}^{p_b} \int_{A} \left( u'^2 + v'^2 + \frac{c_p}{T_r} T'^2 \right) dAdp$$

The symbols u', v', T' are forecast errors (forecast minus verifying analysis) in the zonal wind, meridional wind, and temperature respectively. T<sub>r</sub> is a reference temperature as 273 K. A represents the horizontal domain, pt and ph represent the bottom and top of a layer (Caron et. al. 2007). The forecast error energy is zonally averaged over the SH extratropics (20 - 90 S) for all pressure levels between 1000 hPa to 100 hPa. The error energy is shown for the SH dropout case (00Z on 10 April 2009) with corresponding forecast times of f00-f120. Figs. 6a-f respectively show the domain averaged forecast error energy (J/kg). The 00-h forecast errors (Fig. 6a) show that both the GFS and ECM models exhibit small errors even with a single time step. The forecast error energy at 24-h to 120-h forecasts for the GFS model (red line) demonstrates significantly higher values at all levels compared to the ECMWF model. The forecast error energy for the GFS at the jet stream level (around 300 -200 hPa) is about 2 times that of values corresponding to the ECMWF model. Another interesting feature to note is that the ECM forecast error energy distribution at the 24-h and 48-h forecast draws closer to the ECMWF error energy distribution primarily because the ECM model analysis is designed to have the same information content as the ECMWF analysis. Thus, the ECM run increases the forecast skill with an AC score of 0.73 compared to the GFS dropout AC score of 0.49 (Fig. 5b). The forecast error energy distribution at 72h, 96h and 120h of the ECM model aligns closely with the error distribution of the ECMWF model (Fig. 6a).

A diagnostic analysis of the wind (W term) and mass (M term) terms in the forecast error energy equation is examined elucidating the relative importance of both terms. Figure 7 displays the contribution from the W and M terms of the 24-h forecast error energy for the GFS, ECMWF and ECM models for the SH dropout IC of 00Z 10 April 2009. It is evident that the predominant contribution comes from the W term with a more baroclinic structure with the largest errors around the jet stream level. The contribution from the M term is relatively small and the vertical level structure is more barotropic. Kleist et al. (2009) has recently updated the GSI analysis system by improving the balance between variables achieved through the inclusion of a Tangent Linear Normal Model Constraint. Since the largest contribution of the forecast error energy originates from the Wterm it is critical to understand the overall balance properties between the mass and wind fields in the model analysis and forecast, particularly over the error emanating sensitive regions within a diagnostic framework.

To examine whether the forecast error energy behaves differently over different geographic regions, the error energy at 120-h forecast is displayed over the midlatitude NH domain (20N -90N) (Fig. 8a) as well as over the tropical domain (20S – 20N) (Fig. 8b) for the SH dropout IC at 00Z 10 April 2009 for the GFS, ECMWF and ECM models. The forecast error energy distribution is very similar for all the models and the GFS model (red curve) has only slightly higher error energy when compared to the ECMWF (green curve) and the ECM (blue curve) error is tied to the ECMWF error distribution. The reason may be that both the GFS and ECMWF models in the NH have more similarities than dissimilarities in assimilating the conventional observations that are more prevalent and there is less sensitivity on the 120-h forecast to the IC errors. The forecast error distribution over the tropics for both the GFS and ECM runs exhibit higher errors when compared to the ECMWF and it may be possible that there are large imbalances in the mass wind relationship between the GFS and ECMWF models.

It would be advantageous to have an adjoint or tangent linear version of the model forecast, such as in (Errico and Raeder, 1999), to estimate the analysis error based on the observed 5-day forecast error. However, the uncertainty in the verifying analysis coupled with large error in using such models well beyond their expected usefulness of about one day makes this option non-robust. It would be useful to have a combined adjoint of the analysis and forecast model to estimate whether observed data helped or hurt the forecasts through short ranges such as one day (Zhu and Gelaro 2008). Unfortunately, such adjoint tools are not currently available at NCEP. Since some analysis errors lead to forecast errors that get smaller with time, but some errors lead to forecast errors that amplify with time, diagnostics are needed to check on model forecast sensitivity to analysis errors using simple measures.

In order to delineate the origin of analysis and forecast error differences between two models, it is paramount to understand the critical differences between their respective thermodynamic and dynamical characteristics. This is explored computing the baroclinic instability growth of the transient eddy activity of the GFS, ECMWF and ECM basic flows. The growth of transient waves in the mid-latitude westerlies in the presence of vertical shear originates from baroclinic instability mechanism discovered by Charney (1947) and Eady (1949). The maximum growth rate of the most unstable mode provided by the Eady's model, i.e., the measure of the Eady Baroclinicity Index (EBI) as shown by Hoskins and Valdes, 1990, is given by

# $\sigma_{\rm BI} = 0.31 f | (-gp/RT) \partial \mathbf{V} / \partial \mathbf{p} | N^{-1}$

where f is the Coriolis parameter, V is the total vector wind, N is the Brunt Väisällä frequency and all other parameters have their usual meaning. EBI is proportional to the vertical wind shear and the static stability of the basic flow. As shown in Ballish et al. (2009), the Eady index is computed using the three dimensional analysis and forecast fields of GFS, ECMWF as well as the ECM models to show potential action areas or volatility to propagate IC errors into forecast differences the two NH and SH dropout cases. The EBI also shows some noise at less than 1-day forecasts when using an analysis as a background guess instead of time filtered previous forecasts as the background. Dynamically active areas according to the EBI index intersecting with areas where QC problems in observation types are found and tested to see their relevance to dropouts. These regions compare reasonably with the sensitive regions shown by adjoint sensitivity results found at other national centers.

Figs. 9a,b,c show respectively the total EBI at 500 hPa in units of per day (day-1) for the 24-h GFS forecast (top panel), the corresponding ECMWF model forecast (middle panel) and the corresponding ECM model forecast from 12Z 21 October 2007 ICs. It is quite evident that the GFS model shows more pronounced baroclinicity in the NH over NW United States and the adjacent North Pacific ocean compared to the ECMWF model. The ECM model has hybrid characteristics of both the GFS and the ECMWF model EBI distribution. It may be noted that the ECM 5-day AC score starting from this IC did not alleviate the forecast skill dropout compared to ECM 5-day AC score using the 12Z 22 October 2007 IC which apparently alleviated the dropout using the same ECMWF pseudo obs methodology adopted in generating both ECM analyses and its respective 5-day forecasts. We are currently conducting data denial and impact studies to define the extraordinary characteristics for the 12Z 21 October 2007 IC. It is evident that the greatest baroclinic potential lies in the eastern part of the broad Pacific trough, the differences in this case,

cause a dropout in the 5-day forecast.

The adjoint sensitivity of 24h forecast error to IC for the 00Z 21 October 2007 case for the FNMOC model (Fig. 10) at

# http://www.nrlmry.navy.mil/adap-bin/tcs\_adap.cgi

shows similar sensitive areas. Large differences are along the trough line with dipole structures (not shown) indicating differences in position (phase), and large potential for these Rossby wave details. The GFS model shows more pronounced baroclinicity compared to ECMWF operations. The differences are as much as 20% of the total index. Using this index to find potential baroclinic areas, and intersection with differences between background guess and analysis, shows promise to form the basis for an automated realtime dropout detection system.

Fig 11a,b,c show respectively a longitude-time (x-t) Hovmoller cross-section of the EBI at 500 hPa averaged over the extratropical latitude band (30N - 70N) starting from the NH dropout IC at 12Z 21 October 2007 (00-h) to the 5-day forecast on 12Z 26 October 2007 (120-h forecast) for the GFS (a), ECMWF (b) and ECM (c). It is evident from top and middle panels that there is more pronounced baroclinicity (larger areas of dark yellow and red shadings) for the GFS (a) than the ECMWF (b) particularly over 180W to 120W and also over 60W to 20W. The most unstable baroclinic Rossby waves exhibit well organized east-west propagation characteristics for the ECMWF model than the GFS model. The EBI for the ECM model (bottom panel, c) shows much larger baroclinicity at the 00-h compared to both GFS and ECMWF because of inherent problems in using the GFS analysis (output of the GSI) as the background guess in combination with the ECMWF pseudo obs. This initial problem can be rectified by cycling the ECM runs by using the 6-h forecast as the background guess.

Figs. 12 a,b,c show respectively the total EBI for the 00-h forecast at 500 hPa for the SH dropout IC from 00Z 10 April 2009 for GFS (a), ECMWF (b) and ECM (c). Strong baroclinic regions lie over the latitudinal band around 35 S - 65 S for all the models displaying the baroclinic wave structure. Here again the GFS model displays much stronger potential for baroclinicity than the ECMWF model. The EBI for the ECM model has mixed characteristics of that of GFS and ECMWF

models. Figs. 12 d,e,f, show respectively the total EBI distribution for the 120-h forecasts for all the three models GFS (d), ECMWF (e) and ECM (f). The baroclinicity corresponding to the 120-h GFS forecast (d) are relatively stronger than the ECMWF model (e) and the ECM 120-h forecast exhibits closer correspondence with the ECMWF model.

Fig. 13a,b,c show respectively a longitude-time (x-t) Hovmoller cross-section of the EBI at 500 hPa averaged over the extratropical latitude band (35S - 70S) starting from the SH dropout IC at 00Z 10 April 2007 (00-h) to the 5-day forecast on 00Z 15 April 2007 (120-h forecast) for the GFS (a), ECMWF (b) and ECM (c). The top and middle panels illustrate the fact that there is more pronounced baroclinicity (larger areas of dark vellow and red shadings) for the GFS (a) than the ECMWF (b) particularly over 60E to 180E and also over 60W to 120W. There are well organized propagation characteristics apparent from the most unstable Rossby waves from the ECMWF models than the GFS model. The EBI for the ECM model (bottom panel, c) shows somewhat closer to the GFS model than to the ECMWF model. It is clear that the enhanced forecast error energy distribution for the GFS model could be primarily due to the enhanced baroclinicity of the GFS as measured by the EBI which may signify potential areas that can cause dropouts and could be an indicator in a dropout detection scheme compared to the more expensive and sophisticated adjoint techniques. More detailed diagnostic work needs to be carried out to investigate the correspondence between the forecast error energy and EBI characteristics.

## 4. INVESTIGATION OF DROPOUTS WITH ROSSBY NUMBER AND AGEOSTROPHIC WIND MEASURES

We have seen from Section 4 that the largest contribution of the forecast error energy originates from the W-term. The balance properties between the mass and wind fields in the model analysis and forecasts may be central in identifying the error that can occur over sensitive regions because of deficiencies in QC algorithms. In order to diagnose the strength and weaknesses of the midlatitude baroclinic systems a suitable measure such as Rossby number is calculated for both the NH and SH forecast skill dropout cases. The Rossby number is a measure of the ratio of the inertial acceleration and Coriolis acceleration terms and given by

$$R o = \frac{|u \cdot \nabla u|}{|fu|}$$

where **u** is the horizontal vector wind and f is the Coriolis parameter. The smallness of the Ro (~0.1) over the midlatitude region implies that the flow is principally in geostrophic balance. Whenever intense cyclonic systems form Ro values could approach unity which implies a sharp deviation from geostrophic balance and here the condition of gradient wind balance will be prevalent. We have also calculated the u and v components of the ageostrophic (the deviation from the geostrophic part) winds  $\mathbf{u}_{ag} = \mathbf{u} - \mathbf{u}_{g}$  for both the NH and SH forecast skill dropout cases.

Figs. 14a,b,c show respectively a longitudetime (x-t) Hovmoller cross-section of the Rossby number at 500 hPa averaged over the extratropical latitude band (30N - 70N) starting from the NH dropout IC at 12Z 21 October 2007 (00-h) to the 5-day forecast on 12Z 26 October 2007 (120-h forecast) for the GFS (a), ECMWF (b) and ECM (c). The Rossby number is larger for the GFS than the ECMWF which implies that there is higher acceleration for the GFS than the ECMWF. GFS also shows less progression in 2-4 day forecast. ECM distribution compares closer with the ECMWF than the GFS. Fig 15a,b,c show respectively a longitude-time (x-t) Hovmoller crosssection of the Rossby number at 500 hPa averaged over the extratropical latitude band (70S to 35S ) starting from the SH dropout IC at 00Z 10 April 2009 (00-h) to the 5-day forecast on 00Z 15 April 2009 (120-h forecast) for the GFS (a), ECMWF (b) and ECM (c). The Rossby number is slightly larger for the GFS in certain longitudinal regions than the ECMWF and overall the distribution has similar character. ECM distribution appears similar to both the GFS and ECMWF model. Figs. 16a,b,c show respectively a Hovmoller cross-section of the ageostrophic zonal wind component at 500 hPa averaged over the extratropical latitude band (30N -70N) starting from the NH dropout IC at 12Z 21 October 2007 (00-h) to the 5-day forecast on 12Z 26 October 2007 (120-h forecast) for the GFS (a), ECMWF (b) and ECM (c) and Figs. 16d,e,f show the corresponding ageostrophic meridional wind component. There are some striking differences between GFS and ECMWF for both zonal as well as meridional ageostrophic distributions by day 2 as well as by the end of the forecast period. Figs. 16 a,b,c,d,e,f are the corresponding Hovmoller cross-section of the zonal and meridional ageostrophic wind components for the SH dropout date corresponding to 00Z 10 April 2009. There are moderate differences between the GFS and ECMWF models by day 3 to day 4 forecast period. The ECM model has similar distribution to ECMWF model than the GFS model.

These ageostrophic deviations in the wind components need to be investigated in the light of understanding the wind and mass balance relationship and will be reported in the future.

#### 5. SUMMARY AND FUTURE WORK

Forecast error energy measures, diagnostic tools such as EBI, diagnostic measures to study the mass wind balance relationships are used in identifying the location of sensitive regions from which GSI analysis errors grow and subsequently degrade GFS forecast skill. NH and SH domain averaged forecast error energy calculations between GFS, ECMWF and ECM models verified against its own analyses indicate that the GFS forecast error has higher errors energy concentrated through out the troposphere compared to the ECMWF model errors. The ECM model errors are similar to the ECMWF model errors because of the explicit use of the ECMWF IC to derive the ECM model analysis and forecast. The origin of the larger forecast error energy for the GFS model is probably because of the larger growth rate values of the most unstable baroclinic waves in the GFS model compared to the ECMWF model. These instabilities could play a central role in causing the NH and SH dropouts if coupled with observation error that is assimilated into the analysis system. The inherent sensitive regions of the forecast errors can be investigated by using these simple diagnostic tools in conjunction with the development of more sophisticated adjoint sensitivity schemes. In general, the EBI calculations show that the GFS model possesses more pronounced baroclinicity when compared to the ECM model and the ECMWF operations. Additional diagnostic tools for the dropout analysis are currently being developed.

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Figure 1. The 5-day 500 mb Anomaly Correlation scores for the operational GFS and ECMWF models. Note the table in the lower left corner. EC00 and EC12 refer to the 00Z and 12Z cycles of ECMWF operations; whereas, 00Z, 06Z, 12Z, and 18Z represent the operational cycles of the GFS model.



Figure 2. Comparison of the operational GFS and ECMWF (ECM) models for the 12Z cycle on 21 October 2007. In each panel is a time series of the GFS and ECM (a) F00 (initial condition), (b) F48 (2-day), (c) F72 (3-day), and (d) F120 (5-day) forecasts. The

contour interval is 100 gpm, and the shaded regions represent FORECAST – ANALYSIS differences in the GFS and ECM panels. The  $3^{rd}$  panel is the forecast difference (GFS – ECM).



Figure 3. Comparison of the operational GFS and ECMWF (ECM) models for the initial condition at 00Z on 10 April 2009. In each panel is a time series of the GFS and ECM (a) F00 (initial condition), (b) F48 (2-day), (c) F72 (3-day), and (d) F120 (5-day) forecasts. The contour interval is 100 gpm, and the shaded regions represent FORECAST – ANALYSIS differences in the GFS and ECM panels. The 3<sup>rd</sup> panel is the forecast difference (GFS – ECM).



Figure 4. Schematic representation of an ECM cycled run using the GSI/GFS system and ECMWF pressure grib analysis.



Figure 5. Comparison of a) Northern Hemisphere and b) Southern Hemisphere anomaly correlation skill score dropouts for the GFS, ECMWF, and ECM models.



Figure 6. Forecast error energy (J/kg) of the GFS (red), ECMWF (green), and ECM (blue) 00Z 10 April 2009 model runs at a) 00-hour, b) 24-hour, c) 48-hour, d) 72-hour, e) 96-hour, and f) 120-hour forecasts.



Figure 7. Forecast error energy (J/kg) analysis of the wind (W) and mass (M) terms for the 24-h forecasts of the GFS, ECMWF, and ECM models at 00Z 10 April 2009.



Figure 8. Forecast error energy analysis of geographic regions such as the a) Northern Hemisphere (20-80N) and b) Tropics (20N-20S).



Figure 9. The total Eady Baroclinicity Index (EBI) (day <sup>-1</sup>) at 500 hPa for the 24-h forecast from the 12Z 21 October 2007 initial conditions for a) GFS, b) ECMWF, and c) ECM runs.



Figure 10. FNMOC model sensitivity error estimates from 00Z 21 October 2007.



Figure 11. Hovmoller diagram of the total EBI (day <sup>-1</sup>) at 500 hPa beginning at 12Z 21 October 2007 through the 5-day forecast ending on 12Z 26 October 2007. EBI is calculated between 30-70N for a) GFS, b) ECMWF, and c) ECM runs.



Figure 12. The total Eady Baroclinicity Index (EBI) (day <sup>-1</sup>) at 500 hPa for the initial condition 00-h and 120-h forecast from the 00Z 10 April 2009 initial conditions for a,e) GFS, b,d) ECMWF, and c,f) ECM runs.



Figure 13. Hovmoller diagram of the total EBI (day <sup>-1</sup>) at 500 hPa beginning at 00Z 10 April 2009 through the 5-day forecast ending on 00Z 15 April 2009. EBI is calculated between -35 and -70S for a) GFS, b) ECMWF, and c) ECM runs.



Figure 14. Hovmoller diagram of the Rossby Number at 500 hPa beginning at 12Z 21 October 2007 through the 5-day forecast ending on 12Z 26 October 2007. EBI is calculated between 30-70N for a) GFS, b) ECMWF, and c) ECM runs.



Figure 15. Hovmoller diagram of the Rossby Number at 500 hPa beginning at 00Z 10 April 2009 through the 5-day forecast ending on 00Z 15 April 2009. EBI is calculated between -35 and -70S for a) GFS, b) ECMWF, and c) ECM runs.



Figure 16. Hovmoller diagrams of the ageostrophic zonal wind component (a, b,& c) and the ageostrophic meridional wind component (d, e, & f) at 500 hPa for the latitude band between 30-70N from the dropout at 12Z 21 October 2007. The GFS, ECMWF, and ECM models are represented.



Figure 17. Hovmoller diagrams of the ageostrophic zonal wind component (a, b,& c) and the ageostrophic meridional wind component (d, e, & f) at 500 hPa for the latitude band between 20-70S from the dropout at 00Z 10 April 2009. The GFS, ECMWF, and ECM models are represented.