2.1 DEVELOPMENT OF A MOS THUNDERSTORM SYSTEM FOR THE ECMWF MODEL

Phillip E. Shafer * and David E. Rudack
Meteorological Development Laboratory
Office of Science and Technology
National Weather Service, NOAA
Silver Spring, MD

1. INTRODUCTION

The Meteorological Development Laboratory (MDL) has recently developed an experimental suite of station-based, Model Output Statistics (MOS) guidance from the European Centre for Medium-Range Weather Forecasts (ECMWF) model, and has made this guidance available internally to National Weather Service (NWS) forecasters. MDL has been producing statistical guidance based on the MOS technique for decades (Glahn and Lowry 1972). To date, guidance for temperature, dewpoint, wind speed and direction, sky cover, probability of precipitation, and precipitation type has been developed (Rudack et al. 2014; Shafer and Rudack 2014). Skill of the ECMWF-based MOS guidance has been shown to be superior to Global Forecast System (GFS)-based MOS, and in some cases, ECMWF MOS forecasts have similar or better skill than GFS MOS forecasts valid up to 36 hours earlier (Rudack et al. 2014; Shafer and Rudack 2014).

Forecasts of thunderstorms are important to users throughout the weather enterprise, and they are especially important to aviation interests. Thunderstorms account for the majority of air traffic delays that occur during the spring and summer months. To meet the needs of this diverse community, MDL has produced automated probabilistic guidance for thunderstorms and severe weather for many years, first based on the Nested Grid Model (e.g., Bower 1990, 1993), the Aviation model (e.g., Hughes 2001), the Eta model (e.g., Hughes 2002), and more recently the GFS (e.g., Hughes 2004; Shafer and Gilbert 2008). MDL also has produced probabilistic guidance for thunderstorms for 2-hour periods out to 24 hours in advance as part of the Localized Aviation MOS Program (LAMP; Charba and Liang 2005; Charba and Samplatsky 2009).

*Corresponding author address:
Phillip E. Shafer, 1325 East-West Highway, Station 10434, Silver Spring, MD 20910-3283; e-mail: Phil.Shafer@noaa.gov

This paper describes the development of a new MOS thunderstorm system for the ECMWF model (hereafter referred to as ECM). Several years of forecast output from the ECM and observations of lightning and severe weather are used to develop equations for the probability of a thunderstorm and the conditional probability of a severe thunderstorm for 3-, 6-, 12-, and 24-h periods over the CONUS. A k-fold cross-validation is performed to assess the skill of the new ECM thunderstorm system and its performance compared to climatology and MOS forecasts from the GFS and North American Mesoscale (NAM) models.

2. DEVELOPMENT METHODOLOGY

2.1 *Thunderstorm Predictand*

Cloud-to-ground (CG) lightning data from the National Lightning Detection Network (NLDN; Cummins et al. 1994) is used to define the occurrence of a thunderstorm. Each CG strike was assigned to a grid cell on a 40-km Lambert Conformal grid trimmed to within 150 km of the CONUS boundaries (where the detection efficiency of the NLDN is highest). The geographical coverage of the CONUS thunderstorm grid (Fig. 1) includes all NWS-defined near-shore marine zones. All strikes occurring within a given hour were summed over 3-, 6-, 12-, and 24-h periods and assigned to the center of each grid cell. A thunderstorm "event" occurred if one or more CG strikes was observed within a grid cell during the given time period, while periods with no CG lightning were considered non-events.

2.2 *Conditional Severe Predictand*

Observations of severe weather consisted of individual reports of tornadoes, large hail, and thunderstorm wind gusts (or damage) compiled from storm data reports and quality controlled by the Office of Climate, Water, and Weather Services (OCWWS). Each report was assigned to a grid cell on an 80-km Lambert Conformal grid over the CONUS. An 80-km grid box roughly corresponds to an area within 25 miles of a point, which matches the definition used for outlooks issued by the Storm Prediction Center (Brooks et al. 2003). The severe thunderstorm grid does not extend beyond the borders of the CONUS, and grid boxes in areas of low population density (i.e. where severe events are likely to go unreported) were excluded from the development (Hughes 2001). The NWS criteria for severe hail was changed from 0.75” to 1.0” nationwide on 5 January 2010. For purposes of this development, the new criteria was retroactively applied to all hail reports that pre-date the change, so that the definition of a severe event remained consistent throughout the sample.

The severe reports were summed over 3-, 6-, 12-, and 24-h periods and assigned to the center of each 80-km grid cell. The severe thunderstorm predictand was made conditional on the occurrence of a thunderstorm – that is, only thunderstorm events were considered. Here, a thunderstorm event is defined as the occurrence of one or more CG lightning strikes within the 80-km grid cell during the period. If a thunderstorm occurred during a given period and severe weather was also reported, then a severe thunderstorm occurred. If a thunderstorm occurred and there were no reports of severe weather, then the event was considered non-severe.

2.3 *Climatological relative frequencies*

Monthly relative frequencies of CG lightning and conditional severe weather were used as potential predictors in the ECM MOS thunderstorm system. The relative frequencies were calculated for 3-, 6-, 12-, and 24-h periods from twenty years (April 1994 – March 2014) of NLDN lightning observations and severe weather reports at each 40-km and 80-km grid cell used in the development (see Sections 2.1 and 2.2). The severe thunderstorm relative frequencies tend to be discontinuous in space due to the rarity of severe events, especially during the cool season. To produce a smoother climatology, a 5-pt spatial smoother was applied to the relative frequencies. Figure 2 shows example plots of the 12-h thunderstorm relative frequency for the month of August and 12-h conditional severe relative frequency for June. As evident in the climatology, thunderstorms are a regular occurrence over the Gulf Coast and Southwest U.S. during August. As one would expect, the Great Plains is a hot spot for severe weather during spring, with other maxima over the Ohio Valley and Mid-Atlantic regions.

2.4 *Regression analysis*

Equations to predict the probability of a thunderstorm (PoTS) and the conditional probability of a severe thunderstorm (CPoSvr) for 3-, 6-, 12-, and 24-h periods were developed for both the 0000 and 1200 UTC cycles of the ECM. Roughly 6 years of ECM data were available for this development (April 2008 – March 2014). ECM forecast fields, variables derived from these fields, and climatological relative frequencies (see Section 2.3, above) were offered to the regression analysis. All ECM fields were archived on a 47-km polar stereographic grid and interpolated to each of the 40-km and 80-km gridpoints used to assign the lightning and severe observations (see sections 2.1 and 2.2, above). The developmental data were stratified into three seasons: spring (16 March – 30 June), summer (1 July – 15 October), and cool (16 October – 15 March), with separate equations developed for each season.

As with previous MOS thunderstorm developments, multiple linear regression was used to derive the equations (e.g., Hughes 2002, 2004; Shafer and Gilbert 2008). The method named Regression Estimation of Event Probabilities (REEP) relates the binary predictands to a linear combination of predictor variables by means of a stepwise selection procedure (Miller 1964). In order to obtain stable forecast equations, all gridpoints were combined into one large region for the regression analysis. This produces a Generalized Operator Equation (GOE) that is applicable to all gridpoints within the region. Equations for 3-h periods were developed every 3 hours out to 84 hours in advance, while equations for 6-, 12-, and 24-h periods were developed every 6 hours out to 192 hours. To assess the limit of predictability beyond day 8, additional projections were tested through 240 hours for both PoTS and CPoSvr. Results are presented in Section 3.

Predictors most often selected in the PoTS equations include the model convective precipitation amount, precipitable water, the product of the K-index and thunderstorm relative frequency, and various stability indices such as Convective Available Potential Energy (CAPE) and Showalter Stability Index. The most important predictors for CPoSvr include the above predictors as well as wind speed at various levels, low-level wind shear, and the product of the Severe WEAther Threat (SWEAT) index and the conditional severe relative frequency.

2.5 *K-fold cross-validation*

The skill of the new ECM MOS thunderstorm system was assessed by performing a k-fold cross validation as follows:

1. Season 1 (of 6) was withheld as an independent sample. Test equations were developed for the 0000 UTC cycle using seasons 2 through 6 as training data.
2. Forecasts were made for season 1 from the equations developed in step 1.
3. Forecasts generated in step 2 were post-processed to truncate the probabilities to the 0 to 1 range.
4. Consistency checks were performed on the truncated forecasts generated in step 3. These checks insure that the probability for the longer period is at least as great as the larger of the probabilities for the shorter periods contained within it.
5. Steps 1 – 4 were repeated for each season in the development sample, creating 6 seasons of independent forecasts.

3. VERIFICATION

3.1 *Comparison to climatology*

The percent improvement of the Brier Score relative to climatology (or Brier Skill Score), is used as an objective measure of forecast skill for the new ECM MOS thunderstorm guidance. Here, the reference climatology is the monthly relative frequency of CG lightning and conditional severe weather. Brier Skill Scores (BSS) were calculated for the aggregate of all 6 independent test seasons generated from the k-fold cross-validation for the 0000 UTC cycle (see Section 2.5). Figure 3 shows plots of BSS for the ECM MOS PoTS guidance for the spring, summer, and cool seasons. For the 3-h PoTS guidance (Fig. 3a), the scores are positive for all projections through 84 hours, while scores for the 6-h (Fig. 3b), 12-h (Fig. 3c), and 24-h (Fig. 3d) guidance are positive all the way through 240 hours. Some diurnal variation in skill is evident due to the diurnal nature of thunderstorms particularly during the spring and summer seasons. In all plots, skill scores are generally greatest during the cool season when climatology tends to be a less accurate forecast.

Scores for the ECM MOS CPoSvr guidance are shown in Figure 4. Skill for the 3-h CPoSvr guidance (Fig. 4a) is positive through 84 hours, although only marginally so for the summer season. The 6-h (Fig. 4b) and 12-h (Fig. 4c) guidance appears skillful through at least 144 hours for all seasons, with marginal skill for later projections. Positive skill is achieved for the 24-h guidance (Fig. 4d) through at least 168 hours, and through 240 hours for the more active spring season. This result is encouraging and demonstrates that skillful MOS forecasts of severe weather are possible with the ECM even for projections up to 10 days in advance.

3.2 *Comparison to GFS MOS and NAM MOS*

To assess the skill of the new ECM MOS thunderstorm guidance relative to other MOS guidance produced by MDL, skill scores were calculated for the 0000 UTC GFS MOS and 0000 UTC NAM MOS thunderstorm and conditional severe guidance for the 3-yr period 2011-2013. At present, GFS MOS thunderstorm guidance is produced through 192 hours and severe guidance is produced through 84 hours, so direct comparison with the ECM MOS for later projections is not possible. Figures 5a and 5b show comparisons of BSS for the 12-h PoTS and 12-h CPoSvr guidance, respectively, for the spring season. For PoTS (Fig. 5a), the ECM MOS is clearly superior especially for projections beyond 30 hours, with NAM MOS having the lowest skill. Differences in skill for CPoSvr (Fig. 5b) are not as pronounced, but generally ECM MOS forecasts are superior to GFS MOS and NAM MOS for all projections through 84 hours. Comparisons for the summer and cool seasons (not shown) are very similar.

4. SUMMARY & FUTURE WORK

MDL has developed a new ECM-based MOS thunderstorm system for the CONUS. Equations for the probability of a thunderstorm and the conditional probability of a severe thunderstorm were developed for 3-, 6-, 12-, and 24-h periods for both the 0000 UTC and 1200 UTC cycles. Results from cross-validation indicate the new ECM MOS guidance is skillful for lead times as long as 240 hours, and is superior to corresponding GFS MOS and NAM MOS thunderstorm forecasts.

The new ECM MOS thunderstorm guidance described in this paper will be incorporated into the experimental short-range and extended-range ECM MOS text bulletins that are made available internally to NWS forecasters.[1] This implementation is planned for mid-2015. Forecasts for PoTS and CPoSvr are made at the METAR sites by matching the MOS stations to the nearest 40-km / 80-km thunderstorm gridpoint. The short-range ECM MOS text bulletin will contain the 6- and 12-h probabilities out to 84 hours, while the extended-range message will contain 12- and 24-h probabilities out to 192 hours. In the future, MDL will produce ECM MOS guidance in graphical format for internal NWS use, which will include grids of thunderstorm probability for 3-, 6, and 12-h periods. The development of ECM MOS thunderstorm guidance for Alaska is also planned.

5. ACKNOWLEDGMENTS

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[1] ECMWF data is provided to the National Weather Service for internal use only. ECMWF model data is considered proprietary and confidential. The ECMWF MOS guidance derived from ECMWF data is restricted for internal use only.

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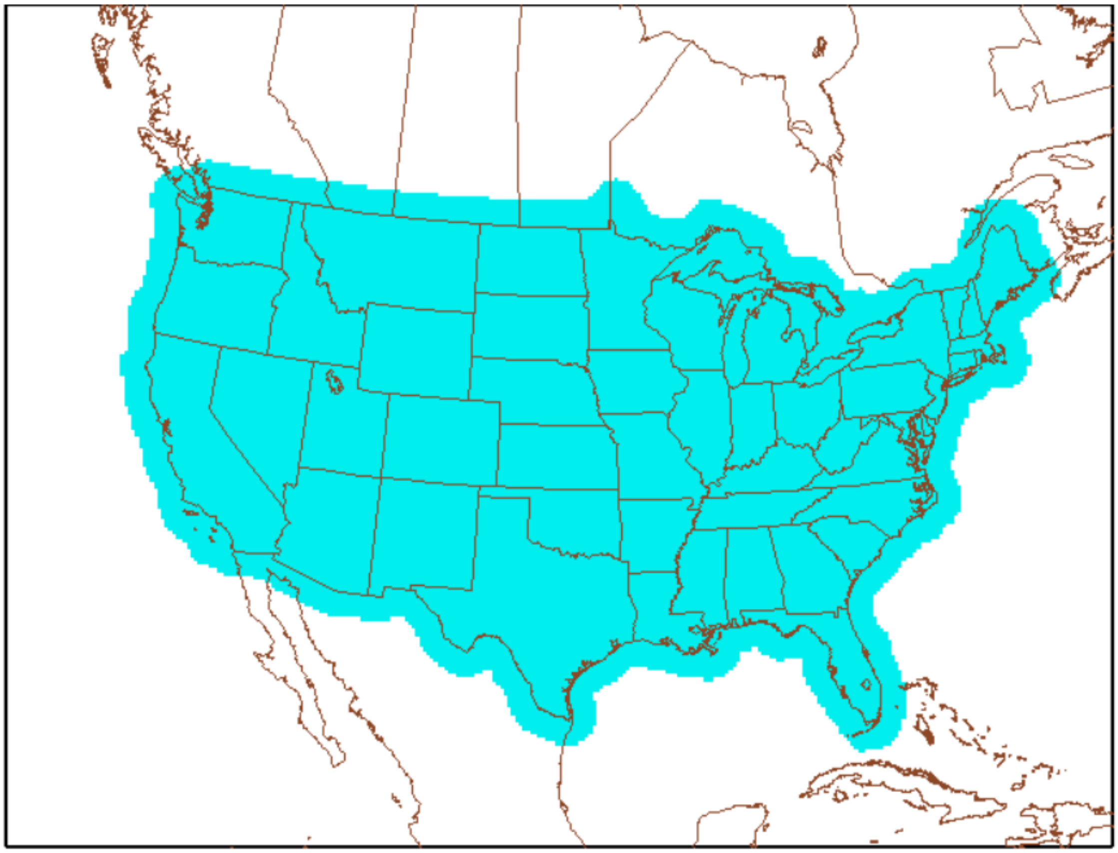


Figure 1. Geographical coverage of thunderstorm forecast grid, which extends 150 km beyond the CONUS boundaries. Forecasts of conditional severe are made within the CONUS boundaries only.

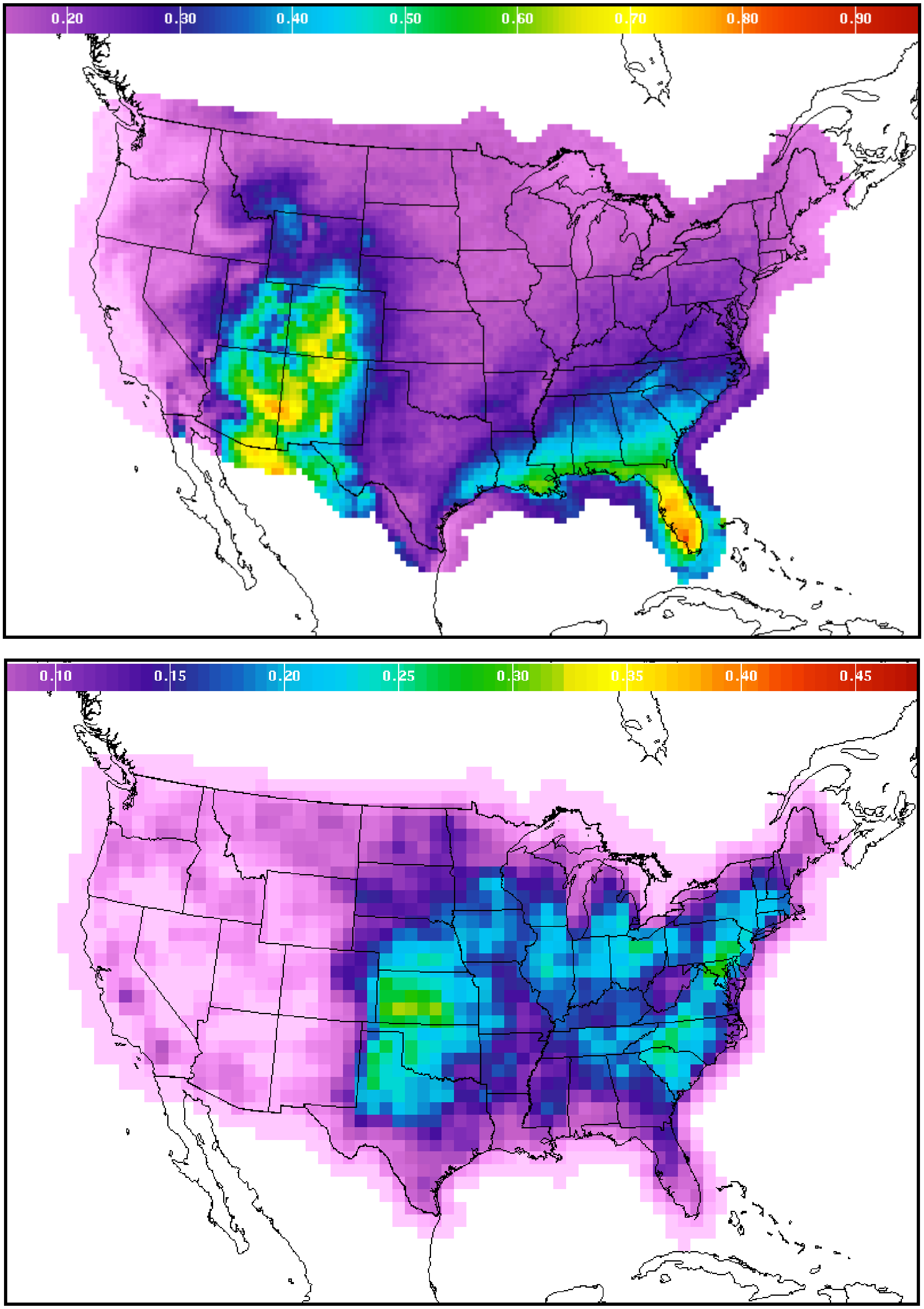


Figure 2. Example 12-h thunderstorm relative frequency for the month of August (top) and 12-h conditional severe relative frequency for the month of June (bottom).

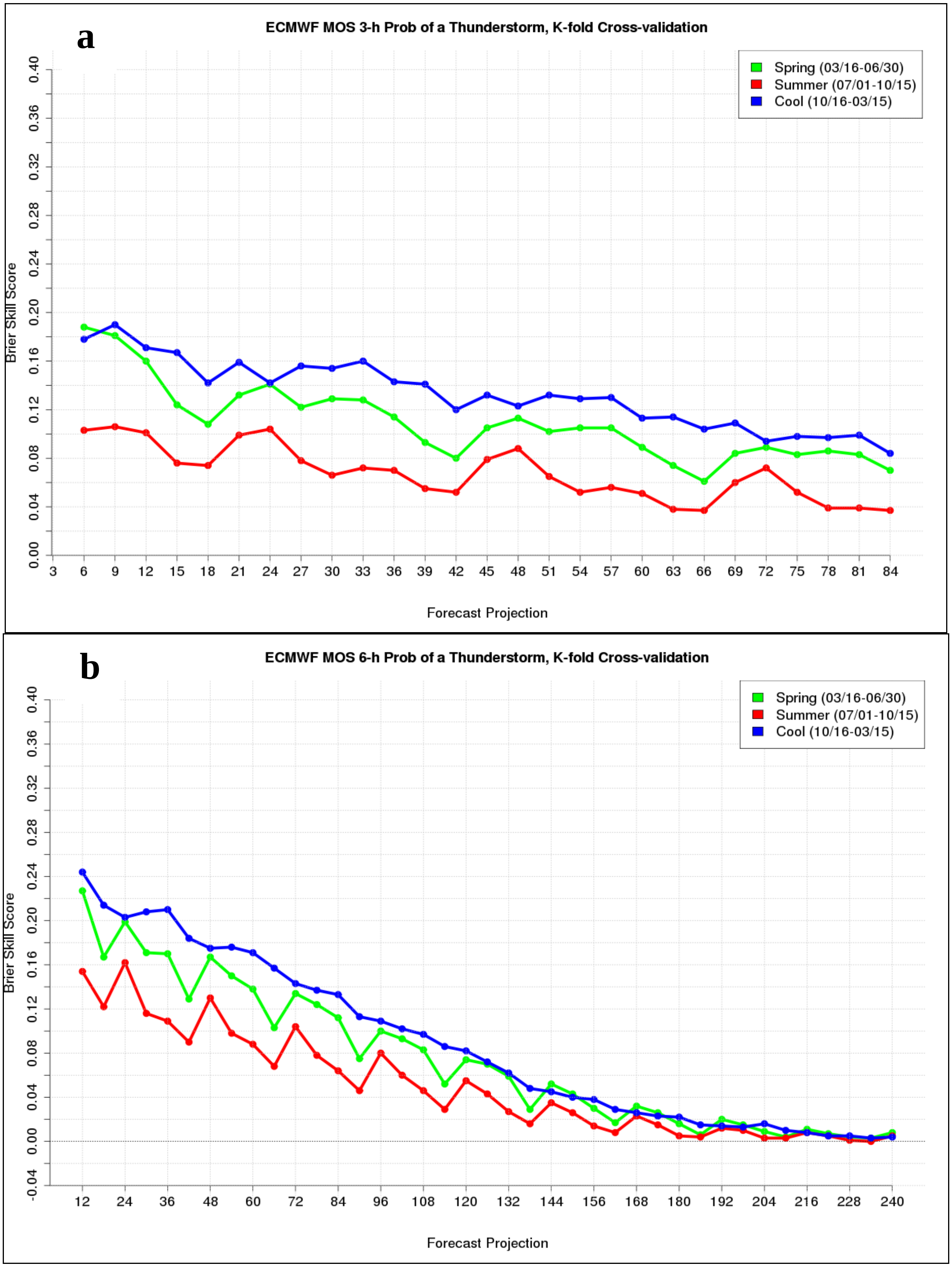
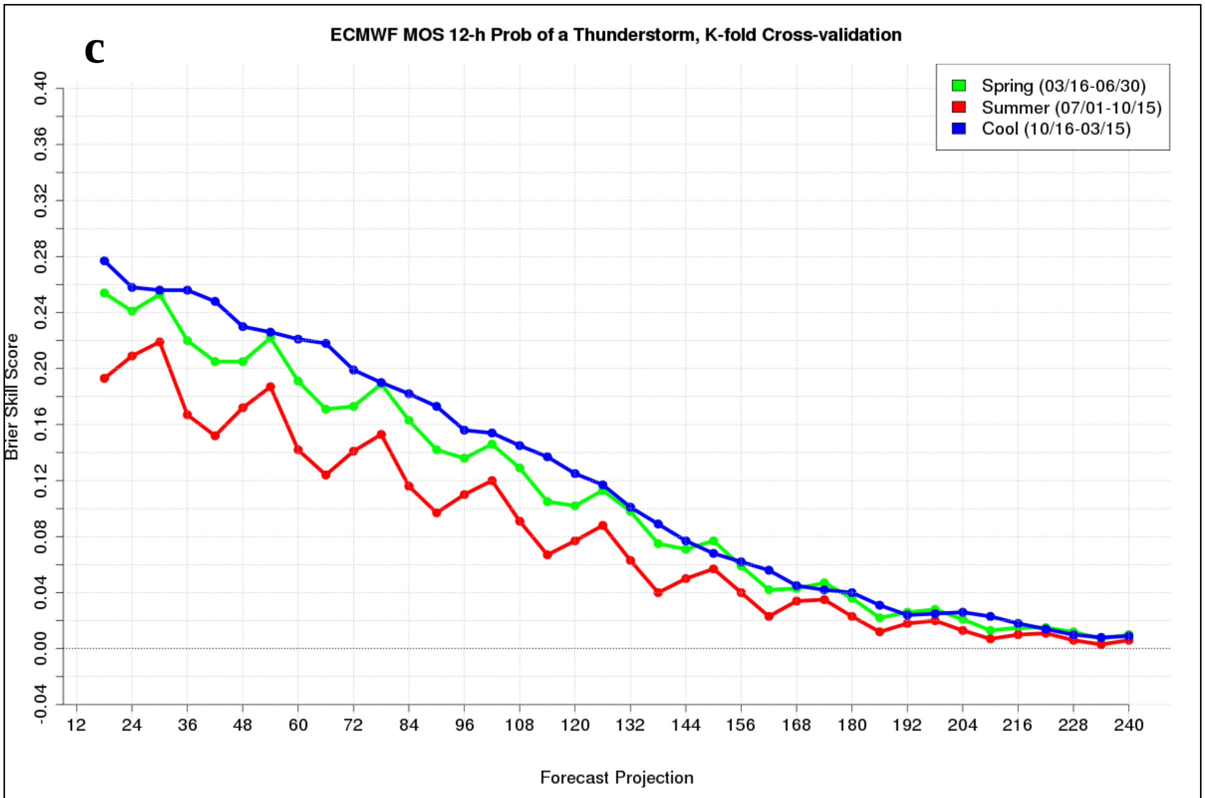
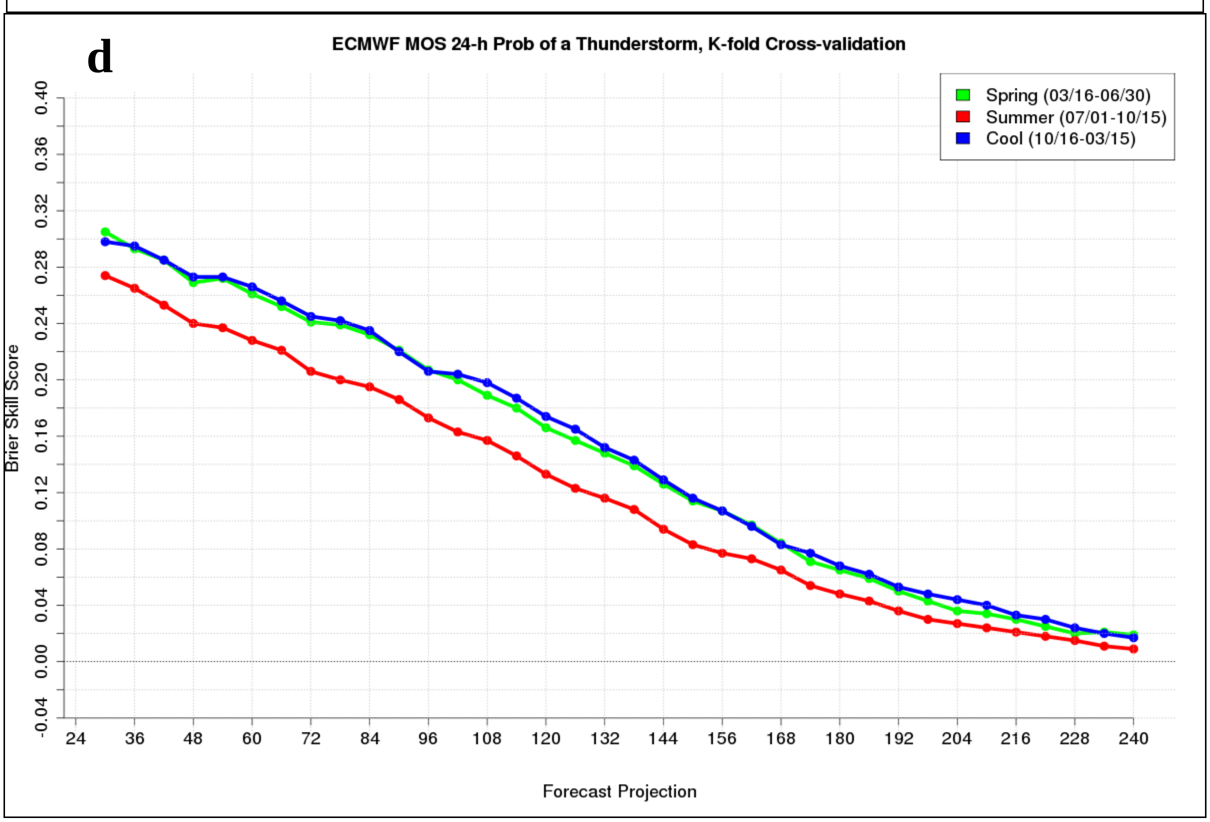


Figure 3. Brier Skill Scores for 3-h (a), 6-h (b), 12-h (c), and 24-h (d) ECMWF MOS probability of a thunderstorm guidance. Plots are from cross-validation for the 0000 UTC cycle.

Figure 3 continued.





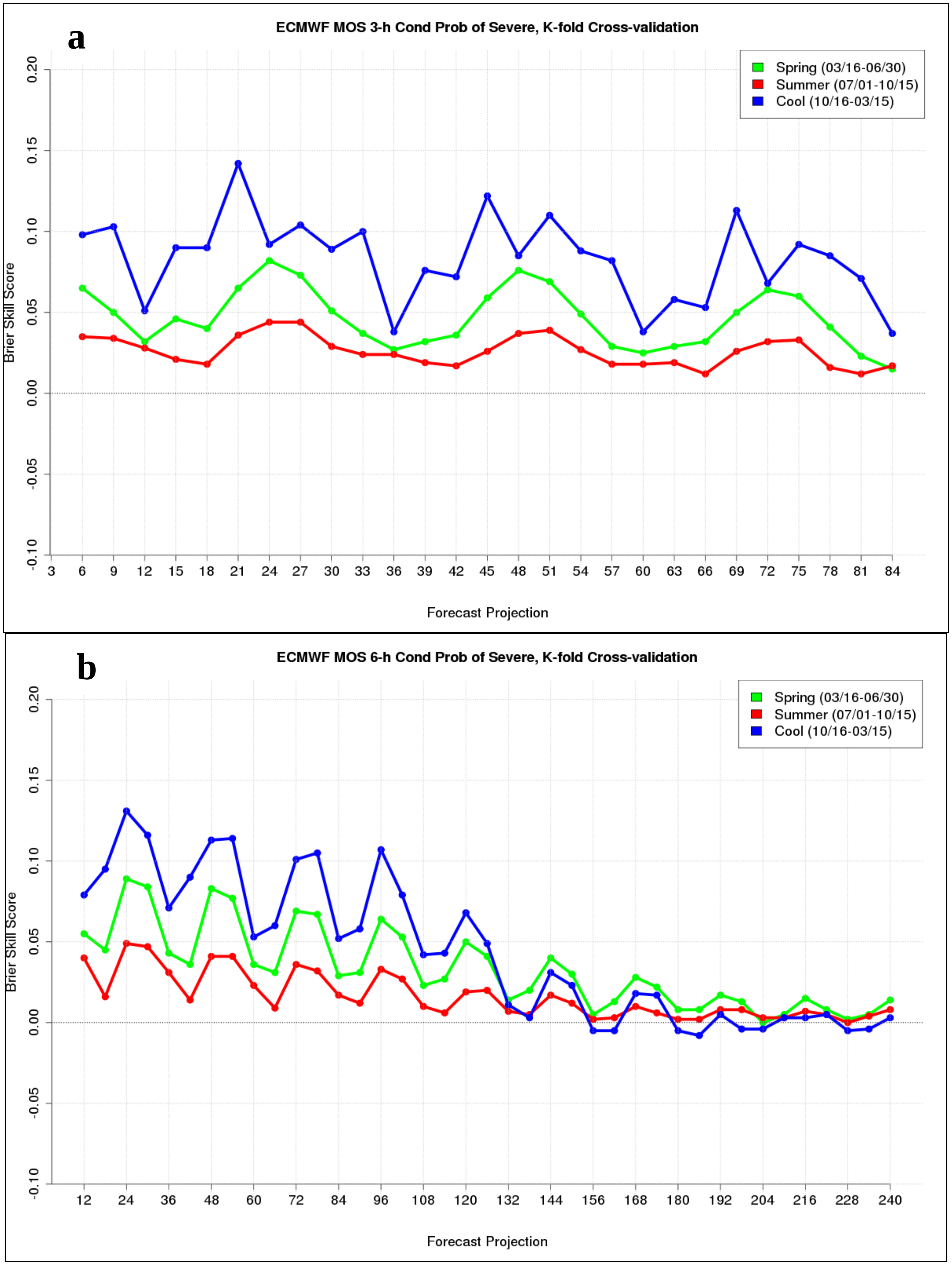
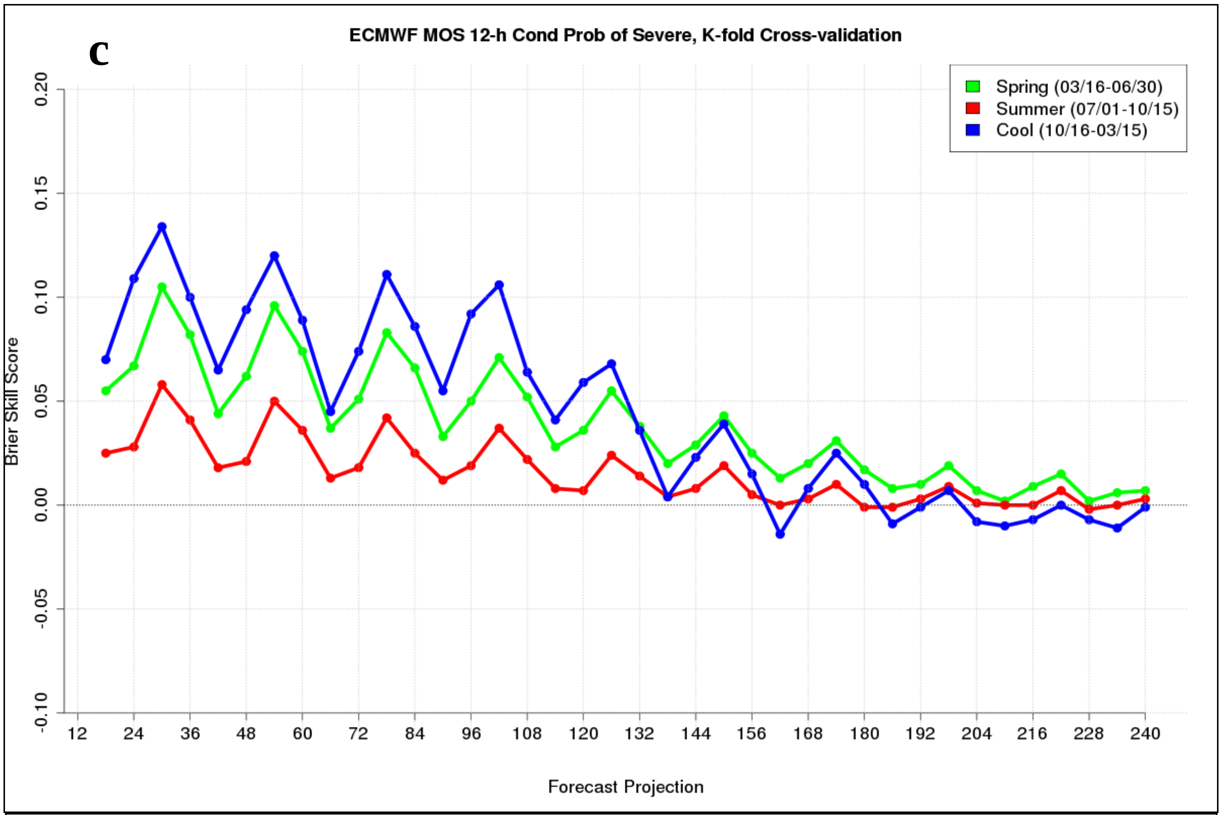
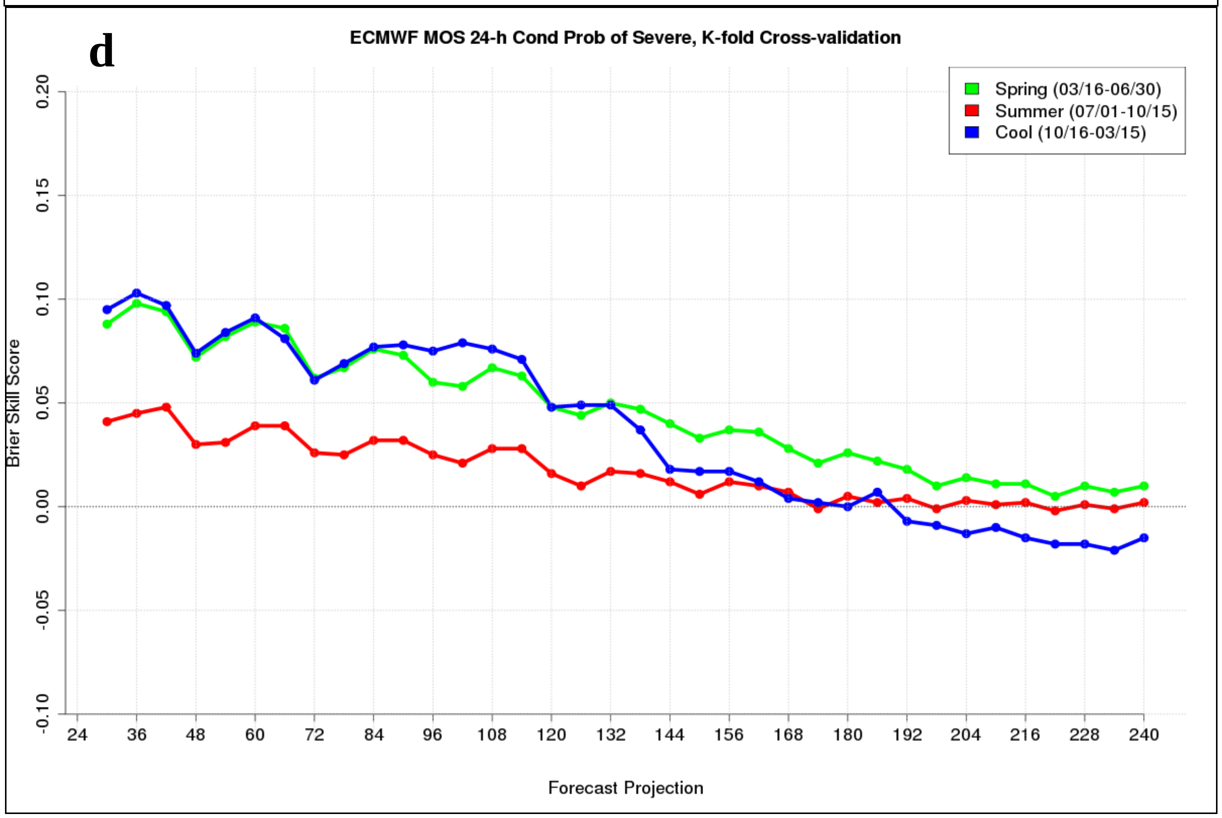


Figure 4. Brier Skill Scores for 3-h (a), 6-h (b), 12-h (c), and 24-h (d) ECMWF MOS conditional probability of a severe thunderstorm guidance. Plots are from cross-validation for the 0000 UTC cycle.

Figure 4 continued.





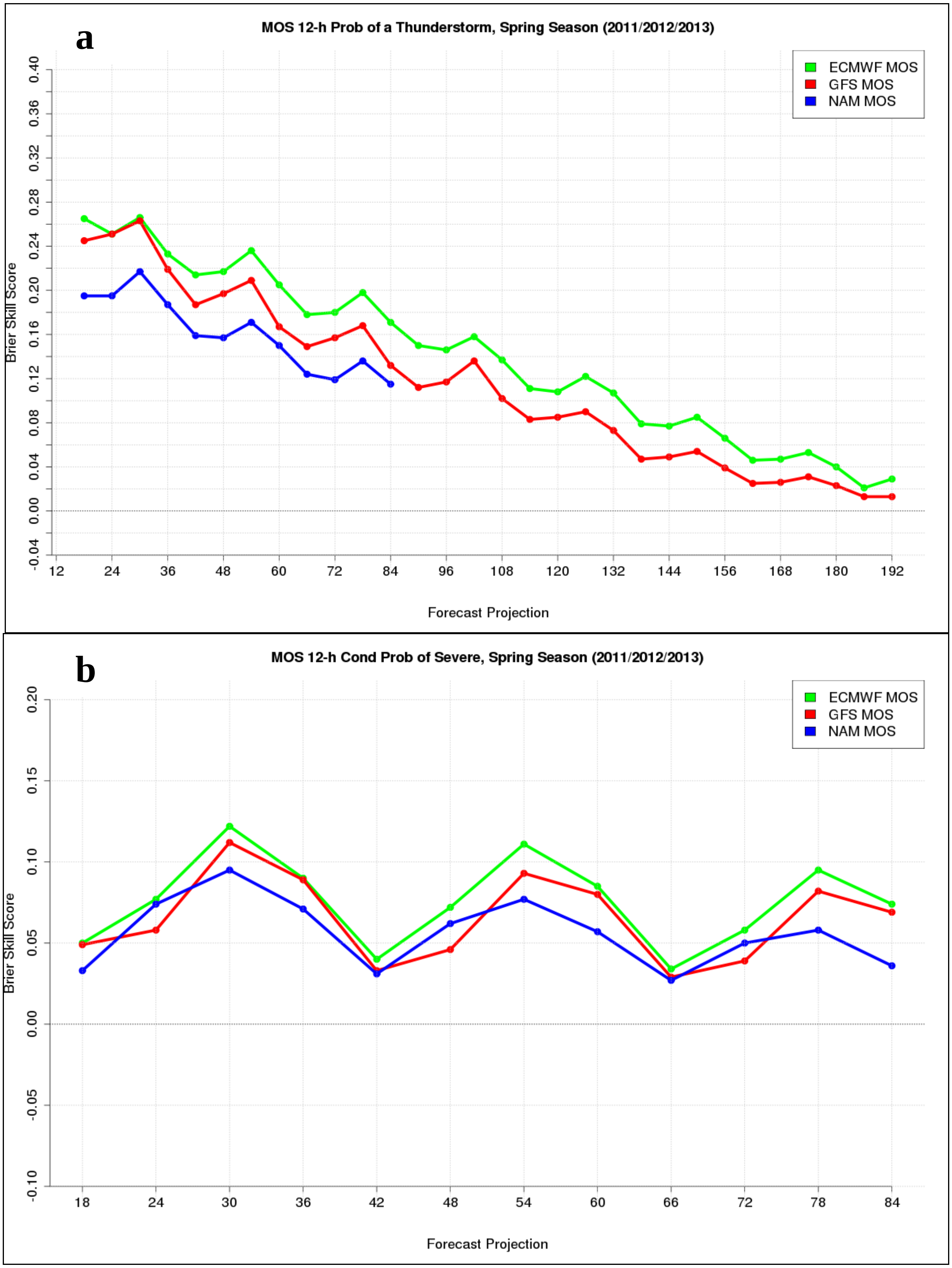


Figure 5. Comparison of skill scores for spring season 12-h MOS probability of a thunderstorm (a) and 12-h conditional probability of a severe thunderstorm (b) for ECMWF MOS, GFS MOS, and NAM MOS.