

# Combination of modeled short-term angular momentum function forecasts from atmosphere, ocean, and hydrology with 90-day EOP predictions

R. Dill · H. Dobsław · M. Thomas

Received: 27 July 2012 / Accepted: 5 March 2013 / Published online: 17 March 2013  
© Springer-Verlag Berlin Heidelberg 2013

**Abstract** Angular momentum forecasts for up to 10 days into the future, modeled from predicted states of the atmosphere, ocean and continental hydrosphere, are combined with the operational IERS EOP prediction bulletin A to reduce the prediction error in the very first day and to improve the subsequent 90-day prediction by exploitation of the revised initial state and trend information. EAM functions derived from ECMWF short-range forecasts and corresponding LSDM and OMCT simulations can account for high-frequency mass variations within the geophysical fluids for up to 7 days into the future primarily limited by the accuracy of the forecasted atmospheric wind fields. Including these wide-band stochastic signals into the first days of the 90-day statistical IERS predictions reduces the mean absolute prediction error even for predictions beyond day 10, especially for polar motion, where the presently used prediction approach does not include geophysical fluids data directly. In a hindcast experiment using 1 year of daily predictions from May 2011 till July 2012, the mean prediction error in polar motion, compared to bulletin A, is reduced by 32, 12, and 3 % for prediction days 10, 30, and 90, respectively. In average, the prediction error for medium-range forecasts (30–90 days) is reduced by 1.3–1.7 mas. Even for UT1-UTC, where AAM forecasts are already included in IERS bulletin A, we obtain slight improvements of up to 5 % (up to 0.5 ms) after day 10 due to the additional consideration of oceanic angular momentum forecasts. The improved 90-day predictions can be generated operationally on a daily basis directly after the publication of the related IERS bulletin A product `finals2000A.daily`.

**Keywords** Earth rotation · Effective angular momentum functions · Polar motion forecast · UT1-UTC · EOP prediction · IERS bulletin A

## 1 Introduction

The quasi-daily rotation of the solid Earth varies in rotational speed and in its position of the rotational axis with respect to the inertial space due to external gravitational forces, internal dynamical processes, and angular momentum exchange between the solid Earth and its fluid envelope, the atmosphere, oceans, and continental hydrosphere. In addition to primarily seasonal and multi-annual variations, irregular short-term signals arise due to wide-band stochastic mass fluctuations within the atmosphere and subsequent mass redistributions in the ocean and, to a substantially lower extent, in the continental hydrosphere. The whole set of Earth orientation parameters (EOP), consisting of variations of the axis defined by the celestial intermediate pole (CIP) with respect to the  $z$ -axis of the terrestrial reference system denoted as polar motion (PM), variations in the Earth's angular velocity UT1-UTC as well as offsets to the precession–nutation conventional model (the celestial pole offsets) are routinely provided by the International Earth Rotation and Reference Systems Service (IERS; [Dick and Richter 2009](#)). Due to the complexity of processing several space geodetic observations, the final EOP coordinates in the IERS EOP-08-C04 series are available only twice a week with 30 days latency ([Bizouard and Gambis 2008](#), see also IERS Message No. 198, 2011). For real-time applications, the IERS Rapid Service Prediction Centre provides rapid solutions with degraded accuracy as well as predictions for up to 1 year into the future. According to the processing of the weekly available long-term predictions in bulletin A

R. Dill (✉) · H. Dobsław · M. Thomas  
Deutsches GeoForschungsZentrum GFZ, Section 1.3,  
Earth System Modelling, Potsdam 14473, Germany  
e-mail: [dill@gfz-potsdam.de](mailto:dill@gfz-potsdam.de)

(Dick and Richter 2003), the IERS publishes at daily intervals quick-look estimates containing EOPs and their errors for the last 90 days and predictions for the next 90 days as `finals2000A.daily`.

EOP real-time coordinates and predictions are typically required for the estimation of highly accurate satellite orbits for navigational purposes as well as for atmospheric sounding for numerical weather prediction models (Luzum et al. 2001). Following the request for improved EOP prediction accuracies, presently exceeding 1 mas after 2 days and 4 mas after 10 days in polar motion (Kosek et al. 2008), in the year 2010, the IERS initiated the Earth Orientation Parameter Combination of Prediction Pilot Project (EOPCPPP) to consider the viability of ensemble predictions for EOP.

Present-day EOP predictions, primarily based on a statistical extrapolation, show EOP prediction errors that are still 2 magnitudes larger than the EOP determination error of 0.05 mas in polar motion. Primarily, unconsidered high-frequency variability in the atmosphere and the oceans are held responsible for this. Recently, the inclusion of effective angular momentum (EAM) functions of the atmosphere (AAM) deduced from numerical weather prediction models reduced the prediction error in length of day ( $\Delta\text{LOD}$ ) by more than 50% down to  $< 0.5$  ms for forecast horizons of 5–10 days (Johnson et al. 2005; Gambis et al. 2011). Short-term polar motion variations (PM) are known to be affected equally by mass redistribution processes in the atmosphere and the ocean (Gross et al. 2003) and, one order of magnitude lower, by water redistributions in the continental hydrosphere (Chen and Wilson 2005), but forecasted dynamics of atmosphere, ocean and continental hydrosphere are not incorporated in IERS polar motion forecasts. So far, investigations involving atmospheric and oceanic excitation functions into Earth rotation predictions are only planned (e.g., Xu et al. 2012). The German Research Centre for Geosciences (GFZ) started in 2010 to provide 10-day forecasts<sup>1</sup> along with the routinely processed hydrospheric EAM functions that are based on the operational analyses of the European Centre for medium-range weather forecasts (ECMWF).

The skills of those 10-day EAM forecasts were analyzed in detail in a hind-cast experiment covering weekly solutions from 2003 to 2008 (Dill and Dobsław 2010). In the forecasted AAMs, especially the wind term shows a limited prediction length of only  $\sim 5$  days. The AAM mass term is predictable up to day 8. Including model states from the ocean model OMCT and the hydrological model LSDM, the effective forecast length of the total EAM functions could be extended to 7–8 days. Compared to IERS bulletin A, the modeled polar motion forecasts show prediction skill scores raised up by

a factor of 5 for the very first prediction days reducing the prediction error by 26% for days 5–10.

The objective of this study was to exploit those 10-day model forecasts for further reductions of the prediction error in the 90-day IERS prediction series by combining the modeled short-term forecasts with the statistically derived long-term forecasts of IERS bulletin A. The combination approach, as described in Sect. 3, is based on combination weights derived from prediction skill scores. The combined EOP forecasts (comEOPP) are contrasted against the original IERS bulletin A predictions (`finals2000A.daily`) by calculation of the mean absolute error (MAE) for each prediction day 1–90, the correlation coefficients for 10-, 30-, and 90-day forecast subsets, and the related explained variances (Sect. 4).

## 2 Earth system model forecast

Predictions of the hydrospheric mass transports and distributions are generated with the ocean model for circulation and tides (OMCT; Thomas 2002) and the hydrological land surface discharge model (LSDM; Dill 2008) forced consistently with 10-day atmospheric forecasts from ECMWF. The daily states of atmosphere, ocean, and continental hydrosphere at 00:00 UTC, which are routinely processed at GFZ, serve as initial states for the subsequent 10-day forecast runs carried out once a day. Principally, the necessary atmospheric information (ECMWF analyses for the present day and atmospheric 10-day forecasts for subsequent days) are available at the time of analysis with only a few hours latency.

Following the angular momentum approach (e.g., Dickmann 2003; Gross 2007), the reported polar motion coordinates and the changes in length of day are calculated by means of a first-order differential equation (e.g., Brzezinski 1992), by taking into account loading of the solid Earth and the rotational response of the solid Earth and the equilibrium ocean (also called pole tide), see detailed description of the EAM data in the README<sup>2</sup> file on the GFZ FTP server.

## 3 Combining 10-day EOP model forecasts with IERS 90-day bulletin A

The modeled EOP forecasts are only available and reliable for a limited length of 10 days. To extend these forecasts to 90 days, comparable to the daily IERS prediction product (`finals2000A.daily`), we introduce the prediction skills of each individual prediction series as weighting information into a combination procedure to benefit from both series by bringing together the mid- and long-term statistical signals from the IERS series and the stochastic rapid variations from

<sup>1</sup> <http://www.gfz-potsdam.de/portal/gfz/Struktur/Departments/Department+1/sec13/services>.

<sup>2</sup> <ftp://ftp.gfz-potsdam.de/pub/home/ig/ops/README>.

the modeled forecasts. The result is a daily updated self-contained EOP prediction series (combEOPP) consisting of 90 days in the past from the IERS rapid solution product, followed by 10 days mainly from the modeled forecast and an adjusted part of the following 80 days from the IERS prediction product taking advantage of the information of the new improved forecast until day 10.

The combination procedure can be divided into three steps: (1) adjust the modeled EOP forecast to present-day initial values taken from bulletin A, (2) weighted combination of modeled EOP forecast with IERS prediction bulletin A, and (3) extension of the combined EOP prediction up to 90 days into the future by means of the statistical information in IERS bulletin A.

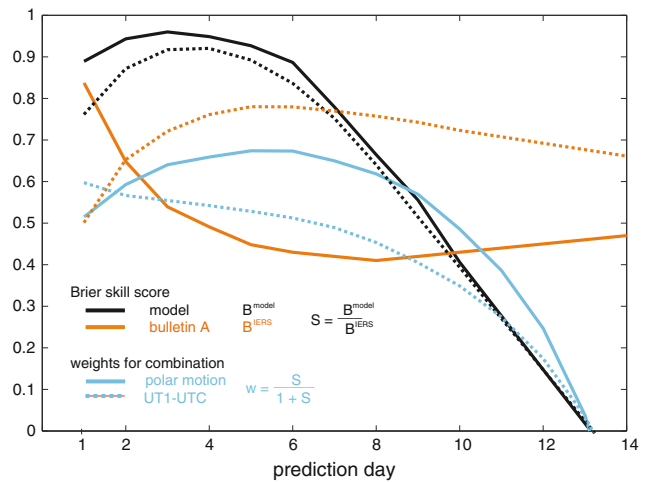
### 3.1 Generation of modeled EOP forecast

Model EOP series are calculated for a time span starting 90 days in the past until 10 days into the future using the EAM output of the Earth system model (ECMWF + LSDM + OMCT) forced with atmospheric data from the operational ECMWF analysis and additional 10-day ECMWF forecasts. As the Earth system model comprises an arbitrary amount of the total Earth masses, the modeled mass changes define only the variations in the EAM functions but not their absolute values. Bias-reduced EAM function are transformed into EOP time series using the actual reported pole coordinate from IERS as initial value and considering the mean pole according to IERS conventions 2010. The modeled EOP time series are adjusted to the IERS rapid solution by adapting the trend and eliminating the offset at the last day before the forecast starts. For the trend estimation, 25 days into the past for the polar motion components and about 40 days for UT1-UTC are sufficient. Due to the decreasing prediction skill of the underlying atmospheric forecasts (Dill and Dobsław 2010), the last 4 days of each modeled EAM forecasts are typically affected by erroneous trends. Estimating and removing a quadratic term in the modeled EOP forecasts from day 7 to 10 and extending the model forecasts by means of the statistical information inherent in the IERS prediction series allow us to generate a modeled EOP forecast that smoothly connects to the past 90 days of the IERS rapid solution and that provides prediction skill scores above the zero level up to approximately 2 weeks, see Fig. 1.

### 3.2 Combination of model forecast and IERS prediction

Starting with the first prediction day  $i = 1$ , the modeled EOP forecast  $P_i^{\text{model}}$  is combined with IERS bulletin A  $P_i^{\text{IERS}}$  to the weighted mean  $P_i$  by

$$P_i = w_i \cdot P_i^{\text{model}} + (1 - w_i) \cdot P_i^{\text{IERS}}.$$



**Fig. 1** Brier skill scores for polar motion (solid lines) and UT1-UTC (dotted lines) of model forecasts (black) and IERS bulletin A (orange). The combination weights (blue) represent the relative prediction skill of the modeled forecasts compared to IERS bulletin A for each individual prediction length

The weights  $w_i$  for every prediction day  $i$  introduce the individual prediction skills of both prediction series into the combination. Using the Brier skill scores  $B^{\text{model}}$  of modeled EOPs and  $B^{\text{IERS}}$  of IERS bulletin A, presented in the former study (Dill and Dobsław 2010), we define a relative skill factor  $S_i$

$$S_i = \frac{B^{\text{model}}}{B^{\text{IERS}}}$$

that can be transformed into the desired combination weights  $w_i$  by

$$w_i = \frac{S_i}{1 + S_i}.$$

The combination weights  $w_i$ , blue lines in Fig. 1, are positive up to prediction day 13, indicating the maximal prediction length, where we can expect positive contribution from the modeled EOP forecast. Up to day 10, combination weights  $>0.5$ , the resulting weighted average  $P_i$  keeps most of the high-frequency variations in polar motion from the modeled forecast. From day 10 to 13, the influence of the model forecast decreases rapidly and from day 14 on the combined series is set to equal bulletin A.

### 3.3 Extension of the combined EOP forecast to 90 days

The trend of the new combination series reflects the long-term trend of IERS bulletin A inflected by short-term features introduced from the modeled forecasts. Using all days from 1 to 13 of the combination series that contain information from the model forecast, the 90-day IERS prediction is adjusted in its trend to the combination series. After trend adjustment,

the last 80 days of IERS bulletin A are used to extend the new prediction series from day 10 on.

For the remainder of this study, the new combined prediction series, which comprised the 90-day IERS rapid solution, the combined modeled 10-day EOP forecast, and 80 days of an adjusted IERS prediction will be called combEOPP. This new prediction series and IERS bulletin A will be compared against the observed ‘truth’ given by the reference EOP series IERS EOP-08-C04 (C04), provided by the IERS as a combination of operational EOP series routinely derived from various space-geodetic techniques. Figure 2 gives some representative examples of the modeled 90-day prediction results of combEOPP (black), IERS bulletin A (orange), and the reference C04 (blue).

A quick look at the individual prediction results shows that predictions are most difficult for periods, where a strong forced polar motion occurs, that last longer than 10 days. The second part of the examples from the end of August until October illustrates the potential and the limits of the modeled 10-day forecasts to predict polar motion variations beyond prediction day 10. A detailed summary of the statistical analysis is given in Sect. 5.

#### 4 Skill of EOP predictions

As discussed in weather forecasting system sciences, the quality of a forecast can be assessed by various verification methods. Quantitative comparisons of a forecast against a corresponding observation or best estimate of the truth led to skill score numbers (e.g., Brier skill score; von Storch and Zwiers 1999). For geodetic applications, the most important skill score is the information about the absolute deviation of the forecast from the truth. Secondly, the nature of the forecast error is also important to benefit from the knowledge of its temporal evolution. The total skill of the optimal forecast is always a sum of two terms, one associated with the initial conditions and the other with the representation of periodic and non-periodic variations. Due to the fact that the variations in the mid- and long-term part of the combined predictions are derived from the IERS prediction, the difference in the total prediction skill will be dominated by the improvement of the initial conditions (offset and trend) around day 10, qualifying the mean deviation, MAE or root mean squared error (RMSE) as primary skill score, which is in line with former studies of EOP predictions (e.g., Kalarus et al. 2010). The skills in predicting the variability become more important when looking at shorter prediction lengths, where the benefits are expected from the 10-day model forecasts. Considering the different time scales, we analyzed not only the total 90-day predictions but also shorter subset with only 10 and 30 days prediction length by means of correlation scores and explained variances. For this study, 384

individual forecasts were analyzed. The following statistics belong to the whole set of 384 predictions as they are assumed to be independent since autocorrelation analysis lead to the conclusion that only 2–3 days of subsequent predictions are correlated to a certain extent in its errors.

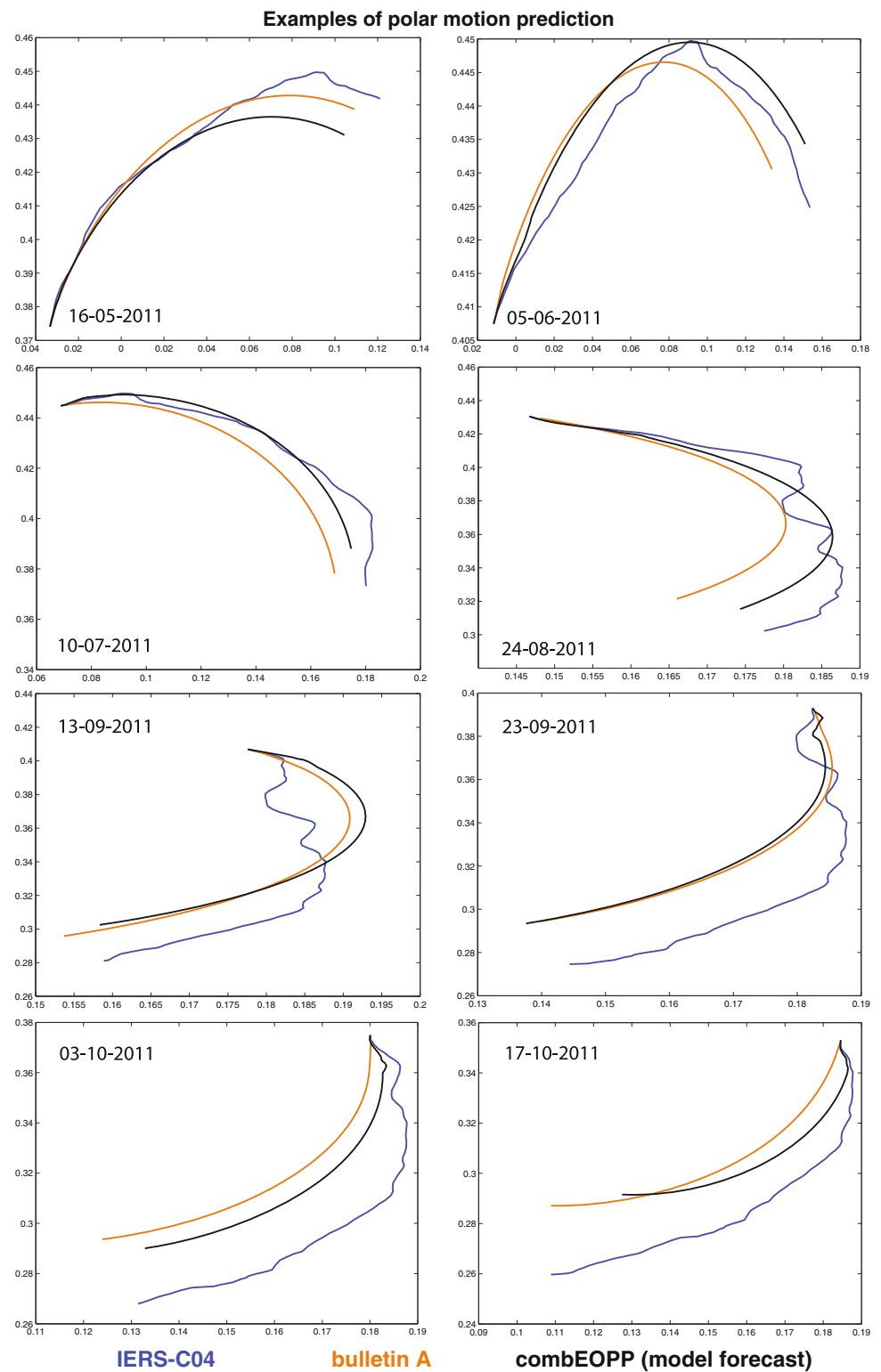
The MAE represents a prototypical measure of the correspondence between individual forecasts and observations. For the following analysis, the MAE is defined in terms of ensemble means for every prediction length (day in the future) as the sum of individual unsigned deviations of the predicted value from the reference value divided by the number of individual contributions. The MAE and even more the comparable RMSE are very sensitive to systematic errors like bias and trends but they do not indicate the direction of the deviation. Initial biases are not a problem due to the fact that the forecast series start from the same initial values taken from the rapid EOP solution, whereas the trend adjustment of the modeled EOP series is very crucial for the long-term evolution of the MAE. The MAE analysis will be slightly more favorably to the combEOPP results than the RMSE, which is more sensitive to large errors (outliers) and favors a damped signal like IERS bulletin A containing less variability.

Note that the polar motion forecast at day 0, which is equivalent to the last available value from the rapid EOP analysis, has an initial error of about 80  $\mu$ as caused by the deviation of the rapid IERS EOP product to the final C04 analysis. As the prediction skill in the  $x$ -component of the modeled EAM functions is slightly higher than in the  $y$ -component (Fig. 3 in Dill and Dobsław 2010), the  $x$ -component can benefit much more from the 10-day modeled forecasts. Figure 3 shows the reduction of the MAE by 1.2 mas in the first 8 prediction days in the  $x$ -component. The improvement continues for the whole 90-day prediction period resulting in a reduction of the MAE for day 90 of combEOPP by at least 7.4% (1.6 mas) compared to bulletin A. The  $y$ -component performs a little worse with almost no improvement for predictions longer than 75 days. Regarding the total polar motion amplitude, the MAE of the combEOPP predictions, compared to the original bulletin A, turns out to be reduced by 1.3–1.7 mas up to prediction day 80 (Fig. 4).

Moreover, the spread within the 384 contributions to the MAE is smaller in the case of combEOPP than for bulletin A, especially for the short-term predictions. The standard deviation of the absolute error from the MAE at prediction day 10 is only  $\pm 2.0$  mas for combEOPP compared to  $\pm 3.0$  mas for bulletin A. At prediction day 90, both prediction series have a standard deviation in the absolute error of polar motion of about  $\pm 20.4$  mas ( $\pm 19.2$  mas in  $x$ -component,  $\pm 7.9$  mas in  $y$ -component).

Due to the fact that principal stochastic contributions excited by the atmosphere are already considered in bulletin A by including AAM forecasts from NCEP, the improvement in the UT1-UTC prediction of combEOPP is only at the level

**Fig. 2** Examples of 90-day polar motion predictions. Bulletin A (orange), combEOPP (black, combined EOP prediction), C04 (blue, IERS reference series EOP-08-C04)



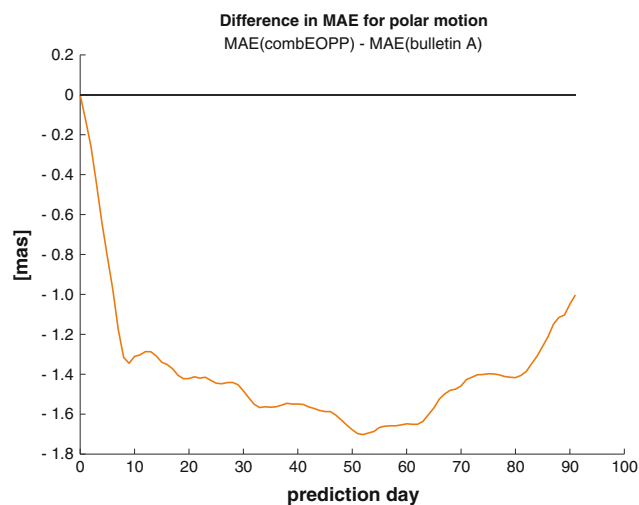
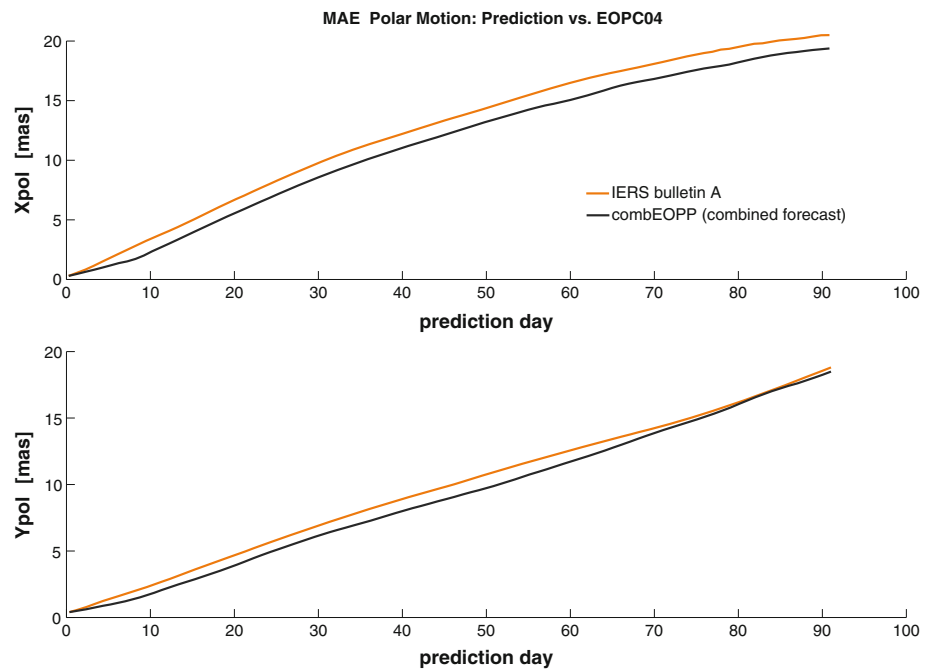
of 0.07 ms (16.7%) at prediction day 8 (Figs. 5, 6). Continuing the prediction up to 90 days, the only slightly improved initial conditions, either due to the additional consideration of oceanic (OAM) and hydrological (HAM) short-term excitations in response to the forecasted atmospheric conditions

or due to better predicting skills of the ECMWF forecasts, lead to a reduction of the MAE at day 90 of more than 0.4 ms (6.5%).

To exclude the possibility that the combination approach introduces a forecast bias that is not detectable with skill



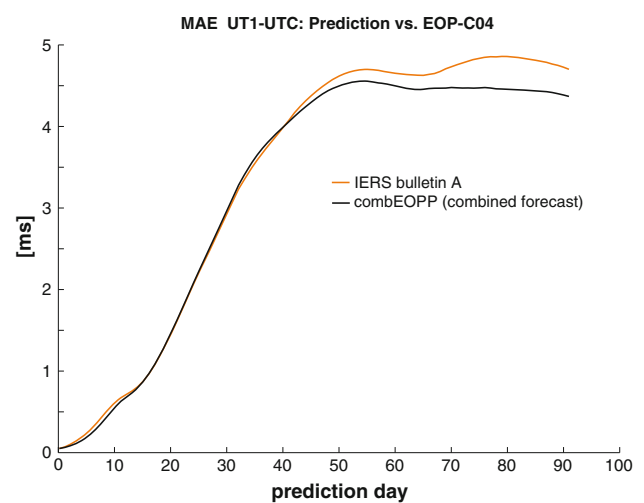
**Fig. 3** Mean absolute error (MAE) of  $x$ -pol and  $y$ -pol for prediction days 1–90 (orange IERS bulletin A, black combined model EOP forecast) to final IERS C04 series



**Fig. 4** Difference in MAE (mean absolute error to final C04 series) of combEOPP (combined model forecast) to IERS bulletin A in polar motion at prediction days 1–90

scores based on unsigned error formulations, we also looked at the mean signed error. The values for the mean signed error of combEOPP follow closely the sign and scale given by bulletin A, indicating that the combination process does not introduce an additional forecast bias. Only in the  $y$ -component of polar motion do the mean signed errors, in both prediction series (+4.6 and +18.2 mas at days 30 and 90), exceed the standard deviation of the absolute error ( $\pm 3.9$  and  $\pm 7.9$  mas), being a potential sign of a weak forecast bias in the  $y$ -component already included in bulletin A for the hindcast period discussed here.

To describe the strength of the linear relationship between individual forecasts, combEOPP and bulletin A, and the cor-

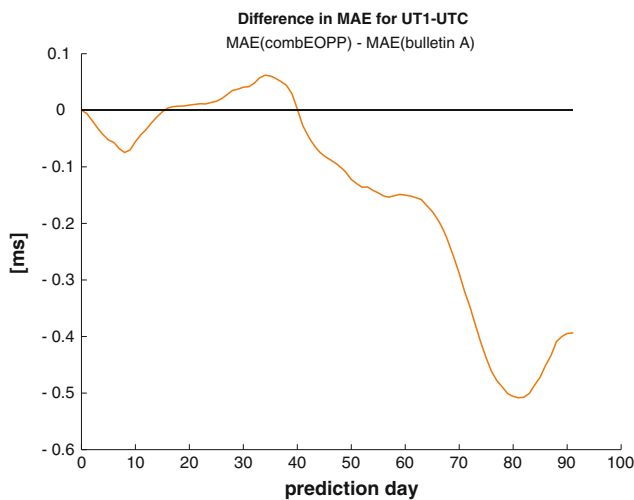


**Fig. 5** Mean absolute error (MAE) of UT1-UTC for prediction days 1–90 (orange IERS bulletin A, black combined model EOP forecast) to final C04 series

responding observation as given in C04, the correlation skill score CORR is computed for the range of the total 90 days as well as for 10-, and 30-day subsets. As the correlation is calculated from standardized forecasts, it is insensitive to systematic errors arising from non-zero means and trends and it is also not changed by a uniform damping of the signals. To this effect, MAE and CORR are able to complement each other. Figure 7 shows a histogram of all correlations computed for 10-day subsets, 30-day subsets and the total 90-day predictions of combEOPP and IERS bulletin A taking C04 as reference series. The results from the previous study treating the prediction skill of the purely model-based 10-day EAM functions are given in green (Dill and Dobsław

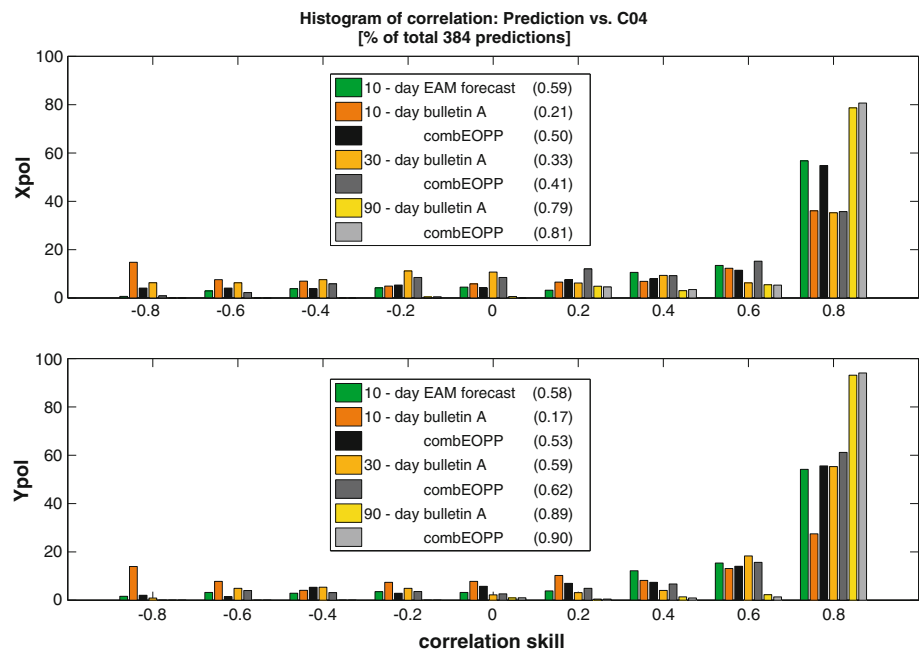
2010, Fig. 4) for comparison. The average correlation coefficient over all 384 prediction samples is given in brackets for each prediction subset and prediction series.

Comparing the results for the original 10-day modeled forecast (green) with the first 10 days of the new combined combEOPP series (black) shows that the combination process suppresses only a small amount of the in-phase variability apparently present in the modeled short-term forecast. The average correlation coefficient in the  $x$ - and  $y$ -components for the 10-day prediction (0.50 and 0.53) is significantly higher than for bulletin A (0.21 and 0.17) but not reaching the level of the original 10-day model forecasts



**Fig. 6** Difference in MAE (mean absolute error to final C04 series) of combEOPP (combined model forecast) to IERS bulletin A in UT1-UTC at prediction days 1–90

**Fig. 7** Histogram of correlation of polar motion in  $x$ - and  $y$ -components with IERS-C04 series for predictions of length 10-day (orange bulletin A, black combEOPP), 30-day (light-orange bulletin A, grey combEOPP) and total 90-day (yellow bulletin A, light-grey combEOPP). For comparison, the correlation of the original 10-day forecast from the modeled EAM functions are given (green). Total mean correlation coefficients are given as numbers in brackets



(0.59 and 0.58). Generally, the number of predictions positively correlated with C04 is enhanced, whereas the number of anti-correlated predictions decreases by the introduction of the modeled forecasts. Most prominent for the 10-day predictions is a 10% reduction of totally anticorrelated predictions ( $< -0.7$ ) and the increase in very well-correlated ( $> 0.7$ ) short-term predictions of more than 17%. As expected, the longer prediction time series are considered, from 30 days till 90 days, the improvement in CORR due to the additional consideration of modeled variations in the first 10 days of combEOPP disappears. The dominant long-term signatures, mainly Chandler, annual wobble and seasonal periods, are already recovered almost perfectly by the underlying IERS prediction product. CORR increases for long-term predictions to 0.79 in the  $x$ -component and 0.89 in the  $y$ -component. The differences in bias and trend between combEOPP and bulletin A do not influence the correlation skill score.

Contrary to polar motion, the predictions for the 3rd component of Earth rotation, UT1-UTC, contain already most of the short-term variations owing to the operational AAM forecasts included in the IERS prediction processing. The bulletin 10-day prediction subsets correlate with 0.59 to the C04 series. This situation cannot be improved much by the combEOPP series, the correlation coefficients reach 0.61 (Table 1). The same argument applies for longer prediction length of 30 and 90 days, changes in the correlation skill score remain marginal.

Complementary to the correlation skill score, the explained variance skill score EXVAR is a measure of the error variance between prediction and reference series normalized by the observed variance in the reference series given by

**Table 1** Total mean correlation for UT1-UTC predictions with final C04 series for the first 10, 30 days and total 90 days predictions

UT1-UTC	combEOPP	Bulletin A
10-day	0.61	0.59
30-day	0.34	0.30
90-day	0.61	0.60

$$\text{EXVAR} = 1 - \frac{\text{var}(\text{prediction} - \text{reference})}{\text{var}(\text{reference})}$$

Negative values of EXVAR indicate that the reference series C04 has smaller error variance than the actual forecast, whereas positive values indicate the proportion of explained variance of the reference series C04. Like the correlation skill score, the explained variance is also insensitive to a bias between forecast and observation, but in contrast, it depends on the correct scale. For a graphical overview, we separated the proportion of explained variance skill score into three categories: forecasts that do not explain any variance of C04 with EXVAR lower than zero, forecasts that do explain up to 50 % of the variance in C04, and forecasts that explain more than 50 % (Fig. 8).

As expected, the explained variances in polar motion for the long-term predictions remain the same in combEOPP and bulletin A. For shorter prediction subsets, especially for the first 10 days only, the proportion of predictions that cannot explain any or <50 % of the observed variance is reduced in combEOPP for the benefit of an increase in well-explained variances for combEOPP as compared to bulletin A. In contrast to the polar motion components, the proportion of explained variance in the UT1-UTC component can-

not benefit from the combination with the modeled 10-day forecasts. The differences in EXVAR for 30- and 90-day predictions between combEOPP and bulletin A are below 1 %. Only for the 10-day subsets, the explained variance is improved from negative values to positive values in the class 0.0–0.5 by around 6 %.

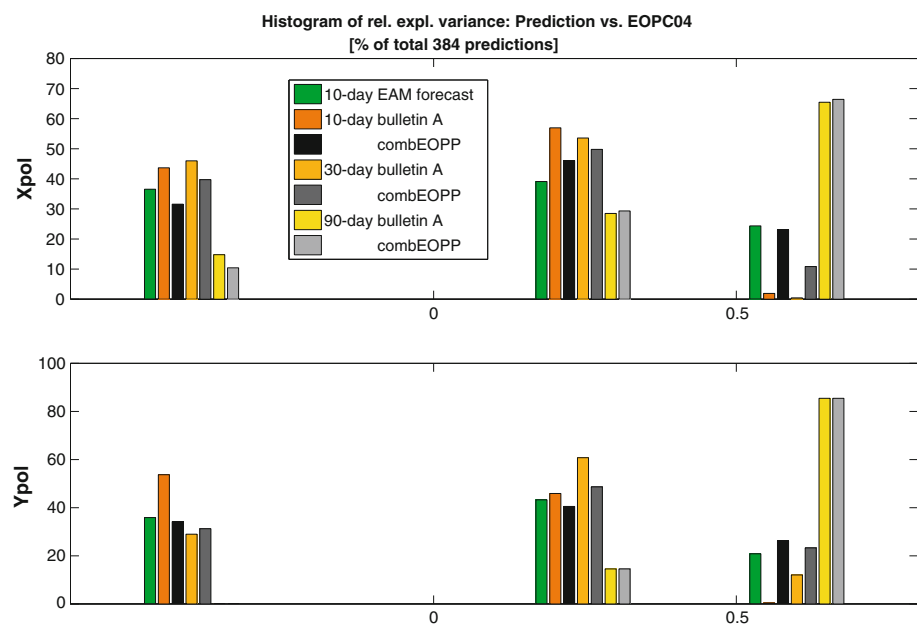
## 5 Discussion

The new combined 90-day predictions combEOPP capture most of the short-term prediction skills of the 10-day EAM forecasts and lead to moderate improvements in the mid-term and long-term predictions of polar motion. Concentrating mainly on the MAE as the decisive skill score, the presented method leads to a reduction of the MAE in polar motion of more than 32 % up to prediction day 10, decreasing continuously until prediction day 90 to about 3 % (Fig. 9).

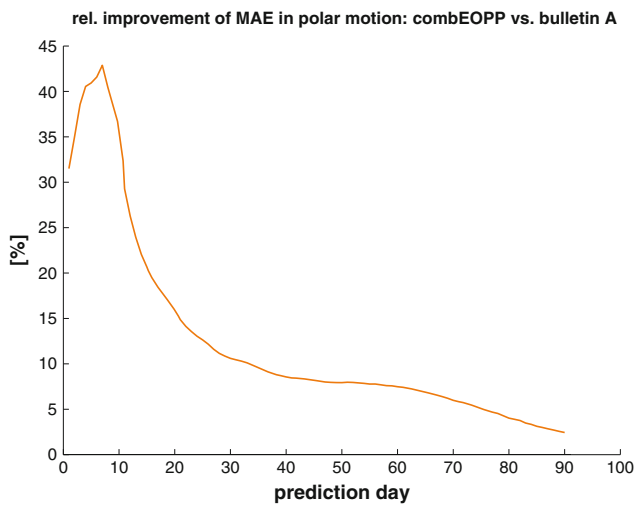
In the axial component UT1-UTC of Earth rotation, bulletin A considers already excitation effects from forecasted atmospheric wind and pressure fields. As expected, the combEOPP could not benefit very much from the additional consideration of oceanic and continental hydrological EAM functions, since those processes are known to be of only secondary importance to UT1-UTC variations. Nevertheless, in comparison to bulletin A, the MAE of the combEOPP prediction could be partly reduced by 5–10 % for prediction longer than 60 days (Fig. 10).

Comparing the prediction errors of combEOPP and bulletin A, it should be kept in mind that, due to the combination procedure, the MAEs are not fully independent. A scatterplot of the individual MAE values indicates that, at least for the UT1-UTC component, the prediction errors are correlated.

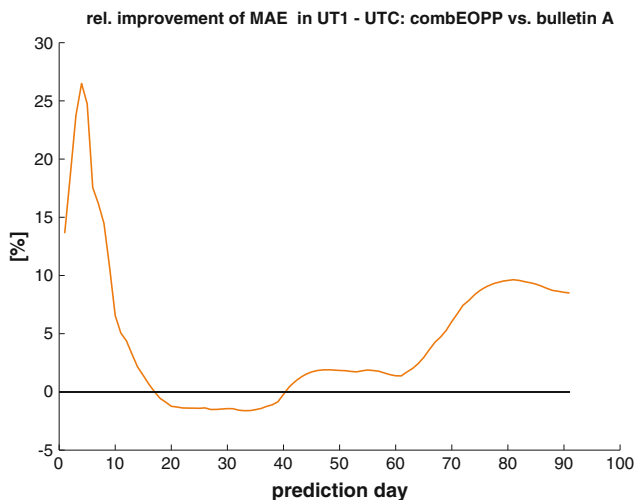
**Fig. 8** Histogram of explained variance (unexplained <0/less explained 0–0.5/well explained >0.5) of C04 series for  $x$  and  $y$  of polar motion predictions for the first 10 days (orange bulletin A, black combEOPP), first 30 days (light-orange bulletin A, grey combEOPP) and total 90-day prediction (yellow bulletin A, light-grey combEOPP). For comparison, the values of the original 10-day forecast from the modeled EAM functions are added (green)







**Fig. 9** Improvement (relative reduction of mean absolute error to final C04 series) in polar motion of combined forecast combEOPP compared to IERS prediction bulletin A at prediction days 1–90

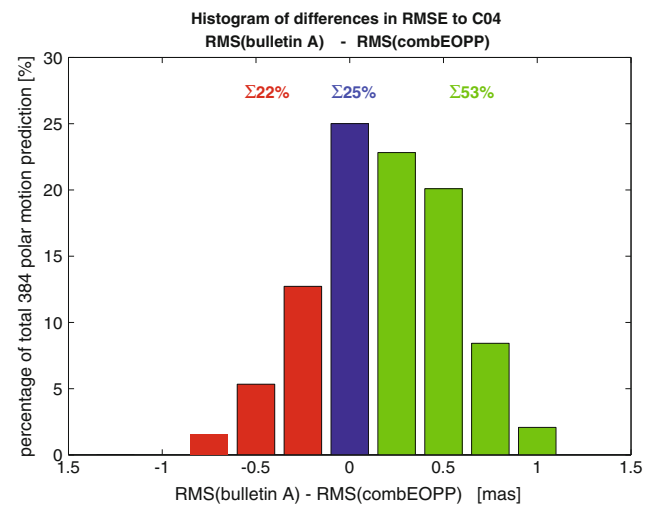


**Fig. 10** Improvement (relative reduction of mean absolute error to final C04 series) in UT1-UTC of combined forecast combEOPP compared to IERS prediction bulletin A at prediction days 1–90

While the correlation in polar motion is around 0.4, the correlation in the axial component reaches 0.8, both statistically significant ( $p < 0.05$ ).

Concluding the analysis of the improved prediction skill of combEOPP compared to the IERS bulletin A, we averaged the prediction error, RMSE, over all 90 days of each prediction to get a synoptic measure of the distribution of the individual prediction skills within the whole set of all 384 predictions.

Figure 11 gives a histogram of the differences in RMSE, related to C04, of each individual bulletin A prediction and the combined combEOPP prediction, separating improved, non-improved, and worse predictions. 25% of the combined combEOPP predictions remain almost at the same skill as



**Fig. 11** Histogram of all individual differences in RMSE (related to C04) for the 384 polar motion 90-day predictions: bulletin A–combEOPP. *Red columns* denote declined prediction skill, *blue* denotes non-improved, and *green* denotes improved prediction skill in 90-day RMSE

the original bulletin A; 53% can be improved, whereas 22% of combEOPP are slightly worse than the bulletin A. The improvement ranges from 0.25 mas to little more than 1 mas. Looking at shorter prediction length of only 30 days, the distribution of improved, non-improved, and degraded predictions increases to 61, 24, 15%.

The benefits coming from the model forecasts are mainly restricted by the limited predictability of the atmospheric dynamics of only 5–7 days. The additional consideration of forced oceanic variability can extend the useful information of the modeled forecasts up to a prediction length of 13 days. Unfortunately, the rapid polar motion variations cannot be extrapolated by statistical methods. Indeed, spectral analysis expose that the high-frequency fluctuations below 20 days, forced by atmosphere and ocean, are very irregular and unstable. Although [Bizouard and Seoane \(2010\)](#) found quasi-periodic variations of 10 and 20 days with amplitudes up to 2 mas, the wavelet analysis of these periods disclosed an extreme irregularity in time. The more stable seasonal and annual periods are already included in the statistical derivation of the IERS prediction, and thus they are considered in the combined predictions of comEOPP as well. It would be beneficial to analyze seasonal atmospheric forecasts with regard to their capability to predict extreme irregular polar motion variations like the strong forced excitation in September and October 2011 or the loops in winter 2005–2006, detected by [Lambert et al. \(2006\)](#), when the Chandler terms were canceled out by the seasonal terms.

Concerning the reliability of the presented results, the reader should also note that they are valid for the limited period of our available modeled 10-day EOP forecast series

from May 2011 till July 2012. The results may differ for other or longer periods. In principle, very few strong excitation events caused by the geophysical fluids with residence times longer than 10 days disturb any ensemble mean skill score in polar motion predictions. However, such epochs of very high variability, typically lasting a couple of weeks, occur usually only one or two times per Chandler period (see Bizouard and Seoane 2010, figure 5). As the presented mean skill scores include already one of these events in September/October 2011, appending an additional 6 months of data will gradually increase the skill scores for both prediction series. To this effect, the given skill score results are judged to be representative, although the ensemble covers only 384 daily members. For comparison, the size of the 9 ensembles of mid-term 30-day predictions contributing to the statistical analysis of the last EOP parameter prediction campaign finished in 2008 vary between 38 and 87 weekly time series, covering minimum of 266 and maximum of 609 days (Kalarus et al. 2010).

## 6 Conclusion

Modeled forecasts of Earth rotation excitation based on predicted states of atmosphere, ocean, and continental hydrosphere are roughly twice as skillful as pure statistical predictions at a forecast horizon of a week. Although the forecast skill of atmospheric wind fields breaks down for predictions longer than 5 days, the predicted Earth rotation excitations from a combined atmospheric, oceanic, and continental hydrological models forced by these atmospheric winds, surface pressure, and water and energy fluxes can provide auxiliary prediction skills until the end of the available 10-day forecasts due to the dampened response of ocean dynamics to changes in the atmospheric forcing. The presented combination approach, using information from the IERS bulletin A predictions to extend the 10-day modeled forecasts, leads to positive prediction skills of the geophysical fluid excitation forecasts for trend and offset even for 13 days into the future. Using the updated knowledge about offset and trend within these first 13 prediction days, the tail of 80 days from the original IERS prediction series bulletin A can be improved significantly as measured by the absolute mean deviation of the new combined 90-day prediction combEOPP from the reference series C04. The successful utilization of the calculated prediction skills of model forecasts and IERS bulletin A as proportional combination weights confirms the informative content of the Brier skill score reflecting perfectly the individual strength of both contributing prediction series at each prediction day. The combination approach will be easily adaptable to upcoming developments, either improved statistical IERS predictions or enhanced model forecasts, by calculating new Brier skill scores necessary for the weight

calculations. Advancements in the model forecasts should comprise mainly the prolongation of the available short-term predictions. For example, Stetzler et al. (2011) tried to extrapolate an annual and semi-annual excitation signal from the modeled AAMs and OAMs reanalysis and forecast series. Additional research is also necessary for the assessment of the prediction skill of seasonal forecasts from operational numerical weather models and their subsequent exploitation as long-term atmospheric forcing for ocean and hydrology models. The presented calculation of the combEOPP series can be principally performed on a daily basis in the framework of the existing operational processing system (OPS) for model-based EAM functions of atmosphere, ocean and continental hydrosphere installed at GFZ with only a few minutes latency to the publication of the IERS rapid solution product finals2000A.daily.

**Acknowledgments** Deutscher Wetterdienst, Offenbach, Germany, and the European Centre for Medium-Range Weather Forecasts are acknowledged for providing data from ECMWF's operational model. Numerical simulations were performed at Deutsches Klimarechenzentrum DKRZ, Hamburg, Germany.

## References

- Bizouard C, Seoane L (2010) Atmospheric and oceanic forcing of the rapid polar motion. *J Geod* 84:19–30. doi:[10.1007/s00190-009-0341-2](https://doi.org/10.1007/s00190-009-0341-2)
- Bizouard C, Gambis D (2008) The combined solution C04 for Earth orientation parameters, recent improvements. In: Drewes H (ed) *Series on international association of geodesy symposia*, vol 134, 330 pp. Springer, New York
- Brzezinski A (1992) Polar motion excitation by variations of the effective angular momentum function: considerations concerning deconvolution problem. *Manuscr Geod* 17:3–20
- Chen JL, Wilson CR (2005) Hydrological excitations of polar motion, 1993–2002. *Geophys J Int* 160:833–839
- Dick WR, Richter B (2003) Rapid Service/Prediction Centre. IERS Annual Report 2002, 46–53. International Earth Rotation and Reference Systems Service, Central Bureau. Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main. ISBN: 3-89888-875-4
- Dick WR, Richter B (2009) Earth Orientation Centre IERS Annual Report 2007, 61–67. International Earth Rotation and Reference Systems Service. Central Bureau. Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt am Main. ISBN: 978-3-89888-917-9
- Dickmann SR (2003) Evaluation of effective angular momentum functions formulations with respect to core-mantle coupling. *J Geophys Res* 108(B3):2150. doi:[10.1029/2001JB001603](https://doi.org/10.1029/2001JB001603)
- Dill R (2008) Hydrological model LSDM for operational Earth rotation and gravity field variations, Scientific Technical Report, STR08/09 GFZ Potsdam, Germany, p 35
- Dill R, Dobsław H (2010) Short-term polar motion forecasts from earth system modeling data. *J Geod* 84:529–536. doi:[10.1007/s00190-010-0391-5](https://doi.org/10.1007/s00190-010-0391-5)
- Gambis D et al (2011) Use of atmospheric angular momentum forecasts for UT1 predictions: analyses over CONT08. *J Geod* 85:435–441
- Gross RM, Fukumori I, Menemenlis D (2003) Atmospheric and oceanic excitation of the Earth's wobbles during 1980–2000. *J Geophys Res* 108(B8):2370

- Gross RS (2007) Earth rotation variations—long period. In: Herring TA (ed) *Physical geodesy, treatise on geophysics*, vol. 11, Elsevier, Amsterdam
- Johnson TJ, Luzum BJ, Ray JR (2005) Improved near-term UT1R predictions using forecasts of atmospheric angular momentum. *J Geodyn* 39:209–221
- Kalarus M, Schuh H, Kosek W, Akyilmaz O, Bizouard CH, Gams D, Gross R, Jovanovic B, Kumakshev S, Kutterer H, Mendes Cerveira PJ, Pasynok S, Zotov L (2010) Achievements of the Earth orientation parameters prediction comparison campaign. *J. Geod* 84:587–596. doi:[10.1007/s00190-010-0387-1](https://doi.org/10.1007/s00190-010-0387-1)
- Kosek W, Kalarus M, Niedzielski T (2008) Forecasting of the Earth orientation parameters—comparison of different algorithms. In: Capitaine N (ed) *Proceedings of the Journées 2007: The Celestial Reference Frame for the Future*. Observatoire de Paris UMR8630/CNRS, Paris, France, pp 155–158
- Lambert S, Bizouard C, Dehant V (2006) Rapid variations in polar motion during the 2005–2006 winter season. *Geophys Res Lett* 33:L13303
- Luzum BJ, Ray JR, Carter MS, Josties FJ (2001) Recent improvements to IERS bulletin a combination and prediction. *GPS Solut* 4(3):34–40
- Stetzler BE, Luzum B, Cline J (2011) Potential use of atmospheric & ocean angular momentum forecasts for polar motion prediction. Poster, American Geophysical Union Fall Meeting 2011
- von Storch H, Zwiers FW (1999) *Statistical analysis in climate research*. Cambridge University Press, Cambridge
- Thomas M (2002) *Ocean induced variations of Earth's rotation—results from a simultaneous model of global circulation and tides*. Ph.D. Dissertation, University of Hamburg, Germany, p 129
- Xu X, Zhou Y, Liao X (2012) Short-term earth orientation parameters predictions by combination of the least-squares, AR model and Kalman filter. *J Geodyn* (in press)