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Short-term Polar Motion Forecasts from Earth System Modeling Data

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Abstract Polar motion predictions for up to 10 days into the future are obtained from predicted states of the atmosphere, ocean and continental hydrosphere in a hind-cast experiment covering 2003 - 2008. High-frequency mass variations within the geophysical fluids are the main cause of wide-band stochastic signals not considered in the presently used statistical prediction approach of IERS bulletin A for polar motion. Taking EAM functions based on forecasted model states, derived from ECMWF medium-range forecasts and corresponding LSDM and OMCT simulations, into account the prediction errors are reduced by 26%. The effective forecast length of the model combination is found to be 7 days, primarily limited by the accuracy of the forecasted atmospheric wind fields. Highest improvements are found for forecast days 4-5 with prediction skill scores of the polar motion excitation functions improved by a factor up to 5. Whereas bulletin A forecasts can explain the observed variance within the first 10 days only by up to 40%, half of the model forecasts reach relative explained variances between 40% and 80%.

Keywords Earth rotation · effective angular momentum functions · polar motion prediction · IERS bulletin A

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1 Introduction

The rotation of the solid Earth with respect to inertial space is not constant in time but changes due to acting external gravitational forces and internal dynamical processes that cause angular momentum exchange between the solid Earth and its fluid envelope. Variations of the axis defined by the Celestial Intermediate Pole (CIP) with respect to the z-axis of the terrestrial reference system are denoted as polar motion (PM), which form together with variations in the Earth's angular velocity as well as nutation and precession the whole set of Earth Orientation Parameters (EOP). EOP solutions are routinely provided by the International Earth Rotation and Reference Systems Service, (IERS; *Dick and Richter, 2009*) on a daily schedule. Due to the complexity in processing space geodetic observations, the final EOP coordinates in the IERS EOP 05 C04 series are available with 2-5 days latency (*Bizouard and Gambis, 2008*). In addition, the IERS provides rapid solutions with degraded accuracy for real-time applications as well as predictions for up to 1 year into the future.

EOP real-time coordinates and predictions are typically required for the accurate pointing of radio antennas to track deep space objects. Recently, accuracy requirements for real-time ephemerides of near-Earth satellites have been tightened in order to provide highly accurate positions required for navigational purposes as well as for atmospheric sounding, where low-Earth orbiting satellites obtain profiles of water vapor and temperature through the atmosphere that are routinely assimilated into numerical weather prediction models (*Luzum et al., 2001*). For weather prediction purposes, orbital positions are required within 3 hours after the observation with errors that do not exceed 30 cm, necessitating polar motion prediction accuracies well be-

low the 1 mas level (*Gendt et al.*, 2000). Present-day polar motion forecast accuracies exceed 1 and 2 mas after 2 and 4 days, respectively. This is not sufficient for a majority of users that require accuracies below 1 mas for medium-range forecasts shorter than 30 days, as revealed by a survey of the IERS Working Group on Prediction organized in 2007 (*Wooden*, 2008).

Presently, polar motion predictions are primarily based on a statistical extrapolation of the most recent polar motion observations and are published in IERS bulletin A once a week (*Dick and Richter*, 2003). While EOP determination errors have been rapidly decreased during the last decades due to the incorporation of space geodetic techniques and currently reach 0.05 mas in polar motion and 0.8 ms in length of day for finalized daily solutions (*Bizouard and Seoane*, 2009), prediction errors in polar motion are still 2 magnitudes larger even for forecast ranges of a few days only (*Kosek et al.*, 2008). High-frequency variability primarily apparent in atmosphere and oceans dynamics causes a wide-band stochastic signal in polar motion which is hardly predictable by the applied statistical methods.

Since variations in the angular velocity of the Earth have been found to be closely related to atmospheric dynamics (*Freedman et al.*, 1994), effective angular momentum (EAM) functions of the atmosphere deduced from numerical weather prediction models have been incorporated into the IERS forecasts for changes in length-of-day (ΔLOD) in 2001, reducing the prediction errors by more than 50% for forecast lengths of 5 to 10 days (*Johnson et al.*, 2005). Since polar motion variations are known to be equally affected by atmospheric and oceanic processes (*Gross et al.*, 2003) and, to a smaller extend, by water re-distributions in the continental hydrosphere (*Chen and Wilson*, 2005), forecasted dynamics of atmosphere, ocean and continental hydrosphere need to be incorporated in order to attempt further improvements in polar motion prediction accuracies.

Here, 10-day forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF) covering 2003 - 2008 are used to consistently force a global ocean circulation model and a numerical model of the continental hydrosphere (section 2). Dynamic states obtained from all three models allow the calculation of EAM functions of the individual sub-systems atmosphere (AAM, atmospheric angular momentum), oceans (OAM, oceanic angular momentum) and continental hydrosphere (HAM, hydrological angular momentum), as described in section 3. The accuracies of these forecasts will be both contrasted against EAM functions obtained from the subsequently produced ECMWF analyses as well as transformed into polar motion variations

in order to evaluate the forecast skills of the modeling system with respect to the polar motion series from EOP 05 C04 (IERS 2008, abbreviated in the following as EOP-C04) and the predictions from bulletin A (section 4).

2 Earth System Modeling Data

Predictions of atmospheric dynamics are obtained from the ECMWF operational forecast runs that are performed every 12 hours starting from a 4D-Var (four-dimensional variational data assimilation) minimization cycle and reach 10 days into the future. Atmospheric state variables were available for this study with 6 hours temporal resolution on a 1° regular grid with a vertical discretization of 25 pressure levels. In addition to the forecasted surface pressure and 3-dimensional wind fields required for the calculation of atmospheric EAM functions, forecasted fluxes of heat, mass and momentum necessary to force the hydrological model LSDM and the ocean model OMCT have been obtained from the ECMWF archives.

The Land Surface Discharge Model (LSDM; *Dill*, 2008) has been developed on the basis of the Hydrological Discharge Model (HDM; *Hagemann*, 1998). Discretized on a regular 0.5° global grid and integrated with 24h time steps, it simulates the vertical and lateral water transport processes on the continental land surface. The model provides global water storage variations and water flows from surface water in rivers, lakes, wetlands and reservoirs, groundwater and soil moisture, as well as from water accumulated as snow and ice. LSDM is forced with precipitation, evaporation, and 2m-temperatures obtained from the ECMWF model.

The Ocean Model for Circulation and Tides (OMCT; *Thomas*, 2002) has been developed by adjusting the originally climatological Hamburg Ocean Primitive Equation Model (*Wolff et al.*, 1996; *Drijfhout et al.*, 1996) to the weather timescale and coupling with an ephemeral tidal model. The model uses a time-step of 30 minutes, a constant horizontal resolution of 1.875° in latitude and longitude, and 13 layers exist in the vertical. It is forced by 6-hourly wind stresses, atmospheric surface pressure, 2m-temperatures and freshwater fluxes that include river runoff from LSDM, and takes into account sea-ice as well as loading and self-attraction of the water column. In its present configuration (*Dobslaw and Thomas*, 2007), gravitational tides have not been turned on, but diurnal and semidiurnal variations in response to periodic atmospheric loading are present in the model output.

Daily initial states for 2003 - 2008 were obtained from LSDM and OMCT simulations that have been

forced with operational 6 hourly resolved ECMWF analysis fields, denoted as *model analyses* in the following. The subsequent 10-day forecast runs were carried out once a day starting from the model analyses states of oceans and continental hydrosphere at 00:00 UTC and are labeled as *model forecasts* throughout the remainder of this study. Principally, the necessary atmospheric information (ECMWF re-analysis 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. Similar as in weather forecasting, the available model states from the analyses run are used for the evaluation of the accuracy of the forecasts.

3 Effective angular momentum functions

Following *Barnes et al.* (1983), effective angular momentum (EAM) functions χ_i for polar motion variations are derived from mass anomalies, surface water flows, and 3-dimensional distributions of winds and ocean currents according to

$$\begin{aligned}\chi_1 &= \frac{1}{1 - \frac{k_2}{k_s}} \frac{1}{\Omega^2(C_m - A_m)} [(1 + k_l) \cdot \Omega^2 \delta I_{13} + \Omega h_1] \\ \chi_2 &= \frac{1}{1 - \frac{k_2}{k_s}} \frac{1}{\Omega^2(C_m - A_m)} [(1 + k_l) \cdot \Omega^2 \delta I_{23} + \Omega h_2]\end{aligned}\quad (1)$$

In Eq. 1, the relative angular momentum contributions h are obtained from wind or current distributions by integrating over the corresponding mass elements dM situated at latitude φ , longitude λ , and radius r following

$$\begin{aligned}h_1 &= - \iiint_{r, \varphi, \lambda} r \cdot (u \sin(\varphi) \cos(\lambda) - v \sin(\lambda)) dM \\ h_2 &= - \iiint_{r, \varphi, \lambda} r \cdot (u \sin(\varphi) \sin(\lambda) + v \cos(\lambda)) dM,\end{aligned}\quad (2)$$

where u, v denote the horizontal velocities in east and north direction, respectively. Changes in the Earth's tensor of inertia, δI_{ii} , reflecting mass redistributions δM , are calculated at the Earth's surface with mean radius R and mean angular velocity Ω by

$$\begin{aligned}\delta I_{13} &= -R^2 \cdot \oint_{\varphi, \lambda} \cos(\varphi) \cdot \sin(\varphi) \cdot \cos(\lambda) d\delta M \\ \delta I_{23} &= -R^2 \cdot \oint_{\varphi, \lambda} \cos(\varphi) \cdot \sin(\varphi) \cdot \sin(\lambda) d\delta M,\end{aligned}\quad (3)$$

therefore neglecting the vertical distribution of the masses and assuming a surface layer of mass anomalies instead.

The elastic response of the Earth due to loading and rotation is included into the EAM functions by means of

corresponding Love numbers ($k_2 = 0.295$, $k_s = 0.938$, and $k_l = -0.301$). The de-coupling of the liquid core from the motion of the solid Earth is taken into account by means of considering the principal moments of inertia $A_m = 7.0999 \cdot 10^{37} \text{ kg m}^2$, $C_m = 7.1237 \cdot 10^{37} \text{ kg m}^2$ of crust and mantle only.

Geophysical EAM functions have been calculated individually for each of the sub-systems atmosphere, ocean and continental hydrosphere with daily resolution. Geodetic excitation functions were derived from EOP-C04 and bulletin A by the de-convolution method of *Wilson and Vicente* (1990). Here, a complex Chandler frequency with period $T_{CW} = 433d$ and damping of $Q = 179$ has been applied. In order to additionally allow comparisons of modeled polar motion predictions with bulletin A and EOP-C04 directly, geophysical EAM functions are transformed into coordinates $p = p_1 + ip_2$ of the CIP as reported in the IERS products by means of a first-order differential equation (e.g. *Brzezinski*, 1992),

$$p + \frac{i}{\sigma_c} \dot{p} = \chi_1 + i\chi_2. \quad (4)$$

with the Chandler resonance frequency $\sigma_c = 2\pi \frac{1}{T_{CW}}$.

4 Polar motion predictions

To assess the prediction skill of EAM contributions derived from the model forecasts, Brier skill scores B_{FR} are calculated according to (e.g. p.396 *von Storch and Zwiers*, 1999)

$$B_{FR} = 1 - \frac{S_F^2}{S_R^2}, \quad (5)$$

which are typically calculated to evaluate the forecast skills of numerical weather prediction systems. Here, S_F^2 and S_R^2 represent the mean squared errors of the forecast and the corresponding reference forecast, respectively, against the truth for each prediction length. Following the procedures for standard weather forecasting the persistence of state was chosen as unskilled reference forecast throughout the remainder of this study. First, the internal skill of the ECMWF atmospheric forecasts with respect to the calculation of model EAM functions is assessed by assuming the subsequently available model analyses as truth (section 4.1). Second, geodetic excitation function derived from EOP-C04 are taken as truth in order to evaluate the external prediction skill of the model system (section 4.2) and compare the results with bulletin A (section 4.3). Third, EAM forecasts are integrated to PM predictions, Eq. 4, using daily initial pole coordinates from IERS bulletin A in

Fig. 1 Prediction skill of EAM functions from model forecasts compared to EAM functions derived from model analyses. Contributions from AAM pressure (red dashed), AAM wind (red dotted), OAM mass (blue dashed), OAM currents (blue dotted), HAM mass (green dashed), HAM motion (green dotted), and sum of all (black solid). Thin black horizontal line denotes the effectively useful forecast length at $B_{FR} = 0.6$, each with χ_1 component (upper panel) and χ_2 component (lower panel).

order to assess the improvement in predicted PM coordinates in terms of the standard RMS error (section 4.4). As the RMS error is mainly sensitive to systematic errors, like bias and trends, and favours smooth forecast schemes, additional correlation skill scores and the relative explained variances (section 4.5) are calculated to obtain a complete picture of the prediction skills of model forecasts and bulletin A.

4.1 Skill of model forecast versus model analyses

The prediction skill of atmospheric forecast data from the ECMWF and their impact on individual EAM contributions of atmosphere, ocean, and continental hydrosphere, separated for matter and motion terms, has been calculated by means of Brier skill scores related to true states obtained from the corresponding model analysis runs (Fig. 1). While perfect forecasts will lead to Brier skill scores of $B_{FR} = 1$, $B_{FR} \leq 0$ indicates no improvement over the persistent forecast. According to *von Storch and Zwiers* (1999, p. 396ff) a Brier skill score of $B_{FR} = 0.6$ gives the effectively useful forecast length.

For the combined system of AAM, OAM and HAM, useful forecast lengths are found to be ~ 7 days. However, large discrepancies exist in predictability of individual components. Global wind distributions are reasonably predicted for ~ 5 days into the future only. Since changes in surface wind stress conditions primarily affect short-term ocean dynamics, OAM mass and motion forecasts are limited to ~ 7 days as well. Instead, atmospheric mass terms are predictable for 8-10 days, since

Fig. 2 Prediction skill of EAM functions from model forecasts compared to geodetic EAM functions from EOP-C04. Contributions from AAM (red), OAM (blue), HAM (green), and sums of AAM+OAM (black dashed) and AAM+OAM+HAM (black solid), each with χ_1 component (upper panel) and χ_2 component (lower panel).

pressure systems over continents well covered with various observation systems are easier to predict and poorly forecasted oceanic areas are less influential due to the inverse-barometric correction applied. Forecast lengths of more than 10 days are obtained for the HAM terms, which are less prominently influenced by atmospheric short-term variations and are therefore easier to predict than corresponding atmospheric and oceanic contributions. In summary, it can be concluded that EAM functions from model forecasts comparable to model analyses are reasonably predictable from the model combination ECMWF+LSDM+OMCT for ~ 7 days into the future.

4.2 Skill of model forecast versus EOP-C04

In order to assess the ability of the model system to predict the observed polar motion variations, skill scores related to a truth derived from the geodetic excitation functions based on EOP-C04 are calculated (Fig. 2).

Compared to Fig. 1, the skill scores are substantially lower since in addition to the forecast error the model errors and insufficiencies themselves contribute to the total deviations from EOP-C04 excitations. Skill scores reach only 0.7. Hence, stating the effectively useful forecast length at $B_{FR} = 0.6$ is not appropriate here. Nevertheless, the skill scores show the importance of individual contributions from the different model subsystems. While atmospheric mass and motion terms by themselves are already able to give reasonable predictions, oceanic and continental hydrological contributions alone do not have any significant prediction skills, especially for the first few days. However, skill scores are

Fig. 3 Prediction skill of EAM functions from model forecasts consisting of AAM+OAM+HAM (black), model analyses consisting of AAM+OAM+HAM (cyan), and bulletin A (orange) compared to EOP-C04. Black dotted lines indicates prediction skill of a synthetic forecast derived from EOP-C04 augmented with white noise of 1 mas, each with χ_1 component (upper panel) and χ_2 component (lower panel).

generally improved when oceanic contributions are considered together with the atmosphere. Although HAM mass and motion terms slightly degrade skill scores in χ_1 , they have been included into the following analyses since they improve the skill scores in the χ_2 component.

4.3 Skill of model forecast compared to bulletin A

The same skill scores, with respect to the truth from EOP-C04 as in section 4.2, have been also calculated for the combined effect of AAM, OAM, and HAM for a sub-sampled time-series of one forecast run every week, yielding 312 forecasts (Fig. 3), in order to allow comparisons with IERS forecasts published weekly in bulletin A. The skill scores of the model analyses have been included in the figure, representing the upper bound of predictive abilities of the model.

In order to re-assess the given skill scores in relationship to the 1 mas prediction error level desired for various applications, a synthetic forecast derived from EOP-C04 augmented with white noise of 1 mas is enclosed. The skill scores of that synthetic forecast reflect the different meaningful skill levels for each component. While the requested score level for χ_2 is still 0.6, it is only 0.3 for the χ_1 component.

Modeled EAM forecasts attain skill scores comparable to the model analyses for ~ 3 days, before they slowly decay and approach the skill level of the synthetic forecast after ~ 7 days. They are substantially higher than scores obtained for bulletin A forecasts, that quickly drop towards zero during the first 4 days. Highest improvements are identified in the χ_2 com-

Table 1 Polar motion forecast error in [mas] at 1, 3, 5, 8, and 10 days prediction into the future for bulletin A forecasts, model forecasts consisting of AAM+OAM+HAM, and model analyses consisting of AAM+OAM+HAM compared to EOP-C04.

	1 day	3 days	5 days	8 days	10 days
polar motion					
bulletin A	1.30	2.03	2.92	4.11	4.92
model forecast	1.29	1.70	2.18	3.00	3.61
model analyses	1.29	1.72	2.18	2.89	3.36
x-pole					
bulletin A	0.85	1.51	2.32	3.35	4.05
model forecast	0.85	1.17	1.50	2.02	2.45
model analyses	0.85	1.19	1.52	2.04	2.35
y-pole					
bulletin A	0.98	1.35	1.77	2.38	2.78
model forecast	0.96	1.24	1.60	2.23	2.66
model analyses	0.96	1.24	1.54	2.05	2.41

ponent, where skill scores are increased for days 2-7 (around 0.5 for day 4), reflecting the ability of the model to capture the major variabilities in the EAM functions due to the short-term dynamics in the hydrosphere. However, skill scores of the modeled forecasts are worse than bulletin A after ~ 9 days, indicating that statistical methods as presently applied for bulletin A prediction should still be used to extend the modeled forecast for prediction times longer than one week.

4.4 Prediction error of modeled forecasts compared to bulletin A

Finally, modeled EAM forecasts are transformed into variations of CIP to assess the pole coordinate accuracies achievable by the presented numerical modeling approach (Tab. 1), keeping in mind that almost 1 mas prediction error arises from the initial deviation of the coordinates reported in IERS bulletin A that were used as start values for the model forecasts.

Substantial improvements are identified following the 3rd day, with more than 26% reduction of the forecast error of bulletin A at the day 10. The 2 mas error level is reached between day 3 and 5 almost 2 days later than in bulletin A. Up to 5 days, modeled EAM forecast accuracies are almost identical with the theoretically achievable accuracies as indicated by the analyses. As expected from the skill scores in Fig. 1, for the subsequent days the model forecast cannot reach the level of the analyses. Improvements in the prediction of the x-pole component are higher than in the y-pole component as expected from the prediction skills of the corresponding excitation functions.

Since initial pole coordinates have been taken from bulletin A in order to allow for a fair comparison, their accuracy (and hence the accuracy of all subsequent po-

Fig. 4 Histogram and mean for correlation with EOP-C04 of 312 individual predictions from bulletin A forecasts (orange), model forecast consisting of AAM+OAM+HAM (black), and model analyses consisting of AAM+OAM+HAM (cyan).

lar motion predictions) depends on the initial offset of bulletin A with respect to the EOP-C04 series. This discrepancy might be further reduced by using extrapolated EOP-C04 pole coordinates with simulated EAM functions obtained from the analysis simulations. Assuming EOP-C04 latencies of 2 days and augmenting the remaining 2 days by EAM functions from model analyses which are available after 6 hours, the initial pole coordinate is slightly improved in x-pole but more than 30% in y-pole. Moreover, the incorporation of rapid products available from GPS solutions might additionally allow to improve the initial pole coordinates, with immediate benefit for the accuracies of the subsequent prediction days.

4.5 Correlation of modeled forecasts and bulletin A with EOP-C04

In order to demonstrate that the dynamic consideration of short-term irregularities within the model forecasts can predict the observed variability in polar motion better than statistical approaches, the correlation between all 312 individual 10-day forecasts with EOP-C04 are calculated. No distinct seasonal dependencies are found, indicating that the model results are equally reliable throughout the whole period. Both, bulletin A and model forecasts show sporadic low correlation skill whereas the scatter is much higher for bulletin A. Figure 4 gives the 312 correlation coefficients in a histogram. For both polar motion components, bulletin A reaches correlations better than 0.5 only for 30% of all forecasts. Using the model forecasts, the correlation is enhanced to be better than 0.7 for 60% of all forecasts.

Fig. 5 Histogram for relative explained variances of EOP-C04 for 312 individual prediction from bulletin A forecasts (orange), model forecast consisting of AAM+OAM+HAM (black), and model analyses consisting of AAM+OAM+HAM (cyan).

The advantage of the model forecasts to depict short-term variabilities better than bulletin A is also reflected in the analogous histogram of the relative explained variances (Fig. 5). Only the model forecast approach leads to relative explained variances better than 50%, obtained for almost half of the forecasts. In contrast, about 75% of the bulletin A forecasts (against 20% of the model forecasts) cannot explain any of the observed short-term variability in EOP-C04.

5 Summary

Medium-Range atmospheric forecasts provided by ECMWF have been used to consistently force the hydrospheric model LSDM and the Ocean Model OMCT. Predicted atmospheric, oceanic and hydrospheric states were integrated to obtain effective angular momentum functions and consequently variations in the coordinates of the Earth's rotational pole every day for 10 days into the future. Comparisons of modeled polar motion excitation forecasts with subsequent analyses indicate effective prediction lengths of ~ 7 days for the combined effect of AAM, OAM and HAM which is primarily limited by the atmospheric motion terms and hence wind fields having prediction lengths of ~ 5 days only.

As compared to bulletin A, modeled forecasts demonstrate higher skills in predicting geodetic excitation functions during days 2-7. Highest improvements are found for the χ_2 component for days 4 and 5, as measured by Brier skill score increases of more than 0.5. Transformation of modeled EAM functions into CIP pole coordinates indicate that the error increase during prediction time can be substantially reduced by more than 26% for days 5 to 10. A further reduction is expected from the incorporation of more accurate initial pole coordinates,

as e.g., obtained by extrapolating EOP-C04 coordinates with model analyses EAM functions. Compared to the statistical bulletin A forecasts, the capability of the dynamic model forecasts to predict the majority of short-term polar motion variations is reflected in an increased average correlation of 10-day forecasts with EOP-C04 from 0.17 to 0.58. Moreover, the model forecasts are able to realistically reproduce the observed variance in EOP-C04.

Results described in this paper have been obtained in a hind-cast setting only. However, all information incorporated into the forecast procedure are principally available at the time of analysis, allowing to provide these forecasts on an operational basis in case that significant demand from potential user communities is identified to justify the acquisition of up-to-date atmospheric forecasts from ECMWF.

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References

- Barnes, R.T.H., Hide, A., White, A., and C.A. Wilson (1983), Atmospheric angular-momentum fluctuations, Length-Of-Day changes and Polar Motion, *Proc. R. Soc. London Ser. A-Math. Phys. Eng. Sci.*, **387**, 1792, 31-73.
- Bizouard, C., and D. Gambis (2008), The combined solution C04 for Earth orientation parameters, recent improvements. In: Drewes, H. (ed), *Series on International Association of Geodesy Symposia*, **134**, 330pp, Springer, New York.
- Bizouard, C., and L. Seoane (2009), Atmospheric and oceanic forcing of rapid polar motion, *J Geod*, DOI 10.1007/s00190-009-0341-2.
- Brzezinski, A. (1992), Polar motion excitation by variations of the effective angular momentum function: considerations concerning deconvolution problem, *manuscripta geodaetica*, **17**, 3-20.
- Chen, J.L., and C.R. Wilson (2005), Hydrological excitations of polar motion, 1993-2002, *Geophys. J. Int.*, **160**, 833-839.
- Dick, W.R., and B. Richter (2003), Rapid Service/Prediction Centre, *IERS Annual Report 2002*, 46-53, International Earth Rotation and Reference Systems Service, Central Bureau. Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, ISBN 3-89888-875-4.
- Dick, W.R., and B. Richter (2009), Earth Orientation Centre, *IERS Annual Report 2007*, 61-67, International Earth Rotation and Reference Systems Service, Central Bureau. Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, ISBN 978-3-89888-917-9.
- Dill, R. (2008), Hydological model LSDM for operational Earth rotation and gravity field variations, *Scientific Technical Report, STR08/09*, GFZ Potsdam, Germany, 35p.
- Dobslaw, H., and M. Thomas (2007), Simulation and observation of global ocean mass anomalies, *J. Geophys. Res.*, **112**.
- Drijfhout, S., Heinze, C., Latif, M., and F. Maier-Reimer (1996), Mean circulation and internal variability in an ocean primitive equation model, *J. Phys. Oceanogr.*, **26**, 559-580.
- Freedman A.P., Steppe, J.A., Dickey, J.A., Eubanks, T.M., and L.Y. Sung (1994), The short-term prediction of Universal Time and length of day using atmospheric angular momentum, *J. Geophys. Res.*, **99**, B4, 6981-6996.
- Gendt, G., P. Fang and J.F. Zumberge (2000), Moving IGS products towards real-time, *Proceedings of the 1999 IGS Analysis Center Workshop*, IGS Cent. Bur., Pasadena, Calif., 391-403.
- Gross, R. M., Fukumori, I., and D. Menemenlis (2003), Atmospheric and oceanic excitation of the Earth's wobbles during 1980-2000, *J. Geophys. Res.*, **108**(B8), 2370.
- Hagemann, S. (1998), Entwicklung einer Parametrisierung des lateralen Abflusses für Landflächen auf der globalen Skala, *Examensarbeit*, **52**, Max-Planck-Institut für Meteorologie, Hamburg, Germany.
- Johnson T.J., Luzum, B.J., and J.R. Ray (2005), Improved near-term UT1R predictions using forecasts of atmospheric angular momentum, *J. of Geodynamics*, **39**, 209-221.
- Kosek, W., Kalarus, M., and T. Niedzielski (2008), Forecasting of the Earth orientation parameters - comparison of different algorithms, *Proceedings of the Journées 2007: The Celestial Reference Frame for the Future* N. Capitaine (ed.), Observatoire de Paris UMR8630/CNRS, Paris, France, 155-158.
- Luzum, B.J., Ray, J.R., Carter, M.S., and F.J. Josties (2001), Recent Improvements to IERS Bulletin A Combination and Prediction, *GPS Solutions*, **4**, 3, 34-40.
- von Storch, H., and F.W. Zwiers (1999), Statistical Analysis in Climate Research, Cambridge University Press, Cambridge, U.K., 484 pp.

- 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, 129 pp.
- Wilson, C. R. and R. O. Vicente (1990), Maximum likelihood estimates of polar motion parameters, in *Variation in Earth Rotation, Geophys. Monogr. Ser., vol. 59*, edited by D. D. McCarthy and W. E. Carter, AGU, Washington, D.C., pp. 151-155.
- Wolff, J.O., Maier-Reimer, E., and S. Legutke (1996), The Hamburg Ocean Primitive Equation Model HOPE, *Technical Report, 13*, 103 pp., DKRZ, Hamburg.
- Wooden, W. (2008), Activities of the IERS working group on prediction, *Proceedings of the Journées 2007: The Celestial Reference Frame for the Future*, N. Capitaine (ed.), Observatoire de Paris UMR8630/CNRS, Paris, France, 145-150.