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Northern Hemisphere climate trends in reanalysis and forecast model predictions: The 500 hPa annual means

I. Bordi,[1] K. Fraedrich,[2,3] and A. Sutera[1]

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[1] The lead time dependent climates of the ECMWF weather prediction model, initialized with ERA-40 reanalysis, are analysed using 44 years of day-1 to day-10 forecasts of the northern hemispheric 500-hPa geopotential height fields. The study addresses the question whether short-term tendencies have an impact on long-term trends. Comparing climate trends of ERA-40 with those of the forecasts, it seems that the forecast model rapidly loses the memory of initial conditions creating its own climate. All forecast trends show a high degree of consistency. Comparison results suggest that: (i) Only centers characterized by an upward trend are statistical significant when increasing the lead time. (ii) In midilatitudes an upward trend larger than the one observed in the reanalysis characterizes the forecasts, while in the tropics there is a good agreement. (iii) The downward trend in reanalysis at high latitudes characterizes also the day-1 forecast which, however, increasing lead time approaches zero. **Citation:** Bordi, I., K. Fraedrich, and A. Sutera (2010), Northern Hemisphere climate trends in reanalysis and forecast model predictions: The 500 hPa annual means, *Geophys. Res. Lett.*, *37*, L11809, doi:10.1029/2010GL043217.

1. Introduction

[2] Trend analysis applied to observational data is a standard tool in climate research [*Intergovernmental Panel on Climate Change*, 2007]. In Figure 1a we show the annual mean 500-hPa geopotential height (hereafter Z500) trends in the Northern Hemisphere (NH) during the last half of the twentieth century (from 1958 to 2001) of ERA-40 reanalysis [*Uppala et al.*, 2005]. The basic features, which are similar to those described for the winter-season based on NCEP/NCAR reanalysis [*Lu et al.*, 2004], show a deepening Aleutian and Iceland low which, connected with an enhanced subtropical high, was associated with an upward trend in the North Atlantic Oscillation (NAO) index. Two competing hypotheses have been suggested to explain these features, which project onto the cold ocean-warm land pattern: the upward trend in the tropical ocean sea surface temperature (SST) [*Hoerling et al.*, 2004] and the strengthening of the circumpolar vortex also affecting stratospheric dynamics [*Scaife et al.*, 2005]. Modelling and adjoint diagnostic analyses suggest a Rossby wave like feature, which emanates from the western tropical Pacific, deepening the Aleutian low and the upper tropospheric/lower stratospheric forcing (i.e., stratospheric zonal wind trend) to determine the trend pattern over the Atlantic-Euro-Asian sector (for a comprehensive review see *Blessing et al.* [2008], and loc. cit.).

[3] The purpose of our trend-analysis for the NH, however, is different: We analyse the trend change in the "climates" of medium-range weather predictions depending on their lead times from one up to ten days. They are issued by the (frozen) ECMWF forecast system initialized by the ERA-40 reanalysis and made available to us by ECMWF. As described by *Uppala et al.* [2005], the reanalysis is forced by greenhouse gas trends and SST data, while aersols loadings have only climatological distributions. Nevertheless, the radiation budget at the top of the atmosphere is accurate up to a systematic 7 Wm^{-2}, mostly due to a poor handling of high cirrus clouds radiative properties in the assimilating model. Since we study the behaviour of forecasts at a maximum of ten day lead time, the latter shortcomings should scarcely influence the trend change. Thus, we use forecasts to study the impact of short-term tendencies on long-term trends when compared with reanalysis. As we are neither analysing the common predictability nor the common climate trend of global change analysis, we believe this to be a novel analysis approach that moves forward the issue of climate forecast. We present our results in a set of analyses commencing with the lead time dependent geographical distribution of the linear trends of the NH Z500 annual mean forecasts. The following section 2 presents the data analysis and results, which are briefly discussed in the concluding section 3.

2. Trends of the Annual Means of the 1–10 Day Forecasts

[4] The trends over the 44 years of 1 to 10 day Z500 forecasts (ECMWF data from 1958 to 2001) are analysed and compared with the trend of the ERA-40 reanalysis for the same years, which includes significance of the fields obtained. First, for each calendar year the ten annual mean height fields are extracted, which are associated with the forecast lead time; this provides ten 44-year climate samples, whose linear trend fields (and their significance) are determined. Secondly, zonal averages provide the meridional trend distribution in the NH and its change with lead time. This is supplemented by the time series of Z500 zonal mean at two selected latitudes.

2.1. NH Trend Maps: Reanalysis and 10 Forecasts

[5] Figure 1 shows the linear trend of the NH Z500 annual mean over 44 years of ERA-40 reanalysis (Figure 1a) and 1 to 10 day ECMWF forecasts (Figures 1b–1k). Shaded areas denote statistical significant trend on the 5% level (i.e.,

[1]Department of Physics, Sapienza University of Rome, Rome, Italy.
[2]Meteorologisches Institut, KlimaCampus, Universität Hamburg, Hamburg, Germany.
[3]Max Planck Institute for Meteorology, Hamburg, Germany.

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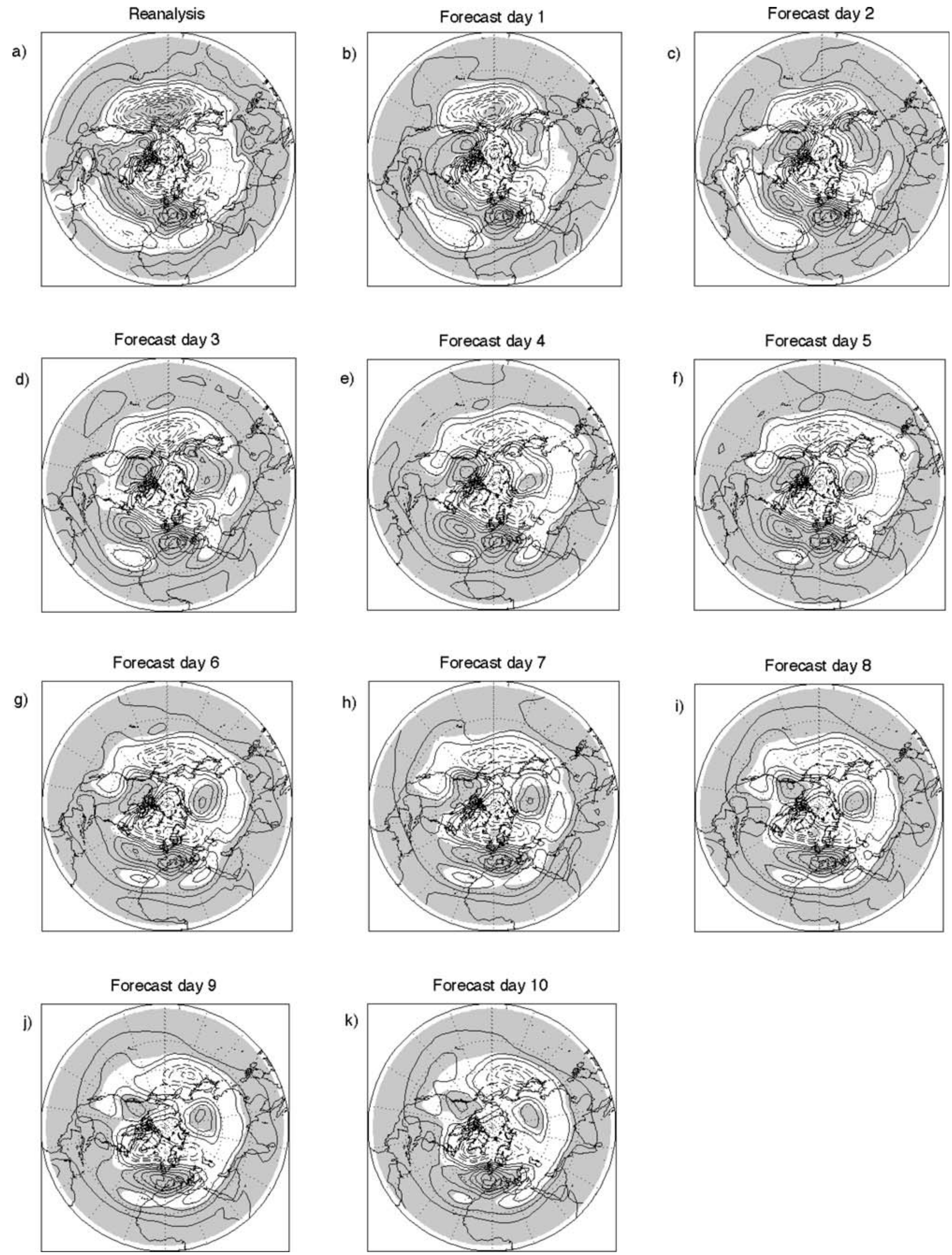

Figure 1. Angular coefficient of the 44-year linear trend in the annual mean Z500 of: (a) ERA-40 reanalysis, and (b–k) ECMWF day-1 to day-10 forecasts. Contours are every $1\text{m} \cdot (10\text{year})^{-1}$, negative regions are dashed and zero line is excluded. Shaded areas denote statistically significant linear trend at 5% level.

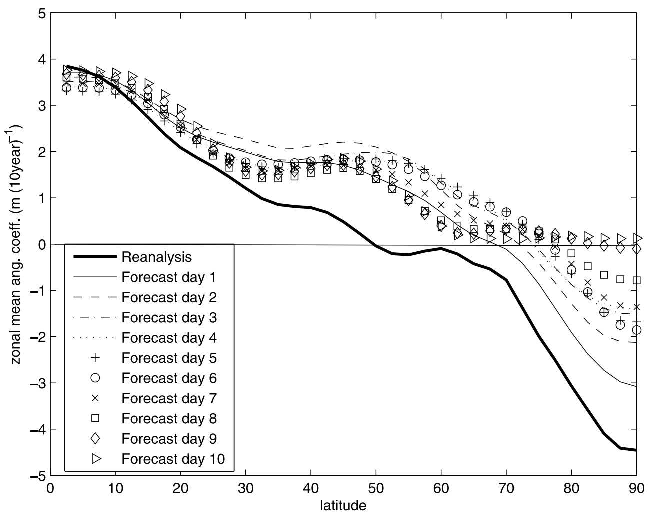

Figure 2. Zonal mean of the angular coefficient of the linear trend in Z500 annual mean as a function of latitude for ERA-40 reanalysis and ECMWF day-1 to day-10 forecast. Units are m · (10year)$^{-1}$.

P-values of the angular coefficients of the least square fittings less than 0.05). Reanalysis data are characterized by significant upward linear trend in all tropical regions up to about 25°N and in the North Atlantic-Mediterranean region, while a strong feature of significant downward trend is noticeable in the North Pacific Sector. The downward trend feature seems to weaken for the day-1 forecast and even more for increasing the forecast lead time: the angular coefficient reaches minimum values in the reanalysis of about −10 m · (10year)$^{-1}$, while day-10 forecast does not fall below −3m · (10year)$^{-1}$. That is, only centers characterized by an upward trend are statistically significant when increasing the forecast lead time. Moreover, in the mid to high latitudes, the trends in the forecasts are at a balance between positive and negative features thus reducing the average trend, whereas a prevailing downward trend is observed in the reanalysis.

[6] It is worth noticing that the systematic errors in ECMWF forecasts [see *Jung*, 2005, and references therein] show some features (for example, the one over the North Pacific) that resemble the maps of the trend change here analysed. However, the trend change is not proportional to the model systematic error: In the subtropics, forecasts fit quite well the reanalysis trend although the systematic error is usually large, while in mid-high latitudes the trend for all realizations is not consistent with the one observed in the reanalysis, regardless the systematic error is large or not. These findings are better illustrated in the next section showing the zonal means of the linear trends.

2.2. NH Trends: Meridional Distributions and Time Series

[7] Figure 2 illustrates the zonal means of the linear trend as a function of latitude for ERA-40 reanalysis and the day-1 to day-10 ECMWF forecasts. It can be noted that in the reanalysis an upward trend characterizes low latitudes (2.5 to 40°N), while it is negligible at mid-latitudes (45 to 70°N), and becomes downward at high latitudes (70 to 90°N). The steep change occurring at about 70°N characterizes also the day-1 forecast climate although the magnitude of the trend is less. However, with increasing forecast lead time, this downward trend decreases approaching zero or becoming slightly upward for day-10 forecast. For latitudes less than 70°N all forecast climates show an upward trend that is generally greater than the one observed in the reanalysis data. In fact, a good agreement with reanalysis is found only for tropical latitudes less than about 30°N. Moreover, it should be noted that the angular coefficients for ERA-40 are statistically significant at 5% level only for latitudes less than 30°N, while those for the forecasts are significant also for latitudes between 30°N and 55°N, depending on the lead time. Thus, no linear trend shown in Figure 2 is statistical significant at high latitudes (>55°N).

[8] To better understand the above discrepancies, we show in Figures 3a and 3b the time series of Z500 zonal mean of the mid and high latitudes at 50°N and 85°N, respectively, both for reanalysis and day-10 forecast. Dash-dot lines represent the fitted linear trends. Both mid-latitude time series (Figure 3a) seem to behave likewise from the beginning of the time record till about 1980. In the last two decades, however, they depart from each other; this difference affects the linear trend that, for ERA-40, is roughly zero (P-value = 0.966), while for the day-10 forecast it is upward (R^2 = 9.2%, P-value = 0.048). Just facing this result one might conclude that the discrepancies are mainly confined to the last two decades or so. However, a closer inspection of Figure 3b excludes this hypothesis, since dif-

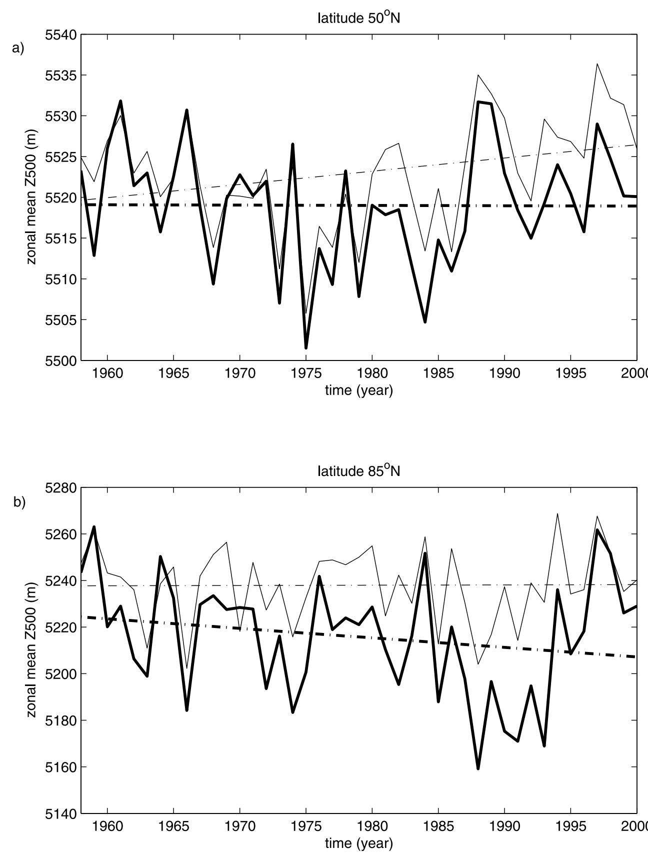

Figure 3. Time series of the zonal mean Z500: (a) at 50°N and (b) at 85°N for ERA-40 reanalysis (thick lines), and ECMWF day-10 forecast (thin lines). Dash-dot lines are the corresponding linear trends. Units are m.

ferences between the two time series are noticeable throughout the whole time record. Almost always the Z500 climate of the forecast exceeds the reanalysis; that is, forecast climate shows no trend (P-value = 0.950) but reanalysis is characterized by a weak downward trend (R^2 = 4.2%, P-value = 0.188), which is mainly due to the period from 1987 to 1997.

[9] Summarizing, all these findings suggest that the forecast model introduces a change in the NH trend different from the one observed in the reanalysis data, which is particularly evident at high latitudes. That is, with increasing lead time the forecast model loses the memory of the initial condition (ERA-40 reanalysis) creating its own climate and trend. On the other hand, all forecast trends have a high degree of consistency with some differences just confined in polar regions. This implies that the trend mismatch at midlatitudes with reanalysis might be connected with the model dynamics response rather than with the variations in the imposed external forcings.

3. Conclusions

[10] To capture the bias of a numerical weather prediction model (ECMWF) we analyse the almost half-century trends of the lead time dependent annual mean Z500 climates of the Northern Hemisphere: (i) Forecasts and ERA-40 reanalysis of the same period show an upward linear trend in all tropical regions (south of 25°N) and in the North Atlantic-Mediterranean area. In the North Pacific sector a strong downward trend is observed (ERA-40), which is weaker in the forecast model's climates (and weakens with increasing lead time) where only regions with an upward trend show significance. (ii) In zonally averaged trends the differences between the model forecast and the observed climates emerge more clearly: all forecast climates show an upward trend larger than the one observed in the reanalysis (south of 70°N); in tropical areas (<25°N) reanalysis and lead time dependent forecast climate trends show good agreement. (iii) At mid latitudes (50°N) reanalysis and day-10 forecast records of the zonal mean Z500 time series show almost zero trend until 1980 while in the last two decades day-10 forecast reveals an upward trend. Further north (85°N) the annual-zonal mean Z500 reanalysis, showing a downward trend, is below the day-10 forecast for the whole period.

[11] On these grounds, we offer the speculation that climate extrapolation, by simply using climate models, may be affected by different trends that observations and models have even at short lead time such as 10 days. Efforts to correct these discrepancies are in order. We wish to point out the great benefit gained in understanding climate behaviour by considering both reanalysis and short-term forecasts obtained by a General Circulation Model (GCM). If climate has to be forecasted by deterministic means, in fact, the pitfalls of the method lie in the understanding of the statistics of the short-term tendencies rather than in the forecast accuracy of long-term averages. Whether a time dependent evolution of the atmospheric aerosol loadings may counterbalance the warming trends (higher geopotential) occurring in midlatitudes remains an open question. This counterintuitive effect may justify the cooling over the Pacific, but it is arduous to account for the warming trend over Eurasia.

[12] **Acknowledgments.** Reanalysis and forecast data have been provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) through their data archive. We thank Massimo Bonavita of the Italian Meteorological Service (currently at ECMWF) for his technical support in processing ECMWF data sets. Also, we gratefully acknowledge the anonymous reviewers for their useful comments that helped improving the presentation of the paper.

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I. Bordi and A. Sutera, Department of Physics, Sapienza University of Rome, piazzale Aldo Moro 2, Rome, I-00185, Italy. (isabella.bordi@roma1.infn.it; alfonso.sutera@roma1.infn.it)

K. Fraedrich, Meteorologisches Institut, KlimaCampus, Universität Hamburg, Bundesstrasse 55, Hamburg, D-20146, Germany. (klaus.fraedrich@zmaw.de)