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ENSEMBLES

Deliverable D2A1.2

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1. Introduction

This report describes the anticipated initialisation strategies for the atmosphere, ocean and sea-ice model components which will be applied by the ENSEMBLES partners participating in the stream 2 decadal hindcasts. The following modelling groups will take part in these activities: ECMWF using IFS/HOPE, CERFACS/CNRM using ARPEGE/OPA, IfM-GEOMAR using ECHAM5/MPIOM, and METO-HC using the Decadal Prediction System (DePreSys) in two different configurations based on HadCM3.

A major challenge to the development of decadal prediction systems is the initialisation of the ocean. There are two key problems: First, there is a lack of ocean data. This is particularly problematic for carrying out retrospective hindcasts, which are essential to the development of a decadal prediction system. Second, there is a lack of understanding of the mechanisms involved, and hence of the key quantities and regions to initialise (see e.g., *Latif et al., 2006*). The following report will give details of how the participating modelling groups plan to address these questions.

Currently the strategies used by the different modelling groups within ENSEMBLES vary, because decadal prediction still is a new challenge to the forecasting problem, and many things need to be tested and checked thoroughly in the individual modelling environments. Thus, in this report, a general recommendation as to a more unified approach among the partners will not be given.

2. Decadal hindcasts in the stream 2 simulations

Beside the production of seasonal and annual ensemble hindcast integrations for the period 1960-2005, the stream 2 simulations will also include a set of multi-annual coupled ensemble integrations over a hindcast lead time of 10 years. The minimum set of runs to be performed by all participating partners is one hindcast ensemble every 5 years, starting the 1st of November 1960, 1965, 1970 and so on. The hindcast production period will cover the years 1960-2005 inclusive, that is, there will be, at least, 10 start dates for decadal simulations in total, with 9 of them being hindcast and 1 being literally a forecast. The ensemble will consist of at least 3 members for each coupled model. The following web site contains a summary of the planned stream 2 simulations: http://www.ecmwf.int/research/EU_projects/ENSEMBLES/exp_setup/stream2.html.

DePreSys will produce a set of “perturbed physics” hindcasts (DePreSys_PPE) by creating ensembles consisting of the configuration of HadCM3 with standard settings for model parameters controlling surface and atmospheric processes, plus eight versions distinguished by multiple perturbations to these parameters. These model variants are a subset of those used in perturbed physics centennial climate change simulations in ENSEMBLES RT1, chosen to span a wide range of model behaviour in terms of climate sensitivity and ENSO amplitude.

Some partners will be capable of doing a larger set of decadal integrations with their systems by running the simulations for more start dates and/or using more ensemble members. For example, DePreSys_PPE will produce decadal hindcasts starting on 1st November each year over the hindcast production period 1960-2005. The ensemble size for DePreSys_PPE will be 9 members.

DePreSys will carry out a further set of 9 member decadal hindcasts (NoAssim_PPE), started from 1st November each year. These will use the same set of model variants and the same time-dependent specifications of external forcing agents as DePreSys_PPE, but will be initialised from perturbed physics HadCM3 simulations of historical climate change rather than from observations. Since the latter simulations were initialised from pre-industrial conditions, the initial conditions for the NoAssim_PPE runs will be statistically independent of the observed states used to initialise DePreSys_PPE, allowing the role of the initialisation to be isolated by comparing the two hindcast sets.

3. Initialisation strategies

In this section we describe the approaches followed by the different partners to initialise their coupled hindcast systems.

ECMWF:

A new operational ocean analysis system (system 3 or S3) has been implemented at ECMWF and will be used to initialise the stream 2 seasonal, annual and decadal hindcast experiments with IFS/HOPE. It is a synthesis of available ocean observations and provides a record of the history of the ocean from January 1959 onward. The system will be continued in real time. A detailed documentation of the S3 ocean analysis system can be found in *Balmaseda et al. (2007a)*. Two main criteria have been considered in the design of the assimilation algorithm: making optimal use of the observation information at the same time as avoiding spurious climate variability in the resulting ocean reanalysis due to the non-stationary nature of the observing system.

The ocean assimilation system for S3 is based on the HOPE Optimal Interpolation (OI) scheme, which allows for assimilation of subsurface temperature and also altimeter derived sea-level anomalies and salinity data. The observations come from the EN3 quality-controlled oceanographic data base of *Ingleby and Huddleston (2007)* (see also http://www.ecmwf.int/research/EU_projects/ENSEMBLES/documents/deliverables_milestones_reports/M1.4_oceanographic_database_m29.pdf), until 2004, and from the Global Telecommunication System (GTS) thereafter. The OI scheme is 3-dimensional with the analysis being performed at all levels simultaneously. The analysis of sea surface temperature (SST) is not produced using the OI scheme. Instead, the model SSTs are strongly relaxed to analyzed SST fields. The maps are daily interpolated values derived from the OIv2 SST product (*Smith and Reynolds 1998*, *Reynolds et al. 2002*) from 1982 onwards. Prior to that date, the same SST product as in the ERA40 reanalysis was used.

When designing a data assimilation system for seasonal and interannual forecasts several considerations need to be taken into account. It is important to represent the interannual/decadal variability in the ocean initial conditions, and therefore strong relaxation to climatology is not recommended. On the other hand, in order to avoid spurious trends and signals due to the non-stationary nature of the observing system, the ocean analysis mean state should be close to the observations. It is also important to avoid large initialization shocks in the coupled model, which may damage the forecast skill. In S3 we have tried to strike a balance between the above requirements: the weight to observations has been reduced and the relaxation to climatology is considerably weaker than in the previous system. This has been possible because an additive bias correction has been included (*Balmaseda et al. 2007b*).

An important feature of the new ECMWF ocean analysis system is that not just a single analysis but several simultaneous analyses are performed. The purpose of the multiple analyses (five in total) is to sample uncertainty in the ocean initial conditions. The ensemble of analyses allows creating ensembles of forecasts that eventually will produce decadal probabilistic predictions. The five simultaneous ocean analyses are created by adding perturbations, commensurate with the estimated uncertainty, to the wind stress while the model is being integrated forward from one analysis time to the next. Descriptions of how the perturbations have been estimated and what their impact on the ocean analysis is are available at http://www.ecmwf.int/research/EU_projects/ENSEMBLES/exp_setup/ini_perturb/index.html.

Atmospheric and land surface initial conditions come from ERA-40, or the operational ECMWF analysis for start dates after August 2001. Perturbations based on singular vectors will be applied in a similar way as in the operational medium range ensemble forecasts (*Leutbecher and Palmer, 2007*). As boundary forcings the interannual evolution of greenhouse gases, a climatological annual cycle of five types of aerosol (sea-salt, desert dust, organic matters, black carbon, and sulphate) and interannual solar activity will be used. Volcanic forcing is not taken into consideration for decadal hindcasts explicitly due to the lack of a-priori knowledge of volcanic eruption under realistic forecast conditions. Of course, the initial conditions already contain the impact of previous volcanic eruptions.

CERFACS:

A specific configuration of the ARPEGE atmosphere-stand-alone model forced with ERA 40 fields carried out by CNRM will be used to produce the atmospheric initialization files. This procedure is the same as the one used by CNRM for the seasonal stream 2 hindcasts.

The oceanic initialization files will be provided by a data assimilation run of the OPA ocean model (OP8-2_VAR3-0). A 3-dimensional variational (3D-VAR) assimilation scheme using an external loop and forty internal loops is used. The observational error covariance model includes a representativeness error estimate to reduce the weight of observations collected in areas where eddy activity is important. The EN3 oceanographic data base of *Ingleby and Huddleston (2007)* is used in the assimilation. The overall decadal experiment for the ENSEMBLES project comprises 9 ensemble members (9 are used to initialise the CNRM seasonal hindcasts for Stream 2, and at least 3 are used for decadal hindcasts at CERFACS) defined as follows: a non-perturbed member, four members with positive perturbations and four with negative perturbations. Each perturbed experiment is forced by the standard ERA40 fields plus a combination of perturbations to the following fields: SST, wind stress and freshwater flux. Some minor differences with the standard ENSEMBLES perturbations have been introduced: Firstly, freshwater flux perturbations are applied, which can have substantial influence on the thermohaline circulation on decadal and longer time scales. Secondly, the SST perturbations are applied daily, with a de-correlation time scale of about one week. The observations are not perturbed, as initially planned, because this may introduce instabilities of the vertical density profiles. The experiments will start for January 1960, and the perturbations are applied continuously to each integration. The spread of this ensemble of reanalyses stabilizes after a few years. A description of these experiments can be found (in French) at http://www.cerfacs.fr/globc/publication/technicalreport/2007/rapport_ensemble, and will be further given in the ENSEMBLES Deliverable D1.9.

The coupler OASIS3 needs initialization files that differ from the atmospheric and oceanic restart files mainly because of the discrepancy between fields transferred as time averages and restart fields as instantaneous snapshots. Those coupler restart files are constructed as part of the oceanic and atmospheric restart files production.

The ocean re-analyses produced as described above have a very crude representation of sea-ice based on the local ocean freezing point and a strong relaxation to observed SSTs, whereas the coupled model used to produce decadal hindcasts has a full thermodynamical and dynamical sea-ice model. Therefore, the sea-ice model needs a special treatment for initialisation. At the start of the coupled integration, the ice field coverage is generated by the ice model itself. The ice model computes the freezing point from the sea surface temperature and sea surface salinity restart fields and, if the sea surface temperature at that point is below the freezing point, the amount of ice at this location is set to the climatological value on that point at the same season.

IfM-GEOMAR:

In contrast to subsurface ocean data, relatively reliable SST and sea level pressure records (SLP) exist back till the late 19th century. Various observational and modelling studies have shown that both of these quantities are intrinsically linked to North Atlantic decadal to multidecadal variability. This provides strong motivation to investigate alternative methods to initialise decadal forecasts using these data. IfM-

GEOMAR has been testing a new method for initialising coupled decadal forecasts using only SST data.

The method, which basically consists of nudging SST anomalies into a coupled model, is tested using the Max-Planck for Meteorology (MPI) climate model. Previous studies with ocean only models have argued that most of the low frequency North Atlantic meridional overturning circulation (MOC) variability is forced by the North Atlantic Oscillation (NAO), through the associated heat flux anomalies (e.g., *Eden and Jung, 2001*). A caveat of these studies is the reliability of the freshwater flux forcing, and hence the role of salinity versus temperature anomalies remains uncertain. Regardless of this caveat, these ocean only experiments indicate an important role of surface heat flux forcing for multidecadal MOC variability, and this motivates the coupled SST assimilation scheme.

The initialisation method consists of nudging SST anomalies into a coupled model. The nudging of SSTs into an ocean model effectively provides a heat flux restoring on the model. The purpose of running the full coupled model is two fold. First, it allows for a dynamically induced response, either through wind or freshwater flux forcing. Second, it provides balanced atmospheric initial conditions for the decadal hindcasts. SST anomalies are assimilated, as opposed to full SST, to minimize initial hindcast drift due to imbalances caused by differences between the model and observed climates. This method is similar to that of *Keenlyside et al. (2005)*, except that full SSTs were assimilated in their case.

The MPI climate model used in this study consists of the ECHAM5 atmospheric general circulation model coupled to the MPIOM ocean model (including a fully interactive sea-ice module) with the OASIS3 coupler. No flux correction is applied in the model. The version of the MPI climate model used for ENSEMBLES is physically identical to that used by MPI for their IPCC scenario simulations, with two exceptions: The solar cycle is now varying, and the impact of major volcanic eruptions is included, through varying the optical thickness. This model version was used by MPI for their 20th century ENSEMBLES simulations.

The SST nudging is constant and strong (0.25 days or $3.8\text{x}10^{-3}$ $\text{Wm}^{-2}\text{K}^{-1}$) between 30°S and 30°N, and reduces linearly to zero at 60°S and 60°N. This design crudely represents observations, which indicate atmosphere-ocean coupling is strong in the tropics and weak in mid-latitudes. Daily SSTs from NCEP reanalysis are assimilated into the model. These data are from the climate analysis branch, NOAA (http://www.cdc.noaa.gov/). Post November 1981, these data correspond to an optimal interpolation analysis of SST linearly interpolated to daily values. Prior to this, the data are an EOF based reconstruction of observed SST.

An ensemble of three initialisation runs was performed for the period 1950 till 2005. Three runs were performed in order to sample uncertainties in ocean initial conditions. The initial conditions for these runs were taken from the three ENSEMBLES-20C simulations performed with the MPI coupled model. Observed SST anomalies were not directly assimilated in the model. Instead, observed SST anomalies added to the model climatology were nudged into the model. Both the observed anomalies and model climatology were computed for the period 1950-2000. The model climatology was computed using all three all-forcing-20C runs. Both observed and model climatologies were created to account for leap years. Care was taken to ensure the daily model climatology that was created from monthly mean ocean model output preserved the monthly mean on interpolation (following *Killworth, 1996*).

METO-HC:

Decadal simulations in ENSEMBLES stream 2 will be carried out with DePreSys, which is based on a configuration of the HadCM3 climate model updated to include a fully interactive sulphur cycle scheme and flux adjustments to restrict the development of regional biases in SST and salinity (*Collins et al., 2006*).

In order to generate initial conditions for hindcasts with DePreSys, each perturbed physics variant of the coupled model HadCM3 will be run in assimilation mode to create time series of initial conditions, including time-varying radiative forcing derived from observed changes in well-mixed trace gases, ozone, sulphate and volcanic aerosol. The set of forcings in the hindcast integrations will be the same, switching from values based on observations to values based on the SRES A1B emissions scenario after the year 2000. Exceptions to this will be the solar irradiance and volcanic aerosol, which would not be known accurately in advance in operational forecasting. In hindcasts, solar irradiance will therefore be estimated by repeating the previous 11 year solar cycle, while volcanic aerosol will be specified to decay exponentially from the value at the start of each hindcast with a time scale of one year. Therefore, the effects of, for example, the Mt Pinatubo eruption will only be included in hindcasts started after the event.

A simple linear relaxation will be used to assimilate ocean and atmosphere analyses of observations into HadCM3. The analyses will be assimilated as anomalies with respect to the model climate, in order to minimise climate drift when the assimilation is switched off. The model climate will be obtained from a historical simulation of the relevant variant of HadCM3. In the atmosphere, 6-hourly data from ERA-40 will be assimilated (switching to ECMWF operational analyses after August 2002), consisting of surface pressure together with potential temperature and horizontal winds on each model level. In the ocean, monthly analyses of temperature and salinity on each model level will be assimilated on each model level. The analyses will be created by 4-dimensional multivariate OI of salinity and sub-surface temperature observations from the latest version of the EN3 oceanographic data base (*Ingleby and Huddleston, 2007*), and SSTs from HadISST (*Rayner et al, 2003*). Covariances required for OI will be computed locally from the relevant historical HadCM3 simulation, using the scheme of *Smith and Murphy (2007)*.

4. Outlook

This report summarises the strategies used by the different partners to initialise their decadal hindcasts for the ENSEMBLES stream 2 period. Presently, it is not yet feasible to make recommendations for a more unified ENSEMBLES-wide initialisation approach as the relative merits of the different strategies have not been tested and explored enough yet.

Having said that, some preliminary analysis of the assimilation - initialisation experiments have already been carried out. While a thorough assessment of these will be given elsewhere, we do summarise below a few key findings.

For ECMWF’s S3 it has been shown that data assimilation has a positive impact on the mean state of the first guess, and thus the bias (*Balmaseda et al., 2007a*). In the tropics, the interannual variability is improved, especially with respect to the ENSO related variability; in the extratropics, the variability has increased. Data assimilation also has a favourable impact on the skill of seasonal forecasts of SST, especially in the western Pacific, where the forecast skill in terms of root-mean squared error is improved at all lead times. In the first 3 months, the forecast skill of the coupled model is improved by more than 20% by using data assimilation in the initialization of the ocean (*Balmaseda et al., 2007c*), see Fig. 1.

The impact of ocean observations on the analysis and forecast skill on seasonal time scales has also recently been studied in *Vidard et al. (2007)*. They find that a key parameter for seasonal forecast initialisation is the depth of the thermocline in the tropical Pacific. Withdrawing the Tropical Atmosphere-Ocean (TAO) buoy data has a big effect, especially in the eastern tropical Pacific. Furthermore, expendable bathythermograph (XBT) data play an important role in the North Atlantic. Whether these also impact the quality of decadal forecast would be an interesting question to study with the set of stream 2 decadal hindcasts.

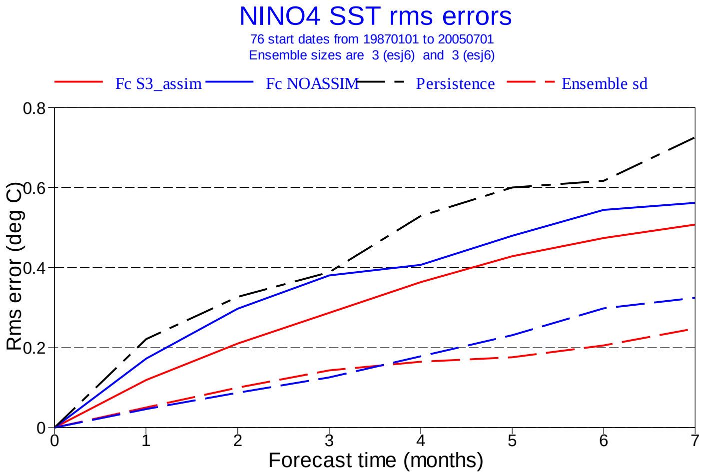

Figure 1: Positive impact of the data assimilation in terms of skill of seasonal forecasts of SSTs in the western Pacific in ECMWF's system 3. Root-mean squared error of forecasts initialised with the new S3 ocean re-analysis (red solid line), of forecasts initialised with an ocean analysis without assimilating observations (blue solid line), of a persistence reference forecast (black dashed line) and the ensemble spread (red and blue dashed lines) versus forecast lead time. Figure from *Balmaseda et al., 2007c*.

In the new SST anomaly assimilation approach applied by IfM-GEOMAR substantial decadal-scale variability of the North Atlantic MOC is found (Fig. 2). The MOC response appears closely tied to convective activity in the Labrador Sea, which is a major site for deep convection in the analysis. The convective activity is driven by both temperature and salinity anomalies. The latter appear to be a dominant factor in the amplification of the MOC anomalies. A robust atmospheric response over the North Atlantic-European sector is also simulated by the analysis. In particular, the observed upward trend in the NAO (DJF) from the mid-1960's to the 1990's is relatively well captured, with observed variability generally falling within the simulated ensemble spread. The method shows quite some promise in its ability to capture multi-decadal variations in the MOC and also in several North Atlantic atmospheric variables.

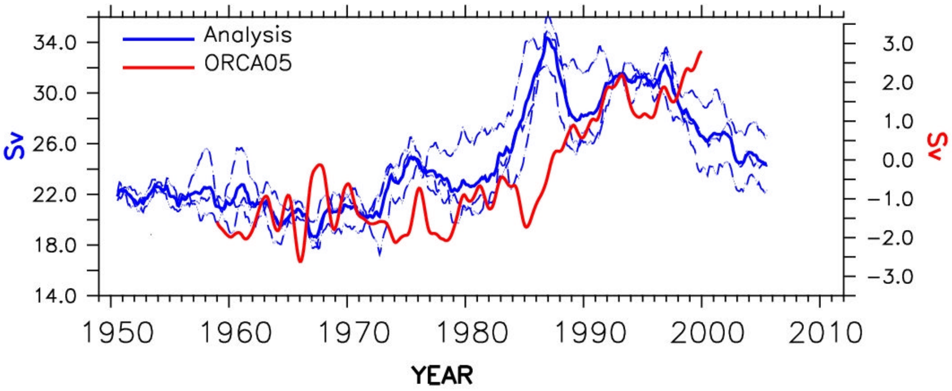

Figure 2. Analysed fields of the North Atlantic maximum meridional overturning stream function at 40°N. Dashed blue lines indicate the individual ensemble members and thick solid blue line the ensemble mean. The red line is from a forced ocean only simulation with the NEMO model (ORCA05 resolution).

The original configuration of the DePreSys system (DePreSys_Orig, defined prior to ENSEMBLES) has been used to investigate the role of initialisation on interannual to decadal forecast skill during the past 25 years. This study was based on the standard configuration of HadCM3 without flux adjustments. A set of 80 ensemble decadal hindcasts with perturbed initial conditions was carried out, started from 1st March, June, September and December in the years 1982-2001, including the effects of projected anthropogenic, solar and volcanic forcings. In order to quantify the impact of initialisation on hindcast skill, a parallel set of “NoAssim” hindcast integrations was carried out, using the same specification of external forcings but initialised from states taken from HadCM3 simulations of historical climate rather than from assimilated analyses of observations (see also Section 2).

Analysis of the results shows that annually and globally averaged surface temperature is predicted with improved skill in DePreSys relative to NoAssim, at all lead times from 1-10 years ahead (*Smith et al, 2007*). During the first year the improvement appears to be explained mainly by skill in predicting the evolution of ENSO events from observed initial conditions, whereas at longer lead times the additional skill is traced to skilful predictions of upper ocean heat content anomalies. The influence of observed initial conditions also leads, on average, to improvements in the skill of regional temperature predictions. The largest improvements generally occur over the oceans, in regions where regional heat content is predicted better in DePreSys. However the average skill over land regions is also improved. Over western Europe, for example, the use of observed initial conditions partly corrects a cool bias in temperature anomalies predicted by NoAssim during the late 1980s, and a warm bias in predictions for the early 1990s (Fig. 3, bottom panel). This leads to better skill measured in terms of root-mean-square error (top panel), and mean bias (middle panel). These improvements are often outside the 5-95% confidence interval associated with the NoAssim results, indicating that they are statistically significant.

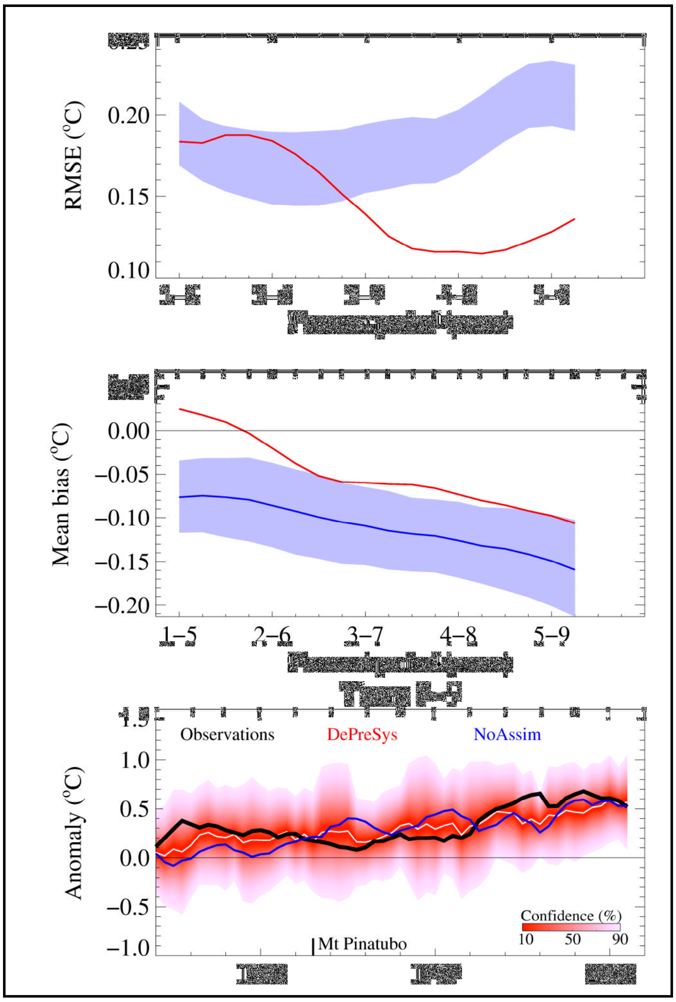

Figure 3: Predictions of five year averages of surface temperature over western Europe, from a set of 80 ensemble hindcasts from the DePreSys_Orig system. Each prediction is based on 16 simulations obtained by pooling the four member ensemble from the relevant start date with those started one, two and three seasons earlier. The top panel shows the root-mean squared error of the ensemble mean DePreSys hindcasts (red curve), compared against the 5-95% confidence range of values diagnosed from the parallel set of NoAssim hindcasts which use the same projections of external forcing agents as DePreSys, but are started from initial states independent of observations. The middle panel shows corresponding results for the mean bias in the predictions, and the bottom panel shows time series of the ensemble mean (white curve) and 5-95% confidence range (red shading) of DePreSys predictions for 5-9 years ahead, alongside verifying observations (black curve) and the ensemble mean predictions of NoAssim (blue curve).

Future plans beyond the immediate stream 2 simulations summarized above include studies on the impact of the new land surface scheme H-TESSEL at ECMWF.

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