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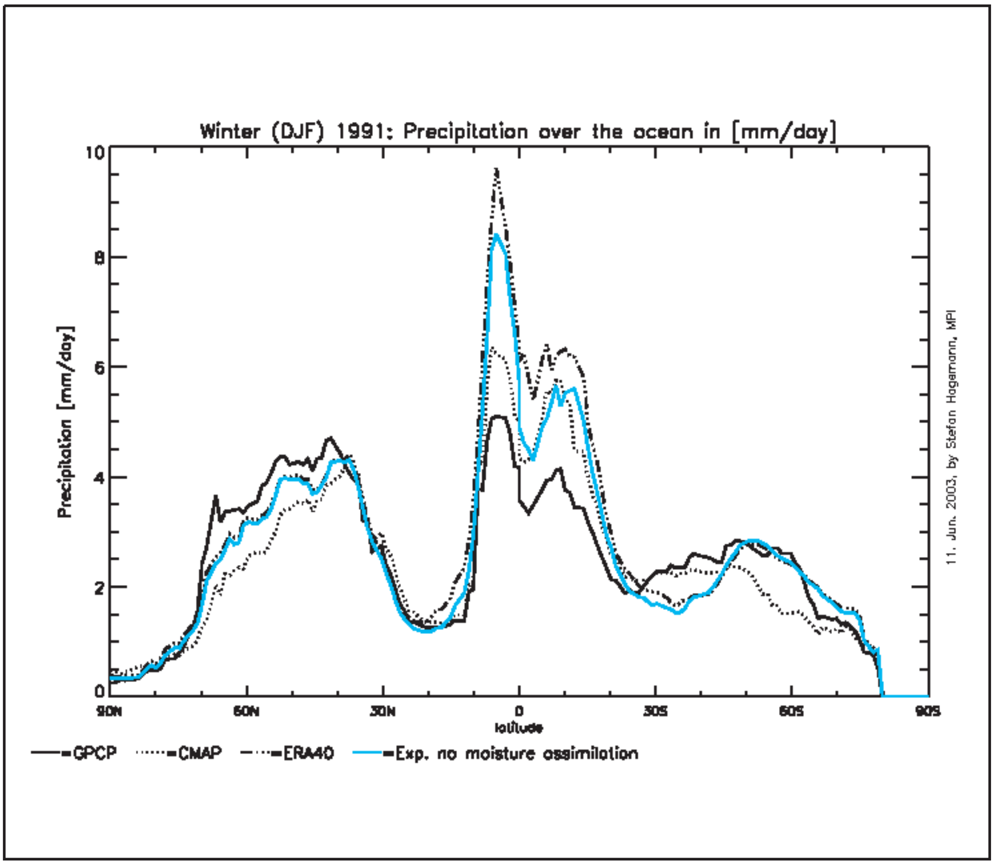

Sensitivity of Large Scale Atmospheric Analyses to Humidity Observations and its Impact on the Global Water Cycle and Tropical and Extra-Tropical Weather Systems

by

L. Bengtsson • K. I. Hodges • S. Hagemann

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Authors

L. Bengtsson	Environmental Systems Science Center, University of Reading, Reading, UK & Max Planck Institute for Meteorology, Hamburg, Germany
K. I. Hodges	Environmental Systems Science Center, University of Reading, Reading, UK
S. Hagemann	Max Planck Institute for Meteorology, Hamburg, Germany

Max-Planck-Institut für Meteorologie
Bundesstrasse 55
D - 20146 Hamburg
Germany

Tel.: +49-(0)40-4 11 73-0
Fax: +49-(0)40-4 11 73-298
e-mail: <name>@dkrz.de
Web: www.mpimet.mpg.de

Sensitivity of Large Scale Atmospheric Analyses to Humidity Observations and its Impact on the Global Water Cycle and Tropical and Extra-Tropical Weather Systems

L. Bengtsson[1], K. I. Hodges[2] and S. Hagemann[3]

1. Environmental Systems Science Center, University of Reading, Reading, UK and Max Planck Institute for Meteorology, Hamburg, Germany

2. Environmental Systems Science Center, University of Reading, Reading, UK

3. Max Planck Institute for Meteorology, Hamburg, Germany

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[1] *Corresponding Author: K. I. Hodges, ESSC, University of Reading, Harry Pitt Building, 3 Earley Gate, Whiteknights, PO Box 238, Reading RG6 6AL, U.K*

Abstract

Re-analysis data obtained from data assimilation are increasingly used for diagnostic studies of the general circulation of the atmosphere, for the validation of modelling experiments and for estimating energy and water fluxes between the Earth surface and the atmosphere. Since these fluxes are not specifically observed, but determined by the data assimilation system, they are not only influenced by the utilized observations but also by model physics and dynamics and by the assimilation method. In order to better understand the relative importance of humidity observations for the determination of the hydrological cycle this paper describes an assimilation experiment using the ERA40 re-analysis system where all humidity data have been excluded from the observational data base. The somewhat surprising result is that the model, driven by the time evolution of wind, temperature and surface pressure, is able to almost completely reconstitute the large scale hydrological cycle of the control assimilation without the use of any humidity data. In addition analysis of the individual weather systems in the extra-tropics and tropics using an objective feature tracking analysis indicates that the humidity data have very little impact on these systems. A discussion of this result and possible consequences for the way moisture information is assimilated as well as the potential consequences for the design of observing systems for climate monitoring is included. It is further suggested, with support from a simple assimilation study with another model, that model physics and dynamics play a decisive role for the hydrological cycle stressing the need to better understand these aspects of model parameterization.

1. Introduction

Short term climate studies of the Earth’s atmosphere (~20-40 years) are increasingly being carried out with datasets produced by advanced data-assimilation methods which make use of operational Numerical Weather Prediction (NWP) techniques. In order to ensure consistency in the assimilation with respect to the model and assimilation method, such studies are mostly undertaken using re-analyses (Bengtsson and Shukla,1988). The approach is to run a “frozen” version of an operational model and data assimilation system in a successive mode (e.g. Gibson et al. 1997, Kalnay et al. 1996, Kistler et al. 2001) generating a sequence of comprehensive meteorological fields for an extended period of time. Some of the available fields are directly analysed by the system including surface pressure, temperature, wind and humidity, other fields consist of derived quantities such as fluxes of water, heat and momentum. These derived quantities consequently depend on the type of model used and are therefore not uniquely determined by the observations. These quantities also depend on different aspects of the assimilation and generally can not be obtained directly from the initial state. Instead they are normally calculated from model estimates used in the assimilation, such as a 6 hourly forecast integrated from the preceding analysis step.

Reanalyses are being used in a multitude of different investigations, including attempts to determine the Earth’s hydrological cycle. Due to the absence of rainfall measurements over the oceans and uncertainties in the calculation of evaporation over both land and sea there are considerable uncertainties in the hydrological cycle. Comparing the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis moisture convergence data with estimated run-off from the Global Precipitation Climatology Project (GPCP) the total land annual water budget (moisture convergence over land = runoff) can presently at best be closed to within 10% (Roads et al., 2002). However, much larger dissimilarities occur over limited regions, for shorter periods and individual processes. This underestimates the error of individual processes that have some cancellation. For example, Adler et al. (2001), showed a precipitation intercomparison which included data from in-situ networks, satellite observations, and results from numerical modelling. Although the data sets are qualitatively similar in that they all capture the tropical maxima, the subtropical minima and the mid-latitude maxima, there are in certain areas considerable quantitative differences between the observational products. The peak value in the Inter-Tropical Convergence Zone (ITCZ) at 8^0N, for example, varies from 1300 to 3200 mm in the annual total.

Several studies to determine the hydrological cycle from NWP data sets have been carried out in recent years (Roads et al. (2002) and references therein, Trenberth and Guillemot (1998)). The hydrological cycle (including sources and sinks) is obtained during the data assimilation by an optimized use of the time evolution of the model and available observations, which directly (via humidity data) or indirectly (via the model as driven by winds, temperature and pressure data) determine the water cycle. At the surface, some implicit analysis adjustment occurs for snow correction as well as for surface moisture, which uses either observed precipitation or the model calculated precipitation. Because of these implicit adjustments one may think that reanalyses cannot be used to study the hydrological budget, or for that matter, budget calculations of energy and water fluxes in general.

Another important question to address is which atmospheric observations are crucial for the determination of the hydrological cycle and which are only of secondary influence. This important question is related to the overall issue of what atmospheric parameters should and can be observed (with present capabilities) and what parameters or quantities are not feasible to observe (because of their very fine structure and very high variability), but should preferably be calculated from models in an assimilating mode.

Here we investigate the relative importance of atmospheric humidity observations with respect to the indirect forcing of the model dynamics. This entails establishing the degree to which the atmospheric humidity observations influence the different components of the hydrological cycle. This will highlight possible weaknesses in the current assimilation systems in making use of the humidity observations (Krishnamurti, 1995). Needless to say, an improved understanding of this issue is of primary importance, since a thorough insight into the use of atmospheric assimilation is needed for setting realistic priorities for the implementation and use of future atmospheric observing systems of relevance to the monitoring of the hydrological cycle. Here we have reasons to assume that atmospheric humidity data are of limited use in present assimilation schemes since they have to be consistent with the divergence field in order to be correctly assimilated. This is generally not the case because of insufficient wind (and temperature) observations of sufficiently high quality. The study will also highlight the choice of model in the data-assimilation, since in areas where the model is inadequately forced by consistent observations then the model dynamics and physical parameterizations will essentially determine the results. This study will also show that the humidity observations have very little impact on the individual weather systems indicating that the dynamical observations are of more importance, this is particularly the case in the extra-tropics.

The paper continues as follows. In section 2 we will describe the data assimilation and the experimental approach. In section 3 we present the global results and the way humidity data may influence the global water cycle including differences between land and ocean areas. In section 4 we explore how humidity data may influence the representation of tropical and extra-tropical cyclones and in section 5 the results are discussed and put into context and finally conclusions are in section 6.

2. The data-assimilation and experimental approach

The assimilation system used for our experiments is the one used in the ERA40 project (Kållberg et al., 1999). In the ERA40 re-analysis, past data for the period 1958-2001 are re-assimilated using a frozen version of the ECMWF forecasting system. The version used is based on a 3-Dimensional Variational (3DVar) data assimilation system and a model with a horizontal spectral resolution of T159 and with 60 hybrid levels in the vertical; an advanced physical parameterization is also used. Precipitation is obtained from the 6 hourly forecast to the assimilation. The data set being produced (to be completed in 2003) will constitute a comprehensive data set expected to be widely used by climate modellers and in relevant climate diagnostic studies. We believe that for such users the study reported here may be of interest.

The main experiment reported here has been set up in the following way. The ERA40 reanalysis system was re-run for a limited periods of time, DJF9091 and JJA91, with all direct humidity observations removed. This means that in this experiment atmospheric humidity is only determined indirectly, as it is forced by the model, which in turn is driven by observations of surface pressure, wind and temperature. Humidity observations are excluded from surface data and radiosondes. All Special Sensor Microwave/Imager (SSM/I) data are excluded, as well as channels 11 and 12 for the HIRS data. A possible route for moisture information to enter the system is via the control against supersaturation in the hydrostatic check, which can create some humidity increments. Another route is via indirect changes to other HIRS channels (6,7 and 8) which may affect humidity. These may take place when these channels are strongly biased with respect to the background state. In such a situation the 3DVar system is unable to adjust temperature any further, and in order to satisfy the radiance observations, adjustment with respect to humidity may occur (E. Andersson and A. Simmons, ECMWF, personal communication, 2002) although we do not anticipate that this has taken place in this experiment.

In the following we will call the standard ERA40 the “control” experiment and the one without humidity observations, the “no-moisture” experiment. For intercomparison and validation we have selected the two well-evaluated precipitation data sets, CMAP (CPC Merged Analysis of Precipitation; Xie and Arkin (1997)) and GPCP (Global Precipitation Climatology Project; Rudolf et al. (1996), Huffman et al. (1997)) which are available as monthly averages since 1979. CMAP is a combination of satellite data and gauge measurements from more than 6500 land stations (Rudolf et al., 2000). GPCP is similar to CMAP but the precipitation data from the land based stations have been corrected for a systematic undercatch of the rain gauges, especially when snowfall, in combination with strong winds, occurs. Consequently, winter precipitation at high latitude land areas is higher in GPCP than in CMAP (see Table 1). Precipitation over extra-tropical oceans is also somewhat higher in GPCP. Over tropical land areas the two data sets agree well, but over tropical oceans precipitation from CMAP is larger than from GPCP. Globally averaged they differ by less than 2% during this period. Over other periods the differences are typically larger with a long term average of some 8%.

3. Global results

The estimated global precipitation, for land and ocean areas separately, from the two empirical estimates together with ERA40 control and the experiment are summarized in Table 1 for the DJF9091 period. The different estimates agree reasonably well over land, but over the oceans the ERA40 control value is some 20% higher than the empirical estimates. While it may be expected that both CMAP and GPCP may underestimate precipitation over the oceans (for example, Trenberth et al., 2001), the ERA40 control precipitation is most likely overestimated and is in fact higher than the corresponding ocean evaporation (112.5×10^{12} versus 111.6×10^{12} m^3 water for the same period). This may be related partly to adjustment processes in the early part of the integration, and may be different when ensembles of predictions longer than 6 hours are used. However, this is a slow process as has recently been demonstrated by Holm et al. (2002) the ERA-40 system requiring some 3-4 days of integration to spin down the overly high initial precipitation. Another cause of the severe imbalance, to be discussed later, is the way satellite moisture data are used in ERA40.

In general the precipitation from the ERA40 control (Table 1, Figure 1(a) and (b)) is higher, over both tropical land and oceans than the estimates from GPCP and CMAP respectively, in particular over the ITCZ region apart from some regions mentioned below. For middle and high latitudes the ERA40 control results fall between the two observational estimates, the estimates from CMAP being higher than that of GPCP. This behaviour is further highlighted in the zonally averaged precipitation, Figure 2(a) and (b), for land and ocean respectively, where the peak in the precipitation between 5˚S and 5˚N is considerably stronger for the ERA40 control than in both CMAP and GPCP both for land and ocean. For the tropical ocean, the empirical data sets are based on indirect assessment of satellite data such as Outgoing Longwave Radiation (OLR) and are dependent on the algorithm used to estimate the rainfall so that there is some uncertainty in these estimates. Over the land the differences between the ERA40 control and the empirical estimates are mainly due to lower model generated precipitation over central Africa, the Amazon basin and Borneo where rather few in-situ rainfall observations exist and to larger model generated precipitation over the Andes. Here, numerical handling of the flow over the mountains may be a contributing factor to very high precipitation. The underestimation of modelled precipitation over central South America is quite pronounced and most likely incorrect, since several in-situ measurements from the GPCP are higher than the results from the assimilation runs. The comparatively large extra-tropical difference in the zonally averaged precipitation between 45˚S and 55˚S over the land comes from the high orographically induced precipitation over southern Chile, though these zonal means will be based on only a few grid-points. On the other hand, the precipitation appears to be underestimated in both CMAP and GPCP in this region.

The precipitation over land from the ERA40 no-moisture experiment (Table 1, Figure 2(a)) is practically identical to the control run, thus showing the same difference relative to CMAP and GPCP. On the other hand, over the ocean regions the precipitation is 10% less than in the ERA40 control run. Polewards of 30˚N and 30˚S the calculated precipitation by both assimilation runs is practically identical (Figure 2(b)). These results suggest that the differences from CMAP and GPCP for the ERA40 control and no moisture experiment *are not related to whether atmospheric humidity observations are included or not.*

Evaporation over land is virtually the same in the no-moisture and control runs, while over the ocean the assimilation without moisture is 3.5% higher, the difference is essentially confined to the tropics (Figure 3). The slightly higher evaporation in the no-moisture run is consistent with a drier atmosphere.

The global water balance for land and ocean separately, is summarized in Table 2. As a result of the high ocean precipitation in the ERA40 control run the global water cycle is unbalanced. This is because the Precipitation-Evaporation (P-E) is close to zero over the oceans, being slightly negative in December, slightly positive in January and close to zero in February (Table 2). For land areas P-E is positive, as of course it should be, amounting on average to 4.3×10^{12} m^3 water per month in both control and the no-moisture assimilation. For the no-moisture experiment P-E over the ocean is now much more realistic and results in the water cycle between land and ocean balancing rather well, having a net water imbalance of -0.6×10^{12} m^3 water over the whole winter season (negative value indicates a land-ocean loss), compared to a net global water imbalance of $+13.7 \times 10^{12}$ m^3 water for the ERA40 control run, or the same amount as the complete water transport from ocean to land. The result strongly suggests that the ocean precipitation in the ERA40 control run is too high.

Although the main interest in this study is on the hydrological cycle we have also investigated the analysed humidity field and the outgoing long wave radiation (OLR) in order to better understand how well the experiment can reconstitute atmospheric humidity. Figure 4 shows the zonal cross-sections for precipitable water content and OLR for the control and no-moisture experiment, respectively. Minor differences can be found in the precipitable water where the control has slightly higher values essentially confined to the equatorial region. The globally integrated values differ by less than 2% (3-4% in the tropics) and are well within the accuracy of individual observing systems

The zonal structure of OLR is also very similar in the two experiments, with slightly higher values in the tropics for the control experiment, suggesting slightly drier conditions in the upper troposphere at least outside the ITCZ. This seems to indicate a somewhat stronger tropical meridional circulation in the control experiment. Globally averaged values differ by 1.6 Wm^{-2}, and again are well within the limits of the available estimates (Kiehl and Trenberth, 1997).

4 Tropical and extra-tropical cyclones

An analysis of the intensity and trajectory of tropical and extra-tropical cyclones, which are likely to be influenced by the moisture data, has been performed. This is based on the methodology described in Hoskins and Hodges (2002) for the extra-tropical cyclones and Thorncroft and Hodges (2001) for the tropical cyclones. For the extra-tropical activity the tracking has been performed on the Mean Sea Level Pressure (MSLP) field as well as the relative vorticity on the 850, 500 and 250hPa (ξ_{850}, ξ_{500}, ξ_{250}) levels. Note, that for the extra-tropical activity the fields have the planetary scales removed before identification and tracking are performed as described by Hoskins and Hodges (2002). This makes the systems easier to identify in particular for MSLP. For the tropical cyclone activity the tracking was performed on the ξ_{850} field only. For both the extra-tropical and tropical analysis only those systems that last at least 2 days and travel further than 1000 km are retained. Since results for only one winter are available, the generation of spatial statistics such as those produced in Hoskins and Hodges (2002) (which where based on results for 20 NH winters) for extra-tropical cyclones will not be statistically meaningful and are not considered. Instead we have used the approach of Hodges et al. (2002) for the direct comparison of track ensembles. This compares two track ensembles track by track to produce statistics. This approach is used for the comparison of the extra-tropical track ensembles for the MSLP and relative vorticty fields. The matching parameters for what constitutes a good match are an overlap in time by at least 60% of the points and a mean geodesic separation computed for those points that match of less than 0.5^0 (see Hodges et al., 2002 for further details). In general, the results for MSLP focus on the larger end of the spatial synoptic scale range, whilst the relative vorticity focuses on the smaller spatial scales and results in many more systems being identified. The summary statistics are shown in Table 3.

For the NH, Table 3 shows that the agreement between the track ensembles for the ERA40 control and no-moisture experiment. For MSLP this shows that the agreement between the tracks is very good with the number of tracks that match being greater than 90% and with the number of tracks that match with greater than 95% of their points being greater than 80%. As was seen in Hodges et al. (2002), the tracks that do not match or that match with fewer than 95% of their points tend to correspond to the weakest systems which are more sensitive to the available observations and the way these are assimilated. This can be seen in Figure 5(a), which shows the distributions, in terms of the mean track intensities (averaged along a track) for NH MSLP, for the tracks that match and those that do not match. The fact that for the two ensembles the distributions for the tracks that do match are very similar indicates that there is very little difference in the system intensities on a point by point basis, a separate point by point comparison confirms this. This situation is also reflected in the ξ_{850} field (Figure 5(c)) where there are now many more systems identified, reflecting the smaller spatial scale nature of these systems. This also shows a good correspondence between the two track ensembles with ~85% matching well and more than 60% matching for greater than 95% of their points. As we go to higher levels where there are fewer observations this view persists, although there is some degradation in the percentage of systems that match for greater than 95% of their points. The distributions of those systems that match for $\xi_{850,500,250}$ between the ERA40 control and the no-moisture experiment, as for MSLP, show good agreement indicating there is little difference in the individual system intensities between the two track ensembles, as with MSLP a point by point comparison confirms this. These results indicate that water vapour observations have a minimal effect on the representation of the synoptic weather systems in the extra-tropics, indicating perhaps the dominance of the dynamics over the water vapour field at mid to high latitudes.

In the Southern Hemisphere (SH) the results indicate a similar picture, although with slightly fewer systems as a percentage of the total providing a good match. The slightly poorer results in terms of the number of systems that match well between the ERA40 control and the no-moisture experiment for all fields may reflect the fact that there are relatively few ground based observations of winds and temperature so that the assimilation is more reliant on the satellite observations.

In terms of tropical cyclones the tropical activity for this period is confined to the SH. However, for this SH summer period there are relatively few tropical cyclones. We have identified several of the tropical cyclones in this period in both the control and no-moisture experiment and compared them with the best track data from the Data Support Section of the Scientific Computing Division at NCAR. These are shown in Figure 6 for tropical cyclones Joy, Chris, Daphne and Bella and indicate that both the ERA40 control and no-moisture experiment have both captured these tropical cyclones quite well. The main differences occur at the beginning and end of the storm life cycles when the storms are quite weak and are more sensitive to the observations used. In terms of the maximum intensities Table 4 shows the maximum attained intensity together with the date this occurred. These results show that whilst three of the storms are marginally less intense in the no-moisture experiment with one more intense these differences are quite small, typically less than $1.0\text{x}10^{-5}$ sec^{-1}. The times at which the maximum intensity is attained are nearly identical for the ERA40 control and no-moisture experiment for all the cyclones. However, comparing with the observed times at which the cyclones reached their maximum intensity in terms of wind speed there are some differences.

The results for tropical cyclone Bella highlight some of the problems in tracking tropical cyclones when they are weak disturbances and are more sensitive to the assimilation. The problems are highlighted by the labels 1, 2 and 3. These indicate a break in the track due to the generation of a multiple center which we have fixed manually; this occurs twice for the ERA40 control (green, label 1 and 2) and once for the ERA40 no-moisture experiment (red, label 3). Ultimately, this problem will be fixed by using a more objective method of merging tracks in the tracking algorithm.

5. Discussions

There are two important results from this study which need to be highlighted. The first point to make is the very limited contribution from humidity observations in general. This does not mean that moisture observations are unimportant per se, but as we have shown here, a comprehensive data-assimilation system is able to reconstitute the moisture field to a considerable degree from the dynamics of the large scale models and from the sources and sinks of water vapour in the model. In addition to the mean field presented here we have also explored the individual maps and the representation of synoptic weather systems in both the tropics and extra-tropics. As demonstrated above there are hardly any noticeable differences in the weather systems identified in surface pressure fields or in the different tropospheric vorticity fields. Where we do see differences between the control and no-moisture experiment are in the global hydrological cycle and precipitation over the tropical oceans where it in fact appears that the no-moisture experiment is more credible than the control assimilation, since the global water balance is practically balanced in the experiment but not so in the control assimilation. We have explored this further in a separate experiment for December 1990 whereby we removed all the SSM/I and HIRS data in the ERA40 control to test the individual effect of these observations on the atmospheric humidity. This experiment resulted in a reduction of the overly high ocean precipitation by 3 x10^{12} m^3 water (~ 10%) and increasing ocean evaporation by 1.3 x10^{12} m^3 water (~ 3%), resulting in close agreement with the experiment without moisture observations. It therefore seems that it is the way moisture data from the satellite observing systems are used that is the main contributing factor to the high ocean precipitation and imbalance of the global hydrological cycle.

These findings are supported by the suggestions of Holm et al. (2002) of an excessive tropical precipitation in the ERA40 assimilation system. If the tropical circulation in the assimilation cycles is too intense then there is a tendency for the descent region to be too dry. When the humidity is assimilated into these regions the data act to modify a region which is seen to be too dry. The excess humidity feeds into the precipitation ascent region, generating too much precipitation, and maintaining the overly strong circulation. This is consistent with the differences in OLR and precipitable water content as shown in Figure 4.

The fact that a comprehensive model driven by observed boundary conditions and atmospheric dynamics through the time evolution of surface pressure and the vertical profiles of horizontal winds and temperatures is a suitable way to calculate atmospheric fluxes has long been recognised (e.g. Charney et al., 1969). The general message from this finding is that dynamical variables are fundamentally important in weather prediction and in the reconstitution of the general circulation of the atmosphere by means of a comprehensive forecasting system. In general observations of pressure, wind and temperature are difficult to observe because of the cost and technical difficulties. In fact, cloud and moisture are generally easier to observe, at least from space-based observing systems. Yet, if we use observations of moisture in data assimilation it is necessary to also adjust simultaneously pressure, wind and temperature in a way that is consistent with the moisture field, so that the divergence pattern set up by the dynamical variables does not destroy the presumed correctly observed moisture field.

This study also highlights the key role of the atmospheric model in the reconstitution of the hydrological cycle. The actual model used in the data assimilation probably influences the hydrological cycle more than the moisture observations. In order to estimate the influence of the choice of model on the hydrological cycle we have dynamically adjusted the ECHAM4 (version 4.5) model (Roeckner et al., 1996) towards the ERA40 analysed fields of surface pressure, temperature and wind by means of a so called “nudging” technique (Jeuken et al., 1996). The ECHAM4 model is successively adjusted towards the ERA40 analyses at every time-step of the integration (interpolated from every 6 hours), in such a way that the difference in surface pressure, wind and temperature after a short period of adjustments stays well within the observational accuracies of these variables. Forced in such a way, the result is very similar to a continuous set of analyses of the same model using observations of surface pressure, temperature and wind. The result can be considered more or less as a no-moisture assimilation with the ECHAM model. The result, together with the two ERA40 assimilation experiments, and the free run with ECHAM4 (only using the same SST) are summarised in Table 5.

We first note that the ECHAM 4 nudged and free runs generate a very similar hydrological cycle, albeit a somewhat weaker one over land for the nudged version. Over ocean areas the difference is about 1% for both precipitation and evaporation. The reduced similarity over land is probably related to inherent inconsistency in the “nudged” run, since for example there is no feedback between the land surface conditions and the atmospheric fields.

A second observation is the more intense hydrological cycle in the ERA40 control and no-moisture runs compared to ECHAM. In the ERA40 no-moisture run, which is based on the same observations as the nudged ECHAM run the precipitation over land is 20% higher and over ocean is ~10% higher. All four experiments, except the ERA40 control, balance the global water cycle as well as could be expected in view of the short integration time.

We have also calculated the energy balance for the two ERA40 assimilation runs. The differences are small and well within the uncertainty limits. The global surface thermal radiation and latent heat flux are 2 and 3% larger, respectively, in the no-moisture experiment while the sensible heat flux is 2% smaller. The largest differences occur over ocean areas. As a result the ocean net warming amounts to 23 Wm^{-2} in the control run and 19 Wm^{-2} in the no-moisture run. A net ocean warming is expected due to the season. We have also compared these flux components from the ERA40 control and no-moisture experiment with a corresponding calculation with the ECHAM4 model, both in a free and “nudged” mode. The different flux components are smaller for ECHAM than for both the ERA40 control and no-moisture experiment by some 10-20%, although the net ocean warming is 16 Wm^{-2} and thus closer to the no moisture run.

In concluding this discussion it is important to also clarify that we do not want to suggest that satellite observed moisture fields are unimportant in the simulation of the general circulation of the atmosphere or for the representation of weather systems but that currently observed moisture data is of insufficient detail and is assimilated in a way that is inconsistent with the fundementally important dynamical variables. For example the HIRS weighting functions for channels 11 and 12 are very broad in the vertical peaking at 700 and 500 hPa respectively. This gives very poor vertical resolution of the moisture fields. In addition to poor resolution in the vertical as well as horizontally, the HIRS satellite observed water vapour is limited to cloud free regions so that in the tropical ITCZ region for example the water vapour field is poorly observed by this instrument. For SSM/I vertical and horizontal resolution is also poor. Recent work has shown that the assimilation of high resolution vertical profiles of water vapour (of relatively high resolution in the horizonatal) provided by active instruments such as airbourne lidar (only in cloud free regions) can have a significant impact on the representation of weather systems and in particular tropical cyclone forecasts (Kamineni et al, 2003). The difficulty with this type of data is its lack of global coverage so that it is limited to particular regions such as the Atlantic coast of North America. New passive instruments may provide better observations of the atmospheric water vapour such as the new Atmospheric Infrared Sounder (AIRS) on the recently launched AQUA satellite although resolution and accuracy are still poor compared to the lidar observations.

6. Concluding remarks

We have shown that the ERA40 assimilation system is able to reproduce the global hydrological cycle without the use of humidity observations, and that there are only small differences in the dynamical fields and the hydrological cycle at high latitudes from the ERA40 control assimilation using all available observations. The differences between the two assimilation cycles are well within the bounds of present empirical estimates. In fact, some aspects of the no-moisture assimilation are more realistic than in the control assimilation, which has a major error in the global water cycle, since the oceans do not provide a net source of water for the atmosphere. We believe this deficiency as supported by a limited experiment is related to the way SSM/I and HIRS data are used in the ERA40 control assimilation.

We have restricted this study to the winter period 1990/91 since we believe the result is representative enough. However, an identical study has also been completed for the summer period 1991, with very similar results, in particular for the water balance. Zonal cross-sections of the integrated water vapour and OLR are in all respects consistent with the winter results.

In addition to the investigation of the extra-tropical and tropical cyclones we have compared daily changes in precipitable water, precipitation and evaporation at individual grid points. These are practically identical for extra-tropical regions but differs slightly in the tropics (not shown). Systematic differences are consistent with the zonal average results.

Determination of the hydrological cycle using the ECHAM 4 climate model at comparable resolution using a nudging technique provides a different estimate of the hydrological cycle. Only surface pressure, temperature and wind field from ERA40 were used for the nudging. The result is a weaker hydrological cycle of some 10% then the ERA40 no-moisture run. The hydrological cycle of the nudged ECHAM 4 run is rather similar to the ECHAM 4 free run which is only constrained by the SST. The result indicates a strong model dependence, and that observed humidity in particular has little influence in determining the global hydrological cycle from data assimilated fields.

The objective of the present study was to obtain better insight into the way the ERA40 reanalysis are able to reproduce the global water cycle and the relative importance of moisture observations in this respect and their influence on extra-tropical and tropical weather systems. We believe this study adds to this understanding and will be of value for the users of the ERA40 dataset. Will these results also be of importance for NWP? We believe this is the case as well. The very small differences between the two assimilations in the extra-tropics suggest that the error growth will be rather similar and any significant differences will be difficult to demonstrate against the background of growing unpredictable noise. The differences in the tropics are detectable and could presumably influence tropical weather forecasts. The importance here though is to assure a better consistency between model dynamics and the assimilation of moisture observations. Some inconsistencies in the assimilation system may be more detrimental than omitting the moisture observations although higher resolution and more accurate observations of the moisture field are likely to be required before the assimilation of water vapour will be of benefit to re-analyses and NWP.

The results of this study raises a number of fundamental questions and issues:

First, how shall we best modify the data-assimilation to make better use of the information content available in observations of humidity, and in atmospheric hydrological information in general?

Second, the result of this study suggests that pressure, wind and temperature data are the most important data for the determination of the hydrological cycle when integrated into an advanced data-assimilation system. This finding is important for the setting of priorities of future observing systems concerned with large scale weather and climate prediction and the determination of the hydrological cycle of the Earth.

Third, since the choice of model appears to be crucial it will be necessary to identify those aspects of the model that are most important in the determination of surface fluxes. Clearly, several re-analysis exercises are called for. Scientists concerned with diagnostic studies or who wish to have estimates of fluxes for ocean and land surface modelling are advised to undertake calculations using more than one data set due to the uncertainties in these quantities.

The results in this study are of further interest when trying to assess how climate may have changed over the last century. The re-analyses data now cover more than 50 years, during which time the global observing systems have undergone substantial changes. It is our intention to undertake similar studies as described here by reducing the present observing system towards a system typical of the pre-satellite era. Whilst the radiosonde system has undergone substantial changes both with respect to networks and sounding equipment, it will nevertheless be possible to estimate how our knowledge of the general circulation of the atmosphere is related to changes in the observing systems. Such investigations have started and will be reported in a future study.

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Figure captions

Figure 1: Precipitation difference for the winter (DJF) 1990/1991 (a) ERA 40 - CMAP and (b) ERA 40 - GPCP. Units in mm/day.

Figure 2: Zonally averaged precipitation (a) over land for GPCP (full line), CMAP (dotted), ERA40 control (dash-dotted), ERA40, no moisture (grey) and (b) for the oceans. Unit mm/day.

Figure 3: Zonally averaged evaporation over land and ocean. ERA40 control over land (full line), ERA40 control over ocean (dash-dotted), ERA40 no moisture over land (dotted) and over ocean (grey).

Figure 4: (a) Outgoing Longwave Radiation (W m^{-2})and (b) Precipitable Water Content (mm), for ERA40 control and the no-moisture experiment over land and ocean for the winter (DJF) 1990/1991.

Figure 5: Tracking statistics of extra-tropical depressions for the NH and SH with respect to surface pressure and relative vorticity at three different levels (850, 500, 200 hPa). Number of weather systems as a function of mean intensity, units of hPa for MSLP and sec^{-1} for vorticity relative to the background field removed. Matching and non-matching systems separately indicated.

Figure 6: Tracks for four tropical cyclones identified during the period. Best track data obtained from the Data Support Section at NCAR (black), ERA40 control (green) and from the no-moisture experiment (red), (a) Joy, (b) Chris, (c) Daphne, (d) Bella.

Table Captions

Table 1: Precipitation over land, P (land), and ocean, P (Ocean) for the period December 1990 through February 1991. Units are 10^{12} m^3 of water, mm/day in brackets.

Table 2: Global Water Balance for Land and Ocean and per Month. Units as in Table 1.

Table 3: Summary Statistics for Extra-Tropical Cyclone Matching in the NH and SH, percentages of totals are in brackets. The keyword Total indicates the total number of systems identified for the ERA40 control and no-moisture experiment; Match indicates the number of systems that match between the two track ensembles; No Match the number of systems that do not match; Match > 95% are the number of systems that match for greater than 95% of their points.

Table 4: Maximum intensities and the dates at which they are attained for the four identified tropical cyclones. Intensities are in units 10^{-5} sec^{-1}, dates are in the format YYMMDDHH.

Table 5: The hydrological cycle integrated over all land and ocean areas, respectively, for the period December 1990-February 1991. Units are 10^{12} m^3 water. For further information see text.

Table 1

	CMAP	GPCP	ERA40 (control)	ERA40 (no moisture)
P (Land)	23.7(1.81)	27.1(2.07)	27.8(2.15)	28.0(2.16)
P (Ocean)	97.0(2.96)	92.3(2.81)	112.5(3.48)	102.2(3.16)

Table 2

Land				
	Total	Dec.	Jan.	Feb.
P-E ERA40 (control)	12.8	4.3	4.9	3.6
P-E ERA40 (no-moisture)	12.8	4.0	5.1	3.7
Ocean				
P-E ERA40 (control)	0.9	-0.6	1.6	-0.1
P-E ERA40 (no-moisture).	-13.4	-5.1	-4.1	-4.2

Table 3

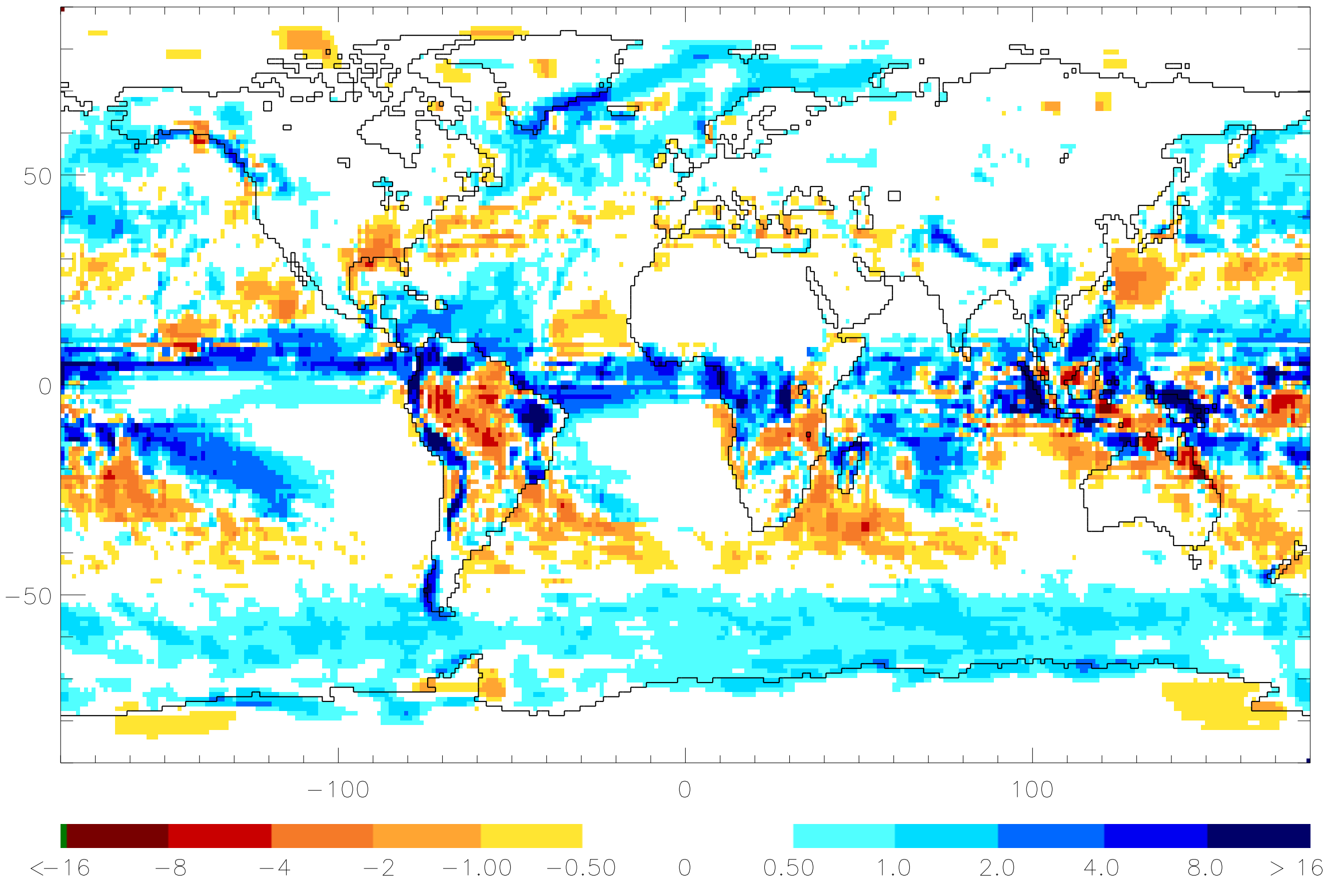
NH				
	MSLP	ξ_{850}	ξ_{500}	ξ_{250}
ERA40 Total (control)	165	439	564	433
ERA40 Total (no-moisture)	163	440	548	432
Match	154 (94)	379 (86)	461 (82.9)	353 (82.6)
No match ERA40 (control)	11 (6.7)	60 (13.7)	103 (18.3)	80 (18.5)
No match ERA40 (no-moisture)	9 (5.5)	61 (13.8)	87 (15.9)	79 (18.3)
Match > 95%	138 (84)	278 (63.2)	269 (48.4)	235 (54.3)
SH				
ERA40 Total (control)	145	359	456	427
ERA40 Total (no-moisture)	153	368	453	441
Match	134 (90)	275 (75.6)	335 (73.7)	341 (78.6)
No match ERA40 (control)	11 (7.6)	84 (23.4)	121 (26.5)	86 (20.1)
No match ERA40 (no-moisture)	19 (12.4)	93 (25.3)	118 (26.0)	100 (22.7)
Match > 95%	105 (70.5)	149 (41)	174 (38.3)	170 (39.2)

Table 4

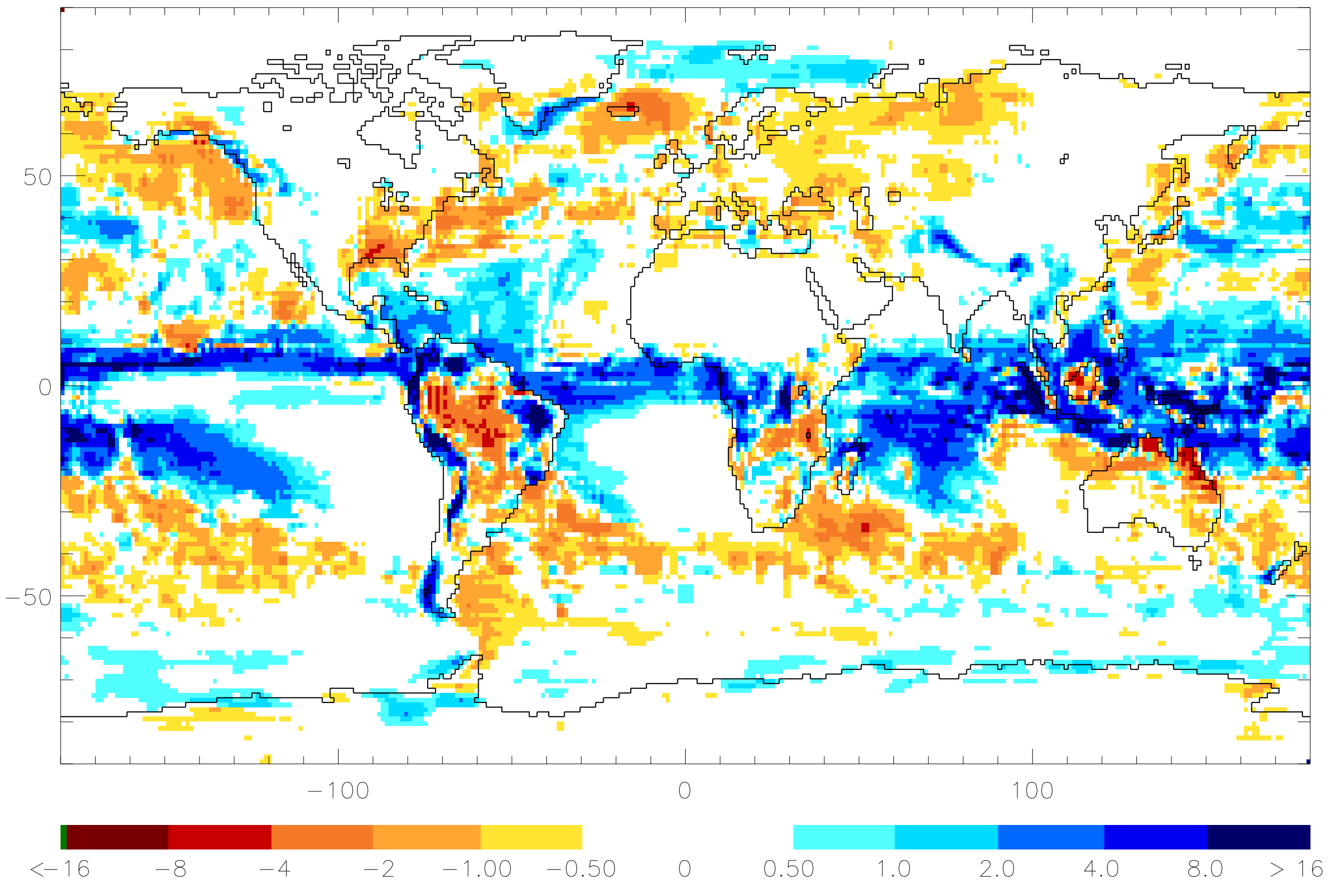
	ERA40 (control)	ERA40 (no-moisture)
Joy	-14.2 (90122500)	-13.7 (90122418)
Chris	-13.4 (91021800)	-12.5 (91021800)
Daphne	-12.6 (91022100)	-11.5 (91022018)
Bella	-12.5 (91020112)	-13.2 (91020112)

Table 5

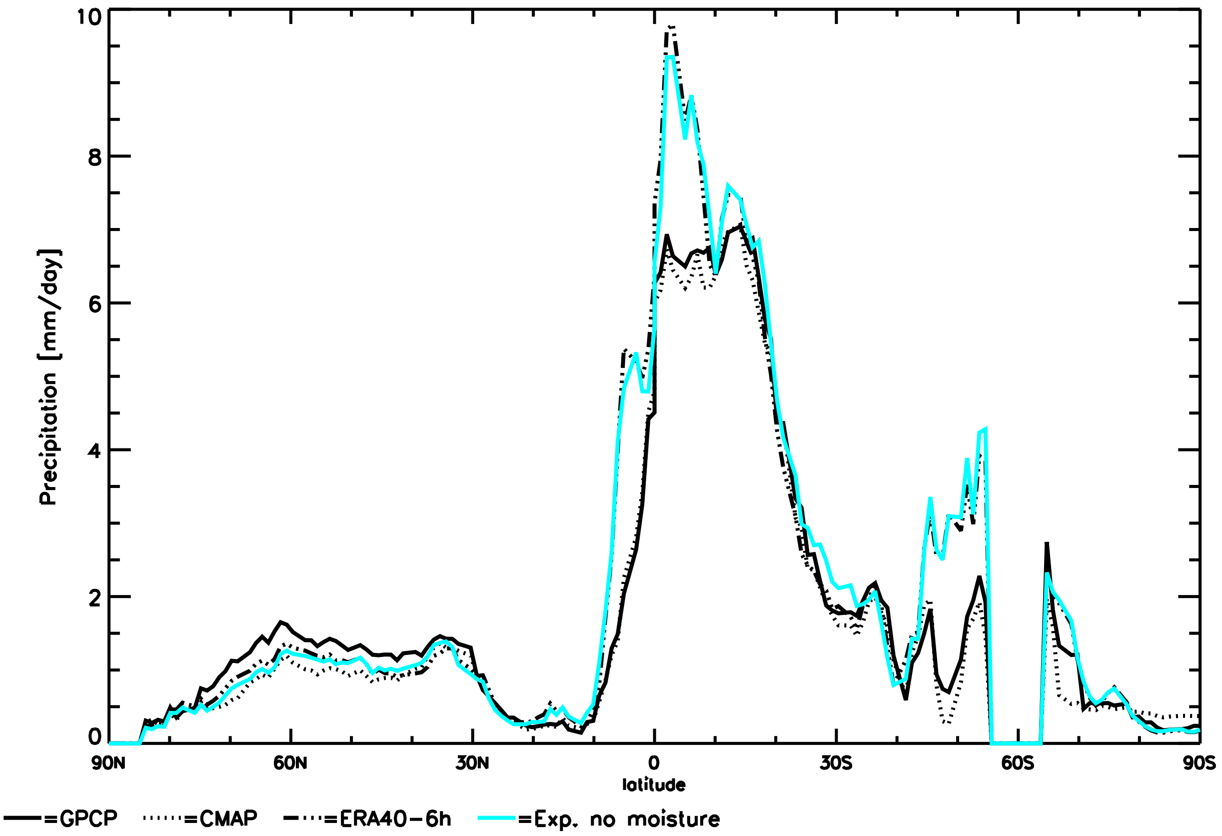
	ERA40 (control)	ERA40 (no-moisture)	ECHAM4 (nudged)	ECHAM4 (free run)
P (Land)	27.8	28.0	21.3	24.1
P (Ocean)	112.5	102.2	95.7	94.5
E (Land)	15.0	15.2	12.5	14.2
E (Ocean)	111.6	115.6	104.9	105.4
P-E (Land)	12.8	12.8	8.8	9.9
P-E (Ocean)	0.9	-13.4	-9.2	-10.9
P-E (L+O)	13.4	-0.6	-0.4	-1.0



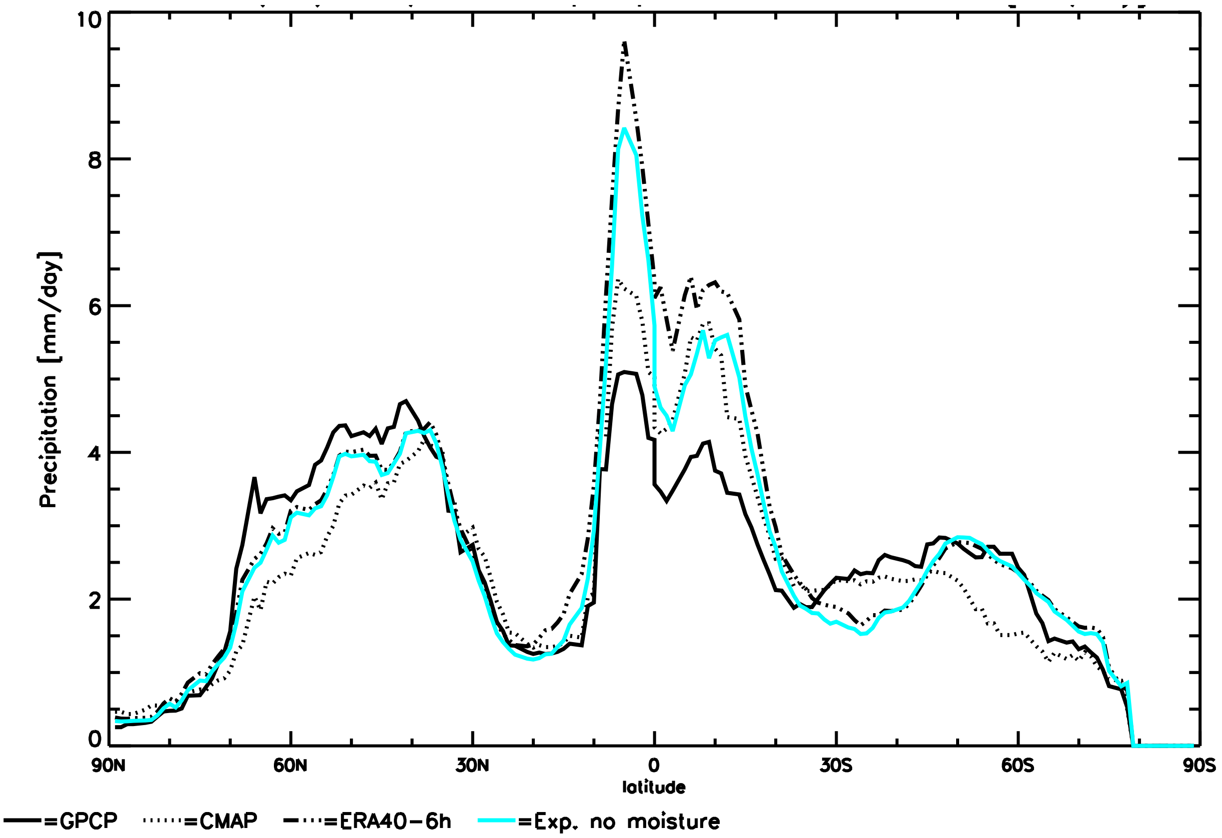
(a) ERA40 control CMAP precipitation



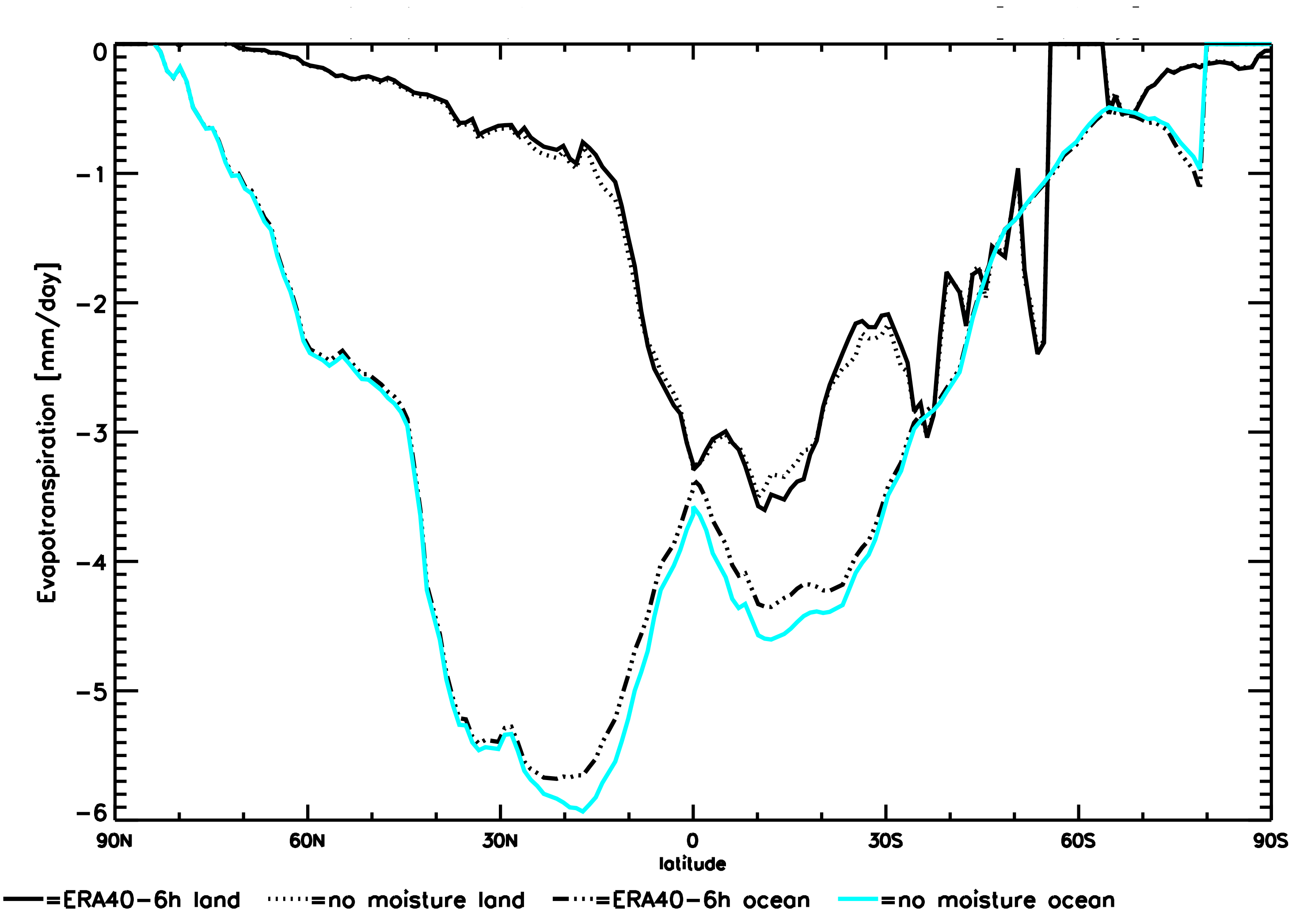
(b) ERA40 control GPCP precipitation



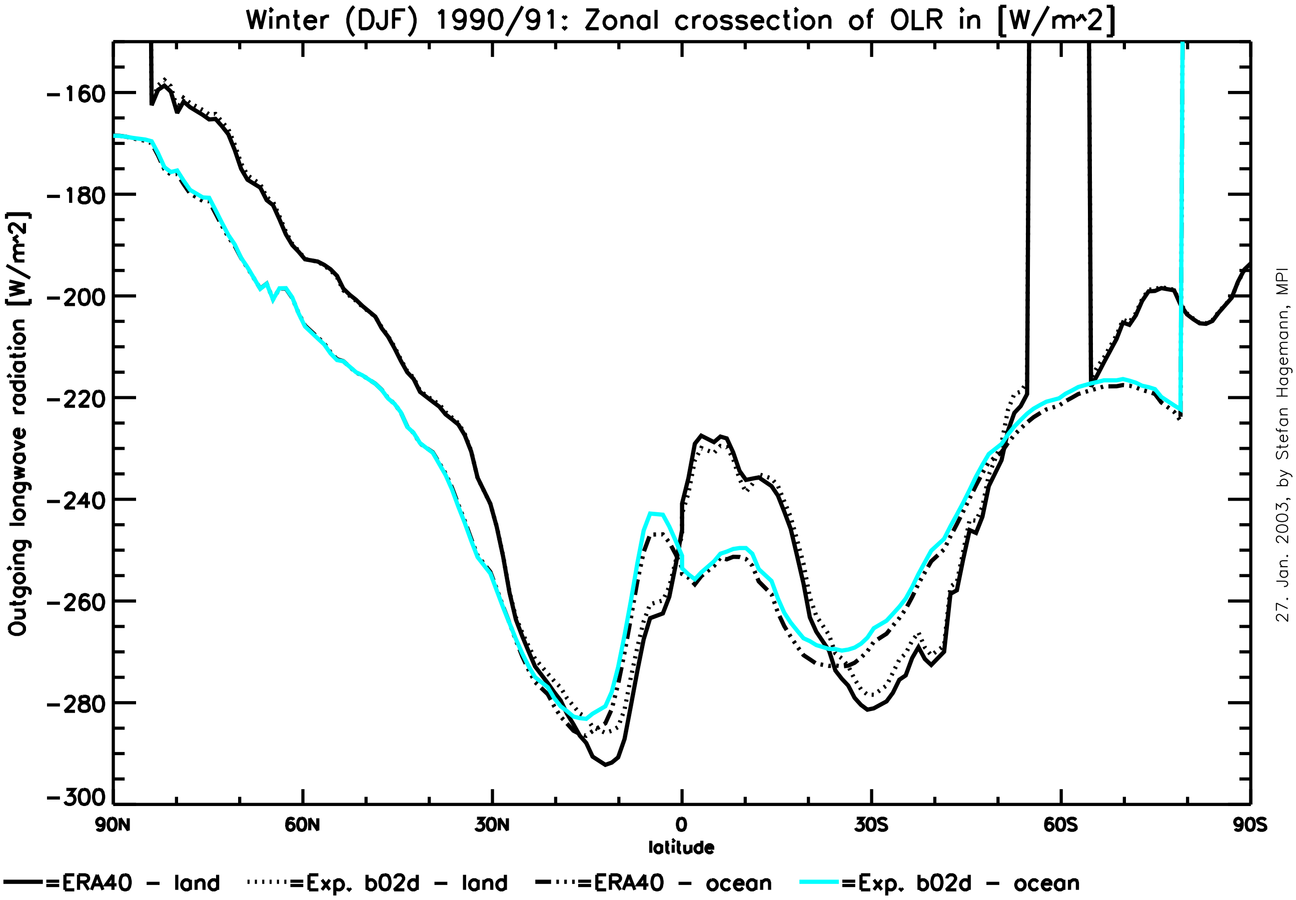
(a) Zonal Precipitation over land (mm/day)



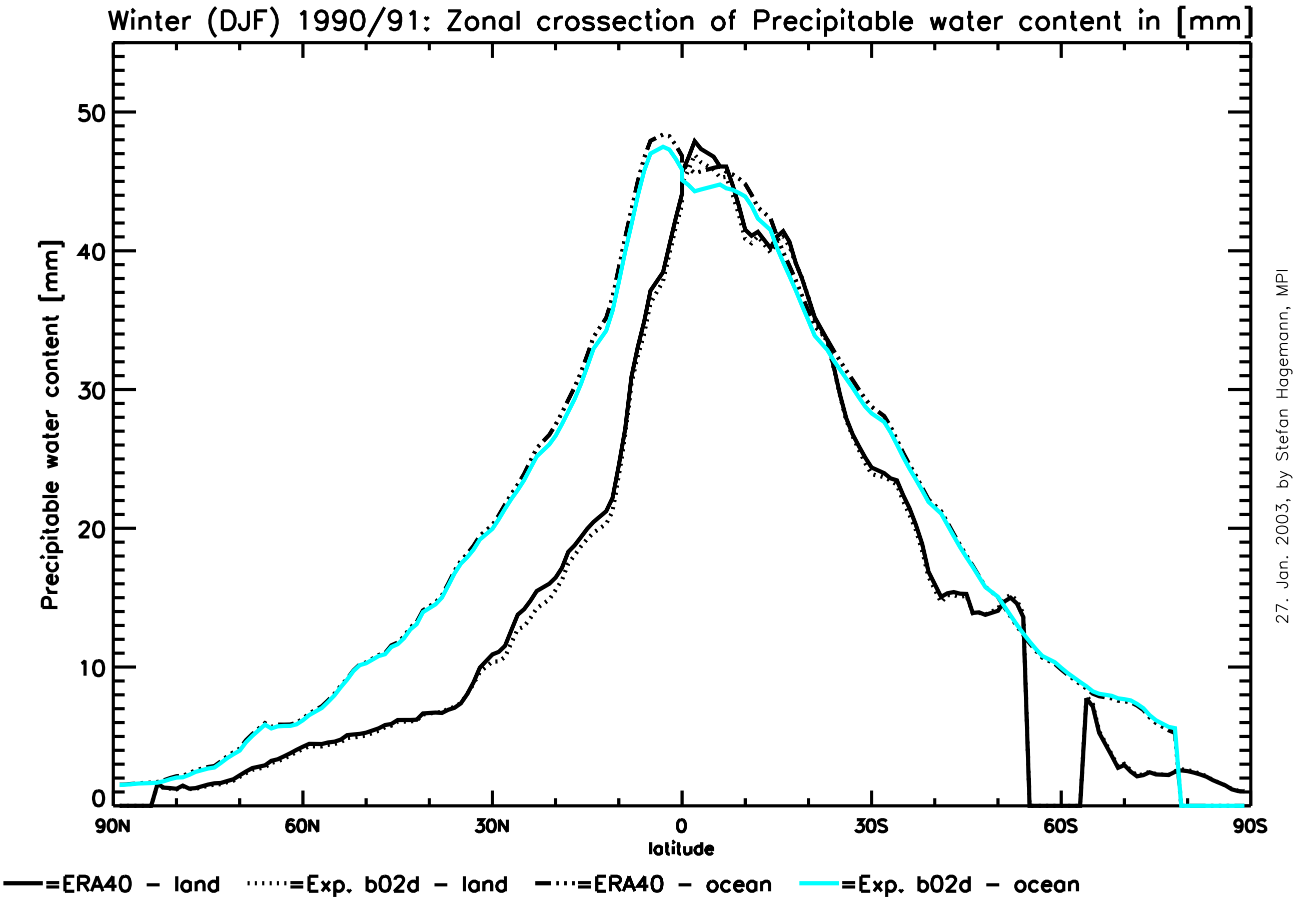
(b) Zonal Precipitation over ocean (mm/day)



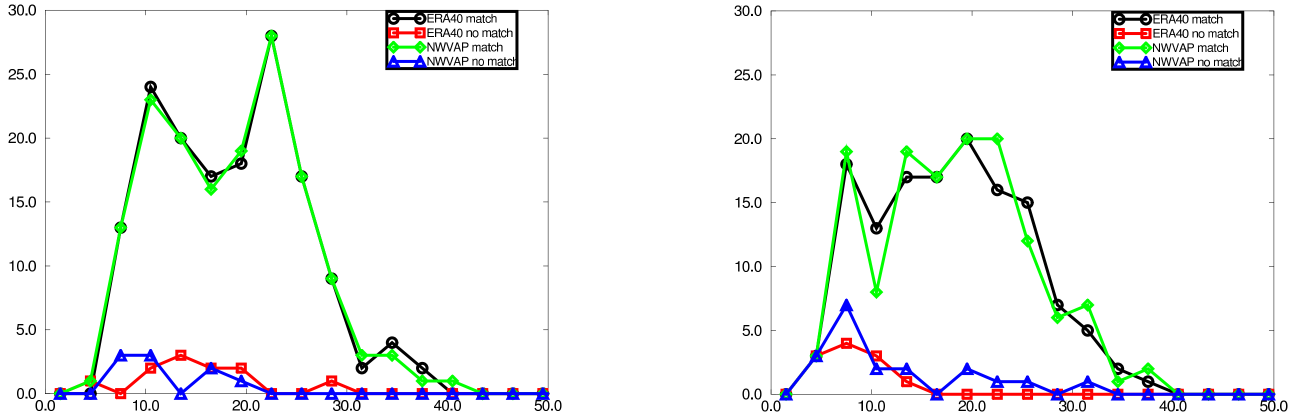
Evapotranspiration [mm/day]
0
-1
-2
-3
-4
-5
-6
90N
60N
30N
0
30S
60S
90S
latitude
=ERA40-6h land
=no moisture land
=ERA40-6h ocean
=no moisture ocean


Winter (DJF) 1990/91: Zonal crossection of OLR in [W/m^2]
Outgoing longwave radiation [W/m^2]
-160
-180
-200
-220
-240
-260
-280
-300
90N
60N
30N
0
30S
60S
90S
latitude
=ERA40 - land
=Exp. b02d - land
=ERA40 - ocean
=Exp. b02d - ocean
27. Jan. 2003, by Stefan Hagemann, MPI

(a)

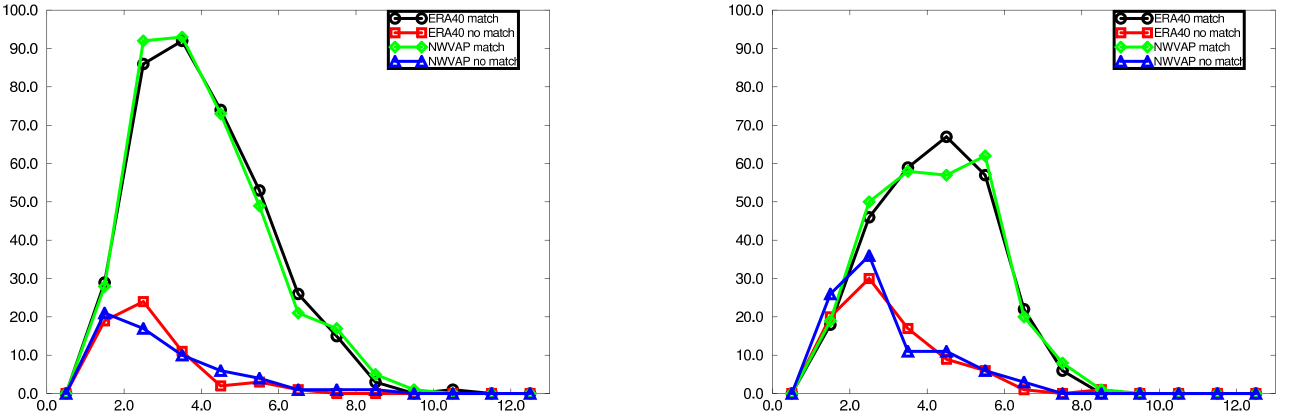

Winter (DJF) 1990/91: Zonal crossection of Precipitable water content in [mm]
Precipitable water content [mm]
50
40
30
20
10
0
90N
60N
30N
0
30S
60S
90S
latitude
=ERA40 - land
=Exp. b02d - land
=ERA40 - ocean
=Exp. b02d - ocean
27. Jan. 2003, by Stefan Hagemann, MPI

(b)



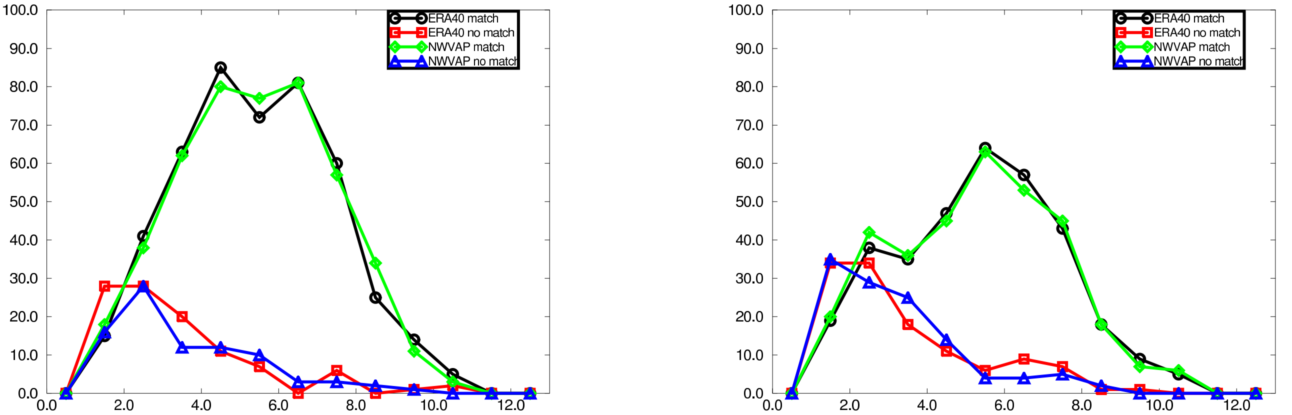
(a) NH MSLP

(b) SH MSLP



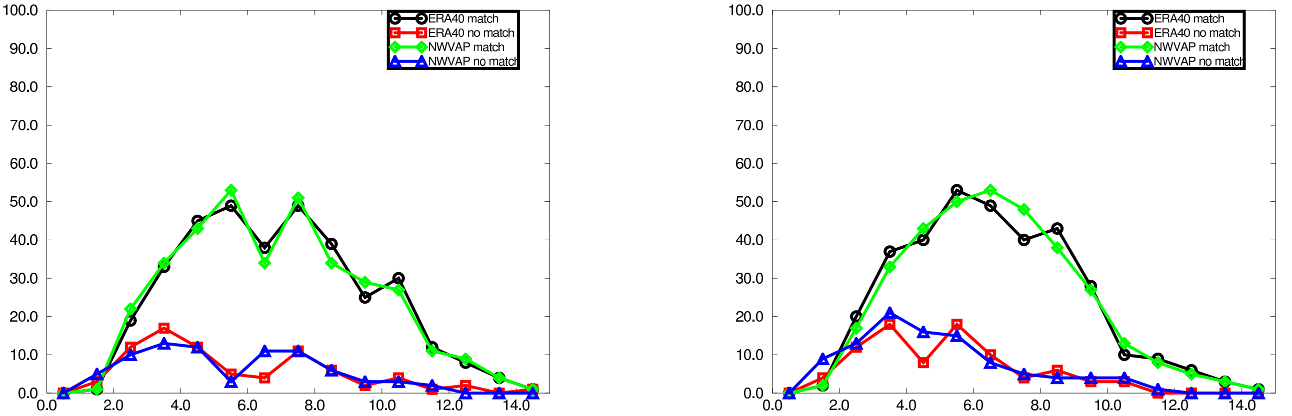
(c) NH ξ_{850}

(d) SH ξ_{850}



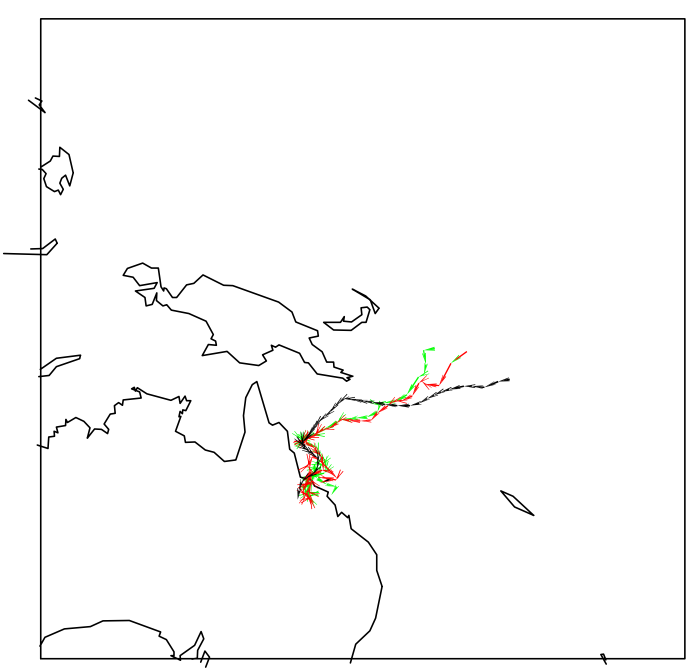
(e) NH ξ_{500}

(f) SH ξ_{500}

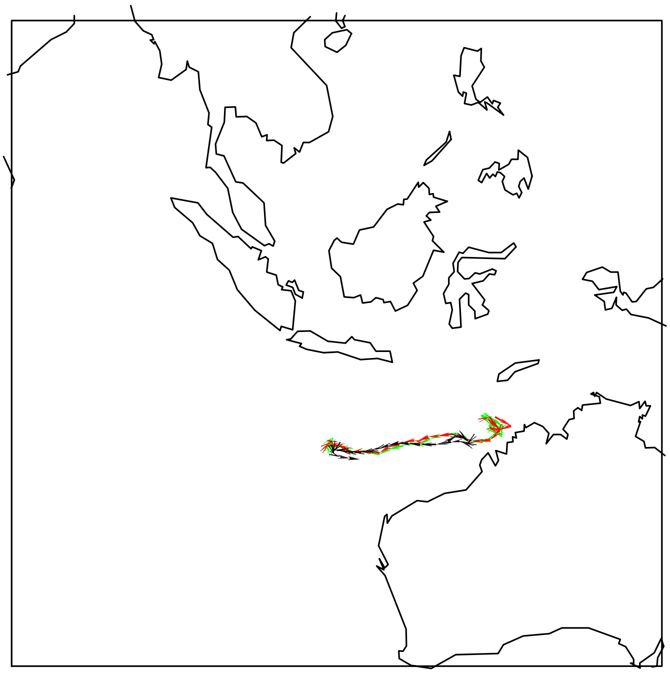


(g) NH ξ_{250}

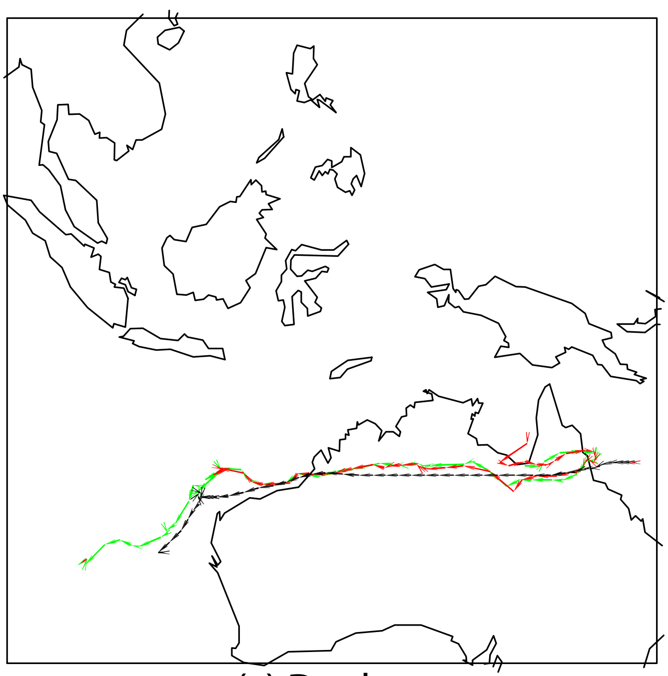
(h) SH ξ_{250}



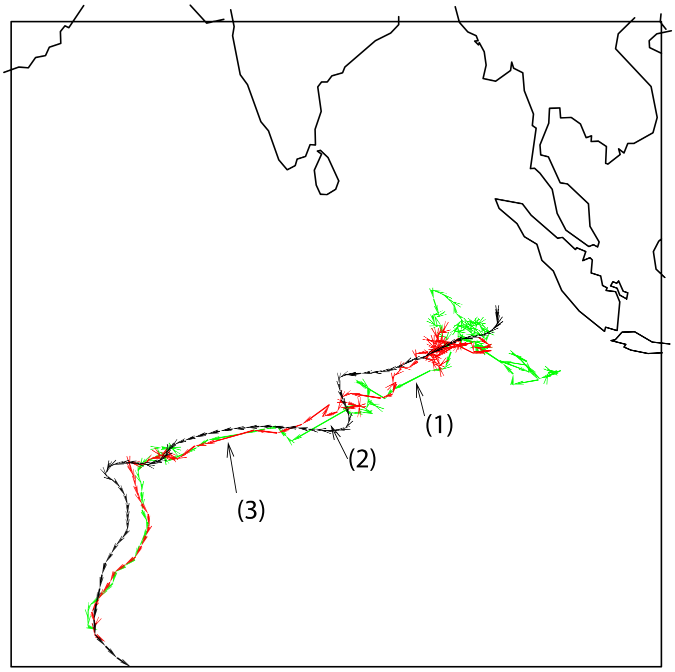
(a) Joy



(b) Chris



(c) Daphne



(d) Bella

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