DIAGNOSIS OF THE ECMWF MODEL PERFORMANCE OVER THE TROPICAL OCEANS

Ernst Klinker
ECMWF

1. Introduction

The large scale dynamics of the ocean and atmosphere are connected by energy fluxes across the boundary which represent exchange of energy and matter across a material surface. The parameterizations have to express the small scale exchange processes in terms of large scale quantities that can be resolved by the large scale ocean and atmospheric model. The quality of the parametrization has a crucial influence on the drift of the sea surface temperature in a coupled ocean-atmosphere model. In a medium range forecasting model where the SST is normally fixed during the integration it is mainly the surface latent and sensible heat fluxes that have a pronounced effect on the atmospheric model performance over oceans. Therefore this paper concentrates on the validation of the two heat flux components over the ocean.

The validation of surface fluxes over the ocean faces problems that are similar to the uncertainties in the formulation of the parameterizations themselves. Apart from direct flux measurements, which are rarely available, ship or buoy observations are often converted to surface fluxes by using again a parameterization.

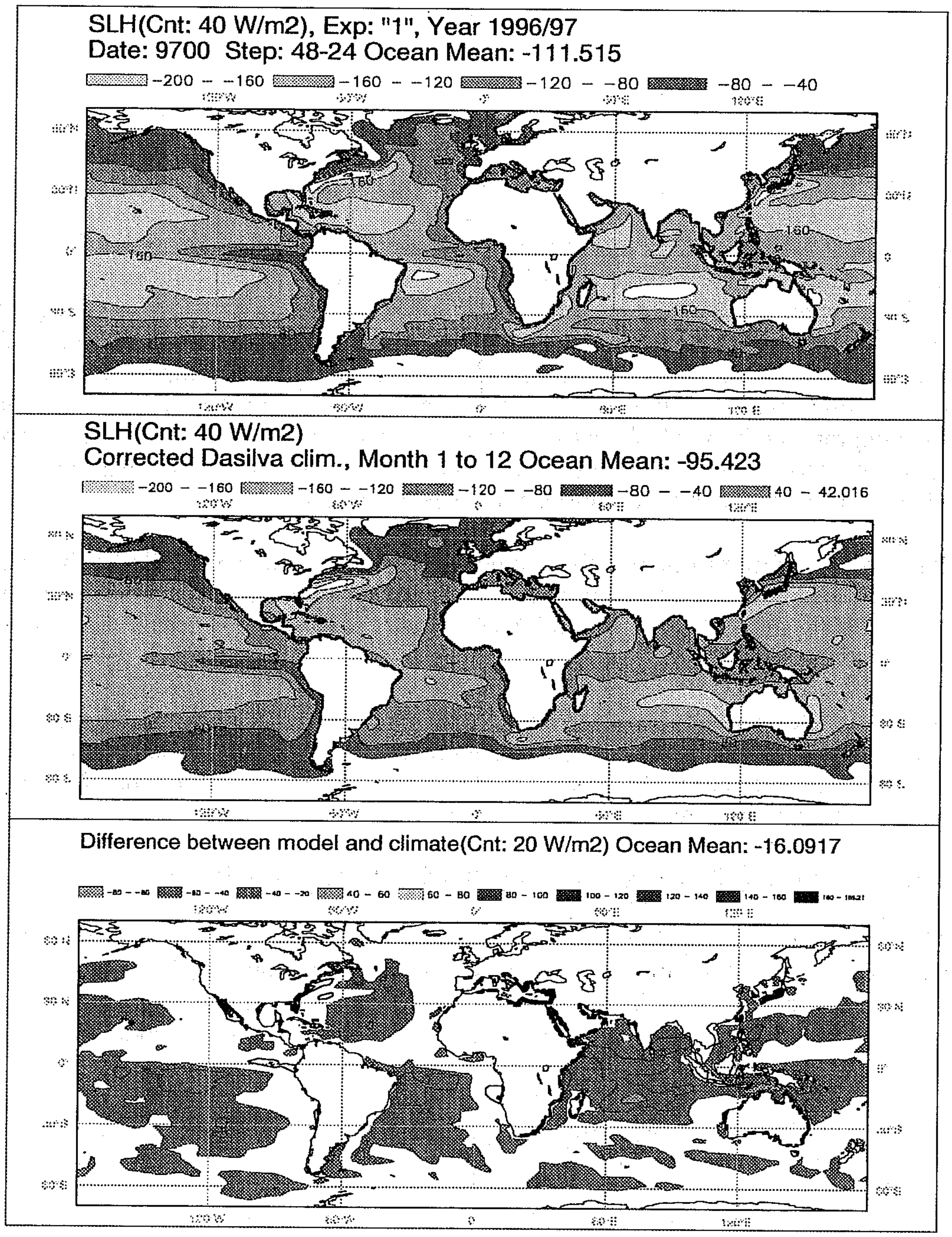
The correlation between wind speed and latent heat flux is generally fairly high for medium to high wind speeds. In low wind speed situations the problem of representing evaporation in large scale models correctly is particularly difficult to solve. Miller et al (1992) found that the tropical circulation is extremely sensitive to the way evaporation is parameterized.

2. Annual mean surface fluxes compared with climatological estimates

Climatological estimates of surface fluxes can serve as a first crude estimate of model biases. Usually a large volume of maritime surface observations from ships and buoys forms the basis of climatological flux calculations. The accuracy of the derived fluxes depends on the quality of the observations, however errors may also arise from the parameterization scheme to calculate fluxes as well.

In this comparison the climatology from da Silva and Young (1994) is used, which is based on the Comprehensive Ocean-Atmosphere Data Set (COADS) from January 1945 to December 1989. Sensible and latent heat fluxes are calculated with bulk formulas using transfer coefficients that are stability dependent. As the obtained outgoing flux is not sufficient to balance the incoming flux, a correction to the fluxes is applied based on balance requirements of heat fluxes and fresh water fluxes.

For the comparison of model fluxes against climatological estimates, the forecast values have been averaged over a year starting in June 1996 and ending in May 1997. As some model and analysis changes have taken place for this period the data set is not completely clean as one might expect from a longer period of operational forecasting. However, throughout the chosen twelve months the 3-dimensional variational analysis has been used operationally with a major change to a new background constraint (the so called Jb-term) contributing only a few days of the last month out of the total average over 12 month. A model change in December 1996 has some relevance for surface fluxes as the increments of humidity at low levels have been reduced.

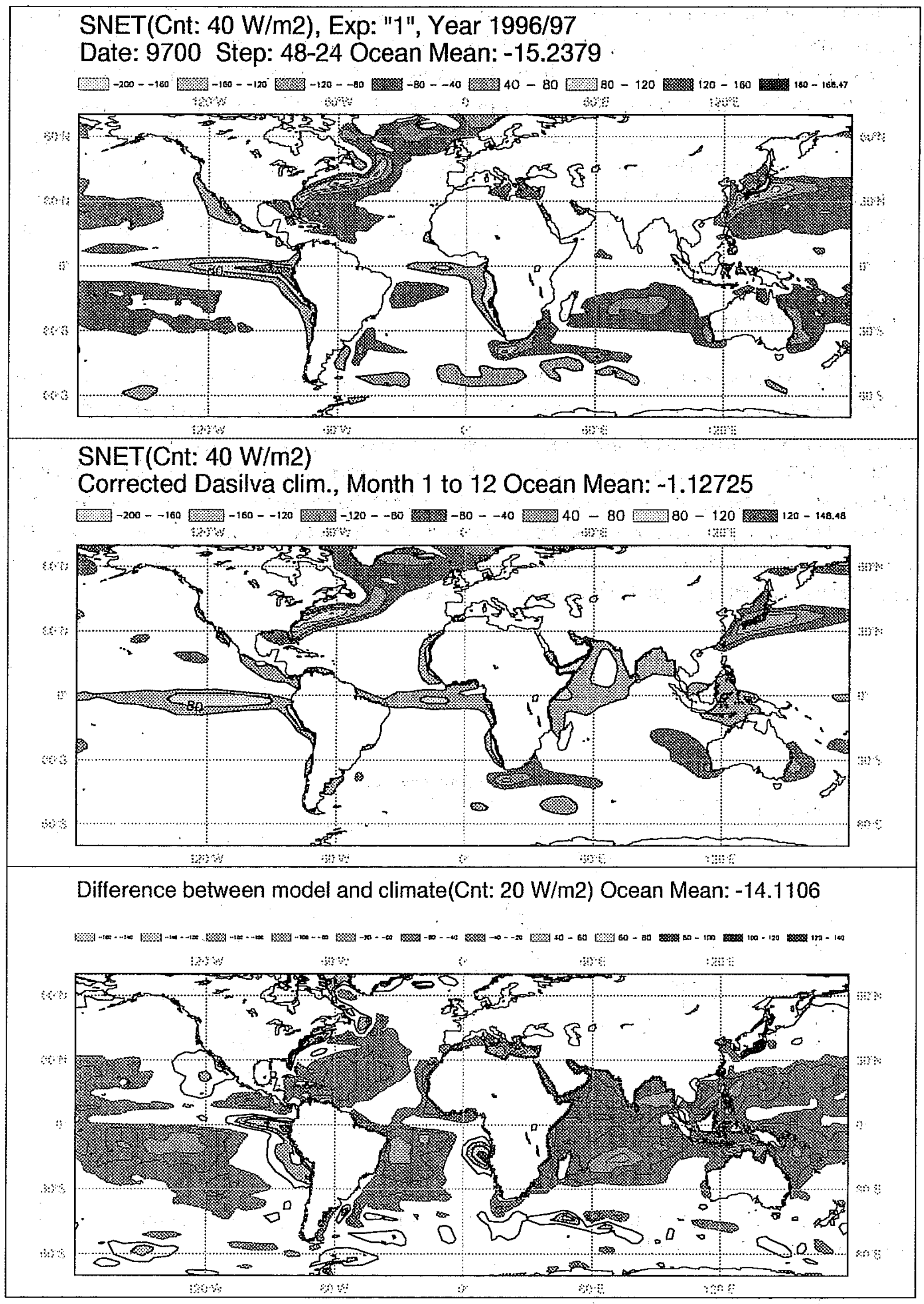


SLH(Cnt: 40 W/m2), Exp: "1", Year 1996/97
Date: 9700 Step: 48-24 Ocean Mean: -111.515

SLH(Cnt: 40 W/m2)
Corrected Dasilva clim., Month 1 to 12 Ocean Mean: -95.423

Difference between model and climate(Cnt: 20 W/m2) Ocean Mean: -16.0917

Fig.1 Annual mean surface latent heat flux. Short range model values (24 hours to 48 hours) for 1996/97 (top panel), climatology (middle panel) and the difference between model and climatology (lower panel).



SNET(Cnt: 40 W/m2), Exp: "1", Year 1996/97
Date: 9700 Step: 48-24 Ocean Mean: -15.2379

SNET(Cnt: 40 W/m2)
Corrected Dasilva clim., Month 1 to 12 Ocean Mean: -1.12725

Difference between model and climate(Cnt: 20 W/m2) Ocean Mean: -14.1106

Fig.2 Annual mean surface net heat flux. Short range model values (24 hours to 48 hours) for 1996/97 (top panel), climatology (middle panel) and the difference between model and climatology (lower panel).

2.1 Geographical distribution of latent heat fluxes

For the atmospheric model the most important flux component at the sea surface is the latent heat flux. Fig.1 shows the annual mean latent heat fluxes from the second day of operational forecasts (24 hours to 48 hours), the annual da Silva and Young climate (corrected), and the difference between the two. The geographical distribution of the model latent heat flux agrees fairly well with the climatological values, showing maximum fluxes in the subtropical trade wind areas and over the two warm ocean currents (Kuroshio and Gulf Stream) close to the east coasts of North America and Asia. However, the model overestimates the latent heat flux compared to climatology in most areas, in particular in the subtropical trade wind area. The differences are between 20 and 60 Watts/m2 locally which amounts to a negative global ocean bias of -16 Watts/m2 of the model compared to climatology.

2.2 Geographical distribution of net fluxes

The negative bias of the latent heat flux is also the dominant feature in the map for the net flux (sum of surface solar and thermal radiation and surface latent and sensible heat flux) in the subtropical areas (Fig.2). A positive biases appears in the western coastal regions of Africa and America where the model underestimates the low level cloud cover over cold water. This model behaviour leads to an overestimation of surface solar radiation. An underestimation of cloud coverage in the extra-tropical storm tracks has a similar effect of a positive bias in the net solar radiation there. The latent heat flux and solar radiation are the main contributor to the net model flux bias. The sensible heat flux and thermal radiation (not shown) have a comparatively small bias.

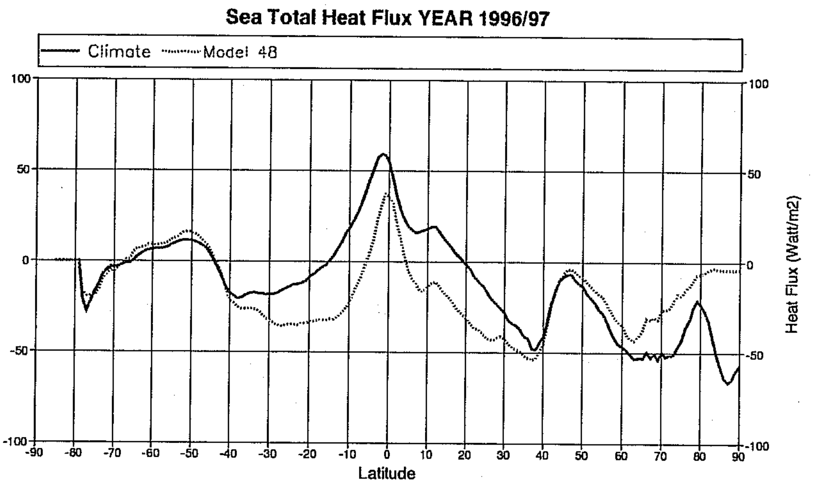


Fig. 3 Zonal integral of annual mean net surface fluxes over the Ocean from climate data (solid line) and short range forecast data (dashed line)

2.3 Zonal integral of ocean surface fluxes

Integrating the ocean surface fluxes in longitudinal direction exhibits the clear difference between the model and climatology. The negative model bias compared to climatology is a predominant feature in the tropics and subtropics. Most of these differences can be attributed to a bias in the latent heat flux. In the extra-tropical storm tracks the net fluxes agree quite closely. However, this is partly the result of two compensating biases, a positive one from the net surface radiation flux as a consequence of insufficient cloud cover and a negative one from the latent heat flux.

2.4 Inferred ocean heat flux

From the assumption that the energy accumulated in the ocean is comparatively small the net heat flux at the boundary between the ocean and atmosphere has to be balanced by the ocean transport of heat. The uncorrected climate data of da Silva and Young (1994) has a large residual of 10.5 PW (10.5x1015 W) for the implied ocean heat transport which is equivalent to a global mean heat flux residual of 30 W/m2. A tuning of the fluxes takes uncertainties in the transfer coefficients as part of the calculation of the latent heat and sensible heat fluxes and known problems in the radiative flux calculations into account. In the corrected climate data the heat transport is constrained to a zero ocean transport residual and a fresh water transport of 0.06 Sv at the southern boundary (65S).

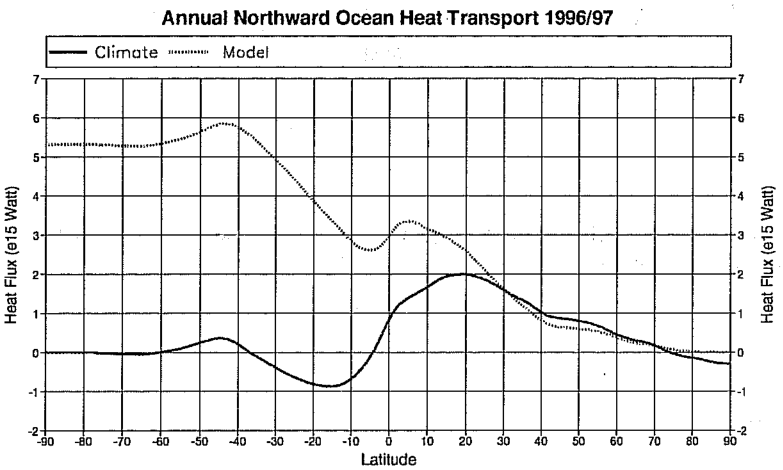


Fig. 4 Zonal and latitudinal integral of ocean fluxes for climatology (solid line) and short range forecast data (dashed line)

The net ocean heat flux of the ECMWF model averaged over one year of short range forecasts (24 to 48 hours) and integrated from north to south has a positive residual of more than 5 PW at the southern boundaries (Fig. 4). The bias compared to climatology can be explained by excessive heat loss of the ocean in the subtropics and insufficient heat gain for the tropical ocean belts mainly due to the negative bias of latent heat fluxes.

Improvements in the model physics, which have been tested during 1997 and have been operationally implemented in December 1997, had a positive impact on the ocean-atmosphere heat budget. The main benefit came from the revised radiation scheme that produced increased net radiation fluxes into the ocean in the subtropics and mid-latitudes. However, the negative bias of the latent heat flux compared to climatology remained almost unchanged.

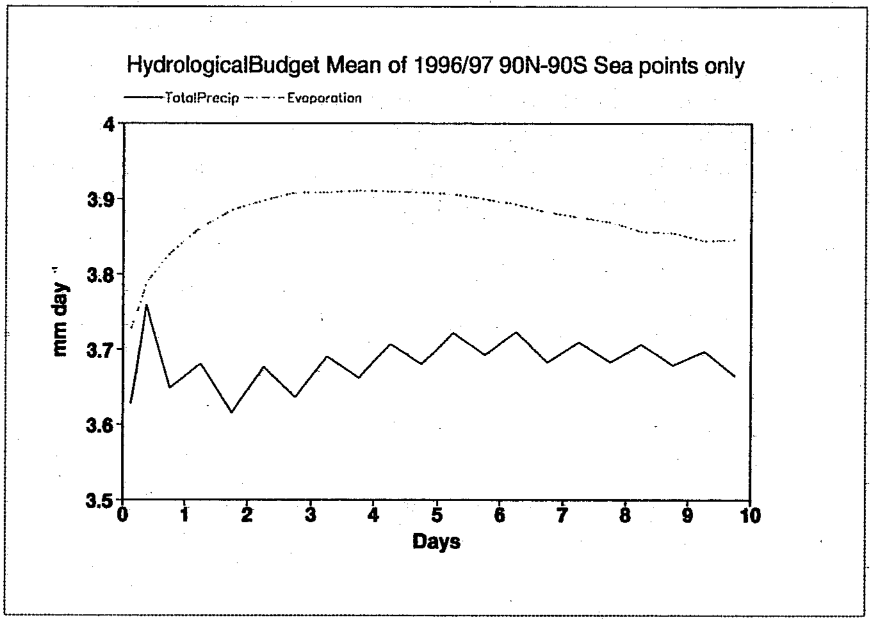


Fig. 5 Hydrological budget averaged aver all sea points and all forecasts for one year (1996/97). Precipitation (solid line) and evaporation (dashed-dotted line)

3. Model consistency

The balance between the precipitation (P) and evaporation (E) in the model and the evolution of the hydrological cycle during the forecast provide further evidence for the quality of the surface fluxes. Fig. 5 shows the annual average of the hydrological cycle for sea points calculated for forecast ranges of 6, 12, 24, 36,...240 hours. Evaporation and precipitation show a different time evolution over the full forecast period of ten days. Evaporation undergoes a marked spin up in the first 3 days before a gradual decrease dominates the second half of the forecast. In contrast precipitation has the largest values during the first day of the forecast and minimum values during the second and third day. The difference between precipitation and evaporation should in the long term average represent the run off from land areas. Climatological values for precipitation and evaporation by Baumgartner and Reichel (1975) are noticeably smaller with ocean precipitation of 2.92 mm/day and evaporation of 3.22 mm/day. Apart from larger absolute values of E and P in the model compared to climatology, the difference between the two (P-E) is mostly smaller in the model, in particular at the beginning of the forecast. The best agreement to run-off values from the Baumgartner and Reichel climatology of 0.3 mm/day can be found at day-2 and day-3 when P-E is close to 0.25 mm/day. The comparison to climatology therefore suggests that the values of P-E that characterize the spin up period of the model cannot be correct as they would imply a run-off of only 0.1 mm/day.

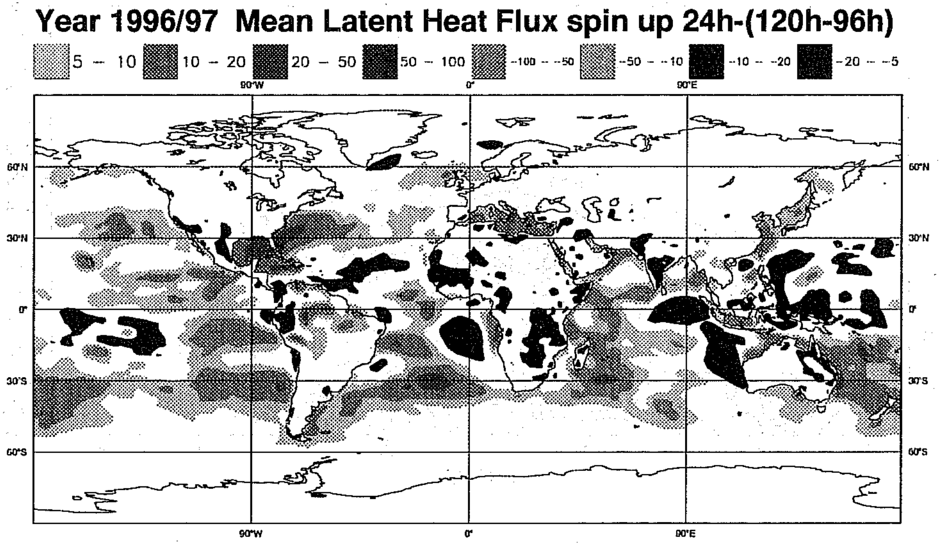


Fig. 6 Mean annual latent heat flux spin up for 1996/97. The map shows differences between the first day and the fifth day of the forecast. Units are Watt/m^2.

The spin up of the latent heat flux and the spin down of precipitation does not seem to be very closely correlated as the two processes occur in different geographical areas. Whereas the spin up of evaporation (Fig. 6) is mainly found in the subtropics and tropics away from the areas of deep convection, the spin down of convection (not shown) is concentrated along the tropical convergence zone.

The latent heat flux is proportional to the low level wind speed and the specific humidity gradient between the first model level and the surface saturation value.Further investigations have shown of how the low level humidity and low level wind speed evolve during the forecast and may influence the changes in the surface latent heat flux. The dominant influence on the error evolution arises from a drying of the low levels which is fairly widespread. The two main areas (Indian Ocean and South Atlantic west of Africa) where the latent heat flux actually decreases during the first 5 days of the forecast (dark shading in Fig. 6) correspond to locations where the low level wind speed is reduced in the later forecasts.

The change of humidity during the forecast has a pronounced effect on the vertical structure as the vertical cross section for annually averaged forecast errors shows (Fig. 7). Close to the surface a negative bias is the dominant feature between 50 degrees north and 50 degrees south. In the tropical convergence zone the drying reaches middle levels as well. A moistening at upper levels compensates the negative bias to a certain extent at lower levels. A verification against observational data which has little vertical structure information - like total column water from SSM/I observations - is therefore not able to reveal problems related to low level humidity and surface fluxes.

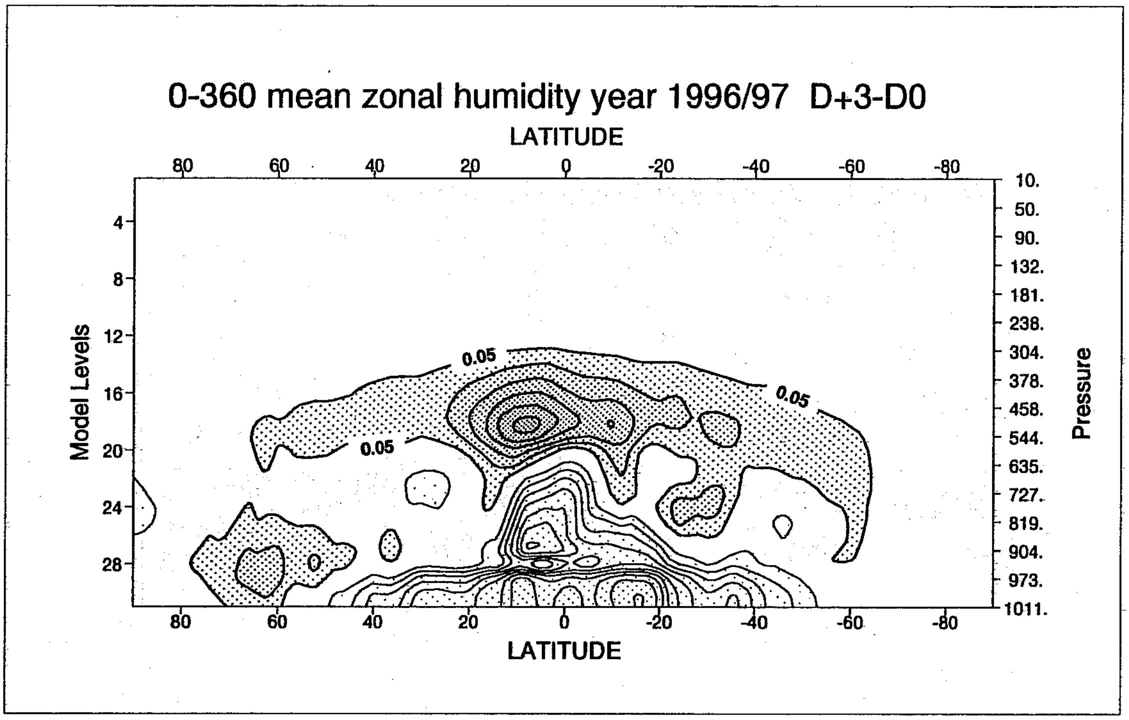


Fig. 7 Vertical cross section of annual mean forecast errors for specific humidity (day-3 - analysis) Units: g/kg.

4. Direct verification of surface fluxes using data from observation experiments

A further way of verifying ocean surface fluxes uses measurements obtained from observation platforms during special experiments like the Atlantic Stratocumulus Transition Experiment (ASTEX) and the Tropical Ocean Atmosphere - Coupled Atmospheric Response Experiment (TOGA COARE). Though these high quality data sets are normally only available for a limited time and for specific locations, they proved to be useful for verifying surface fluxes of the ECMWF model. As part of the ASTEX experiment 5 buoys have been deployed in the Atlantic to measure surface parameters. Time series of surface fluxes of up to 2 years were obtained at these buoys (personal communication with R. Weller) and compared to values from short range ECMWF forecasts. On average ECMWF latent heat fluxes (here positive values represent energy gain for the atmosphere) were 15 Watts/m2 larger than the measurements which represents a positive bias of 14%.

Further flux measurements were made during the TOGA COARE experiment which lasted for a period of 4 months. The so called IMET buoy had been deployed in the centre of the COARE Intensive Flux Array (IFA) at 156E and 1 45' S. Fig. 8 shows a time graph of latent heat fluxes from the observations taken from the IMET buoy compared to the short range ECMWF latent heat flux produced in the ECMWF re-analysis. One of the known shortcomings of the model cycle used for the re-analysis was a drier boundary layer than in later model cycles. However, latent heat fluxes from later analyses were only marginally different.In general the latent heat flux has a high correlation to the surface wind speed, a quantity that seems to be well analysed in the ECMWF data assimilation system as most of the major events with strong heat fluxes are well represented by the ECMWF flux. The largest differences occur during low wind speed periods when the latent heat flux in the observations drops well below 100 Watts/m2. These periods add the largest contributions to an overall positive bias of the ECMWF fluxes of 17 Watts/m2, or 16.5% which is close to the 14% positive bias obtained in the Atlantic comparison.

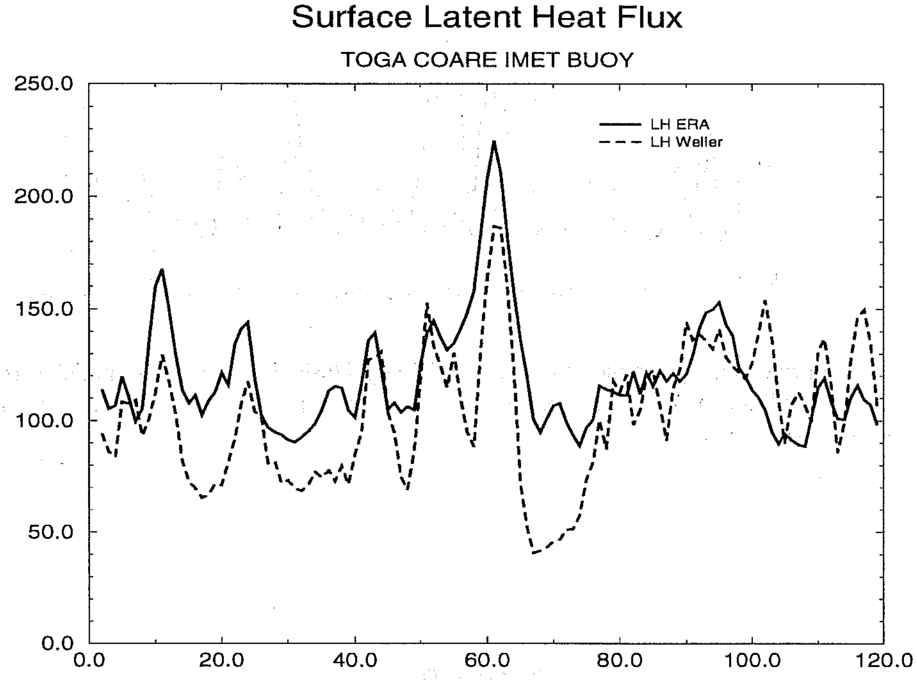


Fig. 8 Surface latent Heat fluxes measured at IMET buoy (dashed line) and for model output fluxes for 24 hour forecasts (solid line). A 3-day moving average has been applied. Units: Watt/m^2. Horizontal axis: Day number starting 1 November 1992

Though the sensible heat flux in the warm pool area is a magnitude smaller than the latent heat flux, differences between model values and observations provide some useful suggestions for possible problems in the parametrization scheme. In contrast to the latent heat flux, the sensible heat flux shows only a small correlation to wind speed but a high correlation to precipitation (Fig. 9) which can be assumed to be largely of convective nature. As convection is more localized than the large scale wind field it is not surprising that the predicted precipitation does not agree very well with the observations (Fig. 10). However, the mechanism that controls the enhancement of sensible heat flux during convective activity seems to be present in the model as well, but is most likely underestimated which would explain at least a part of the large negative bias of the models sensible heat flux. Lin and Johnson (1996) speculated already that the underestimation of ECMWF sensible heat fluxes and a positive bias in the near surface temperature in the TOGA COARE area were signs of a missing parameterization of meso-scale processes like meso-scale downdraughts and meso-scale enhancement of surface fluxes.

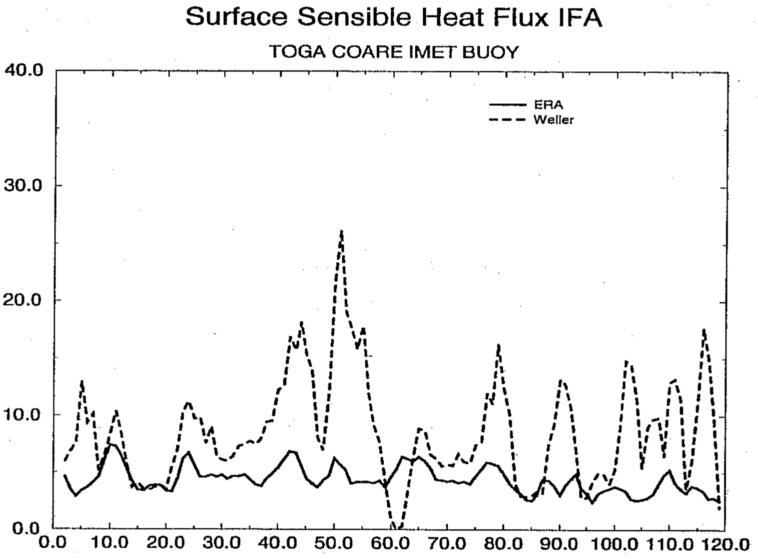


Fig. 9 Surface sensible heat fluxes measured at IMET buoy (dashed line) and for model output fluxes for 24 hour forecasts (solid line). A 3-day moving average has been applied. Units: Watt/m^2. Horizontal axis: Day number starting 1 November 1992

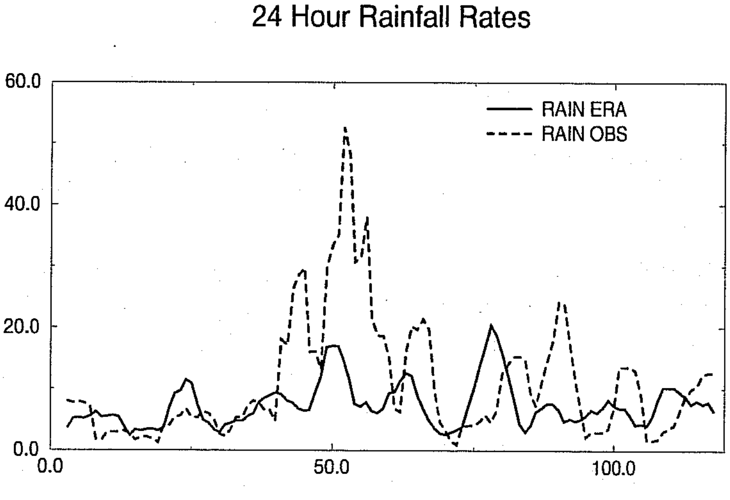


Fig. 10 24 hour rainfall rates at IMET buoy (dashed line) and for model output fluxes for 24 hour forecasts (solid line). A 3-day moving average has been applied. Units: mm/day. Horizontal axis: Day number starting 1 November 1992

5. Deep convection and surface fluxes

The performance of the large scale atmospheric model in terms of ocean surface fluxes will have consequences for other processes in the model. In the tropics the most likely process to be affected is the deep convection. On the other hand model errors in deep convection may influence the surface fluxes. For a more comprehensive validation of the models performance over tropical oceans integrations have been performed in which all parts of the model's diabatic forcing are extracted. For this project the model was run from initial conditions of the re-analysis during the TOGA COARE period.For the validation of deep convective processes in the model the apparent heat source Q1 is compared against estimates from the large scale dynamical tendencies of the model and against observational estimates.

The December 1992 was characterized by a major westerly wind burst at low levels which started during the middle of the month pushing the easterly wind into the upper troposphere (Fig 11). A weak vertical wind shear in the beginning of the month changed to a strong wind shear of more than 40 m/s between 100 and 700 hPa at the end of the month. The time series of diabatic heating (Fig 12) shows three major events of convective activity over the IFA in December 1992 during light predominantly westerly winds. The strongest event occurs just before the onset of the westerly wind burst in the second part of December. There is a high degree of agreement between the model's diabatic heating and estimates derived from sonde data directly (Lin and Johnson, 1996). This is true in particular for the timing of the heating, whereas there are differences in the vertical structure which give an indication of possible model problems. A heating maximum located between 400 and 600 hPa corresponds quite well to the heating profile derived from observation. Adding

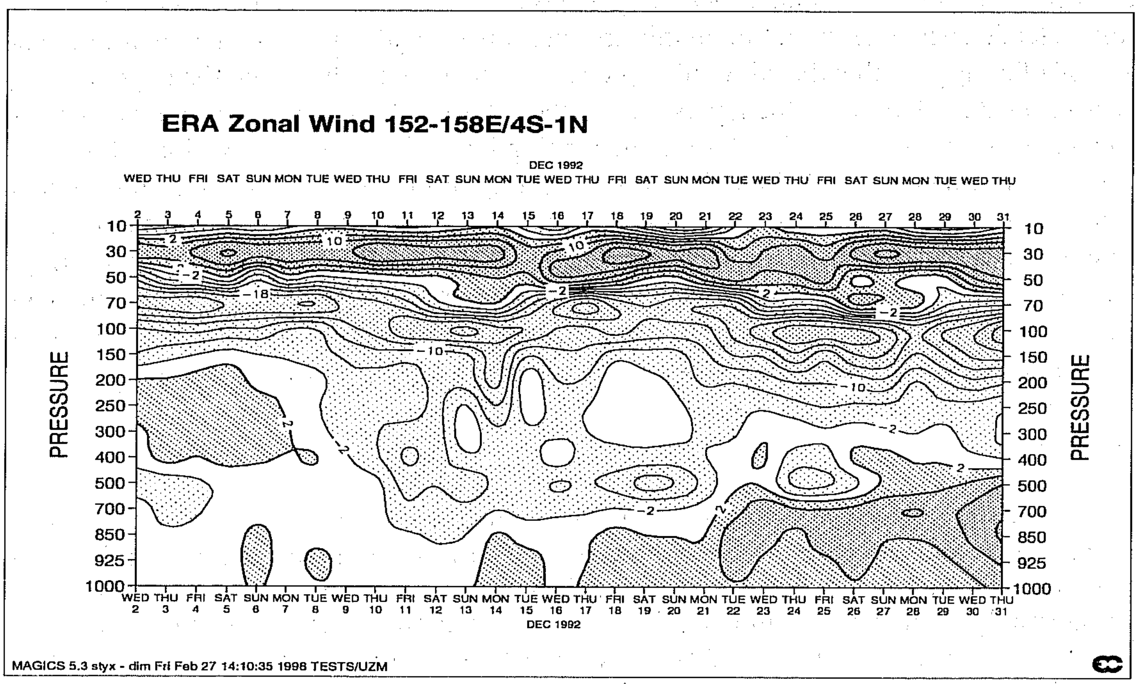


Fig. 11 Time-height cross section of the zonal wind in the IFA area for December 1992. Contour intervals: +/- 2/ 5/10/20 m/s

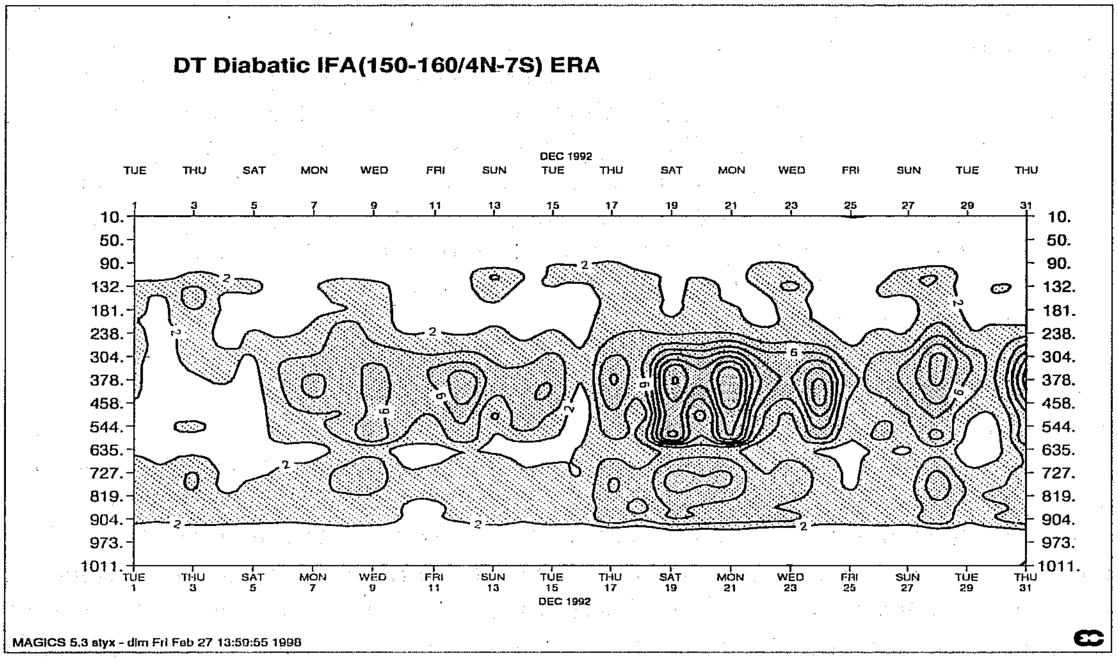


Figure 12. Time-height cross section of the diabatic heating in the IFA area for December 1992. Contour intervals: +/- 0.5/1/2/3/5/10 K/day.

the dynamical and parameterized tendencies and averaging them over a longer period of time (here over December 1992 and January 1993, Fig. 13) is almost identical to day-1 forecast errors as the observed tendencies of temperature in this area are fairly small. The vertical extent of the heating up to 100 hPa suggests that the convective processes penetrate too high into the upper troposphere, a positive residual dominates the layers around these levels. A even more pronounced negative residual appears around 650 hPa close to the melting level. Whereas observations show a gradual decrease of heating below 500 hPa, the model's heating profile has a pronounced minimum due to heat loss by the local melting process. It is possible that this secondary minimum in the heating profile would be smaller if the model would account for the meso-scale downdraughts that could distribute the heat loss over a deeper layer below the melting level and thus produce a more gradual decrease of heating with height. An overestimation of evaporation of precipitation in the free atmosphere would also explain at least part of the negative temperature bias.

6. Summary

One of the major process controlling the interaction between the ocean and atmosphere is the surface latent heat flux. The validation of this crucial parameter faces problems that are similar to the difficulties of formulating a parameterization scheme for large scale models. As directly measured fluxes are rarely available the validation is mostly based on fluxes derived from conventional ship or buoy measurements. Despite the differences in the variety of data sources there is a common message from the diagnostics that the ECMWF latent heat flux over oceans seems to be too large. This is particular the case in the subtropical trade wind areas. A negative bias in the order of 10-15% explains most of the residual of implied ocean heat transport.

Away from the trade-wind zone in regions of low wind speed the validation of evaporation becomes increasingly difficult. A comparison against buoy measurements during the TOGA COARE experiment show the largest deviations of model values from observations during episodes of low wind speed. One might suspect an overestimation of the free-convection adjustment that had been introduced following the arguments of Miller et al (1992). However, in these calm circumstances it is difficult to compare a single point measurement against a model output value representing an area of a grid square of length scale 100 km. Therefore the global bias of more than 10% is more likely to be an overestimate of the true model bias.

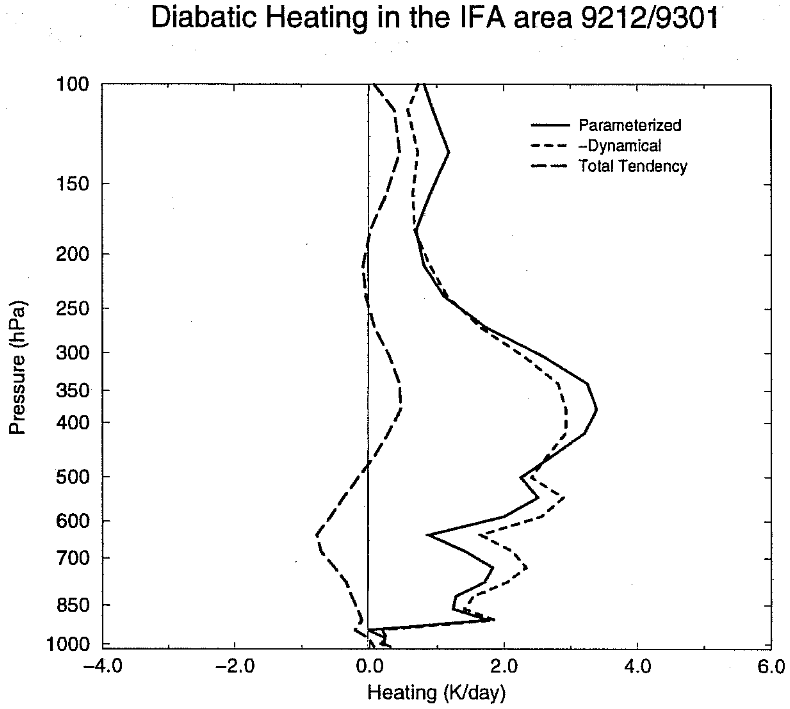


Fig. 13 Heating rates averaged over two month of one day forecasts and over the IFA area. Dynamical tendencies (dashed line), parameterized tendencies (solid line) and total tendency (nearly equal to the day-1 forecast error, long dashed line). units: K/day.

Acknowledgment

A. Beljaars kindly made tools available to compare climate data with model output values. Thanks also to R.A. Weller, who provided long term average flux values for the Atlantic buoys, and flux measurement made by the IMET buoy that had been deployed in the centre of the COARE Intensive Flux Array (IFA).

References

Baumgartner, A. and E. Reichel, 1975: The world water balance. Mean annual global, continental and maritime precipitation and run-off. Elsevier Scientific Publishers. Amsterdam, 179 pp.

Lin, X., and R.H. Johnson, 1996: Heating, moistening, and rainfall over the western Pacific warm pool during TOGA COARE. J.Atmos.Sci., 53, 3367-3383.

Miller, M.J., A.C. Beljaars and T.N. Palmer,1992: The sensitivity of the ECMWF model to the parameterization of evaporation from the tropical oceans. J. Climate, 5, 418-434.

da Silva, A.M. and C.C. Young, 1994: Atlas of surface maritime data 1994. Volume 1: Algorithms and procedures. NOAA Atlas NESDIS 6. U.S. department of commerce. Washington, D.C.