Impact of Cloud Motion Winds in the ECMWF ERA15 Reanalyses

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1. Introduction

The ECMWF 15-year reanalyses, often referred to as ERA15, constitutes a consistent set of global weather analyses for the years 1979 to 1993. They were produced during 1995 and 1996, using a then state-of-the-art version of the ECMWF data assimilation system. Its main characteristics were: Spectral T106L31 (106 waves, 31 vertical levels) resolution, Optimum statistical Interpolation analysis (O/I), 1-dimensional variational analysis of TOYS Cloud Cleared Radiances (CCR) and version CY13R4 of ECMWF's Integrated Forecasting System (IFS) which also went into ECMWF's operations in April 1995. The observations used for ERA15 came primarily from the ECMWF archive of conventional and SATOB data as distributed over the GTS. They were supplemented by several additional data sources such as the COADS ocean surface data, additional TEMP and AIREP from JMA, Tokyo and a few more. Satellite soundings (TOYS CCR) were provided by NESDIS. In 1979 the FGGE (First GARP Global Experiment) level II-b data were used. The ERA15 analysis and forecasting system; the observations and the other forcings that went in as well as details of the available products can be found in Gibson & al., 1997. After completion of production, the resulting analyses and forecasts were the subject of extensive evaluation and validation, both at ECMWF and by external validators. The performance of all the different observing systems have been reported in detail by Uppala, 1997. A discussion on data and model related aspects of and some weaknesses in the ERA15 analyses and short-range forecasts can be found in Kållberg, 1997. Arpe & Stendel, 1998, discuss the ERA15 hydrological budget, and Serrano, 1998, gives an account of tropical cyclones in ERA15. Further validations and comparisons of ERA15 with independent analyses and data may be found in the proceedings from the First WCRP International Conference on Reanalyses, 1997.

Cloud Motion Winds ('CMW'), in ERA15 also referred to as 'SATOB', were available during the entire ERA15 period, and it is of interest to study how these data performed together with all the other types of data in the ECMWF O/I - IFS assimilation system. In section 2 we describe the overall characteristics of the CMW data, the amounts and distribution, their quality in relation to the first guess forecasts and the acceptance in the data assimilation. It is found that there was a gradual but substantial improvement of the CMW quality during the 15 years, reflecting the improving methodology and the increasing experience of the data producers. During the processing we lost almost two and a half years due to an error in the observation decoding which eliminated almost all CMW data from Meteosat and GOES. Winds from GMS (Himawari) were used. The period from June 1990 to October 1992 had to be re-assimilated. With the two series of analyses, we have a large, but involuntary Observing System Experiment (OSE) on the impact of CMW data in the ERA15 analyses. Section 3 will deal with some of the results.

2. Characteristics of the Cloud Motions Winds

Before 1979 cloud motion winds had already in 1972 been produced from the ATS satellite using an automated technique. As part of GARP, five geostationary satellites were launched in 1979; GOES-W, GOES-E, GOES-10, METEOSAT and GMS-l. The processing of cloud motion winds was done by satellite producers for each satellite using their specific algorithms. Between 1979 and October 1982 the winds were produced from the two GOES satellites and GMS satellite. GOES-10 operated over the Indian Ocean during 1979 only. During 1979 the Meteosat winds were produced off-line by ESA/ESOC and from October 1982 Meteosat winds were produced operationally. During the years the methods to derive the winds have been much improved. Thus the precision of the "measurement" is not the same from year to year and consists mainly of the uncertainty in the cloud height assignment and in the target tracking. In the following the performance of the cloud drift winds as a total system is evaluated. Since each satellite observes different weather regimes and the winds are produced by different techniques, intercomparisons between different satellites is difficult. However the relative performance of each satellite during the reanalysis period can be evaluated. Details can be found in Uppala (1997).

Variability of the number used CMWs

Before the data enters the Optimum Interpolation analysis there is a preselection of data. In this preselection parts of the CMWs are either selected or “blacklisted” based on their known quality over different areas/ levels, see Gibson et al. (1997). The selection criteria are fixed through the reanalysis period. All the following statistics apply only to the selected data, which have been used in the analysis.

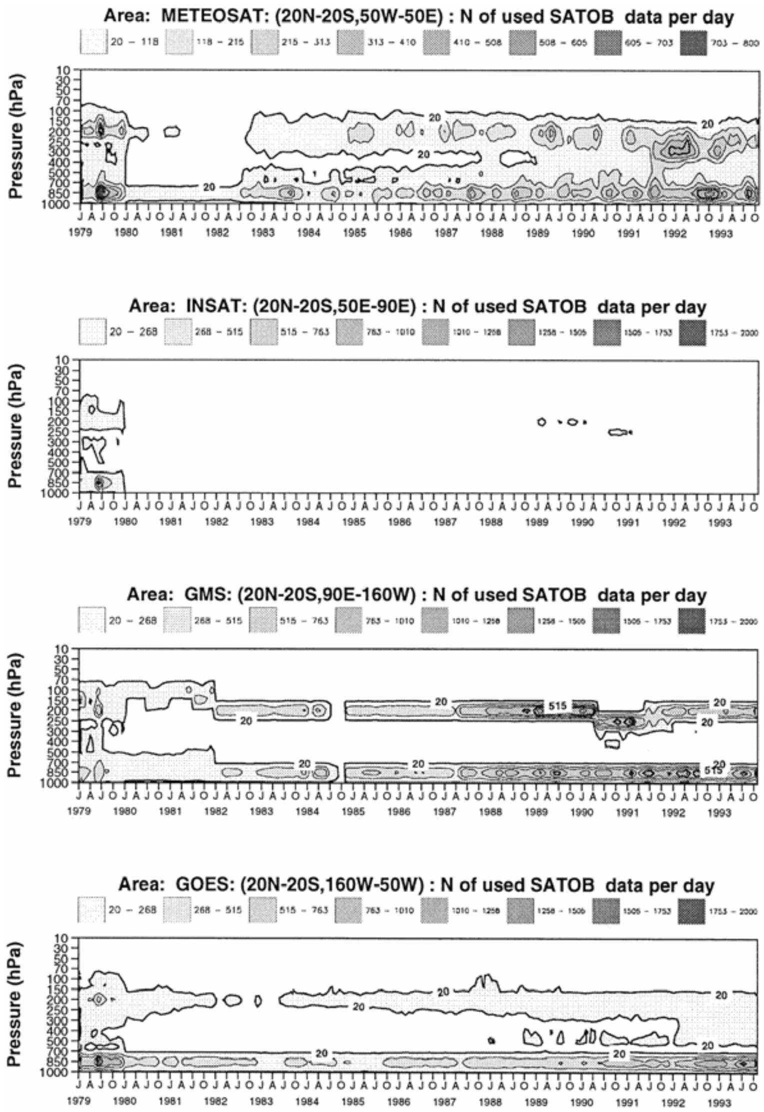

FIGURE 1. The amount of CMW data used in ERA15.

The CMW amount varies considerably through the years. In 1979 many winds were produced, mostly around the tropical belt at both high and low levels. The height assignment was very liberal and winds were produced at all levels from 100 hPa down. Immediately after 1979 the numbers drop significantly, operational Meteosat winds were only available from October 1982. The amount of winds started to increase again from 1982 especially at low levels, and they were also extended towards higher latitudes. Significantly more low level winds were produced in the Southern Hemisphere from 1989 onwards on latitudes south of 40S. There was also a reduction in the number of high level winds in the beginning of 1990. The height assignment of extratropical high level winds shows seasonal fluctuations. Towards the end of ERA15 more winds were produced in the medium levels. In the Tropics in 1982 there is a “discontinuity” in the height assignment of high level winds. This is mainly due to the changes in GMS processing methods, but also the 1979 Meteosat winds were assigned to higher levels than after 1982.

We can also see that the GMS tropical high level winds were temporarily assigned to 250 hPa for about a year from mid 1990. The lack of assimilated cloud motion winds over the Indian Ocean is evident after the FGGE year; the INSAT winds were never used in ERA15.

The quality of low level CMWs and radiosonde Winds

The probability density functions in figure 2 show to what extent the CMW data were influencing the analyses in 1983 and 1993 respectively. The standard deviation of the first-guess fit of the zonal wind from the CMWs in the northern hemisphere drops from about 2.7 m/sec in 1983 to about 2.3 m/sec in 1993 with corresponding improvements in the tropics and the southern hemisphere. The analysis fit is closer and the analysis-minus-first guess increments are considerably smaller in 1993 than in 1983.

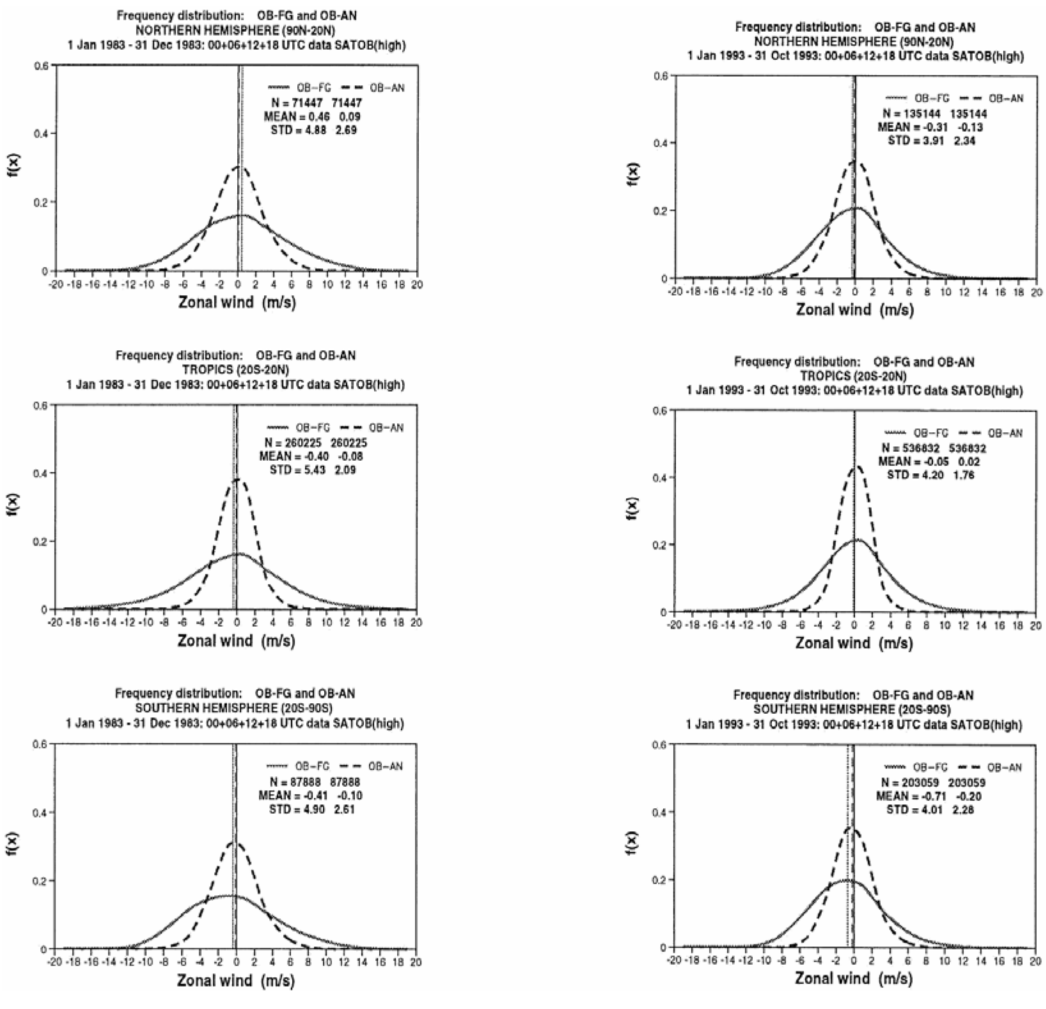

FIGURE 2. Frequency distributions of CMW zonal wind fit to the First Guess (solid) and Analysis (dashed). Northern hemisphere (top), Tropics (middle) and Southern hemisphere (bottom). 1983 in left column, Jan-Oct. 1993 in right.

CMWs compared with Radiosonde and Aircaft winds.

Low level CMWs and radiosonde winds are here defined to include winds from the 1000, 850 and 700 hPa levels. The mean departure statistics are calculated as weighted means of the departures on these levels. The gradual improvement of the low level CMWs is evident from figure 3 left, and can be seen globally. The running mean of RMS first-guess-minus-CMW is reduced from just over 4 ms-l in 1979 to about 3 ms-l in the end of 1993. At the same time the equivalent departure statistics from the analysis start from 1.8 ms-l and end in about 1.5 ms-l, which means that the analysis increment is much smaller and CMWs are assimilated better towards the end of the period. At high levels, around 250hPa, figure 3 right, the gradual improvement is even more impressive with the first guess fit being reduced from 8-9ms-1 to about 6 ms-l over the 15 years. The ‘narrowing’ of the black wavy bands in the figure is a direct measure of the overall improvement of the CMW behaviour in ERA15. The system also included a diabatic non-linear normal mode initialization. Most of the information analysed from the CMWs was retained through the initialization and the “noise” not accepted from the CMWs is roughly comparable to that of radiosondes.

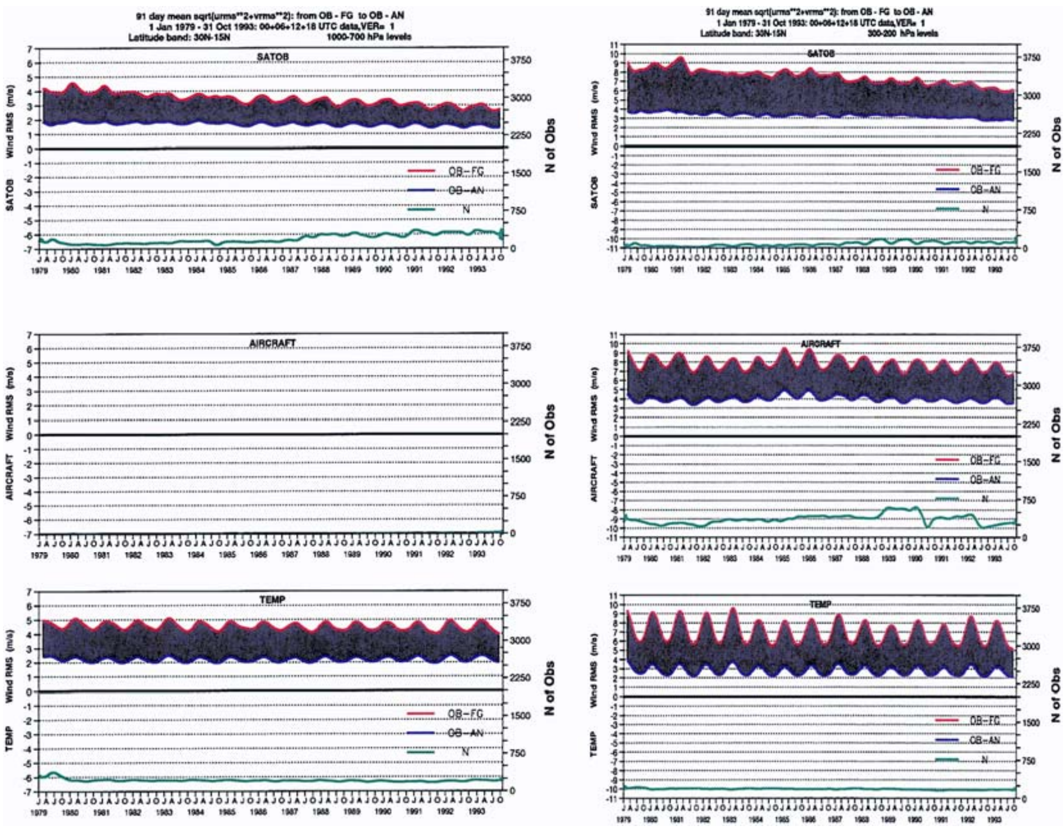

FIGURE 3. Time evolution of the 91-day running mean of the RMS of the first guess departure of the wind speed, (upper limit of black areas) and of the analysis departure (lower limit) of CMWs (top), Aireps (middle) and Radiosondes (bottom). Left: lower troposphere, 1000-700 hPa. Right: Upper troposphere 300-200 hPa.

The improvement in the high level CMW quality can be seen over all geographical areas. At the end of the period they are, in the Northern Hemisphere, of a quality equal to that of the radiosonde winds. In the Tropics and in the Southern Hemisphere they are even slightly better. In the extra tropics the CMW quality is roughly the same from season to season, while the statistics of radiosonde and aircraft winds show considerable seasonal fluctuations with worse fit to the first guess in winter than in summer. Both aircraft and radiosonde wind quality have also been improved over the years. In 1992 and 1993 the fit of aircraft winds in the Southern Hemisphere has improved even more due to the AMDAR data, which, in turn have possibly also contributed to the better fit of CMWs and radiosonde winds during these years. In the RMS sense and relative to the first guess the GMS, GOES and Meteosat winds improved during the years. At the same time the aircraft and radiosonde data also improved over the corresponding areas. The CMW quality is, in the end of the period, more consistent with the first guess than the radiosonde and aircraft data, while in the beginning of the period the opposite was true.

Zonal Mean Biases

Cloud Motion Winds were used successfully by ECMWF already when assimilating the FGGE year - 1979. It was then found, however, that the CMW zonal wind component often suffered from negative biases, particularly in the subtropical jetstreams. (Kållberg, Uppala, Gustafsson & Pailleux, 1982). This problem was also encountered in ERA15 where zonal mean u and v first guess departures for the years 1983 and 1993 indicate that, over areas of westerly flow in the extra tropics, the high level and 700 hPa level CMW winds are 0.6 - 2.8 m/sec weaker than the first guesses in both these years. Radiosonde winds between 250 and 700 hPa are rather unbiased in relation to the first guess, indicating that the 300 to 250 hPa CMWs are too weak. Below 850 hPa and over 30S-15S and 15N-30N the easterlies of the first guess are stronger than the CMWs by 0.2-0.8 m/sec. This is consistent with a low level bias of 0.1-0.3 m/sec against radiosonde winds over the same area, indicating that the low level first guess easterlies are too strong. The southern branch of Hadley cell outflow represented by the CMWs is stronger than that of the first guess which again is stronger than that measured by radiosondes. The first guess and the radiosondes are in agreement within the northern branch of the outflow, while the CMWs want it to be stronger. Both radiosondes and CMWs reveal that the low level inflow is too strong in the first guess.

3. An involuntary OSE

The removal of Meteosat and GOES had a quite large impact on the monthly mean analyses. We will concentrate on the mean impact during the year December 1990 to November 1991. The impact during the subsequent year, December 1991 to November 1992, was very similar. The impact is remarkably different in the two areas - Meteosat and GOES - and will be dealt with separately.

Atlantic Ocean

At 850mb the immediate impact of the Meteosat winds is an enhancement of the northeast and southeast trade winds on each side of the equator. The enhancement is largest near the higher latitude ‘entry’ -areas around 25N/30W and 25S/5E, and amounts to 1-2 m/sec in the annual mean vector at 00UTC. The 12UTC impact is similar, figure 4

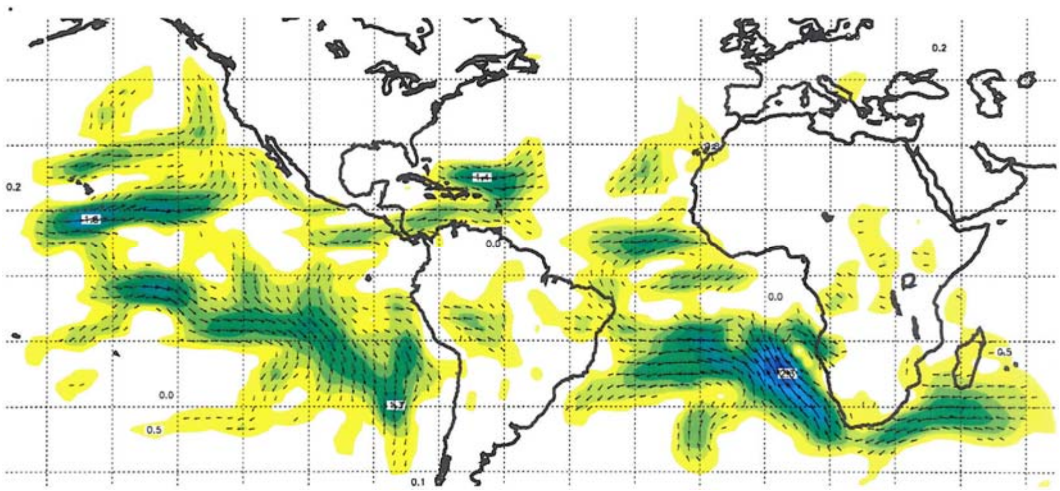

FIGURE 4. Mean difference of the analysed windvector at 850 hPa between one year (1991) with Meteosat and GOES, and the same year without those two CMW sources.

The differences in the mean wind lead to geostrophically balanced pairs of lows and highs in the two hemispheres with the highs on the pole-ward sides. Hydrostatic balance furthermore requires cooling in the lows and warming in the highs through the thermal wind relation, at and below 850mb. At 700mb and 500mb there is a compensating warming on the equator-ward sides and cooling on the pole-ward sides. Another effect of the temperature increments is a static stabilization of the lower troposphere on the equatorward sides of the trades and a destabilisation on the poleward sides. In short, the directly analysed wind changes from Meteosat produces geostrophically and hydrostatically balanced temperature and stability changes. Since the relative humidity was the analysis variable in ERA15, increased temperatures in the lower troposphere lead to increased specific humidity in areas where there is no direct humidity analysis change, and vice versa. Hence there we find a moistening on the warmed poleward sides of the trade wind increments and, a less marked, drying in the cooled areas towards the equator. With the prescribed NCEP SSTs (Sea Surface Temperatures) used in ERA15, (Reynolds and Smith, 1994) a moister boundary layer reduces the evaporation and the latent heat flux in the subtropical highs. Closer to the equator the evaporation increases. This effect on the evaporation is also reflected in the net energy flux at the ocean surface, which changed by up to 14 W/m^2 when the lost CMWs were reintroduced, as seen in figure 5. Note that negative values indicate an increased net energy flux from the sea to the atmosphere. The low level wind increments have a large impact on the surface processes through a fairly complex geostrophic-hydrostatic coupling. The ERA15 air-sea fluxes are very sensitive to changes in the observation coverage and use. Other analysis schemes where, for instance, the humidity is analysed in a different way, may not necessarily be as sensitive.

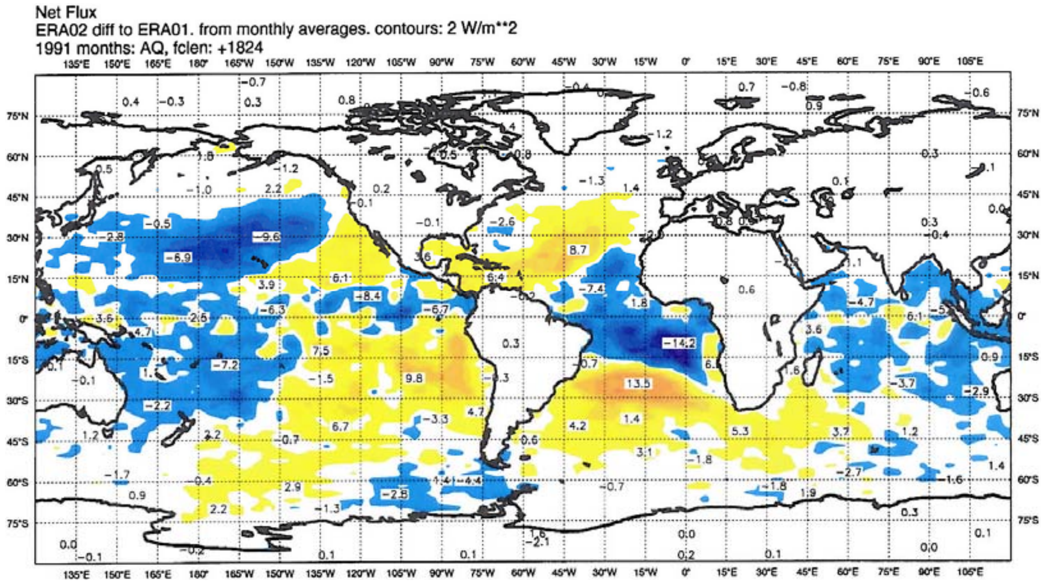

FIGURE 5. The annual mean difference in the net surface energy flux between the 'SATOB' and 'No SATOB' assimilations. The fluxes, in W/m^2 are extracted from twice daily forecasts from +18h to +24h. Negative values indicate more net flux from the Ocean to the Atmosphere in the 'SATOB' assimilation.

The Pacific Ocean.

Over the Pacific ocean the impact from the GOES winds is in the opposite sense to that from Meteosat over the Atlantic, i.e. the SATOB winds reduce the 850mb SE and NE trades. The cross-Panama flow is also reduced. Expressed as annual mean vector wind the differences are of the order 1-1.5 m/sec over substantial areas. The balanced changes in the geopotential and temperature are consequently also in the opposite sense, cooling in the subtropical highs, and some warming near the Chilean-Peruvian coasts at 925hPa. Also here the consequences of using relative humidity as the analysis variable are evident, the near surface air is drier in the subtropical highs and if anything slightly moister closer to the equator. So, for the same reasons as in the Atlantic, there is a large impact on the fluxes, but in the opposite sense. The increase in the net energy flux to the atmosphere is particularly large north of the Hawaiian island chain.

Upper level winds and the impact on the ITCZ.

Cloud motion winds are concentrated at two levels in the troposphere, the trade wind cumulus level around 850 mb and the cirrus level around 200 mb. We have seen above that the negative speed biases in the CMWs during the early years have been gradually reduced due to improved retrieval methods by the data producers. This OSE shows however that the problem was still noticeable in 1991-1992. Figure 6 shows cross-sections of the zonal and meridional wind differences averaged between 120ºW and 60ºE for all 00UTC analyses in 1991. In both hemispheres the CMW data have a definite tendency to reduce the zonal wind, with up to 0.6 m/sec in the upper troposphere between 150hPa and 200hPa. In the southern hemisphere there is a secondary maximum in the bias centred around 700hPa. Furthermore, the equatorial easterlies are also reduced by the use of the observations. It is interesting to note that the reduction of the westerlies is concentrated to the equator-ward side of the jet stream cores. A possible reason may be more frequent detectable cirrus there than in the jet cores. The impact of the data on the meridional wind component seems to be beneficial in that they enhance the divergent outflow. The largest impacts are found at, or just below, the level of maximum outflow around 200hPa.

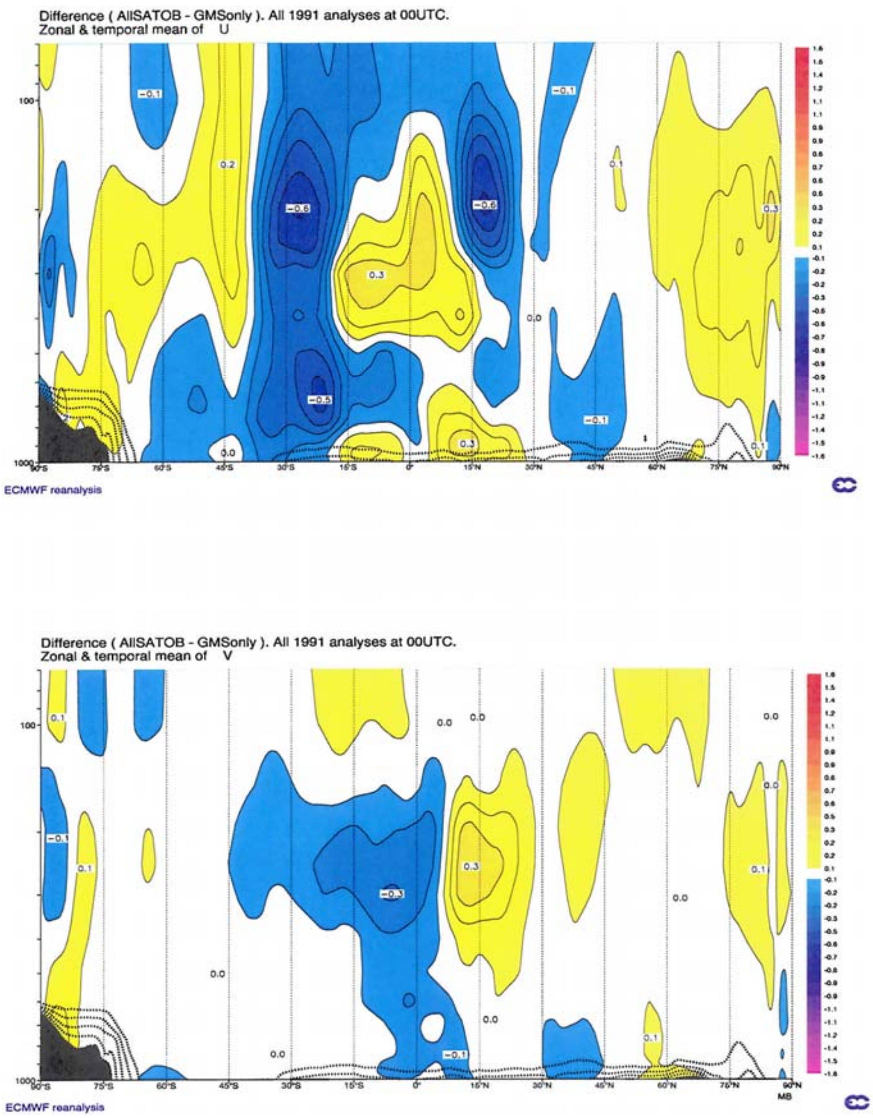

FIGURE 6. One-year zonal mean analysis differences between the two assimilations with and without Meteosat and GOES. The zonal wind in the upper panel and the meridional wind in the lower.

4. Conclusions and continuation.

Cloud Track Winds are a very important source of wind data for reanalyses, particularly over otherwise scantily observed tropical and subtropical ocean areas. The experience from ECMWF's first reanalysis effort was that the CMWs were well accepted by the assimilation and had a definitively beneficial impact. Both their amounts and their quality - defined as the fit of the CMWs to the first guess forecasts - increased markedly but gradually over the 15 ERA years, reflecting the accumulated improvements in retrieval methods, producer quality control and general producer skill.

An involuntary Observing System Experiment - where two CMW satellites were inadvertently omitted from the ERA assimilation during two years - clearly demonstrated that the CMWs are the major source of wind information over large portions of the tropics and subtropics. The ERA data assimilation system turned out to be very sensitive to the exclusion of cloud track winds; the annual mean latent heat flux changed for instance by more than 15 W/m2 over considerable parts of the subtropical ocean. Admittedly, this impact was to some extent exaggerated by the particular choice of humidity analysis in ERA15, but it probably safe to say that other data assimilation systems also will exhibit great sensitivity to the correct use of CTW data.

At ECMWF a second reanalysis, ERA40, is presently in its planning state. The intention is to reanalyse at least 40 years, from 1957 - the International Geophysical Year - to present. The main differences to ERA 15 will be higher resolution both vertically and horizontally, TL159L60 rather than T106L31, 3-dimensional variational analysis rather than Optimum Interpolation, and several major improvements in the physics parametrization, particularly in the treatment of the soil, the oceans, the radiation and the stratosphere. The ERA40 production system is designed so that Observing System Experiments can be carried out very easily, and a new OSE addressing the CMWs will certainly be of great interest.

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