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Uncertainty in tropical winds

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Uncertainty in tropical winds

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Analysing and forecasting the tropical circulations is a challenging task. In contrast to the mid-latitudes, balances are very subtle due to the smallness of the Coriolis force and the large Rossby radius of deformation that allows disturbances to affect the whole equatorial band. Furthermore, due to the thermal contrast between relatively warm surfaces and a troposphere that is continuously cooled by infrared radiative heat loss, widespread convection occurs in the tropics affecting a vast variety of space and time scales. These range from the individual convective cloud to the large-scale convectively coupled waves, the intra-seasonal oscillations, and the monsoon circulations.

A major difficulty in analysing tropical circulations resides in the sparseness of upper-air in situ data over tropical oceans, making satellite products the main source of observational information in these regions. The impact of conventional and satellite data on the analysis is determined by data density and the assigned observation errors. Thus, in areas with extended cloud coverage and convection, the analysis is more strongly driven by the forecast model than by observations, and is therefore more affected by model errors.

Recent international projects that focused on the intercomparison of global analyses from the main meteorological centres demonstrated that analyses agree fairly well for the mid-latitudes but surprisingly large systematic and regional differences persist in the tropical regions. As discussed in *De Szoeke & Xie* (2008), large differences in tropical winds, in particular over the Eastern Pacific, also exist between the different global seasonal-range forecast systems. Assessing the uncertainties and errors in tropical circulations in the ECMWF forecasting system is the challenge that will now be discussed.

Analysis increments

In regions with sufficient and 'accurate' observations, model errors can be quantified by analysis increments which are the corrections added to the background forecast by the 4D-Var analysis due to information from observations. These increments naturally have a seasonal cycle in the tropics. We decided to focus on the autumn season in 2011 where all the areas with large errors are apparent.

The seasonal mean of analysis increments for temperature and vector wind at 1000 hPa are shown in Figure 1a with Figure 1b showing the corresponding standard deviation of the wind speed analysis increments. A characteristic increment pattern emerges at 1000 hPa where high values of the standard deviation of wind speed closely follow the Inter Tropical Convergence Zone (ITCZ). But, at the same time, the vector wind increments increase the convergence in the ITCZ, particularly along its southern flank (situated northward of the equator) in the Eastern Pacific. Mean wind increments and standard deviation are both of order 1 ms^{-1}. The observations responsible for the low-level wind increments are mainly near-surface winds over the ocean from the ASCAT scatterometer.

At 850 hPa (Figure 2a) the increments still tend to increase the convergence near the equator, but now indicate a marked lack of cross-equatorial flow in the model in the East Pacific with a mean error of order 2 ms^{-1}. At 700 hPa (Figure 2b) the East Pacific stands out again with mean cross-equatorial wind increments of order 2 ms^{-1}.

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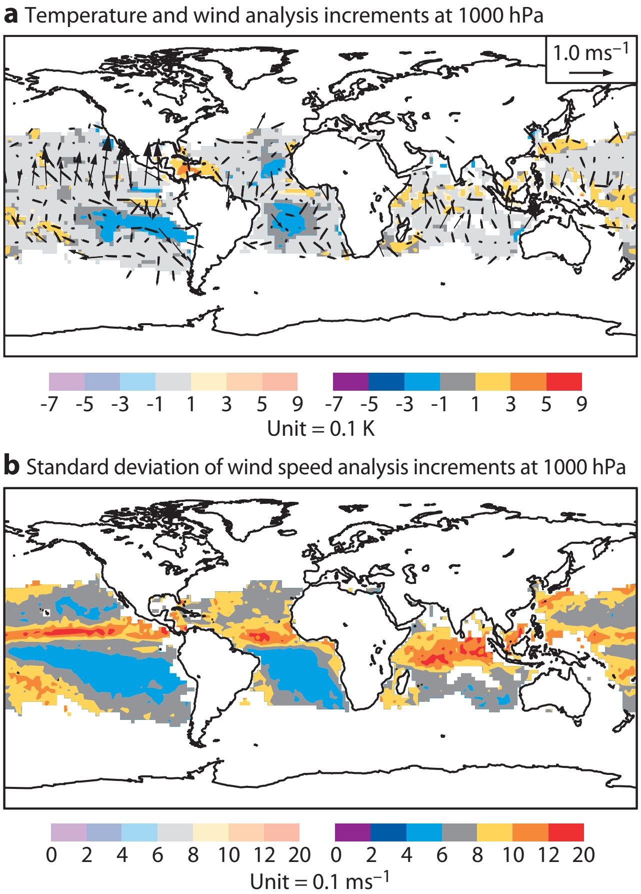

Figure 1 (a) Mean analysis increments for temperature and wind vector and (b) standard deviation of wind speed analysis increments at 1000 hPa for October–December 2011. Statistical significance at the 95% level is denoted by intense colours, pale colours are employed otherwise.

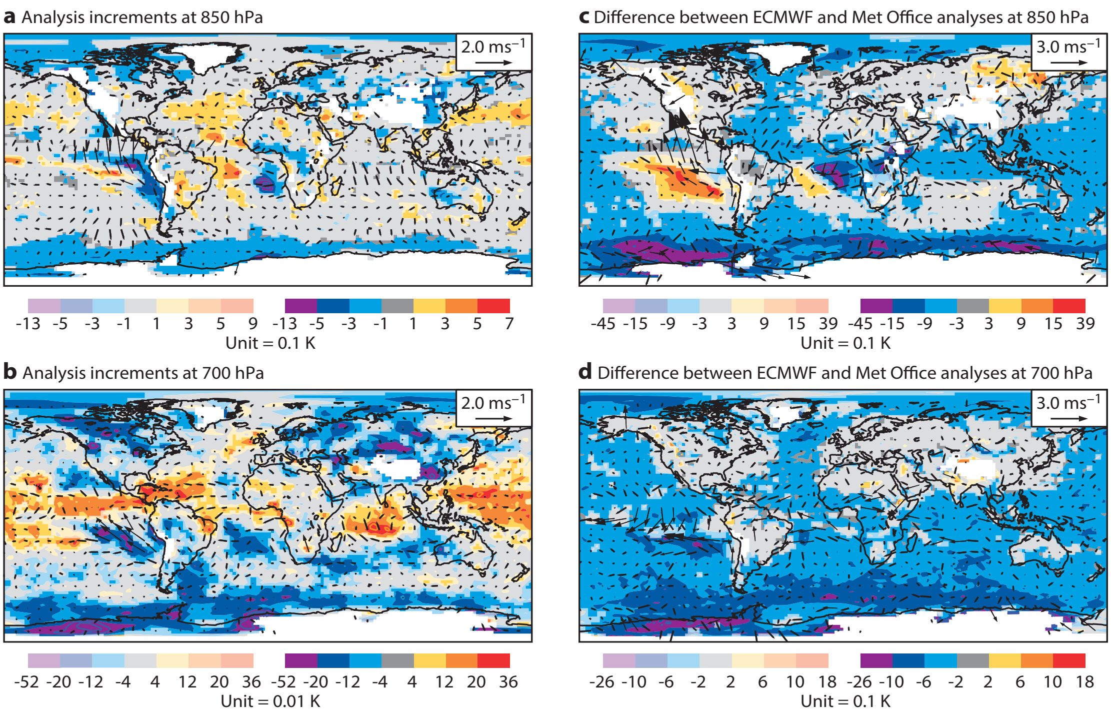

Figure 2 Mean analysis increments for temperature and wind vector for (a) 850 hPa and (b) 700 hPa for October–December 2011. Also shown is the mean difference between ECMWF and Met Office analyses at (c) 850 and (d) 700 hPa for the same period.

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Differences with UK Met Office analysis

So far the findings can be summarized as follows: near the surface along the ITCZ the observations tend to increase the convergence, and at 200 hPa there is a consistent divergent signal (not shown). Mid-tropospheric increments show large-scale structures which are consistent with the findings by *De & Chakraborty* (2004). Also they are consistent with the results from *Žagar et al.* (2012) who showed that systematic model errors in the tropics occur at wavenumbers 1–3, whereas random errors occur in wavenumbers 4–7. However, the signals that stand out from Figures 2a and 2c are the strong wind increments at 850 and 700 hPa in the East Pacific.

Figures 2c and 2d show the differences between the ECMWF and the UK Met Office analyses at 850 and 700 hPa for autumn 2011. Broadly, the ECMWF analyses in the tropical troposphere are about 0.5 K colder than the Met Office analyses. Interestingly, however, these analysis differences appear to have many similarities with Figures 2a and 2b which are analysis increments that form proxies for ECMWF short-range forecast errors. The largest differences between the ECMWF and Met Office analyses occur over Central Africa and in particular in the East Pacific where at 850 hPa the ECMWF winds are more south-southeasterly, while at 700 hPa they correspond to a more north-northeasterly cross-equatorial flow. The question to then be addressed is which analysis is more realistic, or even better what observation types enforce the stronger cross-equatorial flow in the ECMWF analyses? Before doing so, it is useful to assess the model behaviour at longer ranges for ECMWF's high-resolution (HRES) and ensemble (ENS) forecasts.

Day 5 forecast errors

Figure 3 shows the day-5 forecast errors against their own analysis at 1000 and 850 hPa for the HRES forecasts. The tropical troposphere cools by about 0.5 K during the first 5 days. The wind patterns show a divergent signal at 1000 hPa along the ITCZ (Figure 3a), and large wind errors in the East Pacific at 850 hPa (Figure 3b). The results for the ENS forecasts (not shown) are similar to those for HRES. Two important findings can be deduced from these results. Firstly, the similarity in the errors between the HRES and ENS forecasts suggests that essential information on systematic tropical model errors can be obtained by only evaluating the HRES system. Secondly, comparing Figure 3 to the wind increments at 1000 and 850 hPa (Figures 1 and 2), one can readily see that wind increments (analysis minus short-range forecast difference) and day-5 forecast errors have a similar structure but opposite sign. This means that the observations tend to correct a model drift towards a weaker Hadley cell (less convergence in the ITCZ) and increase the low-level cross-equatorial flow in the East Pacific.

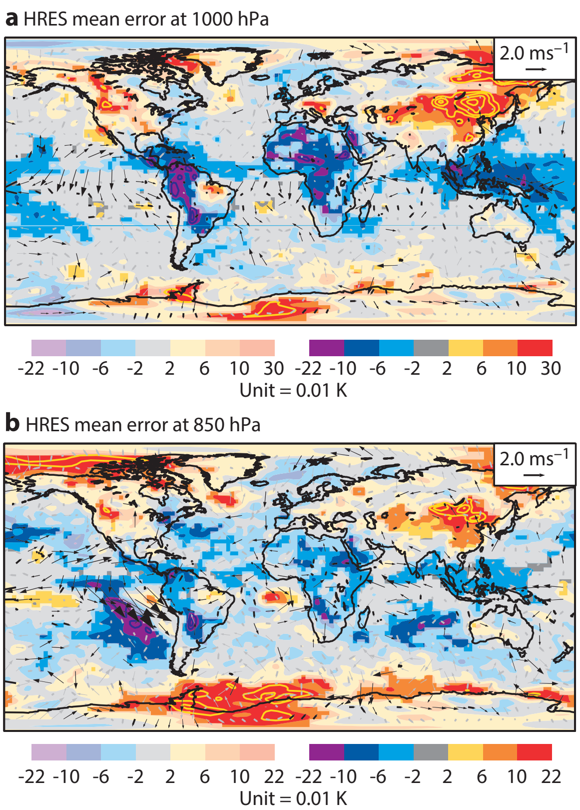

Figure 3 Day-5 mean forecast errors from HRES for temperature and wind at (a) 1000 and (b) 850 hPa for October–November 2011.

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Observational data

Over the tropics, wind data is a very important source of observational information. The two main wind products with global coverage originate from the ASCAT scatterometer and the Atmospheric Motion Vectors (AMVs) that are derived by tracking the cloud and moisture fields. However, observations sensitive to temperature (e.g. infrared/microwave sounders) and moisture (e.g. microwave imagers, selected microwave and infrared sounder channels) can also produce wind increments through the dynamic response to temperature and moisture increments in 4D-Var. These more indirect wind increments are usually broader in scale and thus less specific in height and location.

The East Pacific

Focusing on the tropical East Pacific, Figure 4 shows the mean temperature and wind analysis at 700, 850 and 1000 hPa for October–November 2011. The convergence pattern, which crosses the equator and intensifies towards the east where it intersects with the north-easterly flow from the Caribbean, is particularly strong at lower levels and the position of the ITCZ is easily identified near 10°N. Between 850 and 700 hPa the wind direction changes drastically from south/southwest to north/northwest at the equator, while intensities are fairly similar. These strongly sheared flow patterns intersecting with Central America over areas with large sea surface temperature gradients are difficult to represent correctly in the model.

The East Pacific is the only tropical region where all year-round, apart from spring, low-level south-southeasterly cross-equatorial flow dominates. Also during autumn and winter a reverse cross-equatorial flow prevails at 700 hPa that further enhances the vertical wind shear. As discussed in *De Szoeke & Xie* (2008), general circulation models tend to produce large errors in these regions. *Philander & Pacanowski* (1981) and *Okajima et al.* (2003) explain the particular Pacific wind pattern by the position of the ITCZ north of the equator, the northwest–southeast slant of the American coast, and the Andes orography that breaks the symmetry. On the other hand, *Rodwell & Hoskins* (2001) interpret the anticyclonic flow pattern as a Rossby wave response to the Central and South American monsoon to the east.

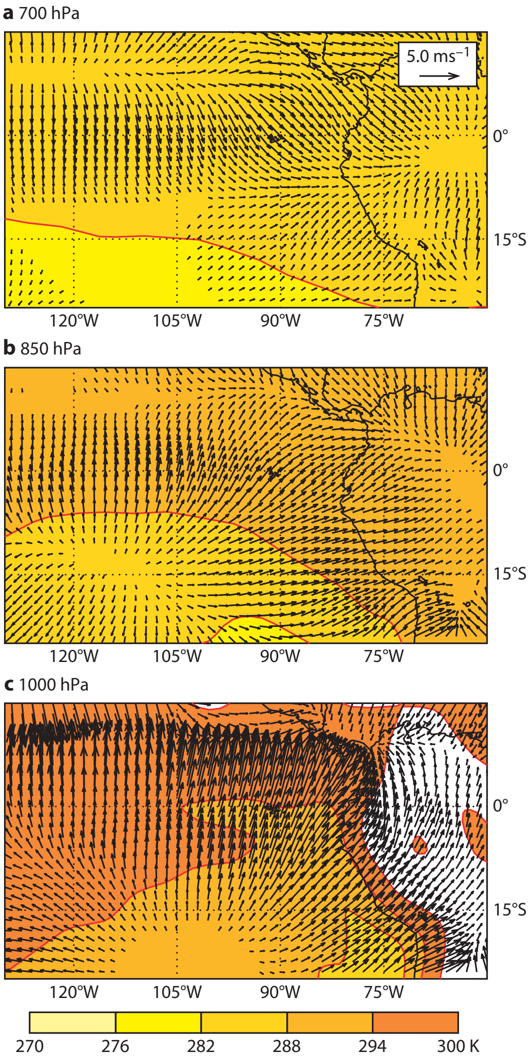

Figure 4 Mean wind and temperature analysis over the East Pacific at (a) 700, (b) 850 and (c) 1000 hPa for October–November 2011.

Data denial experiment

To assess the specific impact of wind information derived from observations, experiments can be conducted in which selected data is withdrawn. Figure 5 shows the mean 850 hPa analysis differences (colours denote temperatures and arrows wind) between the operational analysis and an experiment in which GOES-13 AMV data has been withdrawn in the area 30°S–0°/120°–150°W for October–November 2011. The analysis increments given in Figures 1, 2a and 2c are well reproduced in this data denial experiment and show a similar maximum of wind increments of order 2 ms-1 near 850 hPa (Figure 5a). The broad wind impact across the equator overlaps with a cooling by about 1 K through advection of cooler and drier air masses from the south. The observations therefore amplify low-level convergence across the equator and thus intensify the Hadley circulation in this area. The observations also move the centre of 850 hPa divergence from 15°S/110°W towards the continent.

Into the forecast, the areas with significant temperature increments remain rather stable until day 3. However, in the first 24 hours the enhancement of the cross-equator convergence changes sign (i.e. the model overshoots in response to the large analysis increments). The result of this strong dynamical adjustment process is that beyond day 2 there is barely any difference in the wind fields between the operational analysis using the GOES-13 AMVs and the experiment without that data.

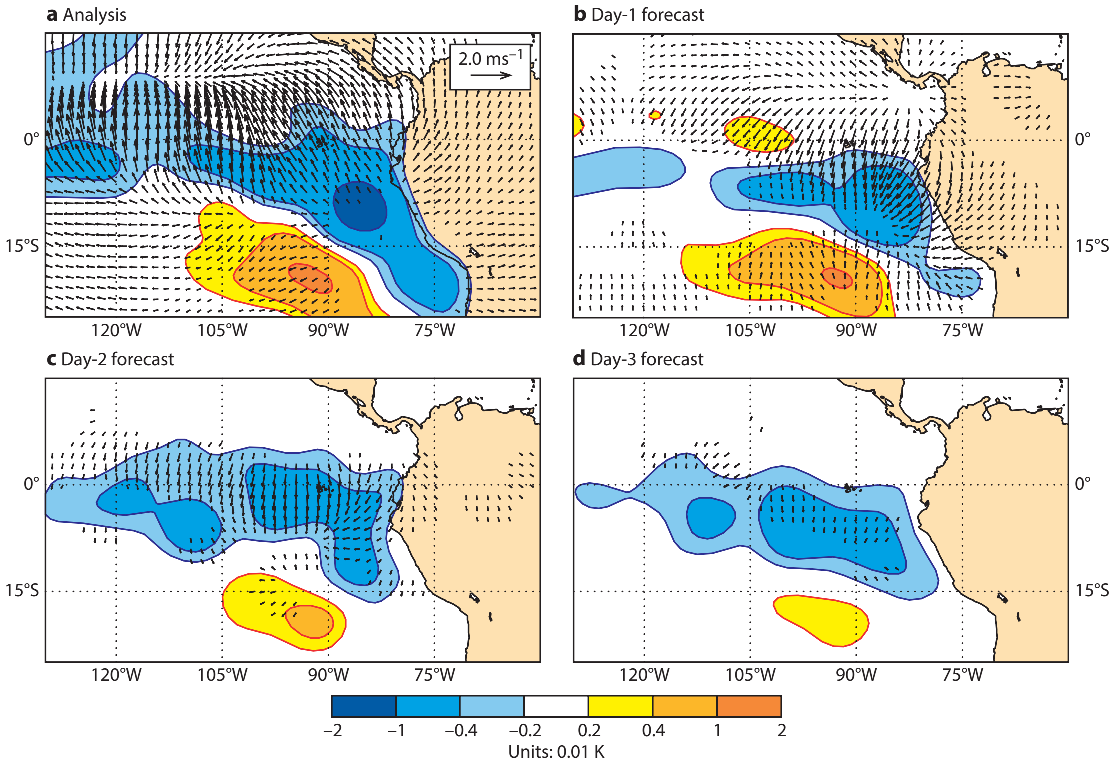

Figure 5 Mean analysis difference between control and the GOES-13 AMV denial experiment for wind (arrows) and temperature (colour scale) at 850 hPa for (a) analysis time, (b) day 1, (c) day 2 and (d) day 3 for October–November 2011.

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Observation sensitivity techniques

Recently, adjoint-based techniques to assess observation sensitivity have been used to measure the observation contribution to the forecast error (*Cardinali & Healy*, 2012). It is interesting to assess whether the impact of AMV observations is generally beneficial for the 24-hour forecasts by means of the observation diagnostic known as Forecast Error Contribution (FEC). Here results are presented for the impact of u-component (Figure 6a) and v-component (Figure 6b) observations.

It is found that the v-component impact is generally positive (i.e. negative FEC) in the East Pacific, especially in the area where the amplification of the lower-level cross-equatorial flow at 850 hPa was noted. Most of the GOES-13 AMV observations provide wind information at 850 hPa (5 times more than at levels below and 10 times more than at 700 hPa). However, the negative impact of u-component observations (i.e. positive FEC) further to the southeast coincides with the area of lower-level divergence at 15°S/110°W. Here, wind speeds are very low and it is suspected that the AMV tracking algorithm may produce questionable retrievals in the presence of weak and divergent winds.

While the investigation described here focused on AMV observations, other wind-related data also impact the analysis as mentioned earlier. For example, ASCAT wind observations most strongly constrain 10-metre winds. Over the East Pacific, they show a more detailed pattern of first-guess departures (Figure 1) that is in contradiction to AMVs just south of the equator. Despite these differences, ASCAT winds also enhance lower-level convergence but along a smaller strip south of the ITCZ.

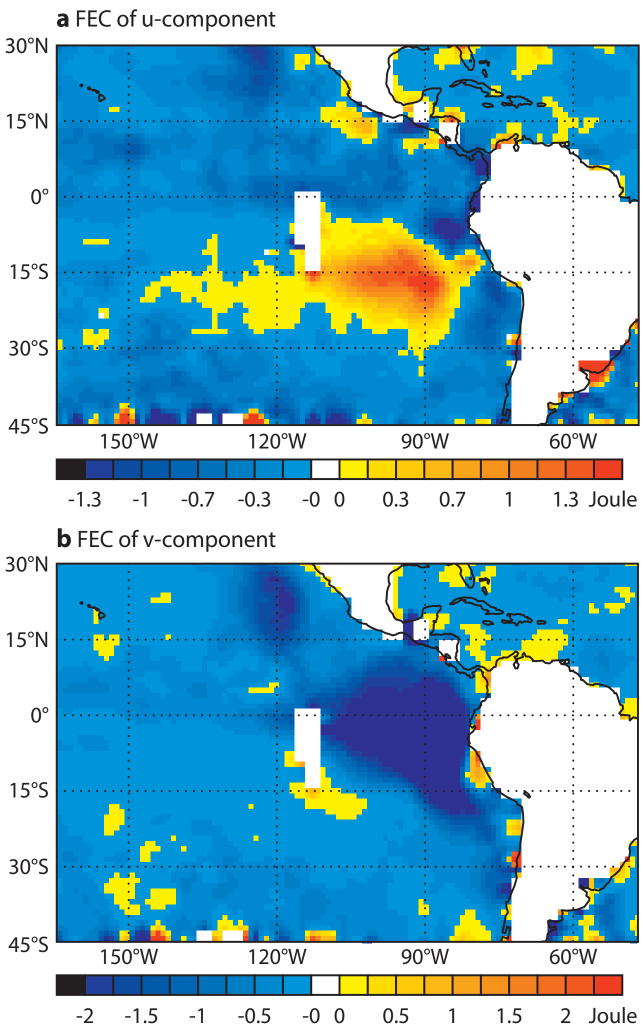

Figure 6 Mean Forecast Error Contribution (FEC) of (a) u-component and (b) v-component AMV observations in the atmosphere between 700 and 1000 hPa for October–November 2011 in the East Pacific. Positive (negative) values denote that the assimilated observations increased (decreased) the global 24-hour forecast error.

Concluding remarks

The task of quantifying analysis uncertainty and 'forecast error' is particularly challenging in the tropics due to the sparseness of in-situ data over the tropical oceans. The analyses from the various modelling centres can also have large differences.

Overall, one can say that the IFS presents a systematic trend to reduce the intensity of the meridional Hadley cell. The impact of ASCAT and AMV data on the analysis is similar in that both increase the convergence in the ITCZ and the low-level cross-equatorial flow, therefore pointing to a model bias in these regions. The model, however, overestimates the strength of the zonal Walker cell (i.e. a deep east-west overturning in the atmosphere normally confined to within about 20° of the equator) in that it overestimates precipitation and convergence over the Maritime Continent and the West Pacific (not shown). Interestingly, this is in agreement with a study by Oort & Yienger (1996) who demonstrated that an increase in the intensity of the Walker cell is associated with a decrease in the intensity of the Hadley cell and vice versa.

The area that stands out in terms of low-level wind errors and large differences in the analysis compared to that from the Met Office is the East Pacific. Data denial experiments further show that model forecasts at lead times beyond day 3 have largely 'forgotten' about the AMV analysis increments, and that the forecast adjustment processes between day 0 and day 3 produce a temporary flow reversal. Comparison with independent buoy data in this region confirms that the ECMWF analysis is indeed realistic but that a low-level flow bias persists in the forecasts. However, given the larger vertical wind-shear and likely larger observation errors of the AMVs in the East Pacific, the flow errors compared to analysis and increments are more uncertain, especially at 850 hPa.

We think that further improvements in tropical analysis will be achieved through improvements in the background error formulation (*Bonavita et al.*, 2012) as already achieved in the most recent operational cycle Cy38r1, the treatment of all-sky radiances, and in particular through the assimilation of tropical wind data from the ADM-Aeolus wind lidar that is expected in the 2015 time frame.

Further reading

Bonavita, **M.**, **L. Isaksen** & **E. Holm**, 2012: On the use of EDA background error variances in the ECMWF 4D-Var. *Q. J. R. Meteorol. Soc.*, **138**, 1540–1559.

Cardinali, **C.** & **S. Healy**, 2012: Forecast sensitivity to observation error variance. *ECMWF Newsletter* **No. 133,** 30–33.

De, **S.** & **D.R. Chakraborty**, 2004: Tropical systematic and random error energetics based on NCEP (MRF) analysis-forecast system – A barotropic approach part II: in wavenumber. *Proc. Indian Acad. Sci.*, **113**, 167–195.

De Szoeke, **S.P.** & **S.-P. Xie**, 2008: The tropical eastern Pacific seasonal cycle: Assessment of errors and mechanisms in IPCC AR4 coupled ocean-atmosphere general circulation models. *J. Climate*, **21**, 2573–2590.

Okajima, **H.**, **S.P. Xie** & **A. Numaguti**, 2003: Inter-hemispheric coherence of tropical climate variability: Effect of the climatological ITCZ. *J. Meteorol. Soc. Japan*, **81**,1371–1386.

Oort, **A.H.** & **J.J. Yienger**, 1996: Observed inter-annual variability in the Hadley circulation and its connection to ENSO. *J. Climate*, **9**, 2751–2767.

Philander, **S.G.H.** & **R.C. Pacanowski**, 1981: The oceanic response to cross-equatorial winds (with application to coastal upwelling in low latitudes). *Tellus*, **33A**, 201–210.

Rodwell, **M.J.** & **B.J. Hoskins**, 2001: Subtropical anticyclones and summer Monsoons. *J. Climate*, **14**, 3192–3211.

Žagar, **N.**, **L. Isaksen**, **D. Tan** & **J. Tribbia**, 2012: Balance properties of the short-range forecast errors in the ECMWF 4D-Var ensemble. *Q. J. R. Meteorol. Soc.*, **138**, DOI: 10.1002/qj.2033.

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