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Sub-seasonal variance of surface meteorological parameters in buoy observations and reanalyses

Yolande L. Serra,[1] Meghan F. Cronin,[2] and George N. Kiladis[3]

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[1] Tropical Atmosphere Ocean (TAO)/Triangle Trans-Ocean Buoy Network (TRITON) and Eastern Pacific Investigation of Climate (EPIC) moorings across the equatorial Pacific are used to evaluate the mean climate and sub-seasonal variance in surface meteorological variables in the NCEP/NCAR, NCEP/DOE, and ERA40 reanalyses. This study focuses on the June–November time period when tropical storms are most frequent in the region. For the mean fields, the reanalysis surface products compare better with the moorings than the 1000 hPa products. In contrast, the variance in the 1000 hPa ERA40 state variables is in best agreement with the mooring variance. As long as these disparities exist, air-sea interaction studies and our ability to drive ocean models with observed fluxes will be limited. **Citation:** Serra, Y. L., M. F. Cronin, and G. N. Kiladis (2007), Sub-seasonal variance of surface meteorological parameters in buoy observations and reanalyses, *Geophys. Res. Lett.*, *34*, L12708, doi:10.1029/2007GL029506.

1. Introduction

[2] Regularly gridded geophysical data with multi-decadal record lengths are necessary for regional and global analyses geared toward improving our understanding of the climate system, as well as predicting future climate change. In addition these data are used to validate both numerical weather forecast and climate models. As the costs of making global observations at such regular time and space scales over long time periods are prohibitive, several global reanalysis products have been produced using state-of-the-art numerical weather prediction and data assimilation techniques to provide regularly gridded, four dimensional state parameters of the climate system from the mid-twentieth century to the present. This study focuses on the NCEP/NCAR (RA1 [*Kalnay et al.*, 1996]), NCEP/DOE (RA2 [*Kanamitsu et al.*, 2002]), and ERA40 [*Uppala et al.*, 2005] products.

[3] Recent comparisons of 10-m relative winds from TAO with satellite winds from QuikSCAT suggest no significant differences [*Chelton et al.*, 2001; *Kelly et al.*, 2001]. However, differences between QuikSCAT and surface reanalysis winds are more substantial, especially in the Pacific ITCZ [*McNoldy et al.*, 2004; T. Shinoda et al., Variability of intraseasonal Kelvin waves in the equatorial Pacific Ocean, submitted to *Journal of Physical Oceanography,* 2007, hereinafter referred to as Shinoda et al., submitted manuscript, 2007]. Errors in the reanalyses' near surface meteorological variables cause significant errors in the surface heat fluxes calculated from bulk flux algorithms, which require these variables in their formulations [*Brunke and Zeng*, 2002; *Jiang et al.*, 2005; *Cronin et al.*, 2006]. Studies of atmosphere-ocean interactions and heat, moisture and momentum budgets for the tropics are currently limited by such uncertainties in surface state variables.

[4] Variability on synoptic time scales is also found to differ significantly among current reanalysis products including RA1, RA2 and ERA40. *Hodges et al.* [2003] find that while storm tracks and intensities in the northern hemisphere lower troposphere compare well amongst various reanalysis products, southern hemisphere and tropical storm tracks and intensities are more inconsistent. They note that in the tropics the differences amongst the reanalyses can be attributed to model resolution and data assimilation methods, as well as to model parameterizations. *Lin et al.* [2006] examine variability in precipitation in the climate models used for the Inter-governmental Panel on Climate Change (IPCC) Fourth Assessment Report and conclude that while most models produce reasonable precipitation climatologies, they have less variance on intraseasonal time scales (2–128 days) than the observations. In addition, the models tend to lack well-defined spectral peaks on weekly to monthly time scales, and most do not simulate the Madden-Julian oscillation (MJO). At lower frequencies, the models tend to have too red of a spectrum in precipitation indicating more persistence in model rain events than in the observations. Model formulations related to parameterized convective processes are thought to be at the root of model difficulties. Similarly, *Schafer et al.* [2007] highlighted deficiencies in the representation of reanalysis lower tropospheric flow over the central equatorial Pacific, suggestive of problems in boundary layer parameterizations.

[5] The purpose of this study is to compare mean values and 12-hour to 120-day variance in the surface winds, air temperature and humidity from RA1, RA2 and ERA40 with observations from the TAO/TRITON and EPIC moorings in the tropical Pacific. This study focuses on how well the reanalyses are performing in the Pacific ITCZ and SPCZ regions. The TAO/TRITON and EPIC data provide a unique opportunity to validate the variance characteristics of the reanalyses over a decade and over a critical range of frequencies in the tropics.

2. Data and Methods

[6] The in situ data used for this study are provided by the TAO/TRITON buoy array and EPIC buoys across the equatorial Pacific. The TAO/TRITON array comprises

[1]Department of Atmospheric Science, University of Arizona, Tucson, Arizona, USA.
[2]Pacific Marine Environmental Laboratory, NOAA, Seattle, Washington, USA.
[3]Earth System Research Laboratory, NOAA, Boulder, Colorado, USA.

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Table 1. Buoy Mean Values and Biases in RA1, RA2, and ERA40 Mean Values With Respect to Buoys for Pacific ITCZ During June–November 1992–2002

	Buoy	Buoy-RA1 1000 hPa	Buoy-RA2 1000 hPa	Buoy-ERA40 1000 hPa
V	1.0 ± 0.3 m s^{-1}	0.1 ± 0.2 m s^{-1}[a]	−0.6 ± 0.1 m s^{-1}	−0.40 ± 0.07 m s^{-1}
U	−2.6 ± 0.4 m s^{-1}	0.34 ± 0.09 m s^{-1}[a]	0.52 ± 0.08 m s^{-1}	0.44 ± 0.07 m s^{-1}
WS	5.2 ± 0.1 m s^{-1}	0.30 ± 0.08 m s^{-1}	−0.31 ± 0.07 m s^{-1}	−0.24 ± 0.04 m s^{-1}[a]
T	27.4 ± 0.1 °C	1.13 ± 0.04 °C	0.82 ± 0.05 °C[a]	1.39 ± 0.04 °C
q	18.4 ± 0.1 g kg^{-1}	1.34 ± 0.07 g kg^{-1}	1.81 ± 0.07 g kg^{-1}	1.20 ± 0.06 g kg^{-1}[a]

[a]Best agreement with buoys.

nearly 70 buoys at 10 lines between 138°E and 95°W, with seven standard sites along each line from 8° S to 8° N [*McPhaden et al.*, 1998]. Each buoy in the array measures air temperature and relative humidity at three meters, and surface winds at four meters. In support of the EPIC experiment, the EPIC buoys were deployed along 95°W at 3.5° N, 10° N, and 12° N in late 1999 and recovered in late 2003 [*Cronin et al.*, 2002].

[7] Sub-seasonal variability in the equatorial Pacific is highest during June–November when tropical waves and associated storms are most active [*Roundy and Frank*, 2004; Y. L. Serra et al., Horizontal and vertical structure of easterly waves in the Pacific ITCZ, submitted to *Journal of Atmospheric Sciences,* 2007, hereinafter referred to as Serra et al., submitted manuscript, 2007]. Because we are primarily interested in the performance of the reanalyses within the storm regions, we limit our analysis to the June–November season and to those buoys at and north of 5°N from 140°W to 95°W and from 8°S to 8°N, 155°W to 156°E. Our TAO/TRITON analysis period is from 1992–2002, while our EPIC analysis period is from 2000–2002.

[8] The RA1, RA2 and ERA40 winds, air temperature, and specific humidity at 1000 hPa are used to compare with the buoy observations. The pressure level data are available at 6-hourly time resolution and 2.5° × 2.5° horizontal resolution. Reanalysis 10-m winds and 2-m air temperatures and humidities are also analyzed and compared with the 1000 hPa and buoy data. The TAO/TRITON and EPIC data are 10-min or hourly, depending on the type of mooring. In order to match the reanalyses, we smooth all high-resolution buoy measurements to 6-hourly using a 12-hour Hanning window. The resulting 6-hourly time series are used for all subsequent calculations.

[9] Our analysis includes calculation of the mean bias between the buoys and reanalyses, as well as comparison of the mean power spectral density for each variable. To obtain the mean bias we find all matching 6-hourly data points at each buoy location for June–November 1992–2002. A mean difference or bias between the buoys and the reanalysis product based on these matching data is then obtained for all buoy locations. Biases are defined as buoy minus reanalysis. The standard error in the mean bias is defined as $\sigma/\sqrt{N-1}$, where σ is the standard deviation of the differences and N-1 are the number of degrees of freedom. Degrees of freedom are defined as the number of buoy locations.

[10] The power spectral density is calculated using the Welch periodogram method with 50% overlap on 120-day segments of 6-hourly data, also limited to June–November 1992–2002. Only those 120-day segments available at the buoys are used for calculation of power spectral densities for the reanalysis products. The overall mean power spectral density is then defined as the average of the power spectrum for all 120-day segments of data, with the standard error defined as for the mean bias except that σ is now the standard deviation of the power spectral estimates at each frequency and one less than the number of 120-day segments gives the degrees of freedom.

[11] According to *Uppala et al.* [2005] only TAO data from 1993–1995 has been assimilated into ERA40. RA1 and RA2 attempt to assimilate daily TAO and EPIC data (J. Whitaker, personal communication, 2007). However, the actual number of TAO and EPIC data points actually assimilated is likely to be small, as the reanalyses are generally not tightly constrained by buoy data. In any event, the comparisons in this study are not entirely independent.

3. Results

3.1. Mean Biases

[12] Our results suggest that within the Pacific ITCZ, RA1 1000 hPa mean wind components show good agreement with the buoy mean wind components. However, the differences amount to a low bias in wind speed of 0.30 ± 0.08 m s^{-1} with respect to the observations (Table 1). The 1000 hPa RA2 and ERA40 products show significant differences in the mean wind components from the observations, amounting to wind speed biases of −0.31 ± 0.07 m s^{-1} and −0.24 ± 0.04 m s^{-1}, respectively, indicating a high bias with respect to the observations. ERA40 has the lowest mean wind speed bias despite significant biases in the individual wind components.

[13] As with the winds, there is also no clear best 1000 hPa reanalysis product for the thermodynamic variables, with RA2 showing the closest agreement for air temperature and ERA40 showing the best agreement for specific humidity (Table 1). In addition, the 1000 hPa reanalyses are all cooler and drier than the observations suggesting that the measurement height is important for these variables.

[14] *Fairall et al.* [1996] suggest that in order to attain a less than 10 W m^{-2} uncertainty in the total surface energy budget calculated from bulk formulae the mean variables used in these formulae need to have systematic errors of less than 0.2 m s^{-1}, 0.2 K and 0.2 g kg^{-1} for wind speed, air temperature and humidity, respectively. Thus, Table 1 suggests that for calculation of surface fluxes, uncertainties in the winds are closer to the *Fairall et al.* [1996] suggested uncertainties than the thermodynamic values. In addition, the biases in the winds are closer to the buoy standard errors in the mean wind than the biases in air temperature and humidity, which exceed the buoy standard errors in these variables by an order of magnitude.

Table 2. Same as Table 1 but for 10-m Winds and 2-m Temperatures and Humidities From Reanalyses[a]

	Buoy	Buoy-RA1 10m/2m	Buoy-RA2 10m/2m	Buoy-ERA40 10m/2m
V	1.0 ± 0.3 m s^{-1}	0.3 ± 0.2 m s^{-1b}	0.5 ± 0.1 m s^{-1}	−0.27 ± 0.06 m s^{-1a}
U	−2.6 ± 0.4 m s^{-1}	0.1 ± 0.1 m s^{-1a}	0.23 ± 0.08 m s^{-1b}	0.17 ± 0.07 m s^{-1b}
WS	5.2 ± 0.1 m s^{-1}	0.66 ± 0.09 m s^{-1}	−0.17 ± 0.07 m s^{-1a}	0.24 ± 0.04 m s^{-1}
T	27.4 ± 0.1 °C	0.25 ± 0.03 °C	−0.16 ± 0.03 °C[a]	0.19 ± 0.03 °C
q	18.4 ± 0.1 g kg^{-1}	0.11 ± 0.07 g kg^{-1a}	0.30 ± 0.6 g kg^{-1}	0.37 ± 0.6 g kg^{-1}

[a]Best agreement with the buoys.
[b]Values within one standard error of the buoys.

[15] Overall, comparisons of the mean values improve when 10-m winds and 2-m air temperatures and humidities from the reanalyses are used (Table 2). For the near-surface data all wind components, with the exception of RA2 meridional wind, are within one standard error of the buoy values. And while none of the 10-m wind speeds are within one standard error of those measured at the buoys, the RA2 10-m wind speed is within the 0.2 m s^{-1} guideline suggested by *Fairall et al.* [1996].

[16] The near-surface thermodynamic mean value comparisons are much improved over the 1000 hPa comparisons, with biases much closer to the *Fairall et al.* [1996] suggested uncertainties. Specifically, RA2 shows the best comparisons for air temperature, while RA1 shows the best comparisons for specific humidity.

[17] Our results suggest that there is no one best reanalysis product that provides accurate near-surface mean state variables in the equatorial Pacific storm regions for use in, for example, bulk formulae calculations. However, we can say that the best agreement in the mean for all products is found with the surface data, as expected. Of these, the mean 10-m zonal wind shows the best agreement for all three reanalyses, while 10-m wind speed fails to meet the *Fairall et al.* [1996] suggested uncertainty for all but RA2. Similarly, air temperature shows better agreement than specific humidity, with only RA1 exceeding the suggested uncertainty in this variable. On the other hand, only RA1 specific humidity is within the suggested uncertainty for this variable.

3.2. Variability

[18] In this section we compare the variance characteristics of the 1000 hPa reanalyses with the observations on sub-seasonal time scales (12-hours to 120 days). The near-surface data were also analyzed but are not shown here as generally better agreement is observed for the 1000 hPa products. Figure 1 shows the power spectral energy for the meridional and zonal wind components plotted such that the area under any portion of the curve is proportional to the variance. In order to reveal the details for both frequency bands, the plots are divided into two panels: 12-hour to daily variability on the left, and 1 to 120-day variability on the right. The 95% confidence limits for the lowest frequency portion of the spectrum representing the largest errors are shown as vertical bars, staggered by five days for readability.

[19] RA1 and RA2 have generally an order of magnitude greater semi-diurnal and diurnal variance than the buoy winds, while ERA40 is within one standard error of the buoy semi-diurnal and diurnal variance for both wind components (Figure 1). In addition only ERA40 variance is less than the observed variance between these two frequencies, with both RA1 and RA2 containing what is likely high frequency noise on sub-daily time scales. Despite the larger magnitudes in RA1 and RA2, the diurnal variance in the meridional wind exceeds its semi-diurnal variance in all three reanalysis products, in agreement with both our buoy analysis as well as that of *Deser and Smith* [1998]. For the zonal wind RA2 and ERA40 show greater semi-diurnal than diurnal variability, also consistent with

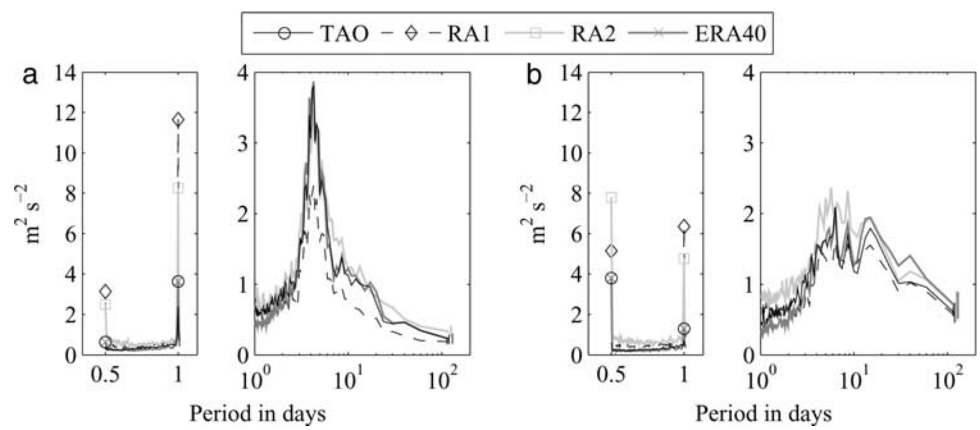

Figure 1. Power spectral energy of buoy and 1000 hPa reanalysis (a) meridional wind and (b) zonal wind for June–November 1992–2002 plotted in variance preserving format. Each figure is divided into two panels, one for the 12- to 24-hour time period and one for the 1- to 120-day time period. The 95% confidence limits for the lowest frequency (largest error) are shown as vertical bars staggered about 120 days for readability.

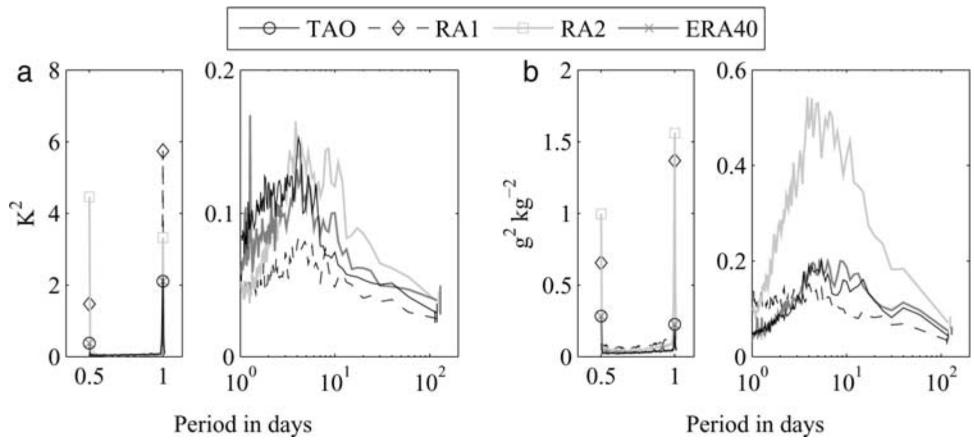

Figure 2. Same as Figure 1 but for (a) air temperature and (b) specific humidity.

the present buoy analysis and *Deser and Smith* [1998]. In contrast, RA1 shows greater diurnal variability in the zonal wind. Furthermore, there is little difference between the 10-m (not shown) and 1000 hPa reanalysis wind spectra on sub-daily time scales suggesting that the disagreements are not an issue of measurement height.

[20] At lower frequencies, both the observations and reanalyses indicate a notable increase in variance at synoptic (3–6 day) frequencies in both wind components, with the peak in the meridional wind especially prominent (Figure 1). Synoptic variability is primarily associated with easterly waves, although some mixed-Rossby gravity waves are also present at these locations [*Roundy and Frank*, 2004; Serra et al., submitted manuscript, 2007]. At even lower frequencies the power in the meridional wind drops significantly, while that for zonal wind suggests activity on 9-day, 15-day, and 40–60-day time scales. Variability on these time scales in the tropics is generally associated with Rossby waves, Kelvin waves, and the MJO, respectively.

[21] ERA40 shows the best agreement with the observed wind spectra for both magnitude and shape of the power spectra, although the RA2 meridional wind spectrum is also in very good agreement with the buoys. That RA2 has the greatest variance on synoptic time scales in the zonal wind and equal variance to the observations in the meridional wind on these time scales suggests that easterly waves in RA2 are the most energetic of the three reanalysis products examined in this study. This is in general agreement with the results of *Hodges et al.* [2003], who find that RA2 storm track intensities in the tropics are the most energetic of the reanalysis products in their study. RA2 and ERA40 meridional and zonal wind variances are equal or greater than the observations at the lowest frequencies, with peaks in the zonal winds at 8.6, 15 and 40 days. The power at these frequencies is in very good agreement with the observations for RA2 and ERA40 10-m zonal winds (not shown), while the power in the RA1 10-m zonal wind spectrum falls well below that of the buoys.

[22] The power spectral energy for buoy and 1000 hPa reanalysis air temperature and specific humidity are shown in Figure 2, with the sub-daily to daily and daily to sub-seasonal time scales separated as for the wind spectra in Figure 1. As for the wind spectra comparisons, ERA40 shows overall better agreement with the observed spectra, both in shape and magnitude, than either RA1 or RA2. We again find that the semi-diurnal and diurnal variance in RA1 and RA2 is significantly greater than that seen in the observations or ERA40 for both air temperature and specific humidity. Striking differences in the shape and magnitude of RA1 and RA2 spectra in comparison to the observations are also observed on daily to sub-seasonal time scales, with RA1 indicating generally less variance and RA2 greater variance than what is observed. The 2-m air temperature and humidity spectra comparisons (not shown) are somewhat worse for RA1, as the power is even less than for the 1000 hPa spectra. There is some improvement for the RA2 comparisons since the variance in the 1000 hPa product tends to be too high compared to the buoys. However, the shape of the spectra is similar for both measurement heights, and thus significant differences are still seen in RA2 temperatures on 1–2-day periods and 8–20-day periods. In addition, the variance in the RA2 2-m humidity also significantly exceeds that of the observations on synoptic to sub-seasonal time scales.

4. Discussion

[23] Comparisons of the variance characteristics of numerical weather forecast and climate models with reanalysis products is important for assessing how well models represent the earth's true climate. In this study we examine the skill of RA1, RA2 and ERA40 at capturing not only the mean near-surface climate, but also the variability of surface state variables on sub-daily to sub-seasonal time scales. This is accomplished by comparing the 1000 hPa and 10-m and 2-m reanalyses products to a subset of TAO/TRITON and EPIC buoy measurements located within the equatorial Pacific storm regions for the June–November 1992–2002 time period.

[24] Our results suggest that the 10-m and 2-m data compare better overall with the buoy mean values than the 1000 hPa reanalysis products, as expected. Of the surface state variables, mean winds compare better with the observations than mean air temperature or humidity for both the 1000 hPa and near-surface products. This is possibly due to the fact that at least RA1 is more tightly constrained by wind data than temperature or moisture data [*Kalnay et al.*, 1996]. Although there is not one clear choice for best agreement with the observations for the mean value comparisons, RA2 shows the best agreement for 10-m wind speed and 2-m air temperature. If 1000 hPa data are considered, ERA40 provides the best comparisons for mean wind speed and specific humidity.

[25] Some of the mean differences are likely due to sampling errors inevitable when comparing a point measurement to a 2.5° × 2.5° grid value. However, the small standard errors in both the mean buoy values and the differences suggest that the mean differences are likely not entirely due to sampling.

[26] Results of our power spectra comparisons suggest that both RA1 and RA2 significantly overestimate variability on semi-diurnal and diurnal time scales in 1000 hPa winds, air temperature and humidity compared to the observations, while ERA40 shows overall better agreement with the observations on these time scales. These comparisons are only marginally improved for RA1 and RA2 10-m winds. Atmospheric tides are the generally accepted cause for the semi-diurnal variability in tropical winds [*Haurwitz and Crowley*, 1973], thus the larger semi-diurnal signal in RA1 and RA2 wind components suggests that these products may have insufficient damping of tides within the model boundary layer. However, this does not explain the large semi-diurnal variance in air temperature and humidity observed in RA1 and RA2. Similarly, the excess variance on diurnal time scales observed in both the winds and thermodynamic variables in RA1 and RA2 cannot easily be explained. We conclude that only ERA40 is accurately representing the semi-diurnal and diurnal variability in the near-surface parameters and should be selected over RA1 or RA2 for studies where these time scales are particularly relevant.

[27] At lower frequencies (2–120 days), RA2 and ERA40 1000 hPa wind components show good agreement with the observations, while RA1 exhibits too little variance in both 1000 hPa wind components across this frequency band. Power spectra for the 10-m reanalysis winds are similar but with less variance, worsening the agreement with the buoys compared to the 1000 hPa wind spectra for all three products. Similar results for buoy versus RA1 10-m winds were obtained over the western Pacific by Shinoda et al. (submitted manuscript, 2007).

[28] The 1000 hPa air temperature and specific humidity spectra comparisons show cause for concern, with only ERA40 capturing the magnitude and structure of the variability seen at the buoys. RA1 exhibits consistently too little power in these variables, while RA2 exhibits too much power, especially for specific humidity. RA2 2-m air temperature and humidity spectra comparisons show some improvement, but significant differences in the magnitude and structure of the variance remain for both variables. RA1 2-m air temperature and humidity show worse agreement with the observations, since the lower measurement height simply reduces the variance in these variables even more.

[29] According to this study, the reanalysis surface products are preferred when accurate mean values of the surface state variables are required, with no one product meeting all the *Fairall et al.* [1996] suggested guidelines for surface flux calculations, while the 1000 hPa ERA40 product is preferred for accurate variance estimates for these variables. As the 10-m power spectra have a similar shape to the 1000 hPa spectra but less variance, the surface products may be the overall best choice for near-surface analyses at the current time. Differences in the mean and variance of the thermodynamic quantities cause the most concern not only for calculation of surface fluxes, as discussed by *Jiang et al.* [2005], but for representation of all air-sea interaction processes in the tropics. Until one reanalysis product can provide accurate mean and variance characteristics of the surface state variables, studies of air-sea interaction processes, along with the ability to drive ocean models with observed fluxes, will be limited.

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Y. L. Serra, Department of Atmospheric Science, University of Arizona, 1118 E. 4th Street, Box 210081, Tucson, AZ 85721-0081, USA. (serra@atmo.arizona.edu)

M. F. Cronin, Pacific Marine Environmental Laboratory, NOAA, Seattle, WA 98115, USA. (meghan.f.cronin@noaa.gov)

G. N. Kiladis, Earth System Research Laboratory, NOAA, Boulder, CO 80305, USA. (george.kiladis@noaa.gov)