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Key Points:

- Unphysical features in leading reanalysis linked to Tropical Pacific moorings
- Large, previously unrecognized annual air-sea heat flux anomalies, up to 50 Wm^{-2}
- Uncertainty in Tropical Pacific heat uptake pattern between 1990s and 2000s

Supporting Information:

- Readme
- Figure S1

Correspondence to:
S. A. Josey,
simon.josey@noc.ac.uk

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Unexpected impacts of the Tropical Pacific array on reanalysis surface meteorology and heat fluxes

S. A. Josey[1], L. Yu[2], S. Gulev[3], X. Jin[2], N. Tilinina[3], B. Barnier[4], and L. Brodeau[5]

[1]National Oceanography Centre, Southampton, UK, [2]Woods Hole Oceanographic Institution, USA, [3]P.P. Shirshov Institute of Oceanology—RAS, Moscow, Russian Federation, [4]Laboratoire de Glaciologie et Géophysique de l'Environnement, Centre National de la Recherche Scientifique, Université de Grenoble, France, [5]Department of Meteorology, Stockholm University, Stockholm, Sweden

Abstract The Tropical Pacific mooring array has been a key component of the climate observing system since the early 1990s. We identify a pattern of strong near surface humidity anomalies, colocated with the array, in the widely used European Center for Medium Range Weather Forecasting Interim atmospheric reanalysis. The pattern generates large, previously unrecognized latent and net air-sea heat flux anomalies, up to 50 Wm^{-2} in the annual mean, in reanalysis derived data sets employed for climate studies (TropFlux) and ocean model forcing (the Drakkar Forcing Set). As a consequence, uncertainty in Tropical Pacific ocean heat uptake between the 1990s and early 2000s at the mooring sites is significant with mooring colocated differences in decadally averaged ocean heat uptake as large as 20 Wm^{-2}. Furthermore, these results have major implications for the dual use of air-sea flux buoys as reference sites and sources of assimilation data that are discussed.

1. Introduction

The Tropical Pacific has a strong influence on the climate system both in terms of impacts associated with individual El Niño events and its potential role in the recent slowdown of global surface warming [*Balmaseda et al.*, 2013; *Kosaka and Xie*, 2013]. In particular, a change in the Tropical Pacific circulation over the past two decades has been advocated as a mechanism for increased uptake of heat by the ocean [*England et al.*, 2014].

Since the early 1990s, the Tropical Pacific mooring array has provided observations of both ocean and near surface atmospheric conditions that are essential for the monitoring and understanding of climate phenomena in this region [*McPhaden et al.*, 2010]. The array is currently undergoing a thorough evaluation and redesign to enable it to continue to play its role as a key element of the 21st century climate observing system [*Tollefson*, 2014].

Surface meteorological and sea surface temperature observations from the array are assimilated into atmospheric reanalyses and provide the dominant source of information in the Tropical Pacific as ship observations are relatively sparse. The number of ship reports is typically less than 2 per month per 2 × 2° box, while boxes with buoys contribute more than 100 reports [*Gulev et al.*, 2007]. However, the dominance of the array also has the potential to lead to strong localized field perturbations if the spatial scale of influence of the assimilated data is small compared with the distance separating the buoys and the reanalysis fields are biased. In this case, the reanalysis fields will be adjusted toward the true value at the buoy sites but remain biased elsewhere. Here, we identify for the first time the existence of such perturbations in near surface meteorological fields (particularly humidity) from several currently used reanalysis and reanalysis-derived products (DFS, ERA-Interim, TropFlux—acronyms detailed in section 2).

Furthermore, we determine that the humidity perturbations have major consequences for the exchange of heat between the ocean and the atmosphere. Our main aims are (1) to reveal the existence of these features to the climate community, (2) to identify their potential impact on estimated patterns of changing ocean heat uptake in the Tropical Pacific, and (3) to inform the debate on the development and use of a global ocean surface observing network for evaluation of major climate data sets.

2. Data Sets and Ocean Model

2.1. Atmospheric Reanalyses and Surface Flux Data Sets

Our primary focus is the latest atmospheric model reanalysis, ERA-Interim [*Dee et al*., 2011], from the European Centre for Medium-range Weather Forecasting (ECMWF). ERA-Interim is at higher resolution than its predecessor [ERA40, *Uppala et al*., 2005] and has revised model physics and a more advanced data assimilation system. It spans 1979 to near present (data through to Aug 2013 obtained for this study). We also show results from the NASA Modern Era Reanalysis for Research and Applications [MERRA, *Rienecker et al*., 2011], National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis [*Kalnay et al*., 1996], and NCEP Climate Forecast System Reanalysis [CFSR, *Saha et al*., 2010].

Various surface flux products have been derived from atmospheric reanalyses in recent years, including TropFlux and the Drakkar Forcing Set (DFS) that are both based on ECMWF fields. TropFlux is an attempt to provide a more accurate tropical air-sea flux data set by adjustment of the ERA-Interim fields following comparisons with the Tropical Pacific mooring array [*Praveen Kumar et al*., 2012]. The Drakkar ocean modeling community [*Drakkar Group*, 2007] developed the DFS boundary conditions for forcing ocean models using ERA40 and ERA-Interim near surface meteorological variables with adjustments following comparisons with reference observations. For example, wind speed is adjusted with reference to satellite data from QUIKSCAT [*Brodeau et al*., 2010].

The Objectively Analysed Air-Sea heat flux (OAFlux) data set [*Yu and Weller*, 2007] is also considered. It is the first to synthesize atmospheric state variables (sea surface temperature, air temperature and humidity, and wind speed) from reanalyses (including NCEP/NCAR, ERA40, and ERA-interim) and, where available, from satellite observations, prior to flux calculation. This approach potentially enables OAFlux to reduce biases that may be present in the individual input data sets.

2.2. The TAO Tropical Pacific Mooring Array

The Tropical Atmosphere Ocean (TAO) project array spans much of the Tropical Pacific and consists of about 70 moorings deployed since the early 1990s [*McPhaden et al*., 2010]. Amongst a wide range of surface and sub-surface variables measured at the TAO moorings, the key ones for the current study are atmospheric humidity and temperature (measured typically at 3 m above the surface) and wind speed (measured at 4 m). These measurements are telemetered in real-time via satellite and assimilated into atmospheric reanalyses. We do not make use of the TAO buoy data directly in the current study but do make use of positional information for the moorings (from http://www.pmel.noaa.gov/tao/).

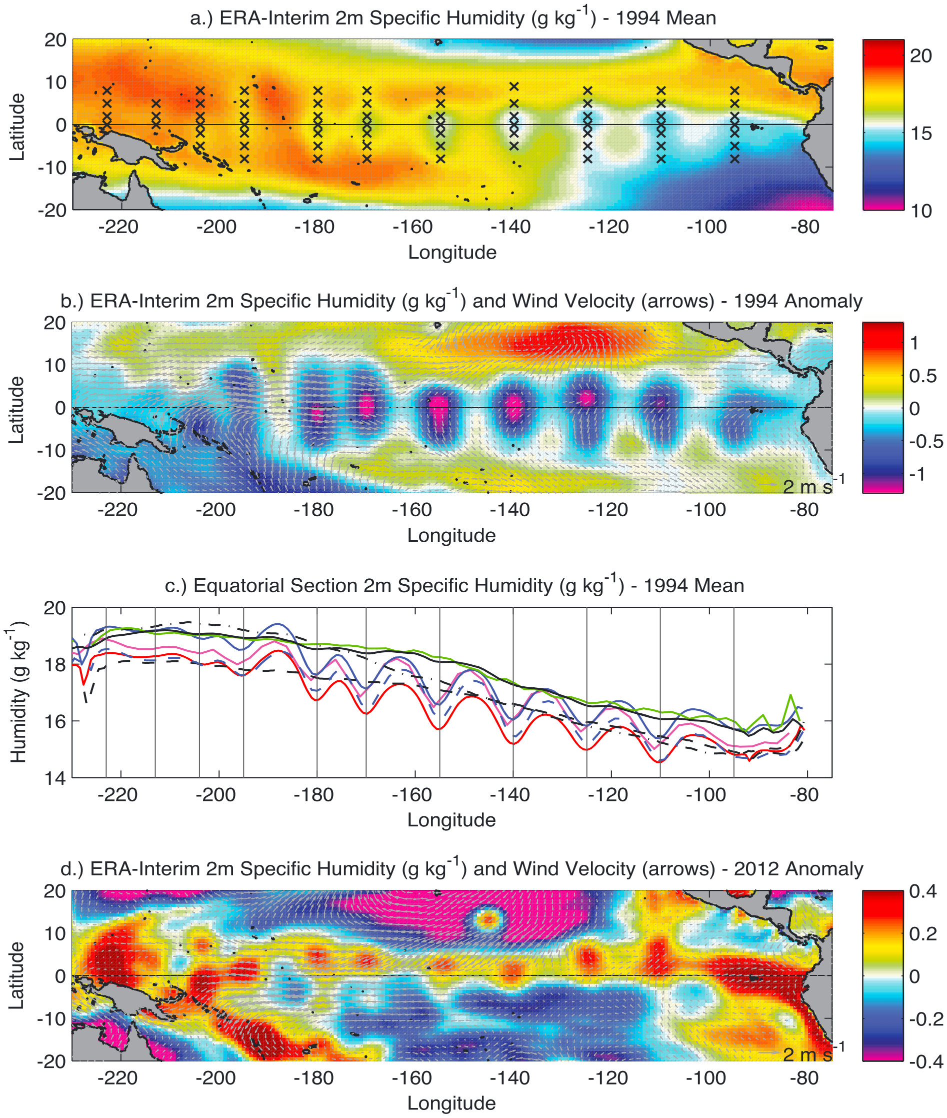
2.3. The ORCA12 Ocean Model

Output from a global ocean/sea-ice hindcast simulation spanning 1988–2011 carried out at the National Oceanography Centre (NOC) with the DFS forced 1/12° resolution ORCA12 model is also employed. In addition, a similar ORCA12 hindcast undertaken at the Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE) is referred to in the text. For general details of the ORCA12 model configuration which is based on the NEMO numerical code (Nucleus for European Modelling of the Ocean [*Madec*, 2008]) see *Deshayes et al*. [2013] or *Treguier et al*. [2014].

3. Results

3.1. Tropical Pacific Humidity and Wind Speed Anomalies

Variability in the near surface meteorological fields and associated components of the net heat exchange has been considered for each data set detailed in section 2 with a focus on the period since 1990. ERA-Interim exhibits a pattern of equatorial near surface specific humidity and wind speed features clearly colocated with the TAO moorings (see examples for 1994 and 2012 in Figure 1). In some years, these features are sufficiently strong to be visible even in the annual mean humidity field (Figure 1a) and become more apparent when the humidity is expressed as the anomaly from the long-term (1979–2012) mean (Figures 1b and 1d). The example year 1994 is characterized by relatively dry equatorial Pacific conditions, and extreme specific humidity anomalies, up to 1.2 g kg^{-1} in magnitude, are centered on the TAO buoy longitudes. These indicate that assimilation of buoy data has generated strong local perturbations in the ERA-Interim humidity fields. The buoy data are of reference site quality, so our


a.) ERA-Interim 2m Specific Humidity (g kg^{-1}) - 1994 Mean

b.) ERA-Interim 2m Specific Humidity (g kg^{-1}) and Wind Velocity (arrows) - 1994 Anomaly

c.) Equatorial Section 2m Specific Humidity (g kg^{-1}) - 1994 Mean

d.) ERA-Interim 2m Specific Humidity (g kg^{-1}) and Wind Velocity (arrows) - 2012 Anomaly

Figure 1. ERA-Interim 2 m specific humidity (colored field). (a) 1994 annual mean (mooring locations, black crosses) and (b) 1994 annual anomaly (relative to 1979–2012, wind velocity anomaly shown by arrows), (c) equatorial section of 1994 mean specific humidity for Drakkar Forcing Set (DFS) (dashed blue), ERA-Interim (red), ERA40 (magenta), Modern Era Reanalysis for Research and Applications (MERRA) (black dash-dot), National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) (green), NCEP Climate Forecast System Reanalysis (CFSR) (black dashed), Objectively Analysed Air-Sea heat flux (OAFlux) (black), and TropFlux (blue), and (d) as Figure 1b but for ERA-Interim 2012 anomaly.

interpretation is that the perturbations arise as a result of buoy data assimilation making the ECMWF products locally more realistic and that elsewhere the model dynamics produces a humidity field that has a significant bias with respect to the true field.

The buoy-centered humidity anomalies tend to be associated with divergent wind field anomalies (see arrows on Figure 1b) most noticeably in the eastern half of the basin. These features may be seen more clearly in Supplementary Fig. 1 that shows both the climatological mean and 1994 anomaly fields for a sub-region centered on the eastern basin. We find similar features in ERA40, and the ECMWF-derived products DFS and TropFlux. These are evident in an Equatorial section in Figure 1c that shows the annual mean specific humidity in 1994 for each data set, with the mooring longitudes indicated by the vertical solid lines. Local minima in the humidity variation are seen to be coincident with the buoy locations. Assimilation of buoy data was suspected to also introduce fixed spatial anomalies in the ERA40 reanalysis that ran until 2002 [*Smith et al.*, 2010], and our results clearly reveal the mooring effects on this earlier ECMWF product as well as ERA-Interim.

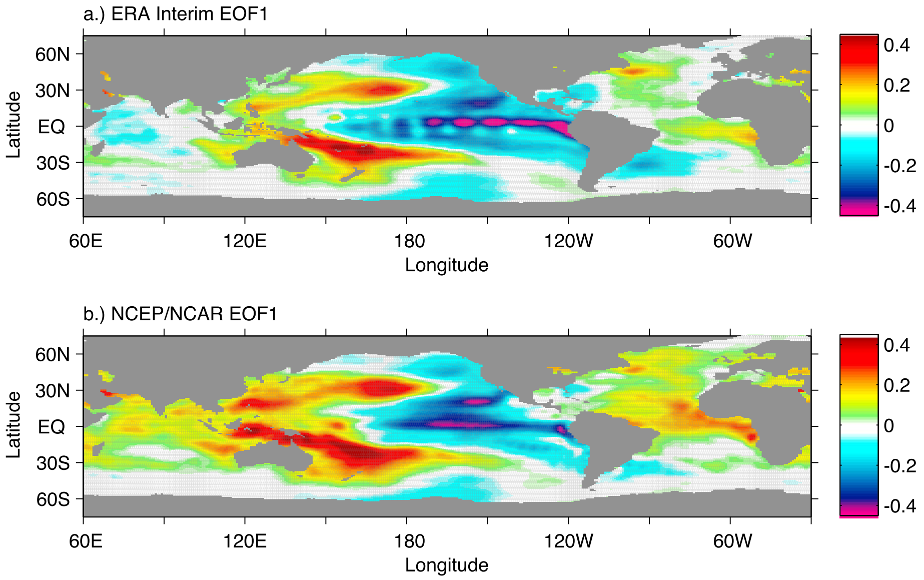


Figure 2. (a) First Empirical Orthogonal Function of 2 m specific humidity from ERA-Interim for the period 1988–2007 (accounts for 23.9% of the variance); (b) as Figure 2a but for NCEP/NCAR (28.1% of the variance).

The humidity field for 2012 provides an example of anomalies in the opposite sense to 1994, i.e., relatively moist air at the mooring sites which in this case is associated with convergent wind field anomalies (Figure 1d). The 2012 anomalies are displaced slightly north of the Equator and are smaller in magnitude than in 1994 (note the difference in color scale) but nevertheless indicate that there is an ongoing problem with the mooring data having too strong and/or too local an influence on the ERA-Interim near surface fields. Similar but weaker features are evident in air temperature; however, the sea surface temperature data set used as a reanalysis boundary condition shows no sign of the array influence (fields not shown). This indicates that SST is not playing a direct role in generating the humidity anomaly pattern evident in the reanalysis. Instead, the results for 1994 and 2012 indicate that the ERA-Interim dry humidity features are linked to divergent wind field anomalies and the moist features with convergent anomalies. In addition to the example years, we have examined the near surface humidity fields throughout the period covered by ERA-Interim. The anomaly pattern occurs with varying strength and sign since the TAO mooring array was first deployed in the early 1990s.

In contrast, fields from the other products considered (MERRA, NCEP/NCAR, NCEP CFSR, and OAFlux) do not contain the strong TAO mooring related patterns seen in the ECMWF data sets. For example, in the Equatorial section for 1994 (Figure 1c), the other products all exhibit a relatively smooth humidity variation without the buoy colocated extrema. It should be noted that the reanalyses without the buoy anomaly patterns may simply be strongly biased everywhere as a result of the analysis process not assimilating sufficient observations or not giving enough weight to the observations that are assimilated to adjust these biases. There are also potential differences arising from variations in model assimilation schemes and physics between the reanalyses. Thus, the absence of mooring features in the other reanalyses should not be taken as an indication that they are more accurate in general than ERA-Interim. Our results highlight the need for all reanalysis centers to make readily available information on exactly which data have been assimilated together with its effective weight.

The impact of the mooring data on Tropical Pacific variability in ERA-Interim has also been identified via an Empirical Orthogonal Function (EOF) analysis of specific humidity from this product (Figure 2). For comparison, results are also shown for NCEP/NCAR as it is not strongly impacted by the moorings. The leading mode of variability is expected to be the east-west variation associated with El Niño, and this is evident in the first EOF from NCEP/NCAR. However, the ERA-Interim first EOF shows strongly localized variability at the mooring sites that dominates the underlying pattern. Thus, the moorings have too strong an influence on ERA-Interim in the Tropical Pacific resulting in an unphysical pattern of variability. Note, the EOF analysis has been carried out on the full data set, thereby indicating the adverse influence of the moorings on the spatial pattern associated with the leading global mode.

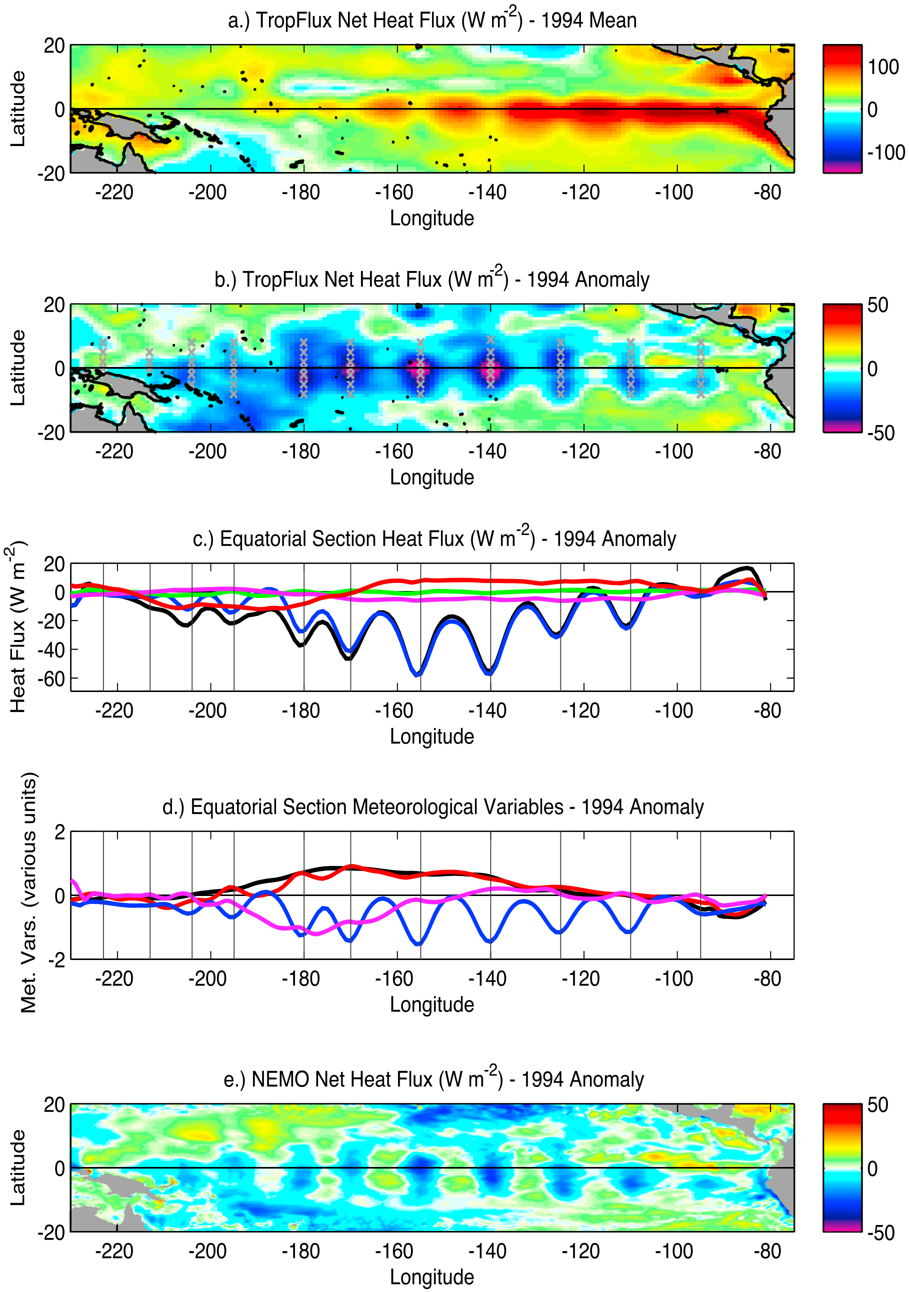


Figure 3. Net heat flux for 1994 (a) TropFlux mean and (b) TropFlux anomaly relative to 1979–2012 (mooring locations, crosses), equatorial section of TropFlux 1994 anomaly for (c) heat flux terms: net (black), latent (blue), sensible (green), shortwave (red), and longwave (magenta), and (d) meteorological variables: specific humidity (blue, g kg^{-1}), air temperature (red, °C), sea surface temperature (black, °C), and wind speed (magenta, m s^{-1}). (e) Net heat flux anomaly for 1994 from DFS forced ORCA12 ocean model.

3.2. Impacts on Air-Sea Heat Exchange

The TAO mooring related humidity anomalies have the potential to significantly impact the latent heat flux and thus also affect net air-sea heat exchange in the Tropical Pacific. We now investigate whether this is the case for TropFlux and DFS. The net heat flux sign convention adopted is for ocean heat loss to the atmosphere to be negative.

Net heat flux mean and anomaly fields for 1994 are shown in Figures 3a–3b. Also, shown are values for each heat flux component and related meteorological variables along the equator (Figures 3c–3d). A previously unrecognized pattern of net heat flux anomalies is prominently colocated with the moorings; these anomalies are particularly large reaching 50 $\mathrm{Wm^{-2}}$ in magnitude, and their influence is also evident in the mean field. The sign of the anomalies is as expected from the ERA-Interim humidity pattern discussed in section 3.1, i.e., anomalously dry conditions correspond to greater latent heat loss and the associated moisture flux will tend to reduce the humidity anomaly in the reanalysis. The latent heat component dominates the net heat exchange (Figure 3c) with the remaining terms (i.e., the sensible, longwave, and shortwave fluxes) making only a small contribution. The latent heat flux is driven by the product of the wind speed and sea-air humidity gradient [e.g., *Josey et al.*, 2013]. The section plot for each of these terms (Figure 3d) shows that the humidity rather than the wind speed is having the major impact on the latent heat flux anomalies. Note the corresponding ERA-interim fields (not shown) also have latent heat flux anomalies colocated with the mooring sites but these are smaller, about 5–10 $\mathrm{Wm^{-2}}$, than the large values found with TropFlux. This reduction in magnitude may reflect the influence of cycling [*Gulev et al.*, 2007] during the ERA-Interim data assimilation process.

Similar mooring related anomaly patterns are evident in each of the DFS forced 1/12° ORCA12 hindcasts detailed in section 2. This is illustrated in Figure 3e by the 1994 anomaly for the NOC ORCA12 run (here the anomalies are determined relative to 1988–2011; the choice of the reference period does not modify our conclusions). Net heat flux anomalies up to 30 $\mathrm{Wm^{-2}}$ in magnitude are colocated with the mooring sites; these are smaller than the TropFlux anomalies but still represent a very strong annually averaged signal (the smaller anomalies are to be expected as the model SST is free to evolve and thus can provide a negative feedback on the heat flux). Investigation of the forcing fields used in both the NOC and LGGE ORCA12 runs reveals that the anomalies are again due to the impact of the specific humidity on the latent heat flux (not shown).

4. Conclusions and Broader Implications

We have identified a pattern of unrealistic anomalies in near surface atmospheric humidity, colocated with the Tropical Pacific array, in the ERA-Interim atmospheric reanalysis and derived data sets (DFS and TropFlux). These anomalies have major consequences for air-sea heat exchange estimates. Associated annual mean heat flux anomalies centered on the mooring sites, as large as 30–50 $\mathrm{Wm^{-2}}$, are evident in the reanalysis derived data sets. The flux anomalies are problematic as these data sets are employed both to characterize ocean-atmosphere interaction (TropFlux) and to force ocean models (DFS). At present there is no standardized methodology for reanalysis evaluation, so we suggest that identification and documentation of artificial anomaly patterns should become part of the quality control diagnostics for all reanalyses.

Further work is required to establish why the mooring data have such a large impact on ERA-Interim and derived products but not on the other reanalyses we investigated (MERRA, NCEP/NCAR, and NCEP CFSR). ECMWF products have previously been recognized to have problems with the accurate representation of atmospheric humidity [*Andersson et al.*, 2005; *Uppala et al.*, 2005; *Dee et al.*, 2011], and improvements in the next generation ECMWF reanalysis are targeted at these issues (D. Dee, personal comm.).

Our major concern here is not the specific source of the anomalies in the data assimilation process but rather that widely used surface humidity and flux data sets contain unrealistically strong TAO mooring related features not recognized by the oceanographic and climate communities. A changing pattern of ocean heat uptake over the past two decades in the Tropical Pacific is thought to be a major factor in explaining the recent slowdown of global surface warming [*Balmaseda et al.*, 2013; *England et al.*, 2014; *Kosaka and Xie*, 2013]. Our results have wider implications for attempts to determine the structure of the changing heat uptake field. The difference in net heat flux between the 2000s and 1990s obtained for each of NCEP/NCAR, TropFlux, and the ORCA12 hindcast is shown in Figure 4. NCEP/NCAR exhibits a broad area of increased heat uptake (warm colours) in the eastern Equatorial Pacific with an extension in the western Pacific north of the equator. The rest of the domain considered shows primarily reduced heat uptake. In contrast, both TropFlux and the DFS forced ORCA12 run show the TAO moorings signature with localized differences in decadally averaged ocean heat uptake as large as 20 $\mathrm{Wm^{-2}}$ at the mooring sites. Progress toward obtaining a coherent picture of ocean heat uptake changes in this key ocean region is made more difficult when both observation based data sets and model hindcasts contain mooring-related artefacts of this magnitude.

Our results also raise major questions regarding the dual use of flux mooring observations as (i) data assimilation input to reanalyses and (ii) a reference for the subsequent evaluation of reanalysis product air-sea exchange data sets. An evaluation of ECMWF products against the Tropical Pacific buoys may reveal reasonable local

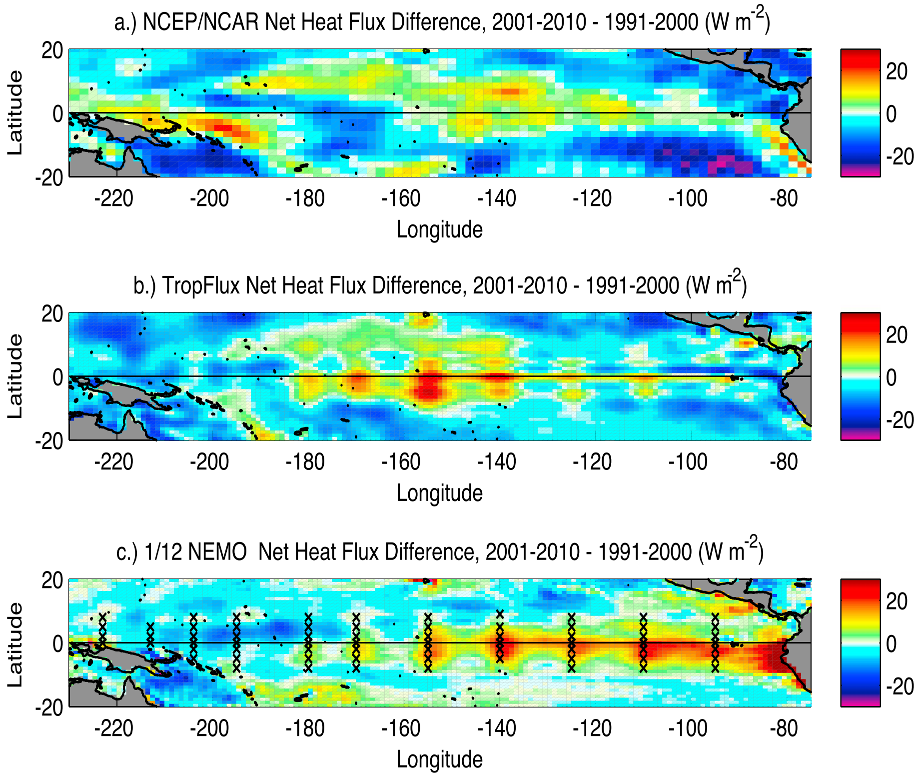


Figure 4. Difference in decadally averaged net heat flux for 2001–2010 from 1991 to 2000 from (a) NCEP/NCAR, (b) TropFlux, and (c) ORCA12 (units Wm^{-2}), mooring locations, crosses.

agreement in humidity given their potential to locally correct biases in the reanalysis humidity field. However, it would be misleading to interpret such results as being indicative of the accuracy of the reanalysis fields across the Tropical Pacific as a whole given the strong variations away from the buoy sites. Observations from the moorings provide a key data source for atmospheric reanalyses, particularly in areas that receive little coverage from ships. However, by assimilating these observations they are of less use as reference sites for subsequent reanalysis evaluations. A balance needs to be achieved between assimilating enough data to improve the reanalysis representation of atmospheric variability and withholding enough to enable valid evaluations to be carried out.

To conclude, this study has revealed a strong dependence of Tropical Pacific near surface atmospheric humidity and air-sea heat exchange on the locations of TAO array moorings in the widely used ERA-Interim reanalysis and derived (DFS, TropFlux) data sets. The presence of such bulls-eye features indicates that significant attention needs to be given to improving the reanalysis model physics and assimilation schemes, so that these features are no longer evident, while at the same time retaining the positive benefits to reanalysis field accuracy that assimilation of high quality buoy data can provide. The impact of the Tropical Pacific buoys, and the potential for additional less obvious effects at other mooring sites, must be given careful consideration in future development, evaluation, and analysis of surface flux data sets.

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