Annual, Seasonal, and Interannual Variability of Air–Sea Heat Fluxes in the Indian Ocean

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ABSTRACT

This study investigated the accuracy and physical representation of air–sea surface heat flux estimates for the Indian Ocean on annual, seasonal, and interannual time scales. Six heat flux products were analyzed, including the newly developed latent and sensible heat fluxes from the Objectively Analyzed Air–Sea Heat Fluxes (OAFlux) project and net shortwave and longwave radiation results from the International Satellite Cloud Climatology Project (ISCCP), the heat flux analysis from the Southampton Oceanography Centre (SOC), the National Centers for Environmental Prediction reanalysis 1 (NCEP1) and reanalysis-2 (NCEP2) datasets, and the European Centre for Medium-Range Weather Forecasts operational (ECMWF-OP) and 40-yr Re-Analysis (ERA-40) products.

This paper presents the analysis of the six products in depicting the mean, the seasonal cycle, and the interannual variability of the net heat flux into the ocean. Two time series of in situ flux measurements, one taken from a 1-yr Arabian Sea Experiment field program and the other from a 1-month Joint Air–Sea Monsoon Interaction Experiment (JASMINE) field program in the Bay of Bengal were used to evaluate the statistical properties of the flux products over the measurement periods. The consistency between the six products on seasonal and interannual time scales was investigated using a standard deviation analysis and a physically based correlation analysis.

The study has three findings. First of all, large differences exist in the mean value of the six heat flux products. Part of the differences may be attributable to the bias in the numerical weather prediction (NWP) models that underestimates the net heat flux into the Indian Ocean. Along the JASMINE ship tracks, the four NWP modeled mean fluxes all have a sign opposite to the observations, with NCEP1 being underestimated by 53 W m⁻² (the least biased) and ECMWF-OP by 108 W m⁻² (the most biased). At the Arabian Sea buoy site, the NWP mean fluxes also have an underestimation bias, with the smallest bias of 26 W m⁻² (ERA-40) and the largest bias of 69 W m⁻² (NCEP1). On the other hand, the OAFlux+ISCCP has the best comparison at both measurement sites. Second, the bias effect changes with the time scale. Despite the fact that the mean is biased significantly, there is no major bias in the seasonal cycle of all the products except for ECMWF-OP. The latter does not have a fixed mean due to the frequent updates of the model platform. Finally, among the four products (OAFlux+ISCCP and ERA-40, NCEP1, and NCEP2) that can be used for studying interannual variability, OAFlux+ISCCP and ERA-40 Q_{net} have good consistency as judged from both statistical and physical measures. NCEP1 shows broad agreement with the two products, with varying details. By comparison, NCEP2 is the least representative of the Q_{net} variabilities over the basin scale.

1. Introduction

The Indian Ocean is the only ocean that is bounded by land at the tropical latitudes around 26°N. On the climatological annual-mean basis, ship-based flux prod-

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ucts indicate that there is net heat going into the ocean north of 15°S (Hastenrath and Lamb 1979a,b; Esbensen and Kushnir 1981; Hsiung 1985; Oberhuber 1988; da Silva et al. 1994; Josey et al. 1999). Of the heat stored by the ocean, part is released to the atmosphere, mostly by latent evaporation and infrared radiation. The remainder is transported southward out of the region by the Ekman currents during June–September (Levitus 1988). The heat transport modulates the Indian Ocean sea surface temperature (SST) and heat content (Godfrey et al. 1995; Garternicht and Schott 1997), and also

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may affect the interannual variability of the Asian monsoon (Loschnigg and Webster 2000). For these reasons, a good knowledge of the change in the oceanic heat budget and transport is of great importance for understanding the Indian Ocean climate and for predicting its short- and long-term changes. Surface heat fluxes are the key component in determining the oceanic heat budget and transport. Several flux products are currently available, but all have uncertainties. The objective of the study is to evaluate the quality of existing flux products for the Indian Ocean and to identify the degree of consistency between the products.

The total net surface heat flux (Q_{net}) going into the ocean is the sum of a number of heat exchange processes at the air-sea interface. The processes include solar radiation, outgoing longwave radiation, sensible heat transfer by conduction and convection, and latent heat release by evaporation of sea surface water. In general, these heat flux components are estimated by using bulk flux algorithms with surface meteorological variables obtained from one of the following sources: numerical weather prediction (NWP) reanalysis outputs (Kalnay et al. 1996; Uppala et al. 1999; Kanamitsu et al. 2000), ship reports from the Comprehensive Ocean-Atmosphere Data Set (COADS) (Oberhuber 1988; da Silva et al. 1994; Jones et al. 1995; Josey et al. 1999), satellite retrievals (Schulz et al. 1997; Chou et al. 2003; Kubota et al. 2002; Zhang et al. 2004), and/or synthesis of the above three data sources (Yu et al. 2004a). Different data sources have different biases, which together with the use of different bulk flux algorithms can result in significant differences between the surface heat flux products (Bony et al. 1997; Sun et al. 2003; Brunke et al. 2003; Toole et al. 2004; Curry et al. 2004). For instance, the buoy measurements of Weller et al. (1998) taken during the Arabian Sea Experiment in 1994–95 showed a net heat gain of 60.3 W m⁻², while the Q_{net} produced from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis had a net heat loss of -4.5 W m^{-2} : the mean differences between the two are nearly 65 W m⁻². Scott and Alexander (1999) demonstrated that the NCEP-NCAR reanalysis underestimates the intermonthly variability of $Q_{\rm SW}$ in the tropical Pacific and Indian Ocean by a factor of 2. Toole et al. (2004) analyzed the time-dependent heat budgets of the tropical warm water pool and found that the flux climatology from the Southampton Oceanography Centre (SOC; Josey et al. 1999) has good consistency with ocean temperature observations, while the $Q_{\rm net}$ from the European Centre for Medium-Range Weather Forecasts (ECMWF; Gibson et al. 1997) and NCEP models are both underestimated. They also

found that the University of Wisconsin—Madison (UWM)/COADS climatology (da Silva et al. 1994) is physically less representative if the fluxes are constrained in a way that the time mean globally integrated air-sea heat flux is zero.

The accuracy of the heat flux estimates impacts the extent and scope of the use of the flux products in climate research studies and operational applications. In light of the divergence in existing heat flux estimates for the Indian Ocean, there is a need to perform a general evaluation to assess the degree of divergenceconsistency. Six heat flux products are examined in the study, including the newly developed Objectively Analyzed Air-Sea Heat Fluxes (OAFlux) product (Yu and Weller 2007), the net shortwave and longwave radiation results from the International Satellite Cloud Climatology Project (ISCCP; Zhang et al. 2004), the NWP model reanalysis and operational products from NCEP-NCAR and ECMWF, and the COADS-based SOC flux analysis. The emphasis is focused mostly on $Q_{\rm net}$, as it represents the collective effects of the four heat flux components. We anticipate that the information coming out of this study will be useful to the flux community for improving flux bulk algorithms and flux estimates, to the modeling community for selecting suitable products for their modeling needs, and to the observational community for planning and deploying in situ flux instruments in regions where the flux products differ considerably. In particular, the information will directly help our ongoing OAFlux project, which has the objective of developing an enhanced global analysis of air-sea latent, sensible, and net shortwave and net longwave radiation fluxes for the past 50 yr (from the mid-1950s onward) through optimally synthesizing satellite observations, NWP model outputs, and in situ measurements (Yu and Weller 2007). The OAFlux project was developed from an initial study of the Atlantic Ocean that demonstrated that such data synthesis improved daily flux estimates over the basin scale (Yu et al. 2004a.b), and its extension to the global ice-free oceans is supported by the National Oceanic and Atmospheric Administration (NOAA) Office of Climate Observations (OCO) and Climate Change Data and Detection (CCDD) programs.

This paper includes a brief description of the six flux datasets used in the study (section 2). Several analyses are conducted, which include the evaluation of differences and similarities in the six mean products (section 3), the validation with in situ flux measurements (section 4), the analysis of the heat flux variability on seasonal and interannual time scales (section 5), and the analysis of the physical representation of heat flux through studying its role in the seasonal-to-interannual

variability of sea surface temperature (SST) (section 6). Summary and discussions are provided in section 7.

2. Datasets

A brief description of the six datasets used in the study is given below.

a. NWP model heat flux products

Four NWP model products are analyzed: two of which are from NCEP and the other two are from ECMWF. The two NCEP products are the NCEP-NCAR reanalysis (hereafter referred to NCEP1; Kalnay et al. 1996) and the NCEP-Department of Energy (DOE) reanalysis (hereafter referred to NCEP2; Kanamitsu et al. 2000), respectively. Both products are generated from a frozen forecast-analysis platform that consists of a T62 model (equivalent to a horizontal resolution of about 210 km) with 28 vertical levels and 6-h intervals. NCEP1 produces an ongoing dataset from 1948 to the present, while NCEP2 corrects known errors in NCEP1 and generates data from 1979 onward. NCEP2 differs from NCEP1 mostly in the parameterization of shortwave radiation, cloud, and soil moisture (Kanamitsu et al. 2000). It is regarded only as an update of NCEP1, not a next-generation reanalysis.

As for the two ECMWF flux products, one is from the ECMWF operational forecast-analysis model (ECMWF 1994) and the other is from the ECMWF Reanalysis-40 (ERA40; Uppala et al. 1999). Unlike in ERA-40, which uses a frozen analysis-forecast system, the ECMWF operational (hereafter referred to ECMWF-OP) system upgrades the model platform to ensure the best analysis-forecast fields and the up-todate parameterizations of air-sea fluxes (Beljaars 1997; Klinker 1997). The change of model platforms brought abrupt changes to the surface heat flux fields (e.g., Yu et al. 2004a), whose effect on the net heat flux in the Indian Ocean is discussed in section 5. ERA-40 covers the period from September 1957 to August 2002 and the ECMWF-OP products are available from 1985 onward. The grid resolution is the same for both models, which is approximately 1.125° in both latitude and longitude.

b. OAFlux+ISCCP

The OAFlux products (Yu et al. 2004a,b) were computed from the bulk flux algorithms but with surface meteorological variables determined from an advanced objective analysis. Satellite observations from the Special Sensor Microwave Imager (SSM/I; Wentz 1997) and the Advanced Very High Resolution Radiometer (AVHRR), along with outputs from NCEP2 and ECMWF-OP, were objectively synthesized to produce an optimal estimate for the surface meteorological variables. Currently, the OAFlux project has produced daily estimates of surface latent and sensible heat fluxes over the global ice-free ocean. To compute the net heat fluxes, surface downward-upward shortwave and longwave radiations are taken from the ISCCP-FD surface radiation fields that were calculated from a radiative transfer model from the Goddard Institute for Space Studies (GISS) GCM using ISCCP observations (Zhang et al. 2004). The ISCCP-FD data are 3 hourly, available for the whole globe with $2.5^{\circ} \times 2.5^{\circ}$ grid resolution and for the time period July 1983–June 2001. The data were daily averaged and linearly interpolated onto a 1° grid to combine with the OAFlux latent plus the sensible heat flux components. The resulting OAFLux+ISCCP net heat flux product covers the period 1988-2000, the time frame that the two datasets overlap.

c. The SOC climatology

The SOC flux climatology¹ (Josey et al. 1999) was also produced from the bulk flux algorithms, but the surface meteorological variables (e.g., wind speed, air humidity, air temperature, sea surface temperature, cloudiness) were taken from ship reports from COADS. The SOC product was the first and so far the only COADS-based product where bias correction was applied at the level of individual ship reports to each variable field to remove sample biases induced by instruments. A successive correction method, which is a form of objective analysis, was used to average, smooth, and fill in data-void regions. The resulting monthly field is gridded at 1° resolution.

The SOC heat flux monthly analysis was constructed for the period 1980–97. An attempt was made to conduct the comparison using the same time frame that all modeled and analyzed flux products were available. However, ship tracks are extremely sparse in the Indian Ocean. If averaged over fewer years, the field structures of the SOC analysis could be affected by the sampling density. To avoid this problem, the SOC analysis of 1980–97 is used and the other five products are compared over the 1988–2000 period.

3. Annual mean

a. Mean pattern

Figure 1 shows the six mean Q_{net} patterns in the Indian Ocean north of 30°S obtained from OAFlux+ISCCP,

¹ Note that the SOC climatology has recently been renamed the NOC1.1 climatology; see the Web site http://www.noc.soton. ac.uk/JRD/MET/fluxclimatology.php for details.



FIG. 1. Mean Q_{net} for the Indian Ocean derived from (a) OAFlux+ISCCP, (b) SOC, (c) NCEP1, (d) NCEP2, (e) ERA-40, and (f) ECMWF-OP. Contour interval is 20 W m⁻². Zero contours are highlighted. Positive (negative) values denote the ocean gains in (losses of) heat. Except for the SOC field that is averaged over the 1980–97 period, all of the fields are averaged over the 1988–2000 period.

the SOC climatology, NCEP1, NCEP2, ERA-40, and ECMWF-OP. The first two products are denoted as analyzed products, simply to indicate that they are not the outputs from the NWP models. However, it is worth noting that the methodology and data sources used in constructing the OAFlux and ISCCP models are completely different from those used by SOC.

The most striking and compelling feature in Fig. 1 is the large difference between the six Q_{net} mean patterns. Three features are most noteworthy. First, the analyzed $Q_{\rm net}$ differs considerably from the modeled $Q_{\rm net}$. On the annual-mean basis, the SOC and OAFlux+ISCCP show that the Indian Ocean north of 15°S is a heat gain region, while the four NWP models show that this northern Indian Ocean is a heat loss region. Second, the same NWP model may not have the same Q_{net} if the model forecast-analysis platform is different. It can be seen that NCEP1 Q_{net} differs from NCEP2 in both pattern and magnitude, and that the ERA-40 $Q_{\rm net}$ varies from ECMWF-OP most clearly in the southern basin. In general, NCEP2 produces the strongest oceanic heat loss among all the products. Finally, OAFlux+ISCCP and SOC, though similar in projecting the Indian Ocean as a heat gain region, differ from each other in the detailed structure.

The existence of large differences in the six Q_{net} products suggests that there are differences in the estimates of each of the four flux components: latent heat flux (Q_{LH}) , sensible heat flux (Q_{SH}) , and net longwave (Q_{LW}) and shortwave (Q_{SW}) radiation. To identify this, latent plus sensible heat fluxes $(Q_{LH}+Q_{SH})$ and net longwave plus shortwave radiations $(Q_{SW}+Q_{LW})$ are plotted in Figs. 2–3, respectively. Figure 2 shows that all six products agree that the Indian Ocean loses latent and sensible heat to the atmosphere on the annualmean basis and the maximum loss is located in the southern Indian Ocean at about 20°S. However, the six $Q_{\rm LH} + Q_{\rm SH}$ products differ considerably in magnitude, with NCEP2 being the strongest and SOC being the weakest. The difference between NCEP2 and SOC can be as large as 60 W m^{-2} in the heat loss extreme center around 20° S in the southern basin, and about 40 W m^{-2} in the Bay of Bengal and the Arabian Sea.

The differences in the six $Q_{SW}+Q_{LW}$ products (Fig. 3) are not only in magnitude but also in pattern. The $Q_{SW}+Q_{LW}$ results from the ISCCP and SOC have similar magnitudes but disagree on where the maximum net radiation is located. ISCCP radiation derived from the satellite cloud observations shows that the maximum heating is confined in the western equatorial region,



while the SOC radiation based on the cloud estimation from ships shows that the maximum heating occurs over a much larger area, extending from the western equatorial region to the western Arabian Sea. The two ECMWF products, ECMWF-OP and ERA-40, are similar to that of SOC as to where the largest net radiation is located, though the magnitude is weaker. By comparison, NCEP1 and NCEP2 are quite different, as their centers of maxima are placed in the western Arabian Sea. On average, the $Q_{\rm SW}+Q_{\rm LW}$ results from the ISCCP and SOC are about 40 W m⁻² stronger than those from the NWP models, particularly in the western Indian Ocean. The large incoming net radiation flux is the major cause of the positive annual-mean $Q_{\rm net}$ in both OAFlux+ISCCP and SOC.

b. Zonally averaged mean fluxes

Figures 4a–c plot the latitudinal variation of the zonally averaged mean $Q_{\rm LH}+Q_{\rm SH}$, $Q_{\rm SW}+Q_{\rm LW}$, and $Q_{\rm net}$ for all six of the products. It is obvious that each estimate is unique and that there are no two alike. The largest differences between products are located in the northern Indian Ocean at latitudes north of 15°S. South of that latitude, all the products are similar in structure, despite the differences in magnitude. The differences in the latitudes north of 15°S can be generalized as follows. First, $Q_{\rm LH}+Q_{\rm SH}$ has two general patterns: one is formed by the NWP modeled fluxes and the other by the analyzed fluxes. For instance, the four NWP $Q_{\rm LH} + Q_{\rm SH}$ values are similar in that they all show large latitudinal variations that feature two maxima, one on the equator and the other at 20°N, and one minimum at 10°N. The change between the two extremes is about 25 W m⁻². The pattern is, however, very different from those for the SOC and OAFlux, as the latter two show that the latitudinal variations north of the equator are small. Second, the pattern of $Q_{SW}+Q_{LW}$ is more diverse. The two ECMWF $Q_{SW}+Q_{LW}$ results are similar but ERA-40 is consistently weaker by $5-10 \text{ W m}^{-2}$ than ECMWF-OP. NCEP1 and NCEP2 bear no similarity, although the range of the variations falls between the two ECMWF estimates. The ISCCP and SOC results are far different from the NWP products. The ISCCP net radiation increases monotonically toward the equator, while SOC has a maximum at about 12°N and its net radiation is at least 25 W m⁻² higher than the NWP estimates in the northern Indian Ocean. Third, the SOC has the largest Q_{net} at all the latitudes, while the NCEP2 (NCEP1) has the smallest Q_{net} south (north) of the equator. Finally, the differences between the SOC and NCEP Q_{net} estimates are large, exceeding 40 W m⁻² at most latitudes. Overall, the OAFlux+ISCCP $Q_{\rm net}$ is closest to SOC, particularly in the southern Indian Ocean.



4. Validation with in situ flux measurements

Flux measurements acquired from flux buoys or research cruise vessels provide important benchmark time series for quantifying regional biases in the gridded heat flux products (Weller and Anderson 1996; Weller et al. 1998; Josey 2001; Wang and McPhaden 2001; Sun et al. 2003). The Indian Ocean is a poorly sampled region. Different data management policies imposed by different countries further complicate the availability of the already limited data sources. For this study, we obtained only two sets of high quality in situ flux measurements (Fig. 5). The first time series was taken from the Arabian Sea Experiment, which took place from October 1994 to October 1995 (Weller et al. 1998). The buoy was located off the coast of Oman at $(15.5^{\circ}N, 61.5^{\circ}E)$, a site where some of the strongest winds associated with the southwest monsoon pass through. The experiment was designed to collect measurements of near-surface meteorology and air-sea fluxes that could be used to ascertain the atmospheric forcing under the influence of strong monsoon winds. The second time series was taken from the Joint Air-Sea Monsoon Interaction Experiment (JASMINE; Webster et al. 2002) pilot study that was designed to document and characterize the changes in the oceanatmosphere system associated with the intraseasonal variability of the monsoon. The field phase of JASMINE was held in the eastern Indian Ocean and the southern Bay of Bengal aboard NOAA's Research Vessel *Ronald H. Brown*. Measurements obtained from the JASMINE field phase II during 5–31 May 1999 are used in this study.

a. Comparisons with the Arabian Sea surface buoy

1) Buoy Q_{NET}

The buoy meteorological sensors of the Arabian Sea Experiment measured the near-surface wind direction and speed (U), barometric pressure (p), air temperature (T_a), sea surface temperature (T_s), relative humidity (RH), precipitation, and incoming shortwave (SW \downarrow) and longwave (LW \downarrow) radiations. The reader may refer to Weller et al. (1998) for a detailed description of the technical specifics (including sampling characteristics and accuracy) of the surface buoy and its sensors. These observations allow Q_{LH} , Q_{SH} , Q_{SW} , and Q_{LW} to be determined from the bulk formulas (Liu et al. 1979):

$$Q_{\rm LH} = \rho L_e c_e U(q_s - q_a), \quad \text{and} \tag{1}$$

$$Q_{\rm SH} = \rho c_p c_h U (T_s - T_a), \tag{2}$$

where ρ is the density of the air; L_e is the latent heat of evaporation; c_p is the specific heat capacity of the air at



long-term mean of the six heat flux products.

a constant pressure; and c_e and c_h are the stability and depth-dependent turbulent exchange coefficients for latent and sensible heat, respectively; In addition, q_s is the sea surface specific humidity obtained from the re-

lation $q_s = 0.98q_{sat}(T_s)$, where a multiplier factor of 0.98 is used to take into account the reduction in vapor pressure caused by a typical salinity of 34 psu, and q_a is the near-surface air specific humidity and is a function of



FIG. 5. The buoy location of the Arabian Sea Experiment and the ship route of the JASMINE phase II field program.

 (T_a, RH, p) . Both Q_{LH} and Q_{SH} were calculated from the bulk algorithm developed during the Coupled Ocean–Atmosphere Response Experiment (COARE) (Fairall et al. 1996; 2003; Bradley et al. 2000).

Incoming shortwave (SW \downarrow) and longwave (LW \downarrow) radiation data were measured by radiometers aboard the buoys; their outgoing components were not measured and needed to be calculated in order to determine the net shortwave and longwave radiations. By using a variable albedo (α) based on the solar elevation angle and an atmospheric transmittance of 0.720 (Payne 1972), Q_{SW} is determined from

$$Q_{\rm SW} = SW \downarrow - \alpha SW \downarrow. \tag{3}$$

Outgoing longwave radiation consists of both the longwave radiation emitted from the surface and the reflected portion of the incoming radiation. By taking these into account, Q_{LW} is computed from

$$Q_{\rm LW} = {\rm LW} \downarrow - [\varepsilon \sigma T_s^4 + (1 - \varepsilon) {\rm LW} \downarrow], \qquad (4)$$

where σ is the Stefan–Boltzmann constant and ε is an infrared emissivity of 0.97. The buoy Q_{net} is calculated as the sum of Q_{LH} , Q_{SH} , Q_{SW} , and Q_{LW} obtained from Eqs. (1)–(4).

2) Comparisons

Figure 6 plots the time series of buoy Q_{net} averaged on a daily basis along with the daily time series of Q_{net} from OAFlux+ISCCP and NWP products. The SOC analysis is not included due to the lack of daily values. The reader may refer to the study by Weller et al. (1998) for the detailed discussions of the high quality SOC mean values. To better characterize the persistent biases in the flux products, a 15-day running mean was applied to all daily time series to smooth out the highfrequency variability. Analysis of air-sea flux variability at high frequencies based on 6- and 12-hourly time series of NCEP1 and ECMWF-OP products can be found in Weller et al. (1998).

Figure 6 shows that Q_{net} from the OAFlux+ISCCP analysis has reasonably good agreement with the buoy Q_{net} in most months except the last two months, from August to September 1995, during which time the OAFlux+ISCCP Q_{net} is underestimated. By comparison, the four NWP Q_{net} values (Fig. 6b) are persistently weaker than the buoy fluxes throughout almost the entire measurement period. ERA-40 is biased least, and NCEP1 is biased most.

Table 1 lists the statistics [the mean, the mean difference, the standard deviation (STD) of the daily difference, and the correlation coefficient] based on the comparisons of the four NWP products and the OAFlux+ISCCP analysis with buoy Q_{net} . All the statistics were computed from daily mean values. Over the 1-yr measurement period, the buoy Q_{net} has a mean of 64.8 W m^{-2} . Except for NCEP1, the other three modeled Q_{net} values and the OAFlux+ISCCP Q_{net} values are all positive but the means are lower than the buoy mean. That the NCEP1 mean Q_{net} has a sign opposite to that of the buoy mean has been reported by Weller et al. (1998), who attributed the bias to the combined effect of an underestimated net solar radiation and an overestimated latent heat loss. Among the four NWP model fluxes, NCEP1 Q_{net} has the largest mean deviation (-69.7 W m^{-2}) and the largest daily STD (89.3 W m^{-2}), while ERA-40 has the smallest mean deviation (-26.7 W m^{-2}) and the smallest daily STD (55.4 W m⁻²). Apparently, ERA-40 Q_{net} is the least biased NWP flux product. The NCEP2 Q_{net} has improved statistics over those of the NCEP1 Q_{net} in terms of the mean and rms differences, but the correlation coefficient (0.79) is less good than that of NCEP1 (0.82). The correlation coefficient quantifies the degree of the linear association between the daily time series of two variables. The smaller correlation coefficient suggests that NCEP2 may not have the same representation of variability as NCEP1. This issue will be further discussed in sections 5 and 6, where we examine the seasonal and interannual variabilities of Q_{net} .

Compared to the NWP fluxes, OAFlux+ISCCP has the best performance, with a mean closest to the buoy mean, the smallest STD, and the highest correlation coefficient. Nevertheless, the mean difference between OAFlux+ISCCP and buoy Q_{net} accounts for about 25% of the buoy mean, which is caused mostly by the underestimation bias during August–September. The buoy site is under the direct monsoonal influence. The southwest monsoon starts between late May to



FIG. 6. Comparisons with the buoy Q_{net} daily time series at the Arabian Sea Experiment site: (a) buoy vs OAFlux+ISCCP and (b) buoy vs the four NWP model products. A 30-day running mean is applied to all the daily time series.

late September, featuring strong winds, cloudy skies, and moist air. The ocean gains heat during this period as a result of reduced latent and longwave heat loss (Weller et al. 1998). The buoy observations show that the largest oceanic heat gain occurred in August, with a monthly mean of 147 W m⁻². Interestingly, OAFlux+ISCCP simulated well a decrease in Q_{net} in the first 2 months of the southwest monsoon (June– July), but did not capture the intensity of the increase in Q_{net} in the following 2 months. Further examination of the cause of the large discrepancy in Q_{net} in August– September reveals that the problem resides in the overestimation of latent heat loss by OAFlux.

TABLE 1. Statistics from the $Q_{\rm net}$ comparison between daily averaged buoy measurements and daily heat flux products at the site of the Arabian Sea Experiment. The data record is 365 days. The threshold correlation coefficient at the 95% significance level is 0.25.

	Buoy	ERA-40	ECMWF- OP	NCEP1	NCEP2	OAFlux+ ISCCP
Mean	64.8	38.1	12.7	-4.9	20.6	48.3
Diff	_	-26.7	-52.1	-69.7	-44.2	-16.5
Rms	_	55.4	75.3	89.3	73.3	38.8
Corr	—	0.84	0.80	0.82	0.79	0.91



FIG. 7. Same as in Fig. 6 but for the air specific humidity at 2 m.

OAFlux synthesizes satellite and NWP surface meteorological variables and determines the optimal estimates for the computation of the latent and sensible heat fluxes (Yu et al. 2004a). Unfortunately, all NWP models have a dry bias in air humidity q_a (Fig. 7) for the second part of the monsoon period from August to September. During this period, the water vapor content in the models continued to decrease, even though the buoy observed a near-constant water vapor content. The dry q_a bias in the OAFlux analysis is inherited from the NWP products during the synthesis. At present, there are neither direct satellite observations nor sufficient ship reports to correct the q_a bias in OAFlux. This q_a bias, when combined with the strong wind speed $(>10 \text{ m s}^{-1} \text{ on average})$ of the southwesterly monsoon winds, amplifies the latent heat loss in the region.

b. Comparisons with the JASMINE phase II field measurements

Figure 8 shows Q_{net} daily mean comparisons between the heat flux products and the JASMINE ship measurements. Again, SOC does not have daily values and so is not included. No running mean is applied as the data record for the phase II field program lasted only 28 days, from 4 to 31 May 1999. The field program included two 5-day periods, named Star 1 and Star 2. During these two periods, the ship remained on station



FIG. 8. Comparisons with the Q_{net} daily time series along the ship tracks of the JASMINE phase II field program: (a) buoy vs OAFlux+ISCCP and (b) buoy vs the four NWP model products. No running mean is applied.

executing maneuvers around star patterns (Webster et al. 2002). To compare the ship measurements, neighboring points along the ship track and star patterns were used to extract $Q_{\rm net}$ from the gridded products.

The OAFlux+ISCCP Q_{net} has remarkably good agreement with the JASMINE-measured Q_{net} in both the mean and day-to-day variability. The two star periods, one for 10–15 May (Star 1) and the other for 21–26 May (Star 2), recorded two very different Q_{net} distributions. There was a change from a net heating during Star 1 to a net cooling during Star 2. Webster et al. (2002) showed that this reversal was caused by the passage of nocturnal gust fronts that led to a severe reduction in the net surface radiation and a significant increase in the turbulent latent and sensible heat fluxes. The reversal in Q_{net} for the two star periods is well captured by OAFlux+ISCCP. By comparison, the four NWP heat flux products simulated the sharp reduction in Q_{net} to some degree, but failed to produce the intensity of the net heating during the undisturbed period including star 1.

The mean, mean bias, STD, and the correlation coefficient of each product with respect to the ship time series are listed in Table 2. Over the field phase II program, the measured Q_{net} has an overall net gain of 47.5 W m⁻². OAFlux+ISCCP has the best comparison with ship measurements, with the mean deviating by only 0.5 W m⁻². The NWP mean Q_{net} results all show a

TABLE 2. Statistics from the Q_{net} comparison between daily averaged JASMINE field measurements and daily heat flux products along the JASMINE ship tracks. The data record is 28 days. The threshold correlation coefficient at the 95% significance level is 0.37.

		OAFlux+				
	Ship	ERA-40	OP	NCEP1	NCEP2	ISCCP
Mean	47.5	-21.6	-61.0	-5.4	-9.6	48.0
Diff	_	-69.1	-108.5	-52.9	-57.1	0.5
Rms	_	91.3	130.9	80.0	74.2	38.7
Corr	—	0.70	0.76	0.71	0.86	0.89

net heat loss, ranging from -5.4 (NCEP1) to -61.0 W m⁻² (ECMWF-OP). ECMWF-OP is the most biased, followed by ERA-40.

5. Q_{net} variability on seasonal-to-interannual time scales

The validation analysis in the above section shows that the OAFlux+ISCCP Q_{net} has the best comparison with the measured Q_{net} , and that all four of the NWP modeled Q_{net} products have an underestimation bias. Despite the existence of the bias, the correlation coefficients between the time series of the five products and the in situ time series are all higher than 0.70 (Tables 1 and 2), which is significant at the 95% confidence level. The threshold correlation coefficient on the 95% significance level is 0.25 for Table 1 and 0.37 for Table 2. The high significance of the correlations suggests that there exists a degree of consistency in the Q_{net} variability between the products. We now focus on the analysis of the Q_{net} variability on the seasonal to interannual time scales by first computing the STD.

a. STD of seasonal variability

The seasonal STD of Q_{net} based on the 12 climatological monthly means is computed for all six products. Interestingly, the differences in the STD patterns (Fig. 9) are much smaller than the differences in the mean patterns (Fig. 1). ECMWF-OP is the only one that shows that the equatorial variations are 40–80 W m⁻², while the other five products all have the equatorial STD at less than 40 W m⁻². The variances increase away from the equator and exceed 80 W m⁻² in the southern basin south of 15°S and in the Arabian Sea, due primarily to the seasonal variations of the latent heat fluxes and shortwave radiations. The six STD patterns differ most in the Bay of Bengal. SOC shows a weak STD of ~20 W m⁻², while NCEP1 and NCEP2 have a much larger STD (>80 W m⁻²).

b. Effect of changing model platforms on ECMWF-OP Q_{net}

The cause of the comparably large seasonal variances in ECMWF-OP (Fig. 9) is the imposed changes in the mean state. ECMWF-OP underwent a few updates of the model platform over the synthesis period from 1988 to 2000. For instance, the moisture transfer coefficients at low wind speed were changed in 1990 and those at high wind speed were changed in 1993. These two changes resulted in a sharp reduction in Q_{net} by more than 80 W m^{-2} when averaged over the tropical Indian Ocean (Fig. 10). In late 1994 and early 1995, a modification in the data handling process produced an additional reduction of 10 W m⁻² at all latitudes. The surface heat fluxes in the Tropics were further affected by the implementation of the temperature and humidity profiles obtained from the inversion of the brightness temperature made during this time (ECMWF 1994). In late 1997, a four-dimensional variational data assimilation scheme became operational. Consequently, several improvements were made to the use of both conventional and satellite data. The assimilation of the totalcolumn water vapor from SSM/I and scatterometer winds affected the forecast of the near-surface humidity and winds and air-sea fluxes (Vesperini 1998).

The year-to-year variation of ECMWF-OP Q_{net} averaged over the Indian Ocean domain is plotted in Fig. 10 along with those constructed from other products. It is apparent that the changes made in the model platform have all introduced discontinuity into the Q_{net} time series. The impact of the model change in 1990 is particularly profound, leading to a reduction in Q_{net} of more than 80 W m⁻². For these reasons, the ECMWF-OP product is not suitable for use in the analysis of interannual variability of Q_{net} .

c. STD of interannual variability

The STD of the Q_{net} monthly anomalies for the period 1988–2000 is computed for the four products: OAFlux+ISCCP, NCEP1, NCEP2, and ERA-40 (Fig. 11). The mean seasonal cycle constructed from the 13yr base period is removed. The computation is used to examine the magnitude and pattern of the interannual variability of Q_{net} . Intercomparison of the four products yields four noteworthy features. First, the variances of the OAFlux+ISCCP Q_{net} are weakest, while those of NCEP2 are strongest. The difference between the two products is most evident in the southern basin, where the two differ by 20 W m⁻², as noted. Second, despite the differences in magnitude, all products indicate that the interannual variations of Q_{net} are larger in the southern basin than in the northern basin. The me-



FIG. 9. Seasonal standard deviations of Q_{net} constructed from the 12 climatological Q_{net} monthly means from (a) OAFlux+ISCCP, (b) SOC, (c) NCEP1, (d) NCEP2, (e) ERA-40, and (f) ECMWF-OP. Contour interval is 10 W m⁻².

ridional displacement of the southeast trade wind in response to the forcing of the El Niño–Southern Oscillation (ENSO) in the equatorial Pacific leads to large changes in the interannual latent heat fluxes (Yu and Rienecker 2000), which is the primary cause of the large interannual variances in the southern basin. Third, OAFlux+ISCCP and ERA-40 are similar in depicting the locations of the largest $Q_{\rm net}$ variances. These loca-



FIG. 10. Year-to-year variations of $Q_{\rm net}$ averaged over the Indian Ocean domain of interest.

(b)

OAFlux + ISCCP

(a)



FIG. 11. Same as in Fig. 9 but for the std dev of the 156 anomalous $Q_{\rm net}$ monthly means for the period of 1988-2000. The seasonal cycle constructed from the 13-yr base period is removed. Contour interval is 5 W m⁻². The SOC and ECMWF-OP products are not included.

tions include the eastern equatorial region off of Java and Sumatra, the western equatorial region off of Somalia, and the central eastern region in the southern basin. Finally, the patterns of Q_{net} variability from NCEP1 and NCEP2 differ not only from each other but also from OAFlux+ISCCP and ERA-40. The major difference between the two NCEP products and the OAFlux+ISCCP and ERA-40 products is in the coastal region off of Java and Sumatra, where the two NCEP fluxes show a minimal variance that is opposite to the latter two. The major difference between NCEP1 and NCEP2 is in the southern basin, where NCEP2 has larger variances that also cover a wider area. Further analysis indicates (not shown) that the magnitude and structure of the NCEP2 southern basin variability is controlled primarily by the Q_{LH} component. At latitudes between 15° and 20° S, the magnitude of the NCEP2 Q_{LH} is more than 20 W m⁻² larger than that of NCEP1 while the NCEP2 radiation is only about 5 W m⁻² higher than that of NCEP1 (Figs. 4a-b), and this makes $Q_{\rm LH}$ the dominant term in NCEP2 $Q_{\rm net}$.

Overall, the NCEP2 STD field is the most different among the four products, not only because its magnitude is at least 10 W m⁻² greater but also because its location of the largest variances in the southern basin is so dissimilar to the other three. Recall that the comparison with the 1-yr buoy time series at the Arabian Sea Experiment location shows that NCEP2 has a better mean and smaller rms than NCEP1 (Table 1) but also a lesser correlation with the buoy daily measurements. It was suggested that NCEP2 may not have the same representation of variability as NCEP1. The STD pattern shown here substantiates the viewpoint that NCEP2 is not as good at representing the variability in Q_{net} .

6. Role of Q_{net} in the seasonal and interannual variabilities of SST

The physical representation of Q_{net} from the six products is tested using a physical relation. If the effects of oceanic processes are not considered, Q_{net} is related to the change of the surface mixed layer temperature through

$$\frac{d\text{SST}}{dt} = \frac{Q_{\text{net}}}{\rho_o c_p h},\tag{5}$$



FIG. 12. Correlation between the seasonal Q_{net} and dSST computed from (a) OAFlux+ISCCP, (b) SOC, (c) NCEP1, (d) NCEP2, (e) ERA-40, and (f) ECMWF-OP. Annual mean is removed from all datasets. Contour interval is 0.1. The threshold correlation coefficient at the 95% significance level is 0.55.

where dSST represents the increment in SST within the time interval dt and dt denotes 1 month. Here, ρ_o is the density of the seawater, c_p is the heat capacity of the seawater, and h is the depth of the surface mixed layer. In the following analysis, the correlation between dSST and Q_{net} (hereafter denoted as $\langle dSST, Q_{\text{net}} \rangle$) is computed to help address the following two issues: 1) how important is the role of Q_{net} in the seasonal-to-interannual variability of SST and 2) how different are the heat flux products in describing the SST variability if the same SST information is used?

In computing the correlation $\langle dSST, Q_{net} \rangle$, Q_{net} was taken as a monthly mean and dSST was calculated as the differences between the mean of the last 5 days and the mean of the first 5 days of the month. The values of dSST derived from the four NWP models are essentially the same. This is due to the fact that all of the models interpolate the weekly optimum interpolation SST (OISST) analysis (Reynolds et al. 2002) into 6-hour intervals and employ it as a surface boundary condition. The values of dSST derived from the daily OAFlux product are very similar to those of the NWP models although the synthesis of OAFlux included the daily averages of the AVHRR retrievals. SOC is the only product that does not have a daily SST product. To ensure that the correlation computations use the dSST constructed in the same way, the dSST from OAFlux is paired with the SOC Q_{net} .

a. Correlation between dSST and Q_{net} on seasonal time scales

Figure 12 shows the six patterns of the correlation $\langle Q_{\text{net}} | dSST \rangle$ constructed from the 12 climatological monthly anomaly fields. There exists a high degree of consistency between the six patterns, although the SOC pattern is comparably noisy. The threshold correlation coefficient at the 95% significance level is 0.55. Large correlation coefficients of 0.9 are found to the south of 15°S and in the central equatorial region, which suggests that Q_{net} plays an important role in the seasonal evolution of SST at these locations. Low coefficients of 0.6 and below are located in three major regions: the western Arabian Sea, the eastern equatorial region off of Sumatra, and the central southern basin along 10°S with a southeastward tilt in the east. In fact, the evolution of SST in these three regions of low coefficients is predominantly influenced by oceanic processes. For example, the western Arabian Sea features strong upwelling in the boreal summertime under the influence of prevailing southwesterly monsoon winds (Schott and McCreary 2001), and the upwelling process cools the sea surface despite the fact that positive Q_{net} goes into



FIG. 13. Same as in Fig. 12 except for the correlation between the Q_{net} and dSST monthly anomalies over the 1988–2000 period. The SOC and ECMWF-OP products are not computed. The mean seasonal cycle constructed from the 13-yr base period is removed. The threshold correlation coefficient at the 95% significance level is 0.16.

the region. The central southern basin between 5° and 12°S is the location of a thermocline ridge (Wyrtki 1971) owing to the persistent Ekman suction (Mc-Creary et al. 1993), where the wind-induced thermocline variations impose a major control on the regional SST variability (Donguy and Meyers 1995; Xie et al. 2002). On the other hand, the structure in the southern basin (0°–5°S, 70°–100°E) has a shape resembling the Rossby wave structure (see Fig. 1 in Yang et al. 1998). Modeling studies together with satellite Ocean Topography Experiment (TOPEX)/Poseidon altimeter (Perigaud and Delecluse 1992) and in situ observations (Masumoto and Meyers 1998) have shown that Rossby waves forced by the annual monsoonal winds are the primary cause of the seasonal change of the thermocline in the southern Indian Ocean, and that the seasonal variability of SST is governed largely by the divergence-convergence of the thermocline induced by wave motions (Yang et al. 1998).

Figure 12 shows that there is a high level of consistency between the six flux products in depicting the physical relationship between Q_{net} and the SST variability on seasonal time scales. The finding is encouraging in that, despite the large differences in the mean pattern (Fig. 1), the six products have a seasonal cycle that is consistent both from a statistical and a physical standpoint (Figs. 9 and 12). In other words, compared to the long-term mean value, the seasonal variability of Q_{net} is less affected by bias.

b. Correlation between dSST and Q_{net} on interannual time scales

The correlation $\langle Q_{net}, dSST \rangle$ on the interannual time scales is also examined for the four flux products (OAFlux+ISCCP, ERA-40, NCEP1, and NCEP2; Fig. 13). The mean seasonal cycle constructed from the base period 1988–2000 is removed from each dataset. For the total of 156 months involved in the computation, the threshold correlation coefficient on a 95% significance level is 0.16. Hence, only the coefficients that are equal to or larger than 0.2 are plotted in Fig. 13. Overall, OAFlux+ISCCP and ERA-40 have good agreement on the pattern and magnitude of the correlation, in which significantly high correlations (>0.5) appear in the southern basin south of 15°S and in the northern basin between the equator and 20°N. NCEP1 produces a similar pattern but has comparably weaker correlation coefficients. Among the four products, NCEP2 has the lowest correlation and the most different pattern, as the correlation is below the 95% significance level over most of the regions north of 15°S. Together with the interannual STD pattern in Fig. 11, it is clear that NCEP2 is not good at representing the variability in $Q_{\rm net}$.

Compared to the correlation $\langle Q_{\rm net}, d\rm{SST} \rangle$ on the seasonal time scales (Fig. 12a), the correlation $\langle Q_{\rm net}, d{\rm SST}\rangle$ on the interannual time scales is changed only in two places: the western equatorial region, where $Q_{\rm net}$ and dSST become negatively correlated, and the thermocline ridge region in the southern basin, where low correlation coefficients extend eastward. The SST in the two regions, on the interannual time scales, is governed largely by the thermocline depth variations in association with the westward propagation of the windinduced Rossby waves (Saji et al. 1999; Webster et al. 1999; Yu and Rienecker 1999; Feng and Meyers 2003). The low or negative correlations in the two regions indicate that Q_{net} is not the primary forcing for the changes in SST, which is consistent with the existing literature.

7. Discussions and summary

This study conducted an evaluation of the state of the estimation of surface net heat fluxes for the Indian Ocean. Six heat flux products were analyzed, which include the newly developed latent and sensible heat fluxes from the OAFlux project and net shortwave and longwave radiation results from ISCCP that together produce the combined OAFlux+ISCCP Q_{net} , the SOC analysis, two NCEP reanalysis products (NCEP1 and NCEP2), and two ECMWF products (ECMWF-OP and ERA-40). With the exception of the SOC dataset, which is based on the period 1980–97, the other five products are compared for the same 1988–2000 period.

The study presents the analysis of the six products in depicting the mean, the seasonal cycle, and the interannual variability. The major results are summarized as follows.

1) The mean value: The six Q_{net} products differ considerably in their long-term mean (Figs. 1–3), with the largest differences occurring in the northern Indian Ocean north of 15°S (Fig. 4). On the annualmean basis, the two analyzed flux products from

OAFlux+ISCCP and SOC show that the northern Indian Ocean gains heat; this is opposite to the Q_{net} estimates from the four NWP products.

Time series of in situ flux measurements obtained from the 1-yr Arabian Sea Experiment (Weller et al. 1998) and the nearly 1-month JASMINE field program in the Bay of Bengal (Webster et al. 2002) were used for validation (Figs. 5-8 and Tables 1 and 2). It was found that the four NWP Q_{net} products all underestimate the net heat into the ocean and the underestimation bias persists throughout the entire measurement record. Along the JASMINE ship track, the observed Q_{net} has a mean of 47.5 W m⁻². The OAFlux+ISCCP mean Q_{net} differs from the measurements by only 0.5 W m^{-2} , while the four NWP mean Q_{net} results are all negative, ranging from -5.4 (NCEP1) to -9.6 (NCEP2) to -21.6 (ERA-40) and finally to -61.0 W m^{-2} (ECMWF-OP). The differences between the ship measurements and the NWP models range between 53 (NCEP1) and 108 W m^{-2} (ECMWF-OP), which is much larger than the observed mean value. At the buoy site of the Arabian Sea Experiment, where the buoy $Q_{\rm net}$ has a mean of 64.8 W m⁻², the NCEP1 product is the most biased with a mean that is negative and deviates from the buoy by more than 69 W m⁻². The OAFlux+ISCCP Q_{net} is the least biased, but the mean is about 25% weaker than the buoy mean. The cause of the underestimation is due primarily to the overestimated latent heat loss related to a dry bias in the near-surface air humidity during the southwest monsoon period.

2) The seasonal cycle: The consistency between the six products in depicting the seasonal variability of $Q_{\rm net}$ was investigated by using the STD analysis and a correlation analysis based on a physical relation between Q_{net} and dSST [Eq. (5)]. The study found that, once the annual mean is removed, the six STD patterns are notably similar (Fig. 9). The magnitude of the five STD patterns (excluding ECMWF-OP) is in good agreement as well. ECMWF-OP has larger variances, because it does not have a fixed mean due to the frequent updates of the model platform (Fig. 10). The study also found that the six products are coherent in depicting the pattern of the correlation $\langle Q_{\rm net}, dSST \rangle$ (Fig. 12), suggesting that $Q_{\rm net}$ plays a positive role in the seasonal evolution of SST in the Indian Ocean with the exception of three regions: the upwelling zone in the western Arabian Sea, the coastal region off of Java and Sumatra, and the central southern basin associated with the thermocline ridge between the equator and 15°S. These findings are encouraging, because they show that the six products have no major bias in the seasonal cycle of Q_{net} although the mean is biased significantly.

3) The interannual variability: The same STD and correlation analyses were also applied to study the consistency between the Q_{net} products on interannual time scales. Only the four products, OAFlux+ISCCP, ERA-40, NCEP1, and NCEP2, were examined. SOC and ECMWF-OP were not included, because the SOC anomaly fields are noisy in regions of low sampling density and the ECMWF-OP anomaly fields are distorted by the changes made in the model platforms.

The study found that OAFlux+ISCCP and ERA-40 have an overall agreement on the interannual STD pattern (Fig. 11). In particular, both show that there are large Q_{net} variances in the southeastern basin around 15°S and in the coastal region off of Java and Sumatra. The NCEP1 STD pattern shows conformity with the two products over most of the Indian Ocean except for the eastern equatorial region, where NCEP1, as well as NCEP2, have low variances. The NCEP2 STD field is the most different among the four products, not only because its magnitude is at least 10 W m⁻² greater but also because its location of the largest variances in the southern basin is so dissimilar to the other three.

The correlation analysis (Fig. 13) showed that OAFlux+ISCCP and ERA-40 also agree with each other on the pattern of the correlation between $Q_{\rm net}$ and dSST. NCEP1 produces a similar pattern; however, the overall correlation coefficient is weaker. NCEP2 is again the most different. Compared to the correlation pattern for the seasonal anomalies (Fig. 12), the correlation pattern for the interannual anomalies is changed only in two places: the western equatorial region where $Q_{\rm net}$ and dSST become negatively correlated and the thermocline ridge region in the southern basin where low correlation coefficients extend eastward. These changes reflect the influence of the thermocline depth variations on SST in response to interannual wind anomalies (Yu and Rienecker 2000).

In summary, the study has three main findings. First of all, there exist large differences in the mean of the six heat flux products. Part of the differences may be attributable to the NWP models that underestimate the net heat flux into the Indian Ocean. Second, the bias effect changes with the time scale. Despite the fact that the mean is biased significantly, there is no major bias in the seasonal cycle of all the products except for ECMWF-OP; the latter does not have a fixed mean due to the frequent updates in the model platform. Finally, among the four products (OAFlux+ISCCP, ERA-40, NCEP1, and NCEP2) that can be used for studying interannual variability, OAFlux+ISCCP and ERA-40 Q_{net} have good consistency as judged from both statistical and physical measures. NCEP1 shows a broad agreement with the two products, with varying details. By comparison, NCEP2 has some improvement in the mean compared to NCEP1 at the buoy location, but it is not good at representing the Q_{net} variability over the basin scale.

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