VARlABILITY OF SURFACE FLUXES OVER THE INDIAN OCEAN; 1960-1989

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A variational-direct minimization objective analysis technique is used to create a set of regularly spaced monthly mean maps from 1960-1989 of temperatures, winds, humidity, sensible and latent heat flux and wind stress over the Indian Ocean using COADS data. The technique simultaneously solves for all the fields through a coupled relationship between the flux parameterizations and the solution fields. The variational method utilizes a set of constraints which express a lack of fit to input data, climatology and kinematics.

Wind fields and latent heat flux in the Arabian Sea and southern hemisphere trade wind regions are positively correlated. The dominant variability in these regions is concentrated in the annual cycle; however, biennial oscillations are evident in the year-to-year magnitudes for most non-summer months. Latent heat in these regions is somewhat correlated to summer monsoon rainfall over the Indian peninsula, but only prior to 1980.

Decadal-scale variability is evident in the latent heat and wind fields for many locations, but especially in the Arabian Sea and southern trade wind regions, where winds and latent heat show marked increases, particularly during the late 1970's and early 1980's. The increase is most dramatic during the fall/winter for wind stress and in summer/winter for latent heat flux. However, there are variations in onset date as well as magnitude of these trends which indicate these shifts/trends cannot be singularly explained by changes in the observation system.

KEY WORDS: Indian ocean, objective analysis, latent heat flux

1. INTRODUCTION

Surface fluxes of heat and momentum provide the link in the interaction between the atmosphere and ocean. This relationship is vital to the understanding of weather and climate in the tropics. However, these surface fluxes are a function of several meteorological and oceanographical variables which may not be adequately measured. Many scientists have estimated climatologies of surface fluxes for the global oceans as well as for specific regions. Hastenrath and Lamb (1979) published an atlas of the oceanic heat budget in the Indian Ocean. Similarly, Oberhuber (1988) and Fu et al. (1990) created atlases of the net heat budget and surface heat fluxes, respectively, over the global oceans. Hsiung (1986) studied the annual and monthly means of the surface energy fluxes over the global oceans. Weare et al. (1981) studied the long term annual mean of net surface heating in the tropical Pacific.

The monsoon systems of India, northeast Africa, southeast Asia and the continent of Australia are partly driven by this air-sea interaction. The southeast trade wind belt west of Australia, the Bay of Bengal and the Arabian Sea are of particular interest in the Indian Ocean regime. Improved surface flux analyses may clarify the spatial and
temporal variability influenced by such large scale phenomena as the El Niño Southern Oscillation (ENSO) and the Indian summer monsoon.

The most predominant phenomenon found in the Indian Ocean region is the annual monsoon reversal. The physical characteristics of the atmosphere-ocean system demonstrate considerably different characteristics between the summer and winter monsoons. In general, the summer monsoon in the lower atmosphere is dominated by strong westerly and southwesterly flow across south and central India. Strong southeasterly trade winds are found in the Southern Hemisphere. Likewise, strong cross-equatorial flow is observed along the east coast of Africa in association with the low-level Somali jet. This cross-equatorial flow is the likely mechanism that transports moisture from the Southern Indian Ocean into the Arabian Sea. (Cadet and Diehl, 1984).

The winter monsoon is characterized by a reversal of this flow. Northeasterlies prevail over the China Sea, Bay of Bengal and Arabian Sea. The northern and southern trades converge at 10–20°S as the Indian Ocean resembles the Atlantic and Pacific Oceans with two trade wind systems present (Knox, 1987) during this season.

Although the monsoons are predominately characterized by their overall flow patterns, the intensity of the monsoon is correlated to other surface parameters. Shukla and Misra (1977) found that higher wind speeds over the Arabian sea were correlated with lower sea surface temperatures. The stronger winds lead to increasing evaporation as well as increasing upwelling and subsequent extension of cold coastal waters. The negative correlation between the surface winds and sea surface temperatures was also noted by Cadet and Diehl (1984). Additionally, they determined that weaker than normal trade winds in the Southern Hemisphere and stronger zonal winds along the eastern coast of Africa were associated with a deficit of rainfall over India during the summer. Moreover, warmer sea surface temperature over the Indian Ocean in the summer is responsible for weak atmospheric circulation found during a dry monsoon period. Conversely, colder sea surface temperature was responsible for stronger atmospheric forcing during a wet monsoon. However, this link between sea surface temperature and rainfall is weak according to Weare (1979). More recently, interest in the correlation between the Indian summer monsoon and ENSO has developed. Again, a negative correlation between the Indian Ocean sea surface temperature and the monsoon is indicated. Verma (1992) suggested the warm (cool) phase of ENSO was associated with weaker (stronger) monsoon activity; i.e. less (more) monsoon precipitation.

Better estimates of the surface fluxes and an estimate of their uncertainty will permit a determination of the importance of the fluxes between the atmosphere and upper ocean thermodynamics.

Knox (1987) notes a surface exchange of heat from the atmosphere to the ocean in the Arabian Sea during the summer despite the strong winds. However, this net warming is offset by the northerly flow of cooler water across the equator from the Somali current. Upwelling along the African and Arabian coasts leads to additional ocean cooling in the northern summer and warming in the winter.

Latent and sensible heat fluxes can have major impacts on the large scale sea surface temperature anomaly fields in the mid-latitudes. A few studies have tested the relationship between the fluxes and the sea surface temperature field over broad scales. These include observational studies (Frankignoul and Reynolds, 1983; Cayan, 1992a, b, c) and an ocean general circulation model (Haney, 1985). These studies indicated that
anomalous heating by the surface fluxes were a major component in producing monthly thermal anomalies in the Northern Hemisphere Oceans.

Many of the above studies focused on the climatological and/or mean annual estimates of the surface fluxes. The research contained in this paper analyzes an objectively determined series of monthly fields of surface fluxes and surface parameters in the Indian Ocean basin for a 30-year period (January 1960–December 1989) based on ship reports. This is the first study which analyzes jointly calculated fields of surface fluxes and the surface variables which determine the fluxes.

In this paper, section 2 describes the data sets and the bulk formulae used in computing the surface fluxes. The objective analysis technique and sensitivity of the scheme are described in section 3. Results of the objective analysis and the variability of the results are discussed in section 4. EOF analyses indicate large decadal-scale variability in the wind stress and latent heat flux. Some correlation is established between Indian Ocean latent heat flux and Indian rainfall. However, no correlation between the latent heat flux and El Niño is found. Finally, the conclusions and findings are recapped in section 6.

2. DATA SET

2.1 COADS data set

Monthly means of individual meteorological reports from ships and buoys on a 2° grid are obtained from the COADS data set. Data which fell outside 2.8 standard deviations of the median of each of the 2° by 2° boxes were trimmed in this data set (see Slutz et al., 1985 for details).

Monthly means of sea surface temperature (SST), air temperature (AT), specific humidity (Q), scalar wind speed (W) and pseudo-stress wind components (the product of the directional wind component and the scalar wind, UW and VW) over the Indian Ocean region (30°S to 24°N, 30°E to 120°E) are extracted from COADS during the period 1960 to 1989. The pseudo-stress components of wind are henceforth noted simply as the wind components. This grid yields 888 stations over the ocean.

2.2 Flux calculations

As direct measurements of surface fluxes are rarely available, the bulk aerodynamic formulae determine wind stress (τ), latent (E) and sensible (H) heat fluxes when needed in this study. For this study, the bulk coefficients of Smith (1988) are used. These coefficients depend on the air-sea virtual potential temperature difference and wind speeds. The flux calculations were computed assuming the winds were all measured at 20 meters height and temperature and humidity variables all measured at 10 meters height - reflecting the usual case of the temperature/humidity instruments mounted at deck level and winds usually either referenced to or observed at 20 m.

Positive heat flux values indicate a net gain of thermal energy by the atmosphere. For wind stress calculations, using monthly mean pseudo-stress components rather than monthly mean wind components is critical; it reduces the difference between the (correctly calculated) stress from the means of coincident stress and the (incorrectly
calculated) stress calculated using the mean winds (Hanawa and Toba, 1987). A previous implementation of this technique (Legler, 1992) showed that a diagnostically determined $W$ generated weak fluxes; thus the scalar wind, $W$, based on COADS data is used in the flux calculations.

For the latent and sensible heat fluxes, the monthly mean fluxes were calculated using monthly mean values of temperatures, humidity, and scalar wind speed. This method of flux calculation introduces only a small error into the values (truth being defined as the mean of daily or more frequent values of the heat fluxes) (Esbenson and Reynolds, 1981; Hanawa and Toba, 1987).

2.3 Climatologies of surface parameters

Climatologies of the surface variables (SST, AT, Q and W), for the 30 years of extracted COADS data set, were created. The climatological fields primarily reflect the summer and winter monsoonal weather patterns and are consistent with other estimations of climate; e.g. Hastenrath and Lamb (1979) and Wright (1988). The computed COADS climatologies are utilized in the objective analysis technique.

3. OBJECTIVE ANALYSIS METHOD

Variational analysis methods allow information in various forms to be combined by minimizing a lack of fit to a set of constraints. The variational concepts were introduced by Sasaki (1958) and previously employed by Legler (1992) to determine surface fields over the Atlantic Ocean; by Hoffman (1984) in order to remove the ambiguity of SeaSat satellite scatterometer winds (SASS); and by Legler et al. (1989) to formulate surface pseudo-stress vectors in the Indian Ocean. A variational approach, which involves direct minimization of a cost functional consisting of 17 terms, is implemented for the Indian Ocean basin. Each term of the functional represents a measure of lack of fit to prescribed constraints. In the present study, the cost functional retains information from the input ship data, as well as some information of the climatic norm and kinematics. Empirical constraints also assist in providing the analyzed fields. Associated with each term is an empirically determined weight, denoted by a greek letter and listed in Table 1.

The minimization of the cost functional produces monthly maps of the surface variables (e.g. temperature, humidity and winds). In addition, monthly fields of the derived fluxes (latent and sensible heat flux and wind stress) are an integral result. The constraints were chosen based on the need to retain as much data information as possible while including terms to provide estimates of the analyzed variables in regions of poor data coverage. The first six terms of the functional describe expressions of misfit to the input data from COADS; the next four terms force the resultant fluxes to approximate the COADS flux data fields. Thus the first set of constraints forces the results to be in proximity to the input data. The next six terms smooth the results by forcing the resultant fields to resemble climatology in a smooth sense; and the final term is a kinematic constraint which approximates the difference from climatology of the
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TABLE 1
The final weights for the functional terms

<table>
<thead>
<tr>
<th>Weight designator</th>
<th>Functional term</th>
<th>Value of the weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Sea surface temperature</td>
<td>60.0</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Air temperature</td>
<td>20.0</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Specific humidity</td>
<td>1.0</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Scalar wind speed</td>
<td>5.0</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Zonal pseudo-stress component</td>
<td>1.0</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Meridional pseudo-stress component</td>
<td>1.0</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>Sensible heat flux</td>
<td>0.05</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Latent heat flux</td>
<td>0.5</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>Zonal stress component</td>
<td>1.0</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Meridional stress component</td>
<td>1.0</td>
</tr>
<tr>
<td>$\rho$</td>
<td>SST smoothing term</td>
<td>10.0</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>AT smoothing term</td>
<td>5.0</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Q smoothing term</td>
<td>5.0</td>
</tr>
<tr>
<td>$\nu$</td>
<td>W smoothing term</td>
<td>5.0</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>UW smoothing term</td>
<td>1.0</td>
</tr>
<tr>
<td>$\Pi$</td>
<td>VW smoothing term</td>
<td>1.0</td>
</tr>
<tr>
<td>$\Theta$</td>
<td>Curl of pseudo-stress</td>
<td>5.0</td>
</tr>
</tbody>
</table>

The symbols in the functional are as follows:

- $\text{SST}_\text{coads}$: Sea Surface Temperature
- $\text{AT}_\text{coads}$: Air Temperature
- $\text{Q}_\text{coads}$: Specific Humidity
- $\text{W}_\text{coads}$: Wind Speed
- $\text{UW}_\text{coads}$ and $\text{VW}_\text{coads}$: Pseudo-Stress components
- $\text{E}_\text{coads}$: Latent Heat Flux
- $\text{H}_\text{coads}$: Sensible Heat Flux
- $\tau_x\text{coads}$ and $\tau_y\text{coads}$: Stress components
- $\text{Climatologies}$: Climatologies
- $L$: Length scale
- $\vec{V}W$: Pseudo-stress vector

The functional is:

$$F = \alpha \Sigma (\text{SST} - \text{SST}_\text{coads})^2 + \beta \Sigma (\text{AT} - \text{AT}_\text{coads})^2$$
$$+ \gamma \Sigma (\text{Q} - \text{Q}_\text{coads})^2 + \delta \Sigma (\text{W} - \text{W}_\text{coads})^2$$
$$+ \epsilon \Sigma (\text{UW} - \text{UW}_\text{coads})^2 + \phi \Sigma (\text{VW} - \text{VW}_\text{coads})^2$$
$$+ \Gamma \Sigma (\text{H} - \text{H}_\text{coads})^2 + \eta \Sigma (\text{E} - \text{E}_\text{coads})^2$$
$$+ \xi \Sigma (\tau_x - \tau_x\text{coads})^2 + \zeta \Sigma (\tau_y - \tau_y\text{coads})^2$$
$$+ \rho L^4 \Sigma (\nabla^2 (\text{SST} - \text{SST}_c))^2 + \Lambda L^4 \Sigma (\nabla^2 (\text{AT} - \text{AT}_c))^2$$
$$+ \mu L^4 \Sigma (\nabla^2 (\text{Q} - \text{Q}_c))^2 + \nu L^4 \Sigma (\nabla^2 (\text{W} - \text{W}_c))^2$$
$$+ \sigma L^4 \Sigma (\nabla^2 (\text{UW} - \text{UW}_c))^2 + \Pi L^4 \Sigma (\nabla^2 (\text{VW} - \text{VW}_c))^2$$
$$+ \Theta L^2 \Sigma (\vec{k} \cdot \nabla \times (\vec{V}W - \vec{V}W_c))^2.$$
The summation is over all points in space on a 2° by 2° grid over the Indian Ocean where the functional and gradient calculations can be computed. At each iteration of the minimization procedure, SST, AT, Q, W, UW are free to vary while H, E, \( t_x \) and \( t_y \) are calculated diagnostically. Note that monthly mean wind speed and wind components are free to vary independently for reasons described in Section 2.2. The Laplacian and curl terms provide curvature information as criteria and link the functional in space. Each difference is non-dimensionalized by the basin-wide RMS value of the respective input field, either COADS or climate. The smoothing as well as the curl term are non-dimensionalized by an appropriate length factor, \( L \), which is chosen to be the grid spacing used in the finite difference operator, 222.2 km. In order to place more weight on input data at locations with more data, each grid location is logarithmically weighted according to the number of observations for the first ten constraints in the functional. Second-order finite differencing in spherical coordinates is used for all derivative calculations.

The analysis is carried out for each of the 360 months of the 30-year period (January, 1960 through December, 1989). The COADS ship report fields are the first guess. If missing data exist in the first guess field, climatology is used. Given the continental and island locations, the six dependent variables are calculated at 888 locations on a 2° by 2° grid. Thus the technique will estimate: \( n = 6 \) variables \( \times \) 888 locations = 5328 solution values; all terms in the functional are expressed as functions of these six physical variables.

This method updates the flux fields at each iteration using the bulk formulae and the most recent values of the resultant fields of SST, AT, Q, W, UW and VW. Any alterations in these resultant fields can influence the other resultant fields through the flux constraint terms. For example, all exchange coefficients in the bulk formulae are dependent on SST, AT, W, Q and Qs. Thus updates in SST or any other resultant variable generates updated flux values and subsequent corrections to other variables. These corrections are due to the imposed empirical constraints. The empirical nature of these constraints can be expanded or altered to reflect any expression or model of the relationship between the variables estimated using this objective analysis technique. In this case, specific bulk formulae were the model.

The conjugate gradient method is the most efficient for determining the minimum of a functional when the number of parameters is large (Navon and Legler, 1987). The specific algorithm used in this study is Conmin (Shanno and Phua, 1980). The convergence criteria was satisfied when the Euclidean norm of the gradient was reduced by nearly three orders of magnitude. In this study, nearly every analyzed month converged within 40 iterations or less. Three of the months required nearly 60 iterations, but all months did converge.

### 3.2 Weight selection

The behavior of the functional and hence the solution fields are determined by the weights on each term of the functional. Empirical studies rather than truly objective means are used in selecting the optimal weights. Objective methods for selecting the optimal weights are intractable due to the large number of solution variables in this study and are also difficult to use since an independent “truth” data set is difficult to
obtain. Several criteria were used to determine the optimal weights: comparison of results to ship means at well sampled locations; qualitative comparisons of results to climatological studies (Hastenrath and Lamb, 1980 and Oberhuber, 1988); and a quantitative data void difference test. A sensitivity analysis provided guidance on which weights needed to be more carefully chosen. A more complete description of these criteria and the selection process is in Jones (1992).

Once the optimal weights were selected, several months’ results were also examined for continuity between the input and resultant fields. The weight selection showed little seasonal dependence. In other words, slight weight alterations improved the results, but the improvements were very small. All resulting climatological means correspond to similar data sets i.e. Hastenrath and Lamb (1980) and Oberhuber (1988).

The SST and AT terms in the functional, Table 1, are weighted more heavily than the other terms. If the temperature constraints, (i.e. weights) were decreased, the flux results degrade. Larger weights on $W$ decrease the accuracy of the SST and heat flux fields indicating a sensitivity to features in the input $W$ data.

The weights, $\rho$, $\Lambda$, $\mu$, and $v$ act as smoothers for the resultant fields of SST, AT, $Q$, and $W$, respectively. These Laplacian terms couple the entire functional in space. The Laplacian SST weight proved more influential than the weights on the other smoothing terms. Sensitivity analyses (see next section) confirm this. The weight is larger than the other Laplacian weights to insure the “smoothness” of the heat flux fields as well as the other fields.

The pseudo-stress winds and their Laplacian terms are all weighted at unity as are the stress terms. Stronger constraints on the pseudo-stress winds decrease the accuracy of the other fields but have very little effect on the pseudo-stress results. The pseudo-stress curl weight is five times as large as the $UW$, $VW$ terms to improve the wind derivative fields.

### 3.3 Sensitivity analysis

A sensitivity analysis is performed on each of the weights in the functional to note the effects on the latent heat flux and the wind stress magnitude resultant fields. A first-order finite difference method detailed by Cacuci (1988) is used to estimate the sensitivity. The goal is to ascertain the change in the results (as depicted in a summary response function) for a prescribed change in the selected weights. The response function is a simple function of the results. Any number of response functions can be chosen, but for this study, a response function describing the total additive latent heat flux ($R_h$) and the total additive magnitude of wind stress ($R\vec{\tau}$) over all points in space is used. A more detailed description of sensitivity analysis can be found in Meyers et al. (1994).

The relative sensitivity is defined as the normalized absolute sensitivity and is an expression of the percentage change in a response function for a given percentage change in weight values. The relative sensitivities of latent heat flux and wind stress magnitude to any weight, $\alpha$, in the functional are defined respectively as such:

$$S_{R_h} = \frac{\alpha \cdot \partial R_h}{R_h \cdot \partial \alpha}, \quad S_{R\vec{\tau}} = \frac{\alpha \cdot \partial R\vec{\tau}}{R\vec{\tau} \cdot \partial \alpha}.$$
Each $a$ is altered slightly (an order of 1/2% from the chosen optimal weights in Table 1) to estimate $S_{r(t)}$ and $S_{r(t)}$. Larger changes could result in convergence to a different, perhaps incorrect, solution.

All weights except the Laplacian term for the SST indicate that there is less than a 1% change in the response functions for a 1% change in each weight, Table 2. Both response functions are most sensitive to the weights on the SST, scalar wind and the corresponding “smoothing” terms. The response function of the wind stress results is more sensitive to these weights than the response function of the latent heat flux results. The wind stress is also sensitive to the weights on the Laplacian terms of the pseudo-stress components. Thus the empirical (bulk formula) relationships do affect the outcome of the analysis.

The errors of the results due to parameter incorrectness or uncertainty can be estimated using sensitivity values (Meyers et al., 1994). It can be expressed as an RMS-type value or as a field to identify regions in which the actual resultant fields (e.g. latent heat flux and wind stress) are most sensitive to the tested weight. For a presumed uncertainty of 10% in the weights, the “error” of the latent heat field due to these relative uncertainties in all of the optimal weights is generally 2 W m$^{-2}$ with maximum values of 3–4 W m$^{-2}$ in the region of the Somali Jet, the Bay of Bengal and off the western coast of Australia where the trade winds are strong (Meyers et al., 1994). In these regions during August, latent heat flux is on the order of 240 W m$^{-2}$, thus a 10% weight uncertainty does not translate into a 10% error in the results.

Similar calculations of uncertainty for the wind stress results, (Jones 1992) show the largest values (~0.1 Nm$^{-2}$) occur in the trade-wind belt and in the region where Arabian sea winds are maximum.

<table>
<thead>
<tr>
<th>Functional Term Weights</th>
<th>$S_{r(t)}$</th>
<th>$S_{r(t)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>+0.0162</td>
<td>+0.0070</td>
</tr>
<tr>
<td>$\beta$</td>
<td>+0.0006</td>
<td>+0.0003</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>-0.0007</td>
<td>+0.0005</td>
</tr>
<tr>
<td>$\delta$</td>
<td>-0.0017</td>
<td>-0.0001</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>+0.0013</td>
<td>-0.0021</td>
</tr>
<tr>
<td>$\phi$</td>
<td>+0.0019</td>
<td>-0.0021</td>
</tr>
<tr>
<td>$\rho$</td>
<td>-0.1737</td>
<td>+0.4860</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>+0.0041</td>
<td>+0.0052</td>
</tr>
<tr>
<td>$\mu$</td>
<td>+0.0072</td>
<td>+0.0005</td>
</tr>
<tr>
<td>$\nu$</td>
<td>+0.1541</td>
<td>-0.3999</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>+0.0122</td>
<td>-0.0145</td>
</tr>
<tr>
<td>$\Pi$</td>
<td>+0.0084</td>
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</tr>
<tr>
<td>$\Gamma$</td>
<td>+0.0033</td>
<td>+0.0044</td>
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<td>$\zeta$</td>
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<td>-0.0070</td>
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<tr>
<td>$\Theta$</td>
<td>-0.0064</td>
<td>+0.0139</td>
</tr>
</tbody>
</table>
4. RESULTS

4.1 Variability of the surface fluxes

From the technique described previously, monthly mean fields of each of the 10 surface variables and fluxes are created for the 30-year period. This paper will focus on air-sea flux results. Significant annual, interannual and decadal variability is observed in the surface fluxes over the Arabian Sea, Bay of Bengal and the southern trade wind belt. Variability is determined through subjective and statistical examination of the results.

Averaging over all 30 years isolates the annual cycle. During July and August, latent heat flux in the southern trade winds exhibits two maxima, in the southern trade winds (70E, 20S and 100E, 15S); a secondary maximum is located in the Arabian Sea 65E, 10N (Figure 1, bottom). Fluxes in both areas are sustained by the strong (Indian) summer monsoon winds. Maximum values of latent heat flux in the summer are generally 160 Wm\(^{-2}\) in the trade winds and 120 Wm\(^{-2}\) off the Somali coast. Latent heat flux over the Arabian Sea decreases westward as evaporation is suppressed due to coastal upwelling (Surgi, 1991). During the northeast (Indian winter) monsoon, latent heat flux exhibits maxima again in the Arabian Sea (55E, 10N and 70E, 20N) and in the southern trade winds just west of Australia 9OE, 20S (Fig. 1, top). During the transition periods between the northeast and southwest monsoons, latent heat flux (not shown) is considerably less (60–80 Wm\(^{-2}\) in the north Indian Ocean and 100 Wm\(^{-2}\) in the trades) than during the monsoon periods.

Sensible heat flux varies little in comparison to latent heat flux. Values are generally positive except where coastal upwelling occurs in the Arabian Sea (60E, 10N) (Fig. 2, bottom). During the southwest Indian summer monsoon, large positive values of sensible heat flux (15–20 Wm\(^{-2}\)) are observed west of Australia (110 – 60E, 15–28S) where the air-sea temperature difference is greater than 1 °C. (Fig. 2, bottom). Smaller values are found in the north Indian Ocean where the air-sea temperature difference is negligible. For the northeast monsoon, sensible heat flux values range from 0–10 Wm\(^{-2}\) over the entire basin as air-sea temperature differences are insignificant (Figure 2, top). Other months of the year (not shown) are characterized by small sensible heat flux values; \(\pm 5 \text{ Wm}^{-2}\).

During the southwest monsoon, wind stress values (not shown) are maximum in the western Arabian Sea in association with the Findlater Jet and in the southern trades, west of 90E. Strong stress values are also observed in the South China Sea during the northeast monsoon as a strong high pressure system builds over Asia. Another high pressure system over Australia increases the stress in the trade wind region between 90–110E during the boreal summer. The other months show large stress only in the southern trade winds.

4.2 Decadal variability

Throughout the early 1960's, latent heat flux remained relatively stable throughout the Indian Ocean. At the end of the 1970's an increase occurs primarily in the Arabian Sea, Southern trades and east of Madagascar. Over the 30 year period of this analysis, latent heat flux values in these regions increased 20–50 Wm\(^{-2}\). A similar trend is observed in
the wind speed and wind stress over the Arabian Sea (Figs. 3–5). For the Arabian Sea region, the increase is present in all seasons, but is most prominent in northern hemisphere summer (June, July, August) and winter (December, January, February). The trends for these seasons exceed 1.0 W m\(^{-2}\) year\(^{-1}\). Corresponding changes in wind magnitude are 0.06 m s\(^{-1}\) year\(^{-1}\) (summer) and 0.04 m s\(^{-1}\) year\(^{-1}\) (winter).

This trend in the winds (and subsequently in latent heat flux) may not be entirely explained by changes in wind reporting techniques. A change in wind speed values due to the changes in wind reporting scales is more evident in regions of lower wind speeds
(Cardone et al., 1990). Thus one would expect the climate shift to be most obvious in the spring—clearly not true in our data. The trend is interesting in that it is present in other regions (e.g. West of Australia, Bay of Bengal), but is inconsistent with season and onset date. In many cases, the trends are most pronounced beginning in the mid-to-late 1970's.

Previously, others have discovered similar trends/shifts of Indian Ocean-related datasets: Cadet and Diehl (1984) noted a wind intensity increase in the early 1970's in the Arabian Sea. This increase created a marked decrease of model ocean upper layer thickness for the Arabian Sea (Dube et al., 1990) but the wind increase was noted to last...
FIGURE 3 Analyzed seasonal/mean latent heat for the Arabian Sea region (7-17N, 57-69E) for the seasons of a) March–April–May, b) Jun–July–Aug c) September–October–November d) December–January–February. Units are in Wm$^{-2}$. Note the scales change in each graph.

FIGURE 4 Analyzed seasonal/mean wind stress for the Arabian Sea region (7-17N, 57-69E) for the seasons of a) March–April–May, b) June–July–August c) September–October–November d) December–January–February. Units are in Nm$^{-2}$. Note the scales change in each graph.
FIGURE 5a The difference in the average scalar wind speed of the sixties and the eighties is shown. Contour intervals are .1 m s\(^{-1}\). The largest difference between the decades are observed in the trade winds and along the Somali coast. Minima are found at 10 S near Madagascar and at the equator near Sumatra. Positive values indicate that the eighties wind speeds are higher than the sixties over the entire domain.

FIGURE 5b The difference in the average latent heat flux in the sixties and the eighties is shown. Contour intervals are in 5 Wm\(^{-2}\). The largest differences are observed in the trade winds and in the Arabian Sea. The maximum differences in the latent heat correspond to the maximum differences in wind speed. Positive values indicate that the eighties latent heat flux is larger than the sixties over the entire domain.

only through the mid 1970’s. Our analyses indicate continued strengthening of the Arabian Sea winds throughout the 1980’s.

The increase in latent heat flux in the Arabian Sea resembles that of the increase in the trade wind region west of Australia. In correlation analyses (not shown) the boreal
summer latent heat flux in these regions are positively correlated \((r > 0.6)\). Latent heat in the Bay of Bengal has some correlation to values in the Arabian Sea; maximum correlation generally never exceeds \(r = 0.5\) and is maximum lagging Arabian Sea latent heat by 1 to 2 months.

Both the Arabian Sea and the trade wind region east of Madagascar experience lower SST when the winds are stronger and subsequently larger latent heat flux are encountered. These results agree with the findings of Joseph and Pillai (1984) and Krishnamurti (1981). Upwelling generated by the strong along-shore winds in these regions generate cooler SST values (McCreary et al., 1993). The enhanced latent heat flux resulting from the high winds may also contribute to these lower values. Lower SST values would normally decrease evaporation, but the impact of SST on latent heat flux is not clear given the role of the wind-driven ocean dynamics. Analysis of SST and monsoon rainfall indicates SST in the Arabian Sea decreases during most wet monsoon years (1961, 1970, 1975, 1983, 1988), and increases during dry monsoon years (1965, 1968, 1972, 1974, 1979, 1982, 1986, 1987), Figure 6. The SST changes are evident through most of the calendar year, and are not limited to the summer monsoon months. Note also the coastal SST is cooler (warmer) than the basin mean during most wet (dry) monsoon years.

### 4.3 EOF Analysis

An EOF analysis is performed on the resultant fields of latent heat flux and wind stress to examine further their variability. Long-term temporal means of the latent heat flux and wind stress components are removed from each monthly field.

For latent heat flux, the first eigenmode accounts for 26% of the total variance, Figure 7. This EOF has its strongest impact on the southern trades and Arabian Sea (positive values) and extreme NW Arabian Sea (negative values). Thus there are negative anomalous latent heat flux resulting from the upwelling off Somalia and Saudi Arabia which correlates with the positive anomalous latent heat flux in the Arabian Sea and trades region east of Madagascar. This pattern also confirms the previous indications that the latent heat flux variability between the Arabian Sea and the Southern trades region are linked. The amplitude of the modulating time series is largest in June. The mean amplitude in June is 50% larger than that in December. The link between Southern ocean and Arabian Sea latent heat flux is strongest in June–July. The dominant periodicities in EOF1 are 1 year and 6 months. Year-to-year variations for the monthly values, Figure 8, indicate oscillations on biennial (and longer) scales.

There is no clear correlation to E1 Nino events. There is some similarity between Indian peninsula monsoon rainfall (e.g., Parthasarathy et al., 1990) and the time series of latent heat flux EOF’s, Figure 9. Prior to \(\sim 1980\), relative year-to-year variations in summertime (June, July, August) latent heat flux from the first EOF correspond to changes in monsoon precipitation variations (correlation \(r = 0.41\)). Latent heat flux increases (decreases) correspond to increased (decreased) monsoon precipitation for 1960–1963 and 66, 67, 70–80. However, the correspondence is far from robust.

Decadal variability corresponding to that indicated previously for the Arabian Sea is also observed in the EOF time series. Decreasing evaporation takes place during the 60’s and 70’s. It increases in the 1980’s and decreases again only towards the late 1980’s.
FIGURE 6  Indian summer rainfall (Parthasarathy et al., 1990) in mm and monthly SST anomalies for the Arabian Sea (average of interior region values are the dashed lines; average of values near the Somalia coast are the solid line). A 5-point running mean has been applied to the SST data.
The net effect is an increase of evaporation in the Southern trades and Arabian Sea, and a decrease in equatorial, Bay of Bengal, and South China Sea regions. Power spectra of the time series indicate most variability is in the 12-month and then 6 month cycles.

The second EOF accounts for only 10% of the variance, Figure 10. It depicts primarily the variance of latent heat flux in the Arabian Sea. The latent heat in the region of the southern trades is out of phase with that of northern ocean basins. The time series indicates a semi-annual cycle, with negative (positive) latent heat flux in the Arabian Sea (southern trades) in March–April, and August–September–October. Additionally, the Arabian Sea (southern trades region) is characterized by positive (negative) latent heat flux during November–December–January.

In summary, from the first two EOF’s, the dominant latent heat flux variability in the Indian ocean is located in the Arabian Sea and in the region of southern trades. Winter months (November–December–January–February) are characterized by below mean
FIGURE 8  Intereannual variability of the EOF-1 time series for latent heat flux organized by month. June and August have the largest overall trends, but November and December have large trends beginning in the mid-1970s.
latent heat flux in the southern trades and greater than mean latent heat flux in the NW Arabian Sea, extending from 60E to the Saudia Arabian Peninsula. For summer months (May–January–July), both the Arabian Sea and southern trades have greater than normal latent heat flux, but Arabian Sea latent heat flux has strong gradients near the coast of Saudia Arabia due to increased upwelling and hence reduced latent heat flux nearer the coast.

Again, from the first two EOF’s the trend of latent heat is evident after ~1977 and is most pronounced in the months of June and July in the Arabian Sea and the southern trades region. A substantial increase of positive latent heat flux is indicated in the Arabian Sea and southern trades regions for the period 1978–1989. The trend is neither uniform in onset or magnitude (i.e. Fig. 8). The months with the largest linear trends are (in decreasing amplitude) June, August, November, December and July. Some months such as November, December and May are characterized by relatively uniform values until ~1978 when there is a very dramatic increase.

Vector EOF analysis (Legler, 1983) is performed on the wind stress fields. The long-term temporal means of the stress components are removed. The first eigenmode accounts for 35% of the total variance. The time series (Fig. 11) indicates the annual variation of the summer and winter monsoon winds. The first EOF indicates the linked variability pattern in the northwest Arabian Sea, Bay of Bengal, and the southern trades. The EOF time series has large biennial oscillations in all months except July, August and September (Fig. 12). The year-to-year variation in magnitude is typically 15% for any month in which these biennial oscillations are noted. A trend is present in
FIGURE 10  Second EOF (10% of the variance) of latent heat flux for Indian Ocean. The spatial pattern (smoothed) contouring (a) has interval of 10 Wm\(^{-2}\). Dashed lines indicate negative values. The associated time series indicate the modulation of the spatial pattern in time (b is the time series; c is after 13-month running mean applied).

the EOF time series, particularly with respect to the January/February/March months. This trend (~0.00013 N M\(^{-2}\) year\(^{-1}\)) indicates an increase of the stress over the 30 year period by approximately 5%. Most notably in September, October, November, December, a sudden decrease in time series magnitudes is apparent beginning in ~1977. (Since the orientation of the EOF pattern during these months is nearly 180° to that indicated in the figure, this decrease in magnitude means smaller negative trade wind stress anomalies, i.e. stronger winds.) The wind stress trend for the summer months (June–July–August) is slightly negative. There is a corresponding trend in the analyzed wind stress fields (no EOF analysis) for the Arabian Sea, but the magnitude (~0.0004 NM\(^{-2}\) year\(^{-1}\)) is 3 times larger than that represented in the first EOF alone for the wintertime Arabian Sea. Thus this trend must be evident in several of the EOFS, indicating the trend is spread across several time and spatial scales.
FIGURE 11  First EOF (35% of the variance) of surface wind stress for the Indian Ocean. The vector magnitudes in the spatial pattern (a) are indicated by length (legend at bottom). The time series are the magnitude (b) and phase angle in radians (c) and low-pass filtered versions of magnitude (d) and phase (e) (eliminated periods less than 18 months).
FIGURE 12. Interannual variability of the wind stress EOF-1 time series magnitude for January (b) and July (a). The best-fit first-order polynomial is indicated by the single line. The slope of the fitted line is 5.1E-04 for January and -1.6E-05 for July.

The second eigenmode (not shown) accounts for 17% of the total variance of the wind stress. It depicts strong northern Indian ocean winds and the southern trades. The associated time series again indicates strong biennial varying amplitudes, especially in December, January, February.

Higher EOF modes contained similar portions of the variance, and were not examined independently.

5. CONCLUSIONS AND SUMMARY

A consistently analyzed set of monthly mean maps of surface variables and fluxes over the Indian Ocean are generated simultaneously using a variational-direct minimization objective analysis technique. The input data are from COADS ship reports for the 30 year period, 1960–1989. A longer period could be examined if sufficient data were available. The surface fluxes are determined by the input surface variables using the bulk formula as empirical constraints in the variational analysis technique.

The optimal weights in the objective analysis technique were selected by comparison of the results to ship means at well sampled locations, a qualitative comparison of the results to previous studies and through a quantitative data void test. Sensitivity analysis narrowed the focus of the weight selection to a few weights which had the largest impact on the results. This sensitivity analysis was not previously performed in other studies. It is noteworthy that this sensitivity analysis can be performed on functions with a large number of parameters. The solutions of latent heat flux and wind stress were more sensitive to the weights on the SST and W (scalar wind) terms.

The variability of the flux results were examined. On a monthly time scale latent heat flux was always positive; i.e. the ocean cooled the atmosphere warmed. Latent heat flux variability is more correlated to the wind variability; however SST exerts a secondary influence which was seen in regions of coastal upwelling especially near Saudia Arabia in June, July, August. Areas of high wind speed such as the southern trade winds and
the Arabian Sea are characterized by larger values of latent heat flux. Latent heat in these two regions were somewhat correlated.

The EOF analysis of latent heat further indicates the link between the northern basins (e.g. Arabian Sea, Bay of Bengal, and South China Sea) and the trade wind regions of the Southern Indian Ocean. Our analysis also indicates a positive correlation between summertime latent heat flux and monsoon precipitation over India, but this relationship is only evident prior to 1980.

Evidence of decadal variability is seen in the latent heat flux and wind stress results for the Arabian Sea and areas of the southern trades. There are increasing wind magnitudes and latent heat flux values during the period, especially during the early 1970's and early 1980's. This increase is most dramatic during the fall/winter for wind stress, and in summer/winter for latent heat flux. The increases of the winds may be partly attributable to a change in wind measurement techniques, but the observed increase cannot be fully accounted for due to its non-uniformity of magnitude and onset date. Seasonal and interannual changes in shipping routes may also explain some of these trends.

A climate shift has been noted in other ocean basins (e.g. Graham, 1994; Trenberth, 1990). The possibility of a similar shift in the Indian Ocean will be explored further in additional papers.

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