Reply

DIETMAR DOMMENGET

Scripps Institution of Oceanography, Physical Oceanography Research Division, La Jolla, California

MOJIB LATIF

Max-Planck-Institut für Meteorologie, Hamburg, Germany

24 January 2002 and 3 September 2002

1. Introduction

The comments of Behera et al. (2003) on our note (Dommenget and Latif 2002, hereafter DL) claim that we have misinterpreted our analysis. In the following section we would like to reply to some of their comments that are directly related to our note. In section 3 we outline how different, apparently contradicting, hypotheses about the origin of sea surface temperature (SST) variability in the Indian Ocean can be tested.

2. Reply to the comments of Behera et al. (2003)

Behera et al. (2003) have some critical comments on DL on which we would like to comment in a point-to-point manner.

In their section 2 Behera et al. (2003) state ''It is obvious that we will find an east–west negative correlation if we consider only this season when the dipole is dominant (. . .): an underlying fact overlooked in DL's analysis.''

It is indeed obvious that a negative correlation has to be present if the dipole mode is statistically dominant over the monopole mode, which may be true in one season, but it is not the case if the entire year is analyzed. We chose to reproduce the statistical analysis by Saji et al. (1999), which was based on the entire year.

Restricting the analysis to a subdomain, such as one season, can indeed result in very different EOF modes. Doing so, one may actually realize that the dipole structure in this season is related to the ENSO response, see papers by Allen et al. (2001) and by Baquero et al. (2002). However, understanding the SST variability of tropical Indian Ocean and its seasonal dependency was not the main subject of DL.

Corresponding author address: Dietmar Dommenget, Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0230.
E-mail: dommenget@ucsd.edu

In their introduction Behera et al. (2003) state ''. . . DL questioned the existence of the IOD [Indian Ocean dipole] as a physical mode. We find that the concern raised by DL on the IOD issue is superficial. This is because the detection of the phenomenon was based not on the EOF analysis but on the physical and dynamical understanding of various ocean–atmosphere parameters (Saji et al. 1999 . . .), . . .''

We would like to point out that the DL note deals mainly with the interpretation of EOFs as physical modes in general. We did not intend to present evidence about the existence or nonexistence of any physical mode in the three examples of observed climate variability in our note. We only pointed out that the existence of a dipole cannot be confirmed based on an EOF or varimax analysis. However, we are indeed very skeptical about the existence of the IOD mode. A detailed discussion of this point can be found in the papers by Allen et al. (2001) and by Baquero et al. (2002).

The argument of Behera et al. (2003), that the analysis of Saji et al. (1999) is not essentially based on an EOF analysis but, ''on the physical and dynamical understanding of various ocean–atmosphere parameters,'' is unreproducible for us. It seems to us that the only quantitative statement in Saji et al. (1999) about the dominance of the dipole modes comes from the EOF analysis. We will discuss the problem with using apparent ''physical and dynamical understanding'' to support the dipole hypothesis in section 3.

In their section 3, Behera et al. (2003) state ''DL anticipated that the presence of the dipole mode should lead to a negative correlation between western and eastern poles . . . and that the varimax rotation should retain the dipole pattern of EOF2.''

We do not find any statement in DL that could or should be interpreted in this way. Indeed we do not believe this at all. However, we think that it is difficult to argue for the existence of a dipole mode if no negative correlation between the poles exist. This problem is also discussed in more detail in section 3.

In their section 4, Behera et al. (2003) state ''It may be noted that the EOFs are unstable in DL's example because the defined variances for the prescribed artificial modes are not significantly different from each other (e.g., Krzanowski 1984; Jolliffe 1989).''

We think this statement of Behera et al. (2003) is wrong. All values of the artificial example that we presented are precisely specified.

Discussion of the instability of EOF modes usually arises in the context of degeneration of EOF modes due to sampling errors as described in North et al. (1982). We made it clear in the introduction, as well as in the description of our artificial three-dimensional example and in the discussion in DL, that our artificial example has by construction no statistical uncertainties.

In North et al. (1982) a rule of thumb for the identification of degenerated EOF modes is described in which the statistical uncertainties of EOF eigenvalues result from the uncertainties in the estimation of the covariance matrix. The uncertainties in the covariance matrix in real datasets, in turn, result from the limited statistics (finite time series) from which the elements of the covariance matrix are estimated. Our artificial three-dimensional example is free of any such statistical uncertainties. The elements of the covariance matrix of our artificial three-dimensional example are not estimated from finite time series, in fact the covariance matrix is well defined by defining our basis modes and the relation between the modes. A degenerated EOF would only be present in our artificial three-dimensional example if the eigenvalues (explained variance) of two or more EOFs are identical to the precision to which we specified them. Numerical instabilities of our computing program are far below the precision that we specified to any value in our artificial example.

It is actually the main advantage of our artificial three-dimensional example, that all the numbers and patterns presented are absolutely accurate. Thus, the whole discussion in DL is not affected by the arguments in North et al. (1982) or other concerns about unstable EOF modes (we note that we do not know the two references given in Behera et al. 2003). It is actually one of our main points in DL that EOF or varimax representations can be very different from the real physical modes, even if no uncertainty in the estimation of the EOF or varimax modes exists.

3. Testing different hypotheses

Behera et al. (2003) report in their comments that several statistical characteristics or relationships are consistent with their dipole hypothesis. We can only agree to this, but we would like to point out that all the characteristics or relationships they present are indeed also consistent with the alternative hypothesis that a dipole mode does not exist. These characteristics can therefore not be put forward as evidence for the existence of the dipole mode.

In the following, we would like to outline how these apparently contradictory hypotheses can be tested. Therefore, we would like to use the concept of the artificial three-dimensional example (described in DL) as a simplification of the Indian Ocean SST variability.

We assume that the response to ENSO is the most dominant mode of SST variability in the Indian Ocean, which can be simplified as a domainwide monopole (see Fig. 1, left). We further assume that the remaining ENSO-unrelated SST variability can be explained by local air–sea interaction, which will most likely favor localized SST modes. In the framework of our three-dimensional example we simplify the remaining variability by two local modes, as shown in Fig. 1 (left).

The dipole hypothesis from Behera et al. (2003) is treated in a similar way in Fig. 1 (right).

The two apparently contradictory hypotheses lead to essentially the same large-scale SST statistics as shown by the EOFs, varimax, and box regressions in Fig. 1. Since both hypotheses describe the same SST statistics, analyses based on these statistics cannot be used to either support or reject one of the two hypotheses. It therefore does not make sense to count the number of dipole events, as Behera et al. (2003) do, in order to support the existence of a dipole mode. The numbers of expected dipole events are the same in both hypotheses.

According to Behera et al. (2003) the linear relationship between the IOD index and the zonal wind anomalies along the Indian Ocean equator as shown in their Fig. 1 should support the ocean–atmosphere coupled nature of the IOD mode. We do not see why this relationship should not exist in our ''local'' hypothesis. Thus the apparent ''physical and dynamical understanding of various ocean–atmosphere parameters'' in Behera et al. (2003) or Saji et al. (1999) cannot be put forward as evidence for the dipole mode, since they are also consistent with the alternative local hypothesis, which does not include a dipole mode.

Furthermore, Behera et al. (2003) state in their section 4 ''The question, which arises here, is: is it possible to identify the dipole mode in the real SST data using these two methods? This can be achieved by filtering out the monopole mode related to ENSO (Fig. 4).''

Removing the ''monopole mode related to ENSO,'' which is the ENSO response mode, would indeed be a good strategy for testing the hypothesis of a dipole mode. However, it cannot be done by removing EOF1, since this already assumes that EOF1 is identical to the ENSO response, which is not necessarily true. In Table 1, the contributions of different hypothetical modes to the time evolution [the principal component (PC)] of EOF1 are shown. For the dipole hypothesis of Behera et al. (2003), the EOF1 is essentially identical to the ENSO response. In our hypothesis the EOF1 is a superposition of all modes, although it is dominated by the ENSO response.

In their section 2, Behera et al. (2003) point out that ''The correlation coefficient peaks at 0.75 when the Niño-3 (5°N–5°S, 90°–150°W) index leads the EOF mode by 4 months.''

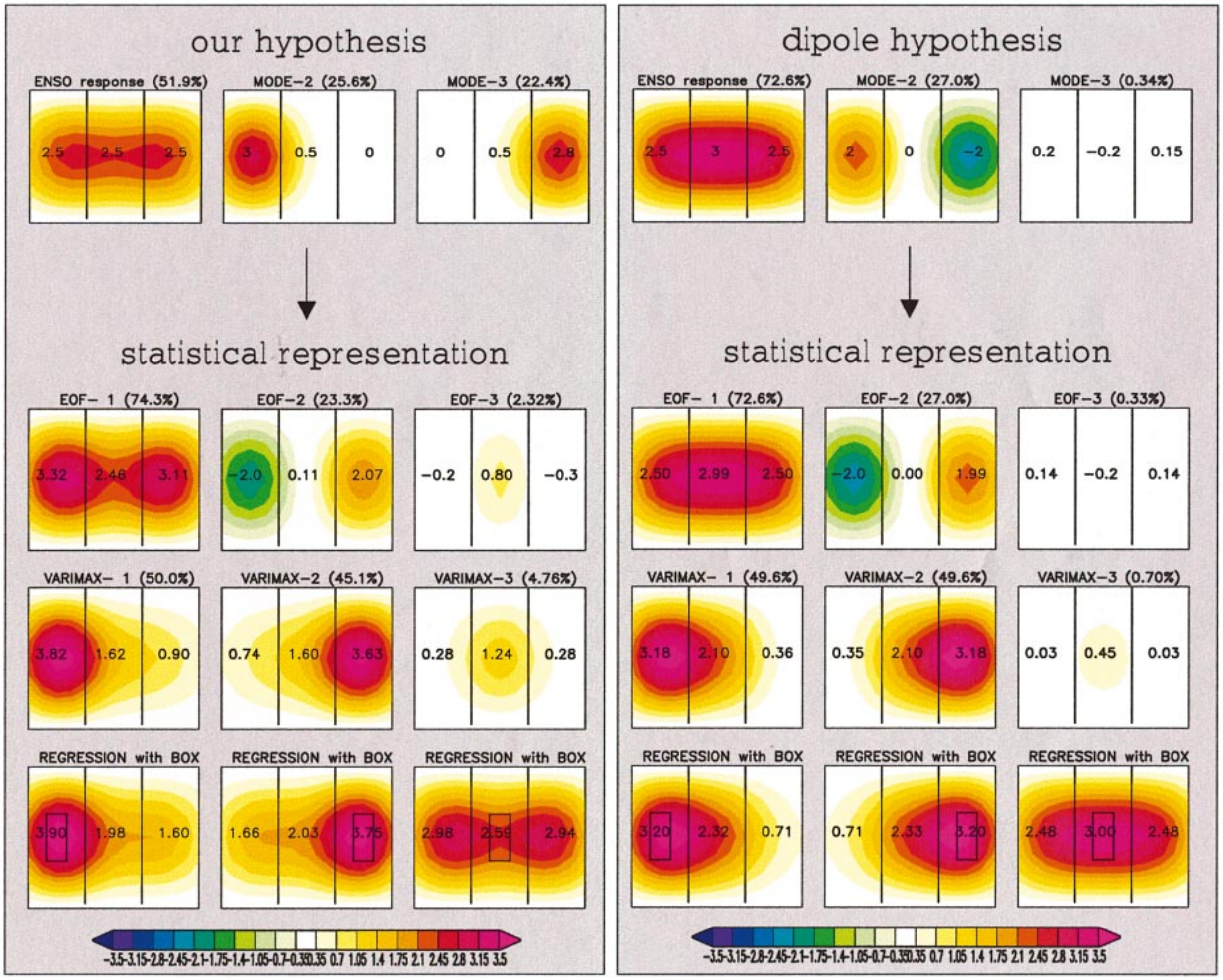

FIG. 1. The hypothetical modes and their statistical representations by EOFs, varimax patterns, and regressions of box-averaged SST in an artificial three-dimensional domain are shown for two different hypotheses. The amplitudes are in arbitrary units.

This indicates that at most 56% (0.75^2) of the variance of EOF1 is related to the ENSO response, while the remaining 44% is not related to ENSO. This appears to be consistent with our local hypothesis, but it is not consistent with the dipole hypothesis, in which EOF1 has to be identical to the ENSO response.

Thus removing EOF1 does not verify the existence of the dipole mode, since it already assumes that the dipole hypothesis is valid. Instead of removing EOF1, the real ENSO response should be removed.

In Fig. 2 we removed the ENSO response from the data prior to the statistical analyses. Now the statistical representations of the two hypotheses are very different. Similar to Fig. 4 in Behera et al. (2003), all statistical representations of the dipole hypothesis would now clearly point toward a dominant dipole mode. In our hypothesis, none of the statistical representations would show a dipole mode as the most dominant mode. Thus, removing the ENSO response mode properly would clearly show which of the two hypotheses is true.

TABLE 1. The contributions of the hypothetical modes to the PCs of the EOF1 vector for both hypotheses are shown.

Principal component	ENSO response	Mode 2	Mode 3
PC-1 (our hypothesis)	0.83	0.42	0.37
PC-1 (dipole hypothesis)	0.9999	0.0001	0.0128

Baquero et al. (2002) followed the strategy outlined above. In their analysis of observed SST variability in the Indian Ocean they removed the ENSO response statistically using the leading principal oscillation pattern (POP) mode of the tropical Pacific. In addition they also analyzed two global coupled general circulation models, one in which a realistic ENSO mode is present and one in which the ENSO mode is suppressed physically.

None of the analyses presented in Baquero et al. (2002) can support the dipole hypothesis. Moreover, all results seem to be consistent with our local hypothesis that the SST variability in the Indian Ocean is dominated

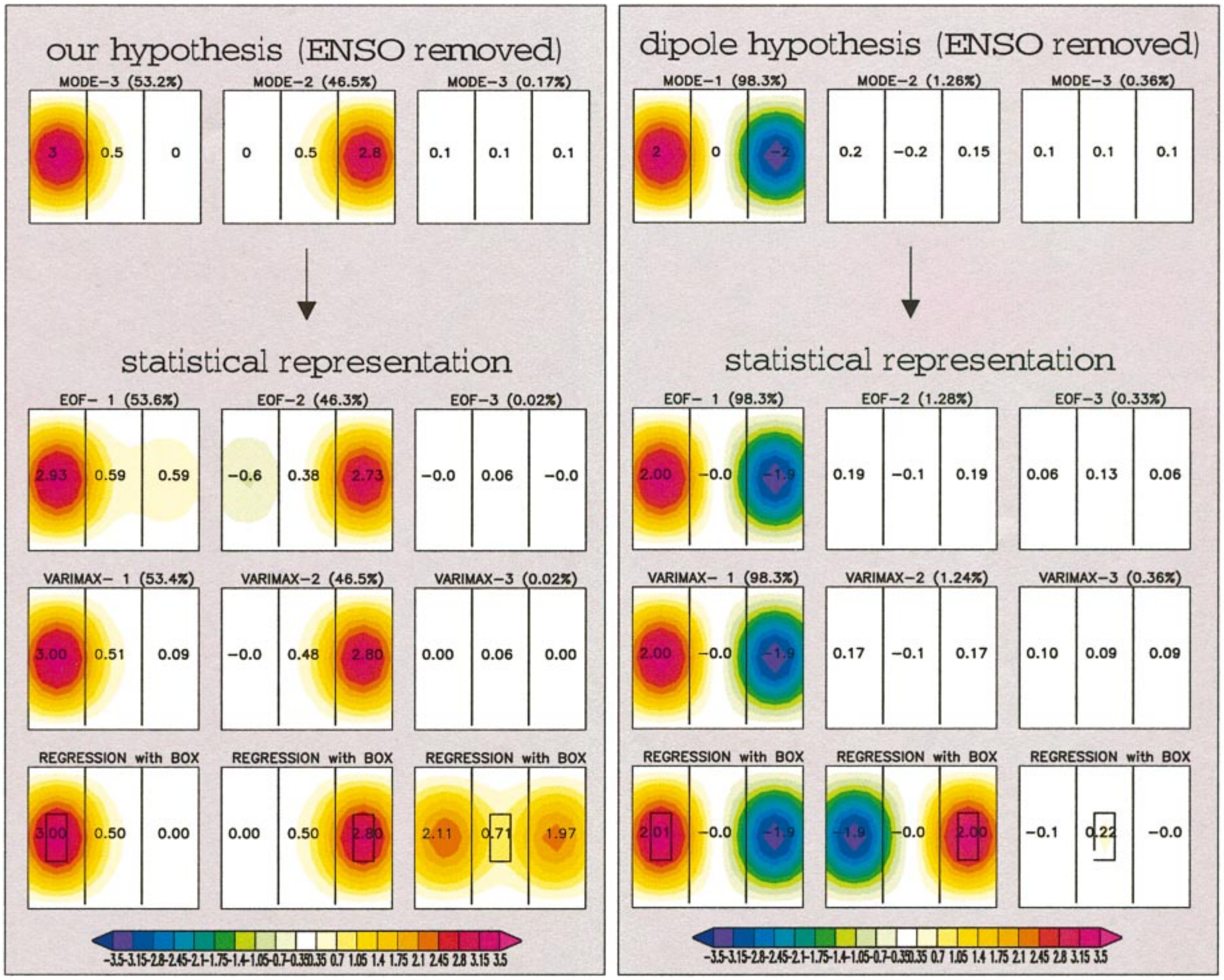

Fig. 2. As in Fig. 1, but the ENSO response mode has been removed from both hypotheses.

by the ENSO response alone and that the remaining ENSO-independent SST variability is consistent with local air–sea interaction.

Acknowledgments. This work was supported by the German government's Ocean CLIVAR program.

REFERENCES

Allen, R., and Coauthors, 2001: Is there an Indian Ocean dipole, and is it independent of the El Niño–Southern Oscillation? *CLIVAR Exch.,* **6** (3), 18–22.

Baquero, A., M. Latif, and S. Legutke, 2002: On dipolelike variability of sea surface temperature in the tropical Indian Ocean. *J. Climate,* **15,** 1358–1368.

Behera, S. K., S. A. Rao, H. N. Saji, and T. Yamagata, 2003: Comments on ''A cautionary note on the interpretation of EOFs.'' *J. Climate,* **16,** 1087–1093.

Dommenget, D., and M. Latif, 2002: A cautionary note on the interpretation of EOF. *J. Climate,* **15,** 216–225.

Jolliffe, I. T., 1989: Rotation of ill-defined principal components. *Appl. Stat.,* **38,** 139–147.

Krzanowski, W. J., 1984: Sensitivity of principal components. *J. Roy. Stat. Soc.,* **46B,** 558–563.

North, G. R., T. L. Bell, R. F. Cahalan, and F. J. Moeng, 1982: Sampling errors in the estimation of empirical orthogonal functions. *Mon. Wea. Rev.,* **110,** 699–706.

Richman, M. B., 1986: Review article: Rotation of principal components. *J. Climatol.,* **6,** 293–335.

Saji, N. H., B. N. Goswami, P. N. Vinayachandran, and T. Yamagata, 1999: A dipole mode in the tropical Indian Ocean. *Nature,* **401,** 360–363.