



## Passage of intraseasonal waves in the subsurface oceans

T. N. Krishnamurti,<sup>1</sup> Arindam Chakraborty,<sup>1</sup> Ruby Krishnamurti,<sup>2,3</sup> William K. Dewar,<sup>2</sup> and Carol Anne Clayson<sup>1,3</sup>

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[1] This study exploits the coverage of ARGO (Array for Real-time Geostrophic Oceanography) float data sets towards identifying passage of intraseasonal waves over the subsurface global oceans. ARGO, a new observing system, has provided an unprecedented data coverage and impact. The assimilation of ARGO data reveals that the subsurface ocean temperature carry signatures on the passage of the intraseasonal waves. This vast oceanic data sets provided an opportunity to explore the usefulness of coupled assimilation for seasonal forecasts on the passage of these waves. The results suggest that the inclusion of subsurface ARGO profiler data sets can be useful for prediction of the intraseasonal waves in the atmosphere/oceans. These improved forecasts hold the promise for improved seasonal outlook projections for the dry and wet spells of the monsoon. We also demonstrate improved phase relationship on the passage of zonal wind anomalies of the intraseasonal waves and the monsoon rainfall.

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### 1. Introduction

[2] The Madden-Julian Oscillation (MJO) [Madden and Julian, 1971, 1972] is a tropically centered low frequency ( $\sim 45$  days), eastward moving, atmospheric wave, with an important expression over the Indian and Pacific Oceans. MJO is a strong meteorological event (zonal wind anomalies are a few meters per second) that is thought to influence regional cloud cover, precipitation and the outgoing long-wave radiation [Madden and Julian, 1971; Waliser, 2006]. As the MJO wave traverses east from Africa to Asia, takes a northward swing during the northern hemisphere summer season at which point it has been associated with the Indian monsoonal Intraseasonal Oscillation (ISO) [Yasunari, 1980; Sikka and Gadgil, 1980; Krishnamurti and Subrahmanyam, 1982; Waliser, 2006]. Recent reviews [e.g., Waliser, 2006; Krishnamurti et al., 1992] addresses the relationship among MJO and ISO. The MJO wave carries its largest amplitude in the equatorial latitude in roughly 20 to 60 days. This wave is generally illustrated using longitude-time diagram. This is a divergent wave and generally propagates west to

east across the Indian Ocean and the western Pacific unabated in amplitude [Krishnamurti et al., 1985]. The ISO is a meridionally propagating wave that seems to originate in the southern equatorial trough (which is located near  $5^{\circ}\text{S}$  and can be seen in the sea level pressure data sets). Two meridionally propagating components one moving north and another moving south originating from the southern equatorial trough can be mapped on latitude-time diagram [Krishnamurti et al., 1992], where it was noted that arrival of an active part of an MJO wave over the equatorial Indian Ocean often seem to trigger the ISO wave. The dynamics of this coupling of MJO and ISO is not clear at the present time. In his review paper Waliser [2006] states that the MJO and ISO are essentially the same phenomenon. The Indian ocean region showing an off equatorial meridional passage. The ISO wave generally moves northward over south Asia at a phase speed of roughly  $1^{\circ}$  latitude per day and has a zonal and meridional scale of roughly 3000 km. The ISO appears to impact dry and wet spells of the Indian summer monsoon [Yasunari, 1980], providing strong rationale for improving MJO and ISO forecasts. Forecasts of both the MJO and ISO have proved difficult. Opinions vary as to why [Lindzen, 1974; Lau and Peng, 1987; Zhang and McFarlane, 1995; Maloney and Hartmann, 2001; Randall et al., 2003; Zhang and Mu, 2005]. Some studies show the value of uncoupled models [e.g., Wang and Xie, 1997; Hendon, 2000] while others emphasize coupled atmosphere-ocean models [e.g., Waliser et al., 1999; Fu and Wang, 2004]. We propose that the oceans have a major impact in the modeling of MJO/ISO, stressing in particular the value of coupled assimilation of the global subsurface ocean.

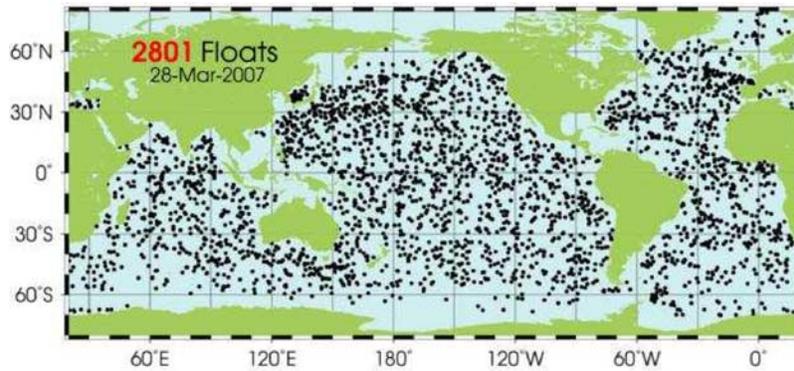
### 2. Models and Methodology

[3] The present study is based on an ensemble of four coupled global models [Krishnamurti et al., 2000; Chakraborty and Krishnamurti, 2006; Krishnamurti et al., 2006]. The atmospheric component consists of the Florida State University (FSU) global spectral model [Krishnamurti et al., 2007] (triangular truncation at 63 waves corresponding to  $1.875^{\circ}$  transform grid, 14 vertical levels), while the ocean component is a modified version of the Hamburg Ocean Primitive Equation (HOPE) model [Latif, 1987]. The ocean model horizontal resolution is  $5.0^{\circ}$  in longitude and from  $0.5^{\circ}$  to  $5.0^{\circ}$  in latitude, finest resolutions being at the equator. The ocean surface is relatively well resolved with 10 of the 17 model layers occurring in the upper 300 meters. The atmospheric model carries a full array of physical parameterizations. The ensemble members differ in the details of the atmospheric physics [Chakraborty and Krishnamurti, 2006; Krishnamurti et al., 2006]. The atmosphere-ocean interface definitions are

<sup>1</sup>Department of Meteorology, Florida State University, Tallahassee, Florida, USA.

<sup>2</sup>Department of Oceanography, Florida State University, Tallahassee, Florida, USA.

<sup>3</sup>Geophysical Fluid Dynamics Institute, Florida State University, Tallahassee, Florida, USA.



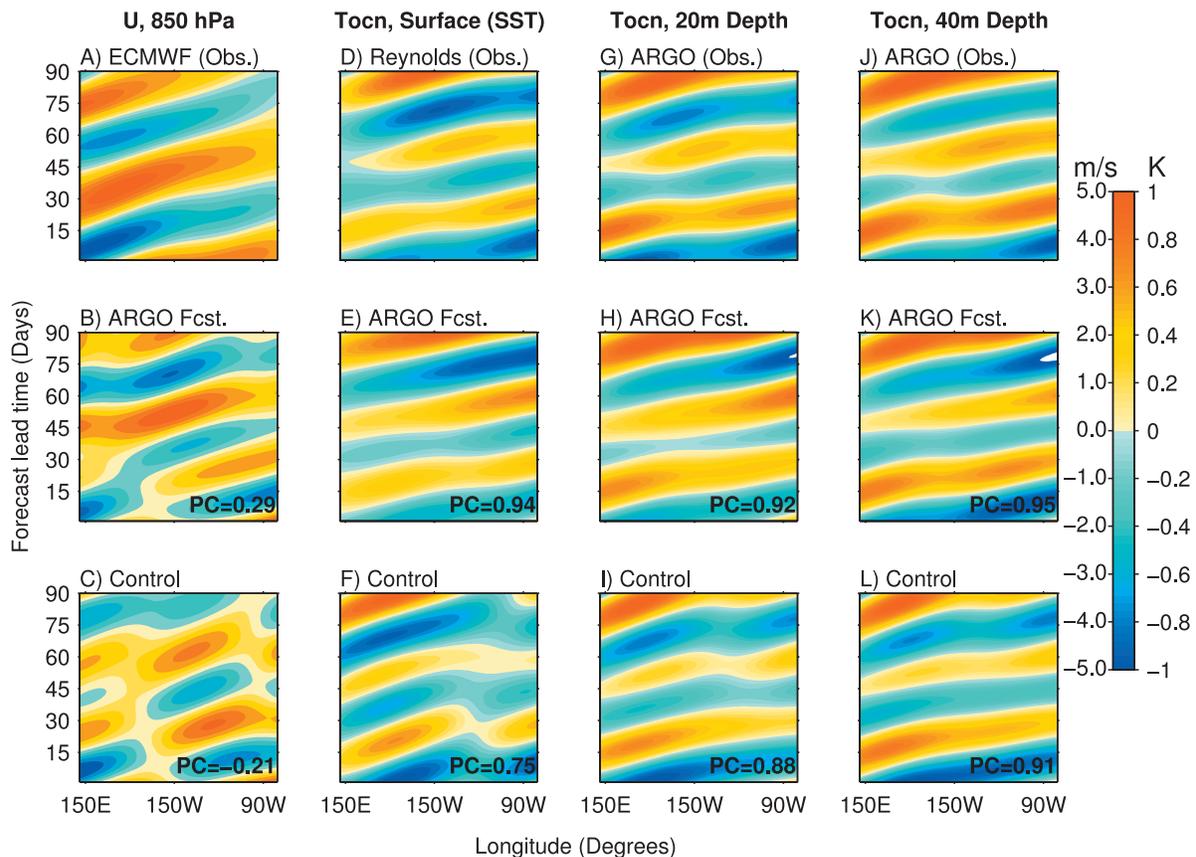
**Figure 1.** Global distribution of ARGO floats as on 28 March 2007 as obtained from <http://www.argo.ucsd.edu/>. These floats provide continuous measurements of temperature, salinity, and velocity profiles up to a depth of 2000 meters in the ocean.

described by *Larow and Krishnamurti* [1998]. The results for the MJO/ISO forecasts shown in this paper are all based on the ensemble averages of these four members. This model successfully simulated 1997/98 El-Niño phenomenon [*Krishnamurti et al.*, 2000].

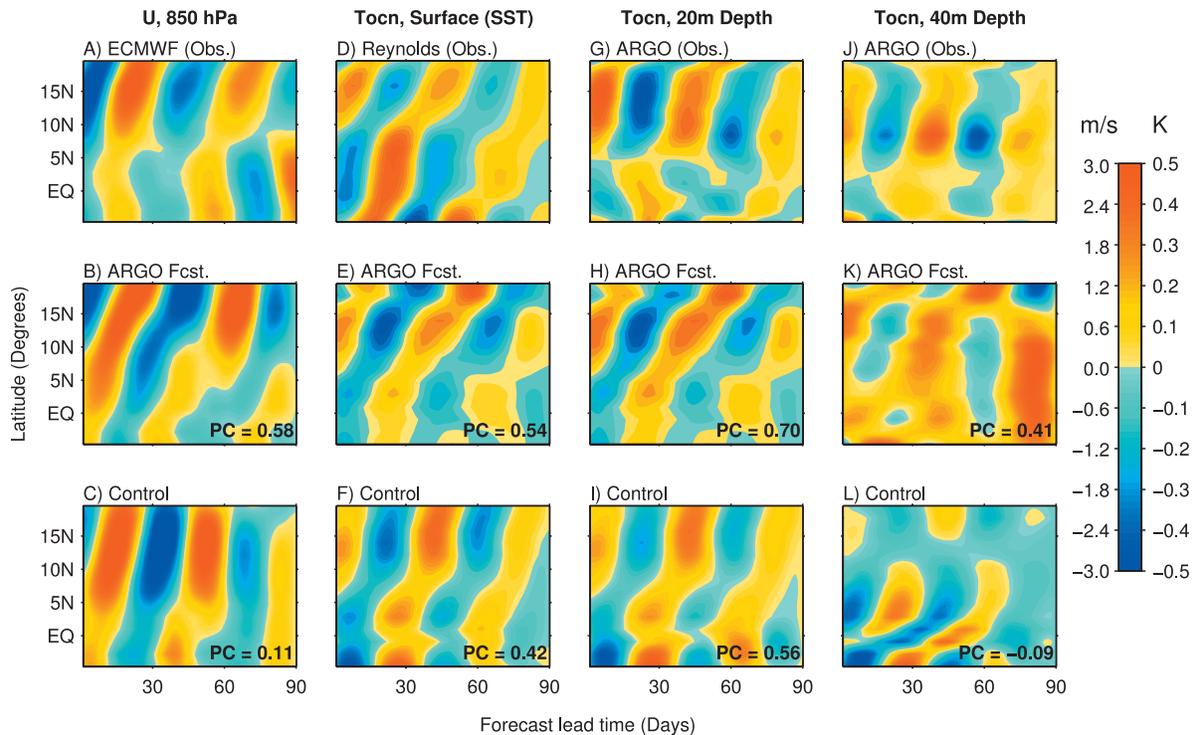
### 3. Experimental Details

[4] The data sets used for our coupled assimilation include (1) ECMWF (European Centre for Medium-Range

Weather Forecasts) reanalysis; (2) daily precipitation from satellites; (3) ocean temperature from satellite and ships of opportunity [*Reynolds and Smith*, 1995]; and (4) the ARGO (Array for Real-time Geostrophic Oceanography) temperature profiling data over global oceans. It is the use of the latter data set that this study departs most importantly from previous studies in its assimilating strategy. Figure 1 illustrates the coverage provided by the ARGO floats. Currently there are close to 2800 floats covering the global ocean providing temperature and salinity profiles over the top



**Figure 2.** Observed and predicted Madden-Julian Oscillation (MJO) waves (time scale of 30 to 60 days) of zonal wind at 850 hPa level and ocean temperatures from 30 May 2004 through 27 August 2004 (averaged over 5°S to 5°N) from observations in the upper panels, and coupled model forecasts that included (did not include) temperature profile data from ARGO floats for its coupled assimilation in the middle (lower) panels. The pattern correlations (PC) between the observed and predicted propagating waves are indicated inside the respective forecast panels.



**Figure 3.** Observed and predicted Intraseasonal Oscillation (ISO) waves (time scale of 30 to 60 days) of zonal wind at 850 hPa level and ocean temperatures from 30 May 2004 through 27 August 2004 (averaged over 65°S to 95°N) from observations in the upper panels, and coupled model forecasts that included (did not include) temperature profile data from ARGO floats for its coupled assimilation in the middle (lower) panels. The pattern correlations (PC) between the observed and predicted propagating waves are indicated inside the respective forecast panels.

2000 m. The irregularly spaced ARGO profiles were interpolated to the ocean model grid using univariate (for temperature) interpolation technique.

[5] The ocean is first spun up over the 10 year span from 1978 to 1987. Here we use a Newtonian relaxation method to assimilate the sea surface temperature (SST) towards observed SST [Reynolds and Smith, 1995] while imposing the wind stresses [Krishnamurti *et al.*, 2000; Larow and Krishnamurti, 1998].

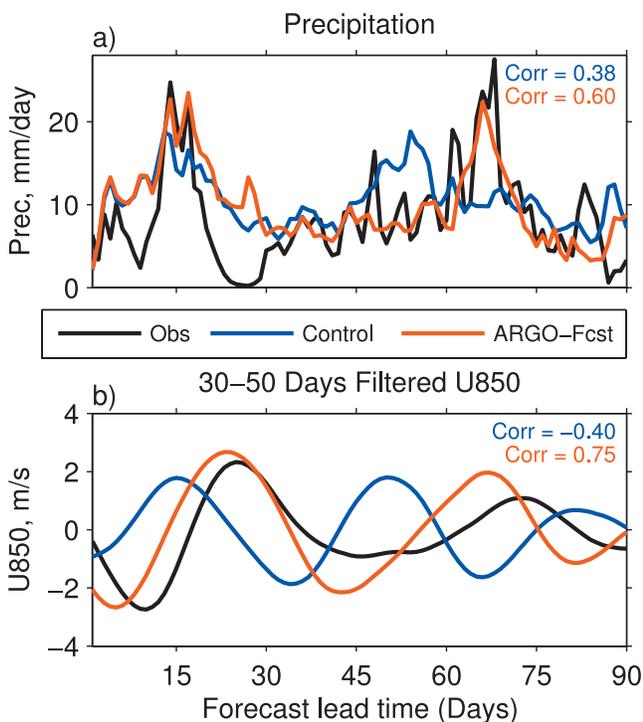
[6] Then coupled assimilation begins, using daily atmospheric assimilation of the ECMWF analysis. The ocean is weakly relaxed on a daily basis towards the observed SST [Krishnamurti *et al.*, 1991]. The set of experiments which used the assimilation procedure described above will be termed as control in this paper. We have performed another set of experiments where, in addition to the procedures adopted for control, the ARGO temperature profiles at the subsurface ocean (from and below 20 m) were assimilated to the model at its coupled assimilation phase using a similar technique [Krishnamurti *et al.*, 1991]. This experiment will be termed as ARGO-Fcst in this paper.

[7] Our forecasts used oceanic initial conditions from the respective coupled assimilation for control and ARGO-Fcst experiments. Atmospheric initial conditions were identical for both control and ARGO-Fcst. Model forecasts commenced at the end of every month during the three years period 2003–05. Each forecast was 90 days long. For comparison purposes, the observed data and model output

were processed using a fourth order Butterworth band pass filter to extract the 30 to 60 days mode of oscillation.

#### 4. Results

[8] Figure 2 illustrates our seasonal forecasts over the Pacific Ocean averaged over 5°S–5°N from June through August, 2004. Alternate passages of westerly (red) and easterly (blue) zonal winds and ocean currents are seen in this figure. For SST fields, the maximum amplitude was roughly 1.0 K. Figures 2g and 2j show corresponding subsurface temperature at 20 m and 40 m depths respectively. Comparison with Figures 2a and 2d depicts the passage of a coherent MJO signal within the subsurface oceans and the atmosphere. Stronger westerly (easterly) wind anomalies relate to warm (cold) SST anomalies on this time scale. Model forecasts of these respective anomalies are presented in the middle panels (with ARGO data assimilation) and in the bottom panels (without ARGO data assimilation). Within each of these panels we have also included the pattern correlations (PC) of the respective forecasts along with the observed field. Clearly, assimilation of ARGO float data results in a superior forecast. A calculation of significance level on correlation coefficient confirmed that the PCs from control and ARGO forecasts were different at a significance level of 99%. To calculate significant level we have considered number of degrees of freedom as the total number points in space (longitude) and time. Figure 2 shows that the eastward phase speed of the



**Figure 4.** (a) Observed (GPCP) and predicted (Control and ARGO-Fcst) time series of daily precipitation (in  $\text{mm day}^{-1}$ ) over north-central India (averaged over  $70^{\circ}\text{E}$ – $90^{\circ}\text{E}$  and  $15^{\circ}\text{N}$ – $25^{\circ}\text{N}$ ) during 30 May through 27 August of 2004. The correlation coefficients between the observed and predicted time series are indicated at the top of the panel. (b) Same as Figure 4a but for 30–50 days filtered zonal wind from ERA40 and model simulations.

MJO is reasonably predicted where the ARGO float data sets are assimilated, i.e., roughly 45 days around the globe. The control experiment (without ARGO data assimilation) carries relatively large phase errors, especially around  $130^{\circ}$ – $150^{\circ}\text{W}$ .

[9] The observed and predicted fields of the zonal wind anomalies on the ISO time scale averaged over  $65^{\circ}$ – $95^{\circ}\text{E}$  are illustrated in Figure 3 in a latitude-time plot from June through August, 2004. We illustrate in Figure 3a the zonal wind at 850 hPa from ECMWF analysis and in Figure 3b an ensemble forecast including ARGO initialization. Northward propagation is seen here, while in Figure 3c, which excludes the ARGO initialization, northward propagation is not predicted. Interestingly, zonally averaged ocean temperature at the ocean surface (Figure 3d), at 20 m depth (Figure 3g) and at 40 m depth (Figure 3j) show a clear meridionally propagating ISO signal in the observations, especially north of  $5^{\circ}\text{N}$ . The amplitude of this anomaly is of the order of 0.5 K. The corresponding predicted fields where the ARGO data sets were assimilated appear in Figures 3b, 3e, 3h, and 3k; the forecasts where ARGO data sets were excluded are shown in Figures 3c, 3f, 3i, and 3l. Pattern correlations of the predicted vs. observed ISO signals are indicated in the respective panels. Forecasts using ARGO initialization carried correlations of 0.58, 0.54, 0.70 and 0.41 respectively. The corresponding corre-

lations where ARGO data sets were excluded were 0.11, 0.42, 0.56 and  $-0.09$  respectively. All these correlations from ARGO-Fcst were significant at 99% with respect to the control (Calculation of the degrees of freedom was similar to that discussed for Figure 2). Further, the control run failed to predict the ISO waves at the 40 m depth.

[10] Wet spells of the monsoon are generally found over regions where the westerly anomalies of ISO coincide with the climatological summer monsoon westerlies of the lower troposphere [Krishnamurti and Subrahmanyam, 1982]. Figure 4 illustrates the time series of total rainfall averaged over north-central India ( $70^{\circ}\text{E}$ – $90^{\circ}\text{E}$ ,  $15^{\circ}\text{N}$ – $25^{\circ}\text{N}$ ) from observations (Global Precipitation Climatology Project, GPCP) [Huffman et al., 2001], and control and ARGO-Fcst experiments. Two wet spells around 9 to 20 June and 28 July to 8 August are captured when ARGO is used in the ocean assimilation phase. Correlations of the forecasted time series with the observation were 0.38 and 0.60 for control and ARGO-Fcst respectively.

[11] The phase relationship among the zonal wind anomalies and precipitation can be seen comparing Figures 4a and 4b. The black line in the top and the bottom panels show the total rain and the zonal wind anomaly based on observations (GPCP for rainfall and ERA40 for zonal wind). The red lines denote the same from the ARGO based model runs and the blue line denote the same from the control experiment that excluded the ARGO data sets in its assimilation. There is clearly an improvement in the prediction of rains when the ARGO data are assimilated for the coupled model forecasts. This improvement is to be attributed to the improved definition of ISO in the atmosphere and the ocean in this forecast.

## 5. Summary

[12] The major finding of this study is on the passage of MJO/ISO waves in the subsurface oceans. The passage of this wave is well known in the atmosphere. Coupled atmosphere-ocean modeling with multimodels including global ARGO subsurface temperature assimilation provides an improved forecast of MJO/ISO. Signal of the waves appear in both the atmosphere and the ocean. These improvements can be used to improve seasonal precipitation outlooks for the monsoon and for the tropical SST fields (not shown). We showed that monsoon precipitation forecasts using ARGO data base carries higher skills compared to the control experiment. This was probably due to improved SST forecasts over the tropics.

[13] The basic question as to whether the MJO/ISO waves are intrinsic to the ocean or the atmosphere or whether they are in a coupled state of equilibrium is not answered here. Air-sea interaction is a vital link between the atmosphere and the oceans. These transfer processes are not linear and involve triple product correlations among waves of different scales in the atmosphere and in the ocean. Computations of the formal scale interaction among relevant scales of the ocean and the atmosphere are necessary to further understand the intrinsic nature of MJO/ISO.

[14] We have also tested the use of prescribed monthly mean SSTs in an atmospheric general circulation model, that failed to simulate the ISO in the atmosphere. Artificial suppression of the MJO signals in SST or surface stress

during coupled model forecasts also failed to produce the ISO.

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A. Chakraborty, C. A. Clayson, and T. N. Krishnamurti, Department of Meteorology, Florida State University, 430 Love Building, Tallahassee, FL 32306, USA. (tnk@io.met.fsu.edu)

W. K. Dewar and R. Krishnamurti, Department of Oceanography, Florida State University, Tallahassee, FL 32306, USA.