The Dynamics and Physics of Multiple Strait Systems

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LONG-TERM GOALS

To determine how island groups interact, so enabling us to evaluate how best to 'parameterize' these groups in 3-D numerical ocean models used in forecasting, which cannot necessarily resolve all of the islands and interconnecting straits. The theories and models are being developed in a general framework, so that they have application to arbitrary multiple-strait systems.

OBJECTIVES

1. To construct models of sub-inertial, wave scattering along gappy shelves with a mean flow through the gaps to explain features of the three years of shallow-pressure gauge data collected around the Indonesian throughflow exit region by Bray, Sprintall et al.

2. To make the best possible estimate of transport through Makassar Strait based on the 20 months of ARLINDO current meter data collected at adjacent moorings in Makassar Strait given the limitations of the data.

APPROACH

1. A preliminary analysis of the shallow-pressure gauge data revealed that the amplitude and phase of the fluctuations at the Sumbawa gauge were almost identical to those at the Bali gauge on all time-scales ranging from days to months. This is in apparent contradiction with Sprintall et al. (2000), who suggest that the semi-annual period Kelvin wave, generated in the equatorial Indian Ocean, propagates along the south Java coast, enters the Lombok Strait, and then continues around the Java Sea and northward up Makassar Strait, so accounting for the reduction in transport there observed in the ARLINDO data during May/June 1997. A theory has been developed, which satisfies the pressure-gauge observations, and also permits a relationship between signals propagating along the Java shelf and transport in Makassar Strait. The theory is subtly different from the mechanism described by Sprintall et al. (2000), which leads to significant consequences, as discussed below. Very high-resolution numerical simulations are being performed to test and extend the theory.

2. Due to failure of the ADCPs on the ARLINDO moorings, there are only data for the upper 250m from one of the mooring for 3 months. Wajsowicz et al. (2001) attempt to reconstruct the velocity profiles over the total depth by fitting normal modes to the available data. The recovery technique has been applied to a range of test profiles to establish error estimates. Time series from GCMs and

TOPEX data have been used to give some sense of how representative statistics, e.g. annual mean, and amplitudes and phases of the annual and semi-annual harmonics, calculated from the Makassar data may be.

WORK COMPLETED

1. Data from the nine shallow-pressure gauges were obtained from Dr. Sprintall including those for the final cycle. These data were processed, and correlation analyses performed to determine the coherency between gauges at various frequencies. Wave-scattering theories and knowledge of the sources at different frequencies were used to build up schematics of the travel paths. The validity of these schematics was tested by making deductions on the exact location of the gauges in relationship to topographic features prior to Dr. Sprintall providing copies of navigation charts showing the location of the gauges. The inconsistency with Sprintall et al. (2000) was noted, and Lombok Strait became the focus of further investigation. A connection between coastal-trapped waves and Makassar Strait transport variations was not ruled out, but the challenge was to develop a theory, which permitted a connection, but allowed most of the wave energy to continue along Java shelf. This theory is in the process of being tested and extended using a very high-resolution GCM developed by Prof. Paul Schopf. In collaboration with Prof. Schopf, a simple box bounded by lines of latitude and longitude with three quasi-isopycnal layers in the vertical was set up spanning the latitudes of Lombok Strait and the Java Sea. A simple island chain with sills at depths equivalent to those in Lombok and Timor Straits is included. A mechanism for conserving total mass, whilst permitting a nonlinear flow between the basins, was incorporated. A wave maker was also included. Several runs of the system have been made to test the grid-resolution and amount of friction needed to ensure that the flow is numerically stable, but governed by nonlinear dynamics in the straits. It has also been demonstrated that the model can simulate hydraulic jumps.

2. A revision of Wajsowicz et al. (2001) has almost been completed. A sample of test profiles has been constructed, which have then been degraded to varying degrees. The normal mode method developed was then used to attempt to reconstruct the profiles over the upper depths. This provides a measure of the errors likely in the reconstruction using the actual data. During this analysis, it was noted that the data from the two moorings are not always well correlated especially over the upper 50-100m for which data is available. This is being investigated further. TOPEX data, and output from two GCM hindcasts, were acquired to investigate the temporal spectra of the region.

3. A detailed survey of the vertical structure, and what governs that over the upper depths, has been made for numerous GCMs, and compared with the ARLINDO data. The results were written up as part of a related study conducted under my NASA-funded research, and the manuscript is in press at Climate Dynamics, Wajsowicz (2001a).

4. Minor revisions were made to the manuscript on my Caribbean research reported last year, Wajsowicz (2001b), which has been accepted and is now in press at Journal of Physical Oceanography.

RESULTS

Equatorial Kelvin waves generated in the Indian Ocean have part of their energy scattered into poleward propagating coastal Kelvin waves (CKWs) at the eastern boundary. If these waves, and others generated locally along the Java shelf, scatter into Lombok Strait and northwards and through

Makassar Strait, as described by Sprintall et al. (2000), then one would except to see the signal at the Sumbawa gauge substantially reduced, as shown in the GCM results of Yamagata et al. (1996). Also, not only should it be true for the semi-annual wave, but also for waves at other frequencies, i.e. one would expect there to be good correlation between Makassar and Lombok Strait transports at other frequencies, unless there were significantly different signals propagating in the other direction in each strait. Analysis of the signal at the Sumbawa gauge shows that it is well correlated with the Bali signal; the agreement is obvious by visual inspection, see Fig. 1a. The wavelength of a first baroclinic mode Kelvin wave of semi-annual period is ~$4x10^4$km. Lombok Strait narrows from about 100km to 40km at its narrowest point. The open-ocean first baroclinic mode Rossby radius at the latitude of Lombok Strait is ~100km. Therefore, irrespective of the presence of a shelf or sill, the wavelength of the coastal Kelvin wave is very large compared with the gap width, and so the semi-annual period wave does not see the gap; this is true for first baroclinic mode CKWs with periods very much greater than 1 day. In the absence of local forcing, the result is a uniform pressure along the coast. If there were no flow through Lombok Strait, then from continuity in pressure and the proximity of a Bali gauge to that on Sumbawa, the pressure signals would be very similar. However, it is important to note that this does not imply the same amount of wave energy propagating past at each location. The Java shelf extends to around 2000m, therefore the Sumbawa signal results from wave energy over this whole depth. In contrast, although the strait is quite deep at the Bali gauge, a wave propagating along the Java shelf has turned into Lombok Strait and crossed a 250m sill to reach the gauge. The total-depth energy in the signal at Bali therefore represents only a small fraction of that propagating along the south Java coastal waveguide, and either will be dispersed as the shelf deepens again around the Java Sea or reflected at the width constriction just to the north, c.f. Wajsowicz (1991). From Fig. 1a, the signal at the Lombok gauge is occasionally similar to that on Bali, but reduced, e.g. through 1998. On other occasions, it is quite different, e.g. through much of 1996 and the first part of 1997. The latter confirms that the Lombok gauge is in a dynamically different region to the Bali gauge; the distance between the Lombok and Bali gauges is of the order of the strait Rossby radius, therefore if CKWs came through the strait from the south Java shelf, they would record on the Lombok gauge. The Lombok gauge is typically recording signals propagating along the northern coast of Lombok, and islands to the east. Occasions when the two gauges are in unison are indicative of similar local forcing.

The seasonal cycle was extracted from the data, as shown in Fig. 1b. With the except of May and June, the signals at the gauges follow the pattern described above with the amplitude at the Bali gauge reduced over that of the Sumbawa gauge, but of the same tendency; the Lombok gauge signal is not obviously related to either. The signal at the Sumbawa gauge is relatively small over these couple of months, the Lombok gauge is at a positive maximum, and the Bali gauge achieves a positive maximum. Harmonic analysis of the data, however, shows that the annual and semi-annual period signals at Bali and Sumbawa are similar in amplitude and phase with the amplitude at Bali weaker. Inspection of the individual years in Fig. 1a shows that May and June 1998 have biased the seasonal cycle estimate. There are a few days in early June 1997 when the Bali signal is greater than the Sumbawa signal. The ARLINDO data did not show a reduction in transport in May/June 1998.

It is noteworthy that the residual annual-scale and intra-seasonal variability, shown in Fig. 1c, is as great as the month-to-month variability, shown in Fig. 1b. The residual annual-scale Bali and Sumbawa signals are very similar in amplitude and phase; that at Lombok slightly weaker and the phase is neither consistently leading or lagging. The source of variability on these time-scales is equatorial Rossby waves generated in the Pacific Ocean, which are partially transmitted through the archipelago when they are incident on the Pacific western boundary. In this case, the signals may be considered generated by Rossby waves emanating from the western boundary of the Australian continent, c.f. Wajsowicz (1995).

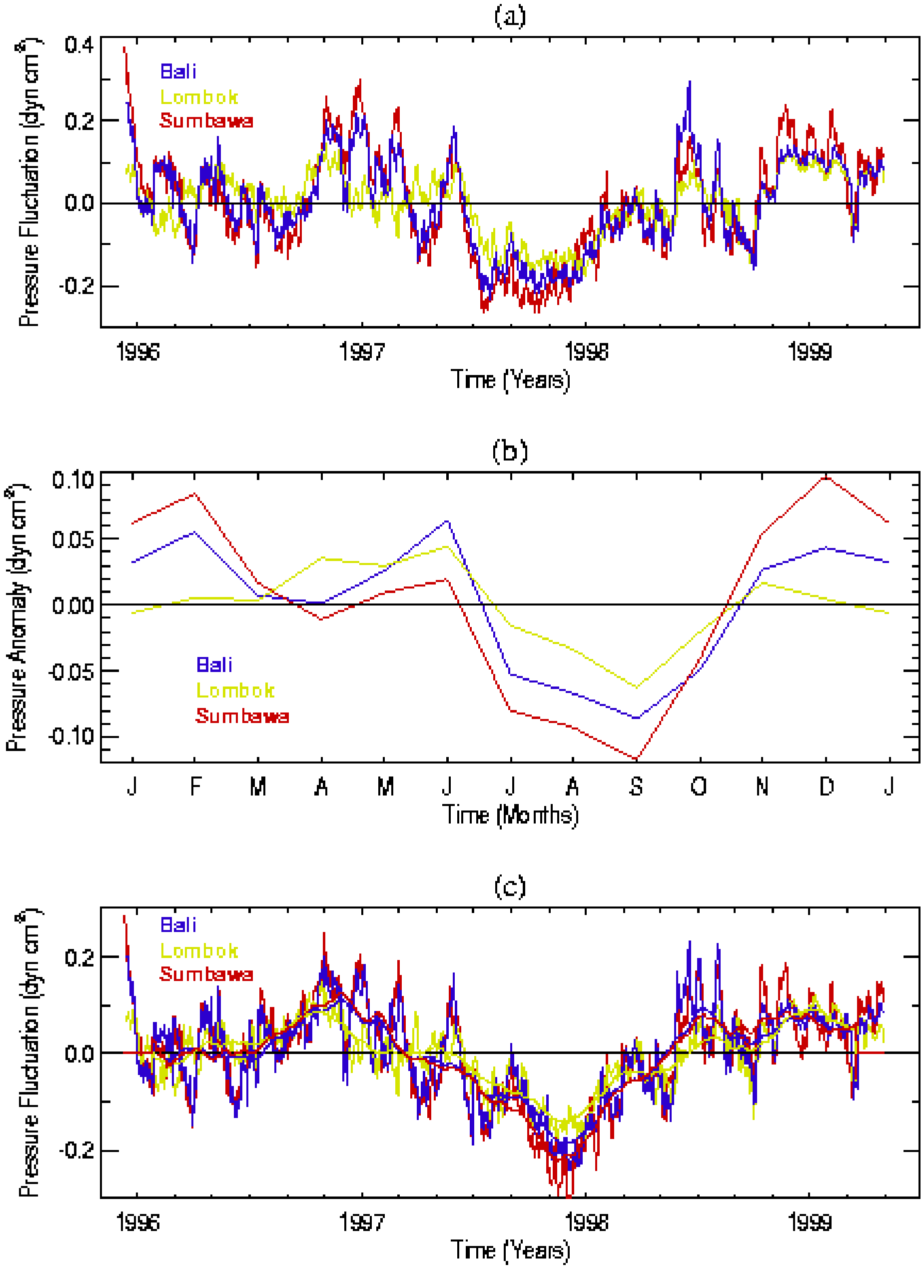

Fig. 1 The near-surface pressure fluctuations at the Bali, Lombok and Sumbawa pressure gauges. The signals at the Bali and Sumbawa gauges have similar amplitude and phase at all sub-inertial frequencies. This indicates that they lie on the same shelf in a dynamical sense – the Bali gauge was indeed located just to the south of the headland at Mt. Seraya – but importantly not necessarily the same wave amplitude. The Lombok gauge signal is quite different implying that it is dynamically isolated from these two gauges – it was 'hidden' behind the Gilli Islands. The daily averaged values are plotted in (a) with the mean and linear trend removed. The monthly averaged values for the 3.3 year time series are plotted in (b), and the resulting anomalies are plotted in (c) along with 90-day running means for each gauge.

The above discussion can be simply formalized. However, questions remain on the effect of a mean flow through the strait, and whether this will prevent smaller scale features such as CKW fronts and higher order modes from penetrating the strait, and also the effect of 3-dimensionality. As the Bali signal is as noisy as the Sumbawa signal, it is unlikely that the flow through Lombok Strait is hydraulically controlled. However, from the current meter observations of Murray and Arief (1988), it is expected that the dynamical balance in the Strait is nonlinear rather than geostrophic. If the Bali and Lombok gauges were directly opposite each other, then the observed difference in their signals would be very surprising, and indicative of a strong cross-strait pressure gradient and a significant geostrophically balanced along-strait transport. However, the gauges were not directly opposite. The Lombok gauge was behind the Gilli Islands to the north, and the Bali gauge just to the south of the headland at Mt. Seraya. Therefore, they may be considered instead a measure of the fluctuating along-strait pressure gradient across the width constriction. In a classical steady, single-layer sill model, if d measures the fluid depth, h the depth of the surface below some reference height in the upstream reservoir where the velocity is zero, and v is the fluid velocity, then the transport is Q=vd, and from Bernoulli's equation $v^2=2gh$, where g is gravity. Therefore, $Q=(2gh)^{1/2}d$. If a wave propagates across the mouth of the strait, so reducing d (and increasing h by the same amount), say, an adjustment will be initiated in the strait. If the wave is of sufficiently low frequency, then the adjustment will have to be substantial and affect the upstream reservoir; it is equivalent to setting a new steady state with a reduced Q. A higher frequency wave crossing the mouth of the strait would also generate an adjustment, but in a realistic framework need not substantially affect conditions in the upstream reservoir. These ideas are currently being tested and extended with a high-resolution numerical model.

The combined theory is subtly different from Sprintall et al. (2000), and the consequences are significant. The above theory satisfies the pressure gauge data, and importantly permits the CKW to continue on along the shelf affecting conditions downstream; energy for the wave adjustment in Makassar is extracted from the mean flow rather than the Java shelf CKW. It also provides a mechanism to decouple the Makassar and Lombok Strait transport variabilities at high frequencies.

IMPACT/APPLICATION

The development of sophisticated, numerical models for forecasting the ocean circulation and hydrographic state is a high priority for ONR, as is knowledge and understanding of the ocean circulation in strategically important regions such as the Indonesian archipelago, other east Asian marginal seas, and the Caribbean.

TRANSITIONS

In general terms, the P.I.'s research provides a theoretical framework in support of ONR's field programs (e.g. Gordon et al.'s ARLINDO and Sprintall et al.'s network of shallow pressure gauges in the Indonesian exit straits), and numerical primitive-equation modeling research at NRL, Mississippi (Hurlburt, Kindle and Preller) and NPGS (Semtner, Tokmakian and McClean). The methods and techniques developed are quite general, and so potentially have widespread application.

Caribbean Circulation Model: The results from this research have been made available to members of the Intra-Americas Seas Initiative, which includes groups at RSMAS, University of Miami and NOAA/AOML, as well as those listed above. The P.I. has convened a special session on the physical oceanography of the Caribbean at the Fall AGU meeting in San Francisco, December 2001, in order to discuss issues raised by this research

Lombok/Makassar Straits Linkage: These results will be written up for publication shortly, and made generally available. They are expected to have an enormous impact on how the region is represented in the next generation of GCMs.

RELATED PROJECTS

The P.I. is funded by NASA to investigate the hydrological cycle in the Indo-Pacific region. This involves running high-resolution, global numerical models. Accurate simulation of the transport of heat and fresh-water fluxes between the Pacific and Indian Oceans is crucial for these investigations. The P.I. is also funded by NOAA to investigate diabatic adjustment processes in the North Atlantic.

REFERENCES

Murray, S.P. and D. Arief 1988: Throughflow into the Indian Ocean through Lombok Strait, January 1985-January 1986, Nature, 333, 444-447.

Sprintall, J., A.L. Gordon, R. Murtugudde and R.D. Susanto 2000: A semisnnual Indian Ocean forced Kelvin wave observed in the Indonesian seas in May 1997, J. Geophys. Res., 105, 17217-17230.

Wajsowicz, R.C., 1991: On stratified flow over a ridge intersecting coastlines, J. Phys. Oceanogr., 21, 1407-1437.

Wajsowicz, R.C. 1995: The response of the Indo-Pacific throughflow to interannual variations in the Pacific wind stress. Part I: idealized geometry and variations, J. Phys. Oceanogr., 25, 1805-1826.

Yamagata, T., K. Mizuno, and Y. Masumoto 1996: Seasonal variations in the equatorial Indian Ocean and their impact on Lombok throughflow, J. Geophys. Res., 101, 12465-12473.

PUBLICATIONS

Wajsowicz, R.C. 2001a: Air-sea interaction over the Indian Ocean due to variations in the Indonesian throughflow, Clim. Dyn., in press.

Wajsowicz, R.C. 2001b: A modified Sverdrup model of the Atlantic and Caribbean circulation, J. Phys. Oceanogr., in press.

Wajsowicz, R. C. and P.S. Schopf 2001: The influence of wave propagation on transport between interconnecting basins, in preparation, to be submitted to J. Phys. Oceanogr.

Wajsowicz, R.C., A.L. Gordon, A.Ffield, and R.D. Susanto 2001: Transport and vertical shear variability in Makassar Strait, submitted to J. Phys. Oceanogr., under revision.