Quantifying the connection between Banda Sea diffusivity and tropical rainfall in a coupled climate model.

Markus Jochum and Jim Potemra

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Corresponding author’s address:

National Center for Atmospheric Research
1850, Table Mesa Drive
Boulder, CO, 80305
1-303-4971743
markus@ucar.edu
Abstract: Several observational studies suggest that the vertical diffusivity in the Indonesian marginal seas is an order of magnitude larger than in the open ocean and what is used in most ocean general circulation models. The experiments described in the present study show that increasing the background diffusivity in the Banda Sea from the commonly used value of 0.1 $cm^2/s$ to the observed value of 1 $cm^2/s$ improves the water mass properties there by reproducing the observed thick layer of Banda Sea water. The resulting reduced sea surface temperatures lead to weaker convection and a redistribution of precipitation, away from the Indonesian Seas towards the equatorial Indian and Pacific oceans. In particular, the boreal summer precipitation maximum of the Indonesian Seas shifts northward from the Banda Sea towards Borneo, which reduces a longstanding bias in the simulation of the Austral-Asian Monsoon in the Community System Climate Model. Because of the positive feedback mechanisms inherent in tropical atmosphere dynamics, a reduction in Banda Sea heat loss of only 5% leads locally to a reduction in convection of 20%.
1 Introduction

The maritime continent at the western edge of the Pacific represents a key region for the Walker circulation, and the overlying atmosphere is characterized by strong precipitation, convection and low level wind convergence. This can be attributed to the high sea surface temperatures (SSTs) in the Indonesian Seas which provide a significant source of energy to the atmosphere [e.g., Palmer and Mansfield 1984; Barsugli and Sardeshmukh 2002]. Thus, the SST in this region exerts a strong influence on the Walker cell and the Austral-Asia monsoon.

For the present study the Java, Flores and Banda Seas (from here on the sum of all three will simply be refered to as Banda Sea, see Figure 1) are of particular interest, because several observations suggest strong vertical mixing there with potentially large impact on SST and atmospheric convection [Ffield and Gordon 1992, 1996; Hautala et al. 1996]. This increased mixing is typically accounted for by the breaking of internal tides and strongly sheared flow over sills. Atmosphere data provides strong evidence for the connection between Banda Sea SST and tropical precipitation (Figure 1): With SST anomalies leading precipitation anomalies by 4 months, the regions of high correlation are in the maritime continent region (positive correlation), the central equatorial Pacific and East Africa (negative correlation). Therefore, warmer than normal SST in the Banda Sea is followed by increases in rainfall in the Java Sea and eastern Indian Ocean and a decrease in rainfall in the central Pacific and East Africa. This is consistent with Banda Sea SSTs contributing to the Walker cell; increases in SST correlate with local increases in convection and increasing subsidence in the remote central Pacific.

It has been shown in an Ocean General Circulation Model (OGCM) that tidal mixing can directly affect SST in the Banda Sea (by approximately 0.3 °C, Schiller 2004), and it
has been shown in observations that there is SST and atmospheric variability on tidal
frequencies [Loder and Garrett 1978; Balling and Cerveny 1995; Ray et al. 2007]. What
has been lacking so far is the demonstration that in a coupled General Circulation Model
(GCM) the Atmospheric General Circulation Model (AGCM) is sensitive to the rather
small SST changes caused by tidal mixing. The present study not only demonstrates
this sensitivity, but it also shows that realistic Banda Sea diffusivity in a GCM leads to
improved precipitation and water mass properties. The next section describes the ex-
periments in detail, section 3 describes the results which are then discussed in section 4.

2 Model description and experimental setup

The GCM is the latest version of the Community Climate System Model (CCSM3) in its
T42x1 configuration. The spectral truncation of the atmosphere yields a 2.8° horizontal
resolution, and in the ocean the horizontal resolution is nominally 1° with an equatorial
meridional refinement to 1/4°. The vertical resolution for atmosphere and ocean is 26
and 40 layers, respectively. Resolution and parameterizations are within the normal
range of current climate models [for details, see Collins et al. 2006].

Within this global system, modelling the climate over the Indonesian Seas is ar-
guably one of the biggest challenges, because it requires a realistic representation of
land, ocean and atmospheric processes. Thus, most climate models have significant
shortcomings in their simulation of Indonesian Sea mean and monsoon climate [Kang
et al. 2002]. In CCSM3, one of the largest biases throughout the year is a warm SST
bias over much of the Indian ocean and the Indonesian seas, which is accompanied by
excessive precipitation [Large and Danabasoglu 2006].
The purpose of the present study is to quantify the effect that an increased vertical
diffusivity in the Indonesian marginal seas has on the states of ocean and climate. The
vertical diffusivity in CCSM3, the present control (KLOW), is determined by the KPP-
scheme [Large et al. 1994], which has enhanced diffusivity in areas of low Richardson
numbers (mostly near the surface), and everywhere else a low background diffusivity.
This background diffusivity is horizontally uniform with values of 0.1 cm²/s in the upper
ocean, and it increases to 1 cm²/s in the abyss to account for increased vertical mixing
near bottom topography.

However, observations suggest that the background diffusivity can vary spatially
by two orders of magnitude [e.g., Gregg et al. 2003, Hibiya et al. 2004]. In particular,
Field and Gordon [1992] and Hautala et al. [1996] suggest for the upper Banda Sea a
diapycnal diffusivity of 1-2 cm² s⁻¹, an order of magnitude larger than what is commonly
used in OGCMs. Most recently, the numerical study on tidal flow in the Indonesian Seas
by Koch-Larouy et al. [2007] also suggested an average vertical diffusivity of 1.5 cm² s⁻¹.

The experiment that was performed (KOBS) has a setup that is identical to KLOW,
except that the background diffusivity in the area between 8°S and 1°S and 104°E and
139°E (mainly Banda, Flores and Java Sea, Figure 2) is increased by a factor of 10 to
match the observed estimates. KLOW and KOBS were both integrated for 100 years,
starting from initial conditions based on Levitus et al. [1998]. The following results are
based on the mean of years 61 to 100; the significant differences between KLOW and
KOBS are mainly restricted to the seasonal and annual mean fields in the Indo-Pacific
domain and are discussed in the next section. Amplitude and spectral characteristics of
El Niño are not changed significantly and are therefore not discussed.


3 Results

The Indonesian Throughflow (ITF) is directed from the Pacific to the Indian Ocean, the dominant route being from the North Pacific via the Mindanao Current through the Makassar Strait (straddling the equator along approximately 119°E, Figure 2) and Banda Sea into the eastern Indian Ocean [Gordon and Fine 1996]. Recent observations suggest an ITF strength of $8.4 \pm 3.4$ Sverdrup [Sv, Hautala et al. 2001]. In both experiments this pathway is reproduced (KOBS results are shown in Figure 2), and the ITF transports and their baroclinic structure are almost identical in both, with a transport of 12.4 Sv for KLOW and 12.6 Sv for KOBS.

Water in the Indonesian Seas is sufficiently different from surrounding water to be a unique water mass. Upper-thermocline, Pacific tropical water (noted by a salinity maximum around $24.5\sigma_\theta$) and lower-thermocline, Pacific intermediate water (salinity minimum near $26.5\sigma_\theta$) are mixed in the Indonesian Seas and become converted into isohaline Banda Sea water [Wyrtki 1961; Bray et al. 1996; Fieux et al., 1996]. North Pacific Intermediate Water (350 to 1500 m, 4°C to 10°C) is characterized by a salinity minimum at $27.4\sigma_\theta$ and enters the Banda Sea north of Halmahera, below the isohaline Banda Sea water [Rochford 1966; Van Aken et al. 1988; Coatanoan et al., 1999].

The effects of mixing in KOBS are illustrated by following the maximum salinity water of the North Pacific upper-thermocline along the streamlines into the Indian Ocean (Figure 2): the water keeps its maximum salinity until it enters the Makassar Strait and Banda Sea where the enhanced diffusivity reduces its salinity. This leads to an improved salinity distribution in the central Banda Sea (Figure 3). The observations show a thick layer of isohaline water from 6°C to 22°C, whereas in KLOW the high salinity signature of the north Pacific thermocline water is still maintained. Banda Sea water
in KOBS is still not isohaline, but the signatures of the individual water masses are weakened. Most importantly for local climate, though, is that increasing vertical mixing weakened the strong surface stratification. The surface salinities of less than 33 \text{psu} and temperatures of more than 29 °C have been improved to resemble more the observations of temperatures of 28 °C and salinities of larger than 34 \text{psu}. The improved watermass properties in KOBS suggest that vertical mixing in the Banda Sea is enhanced indeed, which supports the interpretation of the observations by Ffield and Gordon [1992] and Hautala et al. [1996], and corroborates the OGCM results of Schiller [2004] and Koch-Larouy et al. [2007].

The temporal and spatial mean of the SST in the area of increased mixing is reduced from 29.6°C to 29.3°C (Figure 4; the uncertainty for both means is 0.02°C). For comparison, the Reynolds and Smith [1994] data suggest 28.7°C for this area, and data acquired by the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager [TMI, Gentemann et al. 2004] suggest 29.3°C. The 0.3°C reduction in KOBS is small compared to SST biases of more than 5°C which can be found in coastal upwelling regions or at the boundaries between subpolar and subtropical gyres [Large and Danabasoglu 2006], and is easily within the observational uncertainty [Hurrell and Trenberth 1999]. However, because of the nonlinearities governing evaporation and the high SST in the Indonesian Sea, the atmospheric response is rather profound, and the temporal and spatial mean of precipitation in this area is reduced from 8.7 to 7.6 mm/day (Figure 4; the uncertainty for both means is 0.06 mm/day). Observations (Figure 1), and theoretical considerations [e.g., Gill 1980], suggest that reduced SST leads to weaker mid-tropospheric heating and hence weaker convective activity with potentially global effects. The quantification of these effects is the main result of the present study.
Over the Banda Sea (for the following computations the Banda Sea is given by the area of enhanced diffusivity) the mid-tropospheric convective heating in KLOW averages $2.1^\circ \text{C/day}$ with a maximum of $4.7^\circ \text{C/day}$ at 500 mbar; the reduced SST in KOBS does not change the vertical structure of the heating, but reduces its maximum to $4.2^\circ \text{C/day}$ and its column average to $1.9^\circ \text{C/day}$ (consistent with the rainfall changes above). The reduced atmospheric heating is the result of a changed surface energy budget. The Banda Sea is almost in equilibrium with the overlying atmosphere: in KLOW, $187 \text{ W/m}^2 \text{ incoming shortwave radiation}$ is balanced by $118 \text{ W/m}^2 \text{ latent heat loss}$, $47 \text{ W/m}^2 \text{ longwave radiation}$, $13 \text{ W/m}^2 \text{ sensible heat loss}$, and $9 \text{ W/m}^2 \text{ ocean heat gain}$. In KOBS, the ocean heat gain increased to $21 \text{ W/m}^2$, the additional $12 \text{ W/m}^2$ coming in equal parts from increased solar radiation, and reduced latent and sensible heat loss. Thus, from an oceanic point of view there is an important atmospheric feedback to increased diffusivity: the reduced SST leads to reduced latent heat loss and therefore reduced cloudiness and increased solar radiation, which in turn is a negative feedback on SST cooling. The reduced SST also leads to a shift in precipitation from the Banda Sea towards the Indian and central Pacific ocean (Figure 4). Despite the large local changes in precipitation the total global and tropical precipitation are identical in KLOW and KOBS.

Precipitation is connected to SST through convection, and the center of convection shifts from the northern tip of New Guinea with a maximum annual mean ascent rate ($\omega$) of $0.11 \text{ Pa/s}$ to Borneo with $\omega$ being reduced to $0.9 \text{ Pa/s}$ (both values at 400 mbar). For comparison, the reanalysis products provide maximum values of $0.7 \text{ Pa/s}$ (NCEP, just west of Sumatra at 400 mbar), and $0.17 \text{ Pa/s}$ (ERA40, over New Guinea at 500 mbar).

The analysis above suggests that a 5% reduction in oceanic latent heat loss over the
Banda Sea leads to a 10% reduction in mid-tropospheric convective heating, which in turn reduces local convective activity by 20%. The positive feedbacks associated with the latent heat loss can be understood with tropical atmosphere equilibrium dynamics. Convective heating is the equivalent of moisture convergence, and the difference between latent heat loss and convective heating rate has to be due differences in lateral moisture convergence. Inspection of the model fields show that the change in moisture gradients in this region is negligible (not shown); the wind convergence, however, is reduced indeed (Figure 4), which is consistent with the linear theory of Gill [1980]. One can speculate that the further amplification of the response is tied to a change in stratification: The heating rate is proportional to the product of ascent and stratification [\[Q \sim \omega N^2; Holton 1979\]]. Unfortunately, potential temperature from which to compute the stratification is not saved routinely in CCSM and has to be recomputed from the monthly mean temperature data. Because of the nonlinearities involved, this leads to inaccuracies and it is not possible here to show that the stratification did indeed increase by 10% as suggested by the amplification between convective heating and convection. However, even the recalculated values show that the annual mean stratification averaged over the Banda Sea is increased in the lower troposphere, albeit only by 3% (not shown).

It is shown here so far that the tropical atmosphere is sensitive to vertical diffusivity in the ocean. The analysis of water mass properties in the Banda Sea strongly suggests that vertical diffusivity should be increased there substantially from the low background values that are currently used in OGCMs. However, based on the change in SST or convective activity alone, it is not clear whether the model climate improved. Evidence for improvement mainly comes from the rainfall changes. For the Banda Sea the total annual mean rainfall is estimated to be 5.3 [Global Precipitation Climatology Program (GPCP); Xie et al. 2003], 6.2 [Xie and Arkin 1998] or 6.5 mm/day [TRMM]. Thus, all
three observational products suggest that the precipitation in KLOW (8.7 mm/day) is too large and has improved in KOBS (7.6 mm/day). In particular the JJA precipitation over the Banda Sea is much improved (Figure 5): the CCSM3 biases are largest in the central Pacific (the so called 'double ITCZ'), the equatorial Atlantic and over the southern Indonesian Seas. Whereas during JJA the monsoon has a single center over the Bay of Bengal, CCSM3 has second center over the Indonesian Seas which is removed in KOBS. The CCSM3 biases in DJF are similar, except for an additional major rainfall bias in the western Indian ocean (Figure 6). Over the Indonesian Seas the center of the monsoonal rains in KLOW is shifted east which is remedied in KOBS. The JJA changes in the Banda Sea are a robust improvement with respect to the three data products analyzed above, while the DJF changes are improvements in GPCP and TRMM only.

The differences between the JJA and the DJF response can be explained by the different background states in these seasons. Banda Sea winds during DJF are rather weak and southeasterly, whereas during JJA they are stronger and northwesterly (Figure 7). Thus, in JJA the winds are upwelling favorable in the east Banda Sea, so that the mixed layer shoals and the relatively weak background diffusivity can more easily affect the SST than in DJF with its deeper mixed layer. This results in an SST difference with an average Banda Sea JJA value of 0.39°C and an average DJF value of 0.18°C.

4 Summary and Discussion

It has been shown that in a GCM tropical precipitation and convection are sensitive to the detailed value of vertical diffusivity in the Banda Sea. Increased diffusivity leads to a cooler SST, reduced latent heat loss, less diabatic heating and therefore to reduced convection and precipitation. With increased diffusivity the rainfall in JJA shifts north-
westward towards the Bay of Bengal, whereas in DJF it shifts towards the West Pacific Warm Pool. Because of positive feedback processes in the tropical atmosphere, a 5% drop in latent heat loss over the Banda Sea leads to a 20% reduction of convection.

Since the causal link between diffusivity and convection can be understood with simple equilibrium dynamics, the main contribution of the present study is the quantification of this link. Thus, it is of paramount importance that the model response can be trusted. Even state of the art GCMs like CCSM3 still have biases, the most outstanding are probably the precipitation biases in the Indo-Pacific basin [e.g., Large and Danabasoglu 2006]: CCSM3 features a spurious double ITCZ in the eastern Pacific with too little precipitation along the equator; it also is too dry over the eastern Indian Ocean, and and too wet over Indonesia (Figures 5, 6). However, there are two pieces of evidence to support our interpretation of KOBS. Firstly, the pattern of the observed spatial correlation between precipitation and Banda Sea SST anomalies (Figure 1) matches the pattern of the mean model response (Figure 4). Secondly, and more importantly, increased diffusivity reduces model biases in watermass properties (Figure 3) as well as in precipitation, which in DJF shifts away from Indonesia towards the central equatorial Pacific (Figure 6) and in JJA towards the Eastern Indian Ocean and Bay of Bengal (Figure 5). In both seasons the precipitation shifts towards the warmest SST which is in the western Pacific warm pool during DJF and in the eastern equatorial Indian ocean in JJA (in observations [Reynolds and Smith 1994], and in CCSM3). Especially the precipitation reduction over the Banda Sea during JJA is a major improvement in simulating the Austral-Asian monsoon [see Meehl et al. 2006 for a detailed discussion of the monsoon biases CCSM3].

The sensitivity of tropical precipitation to ocean diffusivity in CCSM3 calls in question the use of horizontally constant diffusivity which is still used in many OGCMs,
and it provides further support to the hypothesis that decadal and shorter term climate variability could be forced by ocean mixing [see Ray 2007 for a recent discussion]. A long term goal of GCM development has to be to identify the areas where vertical diffusivity matters and to develop parameterizations for the dominant processes. Although this is mainly theoretical and numerical work, there is clearly the need for more observational guidance. Inferring vertical mixing from watermass properties is probably only possible in enclosed areas with clearly defined source waters, and the work of Field and Gordon [1992] and Hautala et al. [1996] may have been done in one of the few locations were this is possible. Direct microstructure measurements are possible but expensive, and they only provide data at one point over a short period [e.g., Alford et al. 1999]. For the tidally induced component of vertical mixing, progress has been made with direct modelling of tides and using observations for validation [Simmons et al. 2004, Koch-Larrouy et al. 2007, Schiller and Fiedler 2007]. Modelling the wind induced part of mixing appears to be more challenging, partly because of the nonlocal structure of the problem, and partly because the relevant scales are still being debated [e.g., Nagasawa et al. 2000; Zhai et al. 2007].

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Figure 1: Correlation of SST anomalies (relative to the climatology of the seasonal cycle) in the Java, Flores and Banda Seas (region outlined with box) to precipitation anomalies four months later [based on NCEP, Kalnay et al. 1996]. The correlation for the 95% confidence interval (= 0.15) is marked with a black contour line.
Figure 2: Maximum salinity between 100 and 500 m depth in KOBS (color), and mean barotropic streamfunction (contourlines: 2 Sverdrup). White indicates less than 100 m deep, gray indicates land. The region of increased vertical background diffusivity is outlined with a box.
Figure 3: Temperature-Salinity diagram of the Banda Sea based on Levitus (black squares), KLOW (blue crosses) and KOBS (red crosses).
Figure 4: Differences between KOBS and KLOW for mean SST (contour lines: 0.2°C), precipitation (color intervals: 0.2 mm/day beginning at ± 0.1 mm/day), and surface wind stress (for clarity only changes larger than 10% are shown). The dots illustrate the atmospheric resolution and represent a gridpoint each. The uncertainties for the mean SST are less than 0.1°C and 0.3 mm/day everywhere in the displayed domain. Thus, all the displayed SST changes present a significant change of the mean, whereas the first level of shade in the precipitation changes (0.1 - 0.3 mm/day) are only displayed to highlight the structure of the response. Note, however, that even in the regions that technically do not represent a significant change of the mean the precipitation changes are often co-located with SST changes.
Figure 5: JJA Precipitation rate in mm/day. First panel: observations (GPCP, contour intervals: 2 mm/day); second panel: difference between KLOW and GPCP (contour intervals: 3 mm/day); third panel: difference between KOBS and KLOW (contour intervals: 0.3 mm/day for changes less than 1.5 mm/day and 1 mm/day for values beyond that), the largest change is in the Banda Sea with a 3.9 mm/day reduction.
Figure 6: DJF Precipitation rate in mm/day. First panel: observations (GPCP, contour intervals: 2 mm/day); second panel: difference between KLOW and GPCP (contour intervals: 3 mm/day); third panel: difference between KOBS and KLOW (contour intervals: 0.3 mm/day for changes less than 1.5 mm/day) the largest change is in the Banda Sea with a 1.6 mm/day reduction.
Figure 7: SST difference between KOBS and KLOW for DJF (top) and JJA (bottom), and surface wind stress from KOBS for the respective seasons. Contour interval: 0.2°C.