JOINT DISTRIBUTIONS OF WAVES AND RAIN

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ABSTRACT

The transfer of gases between the atmosphere and ocean is affected by a number of processes, of which wave action and rainfall are two of potential significance. Efforts have been made to quantify separately their contributions; however such assessments neglect the interaction of these phenomena. Here we look at the correlation statistics of waves and rain to note which regions display a strong association between rainfall and the local sea state. The conditional probability of rain varies from ~0.5% to ~15%, with most of the equatorial belt (which contains the ITCZ) showing a greater likelihood of rain at the lowest sea states. In contrast the occurrence of rain is independent of wave height in the Southern Ocean. The 1997/98 El Niño enhances the frequency of rain in some Pacific regions, with this change showing some association with wave conditions.

Keywords: Significant wave height, Rainfall, Dual-frequency altimetry, TOPEX, Air-sea gas transfer velocity, Seasonal, Interannual

1. INTRODUCTION

One of the key concerns of the 21st century is the continued industrial production of CO_2 and how much of it can be absorbed by the oceans. A number of factors affect this — both the transfer of gases between the atmosphere and the ocean through their interface, and the overturning circulation of the ocean to transport such gases to the deep interior for centuries to millenia. In this paper we look at two of the factors that affect the air-sea transfer of gases, viz. waves and rain.

A number of processes have been studied separately in some detail, although there is a wide degree of uncertainty as to the precise modelling of these terms. Early work on the effects of wind has shown the air-sea gas transfer velocity to vary non-linearly with wind speed [1]. Researchers making in situ measurements have developed different formulae to correspond to their particular datasets; the degree of non-linearity and the variation between datasets is summarised in Fig. 1 of Wanninkhof & McGillis [2]. Fangohr & Woolf [3] proposed an alternate formulation using both significant wave height, H_s, and wind speed to characterise the environmental conditions.

Rain makes a contribution through the absorption of gases into raindrops in the air which then fall into the water (wet deposition), altering the temperature and salinity of the surface water (and thus altering the solubility of a gas), as well as via the production of turbulence and sub-surface air bubbles following the raindrop's impact on the sea surface. Ho et al. [4] showed the air-sea gas transfer velocity to increase with rain rate, but not linearly.

As the various relationships are non-linear an accurate mean climatology of air-sea gas transfer cannot be simply constructed by applying the formulations to, say, the monthly mean rain rate and wave height. Rather the formulae must be applied to the probability distribution function (p.d.f.) of the conditions and then averaged. However, a greater complication exists in that the wave and rain conditions may each modulate the transfer function of the other. Both wind and sea surface waves affect the incidence angle of raindrops on the interface, strongly changing the production of sub-surface bubbles [5]. Recent rain on the other hand can produce freshwater slicks, stabilising the surface micro-layer, damping the waves and making them less able to mix water into the interior A quantification of these interactions is still an area of active research [6]. However, it follows that information on the joint p.d.f. of waves and rainfall may be important for the generation of an unbiased climatology of the air-sea gas transfer.

The aim of this paper is thus not to provide new formulations for this transfer, but rather to understand in which regions the statistical association of rain with wave conditions may be important in the calculation of an overall gas flux.

2. DATA SOURCES AND PROCESSING

2.1. Satellite data used

To analyse rainfall and wave height data on a near-global basis requires the use of satellite records. There are a number of different remote-sensing technologies that can make estimates of the rain rate at the Earth's surface [7], but radar altimeters provide the only long-term reliable records for H_s. Since the measurements of

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waves and rain should be nearly simultaneous, we need to use rain-rate data from a dual-frequency altimeter. Although the suite of sensors on Envisat is ideal for rain cloud studies using multiple sensors [8], its dual-frequency altimetry capability was curtailed by instrument failure. Thus we elected to use the long duration of the TOPEX altimeter, which was launched in August 1992 and lasted till September 2005. Its orbit covered the globe between 66˚S and 66˚N every 9.92 days, albeit with a narrow swath.

The altimeter data were extracted from RADS (http://rads.tudelft.nl) because those data have already been corrected for an observed drift in the wave height record from late 1996 to early 1999 [9].

2.2. Processing applied

The difference in radar backscatter values at TOPEX's K_u- and C-band frequencies is used to infer rain rate [10]. Analysis is confined to the latitude range 55˚S-65˚N to avoid potential anomalous results on account of changes in backscatter associated with undetected sea-ice and icebergs. To avoid the likelihood of land contaminating the backscatter data, all points along the coast were discarded, according to the flag setting for the radiometer, which has a larger ground footprint than the altimeter. This not only removes a potential bias to the rain algorithm but also removes coastal areas that may have particular anomalies associated with the orographic control of rain.

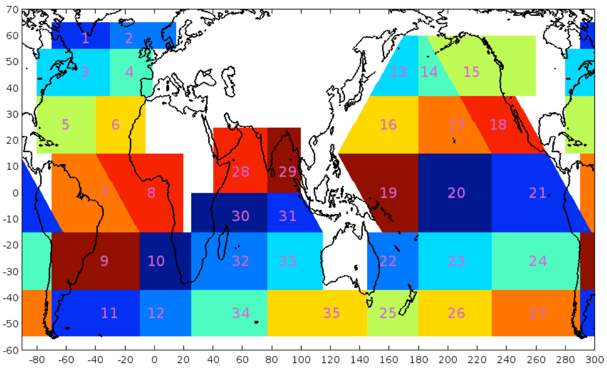

Figure 1. Map showing the 35 regions for which joint wave and rain statistics were collected. Altimetric data were only considered between 55˚S and 65˚N, and for points far from the coast.

Due to its limited spatial sampling (relative to other satellite sensors), we here collated the data in 2-month periods for various regions of interest (Fig. 1). Each point, occurring every ~6km along track, was classified as "no rain", "drizzle", "medium rain" or "heavy rain" according to thresholds of 0.5, 1 and 2 dB for the signal attenuation at K_u-band. For a 4.5 km atmospheric column, these correspond to rain rates of ~2.3, ~4 & ~ 7 mm/hr. These data were also classified according to the altimetric record of wave height, and co-occurrence histograms of waves and rain collated separately for the 35 different regions.

2.3. Presentation of results

Two-dimensional histograms of the joint distributions of wave height and rain rate were acquired for each 2-month period between Nov-Dec 1992 and Jul-Aug 2005 for all 35 defined regions. The obvious way to illustrate one such joint distribution is through a coloured representation of the number density of observations (Fig. 2a), with a logarithmic scaling to help portray changes of more than a factor of 100 in occurrence. This example from the NW Atlantic shows that increasingly high rain rates are associated with lower and lower wave heights.

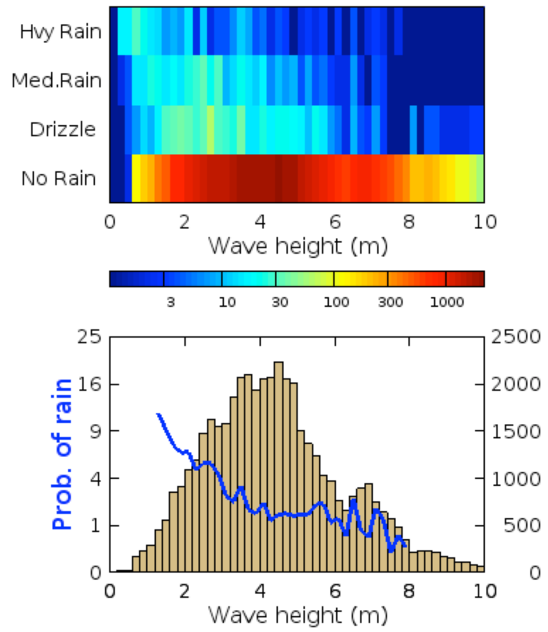

Figure 2. Two representations of the joint wave height-rain rate statistics for region 3 (western N. Atlantic) for Jan-Feb 1994. a) A 2-D histogram, with logarithmic scaling for number of observations (see colour bar). b) A simple 1-D histogram of wave height, with the associated probability of rain (as a percentage, with drizzle, medium & heavy rain all together) indicated by the blue line. Note the use of a non-linear scale to allow small changes in rain occurrence to be discerned, as well as including high likelihoods of rain.

However, a comparison of many such 2-D histograms representing different regions, years and seasons is cumbersome. Instead we reduce the information content by showing the 1-D histogram of H_s plus the conditional probability of rain ("drizzle" + "medium" + "heavy") associated with each wave height bin (Fig. 2b). A non-linear ordinate axis is used in order to allow the wide range of probability values to be easily discerned.

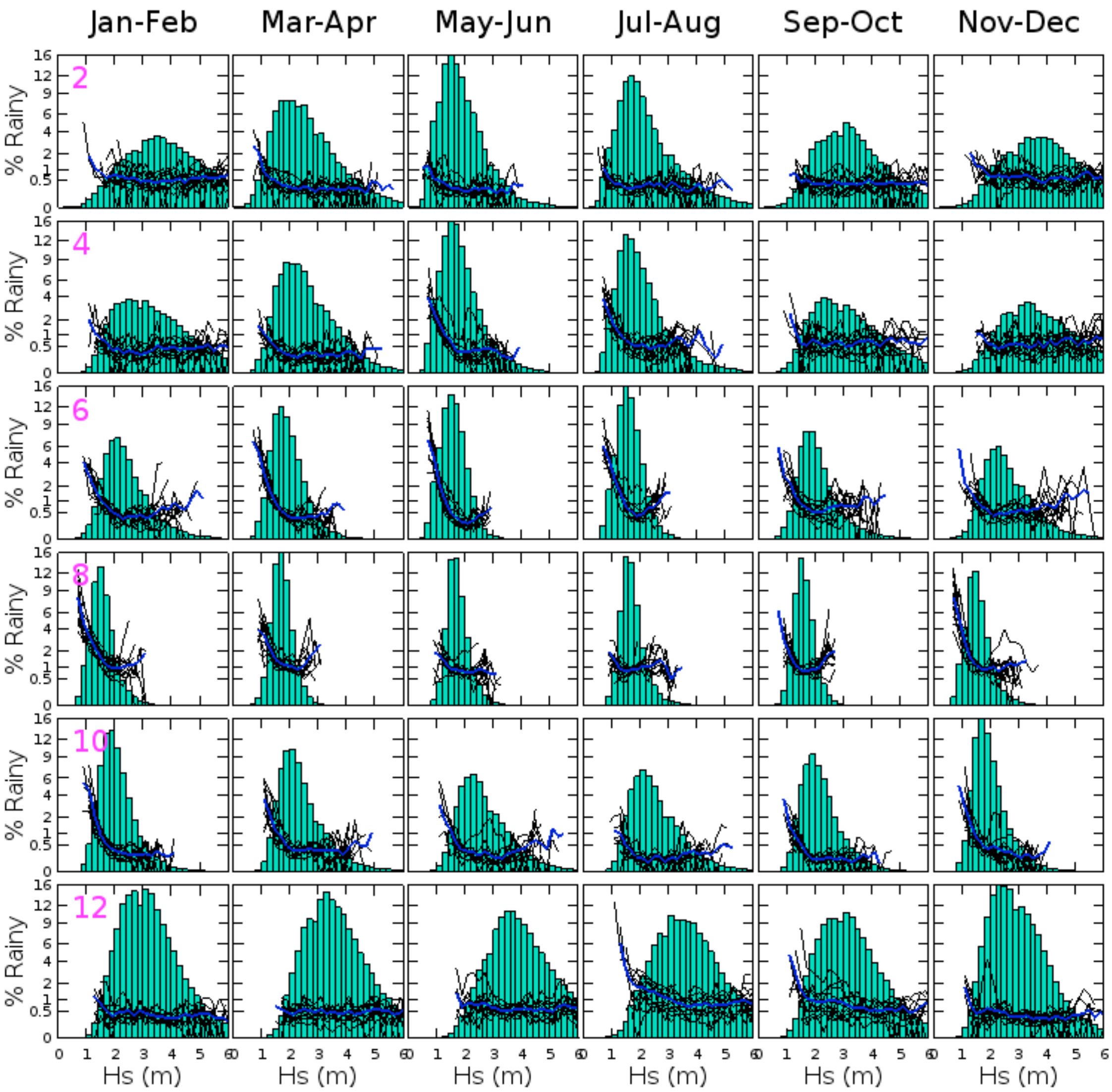

Figure 3. Association of rain with different wave conditions for 6 regions indicated by the number in pink, corresponding to the eastern Atlantic from north to south. The turquoise bars show the p.d.f. of wave height over the 12 years (H_s>6m omitted for clarity), with the black lines indicating the conditional probability of rain for each of those years, and the thick blue line giving their mean.

In further plots (Figs. 3-5), we show the statistics for all 12 years (1993-2004) that are fully sampled by the TOPEX altimeter. In these plots, the histogram represents the mean H_s conditions for that 2-month calendar period, and the 12 lines show the conditional probability for each year. In most cases this reveals the general consistency of the results, but the interannual variation for selected regions is addressed in section 5.

3. EASTERN ATLANTIC

We illustrate the range of associations observed and their latitudinal and seasonal variation through portrayal of the results for the six boxes spanning the eastern side of the Atlantic (Fig. 3). Note the western and eastern limits are not the same for all regions (see Fig. 1).

The histograms of wave height show a wide range of conditions from the tropical region where H_s rarely exceeds 3m to the northern and southern extremes where there is a broad distribution of H_s, not just large waves. The Southern Ocean has large waves year round due to its long fetch, whereas there is a strong seasonality in the northeast Atlantic, with modal H_s values ranging from ~1.5m in the summer to ~3.5m in the winter.

It is known that the prevalence of rain varies strongly latitudinally from more than 10% in the ITCZ (Intertropical Convergence Zone) to almost 0% in the oceanic "deserts". However in this analysis, requiring large areas for statistical robustness, the spatial variation of the mean probability of rain is less pronounced. For the Southern Ocean, rain only occurs ~0.5% of the time almost irrespective of wave conditions, whereas in the tropics the probability is larger across all conditions, with a pronounced effect at low H_s. This is likely to be associated with strong convection cells within the ITCZ.

The increased prevalence of rain at low sea states also occurs for region 6 and further north within region 4 during boreal summer. In the northernmost part of the Atlantic (55˚-65˚N) the probability of significant rain is again reduced, as is also the connection with wave height. In such high latitudes the altimetric detection of rain is less reliable because the melting layer height is much lower than in the tropics, and thus there is a great reduction in the atmospheric column over which the attenuation effect is integrated.

4. MONSOONAL RESPONSE

Some of the greatest seasonal variability is found in the North Indian Ocean (Fig. 4), which is not surprising given the pronounced reversals in wind direction: the winds are from the northeast during December to April, with the southwest monsoon occurring in June to October.

During May-June and July-August the winds act over a much longer fetch producing wave heights in the range 1.5-3.5m, with the warm moist air transported inland to cause precipitation. For the northwest Indian Ocean (Arabian Sea) the likelihood of rain is 1-2%, with slightly higher probabilities at low sea states. The northeast Indian Ocean (Bay of Bengal) meanwhile has a probability of 2% rainfall at the modal conditions, and ~4% for the less common high and low sea states.

During boreal winter the ITCZ still remains as a coherent belt north of the equator, with high rain rates associated with the convective cells offshore. At that time the wave height distribution in both the Arabian Sea and Bay of Bengal is mainly below 2m, with the occurrence of rain strongly tied to conditions of the lowest waves. This work has not demonstrated whether this relates to absence of winds or to rain being associated with very small fetches; however earlier work (Plate 4 of [11]) suggested that a significant proportion of the rain in the tropical band (15˚S-15˚N) is associated with low winds in a swell-dominated sea.

5. INTERANNUAL RESPONSE TO EL NIÑO

The Equatorial Pacific, like the Equatorial Atlantic and the North Indian Ocean in boreal winter, is a region of relatively weak winds and low wave heights, coupled with a high occurrence of rain due to the ITCZ. In all seasons, the rain probability associated with the modal wave height is typically 1-2% (remembering that the area for averaging extends beyond the band of the ITCZ itself), with a much greater occurrence of rain usually associated both with the lower and upper ends of the wave spectrum (Fig. 5]

It is interesting to highlight the conditional probability of rain for several years associated with the major El Niño event in 1997-1998. Previous work [12} had shown the period May-June 1997 to March-April 1998 to be marked by an increase in the meridional width of the ITCZ, a migration of the SPCZ (South Pacific Convergence Zone) to the east, and an increase of the probability of rain within the ITCZ band.

Figure 5 shows that the increases in occurrence of rain in the eastern Equatorial Pacific during Jan-Apr 1998 were across all sea state conditions. However, the changes in the central region occurred mainly at high values of H_s during Mar-Apr 1997 (the onset) and at modal values during Jan-Feb 1998 (near the end).

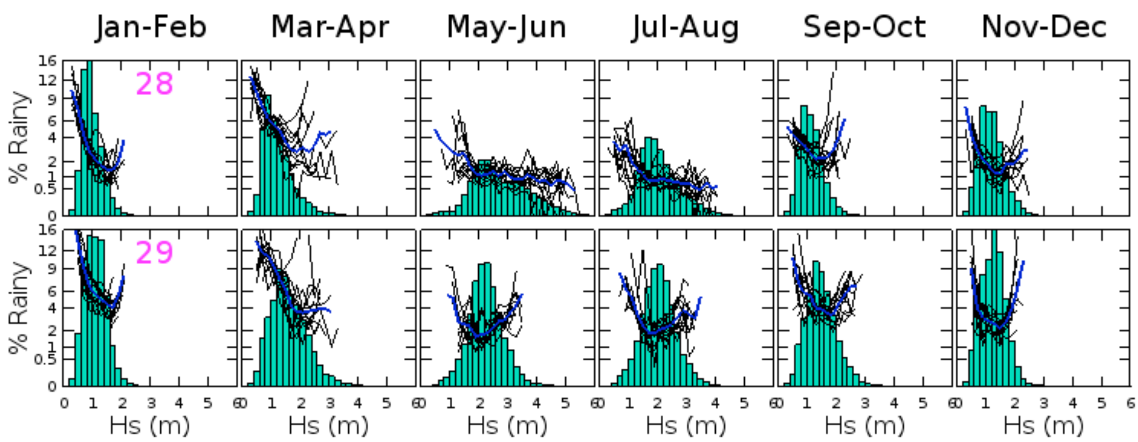

Figure 4 Association of rain with different wave conditions for 2 regions in the North Indian Ocean.

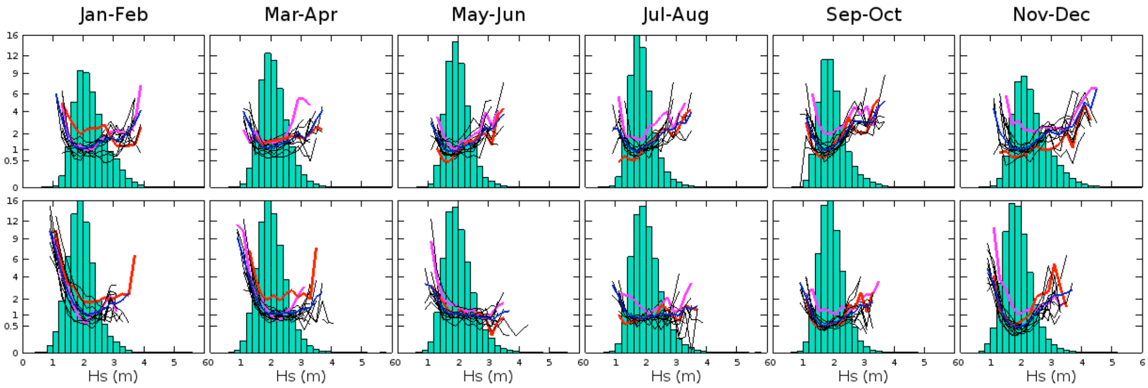

Figure 5. Association of rain with different wave conditions for 2 regions in the Equatorial Pacific (top row is region 20 in the central Pacific; lower row is region 21 in the east). The pink and red conditional probability lines are for 1997 and 1998 respectively, with the blue line showing the mean over all 12 years

6. CONCLUSIONS AND IMPLICATIONS

Rain has always been a hard phenomenon to study in a global marine context, on account of the limitations of in situ measurements and the challenges for satellites of recording a process with relatively small spatial and temporal scales. The dual-frequency radar altimeter provides a unique approach to address the wave height conditions associated with rain.

In general, the probability of occurrence of rain in the high latitude regions is of order 0.5-1%, with only a slight increase for low sea states. On the other hand, tropical regions have a much greater occurrence of rain, and it is strongly associated with the lowest wave conditions. Thus this sector is not only one where rainfall processes could play a significant effect in the gas transfer, but also a region where the interaction between wave and rain-related processes could be important.

Mapping and understanding of the joint distributions of these two parameters will aid efforts to characterise the rate of transfer of CO_2 (and other climatically-important gases) between the ocean and atmosphere. With careful screening to remove observations contaminated by sea-ice, it is anticipated that Sentinel-3 may extend such studies into the Arctic Ocean. A more reliable quantification of the combined effects of waves and rain is essential for understanding whether certain regions will act as sources or sinks of CO_2.

The joint distributions of waves and rain are also required for the monitoring of underwater environmental noise, whether for military purposes or understanding cetacean behaviour. Thus if we "***Listen to the Ocean***" we hear the correlation of these two parameters!

7. ACKNOWLEDGEMENTS

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