Ocean Sci. Discuss., 12, C1312–C1319, 2015
www.ocean-sci-discuss.net/12/C1312/2015/

Ocean Science Discussions

Interactive comment on "Imprint of external climate forcing on coastal upwelling in past and future climate" *by* N. Tim et al.

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Received and published: 15 December 2015

We thank the reviewer for the time and interest in evaluating our manuscript. The reviewer mainly expresses the main concern that the significance of our study is not clear and that our conclusions could have been reached just by studying the available literature. We disagree with this opinion, as we try to explain in the following. We also comment on some of the main points raised by the reviewer.

The sensitivity of upwelling to variations in external forcings in the future has been so far framed by Bakun's hypothesis (Bakun, 1990; Bakun et al., 2015). This hypothesis has also been invoked to explain observed trends over the 20th century and to explain reconstructions of sea-surface temperature over the past millennium in some EBUS

(McGregor et al., 2007). This hypothesis, in summary, states that an increase in external forcing causes a more intense warming over land than over the ocean, changing the sea-level pressure gradient between both, and thus intensifying the along-shore winds that favour coastal upwelling. The formulation of this hypothesis is not dependent on a detailed mechanistic description of the winds along a narrow coastal channel, or on the small-scale ocean dynamics in the upwelling regions. It is formulated in terms of purely large-sale (thousands of kilometres) atmospheric dynamics (and additionally on the differences of atmospheric humidity over land and over ocean). It is also meant to be applicable to all EBUS. This dynamics should be well represented in present climate models. Therefore, we think it makes perfect sense to test this hypothesis in the context of global climate models, in the past centuries, in the 20th century and in the future assuming different scenarios of increase in radiative forcing. In this study, we are not quantitatively estimating the sensitivity of upwelling to climate change, but investigating weather Bakun's hypothesis can be confirmed in simulation with state-of-the-art global climate models. It is, therefore, not totally critical whether or not global climate models faithfully represent the small-scale atmospheric or ocean dynamics. The testing of Bakun's hypothesis would be not meaningful if the connection between upwelling and SLP (or winds) in the models would be totally unrealistic. This is the reason why the 'validation of the models' in our study is limited to this aspect, which encapsulates the link between upwelling and atmospheric forcing in Bakun's hypothesis. Perhaps, the criticism raised by the reviewer stems from the fact that we did not clearly explain this focus of our study.

That being said, I think this paper here is not very valuable for the discussion of EBUS sensitivity to climate change, as there are just too many uncertainties associated with past forcing, too many potential caveats in model simulations, and too simplistic of an analysis provided here.

The uncertainties in past external forcing in the pre-industrial era are known and acknowledged, but not in the period after 1850. Even then, the uncertainties in the past

external forcing prior to 1850, though important, are not a critical point in our reasoning. The uncertainties in past external forcing apply to the amplitude of the variations in this forcing. The CMIP5 models have included the best estimation to-date of these forcings. There are indeed other reconstructions of past solar variability that point to higher amplitude of variations (e.g. Shapiro et al., 2011) but these have been already considered inconsistent with reconstructions of past temperature (Judge et al., 2012). Over the 20th and 21st century, this criticism does not apply. The uncertainties in the external forcing in the 20th century are relatively narrow, and in the 21st century the forcings are prescribed.

More so, the future part (where you could actually hope to find significant changes due to the strong rcp85 forcing) is covered more comprehensively by Wang et al. (2015). This is not totally correct. Wang et al. (2015) analysed the strongest scenario RCP8.5 and calculated the trends since 1950 until 2100 assuming this scenario. Wang et al. did not analyse the weaker scenarios, not the 20th century simulations in isolation, so that from Wang studies it is not possible to know what level of external forcing is needed for Bakun hypothesis to be detectable. We analysed the weaker scenarios as well and found that, in these, the external forcing is still too weak. This is a novel result that could not have been guessed beforehand. Wang et al. did not analyse the past millennium simulations, and we may recall that also in this period variability in upwelling (derived from proxy records) has been interpreted as response to external forcing using very similar arguments as those included in Bakun's hypothesis (McGregor et al., 2007). The set-up used by Wang et al. using 22 models may be considered more comprehensive, as the reviewer does, but it is also more difficult to interpret. Each of the 22 models is different, so that a disagreement among the simulated upwelling trends within the model ensemble could be, in principle, be also caused by the different model structure. Note also that the external forcing 'seen' by each model is also model dependent, since although the atmospheric concentrations of greenhouse gas is prescribed equally for all models, the radiative forcing depends on the mean climatology of atmospheric humidity and temperature of each model, among other factors. Here,

we use more controlled conditions: only two models but for each model we analyse an ensemble of simulations driven by the same forcing. Under these conditions, we can indeed state that the disagreement in the simulated upwelling trends is purely due to internal climate variability and not to different model structure, as could be the case in Wang et al. We are also consistent in that we use the same ensemble size for all periods, past millennium, historical and future, whereas the full CMIP5 ensemble of future simulations include a different number of realizations for each model.

To put it provocatively, one could have reached the same conclusions as this paper (probably even with the same confidence) by studying the existing literature. We respectfully doubt that this is correct. Bakun's hypothesis is being used in very recent papers (e.g. Sydeman et al., 2014) . Trends in atmospheric circulation over the 20th century in other contexts different from upwelling are being explained as a response to external forcing, e.g. the poleward expansion of the Hadley cell (Lu et al., 2007) , shifts in storm tracks (Ma and Xie, 2013). Our study finds that Bakun's hypothesis is not compatible with state-of-the art global climate modelling. To reach this conclusion without analysing the CMIP5 simulations could have been guessed, but it would remain a guess. To our knowledge, there are no systematic studies of the amount of forced response in the atmospheric circulation over the 20th century, and specifically of the SLP land-ocean contrast, as assumed in Bakun's hypothesis.

I recommend major revisions that should focus on providing more in-depth analysis of the mechanisms governing the variability and sensitivity of the EBUS in the models, since this would be a valuable contribution to the field.

The mechanism that give rise to variability of upwelling are well known. It is known that the coastal winds are the main drivers of upwelling. The details of the connection between winds and upwelling may be very complex at small scales, e.g. involving coastally trapped waves, small-scale turbulence, filaments, etc., (see for instance Fennel et al., 2007) but this link must be broadly driven by the large-scale atmospheric circulation and the SLP gradient between land and ocean. To investigate the small-scale

mechanisms, it is clear that high-resolution ocean and probably atmosphere models are needed. But global climate models have to replicate the very basic link between SLP gradient and upwelling, and the imprint of the external forcing on upwelling must be mediated first by the modification of the SLP gradient. So we see little use in evaluating the detailed dynamics of upwelling in ocean models that will certainly not be able to replicate the small-scale wave dynamics and turbulence. This is why we analysed in our study the imprint of forcing on both the simulated upwelling and on the simulated SLP gradient in the context of Bakun's hypothesis.

as to the usefulness of global models in studying EBUS. The winds that actually cause the upwelling can be very narrow (narrower than the model resolution) and coastal topography might play a role (which is not resolved well in global models). So I do not know how we can validate the models on something that they do not simulate well (strong narrow winds). It reminds me of the cloud feedback that gets studied a lot with GCMs, although they do not resolve most of the processes. One might be able to learn something, but one has to be extremely careful as to not over-interpret the model results. I think the authors here lack a little bit of this carefulness in their model validation and I would encourage them to expand that part – especially since there is no forced response to talk about anyway, they could spend more time on the model mechanisms and variability.

Bakun's hypothesis does not take into account the small-scale coastal topographic features. It is a robust and universal prediction that applies in principle to all EBUS. The particular response of each EBU in reality may indeed be dependent on these local details, but the sign of the response to external forcing is clearly stated in Bakun's hypothesis. We are careful not to make any predictions about the magnitude of the sensitivity of upwelling to external forcings in each particular EBU based on these models results. This would be indeed adventurous. We, however, do indicate that the very basic mechanism incorporated in Bakun's hypothesis cannot be confirmed in present climate models, and that a very strong forcing would be needed to see any

effect at all of the external forcing on the SLP gradient. This holds independently of the realism of the simulated upwelling, and even independently of the skill of the ocean model (provided that upwelling does not feedback onto the atmospheric circulation itself).

I believe even under strong anthropogenic forcing people do not expect to easily see a forced response in SLP (Deser et al., 2012 and some of her following papers). As noted before, this is not totally correct, specially in the tropical realm. Gillet and Stott (2009) could attribute the observed SLP trends, especially at low latitudes, to the external forcing in the 20th century. Also, the external forcing is indeed expected to impact, for instance, the ENSO state in the future and therefore the tropical SLP. The papers by Deser et al. referred to by the reviewer mostly analyse the mid-latitude realm. There are other studies, also by one of us (Gómez-Navarro and Zorita, 2013) that analysed the SLP response to external forcing at mid and high latitudes over the past millennium, also finding no clear response. Therefore, we think that its is indeed meaningful to investigate whether the externally simulated trends and multidecadal variability of SLP over all these three periods project onto the land-to-ocean SLP gradient envisaged in Bakun's hypothesis. One conclusion of our study is that they do not, but this could not have been guessed boforehand.

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Interactive comment on Ocean Sci. Discuss., 12, 2899, 2015.