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NRL Memorandum Report: Tropical Waves and Indonesia Flooding – Identifying Predictability Limits

Maria Flatau
James Doyle
Carolyn Reynolds

Atmospheric Dynamics and Prediction
Marine Meteorology Division

Adam Rydbeck

Ocean Dynamics and Predication
Oceanography Division

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14. ABSTRACT

This document describes the role of the tropical equatorial waves in triggering the extreme weather events, namely floods in Indonesia. It is shown that large precipitation in this region is usually related to the passage of the active phase of the equatorial disturbances such as MJO, Kelvin waves and Rossby waves. The mechanism of amplification of tropical convection through interaction with the oceanic equatorial waves is investigated, indicating the atmosphere-ocean feedback loop. It is shown that while the dynamical models such as the Navy ESPC system represent well the relationship between the waves and the extreme precipitation events, prediction of the equatorial waves, especially Kelvin waves is more difficult.

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CONTENTS

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EXECUTIVE SUMMARY

This research describes the meteorological drivers of floods in Indonesia and some aspects of their representation in the Navy ESPC system. The goal this work is to improve the capability of the Navy model to predict extreme events in the Maritime Continent region. The influence of the oceanic processes is also considered and the existence of the feedback loop between oceanic and atmospheric equatorial modes is shown. the analysis described here employs the adjoint model: the new tool developed at NRL to analyze the impact of various physical processes on the model forecast. It indicates that extreme precipitation in Indonesia is usually related to the passage of the active phase of the equatorial disturbances such as MJO, Kelvin waves and Rossby waves. The relationship between extreme rainfall/floods and convectively coupled Kelvin waves is especially strong, particularly for regions near the equator. It is shown that while dynamical models such as the Navy ESPC system represent well the relationship between the waves and the extreme precipitation events, prediction of the equatorial waves themselves, especially Kelvin waves is more difficult and influences the prediction of precipitation extremes. The new tool for visualisation of equatorial modes in the tropics that can be used for research and training purposes is also described

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NRL MEMORANDUM REPORT: TROPICAL WAVES AND INDONESIA FLOODING – IDENTIFYING PREDICTABILITY LIMITS

1. INTRODUCTION

The work described in this report was motivated by our recent investigation of flooding events in Indonesia, with a focus on Sumatra [1]. Indonesia (and entire Maritime Continent) plays a crucial role in atmospheric circulation. It is characterized by the largest average global precipitation and accompanying heat release, for which it has been referred to as the "boiler box" of the Earth [3, 4]. From the societal point of view, Indonesia has an unusually large share of natural disasters, from earthquakes, to fires and floods. While the earthquakes are the most deadly of Indonesian natural disasters, floods affect the large portion of population an can have a devastating economic impact. Both fires and floods are related to extreme precipitation events and therefore could be potentially predicted using the Navy modeling capabilities. The purpose of this work is to further understand meteorological factors that drive extreme precipitation causing flooding in Indonesia and potential for predictability of these events using the new Navy ESPC coupled modeling system.

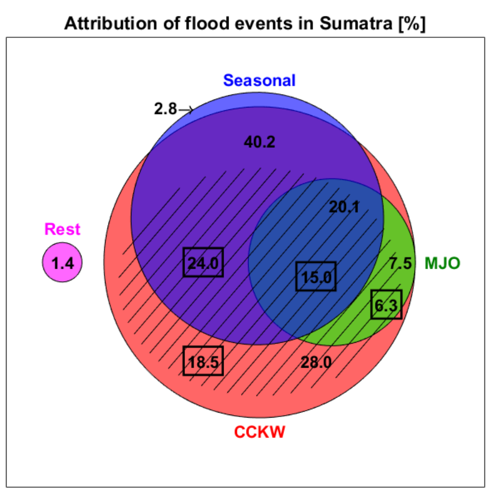

Fig. 1—Attribution of flood events in Sumatra. Data presented as scaled Venn diagram. Total area of the blue circle represents 63.1% of floods associated with above-average seasonal precipitation. Total area of the green circle represents 27.6% floods associated with favorable MJO conditions (MJO in phases 2-5). Total area of the red circle represents 95.8% floods associated with CCKW activity (precipitation anomaly above 2.5 mm/day), while hatching indicates strong CCKWs (precipitation anomaly above 5 mm/day). Numbers indicate percentage of floods in respective categories. Numbers in boxes represent strong CCKWs. The magenta circle represents 1.4% of all floods, which were not attributed to either category considered. The diagram is based on Twitter database, from ([1])

Manuscript approved December 16, 2020.

In [1] we analyzed links between floods in Sumatra and large scale atmospheric circulations using flood data bases created specifically for this work. The data bases employed the information from social media (twitter) and local newspapers available on-line. These data bases supplemented the disaster data gathered by Indonesian agencies and created more complete picture of distribution of floods in time and space, allowing for better attribution of floods to meteorological events. Our analysis (Figure.1) indicated that for Sumatra the majority of floods were related to the convectively coupled equatorial Kelvin waves (CCKW). Other important factors included Madden Julian Oscillation (MJO) and seasonal variability, namely the seasonal shift of Intertropical Convergence Zone (ITCZ). This is a new and significant result, because while earthquakes and tsunamis are the most deadly, floods constitute about 50% of all catastrophic events on Sumatra and this contribution could potentially increase in a warming climate. The analysis of Sumatra floods described in [1] was a collaborative effort between NRL and PIs involved in the NSF-sponsored Equatorial Line Experiment (ELO) project, which in turn is a part of the larger, international effort called Years of Maritime Continent (YMC). YMC is focused on understanding of the coupled convective processes in the Maritime Continent, the interactions between atmosphere and and ocean in this region. and their impact on weather and climate. The NRL researchers were involved in this collaboration through the 6.1 base project ”Equatorial Moist modes” and ONR DRI Propagation of Intraseasonal Tropical Oscillations (PISTON). This work is now continued and extended under the NRL NISE funding. The ultimate goal of our work is to improve the prediction for extreme events such as floods, using the Navy modeling systems through better understanding of underlying physics and the feedback between large scale circulations and local conditions and various parts of the coupled system . At present, the forecast skill for slower equatorial modes such as Madden Julian Oscillation (MJO) is rapidly improving, and for the navy Navy ESPC it is on par with major systems such as European and NOAA models [5]. However, the prediction of other equatorial modes especially CCKW is still a challenge [6] for almost all dynamical models. In this work we seek to understand the importance of equatorial variability modes for prediction of extreme events, the factors in the the atmospheric and oceanic circulations that influence their behavior over Maritime Continent and further examine the capabilities and potential areas of improvement in the Navy modeling system. .

2. RESULTS

2.1 Equatorial Waves and extreme precipitation: Observations and modeling considerations

In this project we seek to extend the results described above [1] to other parts of Maritime Continent. The significance of CCKW for extreme precipitation and floods on Sumatra can be explained by location of the island which is straddling the equator, with one of its largest cities, Padang located at 1N. Kelvin waves, unlike Rossby, or Mixed Rossby gravity waves, are characterized by precipitation anomaly right on the equator, or, in the presence of large vorticity anomalies, on the ”dynamic equator” where absolute vorticity is equal to zero. However, for islands located farther from the equator the impact of other modes and seasonal changes can increase. To address this question we examined floods for the Southwestern Sulawesi that is located at 5S in the Western Pacific warm pool. In particular, we analyzed the very strong event, the major flood that occurred on 22 January 2019 in the area of the major port city Makassar, and was considered the largest flood in this region in the previous 20 years. The contribution of various modes of tropical variability to the total precipitation on the day of this flood is shown in figure 2. It can be seen that both MJO and CCKW exhibited increased precipitation anomaly in South Sulawesi area on the day of the flooding. Our investigation indicates, that the contribution of the Rossby wave had a different character and was reflected in the increased wind speed between the Rossby vortices and large moisture transport in Makassar Strait (not shown).

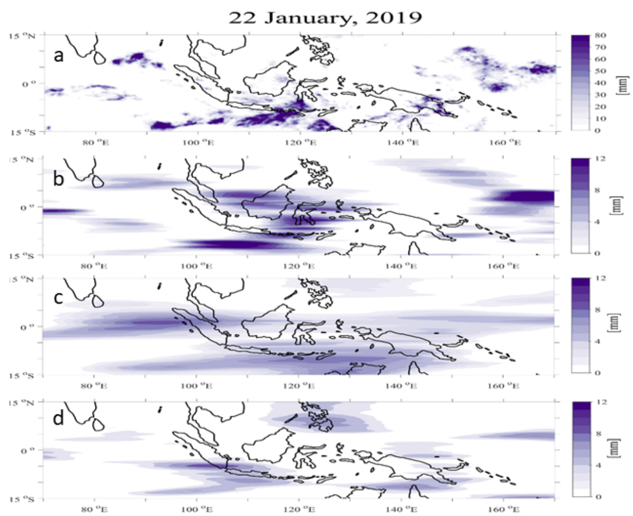

Fig. 2—TRMM precipitation on the day of the Sulawesi flood a) total precipitation b) Convectively Coupled Kelvin wave anomaly c) MJO anomaly, d) Convectively coupled Rossby wave anomaly

Figure 2 also indicates that rainfall anomalies related to CCKW and MJO were significantly smaller than total precipitation. To understand what controls extreme precipitation in this area we used the simulation of this event with adjoint of Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) to calculate the sensitivity of forecasted rainfall in the flood area to changes in the initial state. The adjoint sensitivity studies including moisture have been very successful in pinpointing the major factors influencing precipitation in atmospheric rivers [7] and extra tropical cyclones [8].

The sensitivities obtained using the adjoint system (Fig.3) shed light on what variables and process control the precipitation related to Sulawesi flood on the short time scale, immediately preceding the flood. Two factors appear to dominate: the SST in the Java Sea west of Sulawesi and the divergence in the same region. To understand the source of these sensitivities we examined the relationship between the local phase of Kelvin wave and total precipitation in two locations: over the ocean, west of Sulawesi and over the land at the southwestern tip of the island. The local phase of the wave is defined using the local normalized filtered precipitation and its normalized tendency following methodology of [9, 10]. The CCKW behavior is evaluated at the location of the maximum divergence sensitivity.

Figures 4a and b show the relationship between the wave and total precipitation in at the same location, that is over the Java Sea west of Sulawesi. Figure 4c shows the dependence of the precipitation over the island in the phase of the wave loacted to the wet of it, in the same location as in Figure 4a. The diagrams are based on 15 years of the TRMM data, and the extreme precipitation is defined as precipitation exceeding 4 standard deviations(calculated using the entire zonal belt). The results for January (when the most floods in this region occur) and July (the dry season in Sulawesi) are shown. For all cases, the majority of the extreme precipitation events is related to the active phase of the wave (phase 1) with only a small portion

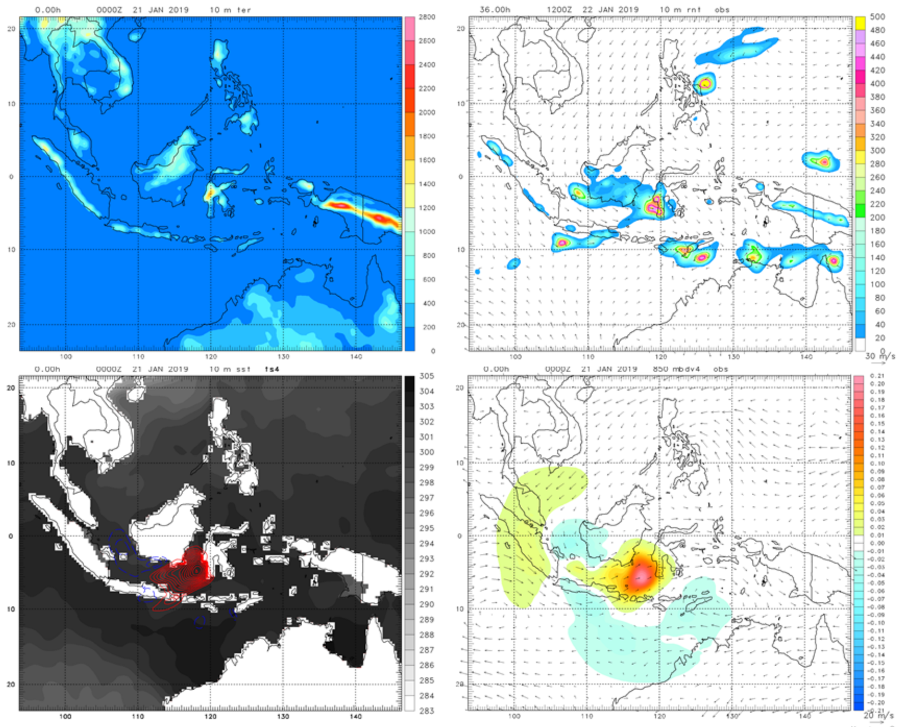

Fig. 3—COAMPS forecast of Sulawesi flood and adjoint sensitivity a) experiment setup b) 36h forecast of 850mb winds and precipitation, c) SST sensitivity, d)divergence sensitivity

of events developing in the dry phase of the wave (phase 3). In June, more precipitation events can be observed where the wave amplitude is less than one, that is no discernible Kelvin wave present in the region. Therefore, it appears that in January the CCWKs exert stronger control over local precipitation in this area. For the precipitation events over the land, the extreme cases shift from the ”moistening” (phase)to the ”drying” (phase 2) phase which is consistent with the eastward propagation of the Kelvin wave and strong sensitivity to the divergence west of Sulawesi. This agrees with the results of [9, 11, 12],who suggest that the convergence related to CCKWs can provide a favorable environment for development of mesoscale convective systems.This importance of oceanic convection west of Sulawesi explains also the sensitivity to SST shown in figure 3c. It is worth noting, that the case of January 2019 flood the mesoscale convective system developing over the ocean and propagating into the land bringing the extreme rainfall, was also observed. Figure 5 summarizes the factors that were responsible for the major January 2019 flood,m with the Kelvin wave providing the favorable conditions for development of extreme rainfall in MCS, and Rossby wave enhancing the transport of the moist air from the South China Sea through the Makassar Strait impinging on the Sulawesi orography.

The climatological analysis of floods in south-western Sulawesi based on Indonesian flood data base and observational data between 1998 and 2019, indicates the CCKW play and important, but not dominant role for the extreme precipitation in this area. Figure 6 shows the flood attribution at Sulawesi, with cross indicating our case study. While the CCKWs still play a role, the importance of other modes of equatorial variability such as MJO or Rossby waves increases compared to Sumatra. In addition all floods develop during winter, especially in January, when the anomalous westerlies over Southern Sulawesi are especially strong. we have shown that one of the roles of equatorial modes is strengthen this westerly flow over the

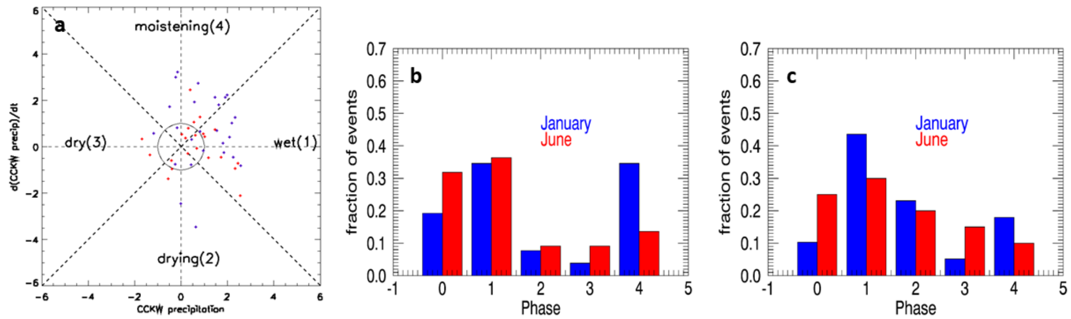

Fig. 4—The relationship between the total rainfall and the local phase of the Kelvin wave a) CCKW phase diagram and precipitation in the region of maximum divergence sensitivity in fig 3 b) fraction of the large precipitation events (larger than 2*standard deviation) per the phase of the Kelvin wave in the same region, c) the same but for the precipitation over the Makassar

Sulawesi mountains. The role of the mountains and the local factors in creating the flood conditions demands further investigation.

Since the extreme precipitation appears be significantly controlled by CCKWs it is important that the global model not only represents the coupled waves but also their impact on extreme precipitation. Figure 7 show the comparison of impact of the CCKW phase on strong precipitation for the equatorial region west of Sumatra which is charcterized by intense convection for TRMM precipitation, the Navy Earth System Prediction Capability (ESPC) model and NCEP Coupled Forecast System Model(CFSv2) coupled system. It appears that both models well represent the strengthening of precipitation in the active region of Kelvin wave. In fact in the Navy ESPC system this relationship is stronger than in observations.

Another factor influencing the predictability of the extreme precipitation and floods is the forecast skill of the phase of convectively coupled waves. While the Navy ESPC model reasonably represents the wave variance [5] the forecast of the propagation of individual CCKWs is still challenging. In the case of the flood analyzed in this chapter, the Navy ESPC system predicted the behavior of MJO and Rossby modes but the Kelvin wave was significantly weakened, leading to under-prediction of precipitation anomaly (8

2.2 The interaction between the atmospheric and oceanic equatorial modes

The important component of this work is to understand the how the ocean dynamics can contribute to modifications of atmospheric convection, especially the Madden Julian Oscillation (MJO). Some of these questions were addressed in our previous research and we are at present preparing a paper on the work funded under this project. the following description is a fragment (a summary) of this upcoming paper: " [13] observed that intraseasonal Ocean Heat Content(OHC) anomalies are maximized during periods of enhanced ISO convection in the central and western Indian Ocean. They observed that the majority of intraseasonal OHC variance is off equatorial and westward propagating and hypothesized that westward propagating ER waves are responsible for the phase alignment of intraseasonal OHC and convection. This study demonstrates the harmonization between intraseasonal modes in the atmosphere and ocean as well as the mechanisms determining their synchronization. In order to identify the leading mode of westward propagating intraseasonal variability in the ocean and investigate its behavior, an index based on EOFs ofArchiving,

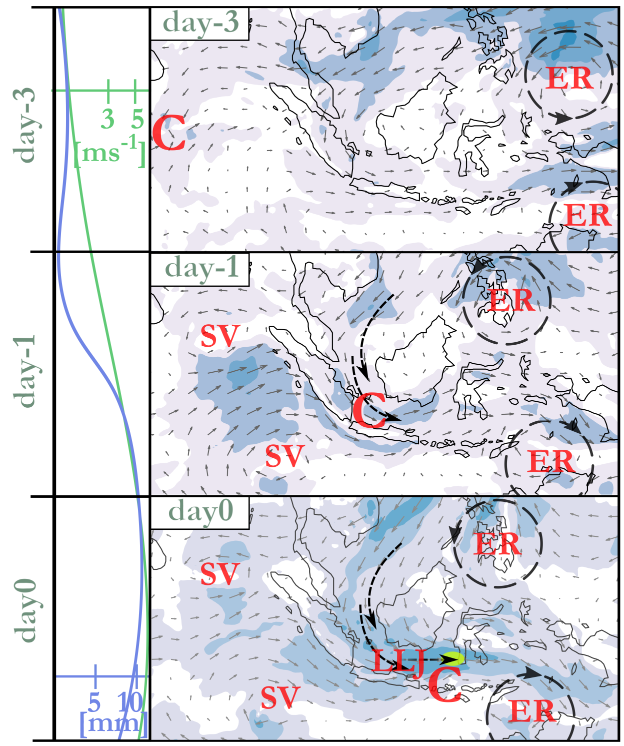

Fig. 5—Right panels: schematic depiction of the key processes responsible for extreme rainfall events and floods in southwest Sulawesi 3 days before (day-3), a day before (day-1) and during the event (day0). Abbreviations are: C – convergence in the CCKW, ER – CCERW, LLJ – Low-Level Jet, SV – Sumatra Vortex. Background are winds at 850 hPa, solid line represents the Equatorial Rossby Wave vortex, dashed line represents cross-equatorial flow. The location of the mesoscale convective system is qualitatively depicted by an ellipse. Left panels: time evolution of approximated zonal wind anomaly (m s^{-1}, green line) and precipitation (mm, purple line) in southwest Sulawesi area.

Validation and Interpretation of Satellite Oceanographic data (AVISO) SSH anomalies is developed. The EOF analysis reveals a mode with a zonal wavelength, phase speed, and frequency that agrees with the first baroclinic mode ER waves 9. The first two EOFs describe 41% of the westward propagating intraseasonal variance in the equatorial Indian Ocean. Composites of ocean and atmospheric variables based on the ER wave index show that the waves are most intense in the eastern and central Indian Ocean and weaken in the western Indian Ocean. The generation of downwelling ER waves in the eastern Indian Ocean is preceded by significant intraseasonal variability characterized by strong westerly wind stress and enhanced convection (Fig. 10) Waves are reinvigorated in the central Indian Ocean by anomalously easterly wind stress associated with the suppressed convective phase of the ISO. ER waves significantly modulate the equatorial ocean environment through which they propagate. OHC anomalies are in phase with ER waves such that maxima/minima of anomalous OHC are also located in the eastern and central Indian Ocean. SST anomalies associated with the waves are largest in magnitude near 82°E with positive (negative) SST anomalies located within downwelling (upwelling) ER waves. The quasi-stationary behavior of the SST anomalies suggests competition between westward and eastward propagating forcing and/or a local preference for anomalous SST formation. The OHC anomalies develop in response to ocean dynamical mechanisms with a secondary role by atmospheric flux forcing. BLT anomalies propagate in phase with the ER waves, modulating the background BLT by 10 – 15% indicating important stratification variations associated with ER waves during ISO events. A summary of the synchronized behavior responsible for the coevolution of ER waves

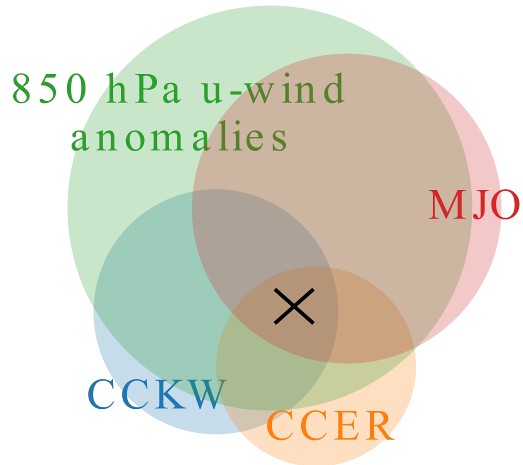

Fig. 6— Meteorological drivers of December-January-February 1998/1999–2018/2019 extreme rainfall in southwest Sulawesi plotted on a Venn diagram. Shown are Madden Julian Oscillation (MJO), Convectively Coupled Kelvin Waves (CCKW), Convectively Coupled Equatorial Rossby (CCER) waves and low-level zonal wind anomalies contributions. Factors that contribute jointly to extreme rainfall are shown as overlapping circles while things that are distinct stand alone. The radii of the circles is proportional to the number of extreme rain events associated with each meteorological factor. The cross sign depicts the January 2019 extreme event,)

and the ISO is shown in Figure 11. In figure 11, westerly surface wind stress associated generated by the ISO accumulates mass in the eastern Indian Ocean generating a westward oriented pressure gradient. In response first baroclinic mode downwelling ER waves are generated and subsequently propagate westward (figure 11b). The waves are reinvigorated by easterly wind stress positioned in advance of the next enhanced convective phase of the ISO (Fig.2.2 This further depresses the isotherms and increases the OHC within the wave. When the westward propagating ER waves and the eastward propagating ISO cross paths in the central Indian Ocean, ISO convection intensifies in association with the positive OHC anomalies (figure11d) In this framework, ER waves are generated and subsequently strengthened by oppositely signed ISO wind stress forcing. The net effect of OHC variations on SST during ISO events is the subject of future fully coupled modeling work."

The results of this work shed a light on the ocean predictors that could be important for extreme rainfall events in the tropics leading to floods. I addition the methodology developed to identify the equatorial waves in the ocean will be used as a diagnostic tool for the Navy ESPC coupled system.

2.3 New scientific display and analysis tools

Since equatorial waves have such a significant impact on tropical convection, diagrams showing various modes of tropical variability such as for example NC State University's North Carolina Institute for Climate Studies (NCICS) MJO monitoring page

`https://ncics.org/portfolio/monitor/mjo/}`

or the wave monitoring page from Michale Ventrice

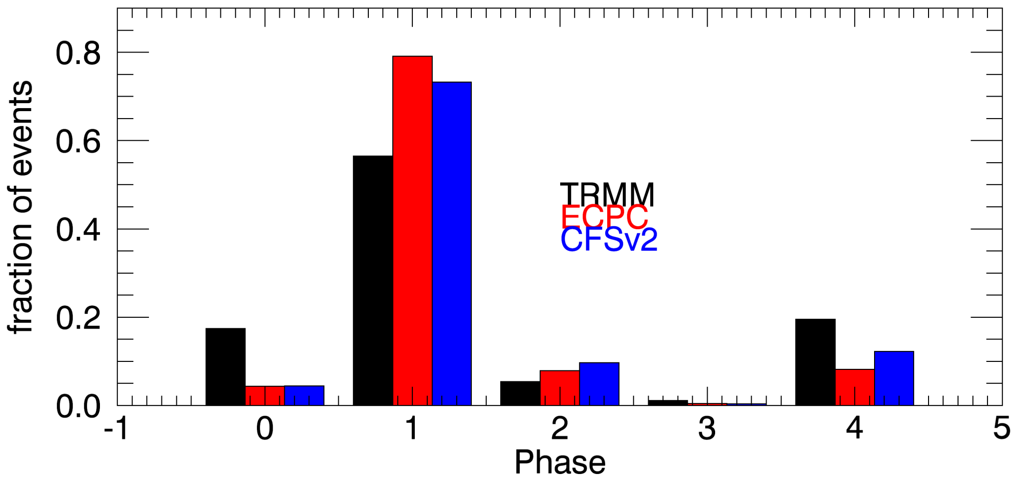

Fig. 7—The relationship between the total daily rainfall exceeding 4 standard deviations and the local phase of the Kelvin wave for equatorial Indian Ocean east o Sumatra(95E-100E) for TRMM, the NAVY ESPC system and NCEp CFCv2 model

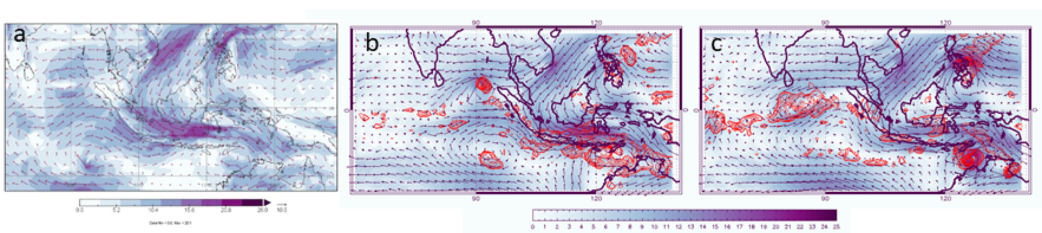

Fig. 8—850 mb wind and for January 22 2019 Sulawesi flood a) era reanalysis b) the Navy ESPC system forecast 4 day lead c) the ESPC system forecasts 8 day lead

`http://mikeventrice.weebly.com/`

became very popular tools used by both research and forecasting community. On the other hand the applications for visualisation of analysis and forecast data on the globe such as windy.com are widely used by general public, because they allow for quick access to a large amount for forecast data displayed in the user friendly form. We collaborated with the Scripps Institution of Oceanography on the project lead by the Equatorial Line Experiment (ELO) lead PI to develop the prototype visualisation tool that would combine these two approaches and allow the researchers to easily display tropical atmospheric and oceanic variables and their spectral components, to better understand the feedbacks involved in triggering and maintaining of tropical convective systems. The NRL team is collaborating with the Scripps/UCSD by testing the system functionality, advising in design and choice of variables that need to be included in the system and contributing some of the filtered variables. We also used this system to guide our understanding of the role of various variability modes in creating the flood conditions, and in research related to other NRL projects such as monsoon oscillations. At present the system is using 2 years (2018 2019) of the observational and ERA-5 reanalysis data and include both atmospheric and oceanic variables that could contribute to development of

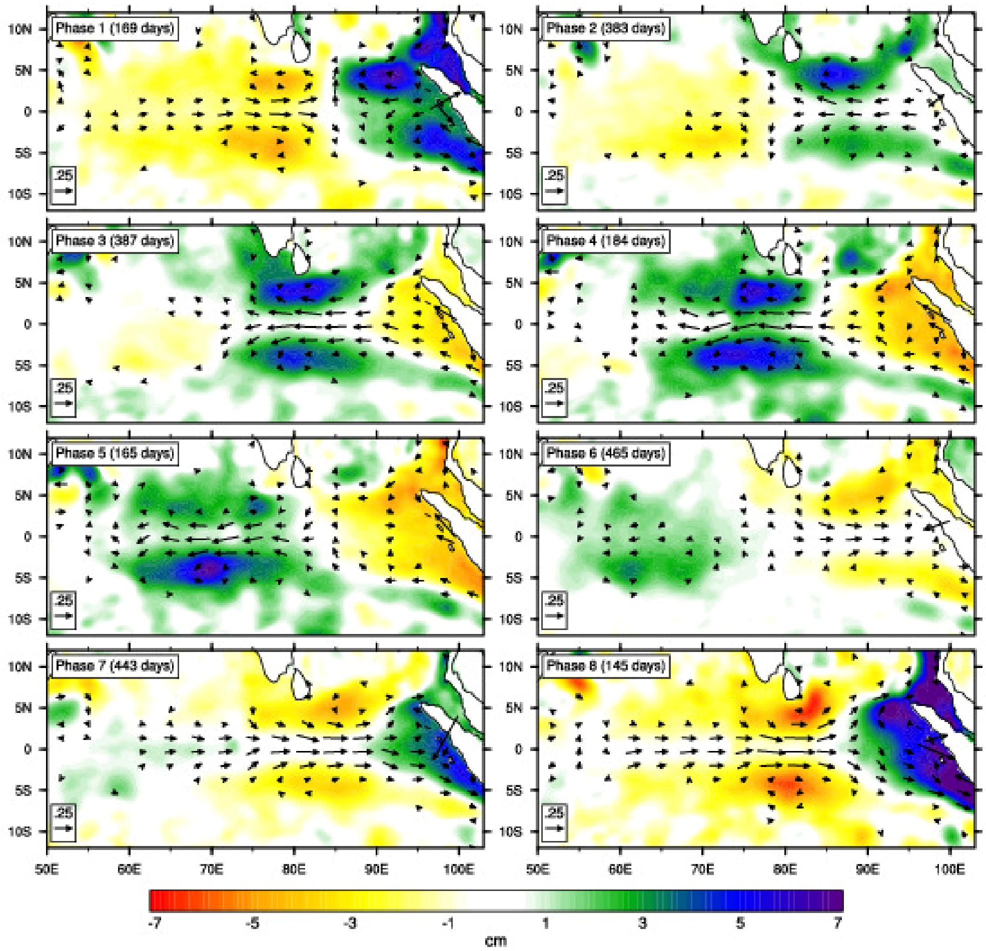

Fig. 9— Composite maps of the 30–150-day band-pass-filtered AVISO sea surface height (shading, cm) and Ocean Surface Current Analysis Real-time surface currents (vector, m/s) anomalies based on the equatorial Rossby wave index are shown for phases 1–8. The number of days in each phase composite is shown in the upper left, and the reference current vector is shown in the bottom left of each panel.

tropical convective systems. The example of the system functionality is shown in figure 12 which represents various variables at the day preceding the intense flood which developed in Sumatra on October 11 2018 and affected about 20000 people on the island.The bar on the right side of images indicates the variables and spectral components that can be displayed in the current version of the system. Figure 12a shows the vertically integrated water transport in the form of ”streamlets” and vertically integrated moisture convergence. The convergence of the moist air in the western Sumatra and over IO next to the Sumatra shore is clearly seen. In addition, even though the wind speed on both sides of Sumatra are similar, the more moisture is carried by easterlies to the east of the island. That could be explained by the high SSTs in the South China Sea (Fig. 12c) Figure 12b displays the SSH anomaly related to propagation of the oceanic Kelvin waves showing the positive anomalies along the Sumatra Coast and negative anomaly over the equator in the Central IO. Figure 12c indicates the are where there was an active MJO convection, using the OLR fields re-constructed form the MJO OMI index [2]. While the publication quality plots have to be created using

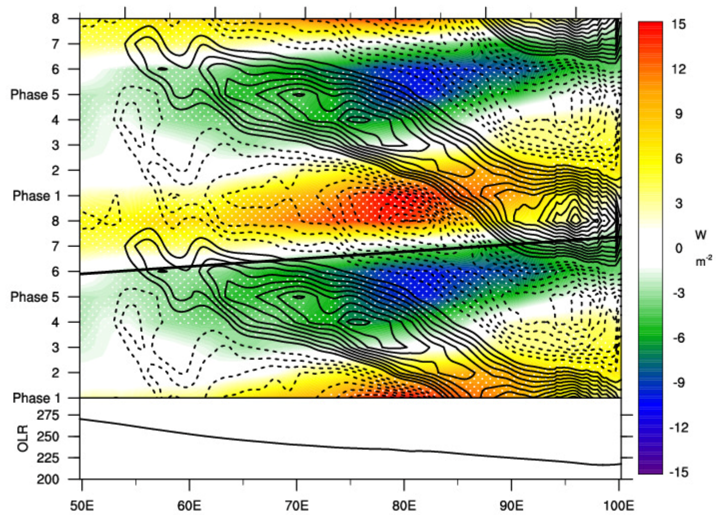

Fig. 10— Composite of 30–150-day band-pass-filtered AVISO sea surface height (contours, cm) and NOAA outgoing longwave radiation (OLR) (shading, W m-2) anomalies based on the equatorial Rossby wave index are shown for phases 1–8. Sea surface height anomalies are averaged from 2° – 6° S and 2° – 6° N. Solid (negative) contours are positive (dashed). The contour interval is 0.5 cm and omits the zero contour line. Outgoing longwave radiation anomalies are averaged from 10° S – 10° N. Climatological outgoing longwave radiation averaged from 10° S – 10° N is shown in the bottom panel. White stippling indicates outgoing longwave radiation values significantly different from zero at the 99% confidence threshold. The black line indicates a phase speed of 4.5 m s-1.

other software, the ”spectral weather” allows to quickly analyze many atmospheric and oceanic variables to test hypotheses or to use as a teaching tool.

3. SUMMARY

We identified the most important factors leading to floods in Indonesia and we examined their representation in the Navy modeling systems. We have shown that over the Indonesian islands the convectively coupled equatorial waves play an important role in triggering the intense precipitation leading to floods. Using the ajoint COAMPS sensitivity simulations, we have shown that while MJO and convectively coupled Rossby waves are also important flood predictors, the Kelvin waves seem to play a critical role in triggering extreme precipitation, likely through creating the favorable condition for development of mesoscale convective systems (MCS) in the region of the wave convergence. The model evaluations indicate that the Navy ESPC represents the impact of the Kelvin waves on the intense precipitation but the prediction of the Kelvin wave itself is not always accurate. We have also shown that the oceanic equatorial modes can be both triggered by equatorial convection, and contribute to its strengthening, therefore the ocean dynamics could also influence the conditions favorable for development of extreme precipitation. In addition, we collaborated with Scripps Institution of Oceanography in developing the new visualisation tool for displaying the atmospheric and oceanic variables across the tropical belt, and their spectral component to better understand the interactions and feedbacks involved triggering and maintenence of organized tropical convective systems.

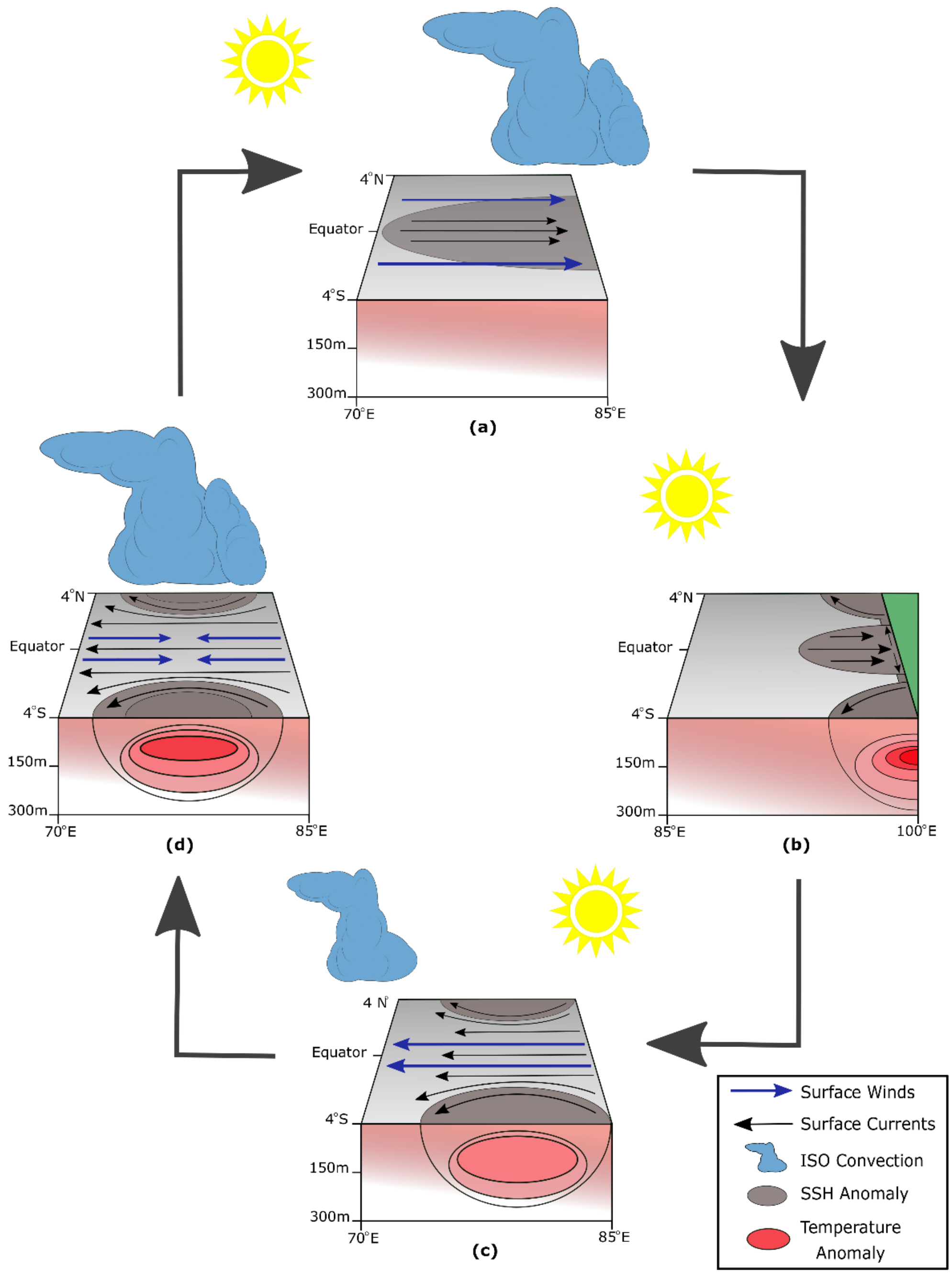

Fig. 11—Schematic showing the temporal evolution of equatorial Rossby waves and intraseasonal oscillation convection in the Indian Ocean. Panel a) shows the generation of the equatorial Kelvin wave associated with anomalous westerly winds behind the convective envelope. Panel b) shows the reflection of the Kelvin wave into equatorial Rossby waves. Panel c) shows the westward propagation of the ER waves and development of easterly wind stress in advance of the intraseasonal oscillation convection. Panel d) shows the resulting strengthening of ER waves and the intensification of intraseasonal convection over the region of increased OHC. The vertical cross section shows the temperature anomalies at 4 °S.

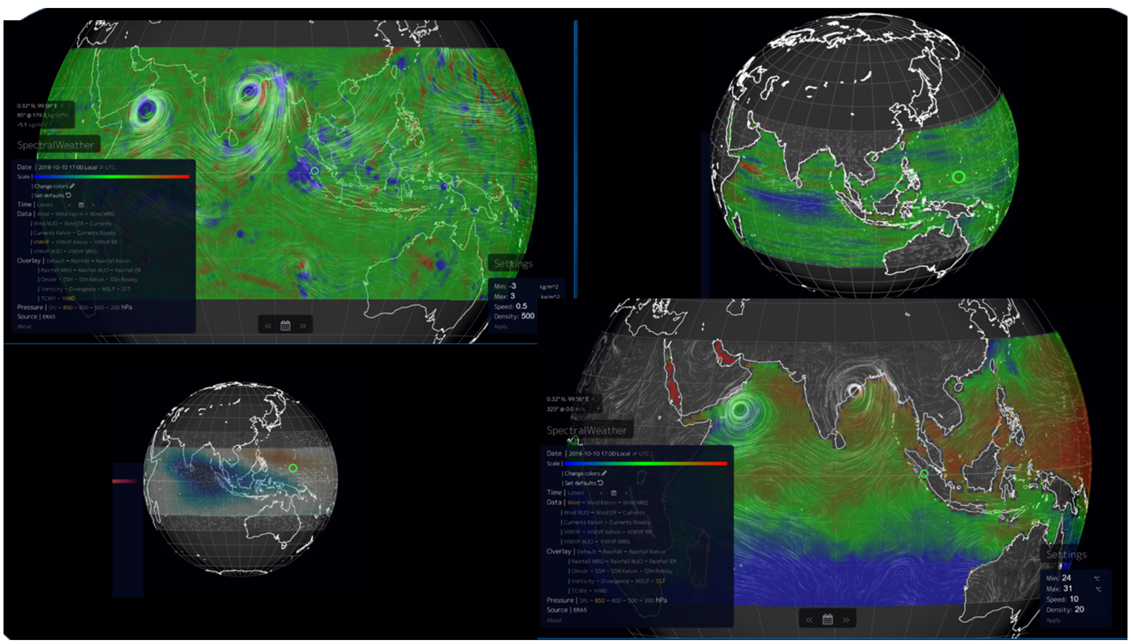

Fig. 12—The example of ”spectral Weather” visualisations for the 10 October 2018 flood in western Sumatra, a) Integrated Vapor Transport(IVT) and integrated moisture divergence b) MJO wind component and SSH anomaly related to oceanic Kelvin waves, c) OLR reconstructed from the MJO OMI index [2] and MJO-filtered 850 wind anomaly c) 850 mb winds and SST

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