# IV. SHALLOW WATER RESULTS

In this chapter we present results for shallow water operations; i.e., for finite water depth beneath the keel. Shallow water corrections are implemented in the software package as described in [Ref. 3]. The results are presented in terms of the two criteria used in deep water, periscope submergence and sail broaching as well as for an additional criterion which quantifies the probability of collision between the boat and the sea bed. This is calculated based on the absolute vertical motion at either the bow or the stern and the clearance from the sea bed at the appropriate motion point. All results are presented for a standard depth between keel and free surface of three diameters.

## A. RESULTS OF PERISCOPE SUBMERGENCE CRITERION

Figures 101 through 109 present the results for the periscope submergence criterion. Each polar plot is for a given depth beneath the keel and for four forward speeds, namely three, five, eight, and eleven knots. Figure 110 shows the operability index in percentage normalized with respect to its deep water value, as a function of both speed and shallow depth. The percent change in the operability index is calculated by subtracting the shallow water value from the deep water value and dividing by the deep water index. Therefore, positive values show that the operability in shallow water is smaller compared to deep water. It can be seen that the operability index does not change much and it does not follow a consistent trend. For certain speeds it decreases in shallow water, while for other speeds, it increases and then starts to decrease. The numerical values are quite small and the shape of the polar plots does not change significantly for different water depths. It appears, therefore, that the operability index with regards to periscope submergence remains essentially the same for deep and shallow waters.

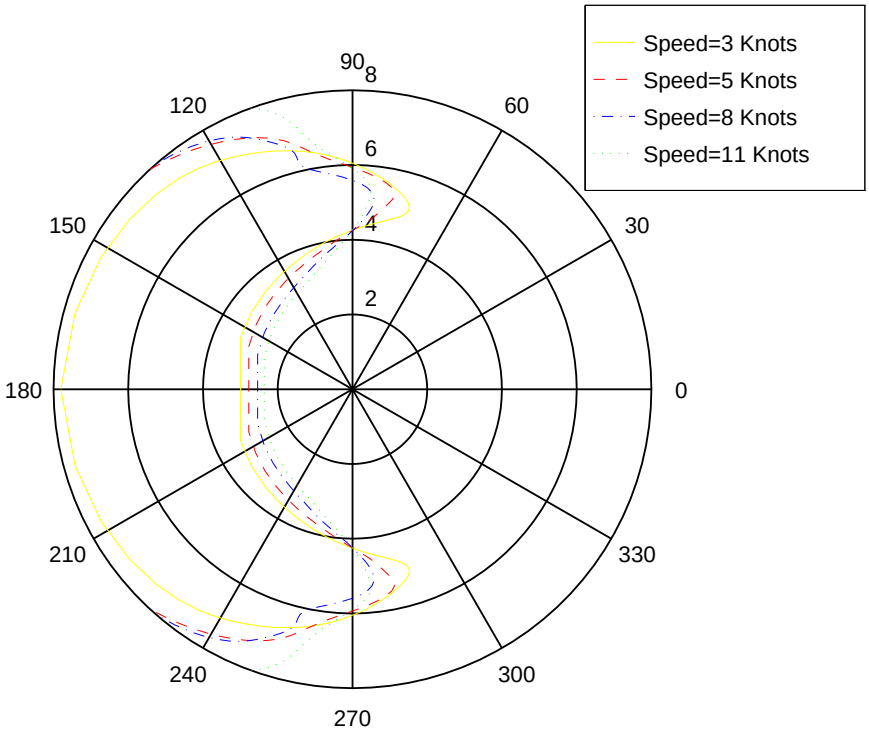


Figure 101. Sea state-polar plot, showing SOE for different *U*'s and 5*D* Water Depth

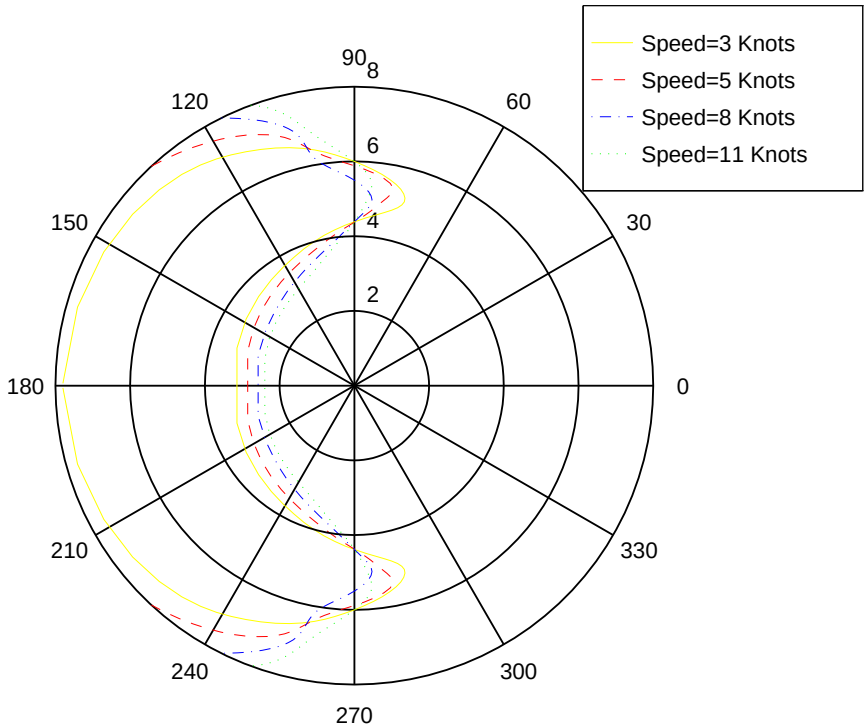


Figure 102. Sea state-polar plot, showing SOE for different *U*'s and 6*D* Water Depth

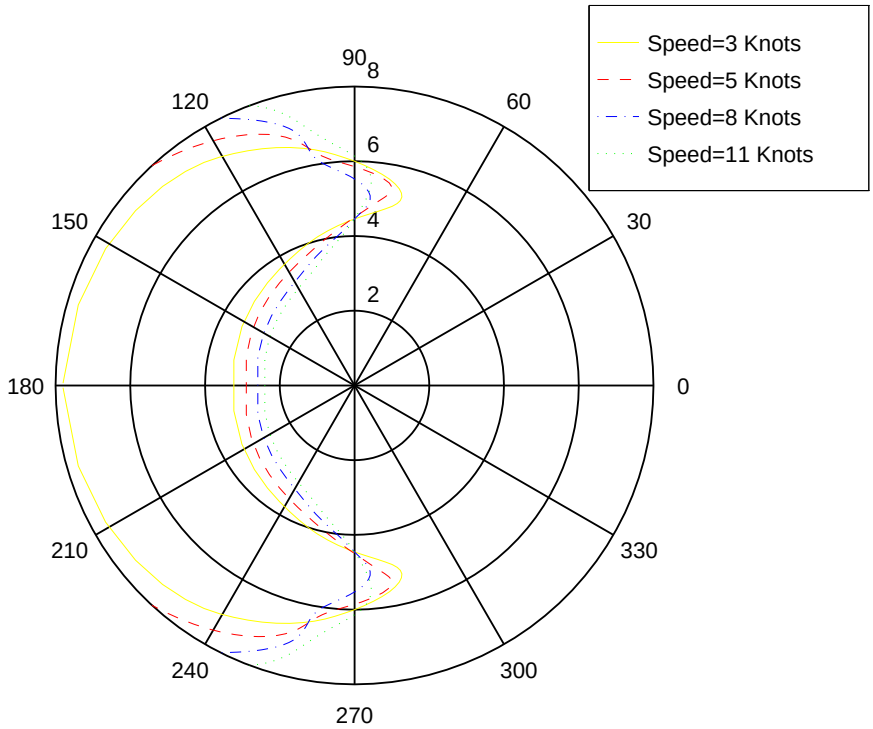


Figure 103. Sea state-polar plot, showing SOE for different *U*'s and 7*D* Water Depth

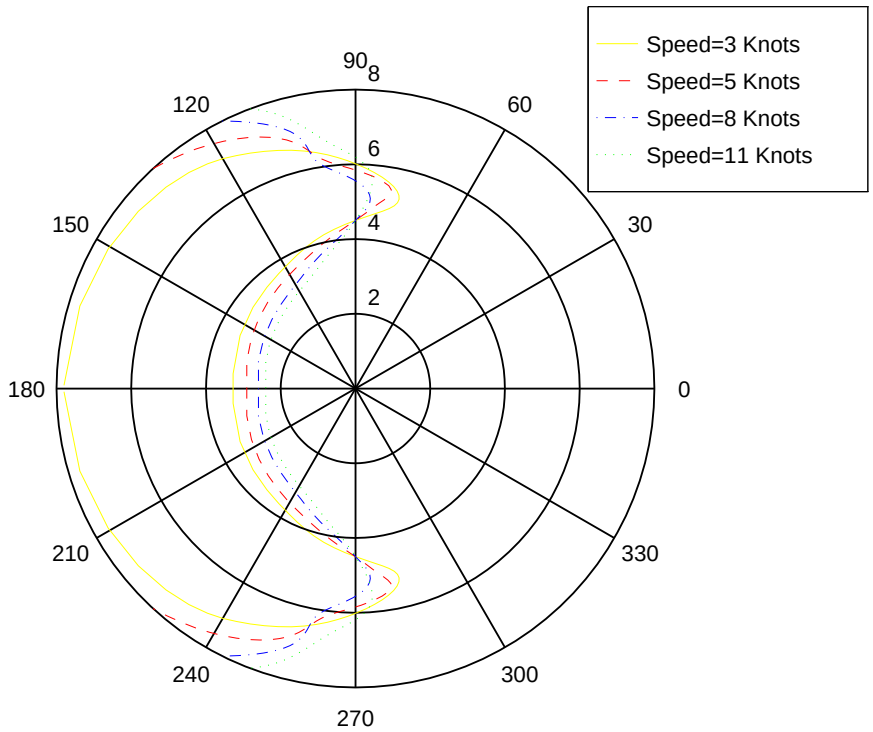


Figure 104. Sea state-polar plot, showing SOE for different *U*'s and 8*D* Water Depth

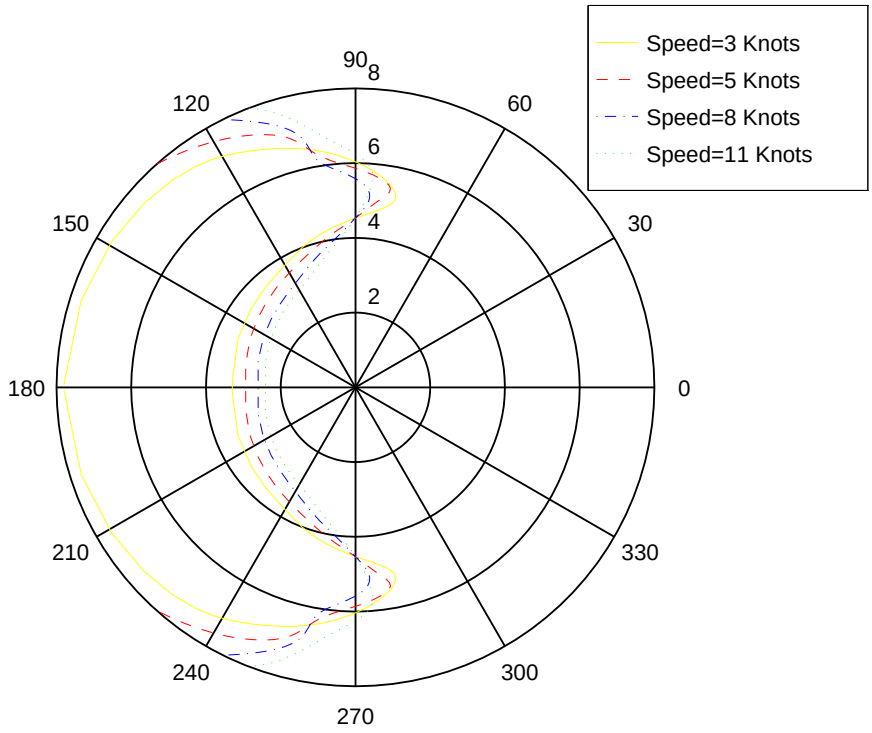


Figure 105. Sea state-polar plot, showing SOE for different *U*'s and 10*D* Water Depth

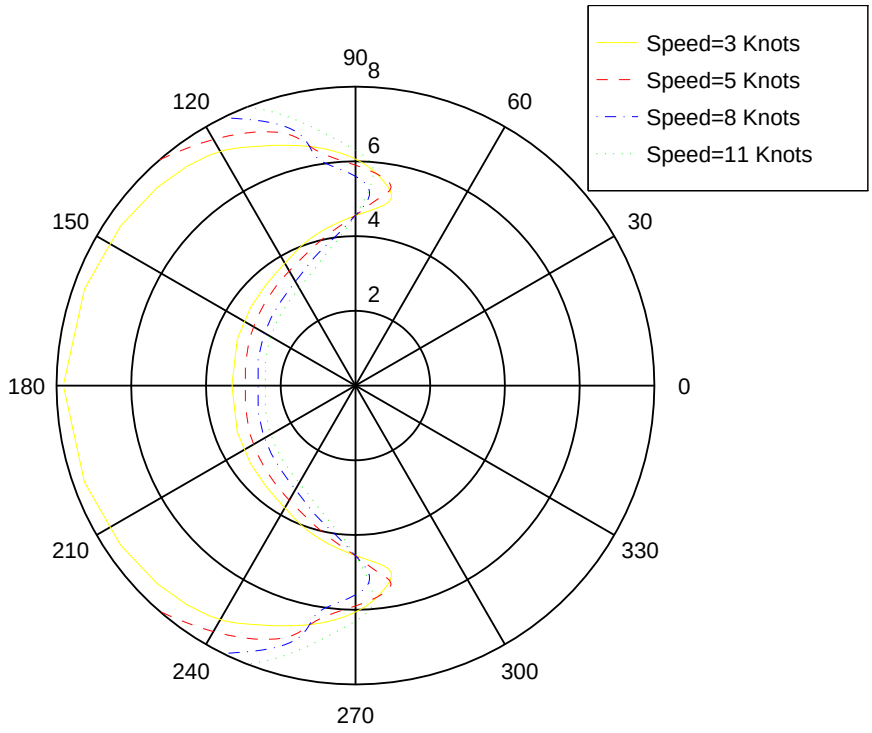


Figure 106. Sea state-polar plot, showing SOE for different *U*'s and 15*D* Water Depth

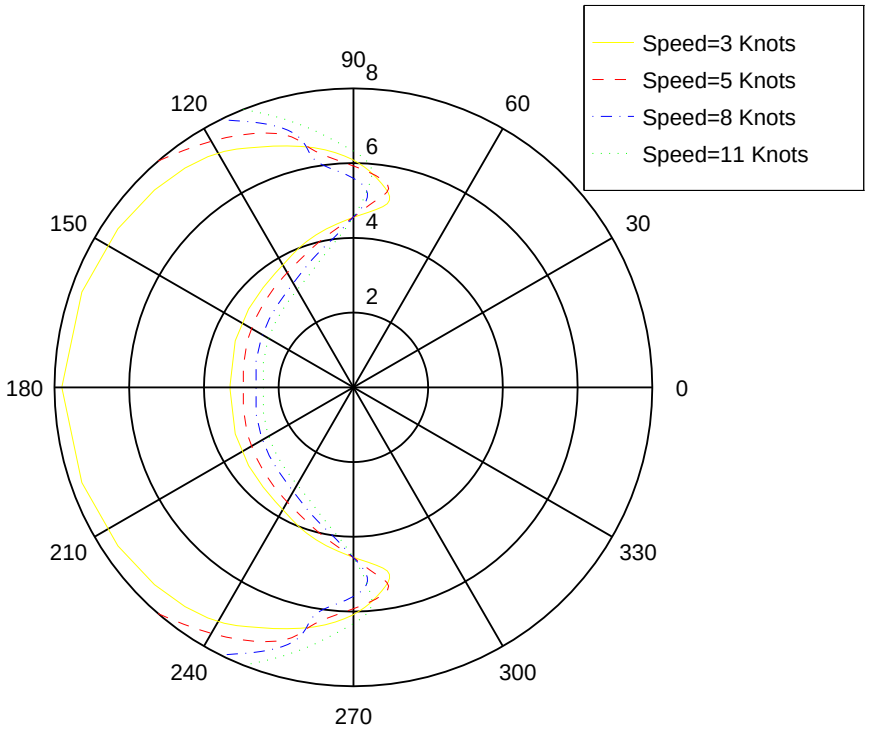


Figure 107. Sea state-polar plot, showing SOE for different *U*'s and 20*D* Water Depth

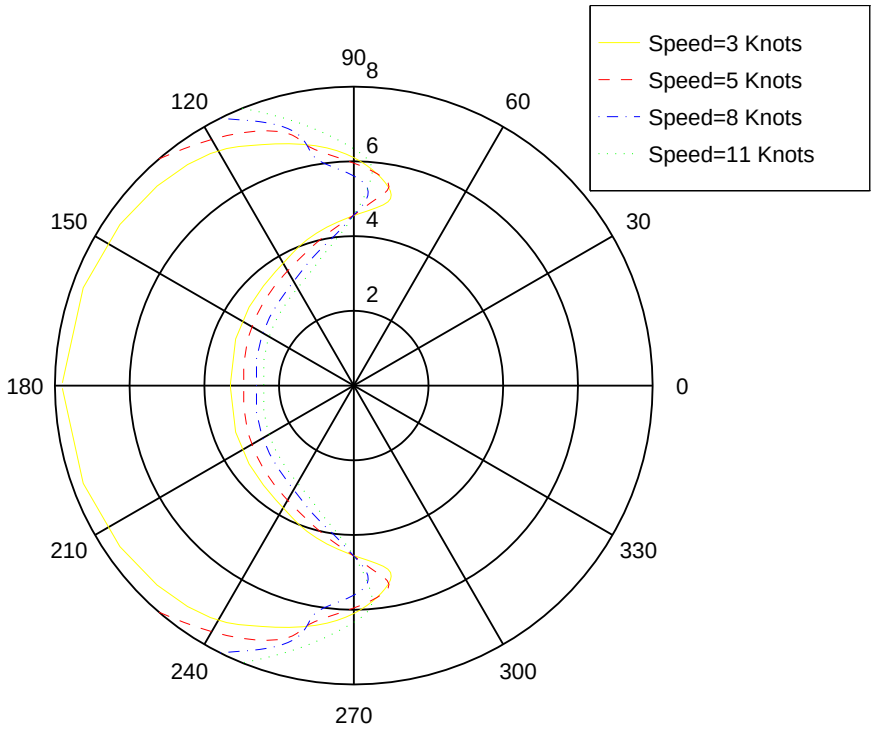


Figure 108. Sea state-polar plot, showing SOE for different *U*'s and 30*D* Water Depth

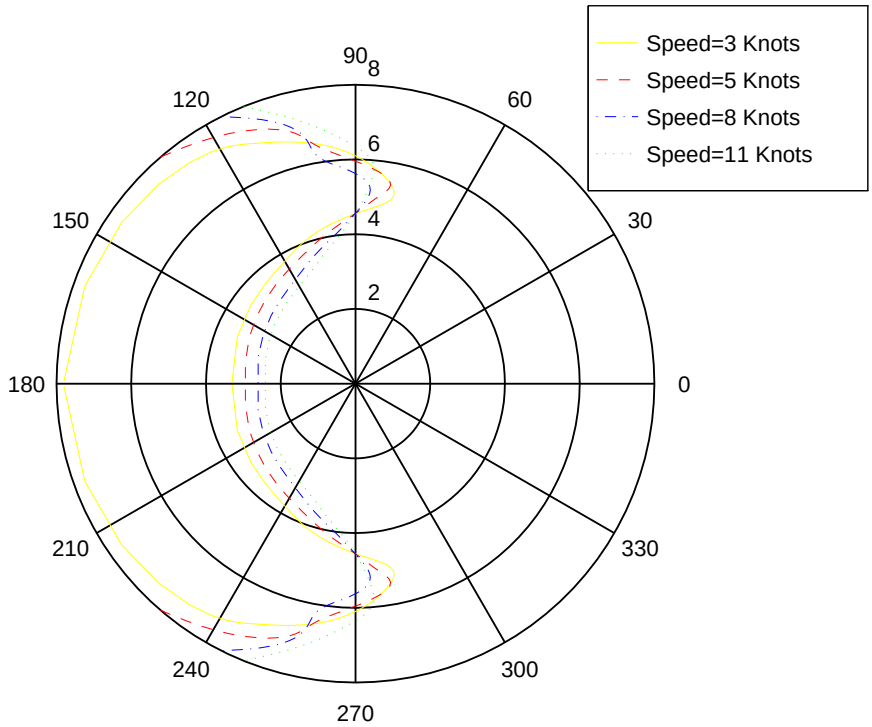


Figure 109. Sea state-polar plot, showing SOE for different *U*'s and 40*D* Water Depth

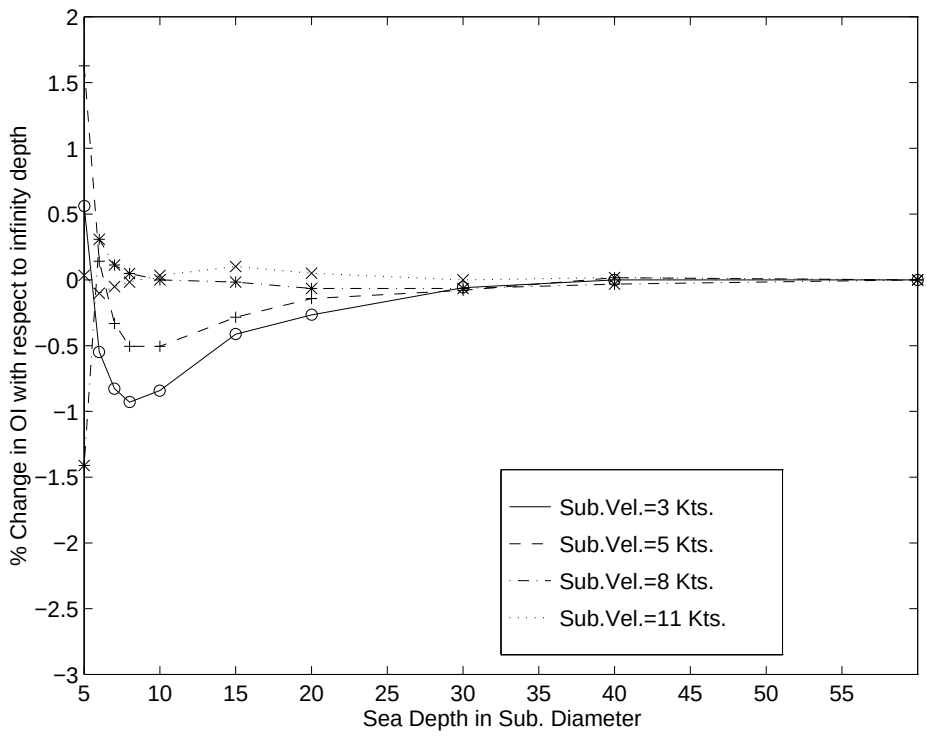


Figure 110. Change in OI with respect to infinite depth vs. Water Depth

## B. RESULTS OF SAIL BROACHING CRITERION

Results for the sail broaching criterion are presented in Figures 111 through 119. The same parameters as for periscope submergence were used here as well. The percent change in the operability index is shown in Figure 120. Here it seems that water depth has a more important effect on both the value of the operability index and the shape of the polar plots. In general, the operability index is decreasing as the water depth becomes smaller.

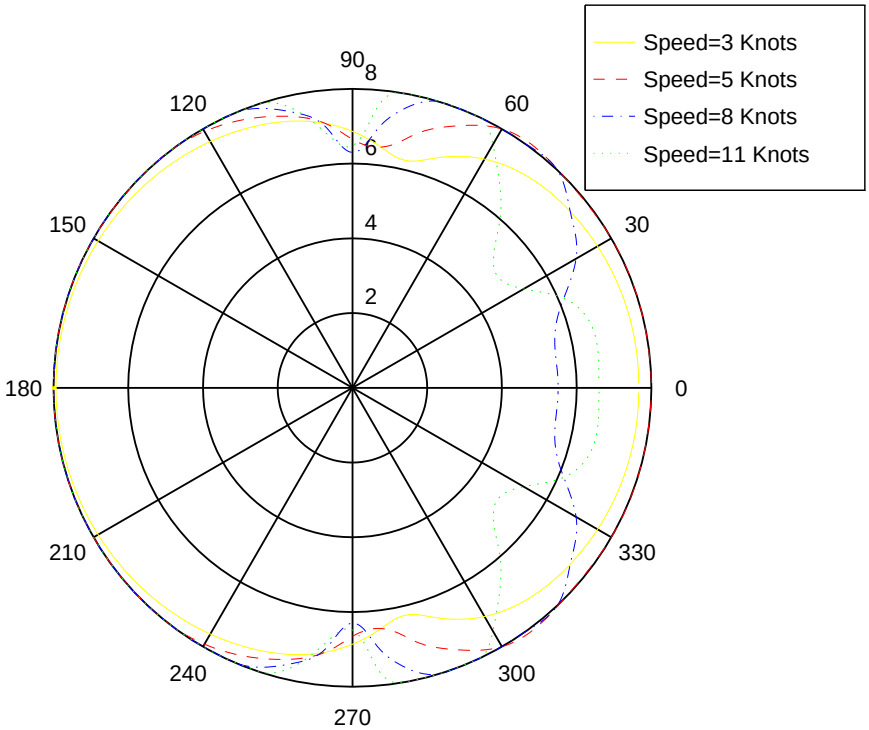


Figure 111. Sea state-polar plot, showing SOE for different *U*'s and 5*D* Water Depth

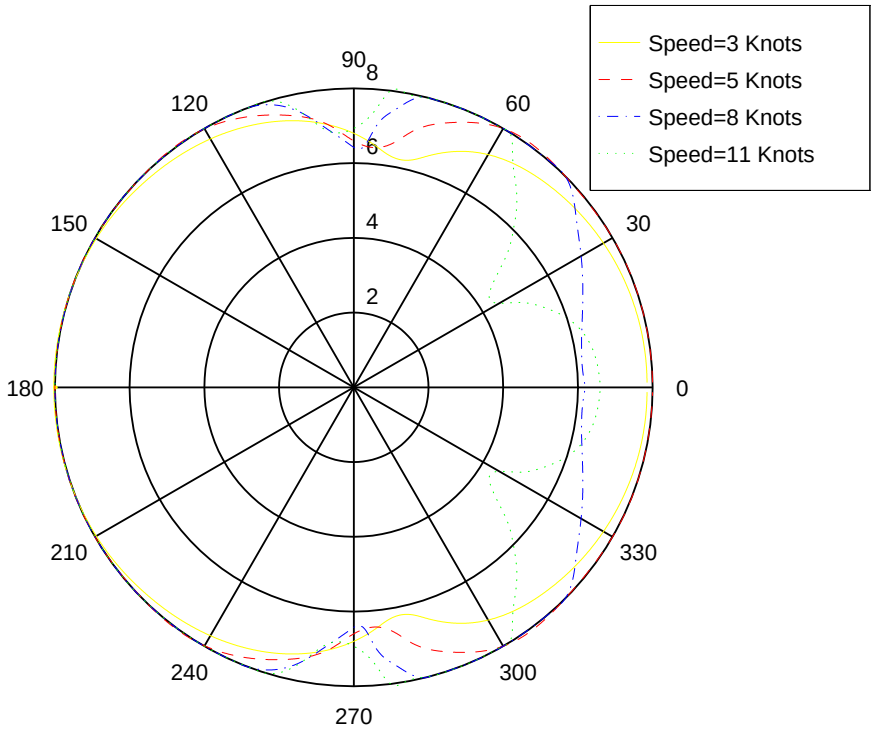


Figure 112. Sea state-polar plot, showing SOE for different *U*'s and 6*D* Water Depth

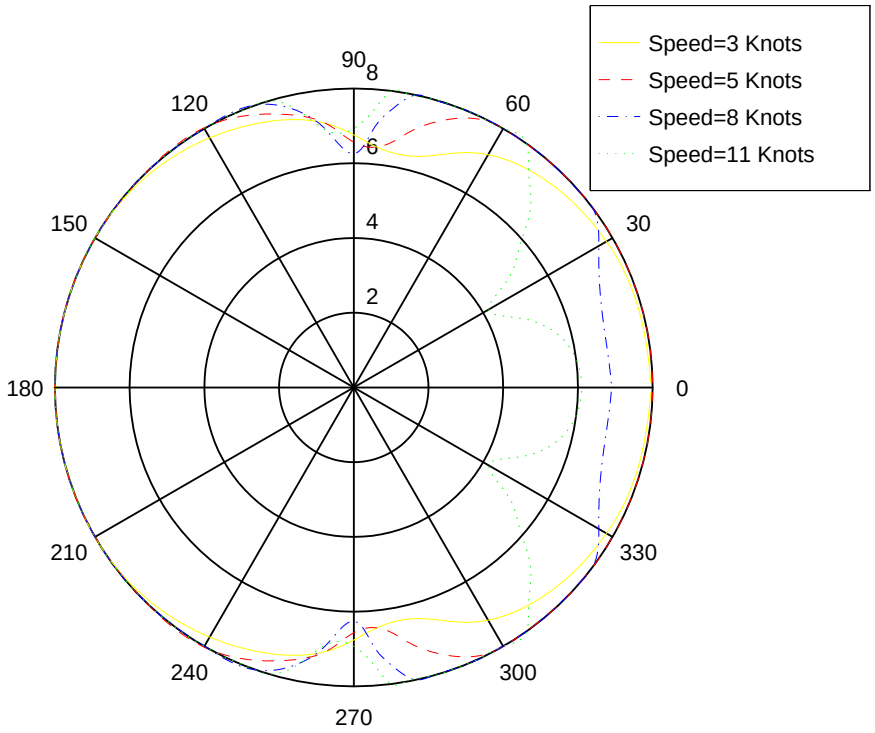


Figure 113. Sea state-polar plot, showing SOE for different *U*'s and 7*D* Water Depth

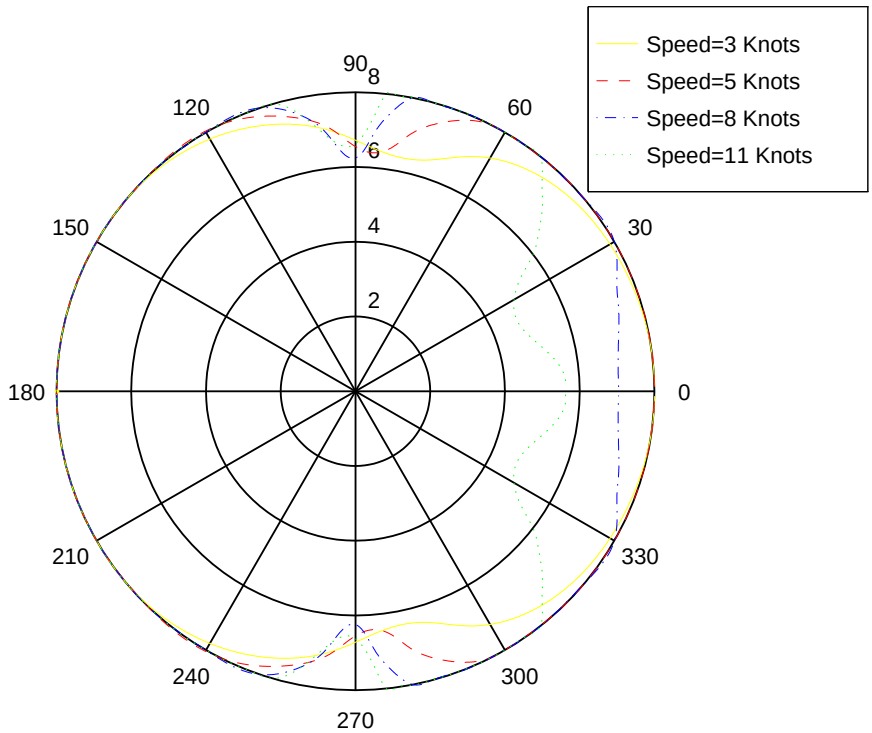


Figure 114. Sea state-polar plot, showing SOE for different *U*'s and 8*D* Water Depth

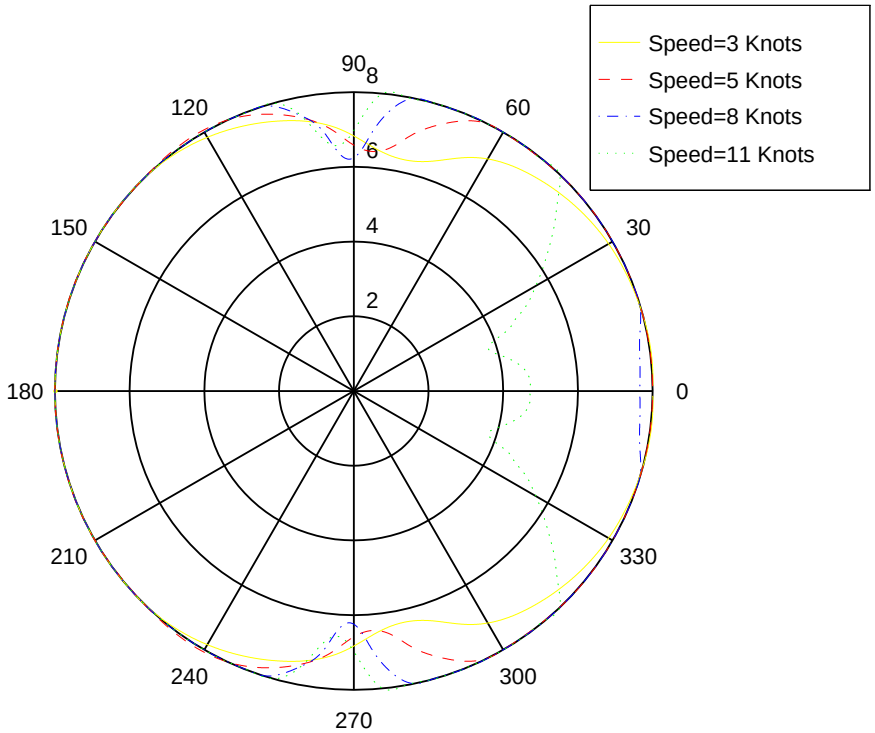


Figure 115. Sea state-polar plot, showing SOE for different *U*'s and 10*D* Water Depth

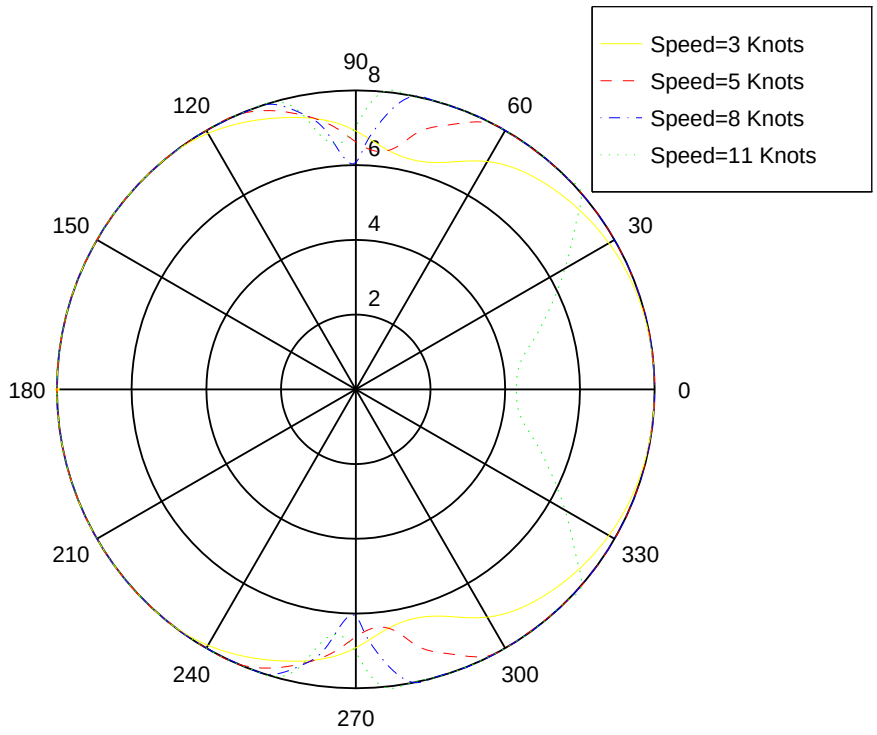


Figure 116. Sea state-polar plot, showing SOE for different *U*'s and 15*D* Water Depth

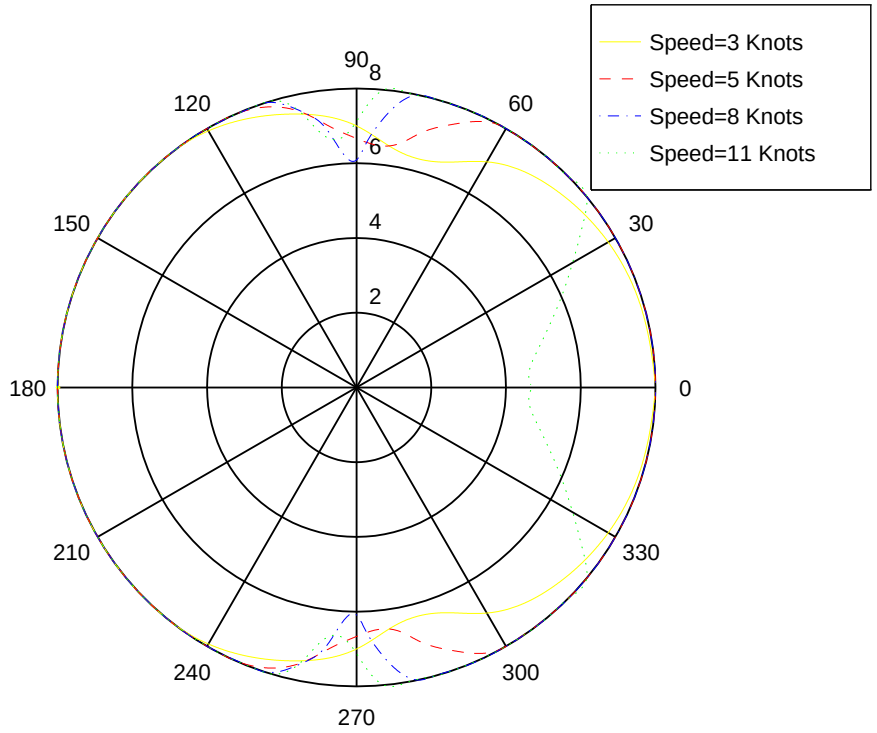


Figure 117. Sea state-polar plot, showing SOE for different *U*'s and 20*D* Water Depth

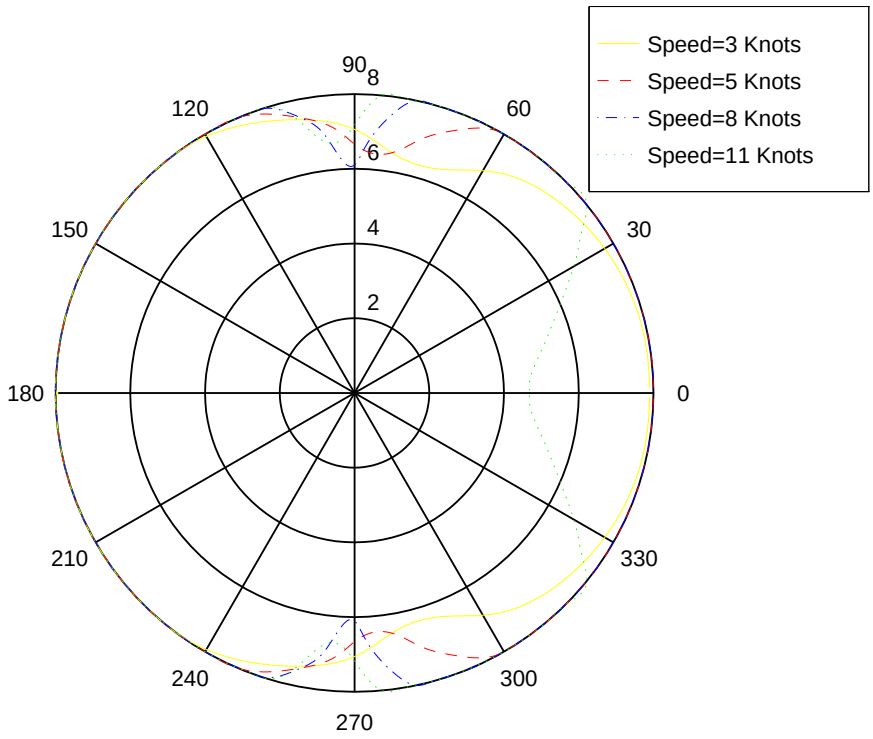


Figure 118. Sea state-polar plot, showing SOE for different *U*'s and 30*D* Water Depth

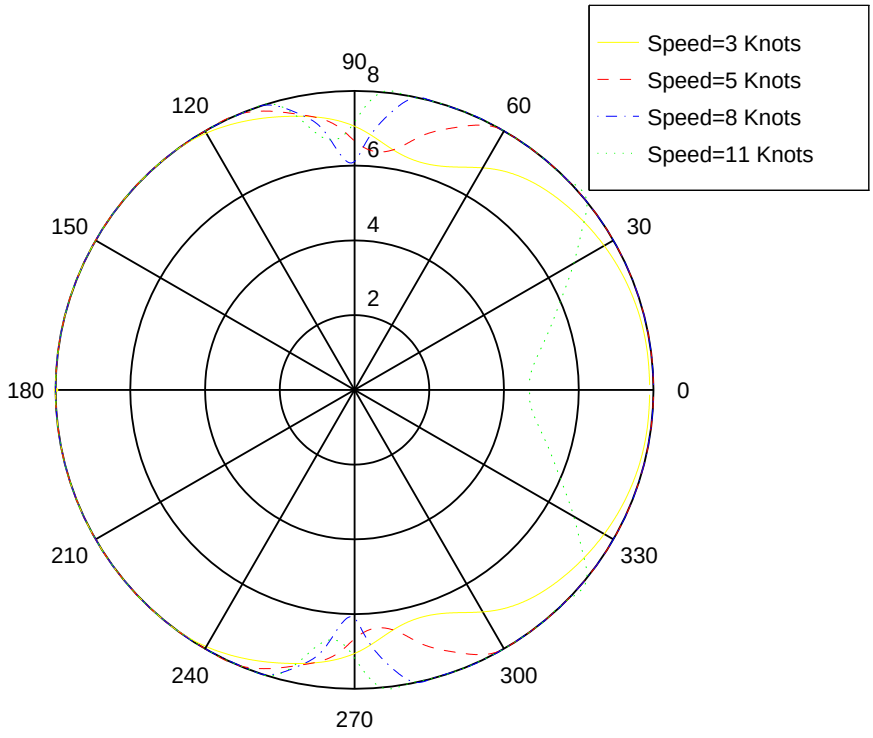


Figure 119. Sea state-polar plot, showing SOE for different *U*'s and 40*D* Water Depth

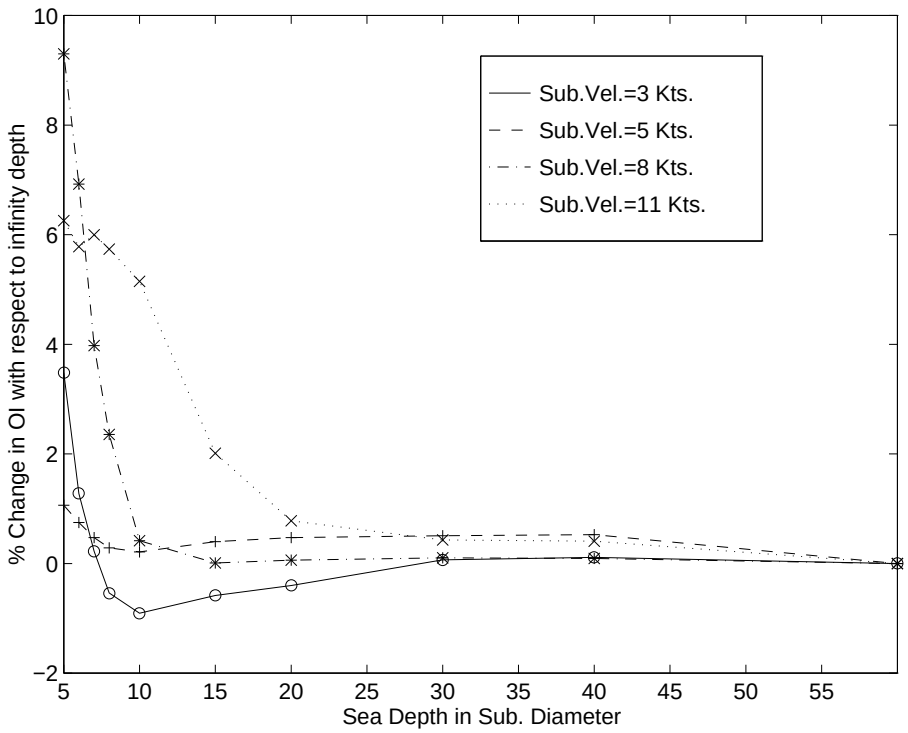


Figure 120. Change in OI with respect to infinite depth vs. Water Depth

## C. RESULTS OF COLLISION CRITERION

Results for the sea-bed collision criterion are summarized in Figures 121 through 126. The operability index is shown in Figure 127. As expected, the operability index decreases with decreasing water depth. The shape of the polar plots; i.e., specific sea state and sea direction combinations also varies significantly with water depth.

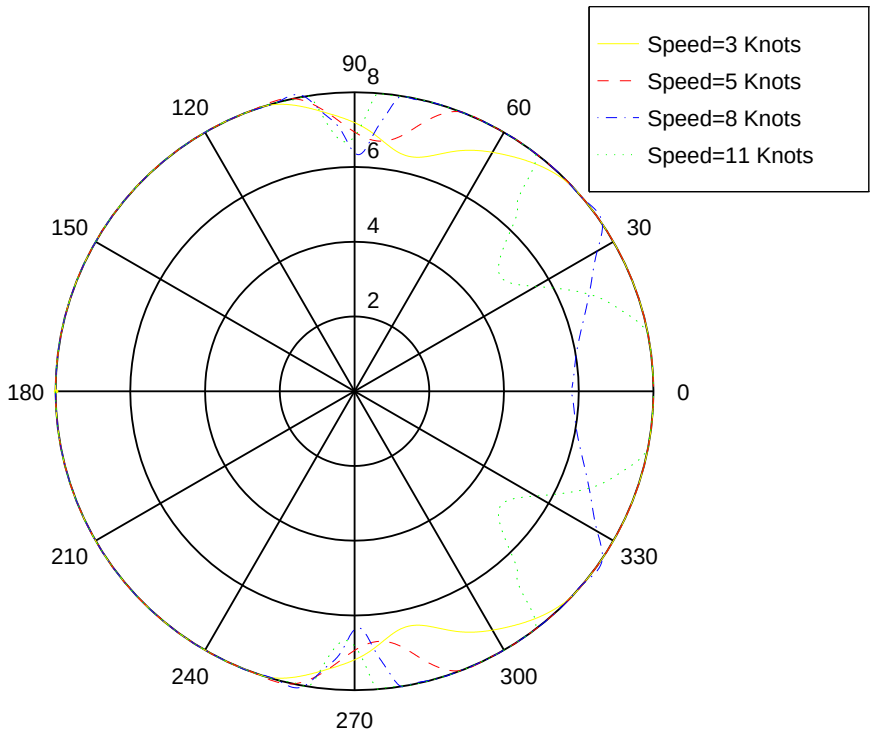


Figure 121. Sea state-polar plot, showing SOE for different *U*‘s and 5*D* Water Depth

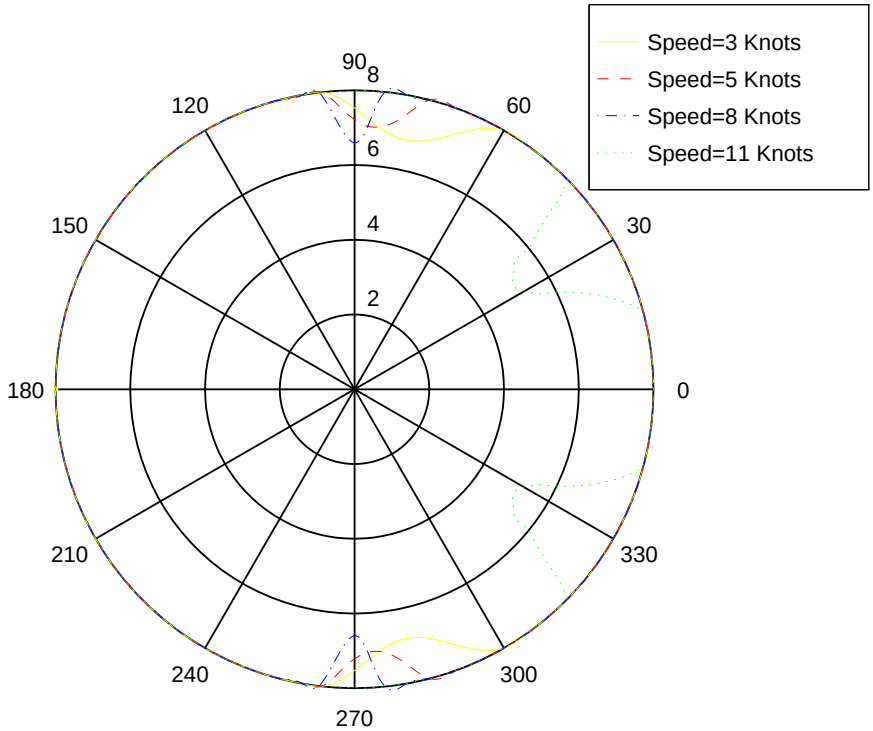


Figure 122. Sea state-polar plot, showing SOE for different *U*’s and 6*D* Water Depth

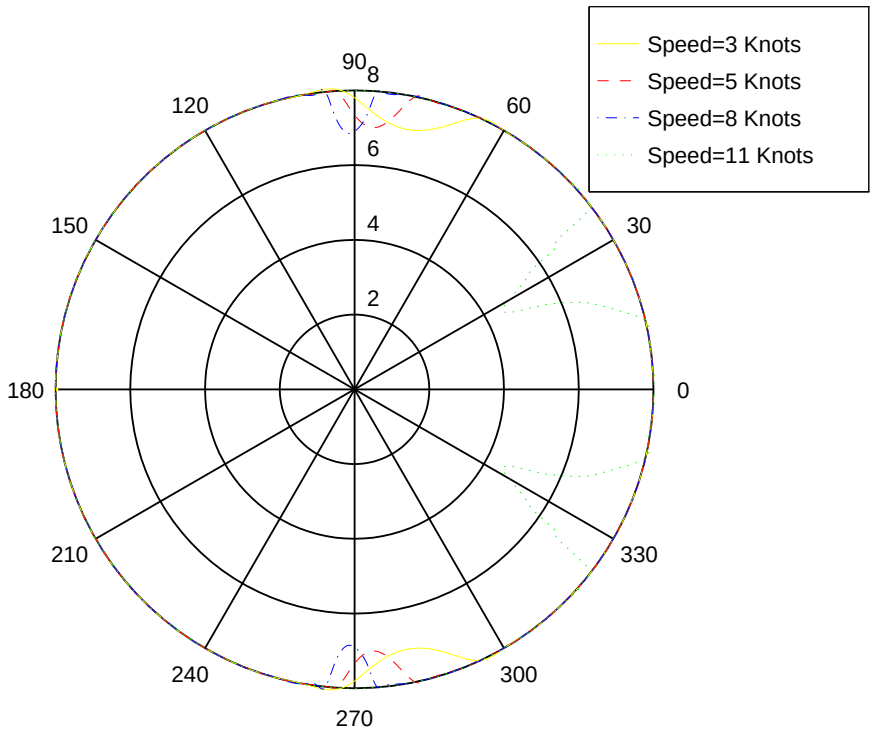


Figure 123. Sea state-polar plot, showing SOE for different *U*'s and 7*D* Water Depth

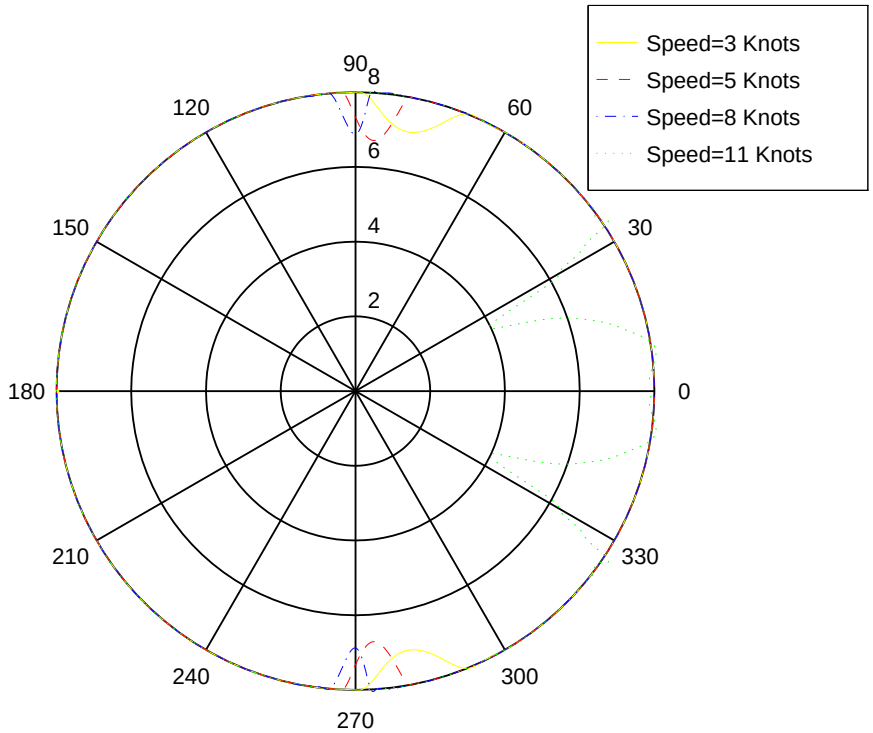


Figure 124. Sea state-polar plot, showing SOE for different *U*'s and 8*D* Water Depth

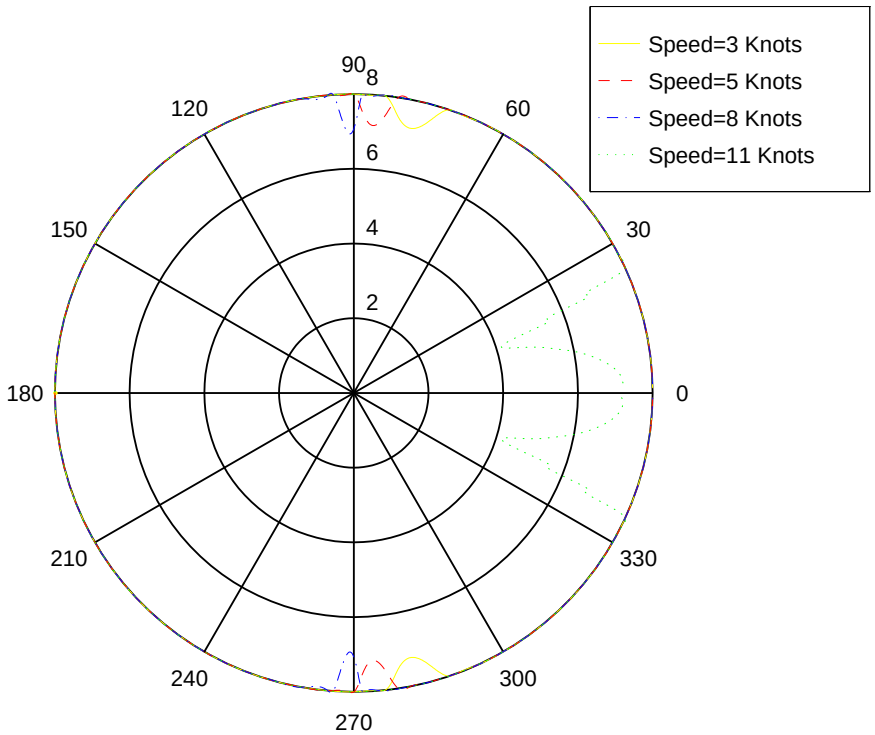


Figure 125. Sea state-polar plot, showing SOE for different *U*'s and 10*D* Water Depth

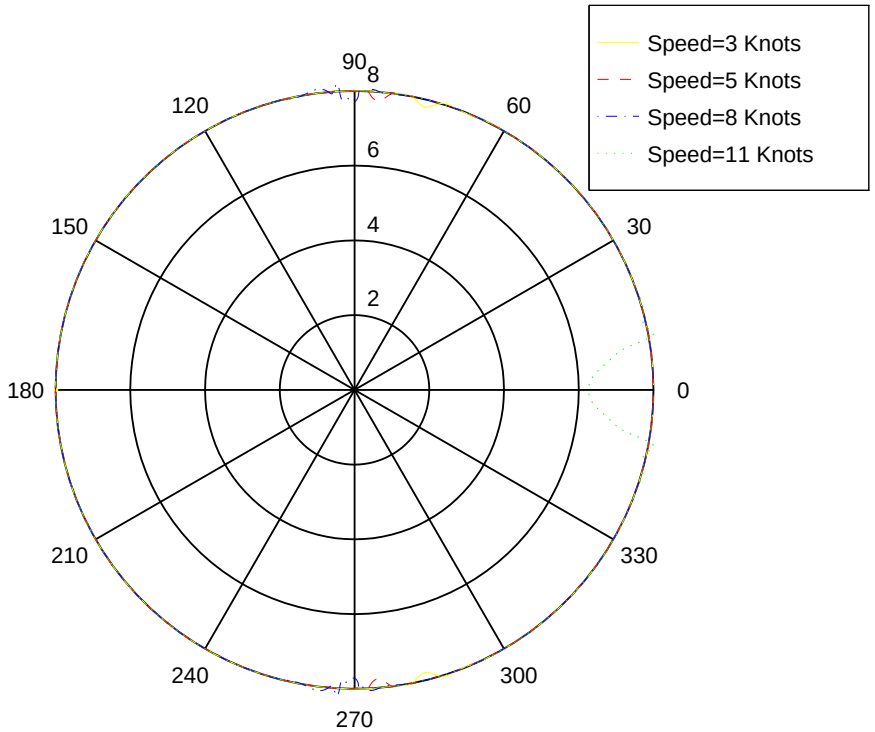


Figure 126. Sea state-polar plot, showing SOE for different *U*'s and 15*D* Water Depth

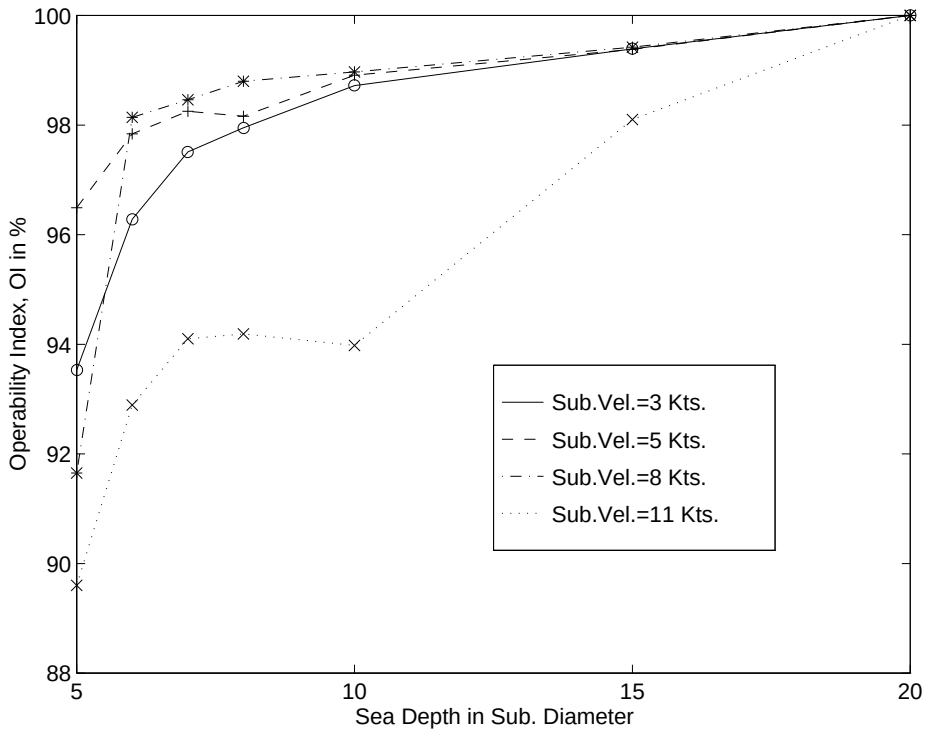


Figure 127. OI vs. Water Depth

## D. RESULTS OF COMBINED CRITERION

Results for all three criteria combined are presented in Figures 128 through 163. Lighter shades correspond to the periscope submergence criterion while the darkest shades correspond to the collision criterion. It can be seen that, in general, the sail broaching criterion dominates the collision criterion for the parameters selected; i.e., one occurrence per hour for sail broaching and one occurrence per two hours for collision. Should different values for the parameters had been selected, the collision criterion might dominate instead. The total change in the operability index is shown in Figure 164. It can be seen that, in general, the operability index is decreasing for decreasing water depth. Shallow water effects seem to be insignificant for depths exceeding 30 submarine diameters.

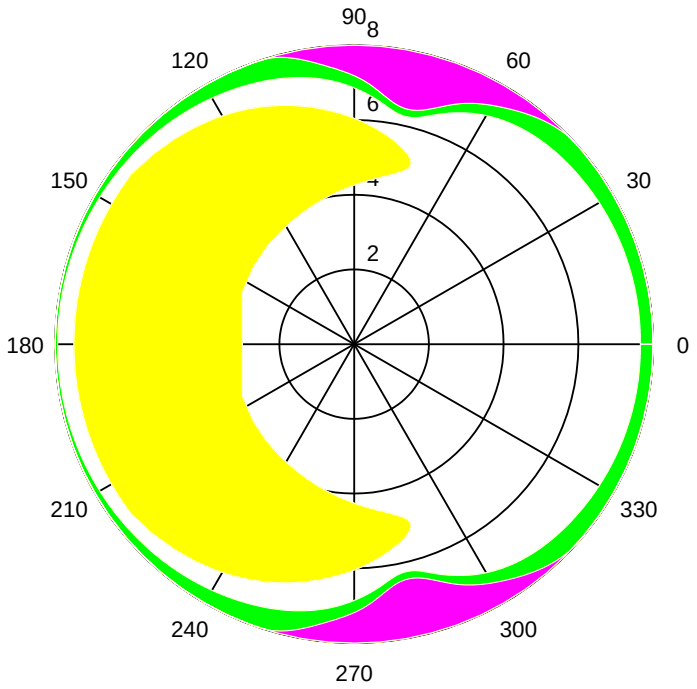


Figure 128. Sea state-polar plot, showing SOE for *U*=3 Knots and 5*D* Water Depth

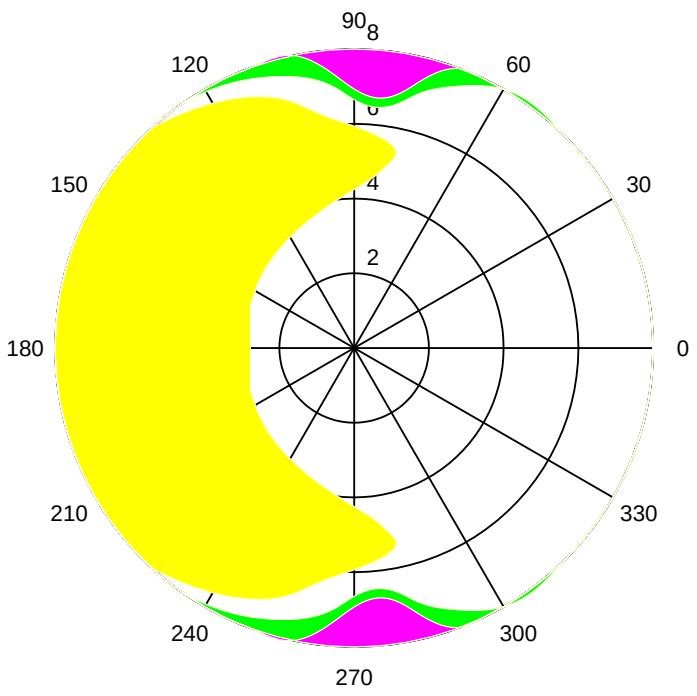


Figure 129. Sea state-polar plot, showing SOE for *U*=5 Knots and 5*D* Water Depth

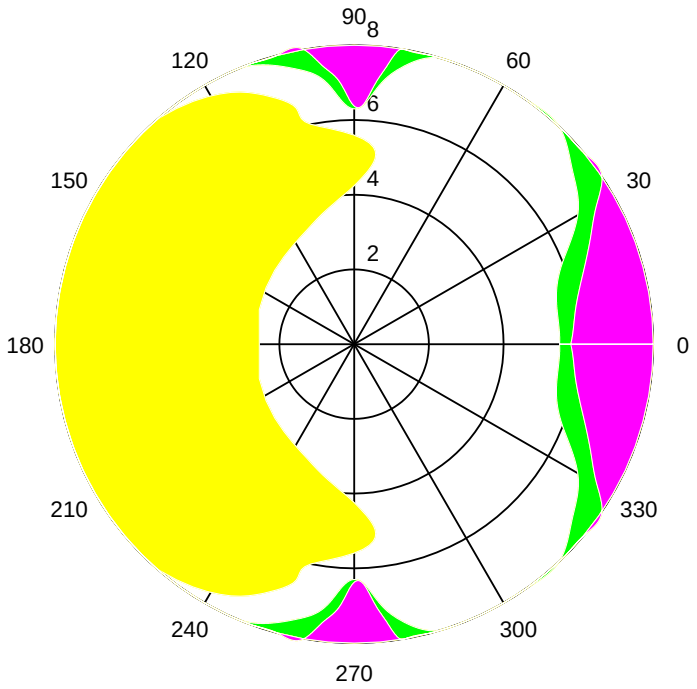


Figure 130. Sea state-polar plot, showing SOE for *U*=8 Knots and 5*D* Water Depth

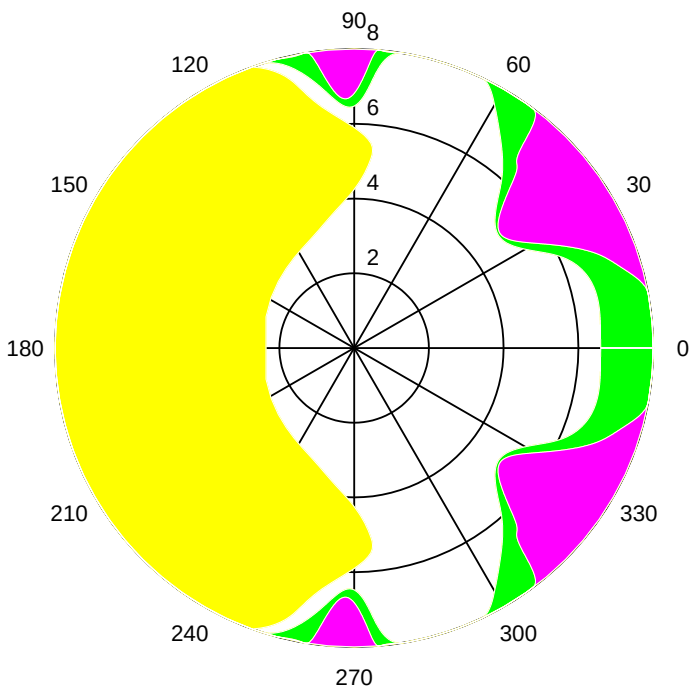


Figure 131. Sea state-polar plot, showing SOE for *U*=11 Knots and 5*D* Water Depth

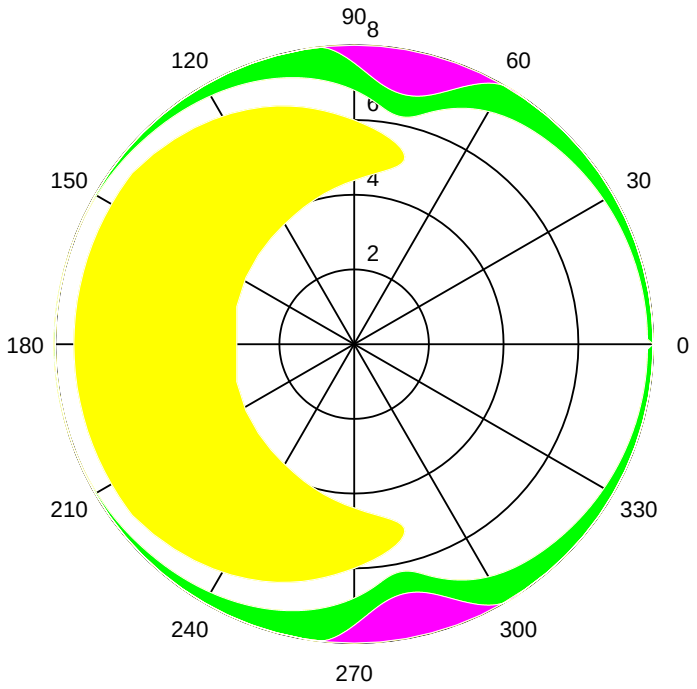


Figure 132. Sea state-polar plot, showing SOE for *U*=3 Knots and 6*D* Water Depth

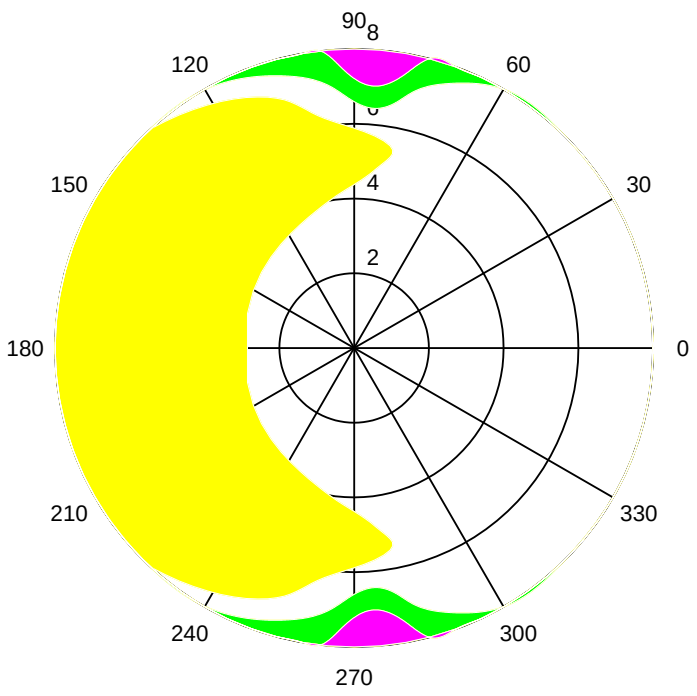


Figure 133. Sea state-polar plot, showing SOE for *U*=5 Knots and 6*D* Water Depth

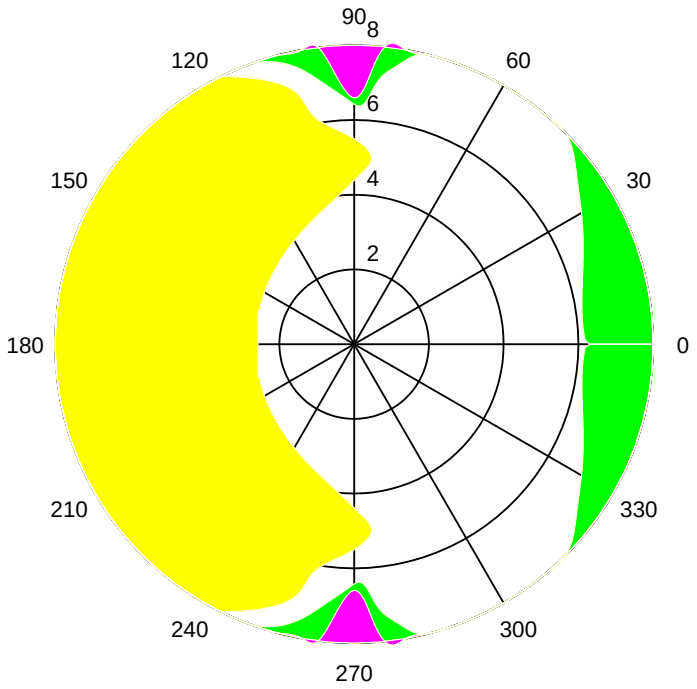


Figure 134. Sea state-polar plot, showing SOE for *U*=8 Knots and 6*D* Water Depth

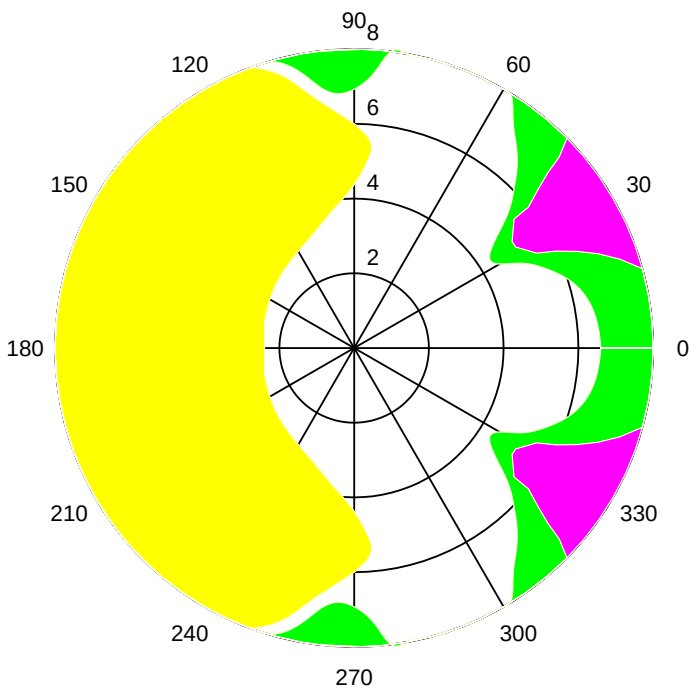


Figure 135. Sea state-polar plot, showing SOE for *U*=11 Knots and 6*D* Water Depth

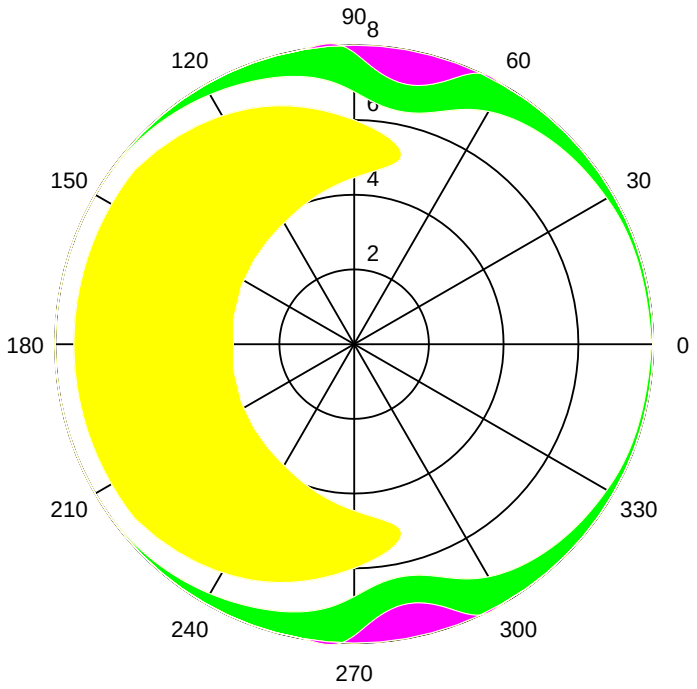


Figure 136. Sea state-polar plot, showing SOE for *U*=3 Knots and 7*D* Water Depth

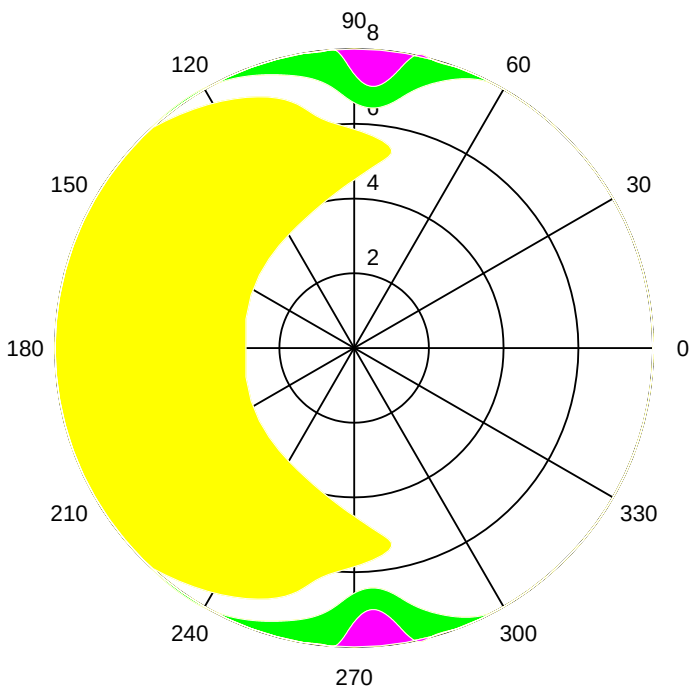


Figure 137. Sea state-polar plot, showing SOE for *U*=5 Knots and 7*D* Water Depth

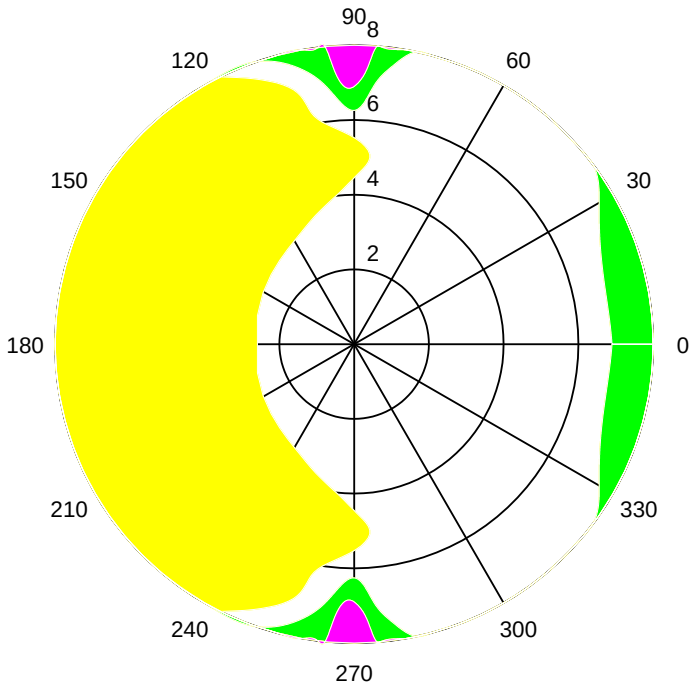


Figure 138. Sea state-polar plot, showing SOE for *U*=8 Knots and 7*D* Water Depth

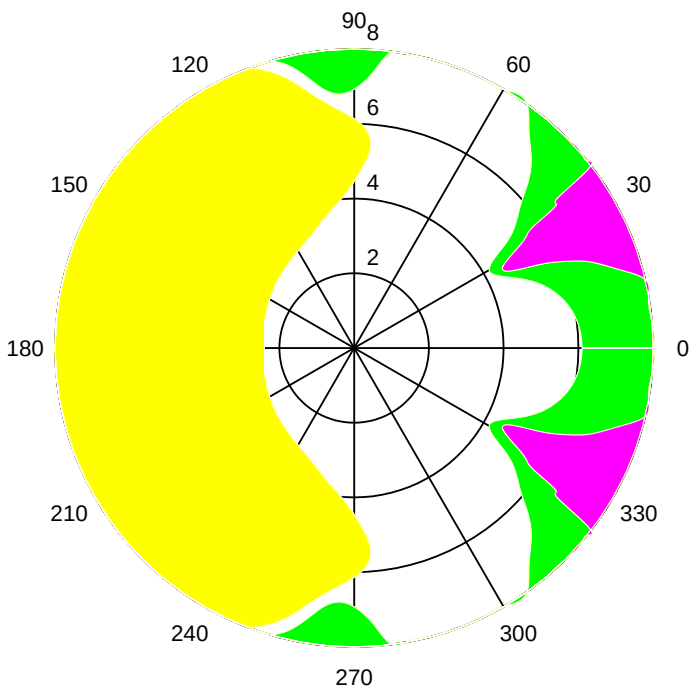


Figure 139. Sea state-polar plot, showing SOE for *U*=11 Knots and 7*D* Water Depth

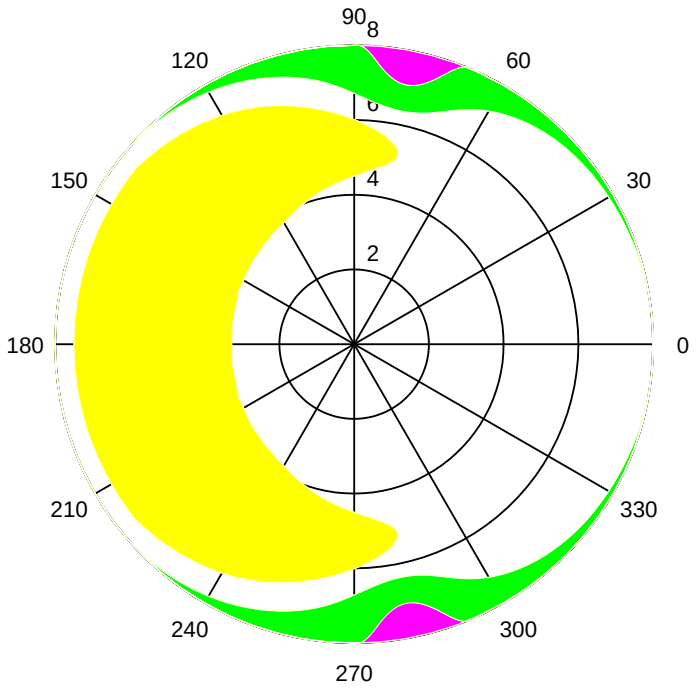


Figure 140. Sea state-polar plot, showing SOE for *U*=3 Knots and 8*D* Water Depth

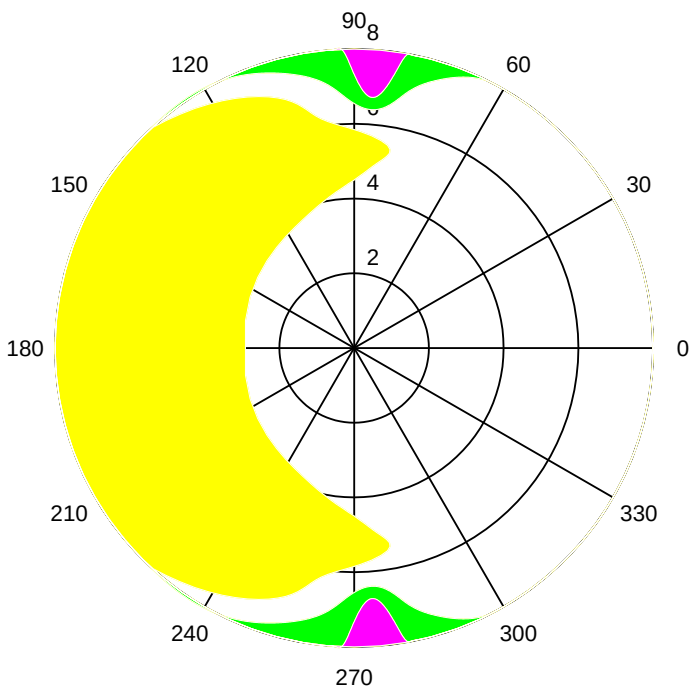


Figure 141. Sea state-polar plot, showing SOE for *U*=5 Knots and 8*D* Water Depth

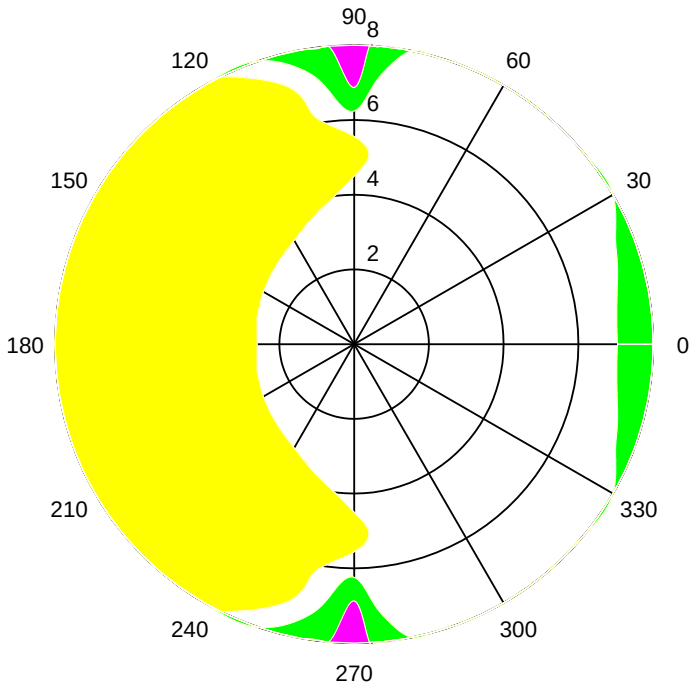


Figure 142. Sea state-polar plot, showing SOE for *U*=8 Knots and 8*D* Water Depth

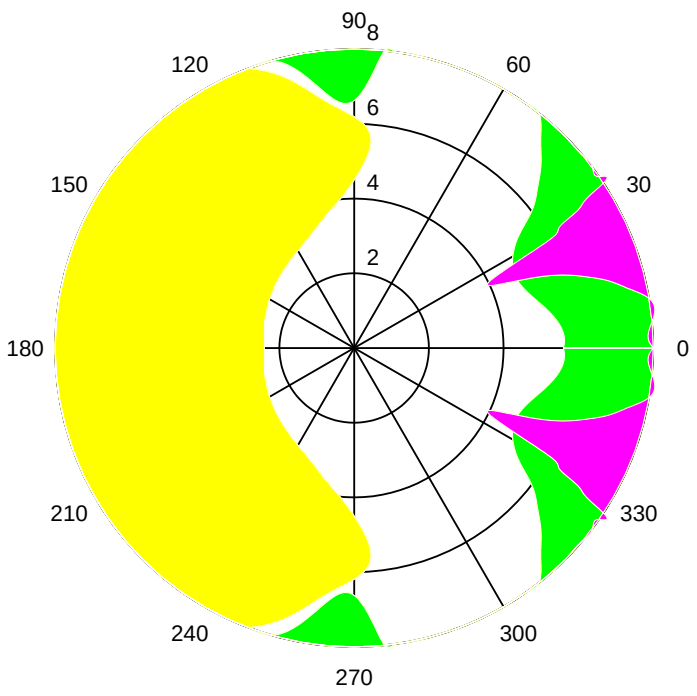


Figure 143. Sea state-polar plot, showing SOE for *U*=11 Knots and 8*D* Water Depth

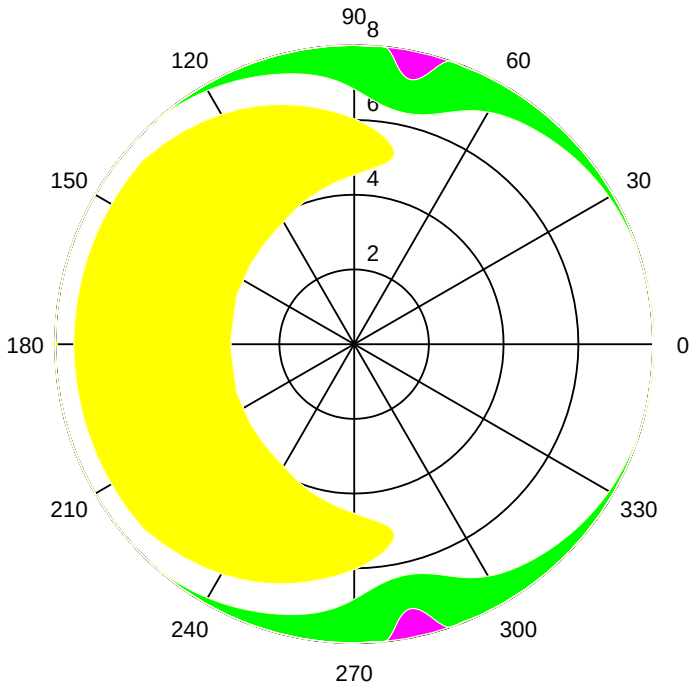


Figure 144. Sea state-polar plot, showing SOE for *U*=3 Knots and 10*D* Water Depth

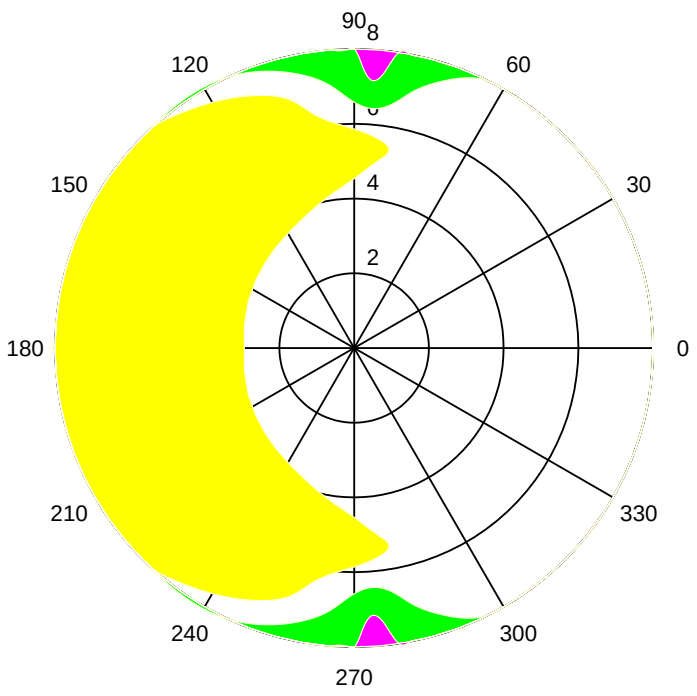


Figure 145. Sea state-polar plot, showing SOE for *U*=5 Knots and 10*D* Water Depth

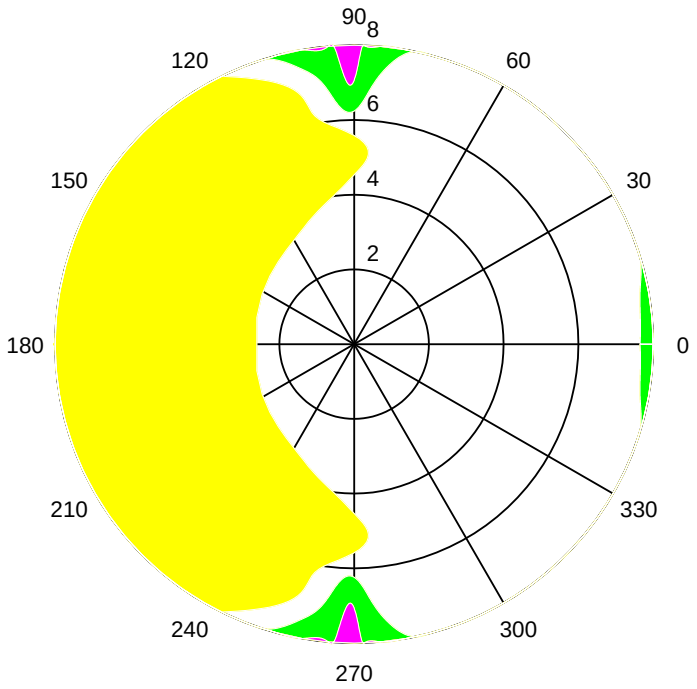


Figure 146. Sea state-polar plot, showing SOE for *U*=8 Knots and 10*D* Water Depth

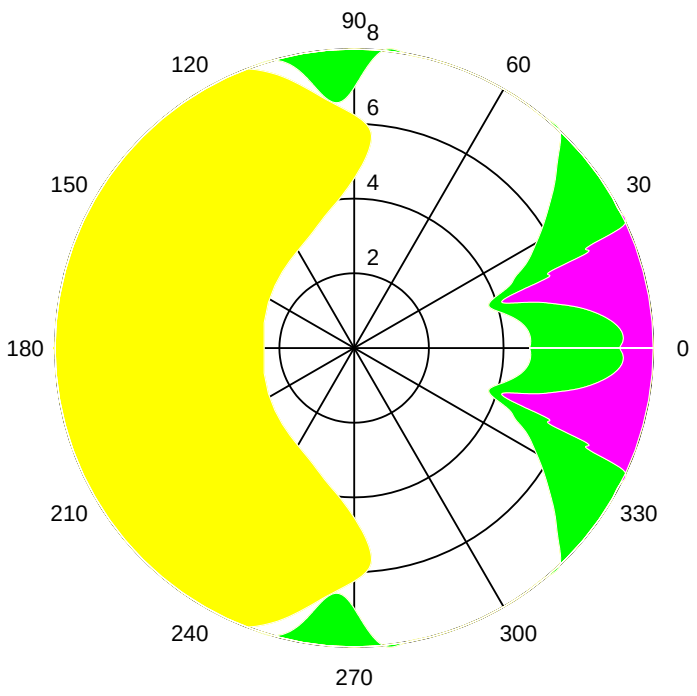


Figure 147. Sea state-polar plot, showing SOE for *U*=11 Knots and 10*D* Water Depth

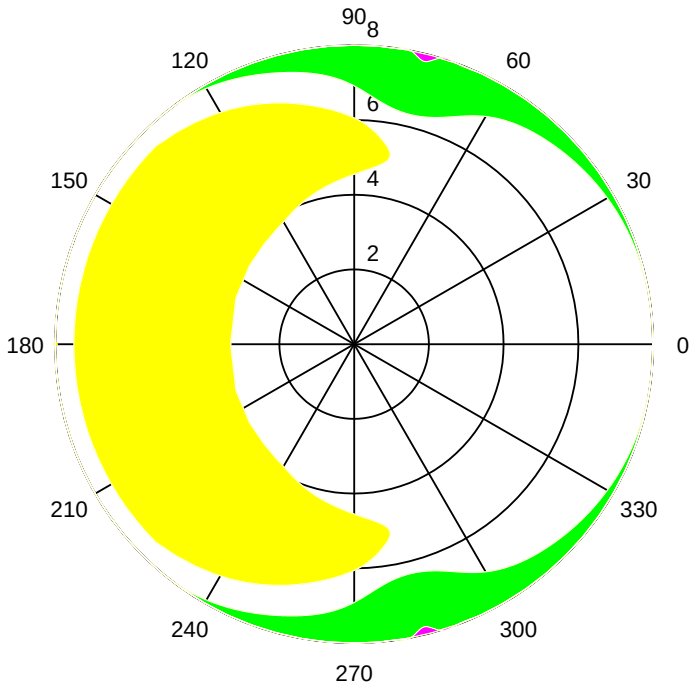


Figure 148. Sea state-polar plot, showing SOE for *U*=3 Knots and 15*D* Water Depth

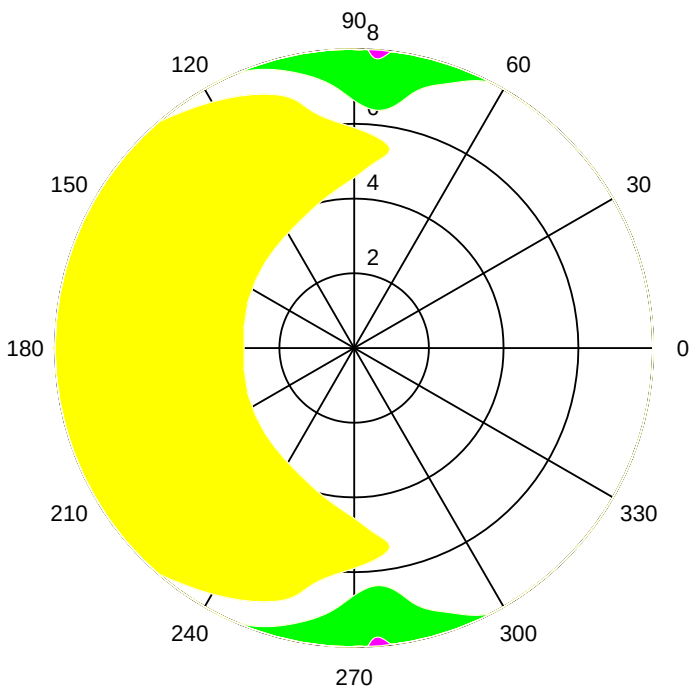


Figure 149. Sea state-polar plot, showing SOE for *U*=5 Knots and 15*D* Water Depth

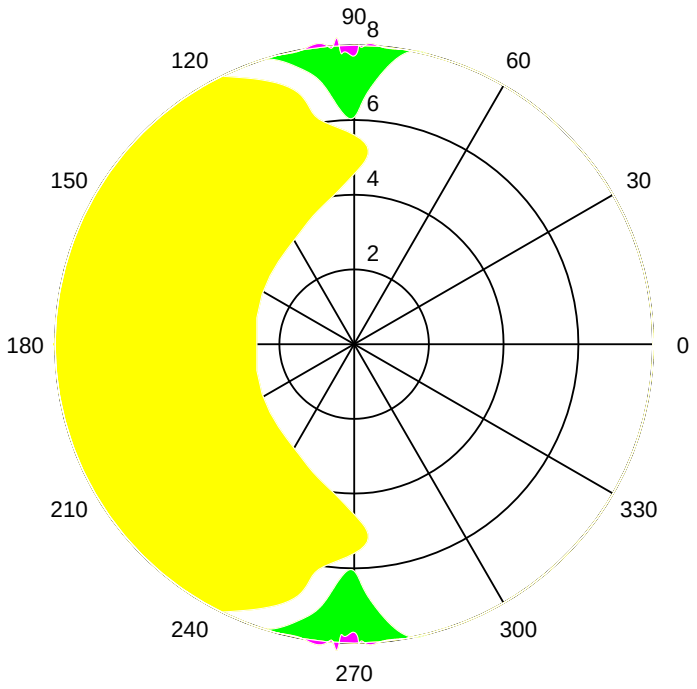


Figure 150. Sea state-polar plot, showing SOE for *U*=8 Knots and 15*D* Water Depth

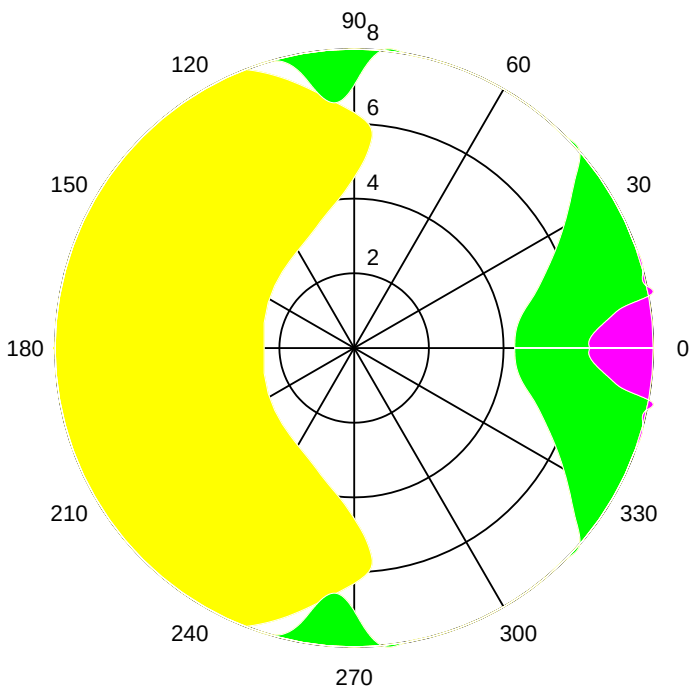


Figure 151. Sea state-polar plot, showing SOE for *U*=11 Knots and 15*D* Water Depth

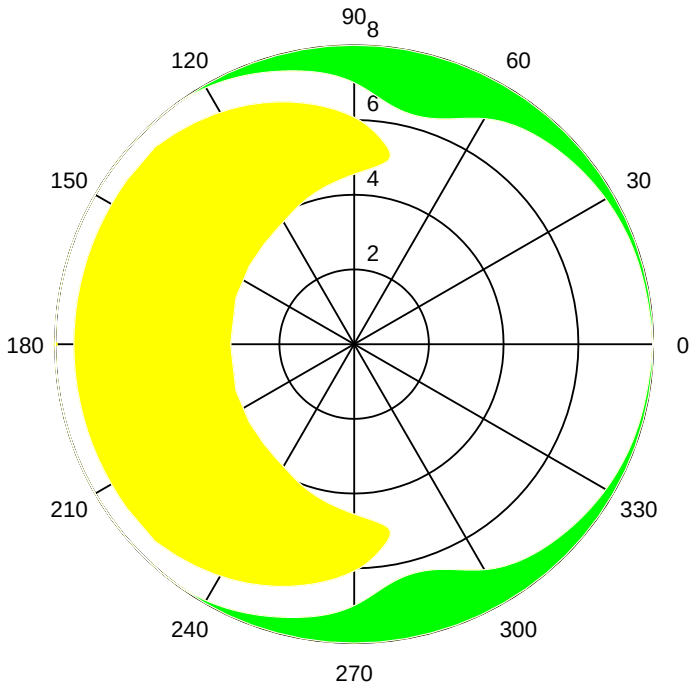


Figure 152. Sea state-polar plot, showing SOE for *U*=3 Knots and 20*D* Water Depth

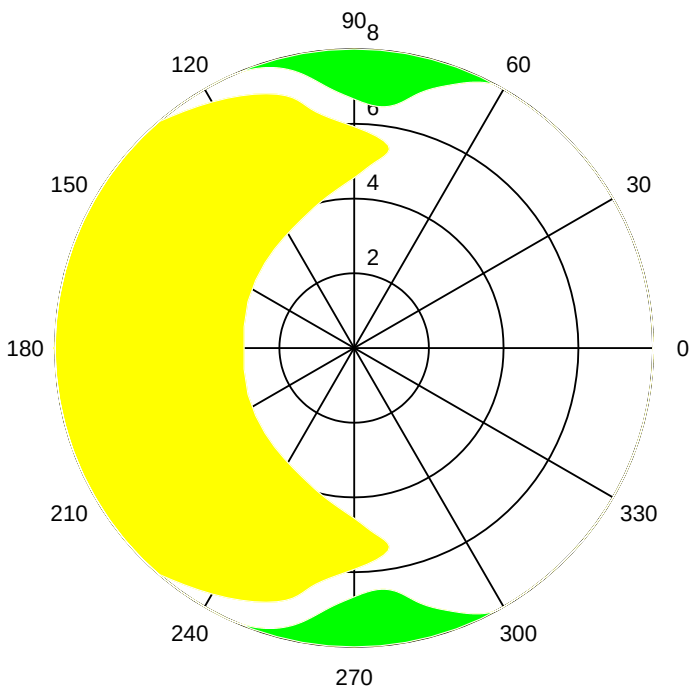


Figure 153. Sea state-polar plot, showing SOE for *U*=5 Knots and 20*D* Water Depth

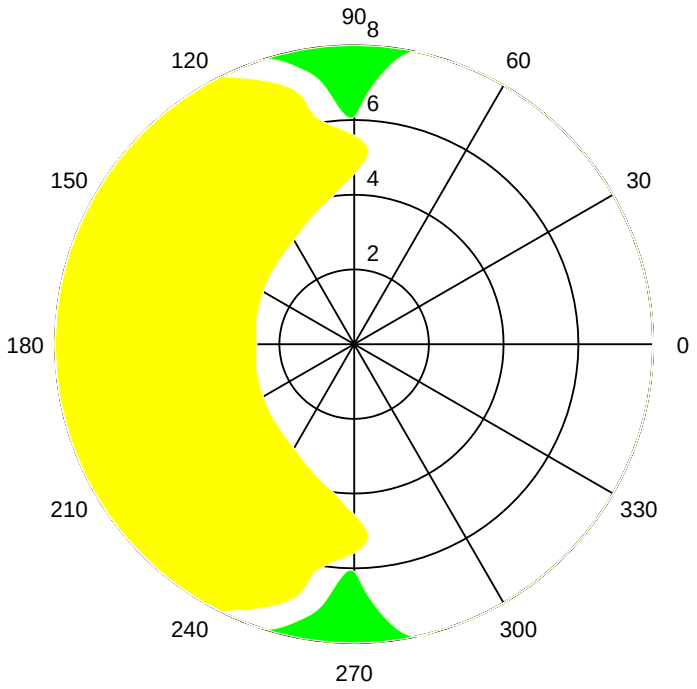


Figure 154. Sea state-polar plot, showing SOE for *U*=8 Knots and 20*D* Water Depth

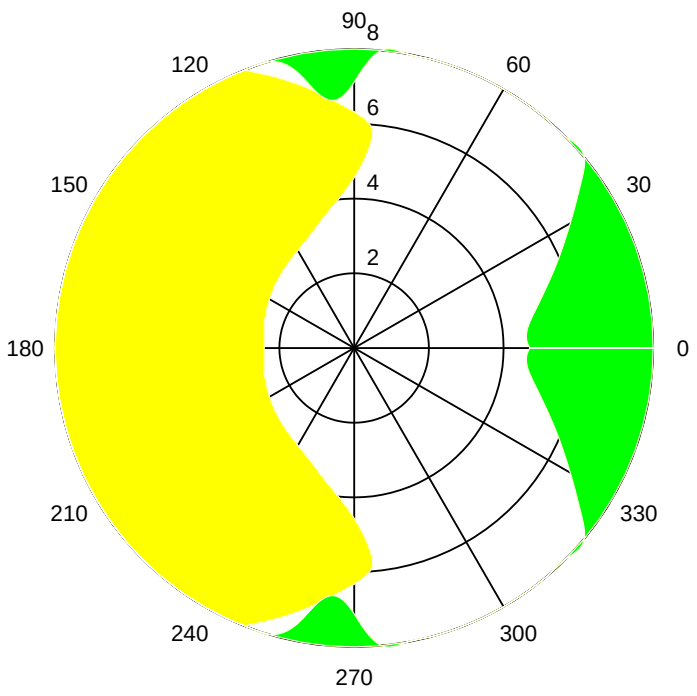


Figure 155. Sea state-polar plot, showing SOE for *U*=11 Knots and 20*D* Water Depth

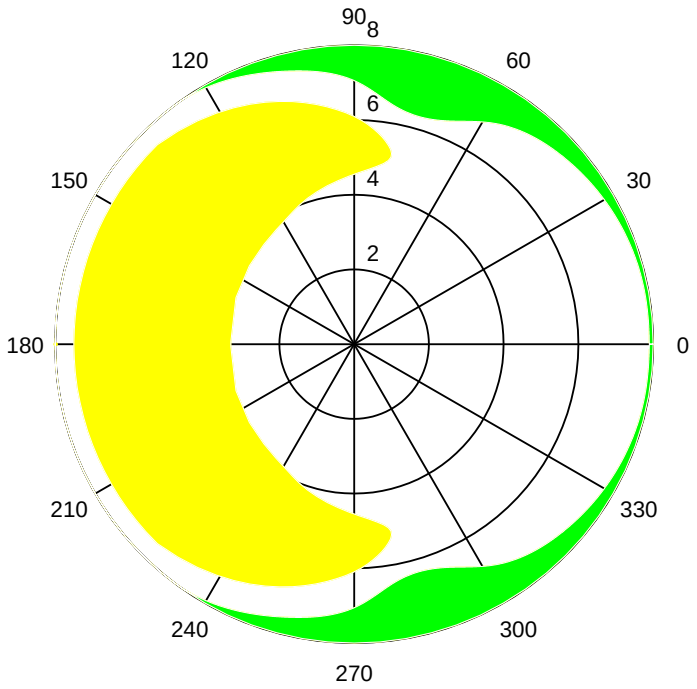


Figure 156. Sea state-polar plot, showing SOE for *U*=3 Knots and 30*D* Water Depth

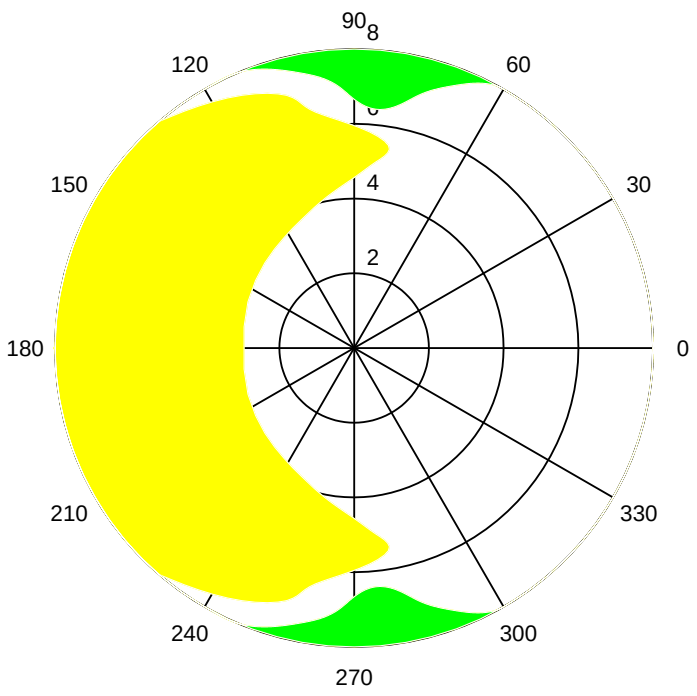


Figure 157. Sea state-polar plot, showing SOE for *U*=5 Knots and 30*D* Water Depth

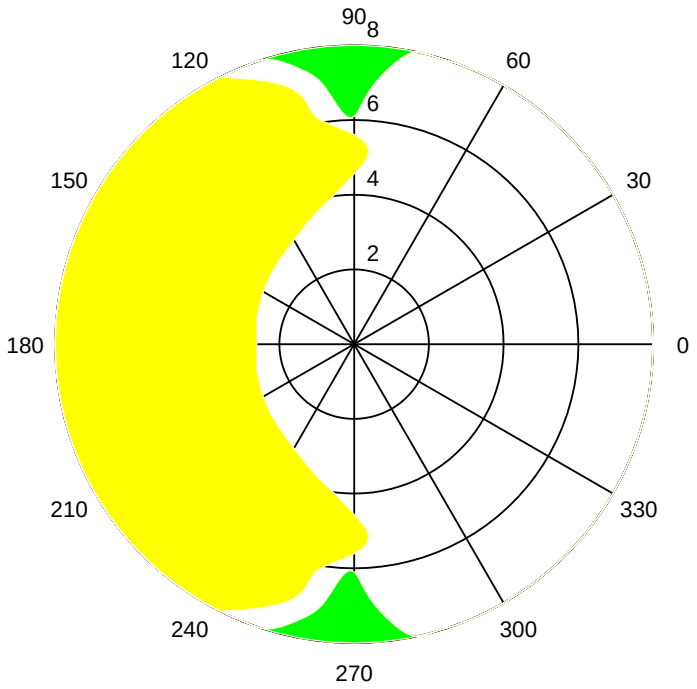


Figure 158. Sea state-polar plot, showing SOE for *U*=8 Knots and 30*D* Water Depth

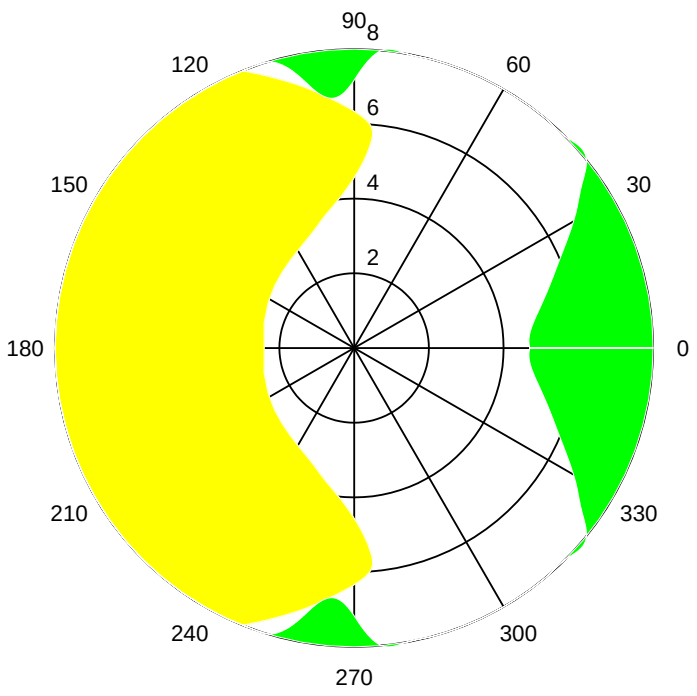


Figure 159. Sea state-polar plot, showing SOE for *U*=11 Knots and 30*D* Water Depth

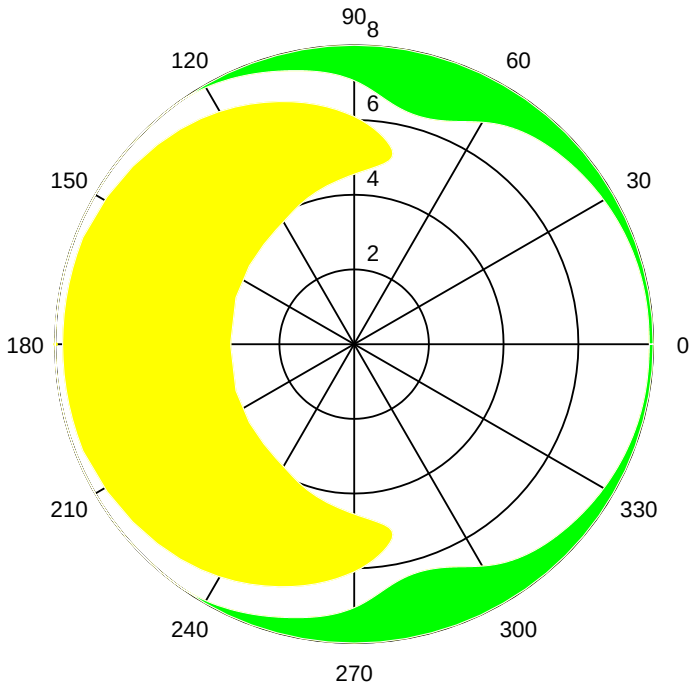


Figure 160. Sea state-polar plot, showing SOE for *U*=3 Knots and 40*D* Water Depth

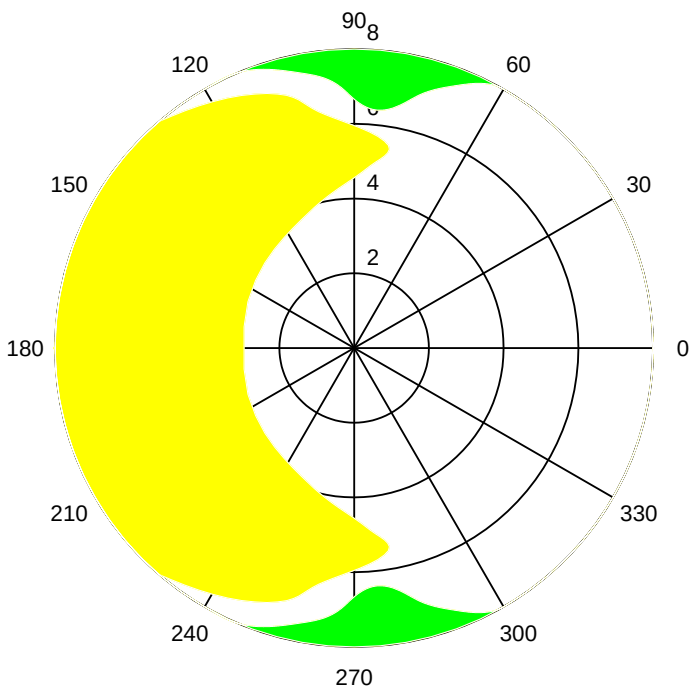


Figure 161. Sea state-polar plot, showing SOE for *U*=5 Knots and 40*D* Water Depth

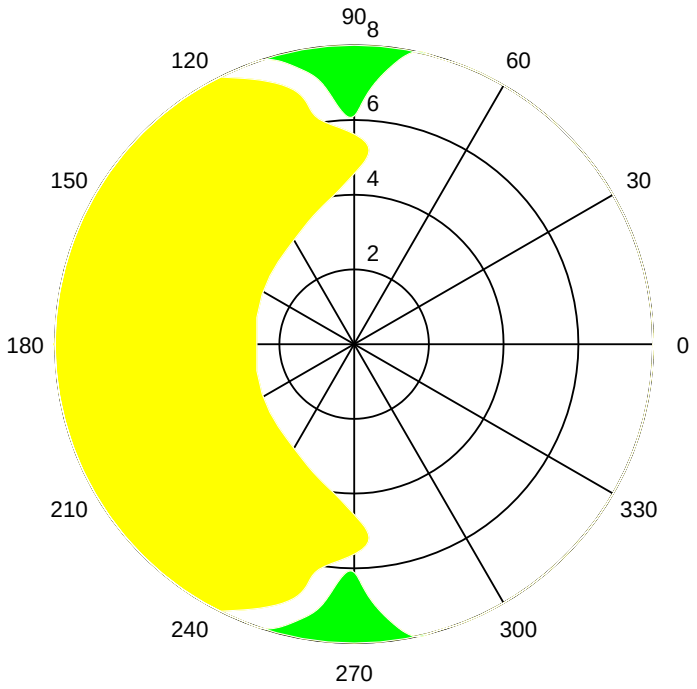


Figure 162. Sea state-polar plot, showing SOE for *U*=8 Knots and 40*D* Water Depth

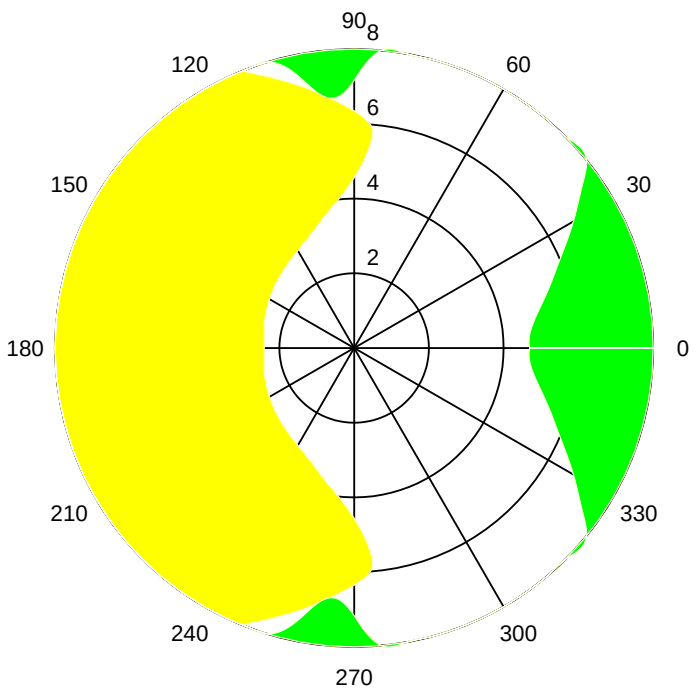


Figure 163. Sea state-polar plot, showing SOE for *U*=11 Knots and 40*D* Water Depth

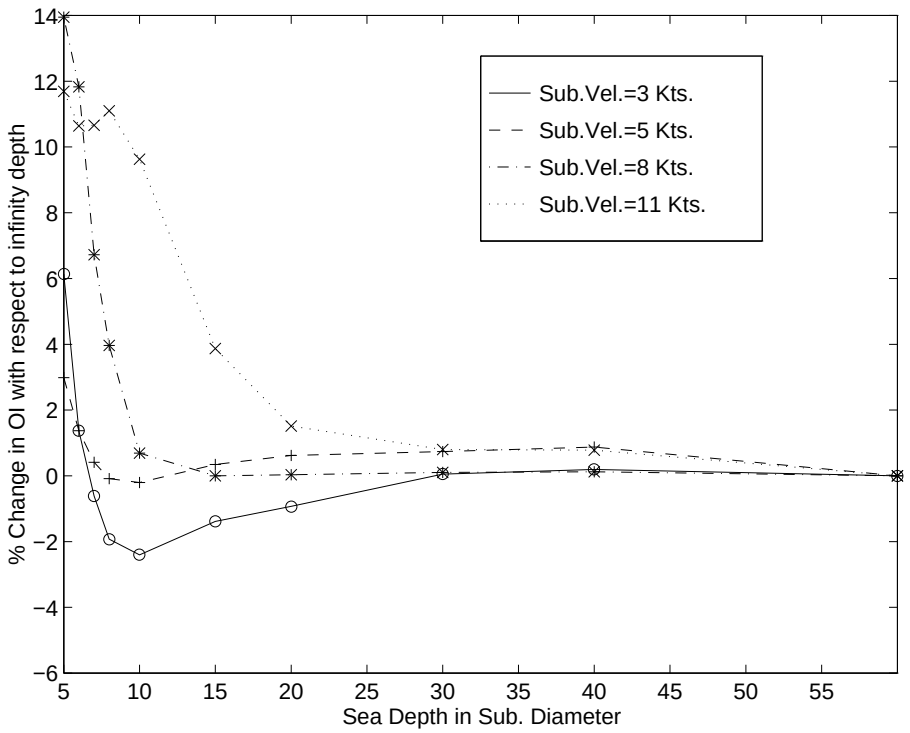


Figure 164. Change in OI with respect to infinite depth vs. Water Depth