Supplemental Material

Supplemental Online Materials for

"The equatorial Pacific cold tongue bias in CESM1 and its influence on ENSO forecasts"

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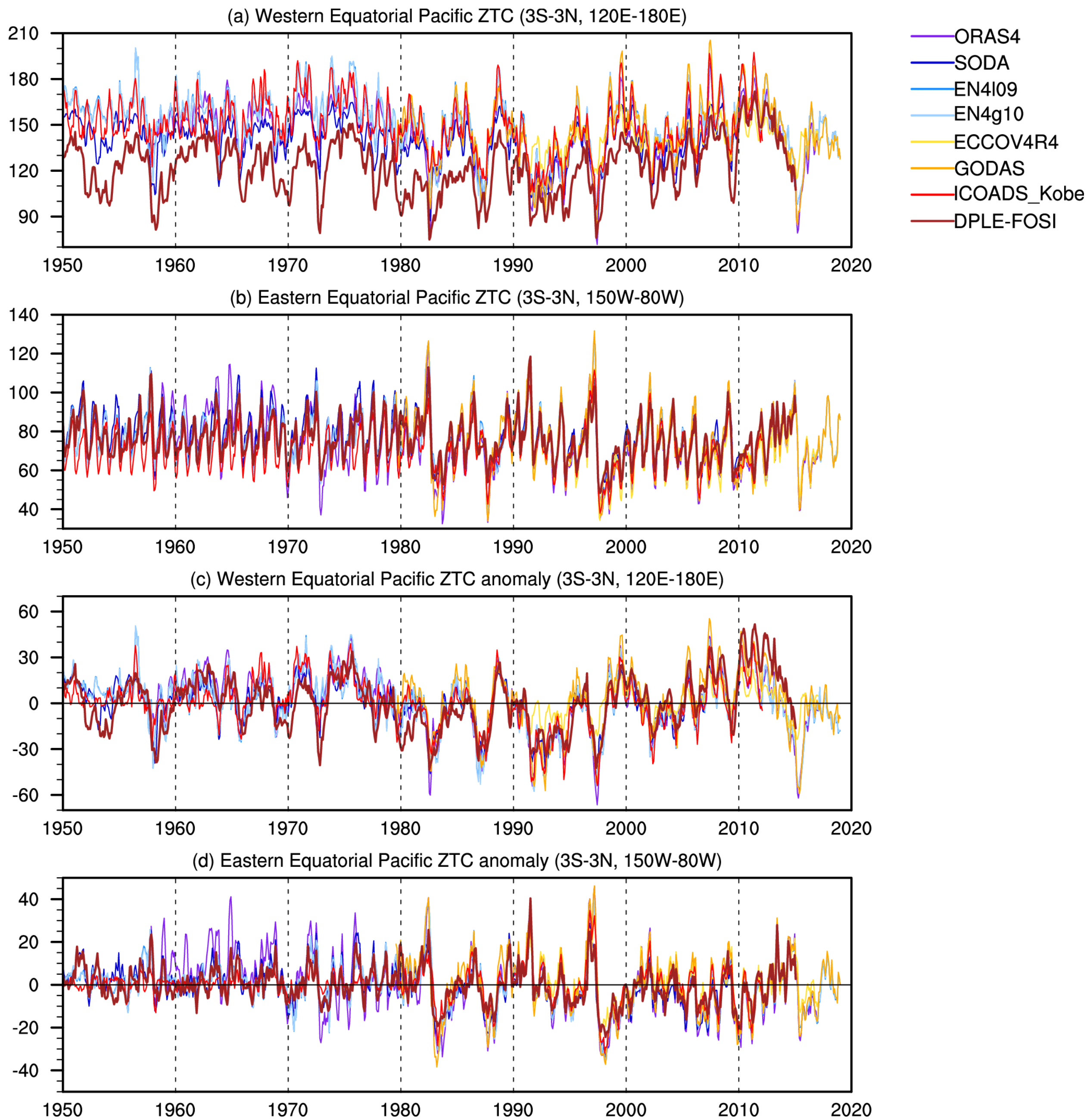


Figure S1. The timeseries of monthly thermocline depth in the (a) western equatorial Pacific (3°S–3°N, 120°E–180°) and (b) eastern equatorial Pacific (3°S–3°N, 150°W–80°W) in the FOSI (dark red) and 7 ocean reanalysis datasets [ORAS4 (purple), SODA (dark blue), EN4l09 (blue), EN4g10 (light blue), ECCOV4R4 (yellow), GOADS (orange), ICOADS_Kobe (red)]. (c,d) as in (a,b) but for the anomalous values after removing the monthly climatology.

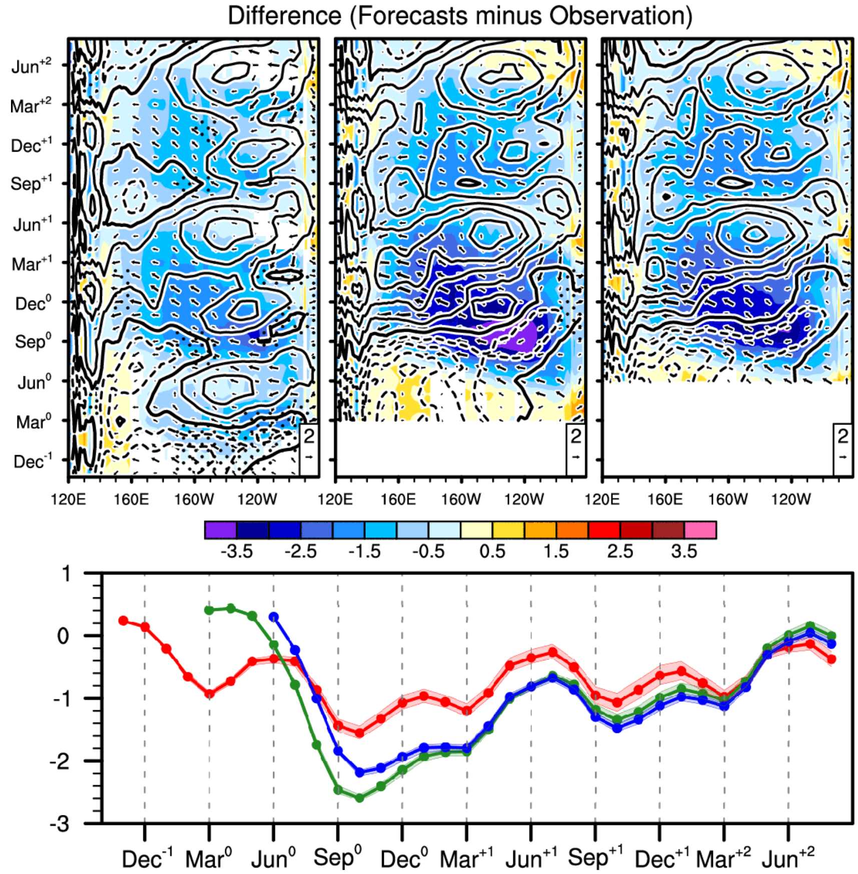
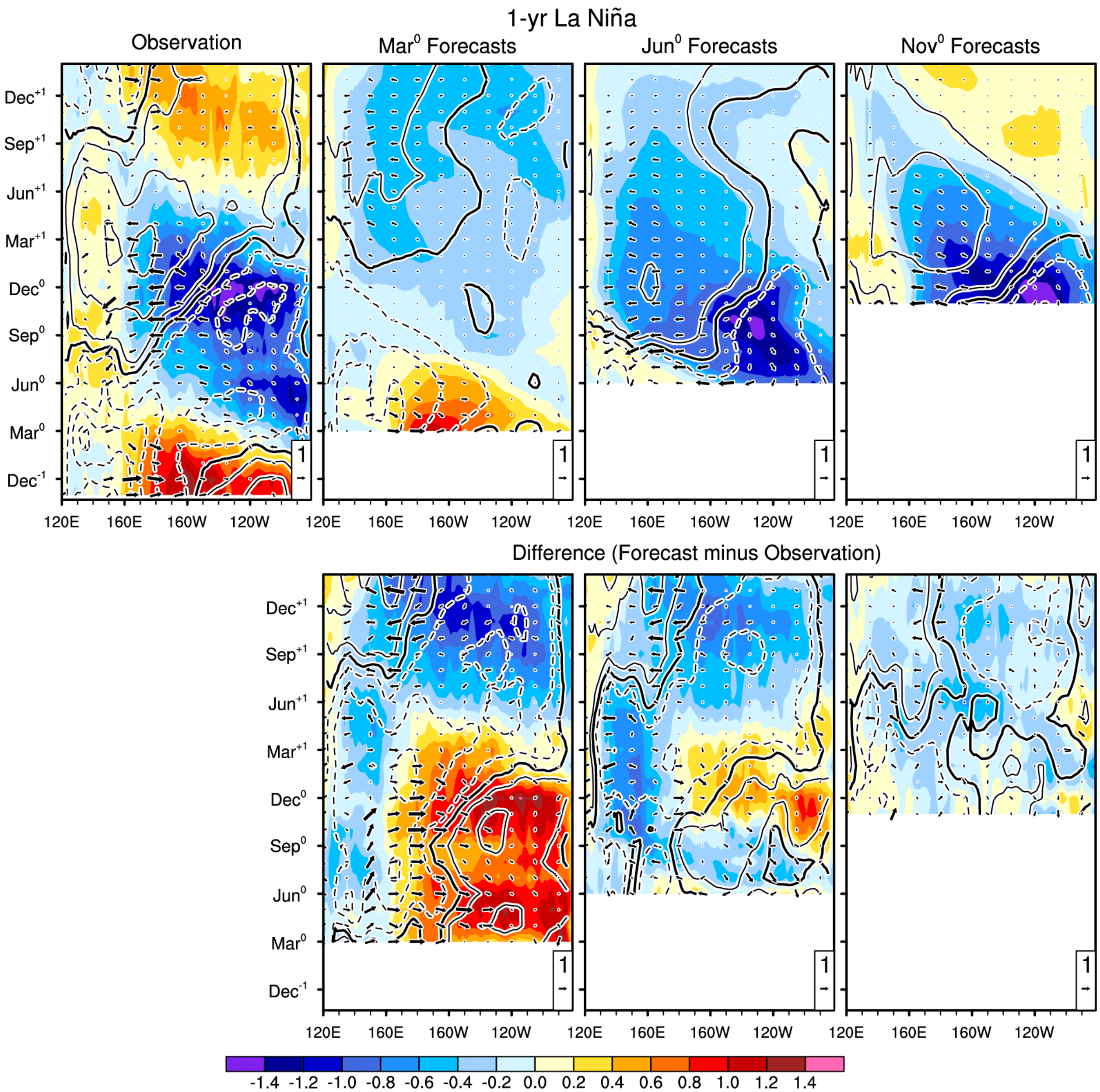
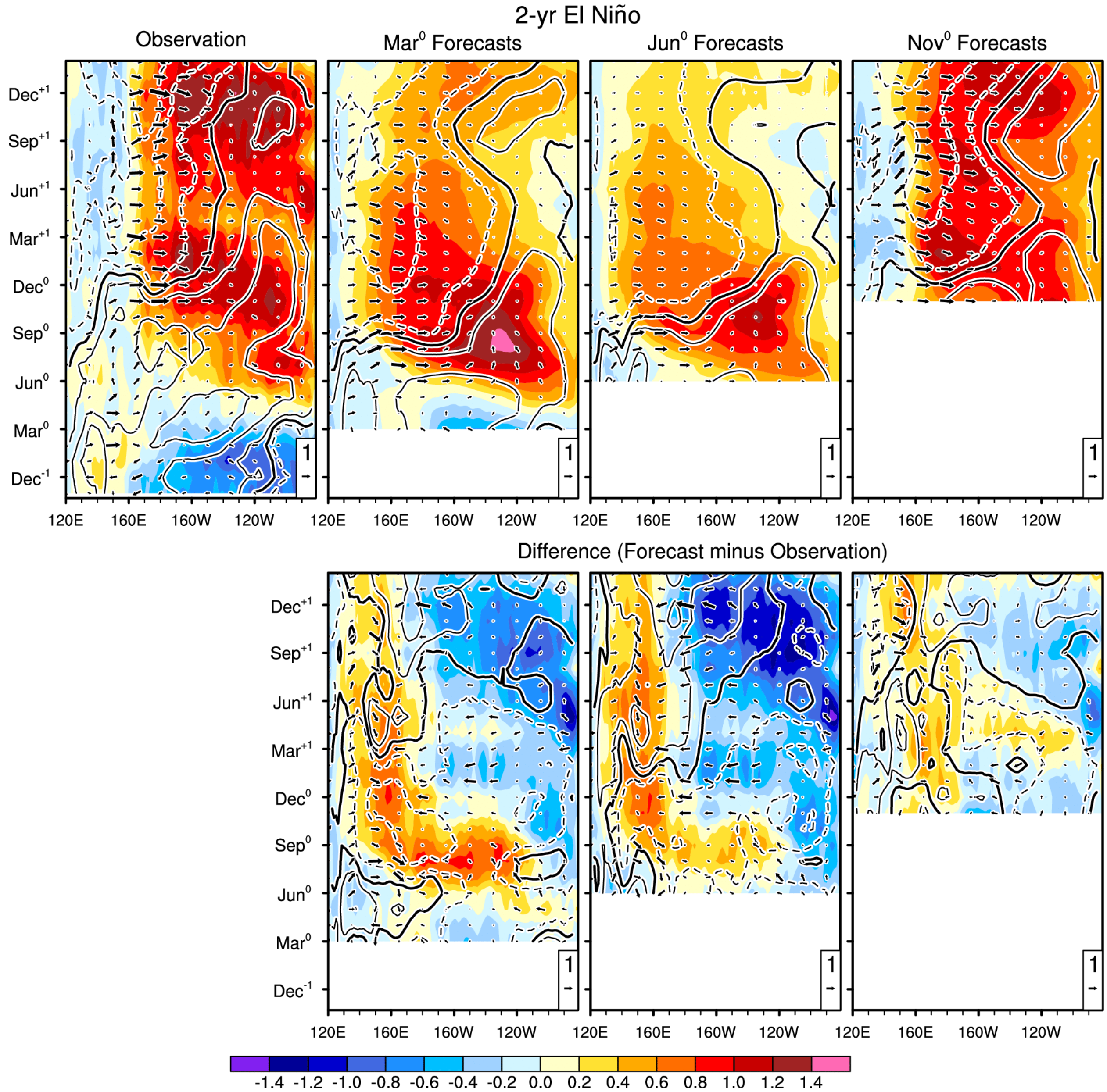


Figure. S2 (top) As in Fig. 1e but only the SST and surface wind biases statistically significant at the 99.5% confidence level. The thermocline depth anomalies (contours) that are not statistically significant at the 99.5% confidence level are masked with black stippling. The effect of different ensemble sizes on the estimate of climatological bias in the three forecast ensembles are evaluated using bootstrap analysis. To test whether a climatological bias is significantly different from zero, a bootstrapped distribution of 5,000 climatological bias is calculated based on any 10 members randomly selected (with replacement) from the full forecast ensemble. A positive bias is significant at 99.5% confidence level if its bootstrapped distribution having fewer than 25 values that are below zero (p<25/5,000), vice versa for a negative bias. (bottom) The climatological SST bias (°C) averaged over the equatorial Pacific (3°S-3°N; 140°E-80°W) for the ensemble forecasts initialized in November (red), March (green), and June (blue). The thick curves represent the ensemble mean based on all available members, and the shading indicates the range (minimum to maximum) of ensemble mean based on 5,000 bootstrapped samples of 10 members. There are 40, 20, and 10 members in the November, March, and June forecasts, respectively.

Figure S3. As in Fig. 5, but for composites of 1-yr La Niña, 2-yr El Niño, and 2-yr La Niña events. The statistical significance of these anomalies is shown in Fig. S4.




2-yr El Niño
Observation
Mar0 Forecasts
Jun0 Forecasts
Nov0 Forecasts
Dec+1
Sep+1
Jun+1
Mar+1
Dec0
Sep0
Jun0
Mar0
Dec-1
120E
160E
160W
120W
Difference (Forecast minus Observation)
-1.4 -1.2 -1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4

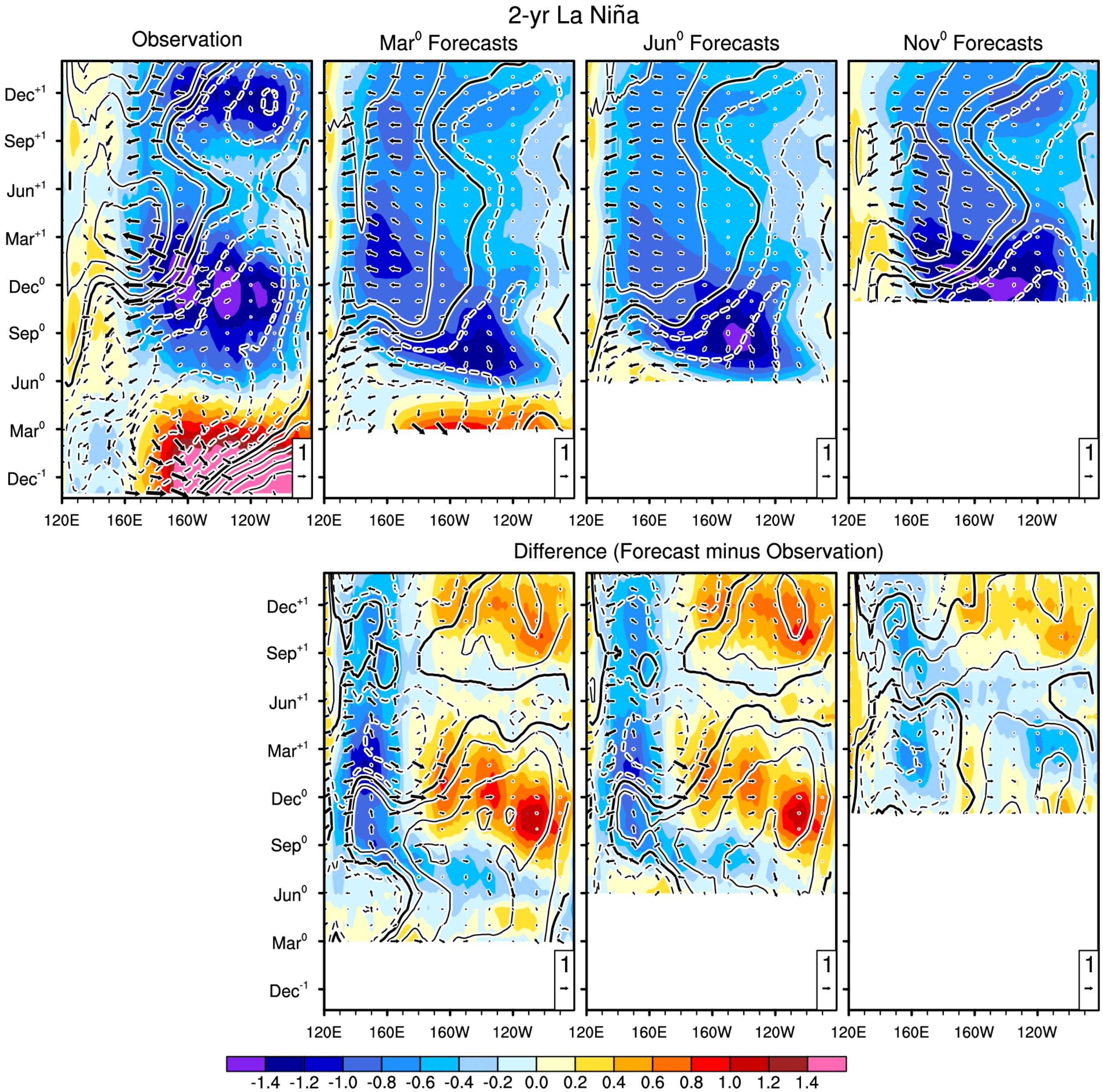
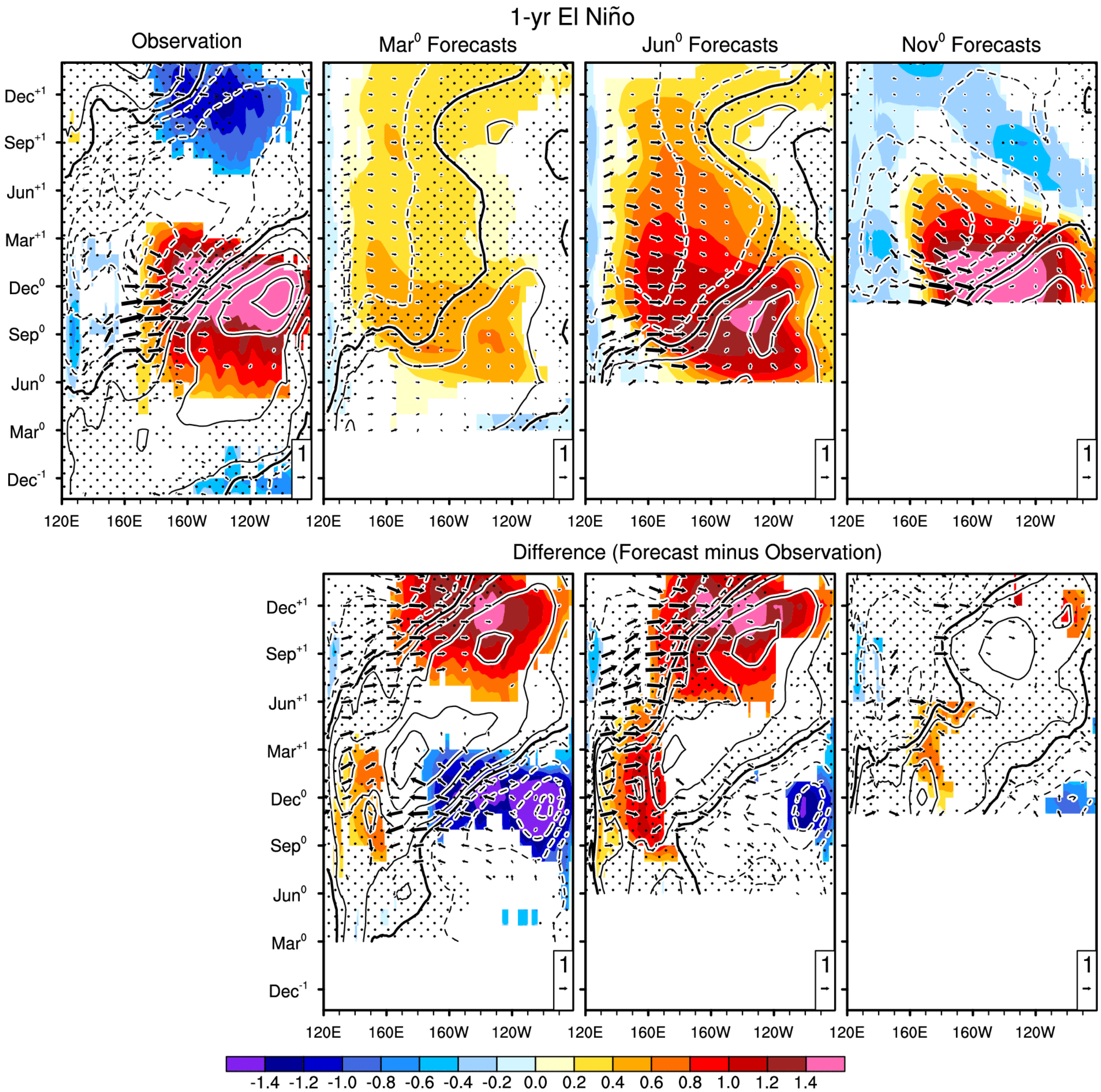
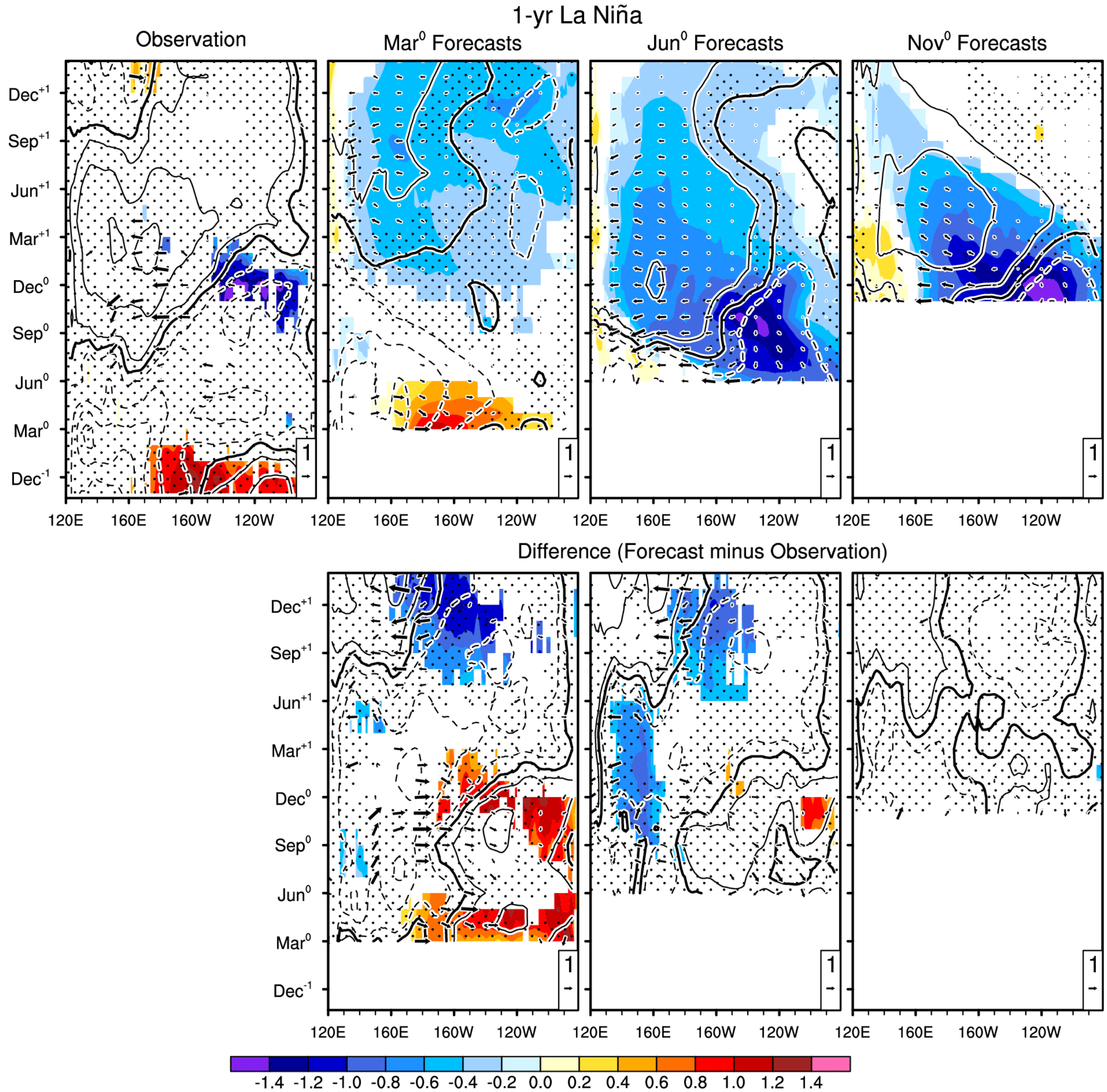
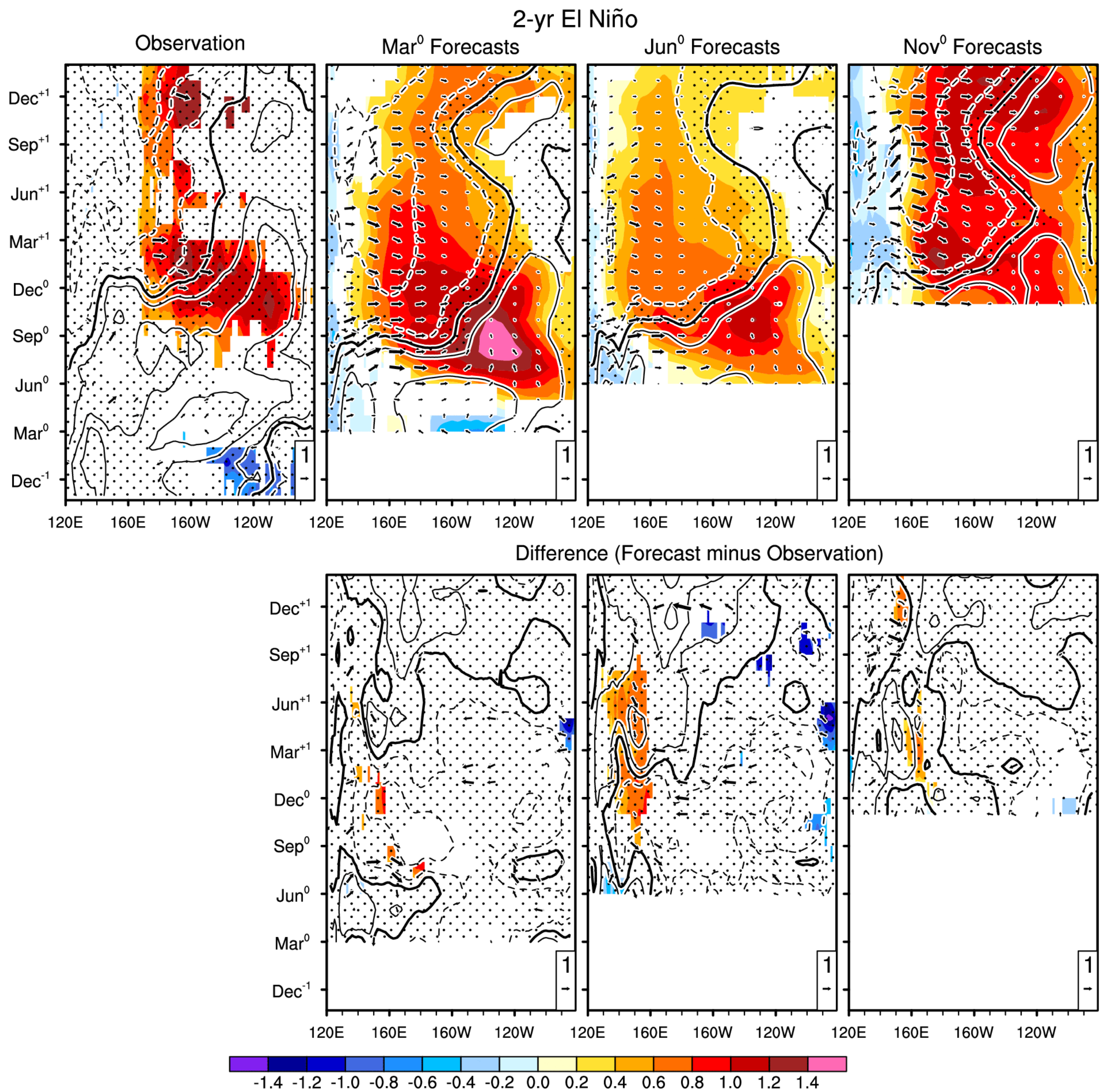
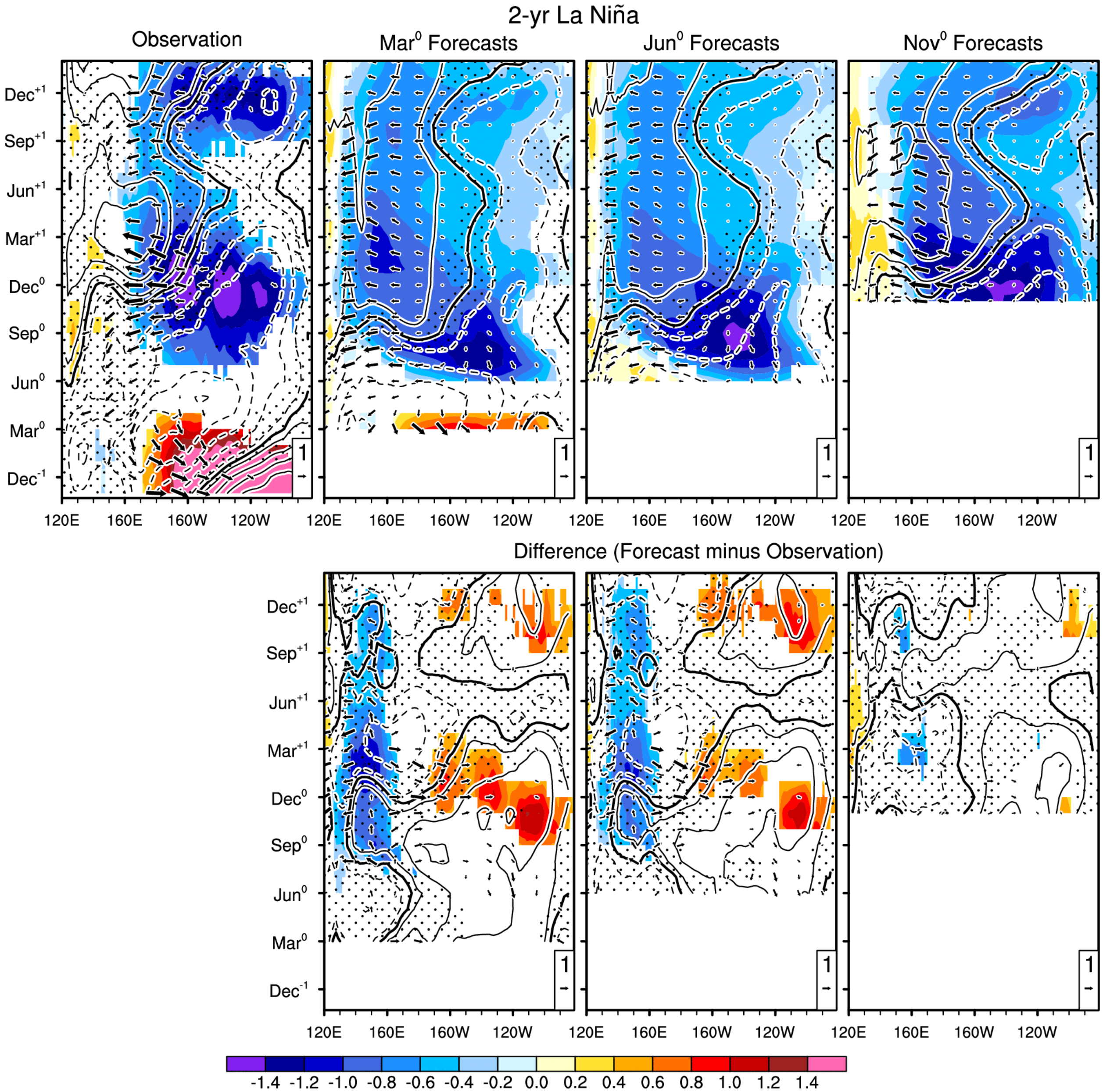

2-yr La Niña
Observation
Mar⁰ Forecasts
Jun⁰ Forecasts
Nov⁰ Forecasts
Dec+1
Sep+1
Jun+1
Mar+1
Dec0
Sep0
Jun0
Mar0
Dec-1
120E
160E
160W
120W
Difference (Forecast minus Observation)
-1.4 -1.2 -1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4

Figure S4. As in Figs. 5 and S3 but only the SST and surface wind anomalies statistically significant at the 95% confidence levels are shown for all four types of events. The thermocline depth anomalies (contours) that are not statistically significant at the 95% confidence level are masked with black stippling.



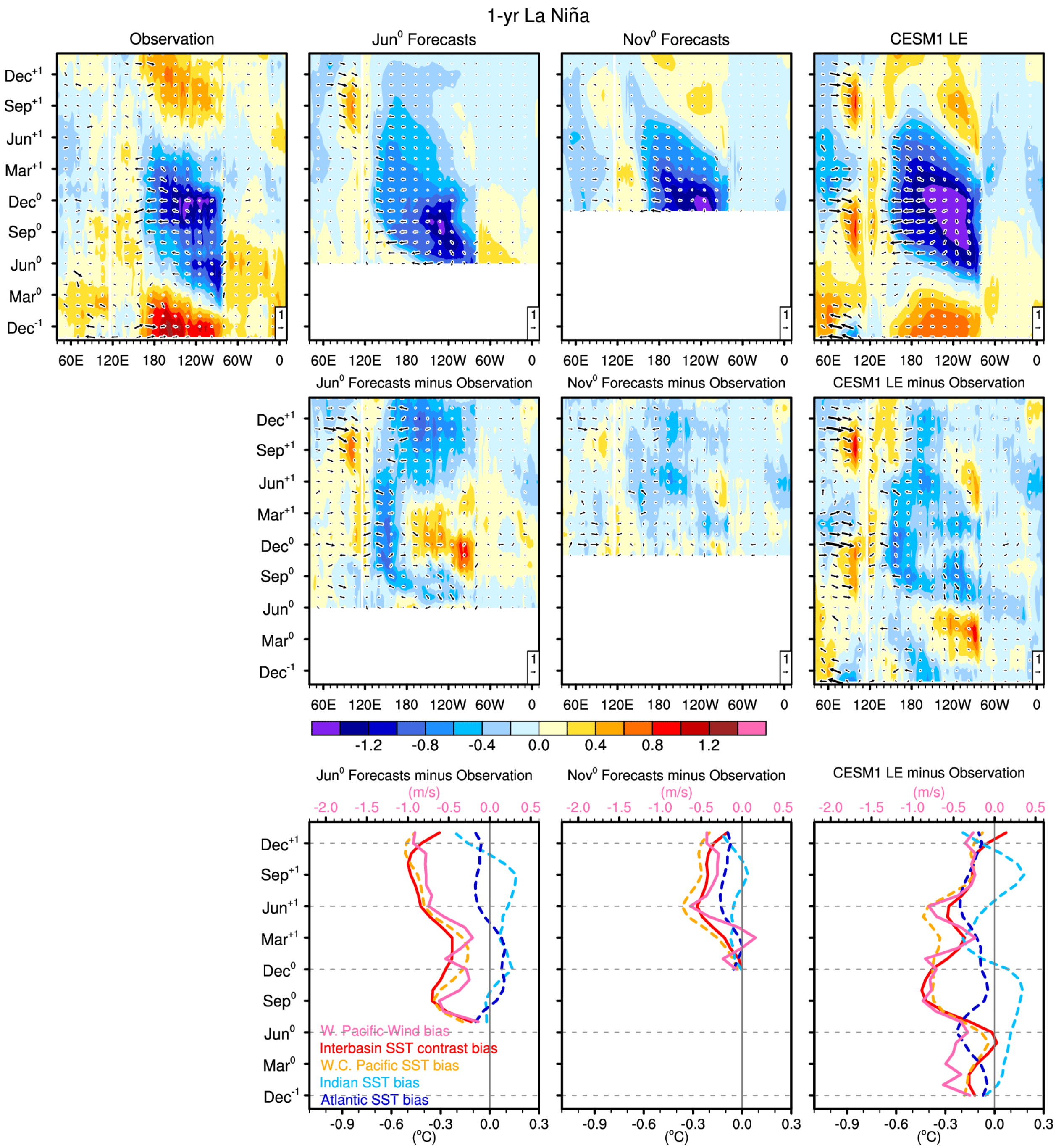

1-yr La Niña
Observation
Mar⁰ Forecasts
Jun⁰ Forecasts
Nov⁰ Forecasts
Dec+1
Sep+1
Jun+1
Mar+1
Dec0
Sep0
Jun0
Mar0
Dec-1
120E
160E
160W
120W
Difference (Forecast minus Observation)
-1.4 -1.2 -1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4

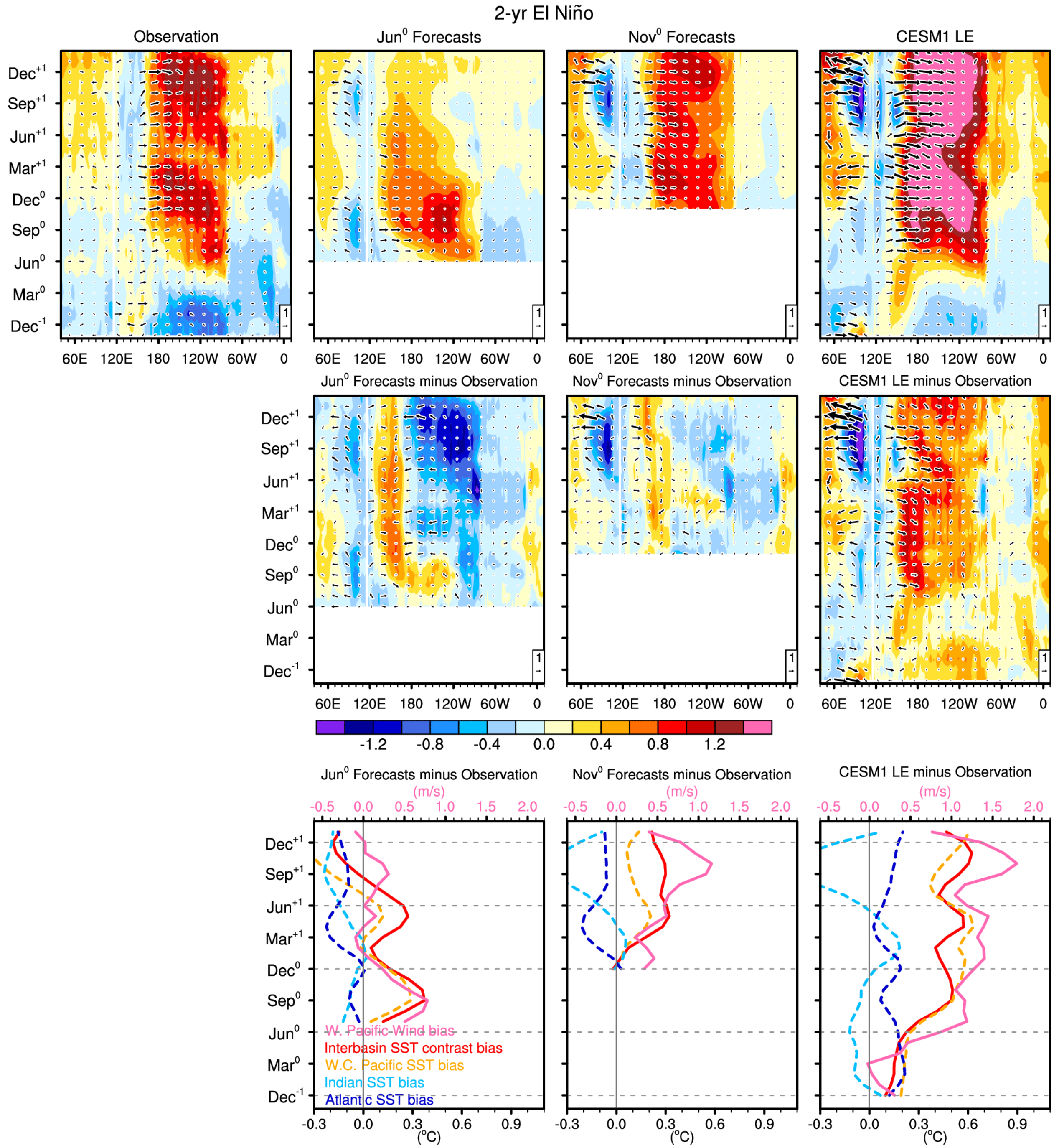

2-yr El Niño
Observation
Mar0 Forecasts
Jun0 Forecasts
Nov0 Forecasts
Dec+1
Sep+1
Jun+1
Mar+1
Dec0
Sep0
Jun0
Mar0
Dec-1
120E
160E
160W
120W
Difference (Forecast minus Observation)
-1.4 -1.2 -1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4



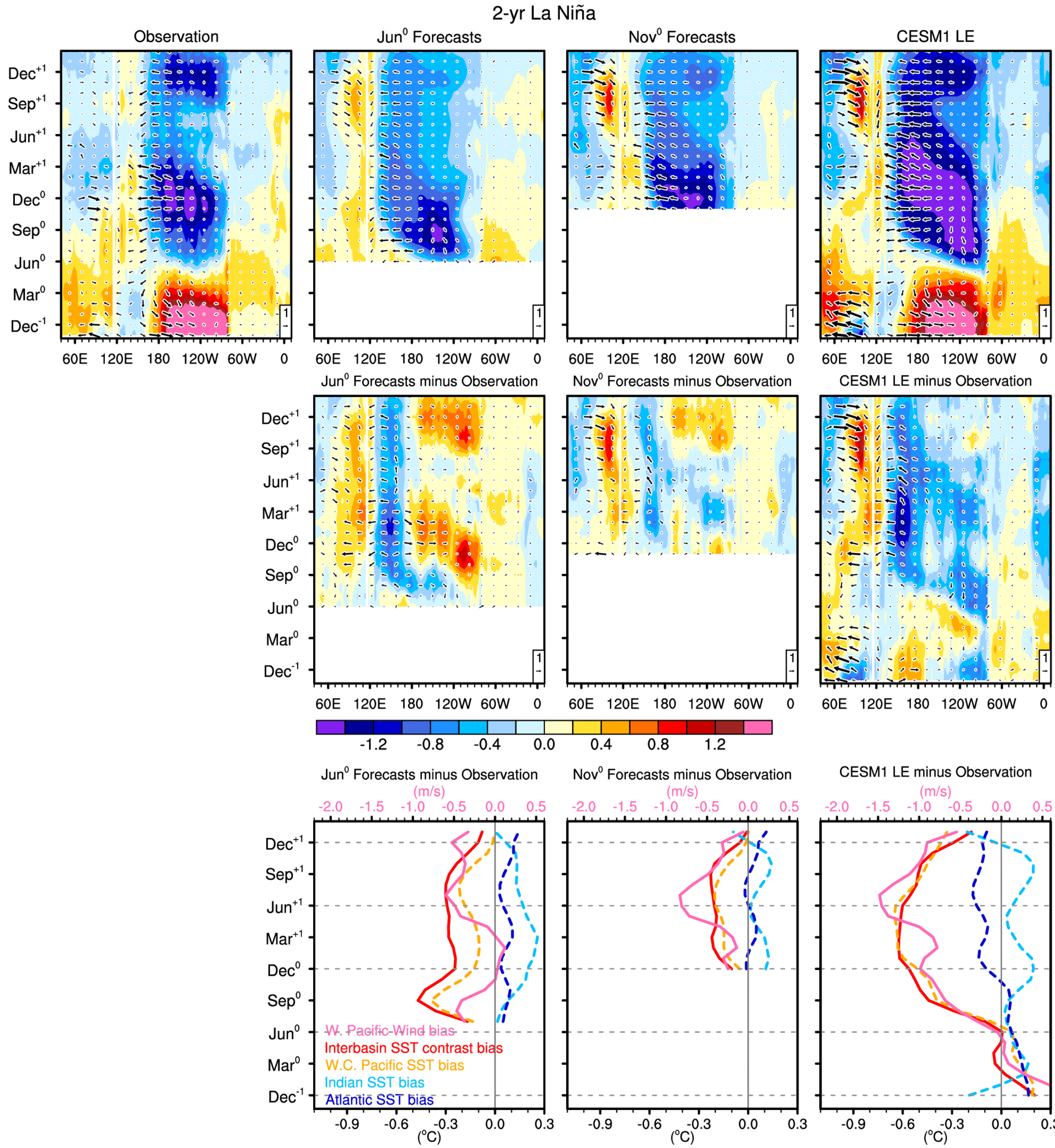
2-yr La Niña
Observation
Mar0 Forecasts
Jun0 Forecasts
Nov0 Forecasts
Dec+1
Sep+1
Jun+1
Mar+1
Dec0
Sep0
Jun0
Mar0
Dec-1
120E
160E
160W
120W
Difference (Forecast minus Observation)
-1.4 -1.2 -1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4

Figure S5. As in Fig. 6, but for composites of 1-yr La Niña, 2-yr El Niño, and 2-yr La Niña events. The statistical significance of these anomalies is shown in Fig. S6.



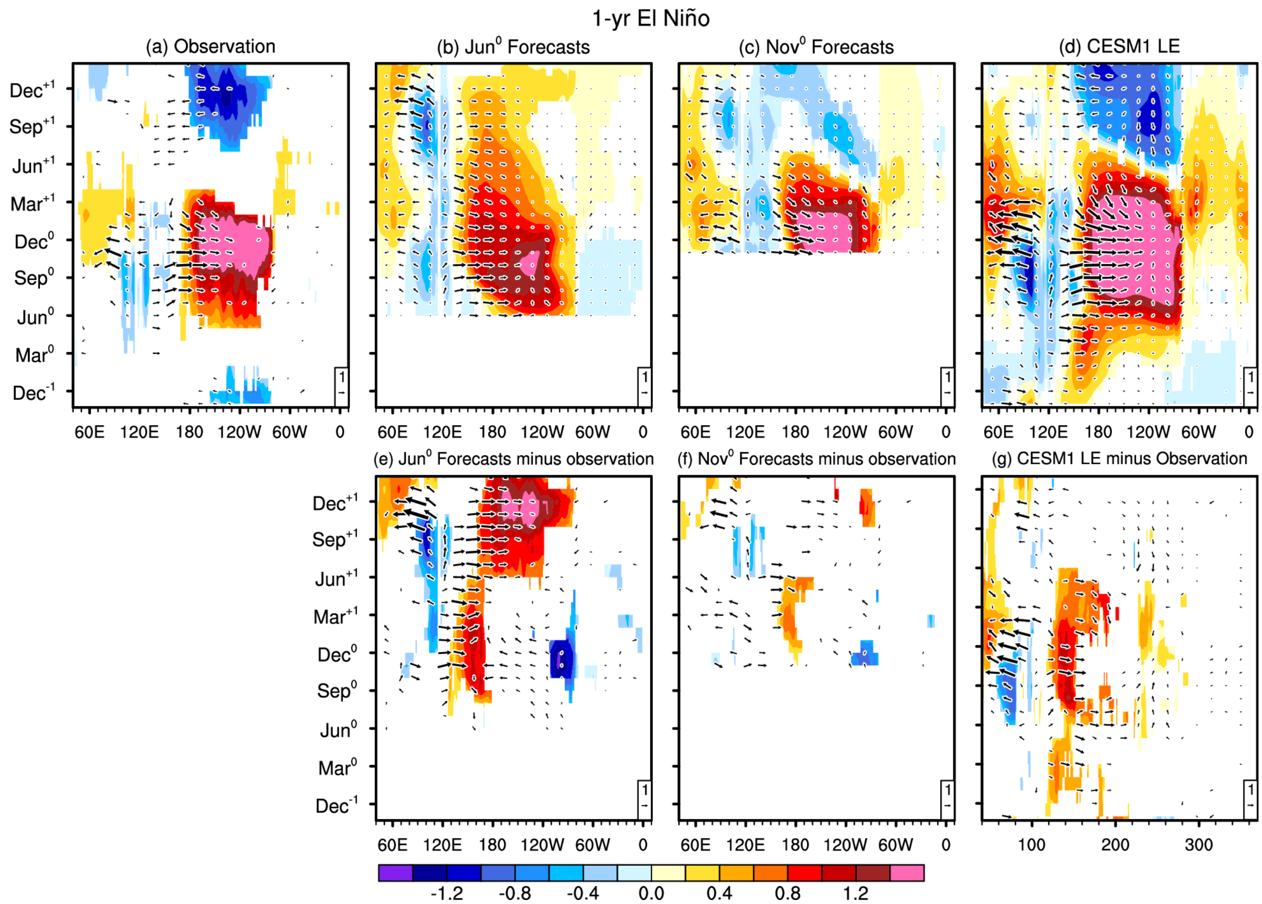


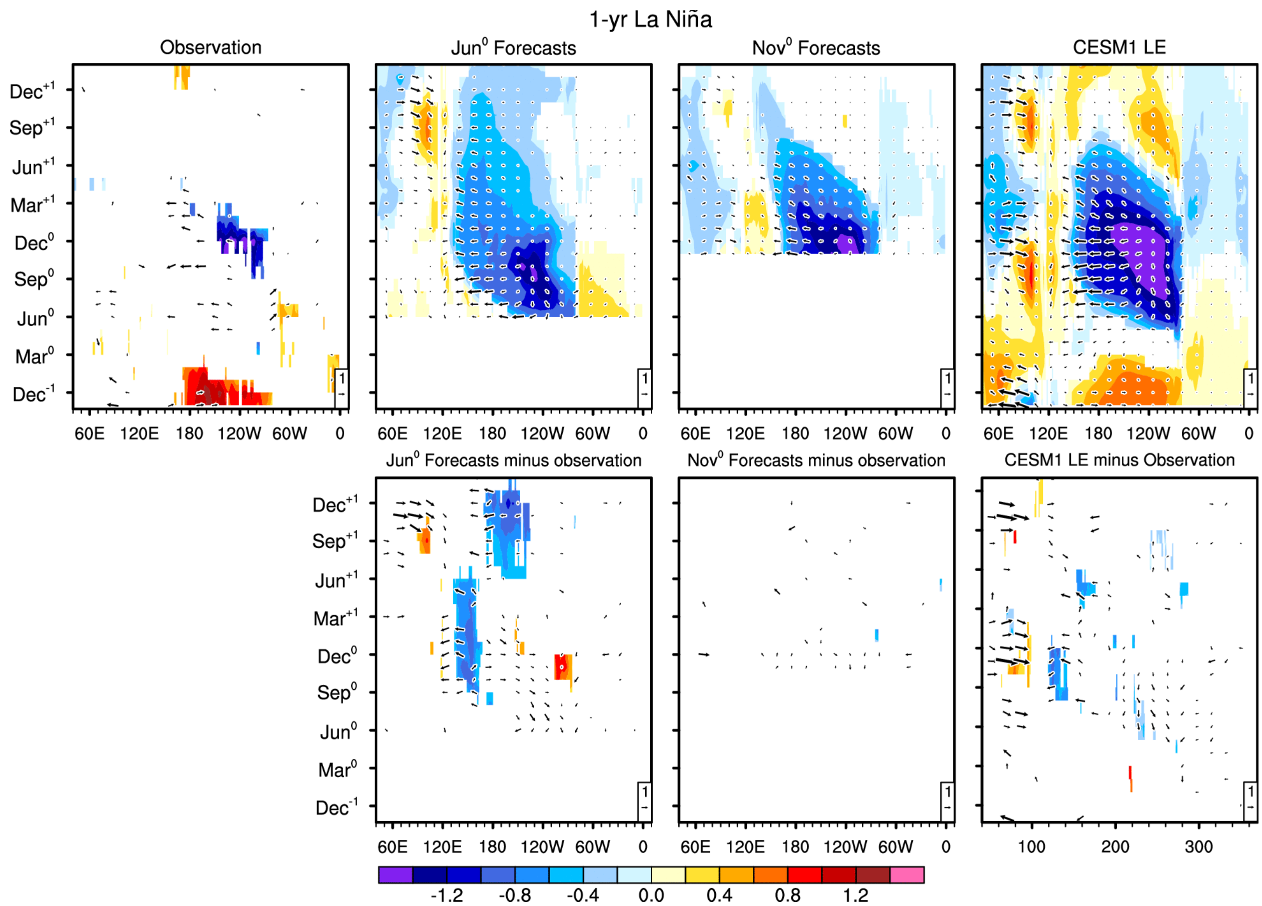
2-yr El Niño
Observation
Jun⁰ Forecasts
Nov⁰ Forecasts
CESM1 LE
Jun⁰ Forecasts minus Observation
Nov⁰ Forecasts minus Observation
CESM1 LE minus Observation
W. Pacific Wind bias
Interbasin SST contrast bias
W.C. Pacific SST bias
Indian SST bias
Atlantic SST bias
(m/s)
(°C)



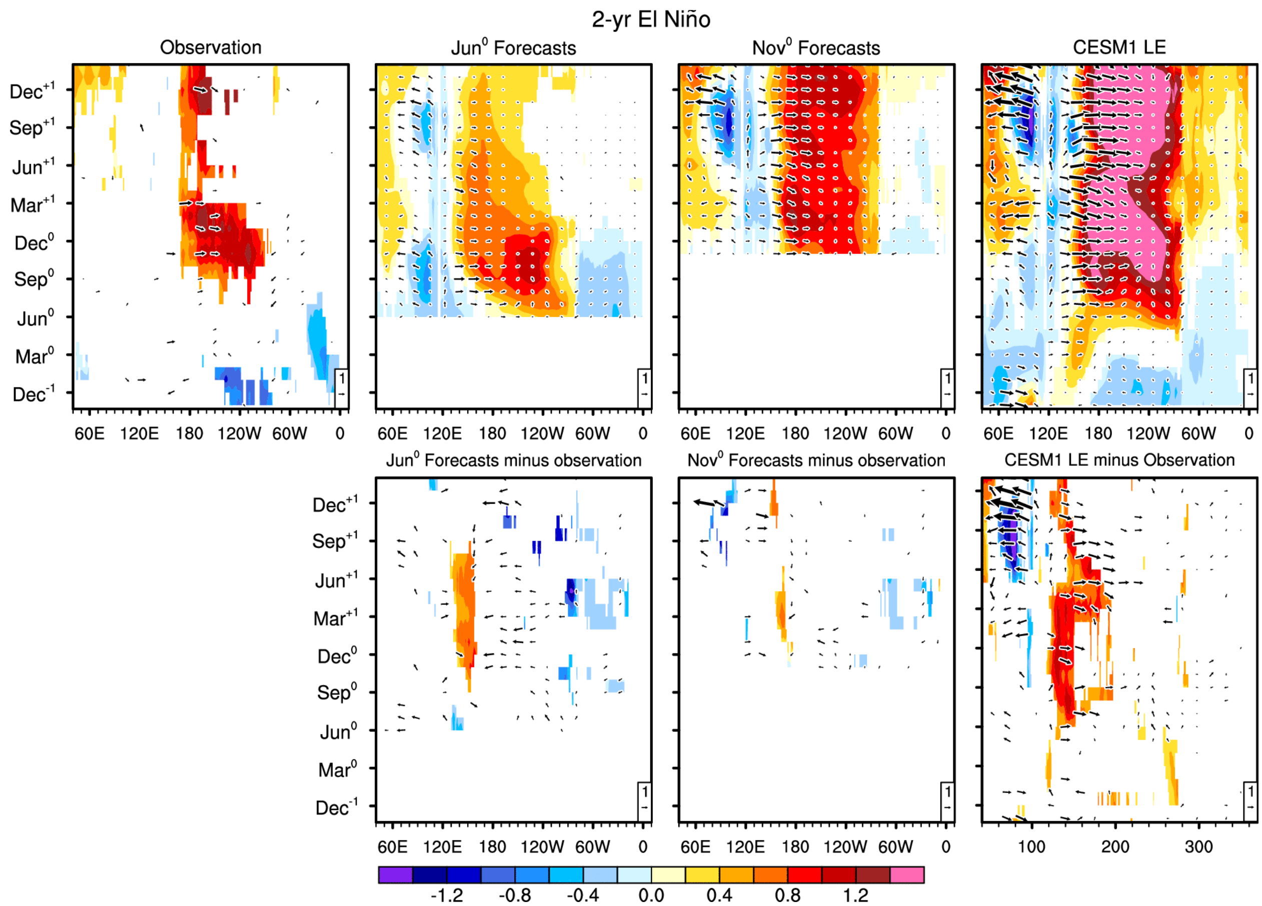
2-yr La Niña
Observation
Jun⁰ Forecasts
Nov⁰ Forecasts
CESM1 LE
Jun⁰ Forecasts minus Observation
Nov⁰ Forecasts minus Observation
CESM1 LE minus Observation
W. Pacific Wind bias
Interbasin SST contrast bias
W.C. Pacific SST bias
Indian SST bias
Atlantic SST bias
(m/s)
(°C)

Figure S6. As in Figs. 6 and S5 but only the SST and surface wind anomalies statistically significant at the 95% confidence levels are shown for all four types of events.





1-yr La Niña
Observation
Jun⁰ Forecasts
Nov⁰ Forecasts
CESM1 LE
Jun⁰ Forecasts minus observation
Nov⁰ Forecasts minus observation
CESM1 LE minus Observation
Dec+1
Sep+1
Jun+1
Mar+1
Dec0
Sep0
Jun0
Mar0
Dec-1
60E 120E 180 120W 60W 0
100 200 300
-1.2 -0.8 -0.4 0.0 0.4 0.8 1.2


2-yr El Niño
Observation
Jun⁰ Forecasts
Nov⁰ Forecasts
CESM1 LE
Jun⁰ Forecasts minus observation
Nov⁰ Forecasts minus observation
CESM1 LE minus Observation
Dec+1
Sep+1
Jun+1
Mar+1
Dec0
Sep0
Jun0
Mar0
Dec-1
60E 120E 180 120W 60W 0
100 200 300
-1.2 -0.8 -0.4 0.0 0.4 0.8 1.2

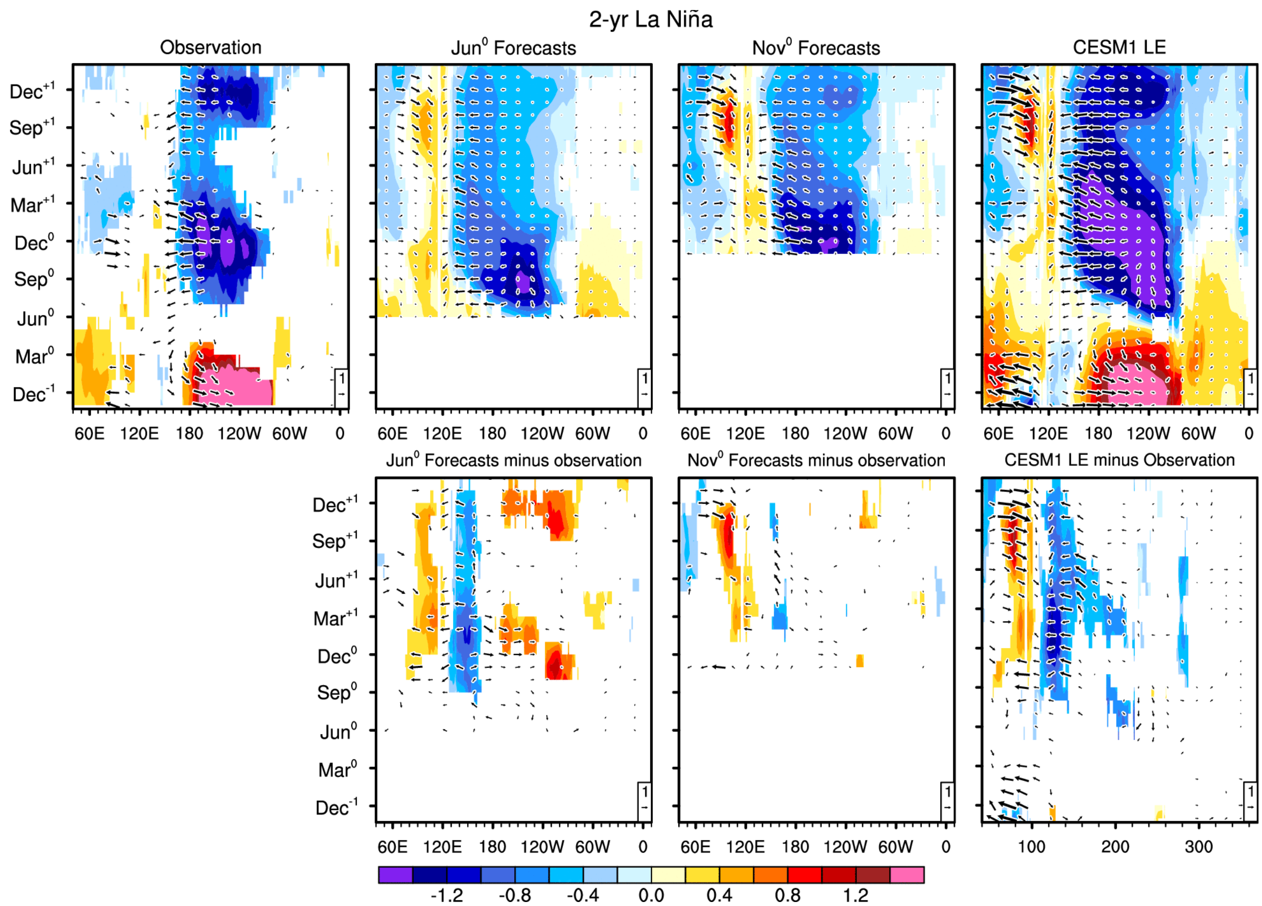
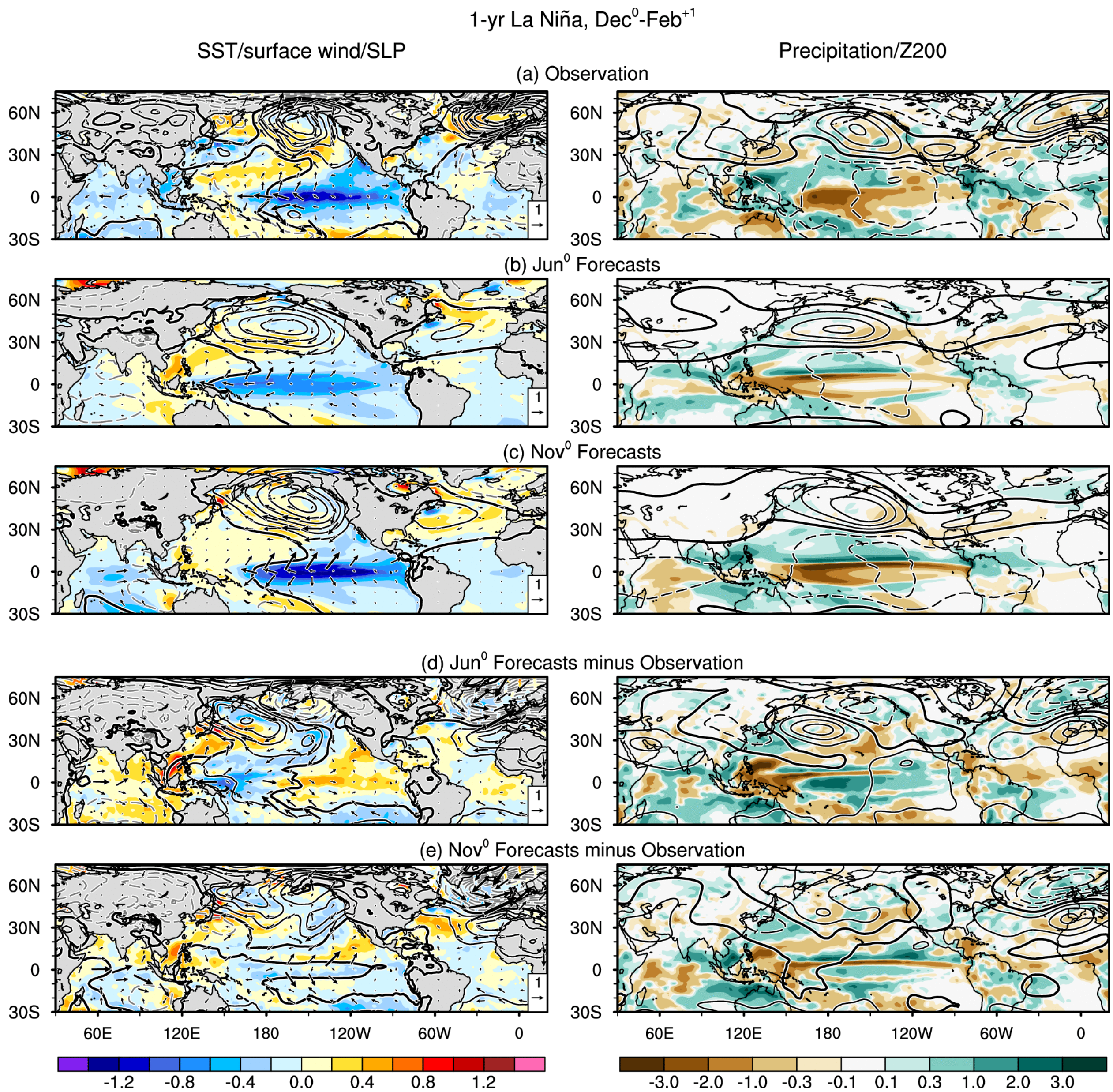
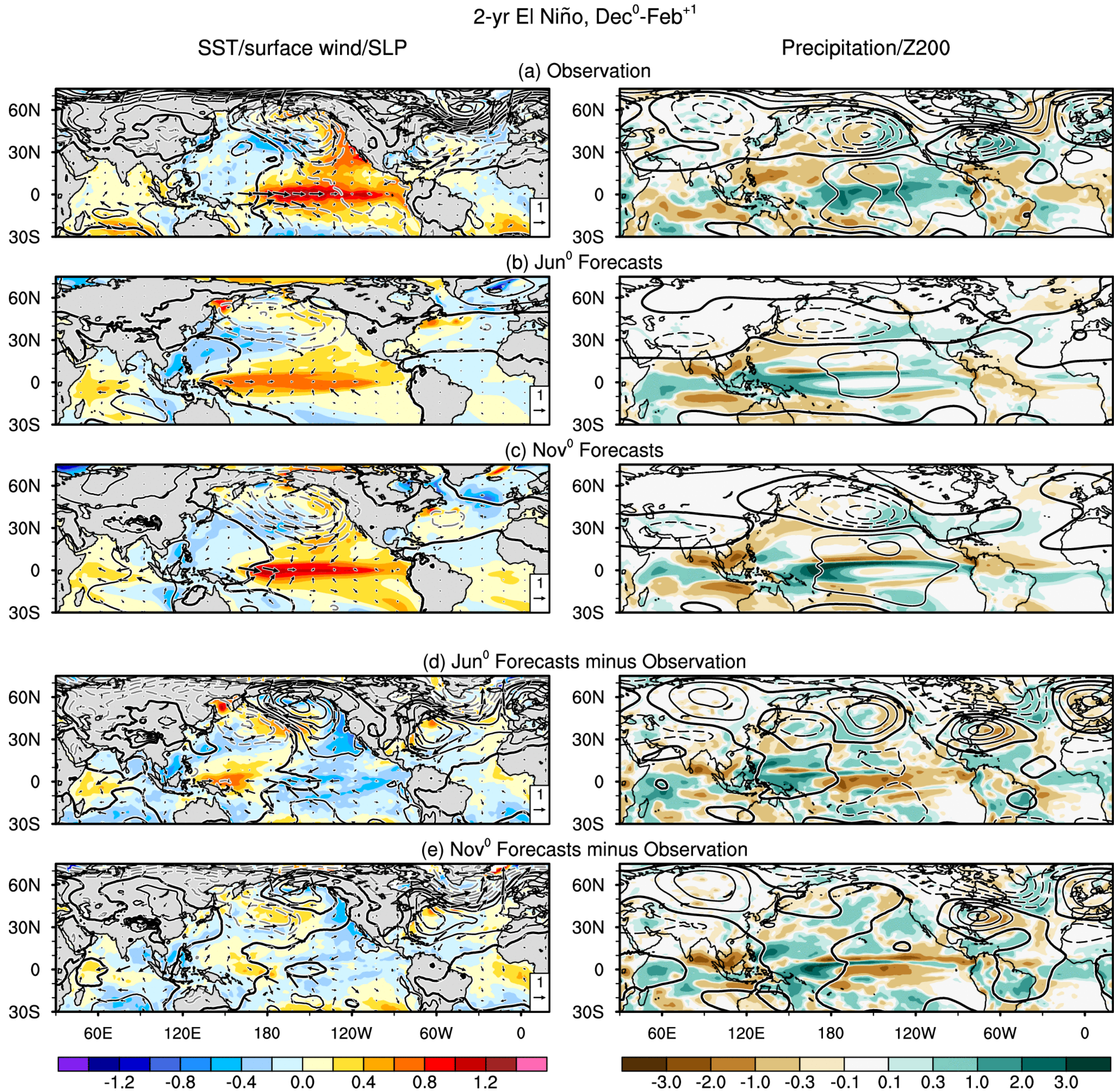

2-yr La Niña
Observation
Jun⁰ Forecasts
Nov⁰ Forecasts
CESM1 LE
Dec+1
Sep+1
Jun+1
Mar+1
Dec0
Sep0
Jun0
Mar0
Dec-1
60E 120E 180 120W 60W 0
Jun0 Forecasts minus observation
Nov0 Forecasts minus observation
CESM1 LE minus Observation
100 200 300
-1.2 -0.8 -0.4 0.0 0.4 0.8 1.2

Figure S7. As in Fig.7, but for composites of 1-yr La Niña, 2-yr El Niño, and 2-yr La Niña events. The statistical significance of these anomalies is shown in Fig. S8.




2-yr El Niño, Dec^0-Feb^{+1}
SST/surface wind/SLP
Precipitation/Z200
(a) Observation
(b) Jun^0 Forecasts
(c) Nov^0 Forecasts
(d) Jun^0 Forecasts minus Observation
(e) Nov^0 Forecasts minus Observation
60N
30N
0
30S
60E
120E
180
120W
60W
0
-1.2 -0.8 -0.4 0.0 0.4 0.8 1.2
-3.0 -2.0 -1.0 -0.3 -0.1 0.1 0.3 1.0 2.0 3.0

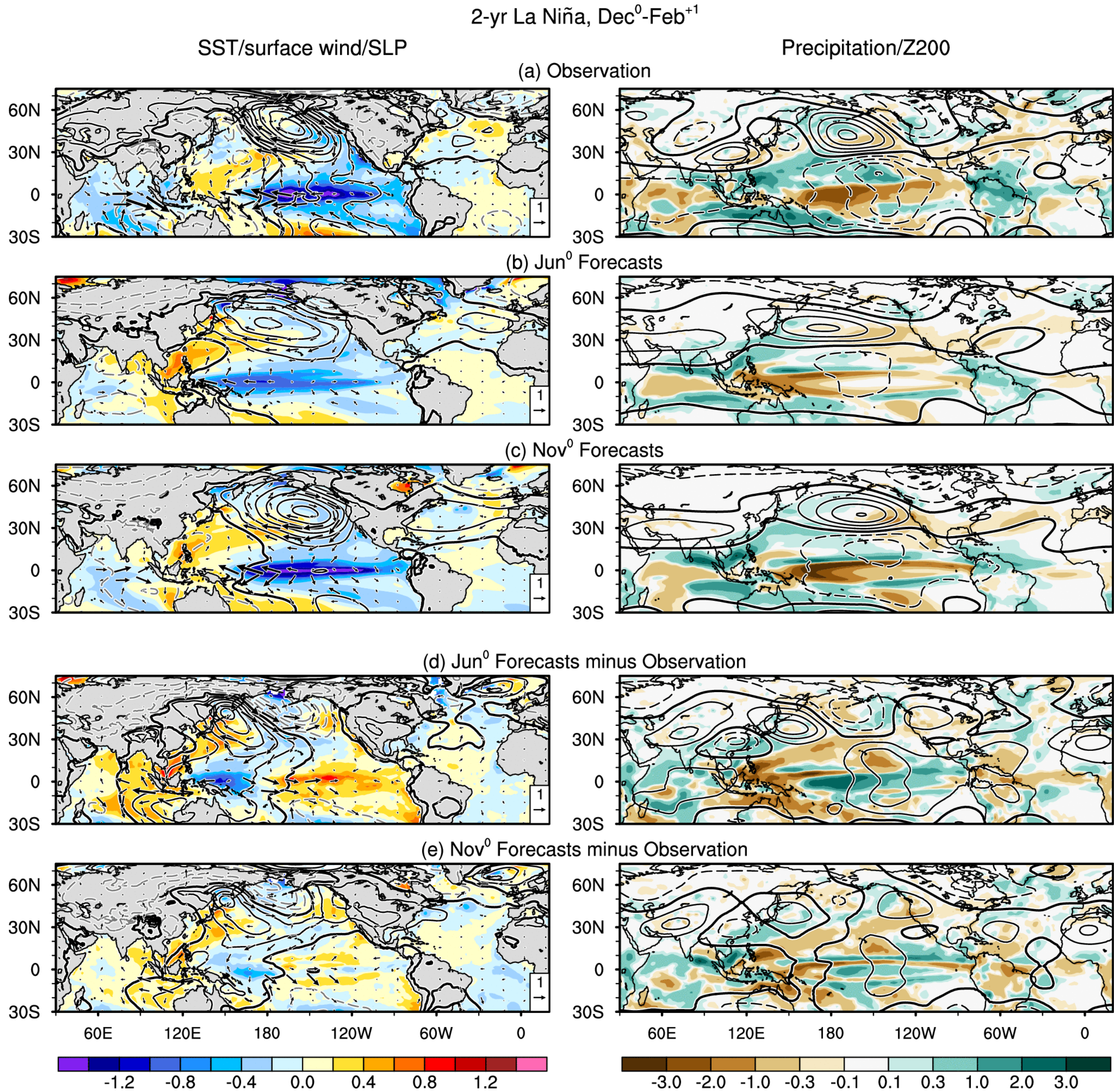
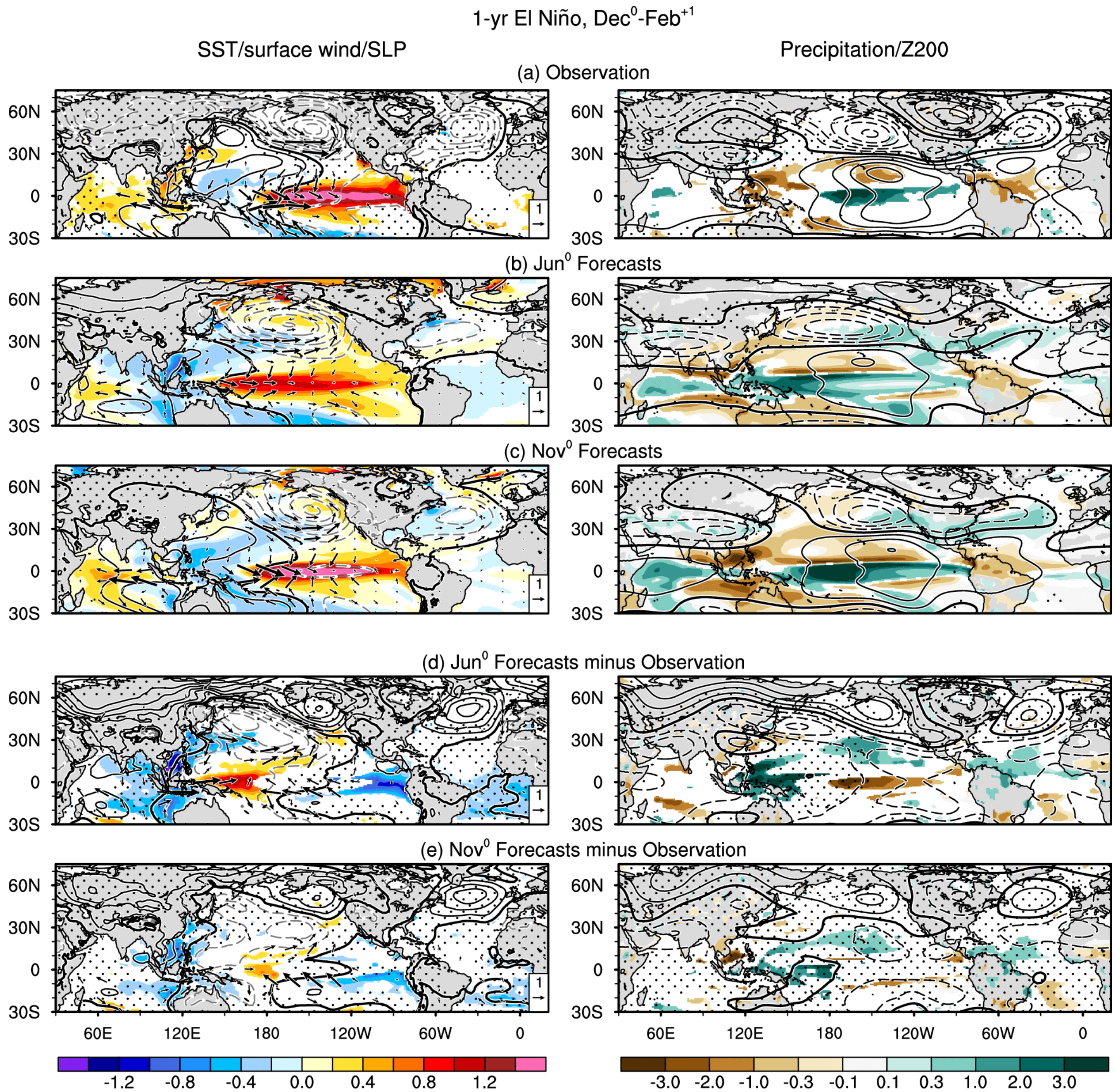
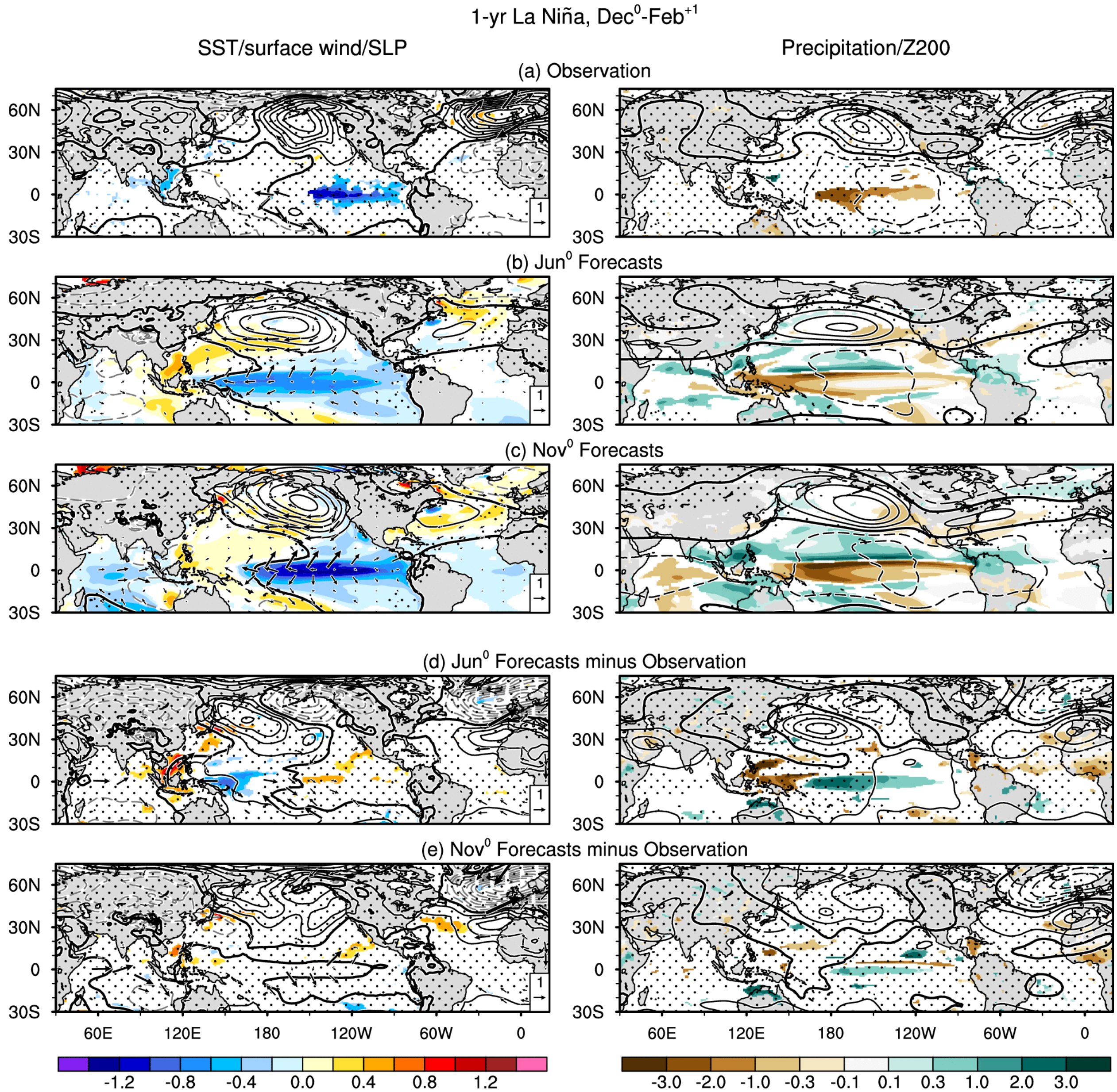
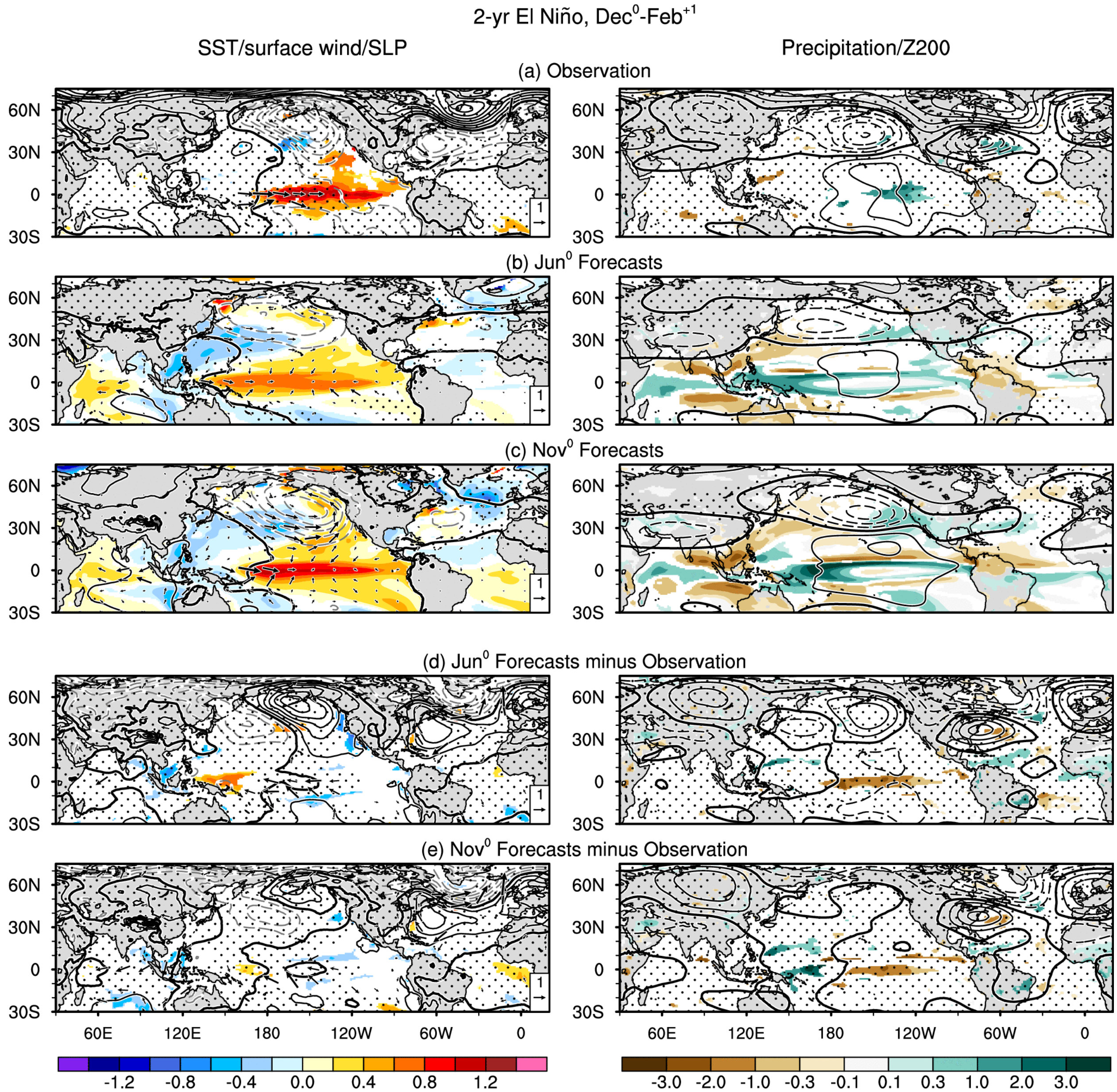

2-yr La Niña, Dec⁰-Feb⁺¹
SST/surface wind/SLP
Precipitation/Z200
(a) Observation
(b) Jun⁰ Forecasts
(c) Nov⁰ Forecasts
(d) Jun⁰ Forecasts minus Observation
(e) Nov⁰ Forecasts minus Observation
60N
30N
0
30S
60E
120E
180
120W
60W
0
-1.2 -0.8 -0.4 0.0 0.4 0.8 1.2
-3.0 -2.0 -1.0 -0.3 -0.1 0.1 0.3 1.0 2.0 3.0

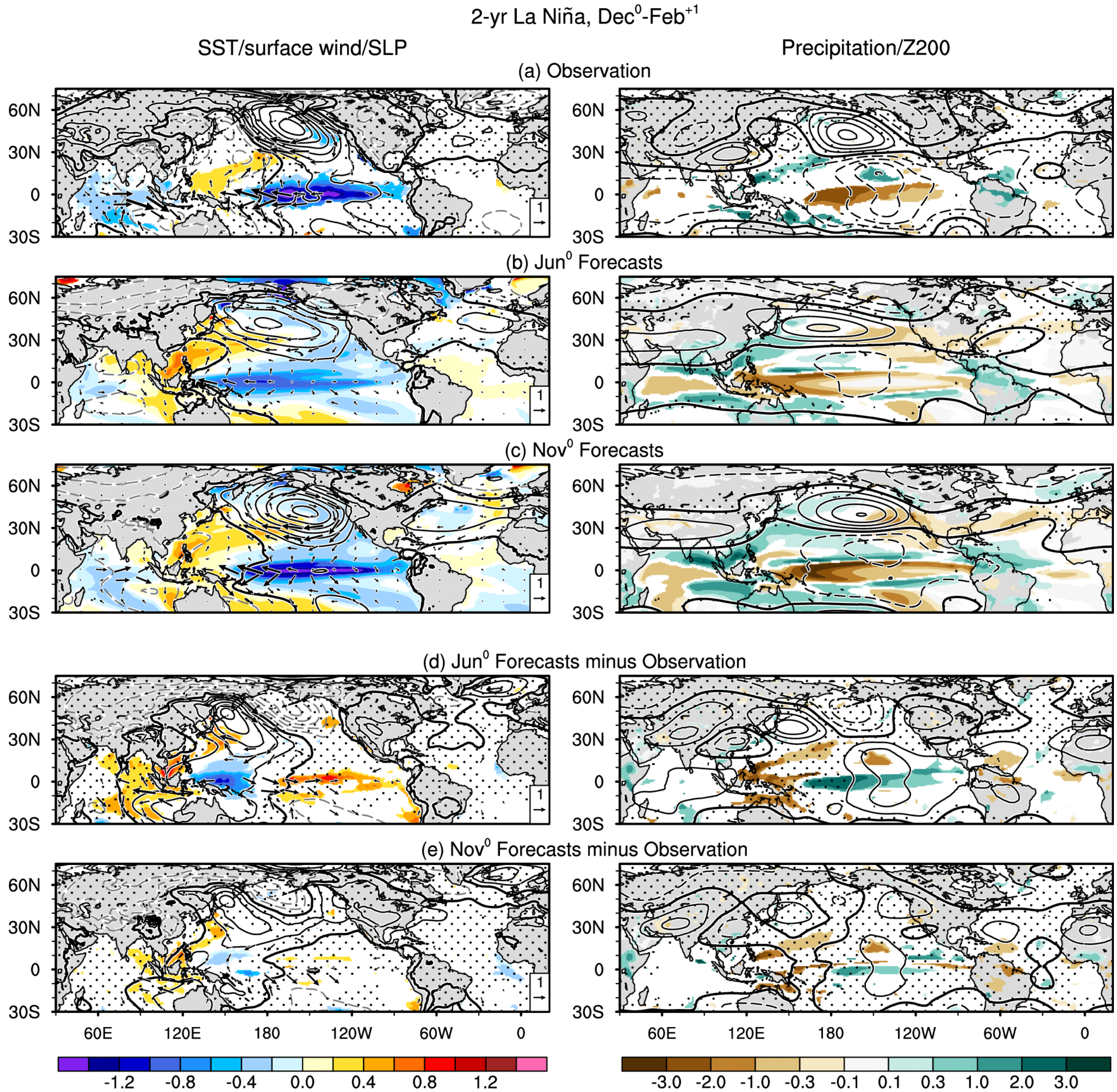
Figure S8. As in Figs 7 and S7 but only the SST and surface wind anomalies statistically significant at the 95% confidence levels are shown for all four types of events. The SLP and Z200 anomalies (contours) that are not statistically significant at the 95% confidence level are masked with black stippling.




1-yr La Niña, Dec0-Feb+1
SST/surface wind/SLP
Precipitation/Z200
(a) Observation
(b) Jun0 Forecasts
(c) Nov0 Forecasts
(d) Jun0 Forecasts minus Observation
(e) Nov0 Forecasts minus Observation
60N
30N
0
30S
60E
120E
180
120W
60W
0
-1.2
-0.8
-0.4
0.0
0.4
0.8
1.2
-3.0
-2.0
-1.0
-0.3
-0.1
0.1
0.3
1.0
2.0
3.0



2-yr El Niño, Dec⁰-Feb⁺¹
SST/surface wind/SLP
Precipitation/Z200
(a) Observation
(b) Jun⁰ Forecasts
(c) Nov⁰ Forecasts
(d) Jun⁰ Forecasts minus Observation
(e) Nov⁰ Forecasts minus Observation
60N
30N
0
30S
60E
120E
180
120W
60W
0
-1.2 -0.8 -0.4 0.0 0.4 0.8 1.2
-3.0 -2.0 -1.0 -0.3 -0.1 0.1 0.3 1.0 2.0 3.0


2-yr La Niña, Dec⁰-Feb⁺¹
SST/surface wind/SLP
Precipitation/Z200
(a) Observation
(b) Jun⁰ Forecasts
(c) Nov⁰ Forecasts
(d) Jun⁰ Forecasts minus Observation
(e) Nov⁰ Forecasts minus Observation
60N
30N
0
30S
60E
120E
180
120W
60W
0
-1.2 -0.8 -0.4 0.0 0.4 0.8 1.2
-3.0 -2.0 -1.0 -0.3 -0.1 0.1 0.3 1.0 2.0 3.0

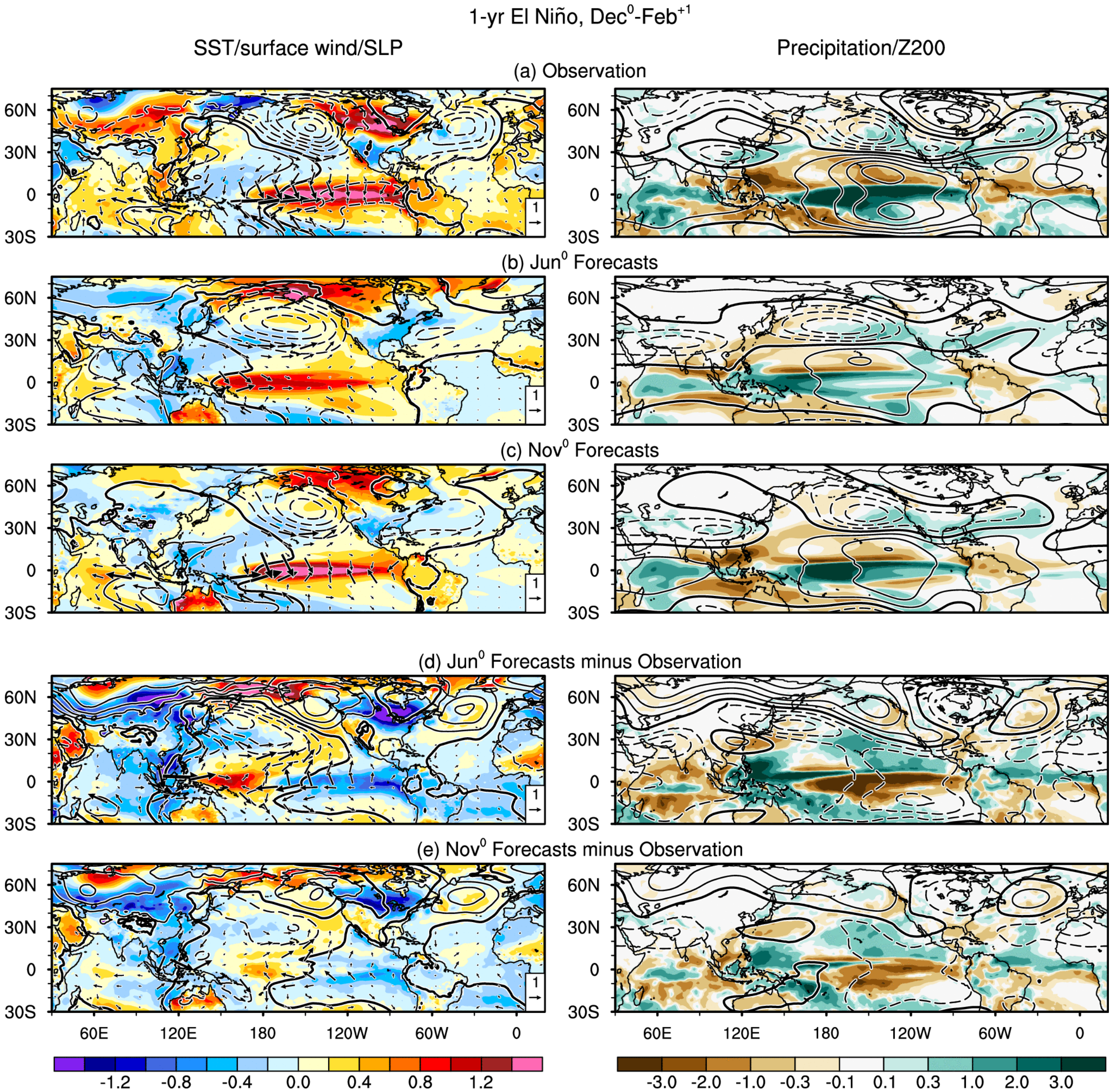


Figure S9. As in Figs 7 and S7 but SLP, surface wind, Z200, and ocean precipitation anomalies are based on the JAR55, and land precipitation anomalies are based on the CRU.