498 **Atmospheric Rivers and Enhanced Integrated Vapor Transport Probability Forecasts as seen During Frontal Passages in Southern California with an Emphasis on Strong Winds**

Ivory J. Small*
NOAA/NWS San Diego, CA

1. Introduction

Atmospheric rivers (e.g., *Ralph et al. 2004;)* are not infrequent visitors to the west coast, but they only occasionally slip far enough south to affect Southern California (Fig. 1). The main impact is typically heavy rain, and when cold enough, heavy snow at the higher elevations in the mountains, but another significant impact is strong winds and severe weather. Integrated water vapor transport (IVT) is a good parameter for determining moisture advection into the region and mainly consists of imbedded strong flow combined with significant amounts of moisture. It has been associated with very moist air masses that invade Southern California with wind damage (Small, 2016). With or without much instability, this can result in the generation of damaging frontal passages and strong wind shear, both from a convective standpoint (possible supercells) and a synoptic scale wind standpoint. Major airport traffic delays, flash flooding, and power outages can occur. In order to look at how well these events are forecast in advance, this study makes some brief comparisons of IVT from the perspective of probability forecasts to damaging impacts in the region using the National Center for Environmental Prediction (NCEP) GFS Ensemble Prediction System.

*Corresponding author address: Ivory J. Small, NOAA/NWS San Diego. 11440 W. Bernardo Ct., Ste. 230, San Diego, CA 92127-1643; e-mail; ivory.small@noaa.gov

The focus will be on the more damaging frontal passages during the 2015-2016 cool season.

2. Strong Cold Frontal Passage Cases

Southern California is more known for strong winds associated with strong winds from the north and northeast, for example, "offshore flow patterns" such as Santa Ana Winds (e. g., Small 1995, Jones et al., 2010). Less known are winds from the south through northwest, called onshore flow patterns (Small, 2006). These patterns can be very damaging as well. Often the winds associated with onshore flow patterns are associated with cold fronts. Strong cold fronts, especially those with southerly winds, create wind shear and crosswind issues (since runway orientations of the major airports are often east-west oriented in southern California). When the cross wind gusts reach about 25 knots (12 m s^{-1}), issues develop concerning landing of aircrafts. When the crosswind gusts reach about 35 knots (17.5 m s^{-1}), significant impacts occur, possibly even divert aircrafts to alternate airports, with no arrivals at all attempted. To add insult to injury, with certain cloud base heights it can make it difficult for aircraft to land when strong winds aloft accompany cloud bases that become low enough. The following cases are example of frontal systems with strong winds that moved through Southern California during the 2015-2016 cool season.

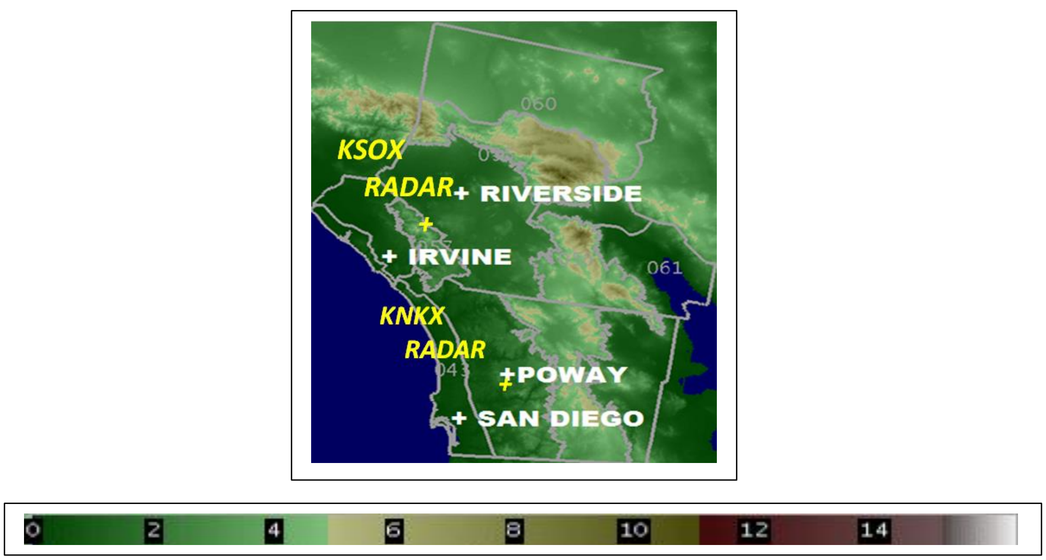

Fig. 1.
Terrain map of the WFO SGX Forecast Area. Color coding in the legend is in thousands of feet MSL.

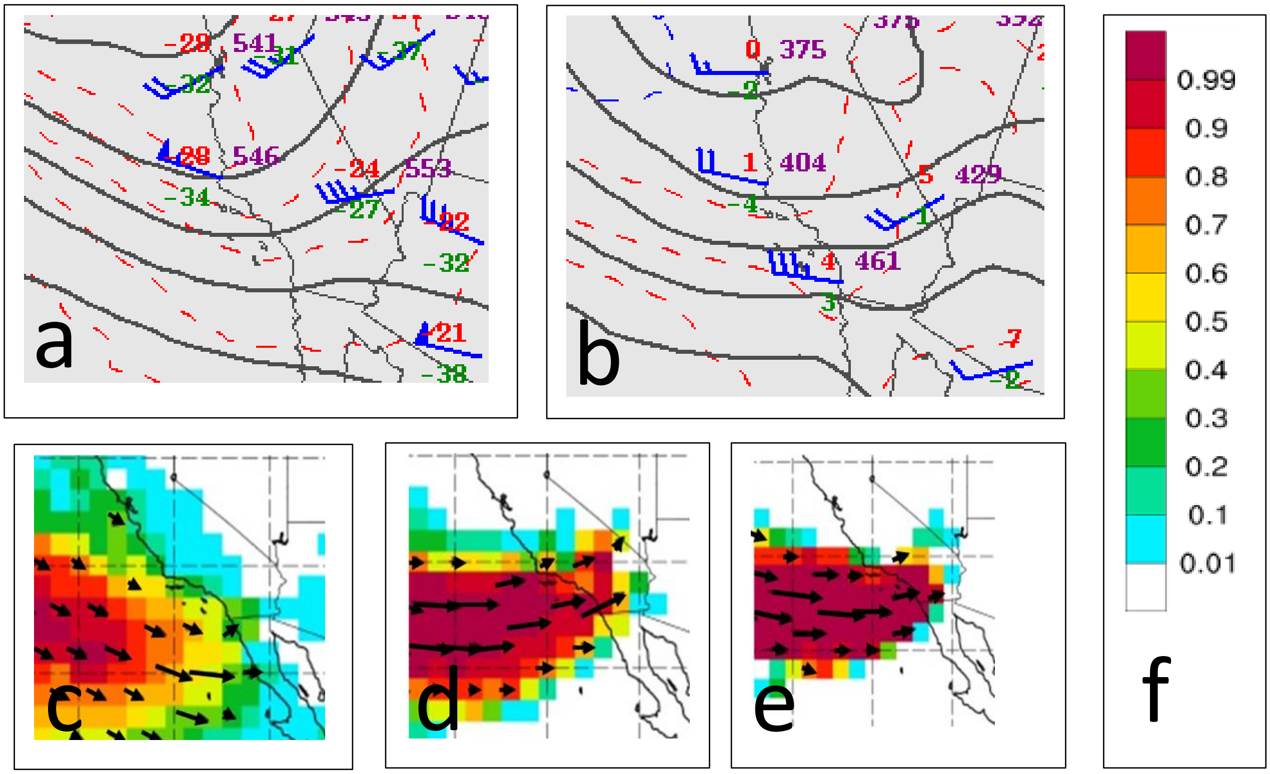

Fig. 2. The upper images are the 0000 UTC 7 January 2016 heights, winds, and temperatures at (a) 500 hPa and (b) 850 hPa. The lower images are the NCEP GFS IVT Probability > 250 (kg m^{-1} s^{-1}) and IVT vector forecasts valid at 0000 UTC 7 January 2016. The images are the (c) 96 hour forecast (d) 48 hour forecast, and (e) 00 hour forecast respectively. The far right image (f) is the probability image scale.

3. Strong Cold Frontal Passage Case on 6-7 January 2016

An obviously negatively-tilted trough was associated with this event (Fig. 2). This indicates strong dynamics over Southern California. Initially, on the 96 hour forecast only the very edge of the 0.5 touches the beaches, indicating that the best chance of reaching 250 kg m^{-1} s^{-1} was over the coastal waters. However, by the 48 hour forecast the values of 0.6 and higher had moved over the coastal areas. By the 00 hour forecast solid areas in the 0.99 or higher category extend inland. [Note that this case has no area of 0.99 displaced to the northwest, (as is seen in later cases)]. Below 2500 feet MSL (0.76 km), KNKX radar winds (not shown) peaked around 42 knots (21 m s^{-1}) for numerous trees down in Poway. A side note is that the radar may not have even seen the strongest winds, which may be nearly perpendicular to the radar beam in this case in the Poway area (Small 2016). Rainfall approaching 3 inches had occurred at San Diego International Airport (KSAN) during the 3-day period prior to the strong winds so soils were rather saturated. In such cases, sometimes trees that are weakened by disease or saturated soil can fall with little or no wind at all. Falling trees can become widespread when sustained wind speeds approach 30 mph and/or gust to 35 mph or more (basically “wind advisory levels” in populated coastal areas) develop. Power outages can become widespread as well, especially in areas where powerlines and power poles are still rather popular rather than powerlines underground.

With 850 hPa winds around 36 knots (18 m s^{-1}) wind gusts could easily surface at this speed, and with the heavier convection wind gusts to about 1 ½ times the 850 hPa wind speed [54 knots (27 m s^{-1})] were possible. With numerous trees down, this was probably close to what occurred.

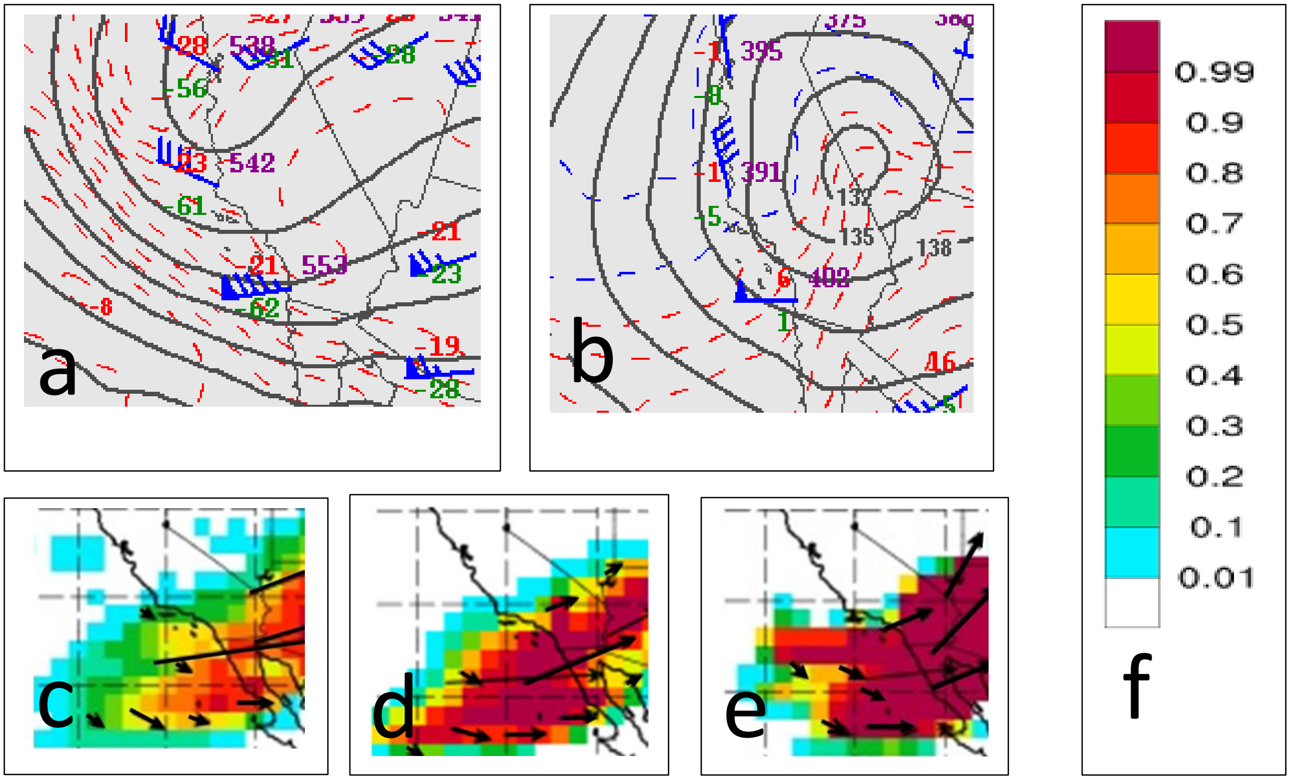

Fig. 3. The upper images are the 0000 UTC 1 February 2016 heights, winds, and temperatures at (a) 500 hPa and (b) 850 hPa. The lower images are the NCEP GFS IVT Probability > 250 (kg m^{-1} s^{-1}) and IVT vector forecasts valid at 0000 UTC 1 February 2016. The images are the (c) 96 hour forecast (d) 48 hour forecast, and (e) 00 hour forecast respectively. The far right image (f) is the probability image scale.

4. Strong Cold Frontal Passage Case on 31 January – 1 February 2016

Similar to the previous case, a negatively-tilted trough was associated with this event (Fig. 3), thus strong dynamic support was available for the event. The 96 hour forecast showed modest coastal probabilities of about 0.5-0.7. There was a strong increase at 48 hours as values jumped up to around 0.99, and blanket the area by the 00 hour forecast. This case has no area of 0.99 displaced to the northwest, as is seen in later cases. The peak KNKX radar estimated speeds at 2500 feet MSL (0.76 km) or lower (not shown) were in excess of 65 knots (32.5 m s^{-1}). Numerous trees and even power poles were blown down, and there was 1 fatality when a large tree fell on an occupied vehicle in the San Diego area.

This event was not a “saturated soils” problem but one resulting from very strong winds since less than 0.25 inches had fallen in the past 3 weeks. With 850 hPa winds around 49 knots (24.5 m s^{-1}) wind gusts could easily surface at this speed. With very strong convection, gusts to about 1 ½ times the 850 hPa wind speed [73.5 knots (37 m s^{-1})] were possible. It is very rare for 850 hPa winds of around 50 knots to develop, and easily causes extreme amounts of wind damage when they occur. Even 40 knot winds at 850 hPa are rare (from any direction), and also cause unusually widespread damage.

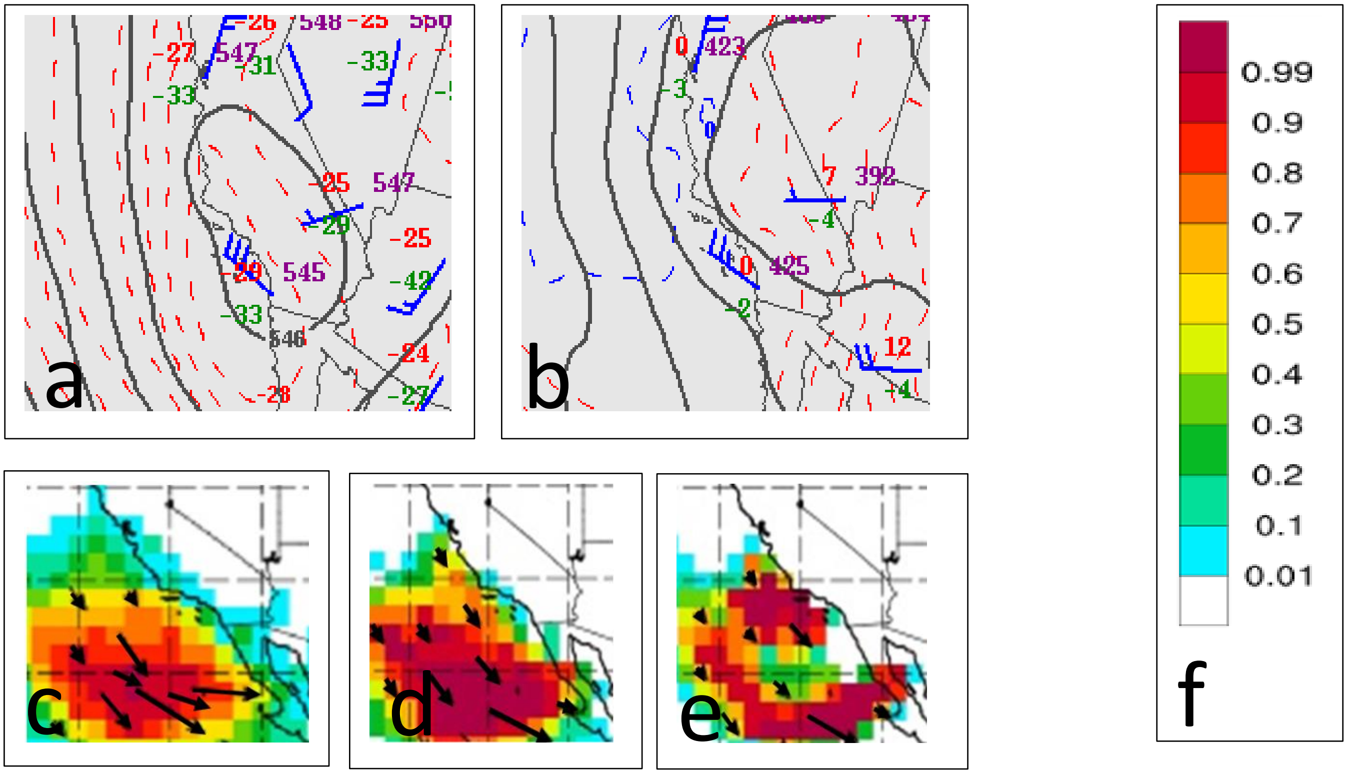

Fig. 4. The upper images are the 0000 UTC 8 March 2016 heights, winds, and temperatures at (a) 500 hPa and (b) 850 hPa. The lower images are the NCEP GFS IVT Probability > 250 (kg m^{-1} s^{-1}) and IVT vector forecasts valid at 0000 UTC 8 March 2016. The images are the (c) 96 hour forecast (d) 48 hour forecast, and (e) 00 hour forecast respectively. The far right image (f) is the probability image scale.

5. Strong Cold Frontal Passage Case on 7-8 March 2016

Yet again, a negatively-tilted trough was associated with this event (Fig. 4) that a small area of 0.9 or higher likely swept through the area just prior to the 0000 UTC 8 March 2016 valid time. Note a core of 0.99 in the coastal waters to the northwest, not far from the "cold core" portion of the low, has developed. Downed trees were reported with surface winds gusting to around 43 knots (21.5 m s^{-1}) in the Irvine area. The KSOX radar, located at 3106 feet MSL (around 0.95 km) precludes measurement of wind speeds at 2500 feet (0.76 km) MSL or below, but did indicate 40 knot (20 m s^{-1}) winds near the base of the vertical cross section of the winds (not shown) at the lowest angle of the radar beam.

This event was not a "saturated soils" type of event but one resulting from strong winds since less than 0.25 inches of rain had fallen during the day of the event, and less than 0.75 inches fell during the week prior to the event. With 850 hPa winds around 24 knots (12 m s^{-1}) wind gusts could easily surface at this speed, and with the heavier activity, gusts to about 1 ½ times that 850 hPa wind speed [36 knots (18 m s^{-1})] were possible in very strong convection. Since it was gusting to 30 knots or more, this is enough to cause some tree damage and damage to power lines in populated areas. With "only" 25 knot 850 hPa winds, the damage was far more local than the extreme event on 31 January – 1 February 2016 where extensive damage was reported.

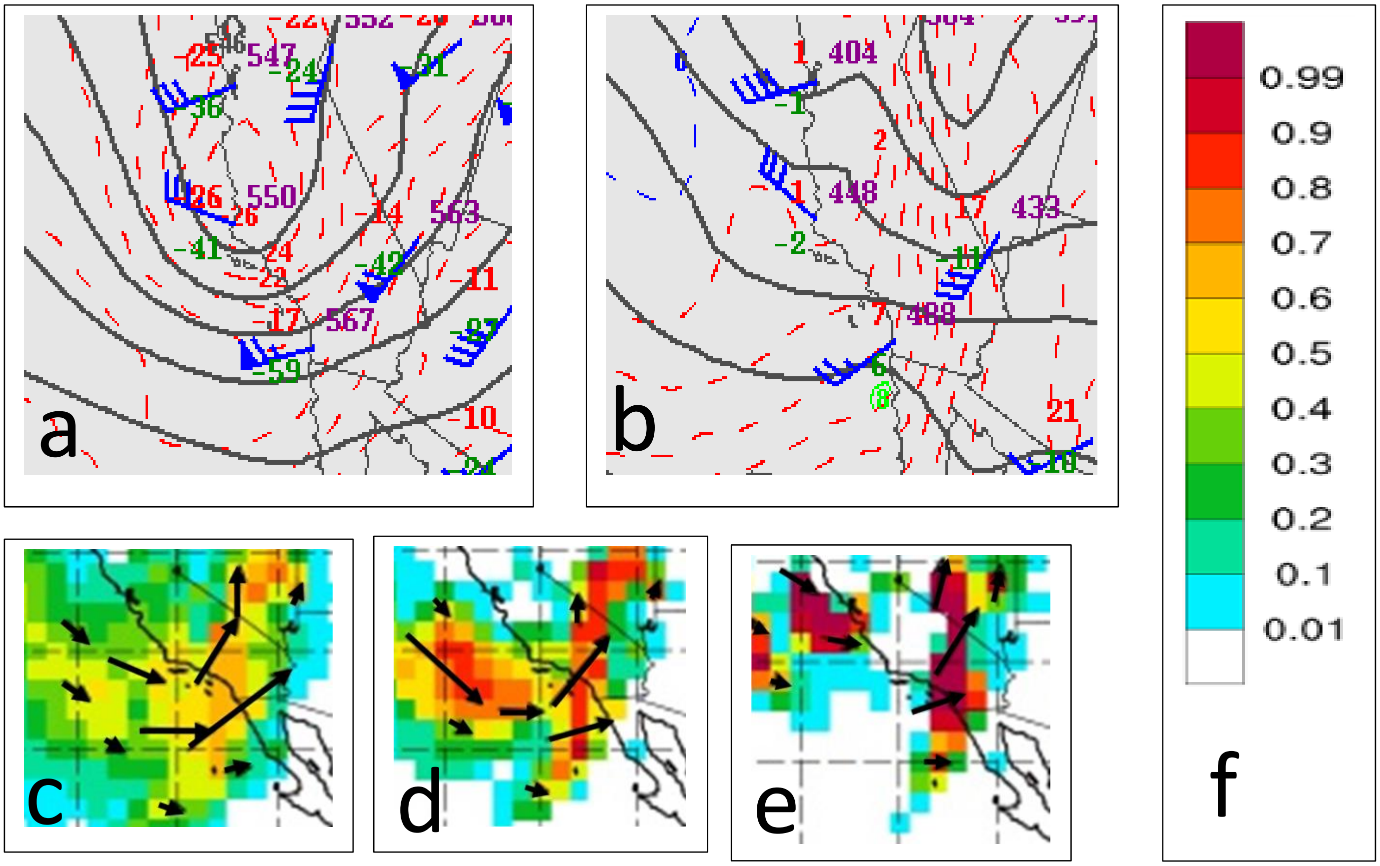

Fig. 5. The upper images are the 0000 UTC 12 March 2016 heights, winds, and temperatures at (a) 500 hPa and (b) 850 hPa. The lower images are the NCEP GFS IVT Probability > 250 (kg m^{-1} s^{-1}) and IVT vector forecasts valid at 0000 UTC 12 March 2016. The images are the (c) 96 hour forecast (d) 48 hour forecast, and (e) 00 hour forecast respectively. The far right image (f) is the probability image scale.

6. Strong Cold Frontal Passage Case on 11-12 March 2016

As was common with strong onshore cases during the 2015-2016 cool season, a negatively-tilted trough was associated with this event (Fig. 5), thus strong dynamic support was available. The 96 hour forecast (Fig. 5) showed modest values, but by the 00 hour forecast, values 0.99 and up in a north-south line dominate the coastal areas. Another core of 0.99 and up values was out over the coastal waters to the northwest. Similar to the 8 March 2016 case, this feature is not far from the “cold core” portion of the low. (Note it was not an obvious feature in the 96 hour forecast).

Seven power poles and associated power lines were down in Riverside. KSOX radar showed 40+ knot winds (20 m s^{-1}), but at around 3000 feet (0.91 km) AGL.

This event was not a “saturated soils” problem but one resulting from strong winds since only about 0.50 inches of rain had fallen just prior to the event and no rainfall for over a month prior to that. With 850 hPa winds around 25 knots (12.5 m s^{-1}) wind gusts could easily surface at this 850 mb speed, and with the heavier convection, gusts to about 1 ½ times the 850 hPa wind speed [37.5 knots (18.8 m s^{-1})] were possible. Since this results in wind gusts of 26 knots (30 mph) or higher, this is enough to cause some tree damage and damage to power lines in populated areas.

7. Summary and Conclusions

Atmospheric rivers with values > 250 kg m^{-1} s^{-1} did develop in Southern California January-May of 2016. Of the seven events detected, 4 events produced wind damage, while 3 events (not shown) did not. Although the dataset is still rather small, some common features with the damaging events are:

1. IVT signatures began to be apparent even out at 96 hours.

2. Negatively-tilted troughs appear to be a common factor

3. Coastal 850 mb winds near 25 knots (12.5 m s^{-1}) or stronger

Among other tools, radar winds around 40 knots (20 m s^{-1}) or stronger about 2500 feet (0.76 km) AGL or lower (AGL closely approximates MSL near the coast) seem to accompany these events. With bowing convective elements, radar winds of only around 35 knots (17.5 m s^{-1}) can be damaging. The 3 events with no strong winds (in contrast to the 4 cases shown above) had radar-interrogated winds at 2500 feet AGL (0.76 km) or lower that were far weaker than 30 knots (15 m s^{-1}). The analysis of the 2 weak cases is not shown above.

As mentioned in Small 2006, with fairly strong cold fronts (and usually south or southwest flow and 850 mb winds at least in the 20-25 knot range), wind gusts of 2 times the upstream 850 hPa wind speed can surface in the windier sites in the mountains.

Occasionally surface wind gusts in the coastal areas are approximately equals the 850 hPa wind speeds, but are generally, but not always, associated with huge frontal systems with heavy rainfall. For the most part, gusts are stronger near the coast than in the valleys west of the mountains during strong onshore flow. For the very strong events (about 30 knots or so at 850 hPa), the coastal wind gusts can be about 1 ½ times the 850 hPa wind speed. This is especially true near the time of frontal passage.

Strong convective elements in the front/baroclinic band can develop into bow echo or strong line segments. They can occasionally “surface” wind gusts equal to 1 ½ times the 850 mb wind speed with lesser 850 hPa wind speeds as a sort of combined ambient flow/convective wind gust. Long lived/steady state convective elements with 50-60 dBZ radar returns are very suspect and may surface such winds.

Radar velocity data (and to an extent, reflectivity data) helps to support the decision making process. When the radar beam height allows viewing of wind speeds at or below 2500 feet AGL (0.76 km AGL) a good estimate of the winds speeds and impacts can be made. This is the case close to the KNKX radar. The KSOX radar located near 3106 feet MSL (0.95 km MSL) can see down to about 2500 feet AGL in the Riverside area to the east, but only down to as low about 3000 feet AGL (0.91 km AGL) to the west, which introduces some difficulties in accurately measuring low level winds in the Irvine area west of the KSOX radar.

Also, as seen in the above examples, if a wind event follows a period of soaking, heavy rains, or if the winds are very strong during the rain event there can be widespread property damage. Many downed trees can occur with moderately strong winds due to saturated soils. Gusts to only 30-40 mph (26-35 knots) can uproot trees in saturated soils. Also power lines are vulnerable to branches falling on them. Sustained winds around 30 mph (26 knots) with gusts 45-50 mph (39-43 knots) at the coastal sites can result in fairly widespread tree damage and power outages due to downed power lines. Wind gusts 50-60 mph (43-51 knots) with locally higher gusts are rather high impact, and power can be out for days along with days of clean-up and recovery.

Air traffic patterns can be reversed (resulting in some airports being “turned around” due to the wind direction), which can reduce the amount of allowable air traffic in and out of the Southern California. Flow near the mountains can result in low level wind shear along with strong up and downdrafts and severe to extreme turbulence.

NCEP GFS IVT Probability > 250 (kg m^{-1} s^{-1}) and IVT vector data shown in these cases point out that this value can result in enough moisture combined with winds for damaging impacts in Southern California.

8. References

Jones, C., F. Fujioka, and L. M. V. Carvalho, 2010: Forecast skill of synoptic conditions associated with Santa Ana winds in Southern California. Mon. Wea. Rev., 138, 4528–4541, http://journals.ametsoc.org/doi/pdf/10.1175/2010MWR3406.1

Ralph, F.M., P.J. Neiman, and G.A. Wick, 2004: Satellite and CALJET aircraft observations of 1997/98. *Mon. Wea. Rev.*, 132, 1721-1745.
http://journals.ametsoc.org/doi/pdf/10.1175/1520-0493%282004%29132%3C1721%3ASACAOO%3E2.0.CO%3B2

Small, I. J., 1995: Santa Ana Winds and the Fire Outbreak of Fall 1993. NOAA Tech. Memo., National Oceanic and Atmospheric Administration, National Weather Service Scientific Services Division, Western Region, 30 pp. [NTIS PB-199520.]
https://docs.lib.noaa.gov/noaa_documents/NWS/NWS_WR/TM_NWS_WR_230.pdf

Small, I.J, 2006: Forecaster's Handbook for Extreme Southwestern California Based On Short Term Climatological Approximations: Part II – Wind Effects on Terrestrial and Marine Environments. NOAA Technical Memorandum NWS WR-278
https://docs.lib.noaa.gov/noaa_documents/NWS/NWS_WR/TM_NWS_WR_278.pdf

Small, I.J., 2016: Atmospheric Rivers and Enhanced Integrated Vapor Transport Episodes: Their Role in Damaging Frontal Passages in Southern California with an Emphasis on Strong Winds. 2016 International Atmospheric Rivers Conference, Scripps Institution of Oceanography, Center for Western Weather and Water Extremes (CW3E), 8-11 August 2016
http://cw3e.ucsd.edu/ARconf2016/Presentations/Wednesday/S2_ImpactsofARs2/Small_IARC2016.pdf

9. Acknowledgements

Thanks to Dr. Jason Cordeira, Plymouth State University, CW3E/Scripps Institution of Oceanography, for the IVT probability data.