of the physical model and assimilation of high density observations with which to reduce the errors. However, they are not fully immune to such issues, and changing data streams over time can introduce inhomogeneities that can be substantial (Kent et al. 2014).

Despite these uncertainties, there is generally good agreement between the various estimates presented here [described more fully in Willett et al. (2013a, 2014a)]. The new MERRA-2 reanalysis (R. Gelaro et al. 2016 unpublished manuscript; Bosilovich et al. 2015) shows better agreement than the previously used MERRA, owing to improved data selection, inclusion of modern data, and model and data assimilation advances. MERRA-2 uses observation-corrected precipitation for forcing the land surface, which helps constrain the near-surface temperature and moisture over land (Reichle and Lui 2015). While the year-to-year variability is similar to the other estimates, there are some deviations around 2002 and 2007–09 (Fig. 2.15). These are thought to be linked to variability in the precipitation forcing at those times. All agree on the most recent period having the highest specific humidity levels on record while also being the most arid in relative humidity terms (Fig. 2.15).

Spatially, specific humidity was anomalously high over much of the land, especially over India and Southeast Asia, which was also common to 1998 and 2010 (Plate 2.1k; Online Figs. S2.10, S2.11). In contrast to 2014, the United States experienced almost entirely above-average specific humidity. Southern Africa was particularly dry. Over oceans, data quality significantly impacts the spatial coverage of the in situ data, meaning that the key El Niño–Southern Oscillation (ENSO) region of the Pacific Ocean is not well observed. ERA-Interim and MERRA-2 show strong moist anomalies there, in good agreement with the other hydrological cycle ECVs and the very warm SSTs (Plate 2.1c, Online Figs. S2.1 to S2.3).

Relative humidity was anomalously low over much of the land (Plate 2.1l; Online Fig. S2.12). Interestingly, some regions, such as southern Africa and Australia, experienced both below-average water vapor amounts (specific humidity) and levels of saturation (relative humidity), while other regions, such as the United States and southern India, experienced above-average water vapor but below-average saturation. The regions of low relative humidity are broadly, but not exactly, consistent with below-average precipitation (Plate 2.1h). Over the oceans there was a strong dipole along the equatorial Pacific with much lower-than-average values to the south. This was slightly farther north than the specific humidity dipole associated with the El Niño warm pool.

2) TotAl column water vapor—C. Mears, S. Ho, J. Wang, H. Holmes, and L. Peng

Total column water vapor (TCWV) rapidly increased during 2015 in response to the 2015/16 El Niño event (Fig. 2.16), with the annual average anomaly lying well above the long-term average. Estimates come from satellitborne microwave radiometers over ocean (Wentz 1997, 2015), COSMIC

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**Fig. 2.15.** Global average surface humidity annual anomalies (base period: 1979–2003). For in situ datasets, 2-m surface humidity is used over land and ~10-m over the oceans. For the reanalysis, 2-m humidity is used across the globe. For ERA-Interim, ocean-only points over open sea are selected and background forecast values are used as opposed to analysis values because of unreliable use of ship data in producing the analysis. All data have been adjusted to have a mean of zero over the common period 1979–2003 to allow direct comparison, with HOAPS given a zero mean over the 1988–2003 period. ERA values over land are from ERA-40 prior to 1979 and ERA-Interim thereafter. [Sources: HadISDH (Willett et al. 2013a, 2014a); HadCRUH (Willett et al. 2008); Dai (Dai 2006); HadCRUHext (Simmons et al. 2010); NOCSv2.0 (Berry and Kent, 2009, 2011); HOAPS (Fennig et al. 2012) and reanalyses as described in Fig. 2.1. Data provide by authors, A. Dai, M. Bosilovich and S. Kobayashi.]
GPS-RO (Global Positioning System–Radio Occultation) over land and ocean (Ho et al. 2010; Teng et al. 2013; Huang et al. 2013), and ground-based GNSS (Global Navigation Satellite System) stations (Wang et al. 2007) over land. The 2015 anomaly map (Plate 2.1o) combines data from satellites over ocean and COSMIC GPS-RO over land with ground-based GNSS stations (Wang et al. 2007) also shown. Most of the tropical Pacific showed a large wet anomaly, which grew to unprecedented size by the end of 2015. Wet anomalies, albeit less pronounced, covered most of the rest of the globe, except for dry anomalies over the Maritime Continent, north of New Zealand, to the south of Greenland, southern Africa, and the Amazon basin. The spatial patterns in TCWV over the ocean (Plate 2.1o) are confirmed by similar features in COSMIC ocean measurements and supported by reanalysis output.

Over the ocean, the TCWV anomaly time series (Fig. 2.16a,b) from reanalysis and microwave radiometers show maxima in 1983/84, 1987/88, 1997/98, 2009/10, and late 2015, each associated with El Niño events. The December 2015 anomaly is the largest recorded for any month, particularly in the satellite radiometer data. This is a result of the large wet anomaly in the tropical Pacific Ocean, coupled with the lack of large dry anomalies across the rest of the world. The radiometer data show a discernible increasing trend over the period. The different reanalysis products show reasonable agreement from the mid-1990s but deviations prior to that, resulting in a range of long-term trends. Minima are apparent in Northern Hemisphere winters during the La Niña events of 1984/85, 1988/89, 1999/2000, 2007/08, and late-2010 to mid-2012. The ocean-only COSMIC data are in general agreement with the reanalysis and radiometer data, but show a sharp peak in early 2012 and a small dip relative to the other data after 2013.

Over land, average anomalies from the ground-based GNSS stations are used in place of the satellite radiometer measurements (Figs. 2.16c,d), providing a record back to 1995, alongside the much shorter COSMIC record. The various reanalysis products, COSMIC, and GNSS are in good agreement throughout the record and all show a subtle increase in TCWV, similar to over ocean.

A land-and-ocean time–latitude plot derived from JRA-55 (Fig. 2.17) indicates that the long-term increase in TCWV is occurring at all latitudes, with less variability outside the tropics. The El Niño events are clear, especially the 1997/98 event. The previous strong El Niño events during 1983/84 and 1997/98 showed pronounced drying in the northern tropics that accompanied moistening on the equator and the southern subtropics. Although similar in strength in terms of sea surface temperature, the TCWV response to the current El Niño does not show this feature (see Sidebar 1.1; Online Fig. S2.13).