Thousands of transiting exoplanets have been discovered, but spectral analysis of their atmospheres has so far been dominated by a small number of exoplanets and data spanning relatively narrow wavelength ranges (such as 1.1–1.7 micrometres). Recent studies show that some hot-Jupiter exoplanets have much weaker water absorption features in their near-infrared spectra than predicted\(^1\)–\(^5\). The low amplitude of water signatures could be explained by very low water abundances\(^6\)–\(^8\), which may be a sign that water was depleted in the protoplanetary disk at the planet’s formation location\(^9\), but it is unclear whether this level of depletion can actually occur. Alternatively, these weak signals could be the result of obscuration by clouds or hazes\(^2\)–\(^4\), as found in some optical spectra\(^2\)–\(^4\),\(^10\),\(^11\). Here we report results from a comparative study of ten hot Jupiters covering the wavelength range 0.3–5 micrometres, which allows us to resolve both the optical scattering and infrared molecular absorption spectroscopically. Our results reveal a diverse group of hot Jupiters that exhibit a continuum from clear to cloudy atmospheres. We find that the difference between the planetary radius measured at optical and infrared wavelengths is an effective metric for distinguishing different atmosphere types. The difference correlates with the spectral strength of water, so that strong water absorption lines are seen in clear-atmosphere planets and the weakest features are associated with clouds and hazes. This result strongly suggests that primordial water depletion during formation is unlikely and that clouds and hazes are the cause of weaker spectral signatures.

We observed the transits of eight hot Jupiters as part of a spectral survey of exoplanet atmospheres with the Hubble Space Telescope (HST). The eight planets covered in our survey (WASP-6b, WASP-12b, WASP-17b, WASP-19b, WASP-31b, WASP-39b, HAT-P-1b and HAT-P-12b) span a large range of planetary temperature, surface gravity, mass and radii, allowing for an exploration of hot-Jupiter atmospheres across a broad range of physical parameters (see Table 1). In this survey, we observed all eight planets in the full optical wavelength range (0.3–1.01 μm) using the Space Telescope Imaging Spectrograph (STIS) instrument. We also used the Wide Field Camera 3 (WFC3) instrument to observe transits of WASP-31b and HAT-P-1b in the near-infrared (1.1–1.7 μm), and used additional WFC3 programmes to observe transits of four other survey targets (WASP-12b, WASP-17b, WASP-19b and HAT-P-12b). The HST survey was complemented by photometric transit observations of all eight targets at 3.6 μm and 5.0 μm by the Spitzer Space Telescope. The resulting transmission spectra are shown in Fig. 1 and exhibit a variety of spectral absorption features due to Na, K and H₂O, as well as strong optical scattering slopes (for example, WASP-6b and HAT-P-12b). Planets such as WASP-39b show prominent alkali absorption lines with pressure-broadened wings, whereas other planets such as WASP-31b show strong but narrow alkali features, which implies that these planets are limited to lower atmospheric pressures. H₂O vapour has been predicted to be an important source of opacity for hot-Jupiter atmospheres\(^17\)–\(^19\), and it is detected in five of the eight exoplanets where WFC3 spectra are available\(^1\),\(^3\),\(^5\),\(^11\). However, the amplitude of the H₂O absorption varies greatly across the ten planets, ranging from features that are very pronounced (as in WASP-19b)\(^14\) to those that are much smaller than expected (HD 209458b)\(^1\) or even absent (WASP-31b)\(^4\).

Previous studies using HST/WFC3 spectra have shown that HD 209458b, HD 189733b and WASP-12b have low-amplitude water features\(^3\),\(^5\), which can be attributed to a severe depletion of atmospheric H₂O abundance relative to solar values\(^6\)–\(^8\). Any such depletion would be a remnant of planet formation, as H₂O is expected to be well mixed in a hot atmosphere, such that currently measured molecular abundances would be consistent with primordial values. The depletion of water vapour can occur beyond a protoplanetary disk’s snow line\(^5\), where water is found predominantly as solid ice. Therefore, a hot Jupiter with a large depletion in H₂O gas would imply that the planet formed at large orbital distances beyond the snow line and

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Table 1 | Physical parameters of hot Jupiters and associated spectral results

| Name      | \( T_{\text{eq}} \) (K) | \( g \) (m s\(^{-2}\)) | \( R_p \) (\( R_J \)) | \( M_p \) (\( M_J \)) | \( P \) (days) | log\( R'_{\text{HK}} \) | \( \Delta Z_{\text{UB}} - \text{LM}/H_{\text{eq}} \) | \( \Delta Z_{\text{J}} - \text{LM}/H_{\text{eq}} \) | H\(_2\)O amplitude (%) | Features | Reference |
|-----------|--------------------------|---------------------------|------------------------|------------------------|----------------|-------------------|--------------------------|------------------------|----------------------|----------|----------|
| WASP-17b  | 1,740                    | 3.6                        | 1.89                   | 0.51                   | 3.73           | -5.531            | -0.80 ± 0.36             | -1.48 ± 0.71           | 94 ± 29              | Na, H\(_2\)O     |          |
| WASP-39b  | 1,120                    | 4.1                        | 1.27                   | 0.28                   | 4.06           | -4.994            | 0.10 ± 0.41             |                       | Na, K                |          |
| HD 209458b| 1,450                    | 9.4                        | 1.36                   | 0.69                   | 3.52           | -4.970            | 0.73 ± 0.36             | -0.49 ± 0.36           | 32 ± 5               | Aer, Na, H\(_2\)O |          |
| WASP-19b  | 2,050                    | 14.2                       | 1.41                   | 1.14                   | 0.79           | -4.660            | 1.04 ± 1.79             | -1.97 ± 1.32           | 105 ± 20              | H\(_2\)O       | 14       |
| HAT-P-1b  | 1,320                    | 7.5                        | 1.32                   | 0.53                   | 4.46           | -4.984            | 2.01 ± 0.81             | 0.19 ± 0.93            | 68 ± 19              | Na, H\(_2\)O     | 12, 13   |
| WASP-31b  | 1,560                    | 4.6                        | 1.55                   | 0.48                   | 3.40           | -5.225            | 2.15 ± 0.77             | 1.25 ± 0.77            | 31 ± 12              | Aer, K       | 4        |
| WASP-12b  | 2,510                    | 11.6                       | 1.73                   | 1.40                   | 1.09           | -5.500            | 3.76 ± 1.59             | 1.65 ± 1.47            | 38 ± 34              | Aer         | 3        |
| HAT-P-12b | 960                      | 5.6                        | 0.96                   | 0.21                   | 3.21           | -5.104            | 4.14 ± 0.77             | 1.37 ± 0.79            | 17 ± 23              | Aer, K       | 4        |
| HD 189733b| 1,200                    | 21.4                       | 1.14                   | 1.14                   | 2.22           | -4.501            | 5.52 ± 0.50             | -0.56 ± 0.50           | 53.6 ± 9.6           | Na, H\(_2\)O     | 5, 10     |
| WASP-6b   | 1,150                    | 8.7                        | 1.22                   | 0.50                   | 3.36           | -4.741            | 8.49 ± 1.33             |                       |                     | Aer, K       | 11       |

The listed physical parameters are based on data compiled from our HST and Spitzer results\(^{3,4,10–14}\) and online databases. Sources for published spectral results are also listed. Atmospheric features detected of cloud or haze aerosols, sodium, potassium and water are listed (Aer, Na, K and H\(_2\)O, respectively). The equilibrium temperature \( T_{\text{eq}} \) assumes zero albedo and uniform redistribution. Also listed are the surface gravity, \( g \); radius of the planet, \( R_p \); planet mass, \( M_p \); orbital period, \( P \); and Ca \(_{\text{II}}\) H and K stellar activity index log\( R'_{\text{HK}} \). \( R_J \) is the radius of Jupiter and \( M_J \) is the mass of Jupiter. \( \Delta Z_{\text{UB}} - \text{LM}/H_{\text{eq}} \) gives the difference in pressure scale heights between the optical and mid-infrared transmission spectra, while \( \Delta Z_{\text{J}} - \text{LM}/H_{\text{eq}} \) is the difference between the near- and mid-infrared (see Methods). The atmospheric scale height, \( H_{\text{eq}} = kT_{\text{eq}}/\mu g \), is estimated using the planet-specific equilibrium temperature and assuming a H/He atmosphere with a mean molecular mass of \( \mu = 2.3 \) atomic mass units. The H\(_2\)O amplitude is measured using the WFC3 data, taking the average radii from 1.34 \( \mu \)m to 1.49 \( \mu \)m and subtracting it from the average value between 1.22 \( \mu \)m to 1.33 \( \mu \)m, then dividing that value by the theoretical difference as calculated by models\(^{16}\) assuming clear atmospheres and solar abundances.

Figure 1 | HST/Spitzer transmission spectral sequence of hot-Jupiter survey targets. Solid coloured lines show fitted atmospheric models with prominent spectral features indicated. The spectra have been offset, ordered by values of \( \Delta Z_{\text{UB}} - \text{LM} \) (the altitude difference between the blue-optical and mid-infrared; Table 1). Horizontal and vertical error bars indicate the wavelength spectral bin and 1\( \sigma \) measurement uncertainties, respectively. Planets with predominantly clear atmospheres (top) show prominent alkali and H\(_2\)O absorption, with infrared radii values commensurate with or higher than the optical altitudes. Very hazy and cloudy planets (bottom) have strong optical scattering slopes, narrow alkali lines and H\(_2\)O absorption that is partially or completely obscured.
HD 189733b based on Galileo probe measurements that indicate it to indicate the pressures probed in transmission.

which is strongest at blue-optical (0.3–0.57 μm) wavelengths, to that yields a Rayleigh-scattering-like opacity, which could be due to small (sub-micrometre size) particles. Silicate or higher-temperature cloud condensates are expected to dominate the hotter atmospheres, like those observed for brown dwarfs, while in cooler atmospheres sulfur-bearing compounds are expected to play an important part in the condensation chemistry. In Fig. 2, we plot model atmospheric pressure–temperature profiles for the planets in our comparative study and compare them to the condensation curves for the expected cloud-forming molecules. The base, or bottom, of a condensate cloud is expected to form where the planetary pressure–temperature profile crosses the condensation curve; in this case, Cr, MnS, MgSiO₃, MgSiO₄ and Fe are possible condensates. For example, the spectra of WASP-31b shows clouds, which probably form at pressures of about 10 mbar and can be explained by Fe or MgSiO₃ condensates. However, the curves alone cannot explain cloudy versus cloud-free planets, because hazy planets such as HAT-P-12b and WASP-12b do not cross condensation curves at observable pressures. Therefore, atmospheric circulation must also play a part, as vertical mixing allows for particles to be lofted and maintained at pressures probed in transmission at the terminators. Additionally, equatorial eastward superrotation arising from day–night temperature variations can allow clouds that form on the nightside to be transported to the terminator.

We compare spectral features from our large survey to both analytic spectral-transfer models assuming varying degrees of clouds and hazes. In order to evaluate the spectral behaviour of the sample as a whole, we define and measure three broadband spectral indices, which can then be compared to both the observational data and the theoretical models (see Table 1 and Methods). We first define an index ΔZUB–LM that compares the relative strength of scattering, which is strongest at blue-optical (0.3–0.57 μm) wavelengths, to that of molecular absorption, which is strongest at mid-infrared (3–5 μm) wavelengths and dominated by H₂O, CO and CH₄. We also define ΔZJ–LM to measure the relative strength between the near-infrared continuum (1.22–1.33 μm, located between strong H₂O absorption bandsheads) and the mid-infrared molecular absorption. Lastly, we quantify the amplitude of the H₂O absorption feature seen in the WFC3 data, calculating the ratio of the observed feature to that of radiative transfer models assuming clear atmospheres and solar abundances.

Comparisons between these indices (Fig. 3, Extended Data Figs 1 and 2) show trends between cloudy and cloud-free planets. When comparing the ΔZJ–LM index to the H₂O amplitude (Fig. 3), the hot-Jupiter transmission spectra strongly favour models in which the H₂O amplitude is lower owing to obscuration by hazes and clouds, rather than to lower abundances (5.9σ significance). Contaminating effects of persistent unocculted star spots and plages have been proposed in order to mimic the optical haze-scattering signature of hot Jupiters (particularly HD 189733b, which orbits an active star; see Methods). However, our survey sample is sufficiently varied in stellar activity, such that we find no correlation between stellar activity and the strength of the optical scattering slope (as measured by the ΔZUB–LM index) for planets in our sample (Extended Data Fig. 3). One of the main distinguishing features between hazy atmospheres and those that are clear and have sub-solar abundances resides in the near-infrared continuum, measured with the WFC3 spectra. The presence of haze raises the level of the near-infrared continuum relative to the mid-infrared continuum, leading to high ΔZJ–LM index values with low near-infrared H₂O amplitudes (Extended Data Fig. 4). In clear-atmosphere models, where the abundances are lower, the continuum level drops at both near- and mid-infrared wavelengths, accompanied by a reduction in the amplitude of absorption features, resulting in ΔZJ–LM index values that are too low to explain the data (Fig. 3).

The hot-Jupiter transmission spectra ordered by the ΔZUB–LM spectral index reveals a continuum from clear atmospheres to atmospheres with strong clouds and hazes (Fig. 1 and Table 1). The presence of clouds has also been inferred for brown dwarf atmospheres, which
have similar temperatures to hot Jupiters\(^9\). Although there is a well-defined sequence from the warmer, cloudy L-dwarfs to the cooler, clear T-dwarfs\(^26,30\), hot Jupiters do not exhibit a strong relationship of temperature to cloud formation, given that both cloudy and not cloudy planets appear throughout the entire 1,000–2,500 K temperature range (Fig. 2).

We suggest that the difference between hot Jupiters and brown dwarfs is due to the vertical temperature structure of hot-Jupiter atmospheres. Hot Jupiters have very much steeper pressure–temperature profiles compared to isolated brown dwarfs, owing to the strong incident stellar flux heating the top of the planetary atmosphere (see Extended Data Fig. 5). Since cloud condensation curves run nearly parallel to hot-Jupiter profiles, a relatively small temperature shift (about 100 K) could easily move a cloud base by a factor of tens or hundreds in pressure, in or out of the visible atmosphere. In comparison, because brown dwarfs have shallow pressure–temperature profiles, clouds will form in the visible atmosphere across a very wide temperature range. Furthermore, the expected nearly isothermal region of a hot-Jupiter profile at pressures from about 1 bar to 100 bar may cause some planets, but not others, to have cloud materials cold-trapped at depth, out of the visible atmosphere. Given this temperature sensitivity, the role of clouds in hot Jupiters may appear almost stochastic from planet to planet. In addition, hot Jupiters have a wider range of gravities and metallicities, both of which will affect the planet’s atmospheric temperature structure, circulation and condensate formation.

Future studies will benefit greatly from broad atmospheric surveys that can further distinguish between clear and cloudy exoplanets. If the \(\Delta Z_{UB} - \Delta Z_{LM} \) and \(H_2O\) indices can be measured in advance of such surveys, planets with clear atmospheres can be identified and studied in greater detail, allowing reliable chemical abundances to be measured and thus providing valuable constraints on formation models.

**Online Content** Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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METHODS

HST observations. The overall observational strategy is similar for each of the eight targets in the Large HST programme (GO-12473; principal investigator D.K.S.), which have been presented for WASP-1b14, HAT-P-1b12,13, WASP-12b, WASP-31b and WASP-6b11 with the details summarized here and applied to the remaining targets HAT-P-12b, WASP-17b and WASP-39b. We observed two transits of each target with the STIS G430L grating, and one with the STIS G750L. The G430L and G750L data sets contain typically 43 to 53 spectra, which span either both 530–1,040 and 1,040–2,550 Å. Each observation lasts 52 s on average with a wide 52 × 2 arcsec slit to minimize slit light losses. Both gratings have resolutions of R = λ/Δλ = 530–1,040 (∼2 pixels is 5.5 Å for G430L and ∼2 pixels is 9.8 Å for G750L). The G430L grating covers the wavelength range from 2,900 Å to 5,700 Å, while the G750L grating covers 5,240 Å to 10,270 Å. The visits of HST were scheduled such that the third and/or fourth spacecraft orbits contain the transit, providing good coverage between second and third contact, as well as an out-of-transit baseline time series before and after the transit. Exposure times of 279 s were used in conjunction with a 128-pixel-wide sub-array, which reduces the readout time between exposures to 21 s, providing a 93% overall duty cycle.

The STIS data set was pipeline-reduced with the latest version of CALSTIS, and cleaned for cosmic ray detections with a customized procedure11. The G750L data set was dereddened using contemporaneous fringe flats. The spectral aperture extraction was done with IRAF, using a 13-pixel-wide aperture with no background subtraction, which minimizes the out-of-transit standard deviation of the white-light curves. The extracted spectra were then Doppler-corrected to a common rest frame through cross-correlation, which helped remove sub-pixel wavelength shifts in the dispersion direction. The STIS spectra were then used to create both a white-light photometric time series and custom wavelength bands covering the spectra, integrating the appropriate wavelength flux from each exposure for different bandpasses.

Observations of HAT-P-1b and WASP-31b were also conducted in the infrared with the HST WFC3 instrument as part of GO-12473 and are detailed in refs 4 and 13. The observations use the infrared G141 grism in forward spatial scan mode over five HST orbits. Spatial scanning is done by slewing the telescope in the cross-dispersion direction during integration in a similar manner for each exposure, which increases the duty cycle and greatly increases the counts obtained per exposure. We used the ‘ima’ outputs from the CALWFC3 pipeline, which performs reference pixel subtraction, zero-read and dark current subtraction, and a nonlinearity correction. For the spectral extraction, we trimmed a wide box around each spectral image, with the spectra extracted using custom routines from the programming language IDL, similar to IRAF’s procedure from the APALL program. The aperture width was determined by minimizing the standard deviation of the fitted white-light curve. The aperture was traced around a computed centring profile, which was found to be consistent in the y axis with an error of <0.1 pixels. Background subtraction was applied using a clean region of the untrammed image. For wavelength calibration, direct images were taken in the F139M narrow-band filter at the beginning of the observations. We assumed that all pixels in the same column have the same effective wavelength, as the spatial scan varied in the -axis direction by less than one pixel, resulting in a spatial range from 1.1 μm to 1.7 μm. This wavelength range was later restricted to avoid the strongly sloped edges of the grism response, which results in much lower signal-to-noise light curves.

For the comparative study, we also included the WFC3 observations for WASP-1b14, HD 209458b1, HAT-P-1b12 and WASP-17b13 (GO-12181; principal investigator D.D.). The WFC3 observations of WASP-12b14 were also included (GO-12230; principal investigator M. Swain), as was HD 189733b12 (GO-12881; principal investigator P. R. McCullough). The WFC3 observations of WASP-12b, WASP-17b, WASP-19b and HAT-P-12b were observed in stare mode, rather than with spatial scanning, and therefore have generally poorer overall photometric precision. See Table 1 for a list of all observations with a wide 52 × 2 arcsec slit and any measured systematic errors correlated in time (‘red noise’), thus taking into account any underestimated errors calculated by the reduction pipeline in the data points. The uncertainties on the fitted parameters were calculated using the covariance matrix from the Levenberg–Marquardt algorithm, which assumes that the probability space around the best-fitting solution is well described by a multivariate Gaussian distribution and equivalent results were found when using an Markov Chain Monte Carlo analysis36. Inspection of the two-dimensional probability distributions from both methods indicated that there were no significant correlations between the planet-to-star radius contrasts and systematic trend parameters. In an additional analysis step compared to our previous results4,11,12, we also marginalized over the systematic models37 for the spectra of WASP-17b, WASP-39b, HAT-P-1b, HAT-P-12b and HD 209458b. Under this approach, we effectively averaged the results obtained from a suite of systems models in a coherent manner. For each systematic model used to correct the data, we calculated the evidence of fit, which is then used to apply a weight to the parameter of interest (Rstar/Rp) measured using that model. In doing so, we marginalized over our uncertainty as to which model is actually the ‘correct’ model. For the STIS data we included all combinations of factors up to the 4th order in both HST phase, 3rd order in detector positions x and y, 3rd order in wavelength shift, and 1st order in time. For the WFC3 data, our grid of parameterized models includes all combinations of factors up to the fourth order in both HST phase, to correct for ‘HST breathing’ effects, and up to the fourth order in wavelength shift, in addition to the visit-long linear trend. In addition, we also included exponential HST phase models, with a linear and squared planetary phase trend. For the Spitzer data, we included all combinations of the x and y positions of the stellar point spread function (PSF) in the detector, cross-products of x × y and x × y up to a second-order. We note that the best-fitting systematic models for HST and Spitzer are generally well constrained and the marginalized results were very similar to those based on model selection by the Bayesian Information Criteria38. For HD 209458b, lightcurve analyses and marginalization were performed using Gaussian process models39. Owing to the flexibility of Gaussian process models, a broad range of systematics behaviours can be captured without the need to provide an explicit functional form. The results of a single Gaussian process model are thus comparable to marginalizing over many simpler parametric systematics models, as was done for the other lightcurves40.

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Atmospheric models. To create synthetic spectra12,39 used for this study include isothermal models as well as those with a self-consistent treatment of radiative transfer and chemical equilibrium of neutral and ionic species. Chemical mixing ratios and opacities were calculated assuming local thermochromial equilibrium accounting for condensation and thermal ionization but not photoionization40–43, for both solar metallicity and sub-solar metallicity abundances.
A simplified treatment adding in small aerosol haze particles was performed by including a Rayleigh scattering opacity (that is, \( \sigma = \sigma_0(\lambda/\lambda_0)^{-4} \)) that had a cross-section which was \( 10 \times \), \( 100 \times \) and \( 1,000 \times \) the cross-section of molecular hydrogen gas (\( \sigma_0 = 5.31 \times 10^{-27} \text{cm}^2 \)) at \( \lambda_0 = 350 \text{nm} \); ref. 44). Similarly, to include the effects of a flat cloud deck we included a wavelength-independent cross-section, which was \( 1 \times \), \( 10 \times \) and \( 100 \times \) the cross-section of molecular hydrogen gas at 350 m (see Extended Data Fig. 4).

**Transmission spectral indices.** To enable a direct comparison between planets, the transmission spectra have been plotted on a common scale by dividing the measured wavelength-dependent altitude of the transmission spectra, \( \Delta Z(\lambda) \), by the planet’s atmospheric scale height \( (H_\text{LM}, \text{vertical distance over which the gas pressure drops by a factor of } e) \) estimated using the equilibrium temperature. The analytical relation for the wavelength-dependent transit-measured altitude \( \Delta Z(\lambda) \) of a hydrostatic atmosphere is:

\[
\Delta Z(\lambda) = \Delta Z(\lambda') = H \ln\left( \frac{\alpha}{\alpha'} \right)
\]

where \( \alpha \) is the abundance of the absorbing or scattering species, \( P \) is the pressure at a reference altitude, \( \sigma(\lambda) \) is the wavelength-dependent cross-section, \( \tau \) is the optical thickness at the effective transit-measured radius, \( k \) is Boltzmann’s constant, \( T \) is the local gas temperature, \( \mu \) is the mean mass of the atmospheric particles, \( g \) is the planetary surface gravity, \( R_p \) is the planetary radius, and \( H = k T g \) is the atmospheric pressure scale height. The altitude difference measured between two wavelength regions (\( \lambda' \) and \( \lambda \)) in a transmission spectrum is proportional to the quantity:

\[
\Delta Z(\lambda) - \Delta Z(\lambda') = H \ln\left( \frac{\alpha}{\alpha'} \right)
\]

Thus, the quantity \( \Delta Z(\lambda) - \Delta Z(\lambda') \) is related to the ratio of the total absorption plus scattering of the atoms and molecules between the wavelength regions \( \lambda \) and \( \lambda' \), and we use the quantity \( \Delta Z(\lambda) - \Delta Z(\lambda') = H \ln(\alpha/\alpha') \) as a metric to intercompare the atmospheric extinction for the different planets in our survey. Note that the temperature and scale height of the upper atmosphere can differ from the equilibrium value, especially at high altitudes where hot upper layers in hot Jupiters have been found.

We defined indices around three main wavelength regions (see Table 1). We used a blue-optical band consisting of the G430L grating, which is sensitive between 0.3–1.14 µm and roughly covers the Johnson U and B photometric bands. This wavelength region is almost always exclusively dominated by scattering for clear, cloudy and hazy exoplanets (see Extended Data Fig. 4). The second is a near-infrared band between 1.22–1.65 µm, which has overlap with the Johnson J photometric band, and is located between the strong H₂O absorption bands centred around 1.15–1.45 µm. This wavelength region is sensitive to scattering in hazy, cloudy and highly sub-solar models and the H₂O continuum in clear atmospheres with abundances near solar (see Extended Data Fig. 4). We also used a third wavelength region in the mid-infrared between 3–5 µm, which overlaps with the Johnson L and M photometric bands and consists of the two Spitzer IRAC photometric channels 1 and 2. This wavelength region is highly sensitive to strong H₂O, CO and CH₄ absorption bands, which are the main active molecular species expected in hot Jupiters and, only sensitive to scattering in the cloudiest cases, making it an overall effective measure of the total molecular extinction (see Extended Data Fig. 4).

From the data, \( \Delta Z(\lambda, \text{LM}) \) was measured taking the difference between the planet radius measured in the blue-optical HST data using the G430L grating (UB, wavelengths 0.3–0.57 µm) and the weighted-average value of the radii measured in Spitzer IRAC photometric channels 1 and 2 (LM, wavelengths 3–5.3 µm). \( \Delta Z(\lambda, \text{LM}) \) was measured similarly, although using the near-infrared WFC3 data (J, wavelengths 1.22–1.33 µm).

In addition, we also measured the amplitude of the near-infrared H₂O absorption band using the WFC3 spectra (see Table 1), measuring the average radii in a band containing strong H₂O absorption (between 1.34–1.49 µm) compared to an adjacent band between strong H₂O features (1.22–1.33 µm). The measured H₂O amplitude for each exoplanet was then divided by the value predicted by atmospheric models calculated for each planet using a planet-averaged temperature–pressure profile assuming clear atmospheres and solar abundances.

From Fig. 3, a likely inverse correlation is seen between the H₂O amplitude and the \( \Delta Z(\lambda, \text{LM}) \) index, with the Spearman rank correlation coefficient measured to be –0.76 which has a false alarm probability of 2.8%. We note that this false alarm probability is not the probability that the water depletion scenario is correct, as that is excluded with Fig. 3 to a much higher degree (5.9% significance). A much weaker inverse correlation of –0.48 is found with \( \Delta Z(\lambda, \text{LM}) \) in Extended Data Fig. 2, although that has a high false alarm probability of 23%.

**Stellar activity.** As stellar activity can affect the measurement of a transmission spectrum, we photometrically monitored the activity levels of our target stars with the Cerro Tololo Inter-American Observatory (CTIO) 1.3–m telescope for the southern targets and the Tennessee State University Celestron 14-inch (C14) Automated Imaging Telescope (AIT) located at Fairborn Observatory in Arizona for the northern targets. All of our targets showed low levels of stellar activity, with observed photometric variations or upper limits which are sufficiently small that their effects on measuring the transmission spectra are minimal compared to the measurement errors. The two most active stars in the survey, WASP-19A and HD 189733A, were corrected for occulted and un-occulted star spots.

As no contemporaneous photometric monitoring of WASP-19A is available for the July 2011 WFC3 spectra from ref. 14, we corrected the spectra to the spot-correlated transit depth of \( R_p/R = 0.14019 \pm 0.00073 \) as measured using HST on 12 June 2014 from GO-13431 (principal investigator C. M. Huitson), which had simultaneous CTIO activity monitoring. We also normalized the differential transit depths of the WFC3 spectra to a transit depth value consistent with ref. 10, which has a uniform treatment between the HST and Spitzer data sets of system parameters, limb-darkening and activity correction.

As effects of stellar activity could potentially mimic an optical scattering slope in a transmission spectrum, we searched for a relationship between the activity levels of the stars in our survey and the presence of a strong optical slope. If stellar activity were the main cause of the enhanced optical slopes, rather than scattering by hazes or clouds, then it is expected that highly active stars would have higher levels of spots and plages, and should show preferentially larger transmission spectral slopes. As an additional measure of stellar activity, we used the strength of the Ca ii H and K emission lines as a stellar activity indicator \( (\log R' \text{HK}) \), as measured by Keck HIRES; see Table 1. We searched for a correlation with the chromospheric activity index \( \log R' \text{HK} \) as it is correlated with the stellar photometric variability and can be used to quantify stars with low activity levels, for which the photometric variations would be undetectable. We found no significant correlation with \( \log R' \text{HK} \) activity and either the presence of haze or the strength of optical transmission spectral slopes, as measured with the \( \Delta Z(\lambda, \text{LM}) \) index (Extended Data Fig. 3). This suggests that the effects of stellar activity are not the overall cause of the strong optical slopes seen in some of the transmission spectra.

There are also other indications that stellar activity does not have a dominant role. For one, while changing stellar activity levels should have an effect on the transmission spectra, no significant variations were seen between the three epochs of the HST STIS spectra, which has an overlapping wavelength region, for all of our targets, including active stars. In addition, the atmospheric temperature can be derived by measuring the transmission spectral slope in an atmosphere dominated by Rayleigh scattering and, the temperatures found fitting a Rayleigh scattering slope for HD 189733B, HAT-P-12B and WASP-6b (1.340 ± 150 K, 1.010 ± 80 K and 973 ± 144 K, respectively) are in good agreement with the planetary temperatures expected (1,196 K, 958 K and 1,185 K, respectively). This agreement is consistent with the atmospheric temperature, rather than stellar activity, being probed by the scattering haze. For these three stars, where HAT-P-12 has a much lower activity than the other two, the individual activity levels would have to be finely tuned for the spectral slopes to mimic the planetary temperatures.

In addition to condensation chemistry, hazes can also form through photochemical processes resulting in hydrocarbon aerosols. This process is more effective for cooler exoplanets and the incident stellar ultraviolet irradiation also plays an important factor in hydrocarbon formation. Our results indicate no correlation with the presence of haze to either the atmospheric temperature or levels of ultraviolet irradiation (as traced by stellar activity indicators), which generally favours condensation chemistry over photochemical processes as the general source of the observed hazes and clouds.

**Code availability.** We have opted not to make the customized IDL codes used to produce the spectra publicly available owing to their undocumented intricacies.

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Extended Data Figure 1 | ΔZ\textsubscript{J-LM} versus ΔZ\textsubscript{UB-LM}. Black points show the altitude difference between the near-infrared (near-IR) and the mid-infrared (mid-IR) spectral features (ΔZ\textsubscript{J-LM}) versus the difference between the blue-optical and mid-infrared (ΔZ\textsubscript{UB-LM}, see Table 1). Error bars represent the 1σ measurement uncertainties. Purple and grey lines show model trends for hazy and cloud atmospheres, respectively, with increasing Rayleigh scattering haze and grey cloud deck opacity corresponding to 10×, 100× and 1,000× solar. We also show clear-atmosphere models with sub-solar abundances of 0.1×, 0.01× and 0.001× solar (red line).
Extended Data Figure 2 | $\Delta Z_{UB-LM}$ index versus H$_2$O amplitude.

Black points show the altitude difference between the blue-optical and mid-infrared (mid-IR) spectral features ($\Delta Z_{UB-LM}$) versus the amplitude of the 1.4-$\mu$m H$_2$O absorption spectral feature (see Table 1). Error bars represent the 1σ measurement uncertainties. Purple and grey lines show model trends for hazy and cloudy atmospheres, respectively, with increasing Rayleigh scattering haze and grey cloud deck opacity corresponding to $10 \times$, $100 \times$ and $1,000 \times$ solar. We also show clear-atmosphere models with sub-solar abundances of $0.1 \times$, $0.01 \times$ and $0.001 \times$ solar (red line).
Extended Data Figure 3 | Stellar activity (log $R_{\text{HK}}'$) versus $\Delta Z_{\text{UB-LM}}$ index. Exoplanets with strong haze signatures have prominent optical slopes with $\Delta Z_{\text{UB-LM}}$ values above 3, while clear atmospheres have $\Delta Z_{\text{UB-LM}}$ indices near zero. The datapoint colours correspond to those in Fig. 1. The red solid line shows the linear regression between the two indices, with 1$\sigma$ uncertainties (red dashed lines).
Extended Data Figure 4 | Theoretical model transmission spectra. Model spectra\textsuperscript{17,39} assume a 1,200-K hot Jupiter with a surface gravity of 25 m s\textsuperscript{−2}. Spectra in each panel are compared to a clear, solar-metallicity atmosphere (black line). a, Purple spectra have an added Rayleigh scattering haze corresponding to metallicities of 100× and 1,000× solar. b, Blue and grey spectra have an added grey cloud deck corresponding to 1× and 10× solar. c, Red and green spectra show clear atmospheres with sub-solar abundances of 0.01× and 0.001× solar.
Extended Data Figure 5 | Brown dwarf and hot Jupiter pressure–temperature profiles and condensation curves. Similar to Fig. 2, but alongside the ten hot-Jupiter pressure–temperature profiles we plot the profile of an 1,800-K brown dwarf (green line). The thicker portions of the lines indicate the pressures probed in transmission for the hot Jupiters (plotted in greyscale) and the visible photosphere for the brown dwarf (0.1–10 bar). While a shift in the pressure–temperature profile of a hot Jupiter to hotter and cooler temperatures could dramatically change which condensates may be found in the visible atmosphere, the same would not be true for much shallower brown dwarf pressure–temperature profiles.
| Planet      | V mag. | Optical HST STIS, ACS 0.3 – 1 μm grating, Date (UT) | near-IR HST WFC3 1.1 – 1.7 μm grism, Date (UT) | mid-IR Spitzer IRAC 3 – 5.2 μm band, Date (UT) |
|------------|--------|---------------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| HAT-P-1b   | 9.87   | G430L, 2012/05/26 G750L, 2012/05/30 G430L, 2012/09/19 | G141, 2012/07/05                              | 3.6, 2013/09/11 4.5, 2013/09/20               |
| WASP-6b    | 11.91  | G430L, 2012/06/10 G430L, 2012/06/16 G750L, 2012/07/23 | —                                              | 4.5, 2013/01/14 3.6, 2013/01/21               |
| WASP-12b   | 11.57  | G430L, 2012/03/14 G430L, 2012/03/27 G750L, 2012/09/09 | G141, 2011/04/12                              | 3.6, 2010/11/17 4.5, 2010/12/11               |
| WASP-31b   | 11.98  | G430L, 2012/06/13 G430L, 2012/06/26 G750L, 2012/07/10 | G141, 2012/05/13                              | 3.6, 2013/09/13 4.5, 2013/03/19               |
| HAT-P-12b  | 12.84  | G430L, 2012/04/11 G430L, 2012/04/30 G750L, 2013/02/04 | G141, 2011/05/29                              | 3.6, 2013/03/08 4.5, 2013/03/11               |
| WASP-19b   | 12.59  | G430L, 2012/04/30 G430L, 2012/05/04 G750L, 2012/05/09 | G141, 2011/07/01 G141, 2014/06/12             | 3.6, 2011/08/03 4.5, 2011/08/13               |
| WASP-39b   | 12.09  | G430L, 2013/02/08 G430L, 2013/02/12 G750L, 2013/03/17 | —                                              | 3.6, 2013/04/18 4.5, 2013/10/10               |
| WASP-17b   | 11.83  | G430L, 2012/06/08 G430L, 2013/03/15 G750L, 2013/03/19 | G141, 2011/07/08                              | 4.5, 2013/05/10 3.6, 2013/05/14               |
| HD 209458b | 7.63   | G430L, 2003/05/03 G750L, 2003/05/31 G430L, 2003/06/25 G750L, 2003/07/05 G750M, 2000/04/25 G750M, 2000/04/28 G750M, 2000/05/05 G750M, 2000/05/12 | G141, 2012/09/25                              | 3.6, 2007/12/31 3.6, 2008/07/19 3.6, 2011/01/14 3.6, 2014/01/19 4.5, 2008/07/22 4.5, 2010/01/19 |
| HD 189733b | 7.648  | G800L, 2006/05/22 G800L, 2006/05/26 G800L, 2006/07/14 G430L, 2009/11/20 G430L, 2010/05/18 G750M, 2009/10/30 G750M, 2009/11/13 G750M, 2010/09/30 G750M, 2010/11/29 | G141, 2013/06/05                              | 3.6, 2007/11/25 3.6, 2006/10/30 3.6, 2010/12/29 4.5, 2007/11/22 4.5, 2009/12/23 |

Transit observations using the Hubble and Spitzer Space Telescopes. Dates are given in universal time (UT) listed along with the instruments and wavelength ranges used.