MARINE STRATUS AND FOG - BOUNDARY LAYER MIXING AND A WATER DROPLET SINK.

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A simple 1-D RANS model of the time evolution of the Planetary Boundary Layer is extended to include water vapor and cloud droplets plus transfers between them. Radiative fluxes and flux divergence are also included. An underlying ocean surface is treated as a source of water vapor, and as a sink for cloud or fog droplets. With a constant sea surface temperature and a steady wind, initially dry or relatively dry air will moisten, starting at the surface. **Turbulent boundary layer mixing will then lead towards a layer with well-mixed potential temperature (and so temperature decreasing with height) and well mixed water vapor mixing ratio. As a result the air will, sooner or later, become saturated at some level and stratus cloud will form.** If that air is later advected over colder water the air will cool and the base of the stratus cloud will lower. Fog may then extend down to the surface.

The liquid water mixing ratio is essentially zero at the surface but will increase with height to a maximum, typically in the lowest 100- 500 m height range, depending on conditions. Relative humidity is 100% throughout this layer and is what is typically observed, e.g. by G.I. Taylor in 1915. There are however no published observations that we know of, that provide the variations of liquid water mixing ratio with height in marine fog. I am hoping that analysis of data from the 2022 FATIMA program may provide these critical measurements.

Terrestrial vs Marine fog

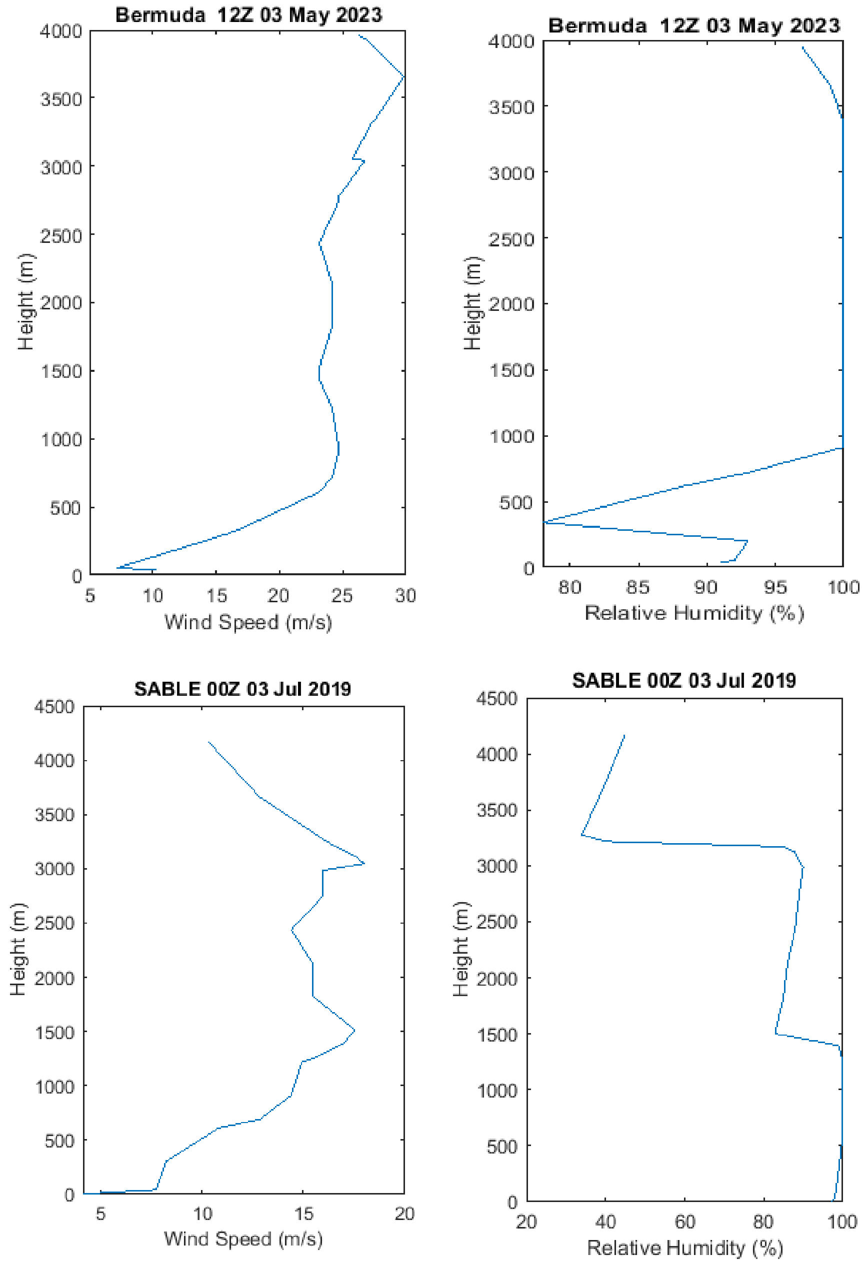
- Fog on land
- Mostly radiation fog, nocturnal cooling of land surfaces,
- Often light winds, stable stratification. May be drainage flows taking cold air to lower locations.
- Advection effects – uphill winds leading to adiabatic cooling.
- Onshore advection of marine fog in coastal areas.

- Marine fog
- Surface radiation effects small – low diurnal temperature variation.
- Fog often in moderate-strong winds. Stratus lowering may occur
- Advection effects – warm moist air advected over colder sea surface., e.g. N. Atlantic Gulf stream and Labrador current.
- Yellow Sea, tidal mixing cools coastal waters

Some ideas:

In a steady, well mixed boundary layer above a water surface, potential temperature (θ) and water vapour mixing ratio (q) should, over time, become equal to surface values. The atmospheric boundary layer over the ocean is often capped by stable stratification above 1-2 km, and winds can be strong (of order 40 kt). See sample profiles from Bermuda and Sable Island.

With $\theta(z) \approx \theta(0)$, we expect $T(z) \approx T(0) - \Gamma z$, and as a result the saturation vapour pressure and saturation mixing ratio will decrease with z so that upward mixing of water vapour will lead to condensation at some level. Since we are assuming saturation at the water surface we might expect this to start as a surface based cloud, but we are also assuming that the water surface is a sink for water droplets, and also that there will be some gravitational settling of water droplets. There may be 100% Relative Humidity (RH) in the lower layers of the boundary layer but the liquid water mixing ratio (ql) will be small and is assumed 0 at z = 0. Katata (2008, 2014) used similar ideas about droplet deposition over vegetation and forests.



Our 1-D PBL model: ON MODELLING THE ONE-DIMENSIONAL ATMOSPHERIC BOUNDARY LAYER, WENSONG WENG and PETER A. TAYLOR, *Boundary-Layer Meteorology* **107:** 371–400, 2003.

In an idealized, horizontally homogeneous ABL and in the **absence of radiative flux divergence and moisture**, the Reynolds averaged equations (RANS) describing the dynamics of the ABL can be written as below. **We have added water vapour, liquid water, radiative fluxes …..**

$$\frac{\partial U}{\partial t} = f(V - V_g) - \frac{\partial \langle uw \rangle}{\partial z},$$

$$\frac{\partial V}{\partial t} = f(U_g - U) - \frac{\partial \langle vw \rangle}{\partial z},$$

$$\frac{\partial \Theta}{\partial t} = -\frac{\partial \langle w\theta \rangle}{\partial z},$$

$$\frac{\partial E}{\partial t} = P_s + P_b - \epsilon + \frac{\partial}{\partial z}\left(K_m \frac{\partial E}{\partial z}\right)$$

$$-\langle uw \rangle = K_m \frac{\partial U}{\partial z},$$

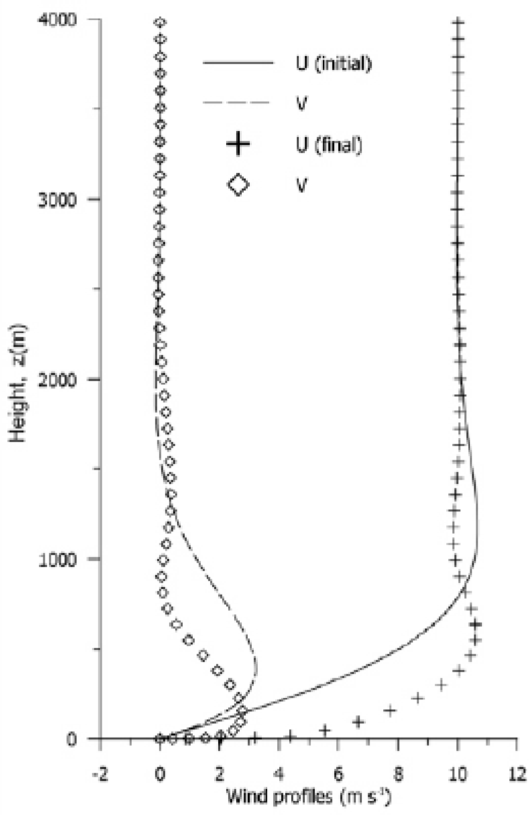
$$-\langle vw \rangle = K_m \frac{\partial V}{\partial z},$$

$$-\langle w\theta \rangle = K_h \frac{\partial \Theta}{\partial z},$$

$$K_m = \ell_m (\alpha E)^{1/2},$$

$$K_h = \ell_m (\alpha E)^{1/2} / Pr,$$

$$\frac{1}{\ell_m} = \frac{1}{\kappa(z + z_0)} + \frac{1}{\ell_0} + \frac{\beta_c}{\kappa L_O},$$



Water Vapour – cloud droplet transition.

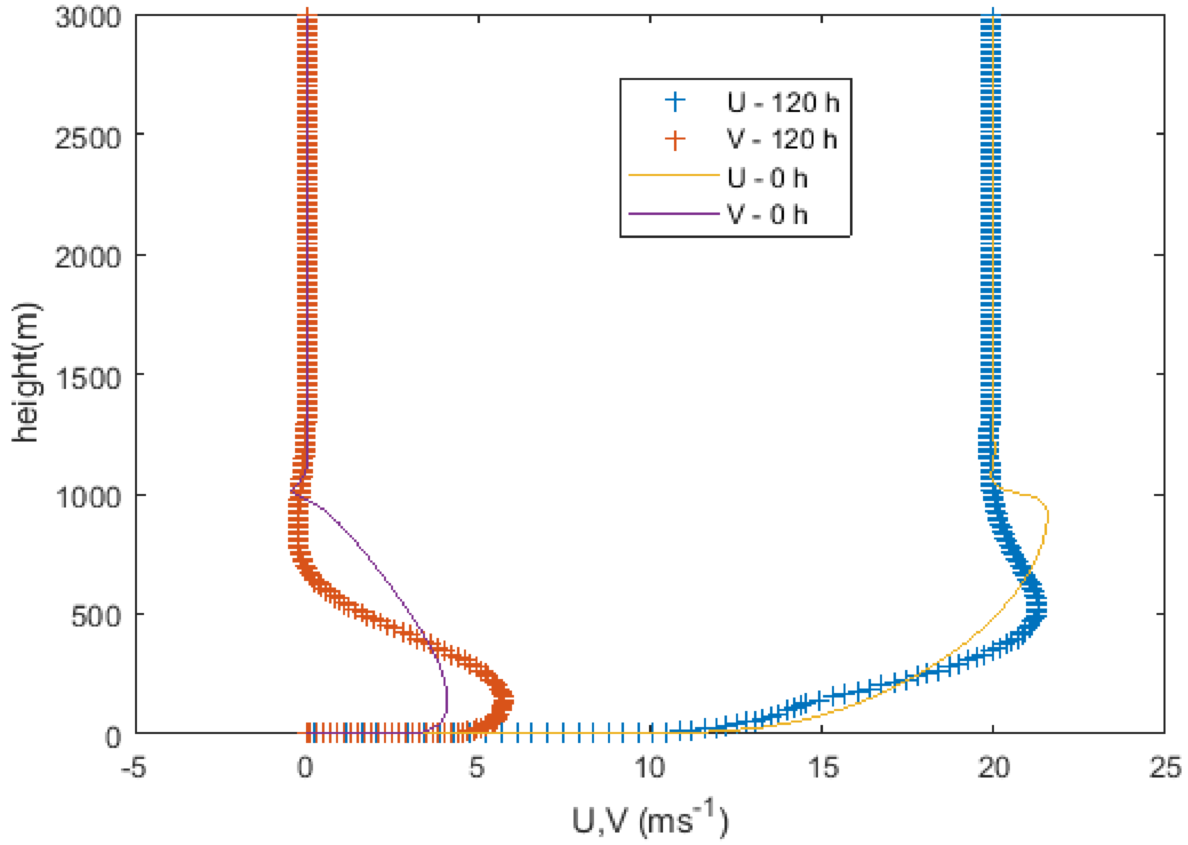
Our microphysics will simply be that condensation occurs instantaneously if the mixing ratio, q > qsat(T), the saturation value at air temperature, T. Then q instantly reduces towards that saturation value with the excess becoming liquid water, ql. This releases latent heat, raises T and modifies qsat. An adjustment is made in the opposite direction when liquid droplets diffuse into a sub-saturated layer. A similar approach was used by Brown and Roach (1976 - section 2, Theory). Both transformations are assumed to take place at constant total pressure and with no external source or sink of heat. A simple Bulk Microphysical Parameterization, or **BMP**

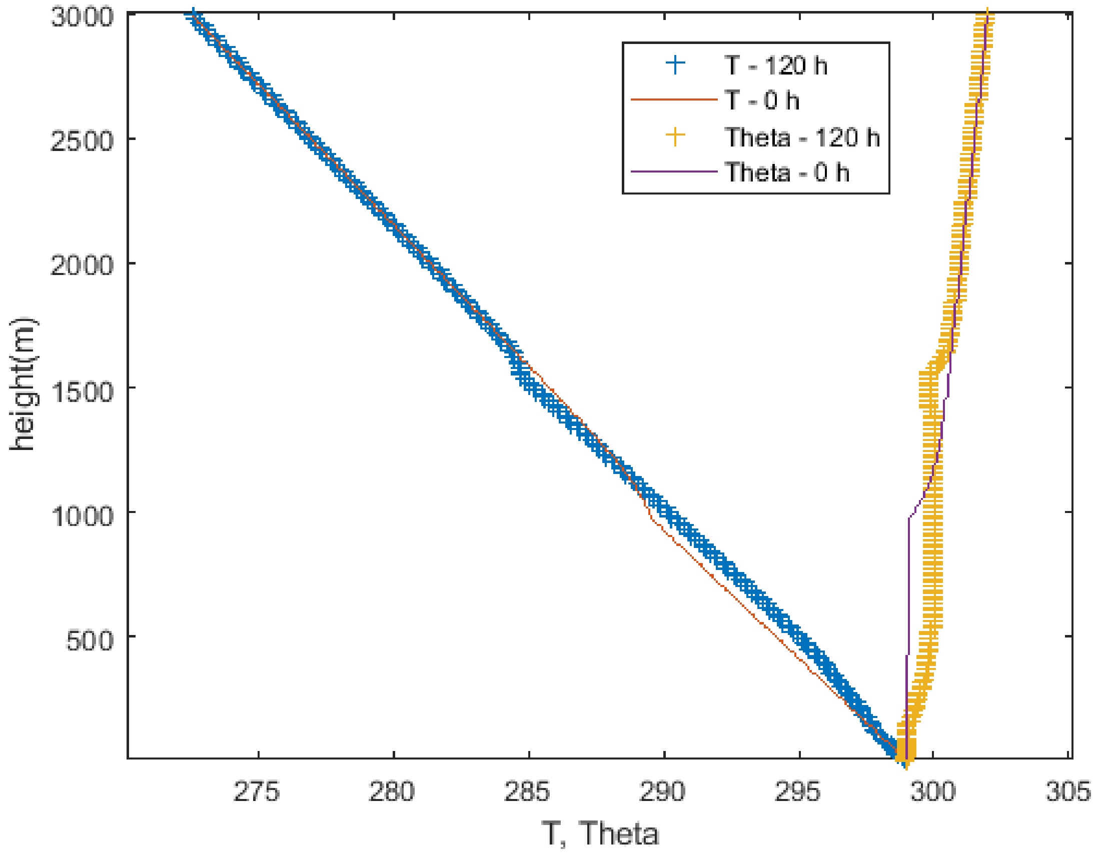
Radiative fluxes, solar and long wave.

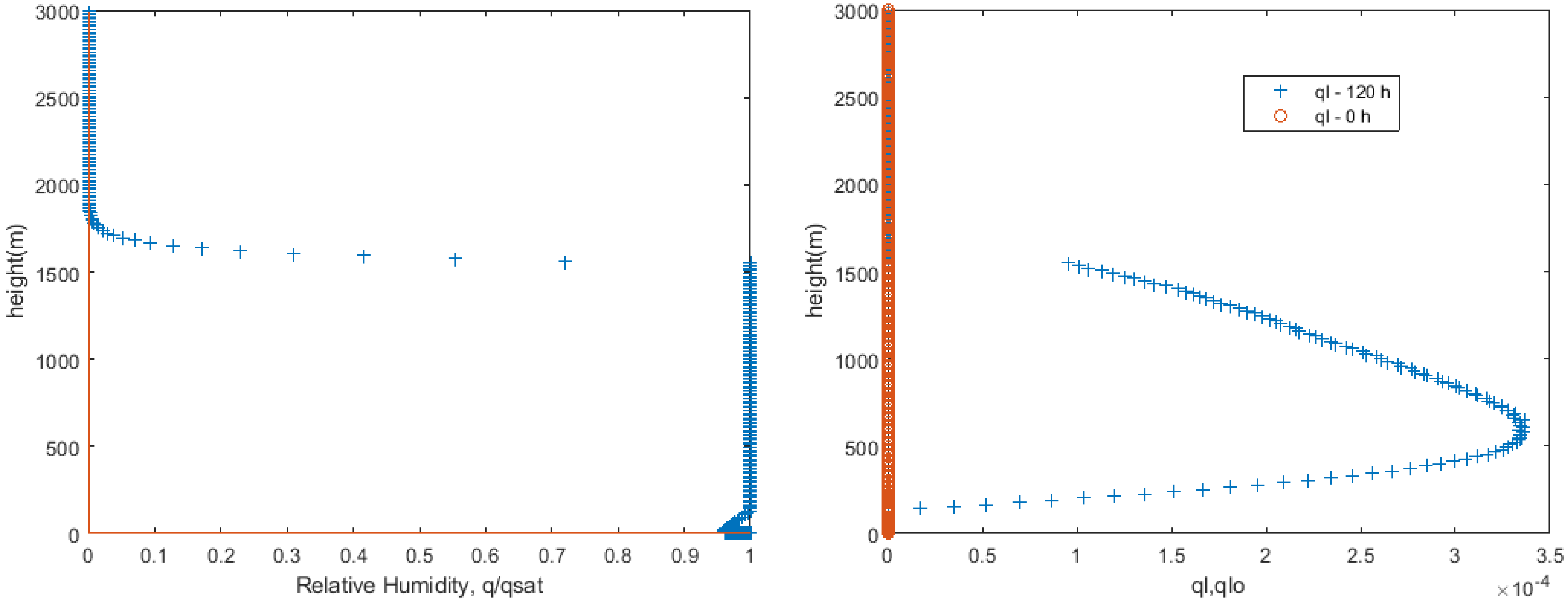
Water droplets can be significant absorbers and emitters of long wave radiation. For solar radiation it is often argued that cloud and fog droplets scatter rather than absorb solar radiation and the direct impact may be small. One web site (https://www.foxweather.com/learn/does-fog-really-burn-off-dispelling-the-myth-of-combustible-clouds) states “People commonly refer to the dissipation of fog as ‘burning off’ but the reality is much less exciting”. Fog will forward scatter much of the solar radiation and, over land, will raise the surface and near-surface air temperatures, causing fog to dissipate. Solar radiation will heat up the upper layers of the ocean, but the increase in sea surface temperature is far less than land surface temperatures and the absorption of solar radiation by fog droplets may be more relevant.

We use a 2-stream model incorporating divergences of upwelling and downwelling irradiances.

Some initial results**, no radiative fluxes.** Initial profiles, stable after 5 days – completely dry air, slight stable stratification, **dθ/dz = 1K/km**, Tsurf = 299K, z_0 = 0.001m, f = $10^{-4}s^{-1}$, $\underline{U}_g$ = (20, 0) ms^{-1}. A relatively well-mixed layer develops with a capping stable layer. Then restart computations with these $\underline{U}$, θ profiles but surface mixing ratios q = qsat, ql = 0. Profiles below after a further 120 hours (5 days). Water vapour diffuses upwards, some condenses and warms the air, liquid water diffuses upwards and downwards, some evaporates, causing local cooling.







After 5 days, starting with RH = 0!, water vapor has condensed and formed a cloud layer, from about 100m to 1600 m above ground. The drop in ql at the top is sharp. If we start with some moisture present the cloud forms more quickly and cloud water mixing ratios are higher. Note that ql << q or qsat. Here $w_s = 0$. These results are with 241 vertical levels, bur very similar with 121 levels. Some sensitivity to treatment of mixing in stable conditions at top of cloud – these are with TKEmin = 0.00001 m^2s^{-2}. **No radiative flux effects yet**.

A settling velocity, w_s, of 0.005 ms^{-1} corresponds (Stokes law) to a droplet of diameter ~ 13 µm. Increasing w_s (0.01, 0.02 ms^{-1}) reduces the peak ql values but the variations with height remain similar. Studies with lower wind speeds or with lower temperatures all predict stratus and fog formation over water. These can be common features but there are clear days over the oceans. Why? Radiative flux effects? Advection effects, both positive and negative?

Radiative flux absorption, in clear air and in clouds. A complex process with strong and detailed wavelength and droplet size dependence. Will aim for a simple 2-stream approach for irradiance. Upwelling and Downwelling, Long Wave (RFU, RFD) and Solar (SFU, SFD). Basically we use the Radiative Transfer Equation, or, Schwarzschild's equation, integrated over the wavelengths concerned, azimuthally and zonally averaged and applied to irradiance. We assume all scattering is forward and that long wave emissions from cloud droplets produce both upwelling and downwelling long wave radiation.

With air density ρ_a, and using mass absorption coefficients (k_a, k_w, ks_a ks_w), AND, so far, ignoring **back**scattering, $x = 2\pi r/\lambda > 1$. We can then write the equations for irradiance as,

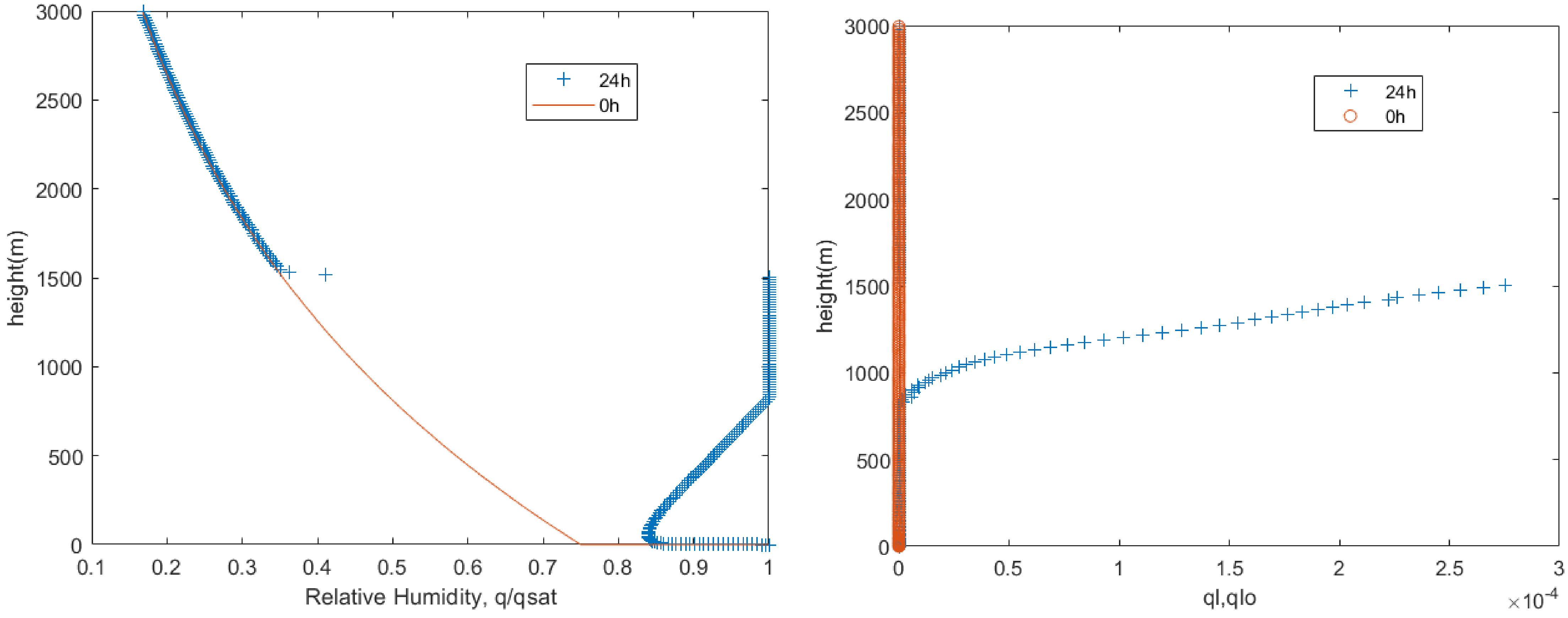
$$dRFU/dz = (-RFU + \varepsilon\sigma T^4)\,(ql\ k_w + k_a)\rho_a \ :\ dRFD/dz = (RFD - \varepsilon\sigma T^4)\,(ql\ k_w + k_a)\,\rho_a$$

$$dSFU/dz = -SFU\,(ql\ ks_w + ks_a)\,\rho_a \ :\ dSFD/dz = SFD\,(ql\ ks_w + ks_a)\,\rho_a$$

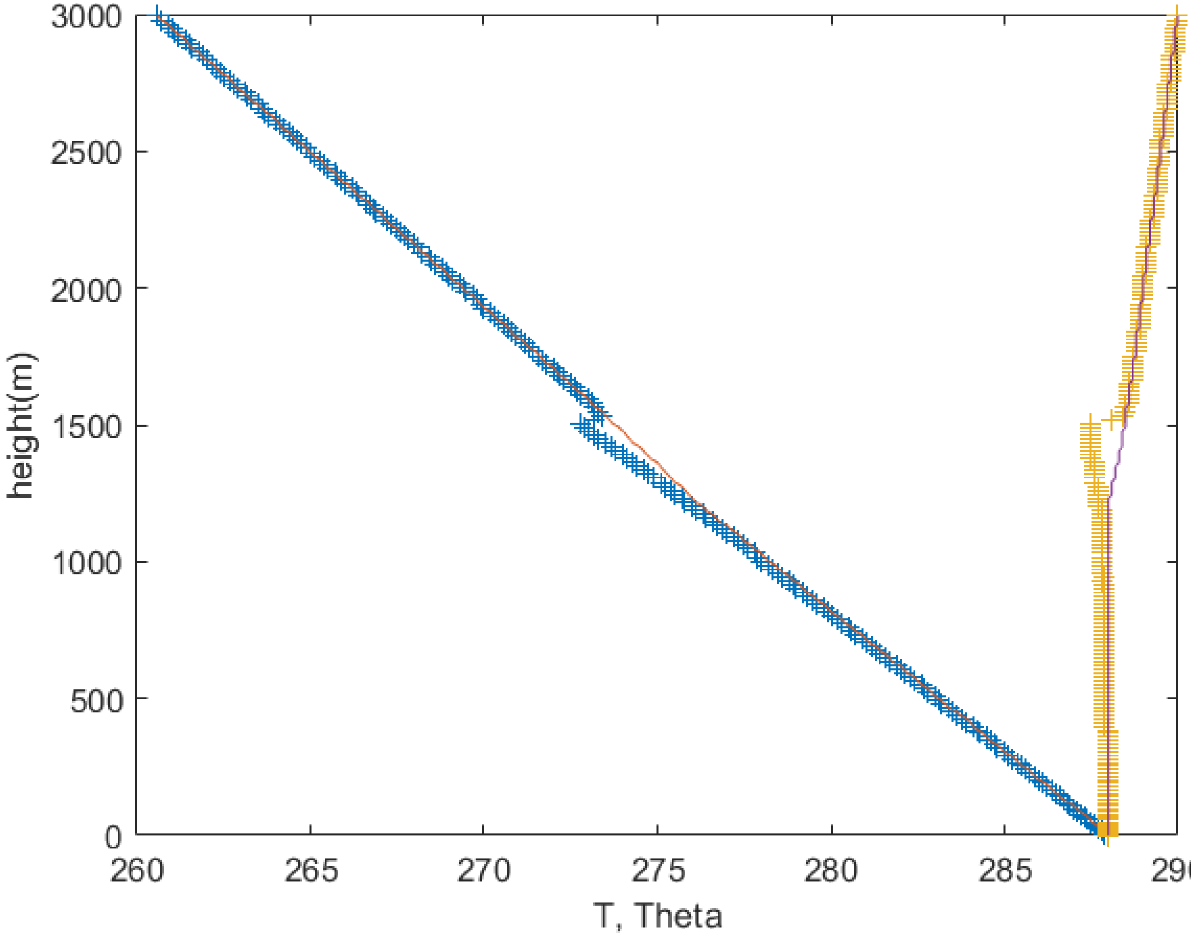
Initially we neglect clear air (k_a, $ks_a = 0$), set $\varepsilon = 1$, and focus on cloud droplets (k_w, ks_w).

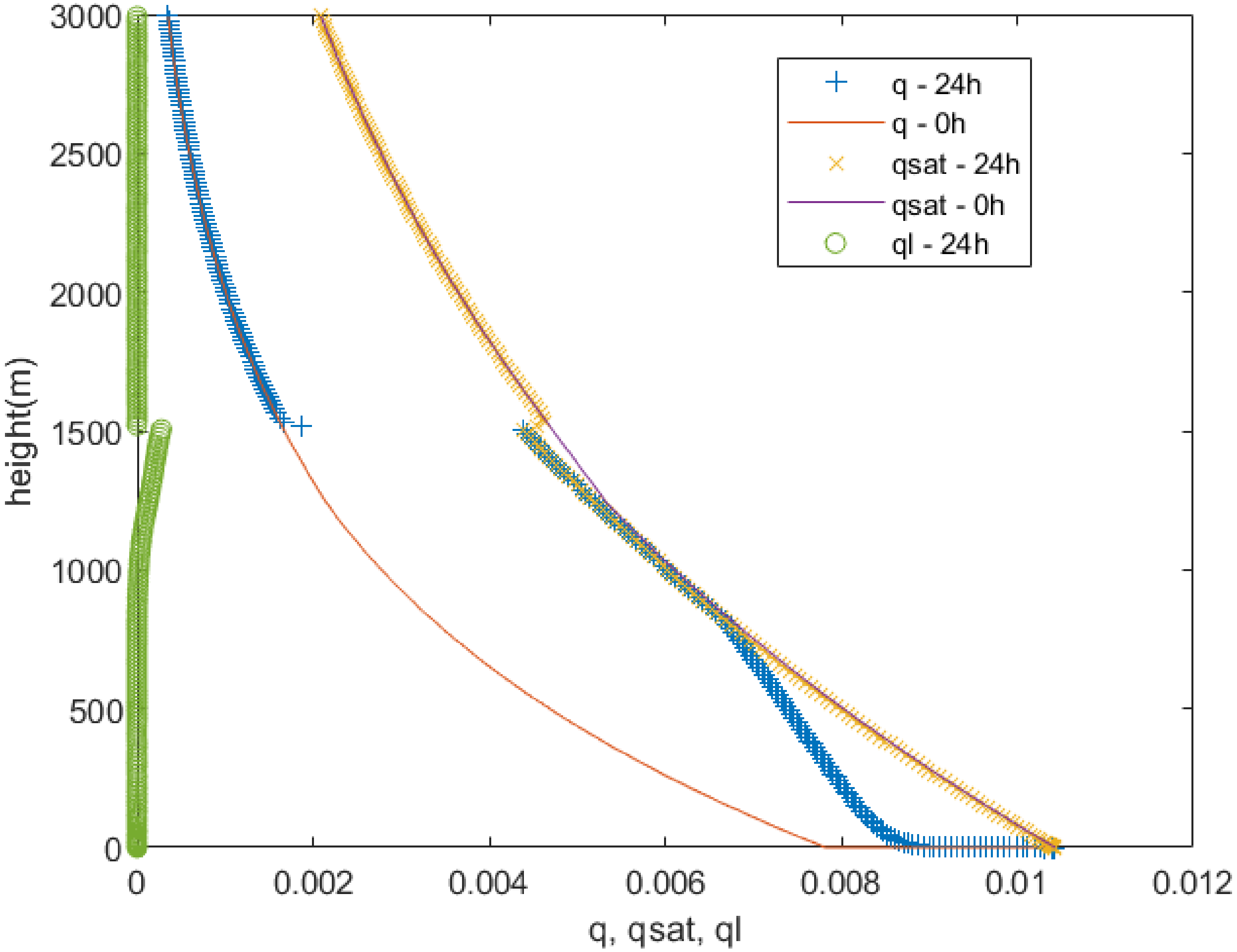
One problem is finding appropriate grey body irradiance values of the long and short wave mass absorption coefficients for water droplets, k_w, ks_w. Units will be m^2kg^{-1}. Stephens papers (1984, Table 3) lead us to use $k_w = 80\ m^2kg^{-1}$ for infrared irradiance. For solar radiation we take $ks_w = 3Q_a/(4\rho r) = 40\ m^2kg^{-1}$ assuming 12 µm diameter water droplets and an absorption efficiency, Q_a, of about 0.3. Adjustment for solar angle with time of day are needed for SFD above the cloud, and for ks_w.

Impacts of radiative fluxes and surface cooling. We look at a simple sample case. a) LW fluxes and **no surface cooling**; 24 h run. $\underline{U}_g$ = (20,0) ms^{-1}, initial dθ/dz = 1 K/km, initial surface temperature, 288 K, initial RH = 0.75 exp(-z/2000.0), No cloud in first 12 h. Note sharp cloud top. Max Ql at top.

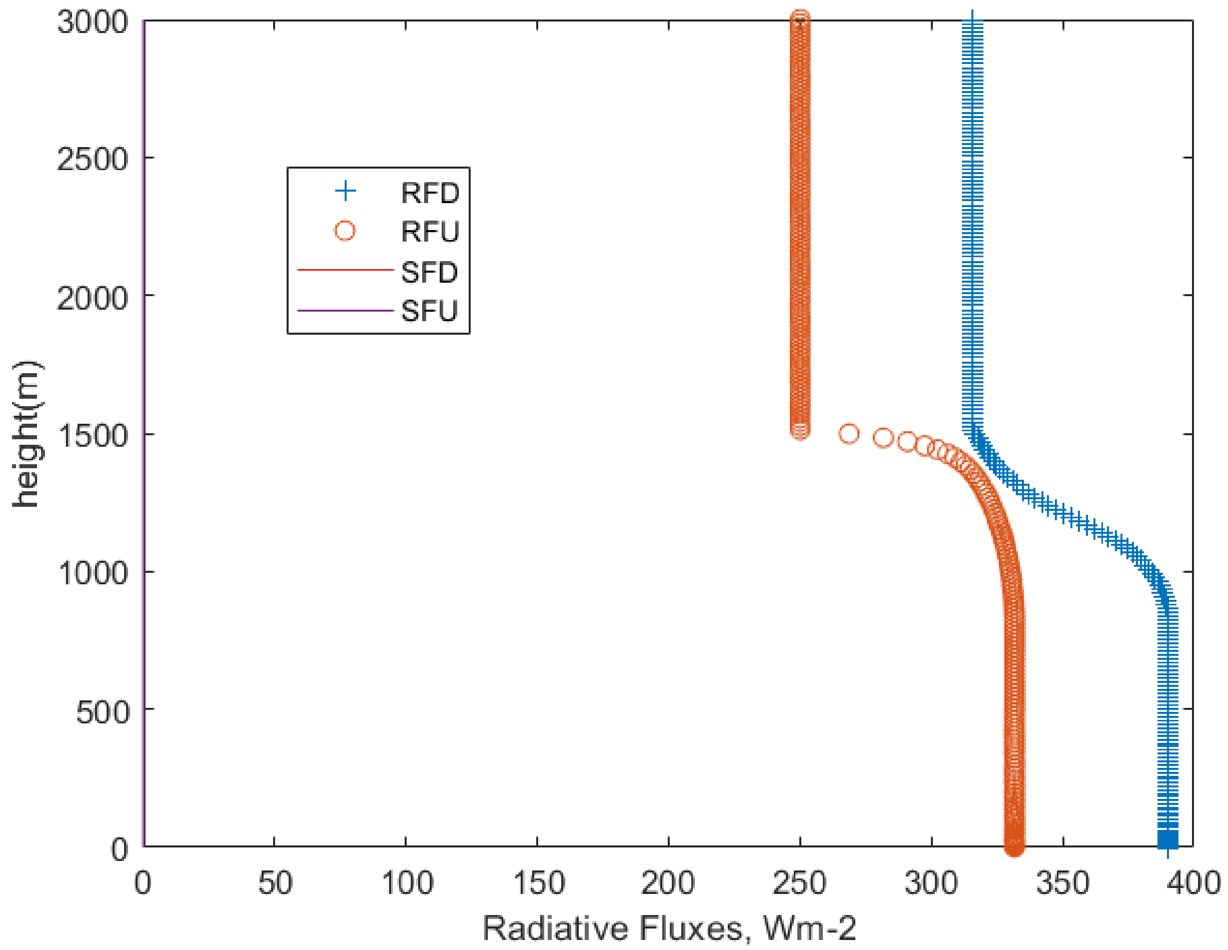


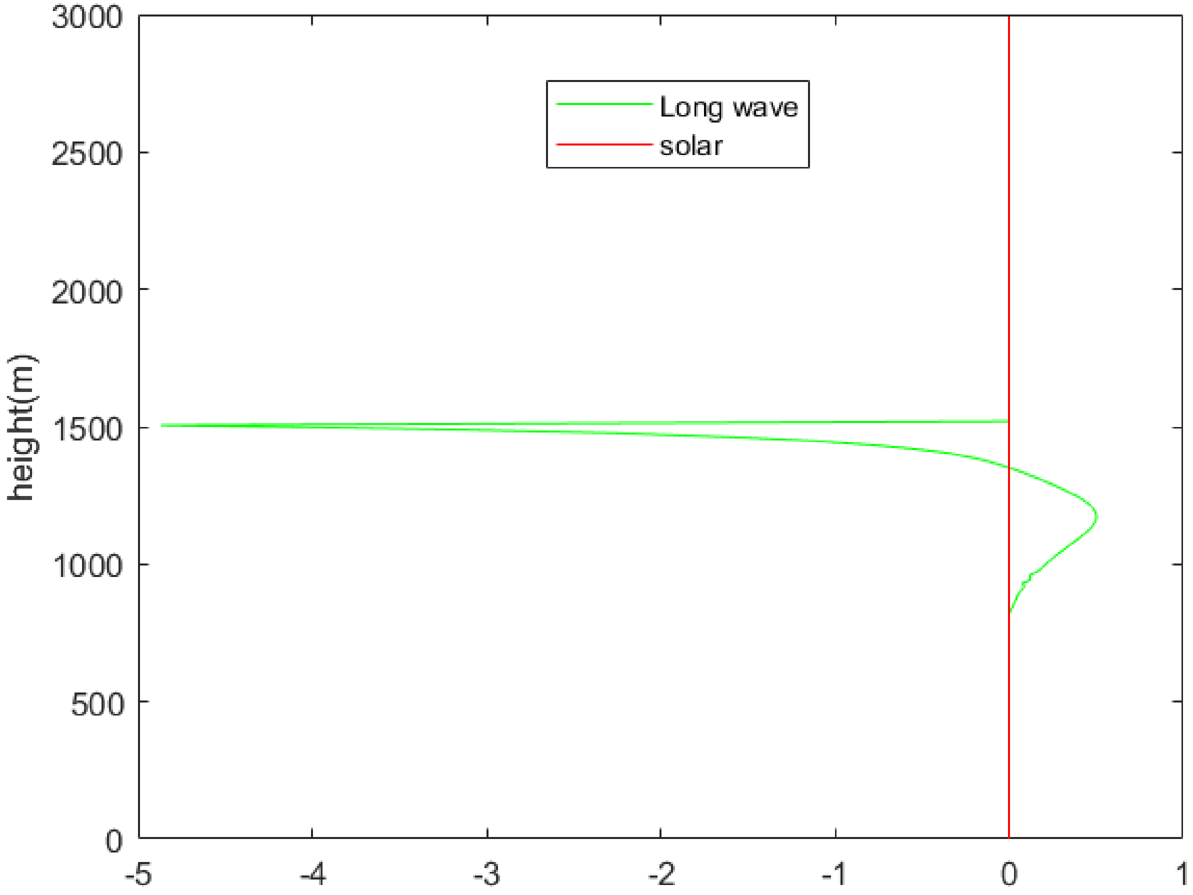
Temperature and Potential temperatures, t = 0 and 24h. Also q, qsat, ql



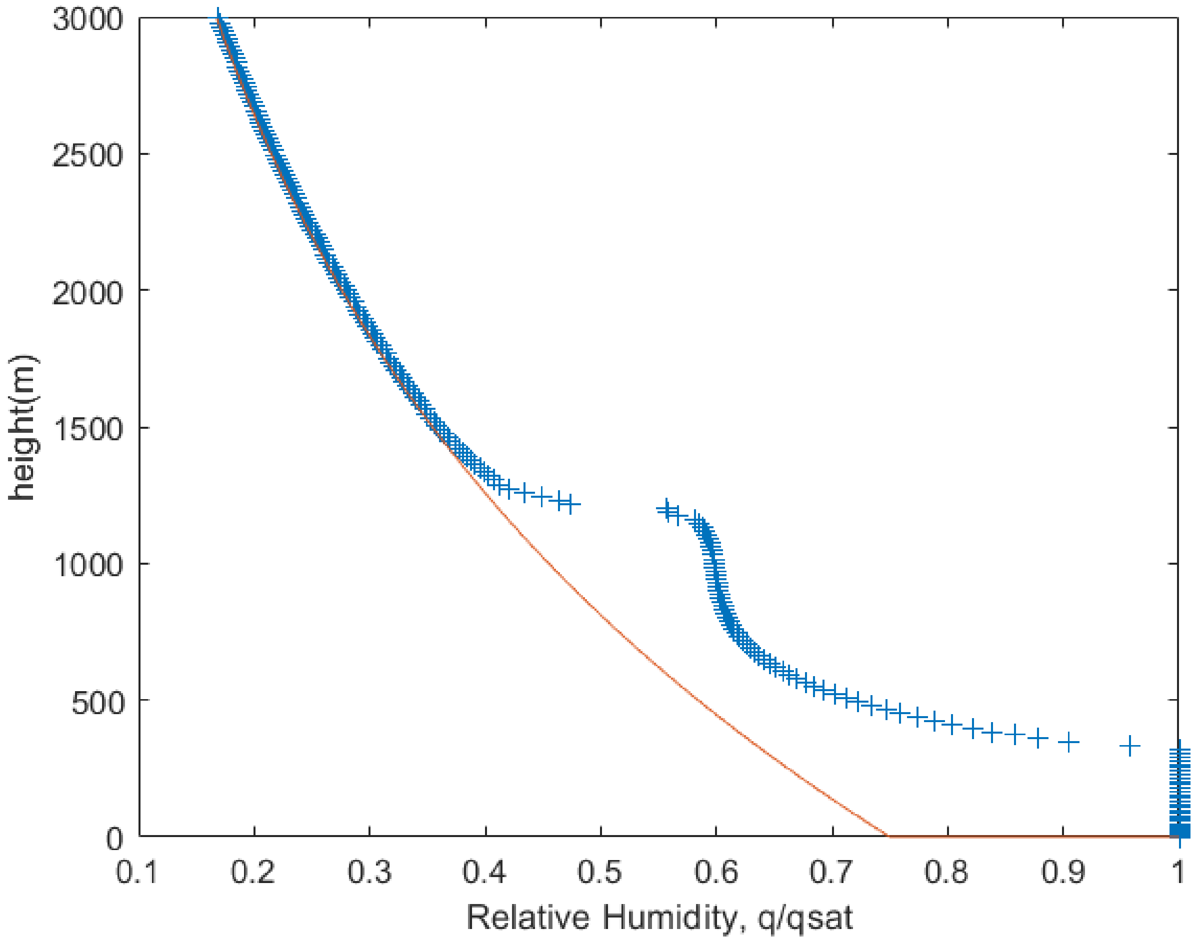


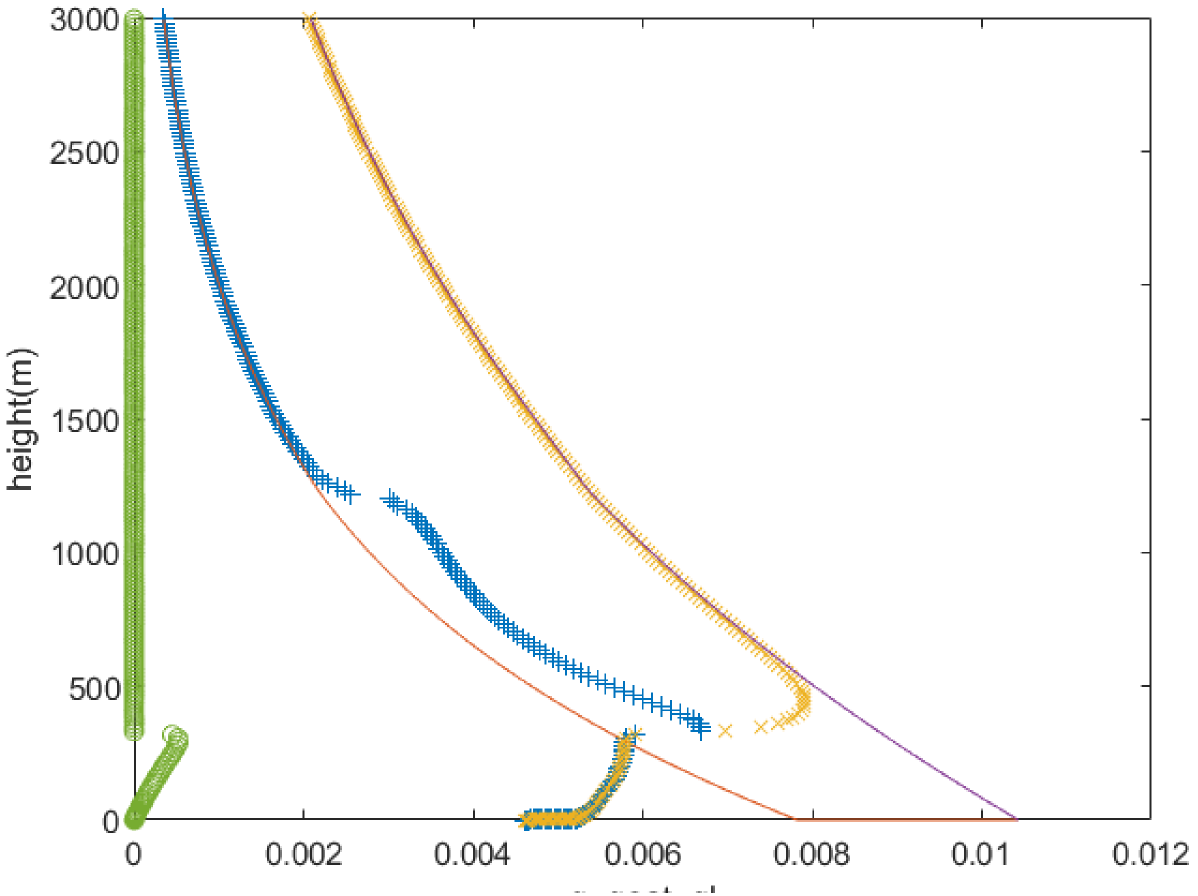
Radiative fluxes and heating, 24 hours but < 12h with cloud



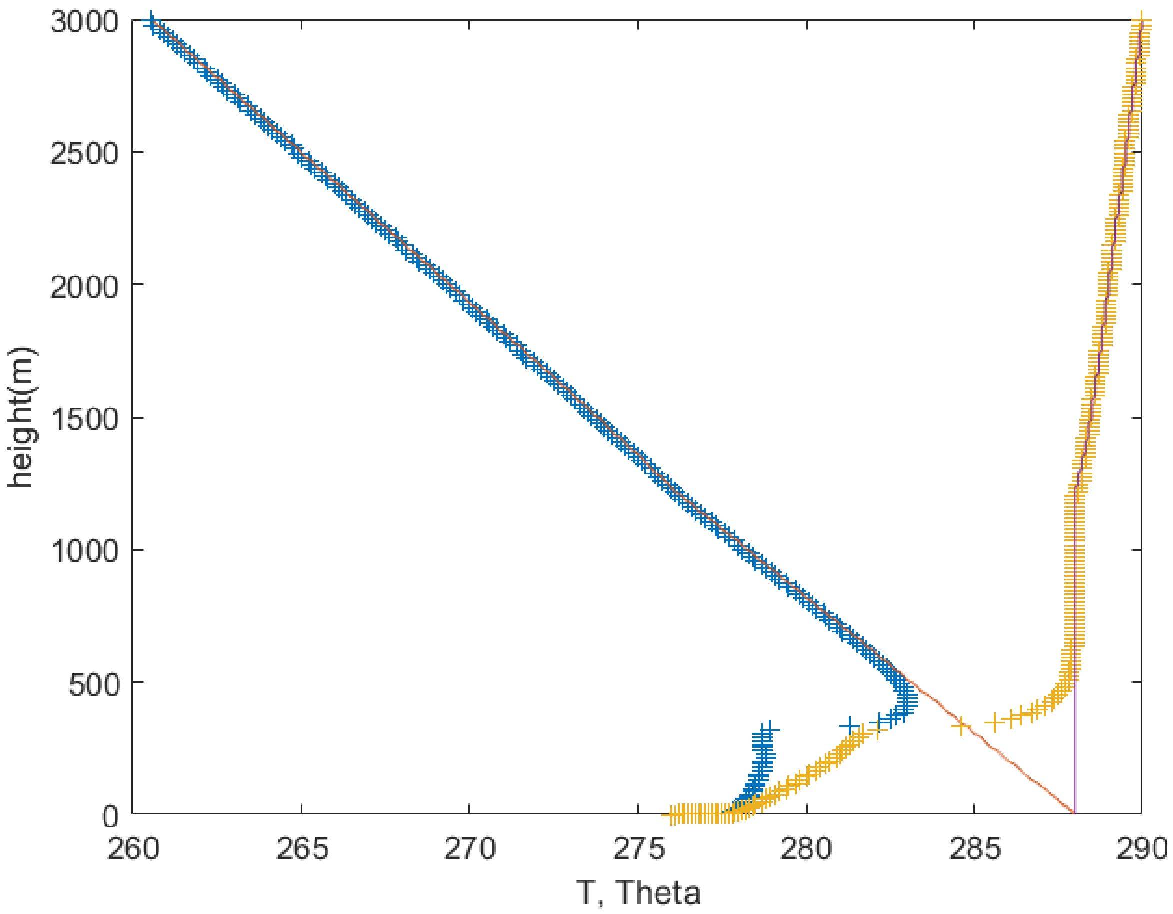


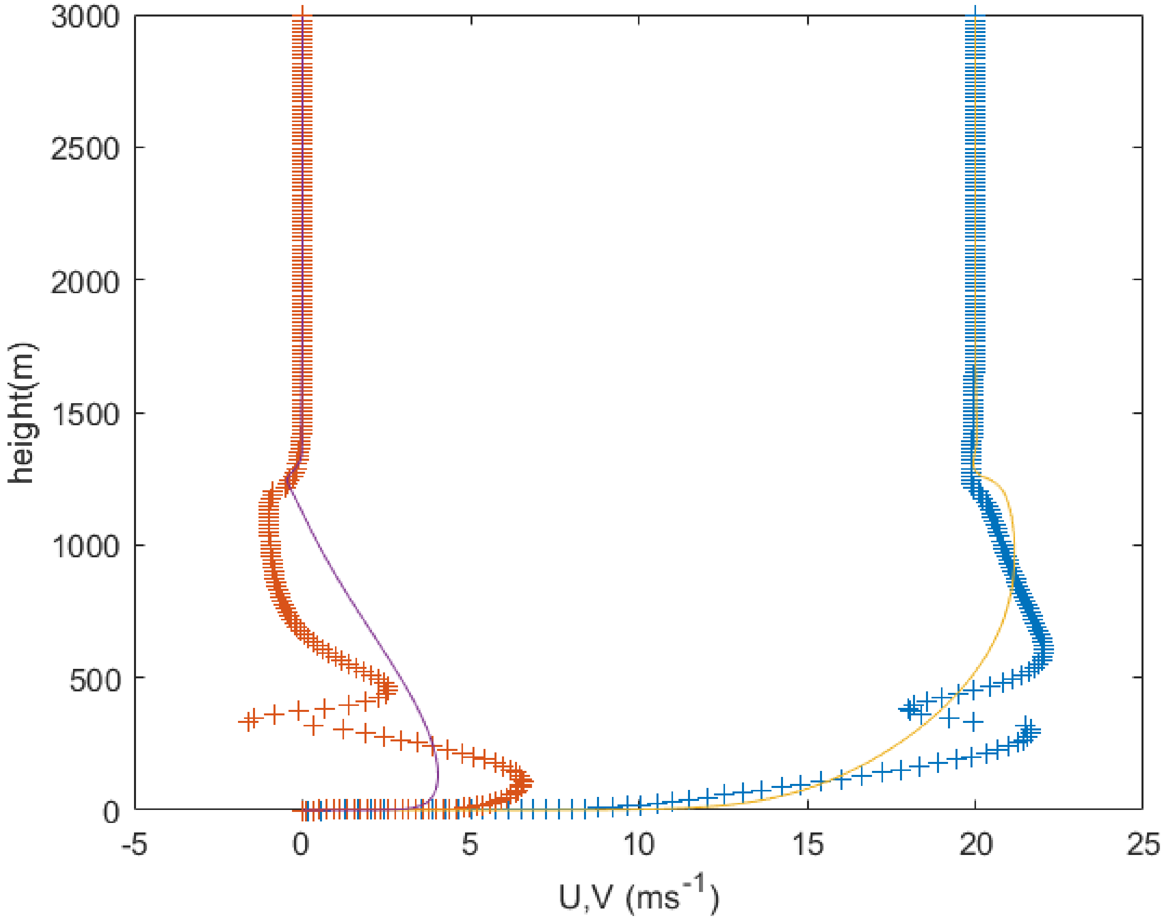
Adding surface cooling, 0.5k/hr





With surface cooling, 0.5 K/hr





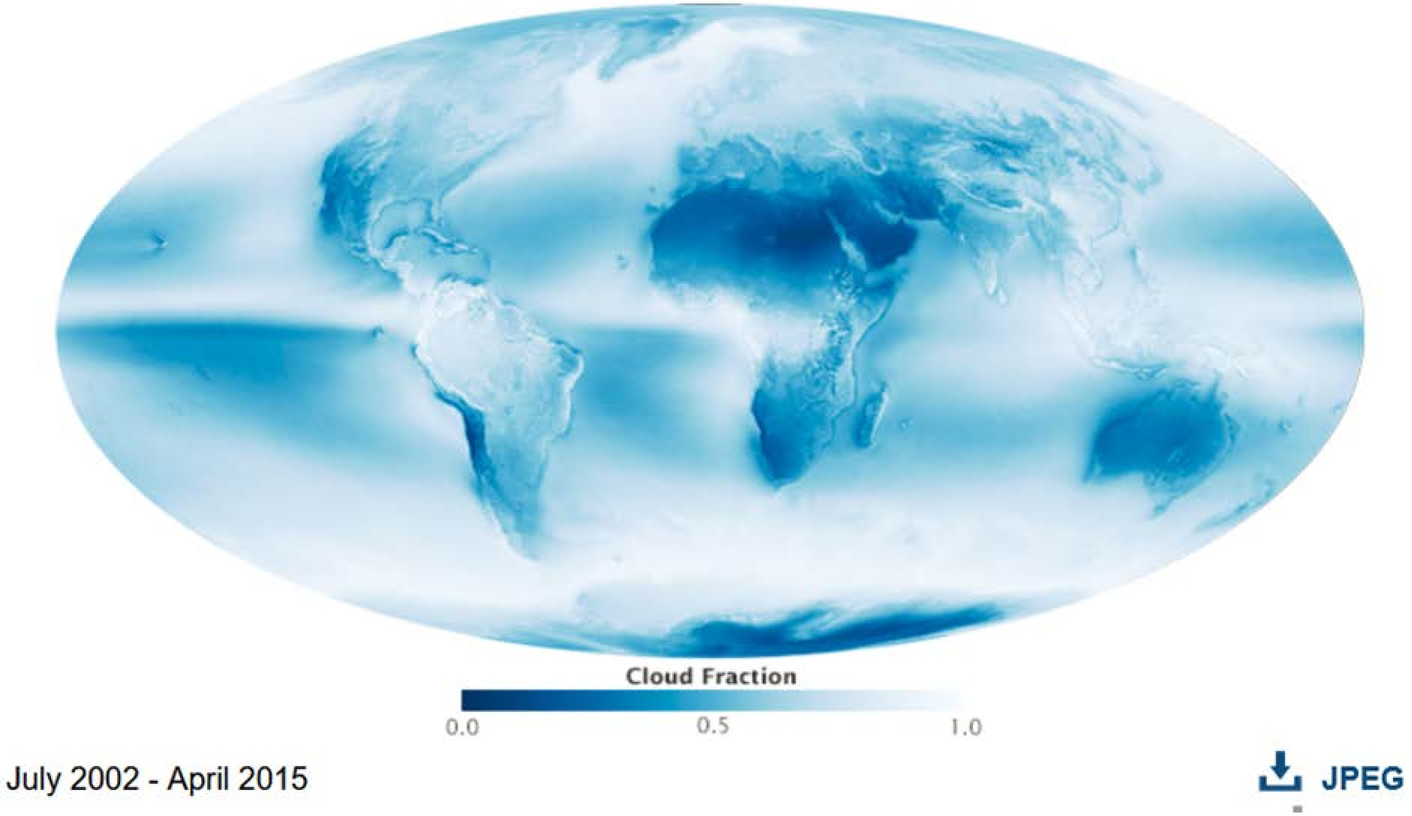
Conclusions.

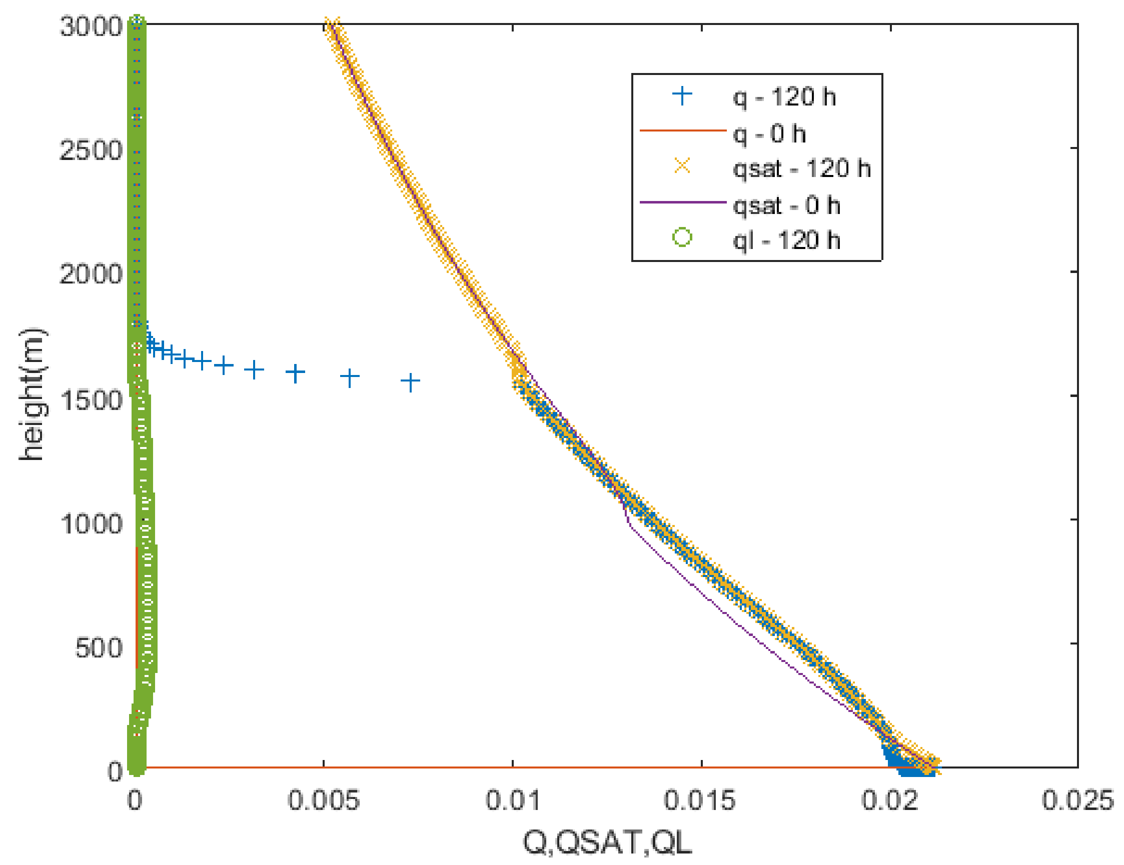
It seems easy to understand how and why marine clouds and fog occur, but a simple model suggests that the oceans should almost always be cloud covered. Solar heating and rainout will allow clear skies some times. These are preliminary results from a simple model but perhaps illustrate the complexity of marine clouds and fog. Fatima (https://efmlab.nd.edu/research/fatima/) has collected interesting field data, from Sable Island and the Grand Banks and from the Yellow Sea. I look forward to working with those.

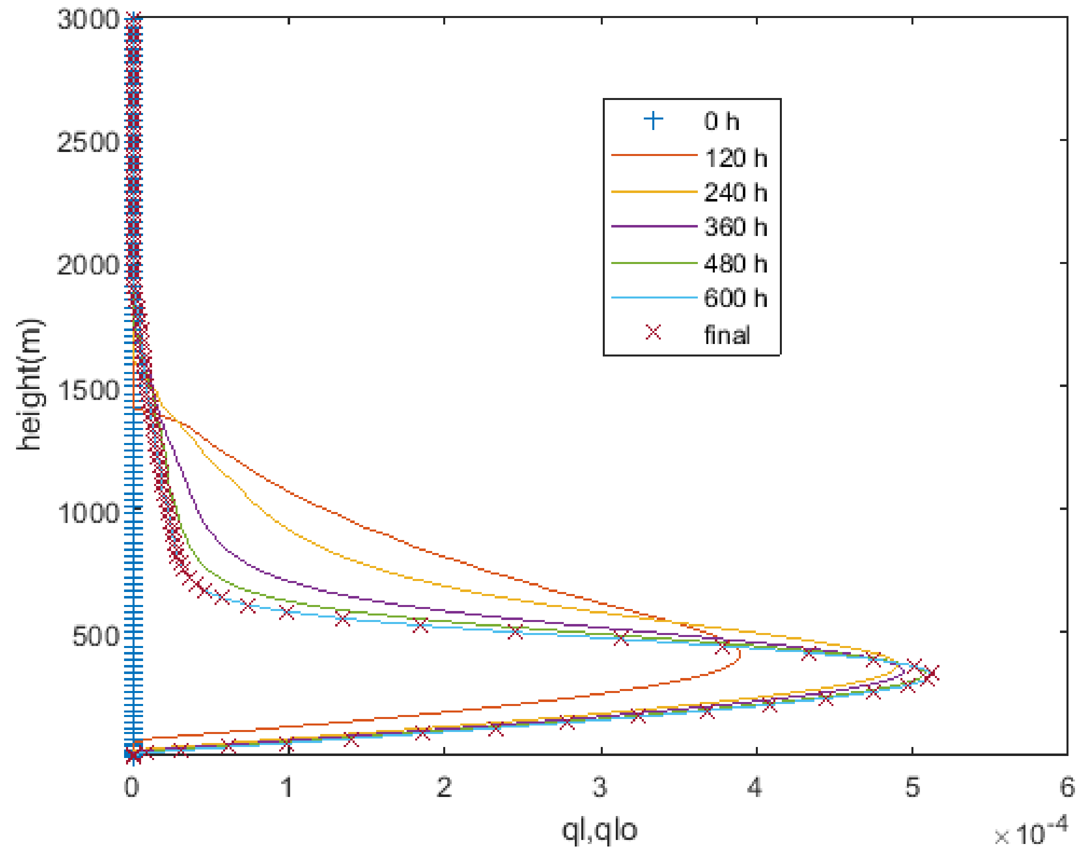
Acknowledgement: Results are based on a PBL model developed over many years with Wensong Weng and with NSERC and CFCAS support.

Particularly over the oceans cloud cover is persistent with an average 72% of cloud cover.[4]

One study based on nearly a decade of satellite data estimated that about 67 percent of Earth's surface is typically covered by **clouds**. **This is especially the case over the oceans, where other research shows less than 10 percent of the sky is completely clear of clouds at any one time.** Over land, 30 percent of skies are completely **cloud** free. https://earthobservatory.nasa.gov/images/85843/cloudy-earth







Comparing ql with q we see a relatively small fraction as liquid water, but it may still have a significant radiative effect. Beyond 120 h the cloud grows deeper until it reaches the top of the domain. We will add radiation – with a simple 2-stream model, but first consider longer time runs and allow gravitational settling of fog/cloud droplets, w_s.

To limit the vertical growth we could use stronger initial stable stratification OR impose gravitational selling on the cloud droplets. The plot above is with $w_s = 0.005$ ms^{-1}. After the 120 h point the peak ql increases while the vertical depth is reduced. **After 25 days** it is approaching a steady state with a max ql of about 0.5 g/kg. Typical stratus cloud values are ~ 0.3 g/kg (Wikipedia) and marine fog ~ 0.05 g/kg. (Isaac et al).