The response of the ocean thermal skin layer to air-sea surface heat fluxes

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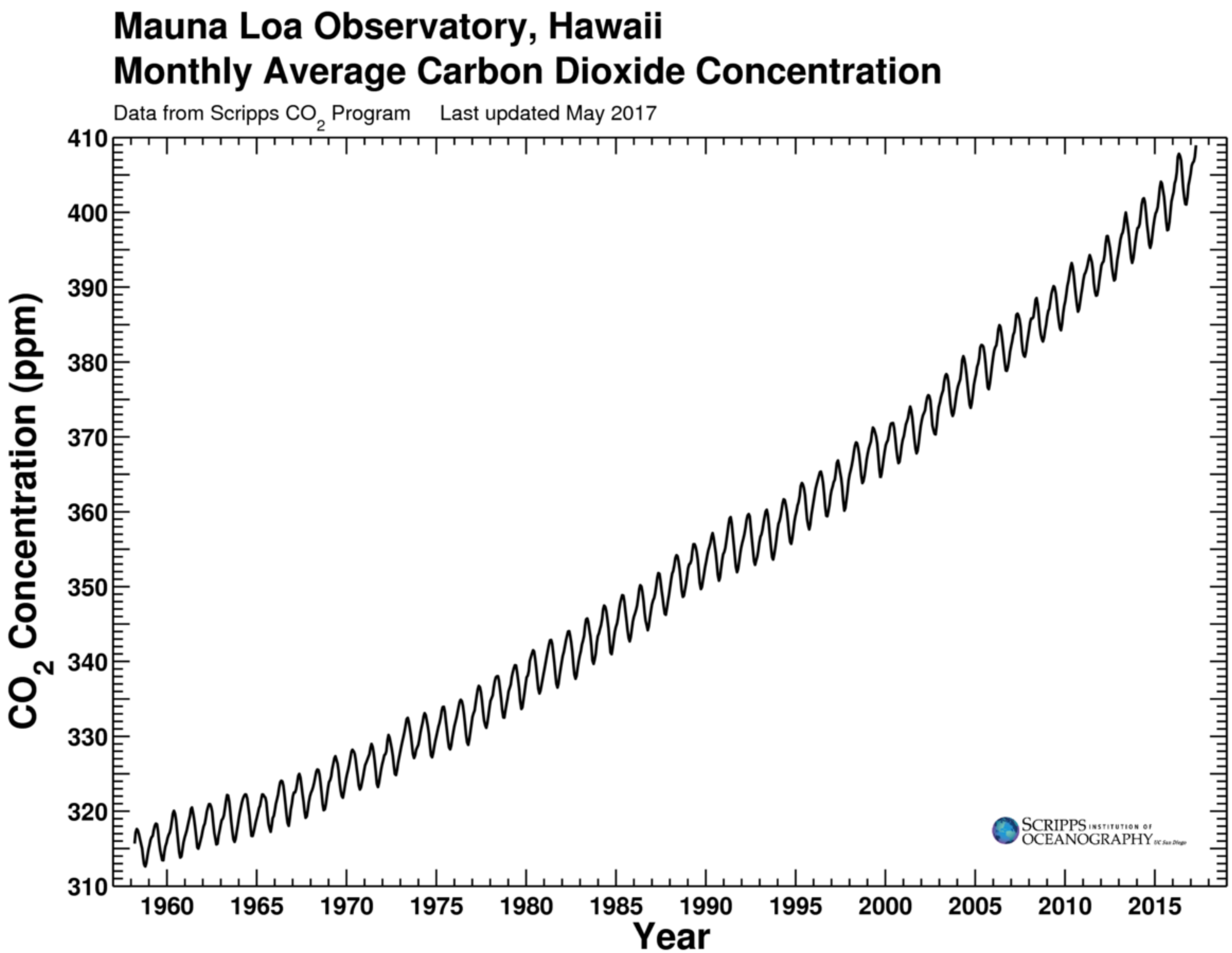
GHRSST XVIII
Ocean University of China, June 2017

Motivation and objective

- Evidence that climate is changing, levels of greenhouse gases in the atmosphere are increasing.
- Evidence that the ocean is heating, presumed to be a result of increasing levels of greenhouse gases.
- How can the increased levels of infrared radiation at the ocean surface increase the ocean heat content given the e-m skin depth in the infrared is so small, and embedded in a viscous skin layer?
- Need to study response of the thermal skin layer to infrared radiative forcing.

The Keeling Curve



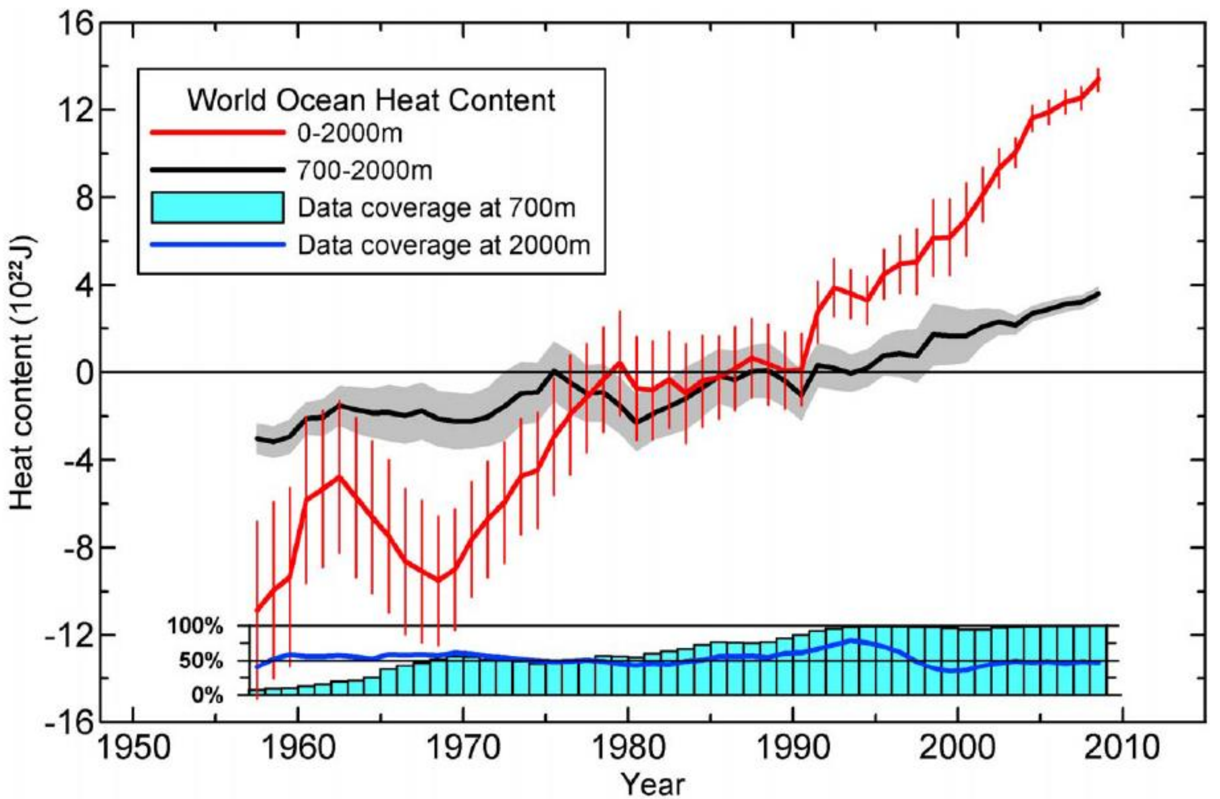
http://scrippsco2.ucsd.edu/history_legacy/keeling_curve_lessons

Ocean heat content

Time series of ocean heat content (10^{22} J) for the 0-2000 m (red) and 700-2000 m (black) layers based on running pentadal (five-year) analyses. Reference period is 1955-2006.

Red bars and grey-shading represent ±2 standard errors.

The blue bar chart represents the percentage of one-degree squares (globally) that have at least four pentadal one-degree square anomaly values used in their computation at 700 m depth. Blue line is the same as for the bar chart but for 2000 m depth. (Levitus et al., 2012)



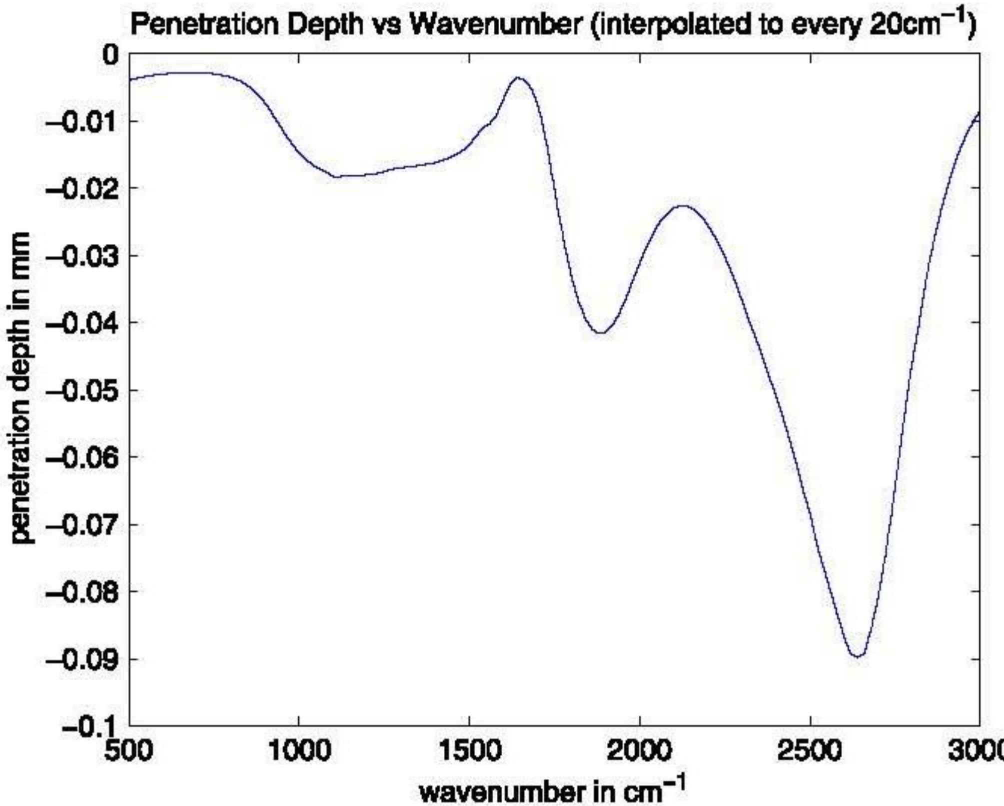
Levitus, S., Antonov, J.I., Boyer, T.P., Baranova, O.K., Garcia, H.E., Locarnini, R.A., Mishonov, A.V., Reagan, J.R., Seidov, D., Yarosh, E.S., & Zweng, M.M. (2012). World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010. *Geophysical Research Letters 39*, L10603. 10.1029/2012GL051106

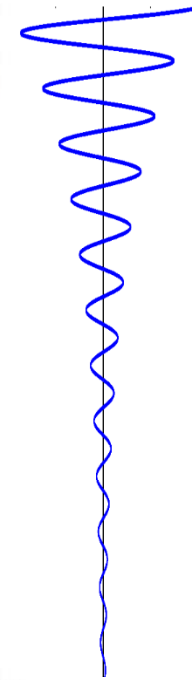
The heat content of the World Ocean for the 0–2000 m layer increased by 24.0±1.9 10^{22} J (±2S.E.) corresponding to a rate of 0.39 Wm^{-2}.

Absorption of IR radiation at the sea surface

Penetration depth versus wavenumber. Penetration depth obtained from $I(z)=I_o\ e^{-\alpha z}$ with R_{img} obtained from Bertie and Lan (1996).

z is along the direction of propagation of the e-m ray.





Bertie, J.E., & Lan, Z.D. (1996). Infrared intensities of liquids XX: the intensity of the OH stretching band revisited, and the best current values of the optical constants of H_2O (l) at 25°C between 15,000 and 1 cm^{-1}. *App. Spectroscopy 50*, 1047-1057.

Mean surface skin layers

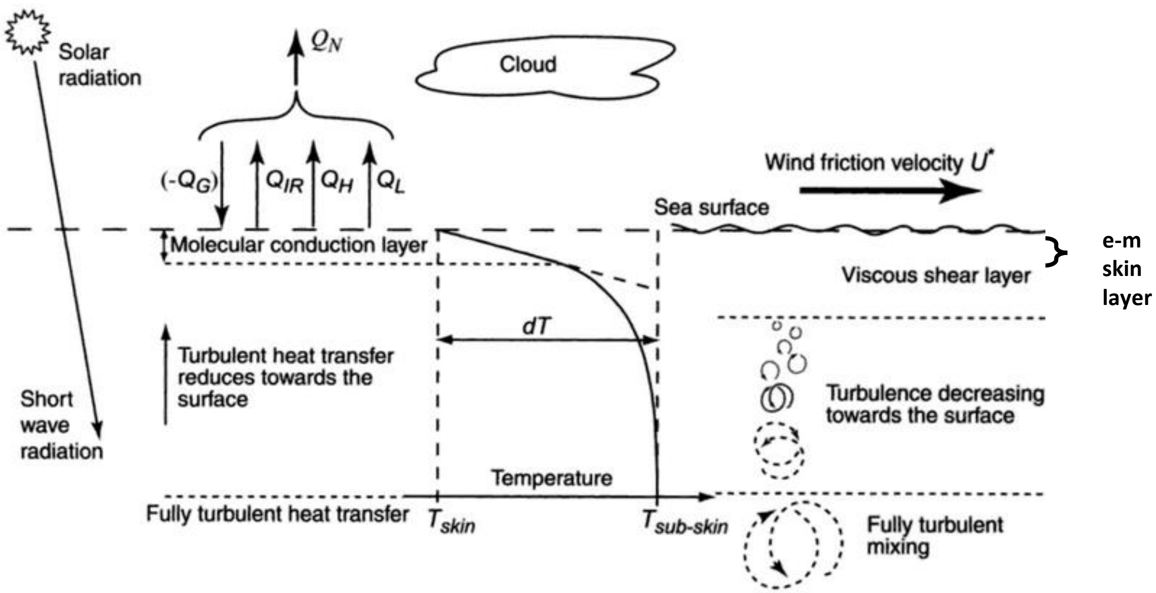


Figure 7.17. Physical factors influencing the thermal skin layer in the ocean.

Electromagnetic (e-m) skin layer and thermal skin layer are embedded in viscous skin layer.

Absorption of infrared radiation from sun and atmosphere in e-m skin layer.

Infrared emission from sea is from e-m skin layer.

Turbulence is damped in the viscous skin layer, leading to reduction of vertical eddy transport of heat near the surface.

Temperature gradient in thermal skin layer leads to conduction of heat to the interface to supply the heat losses.

After: Ian S. Robinson, Measuring the Oceans from Space: The principles and methods of satellite oceanography. p 274.

Hypothesis

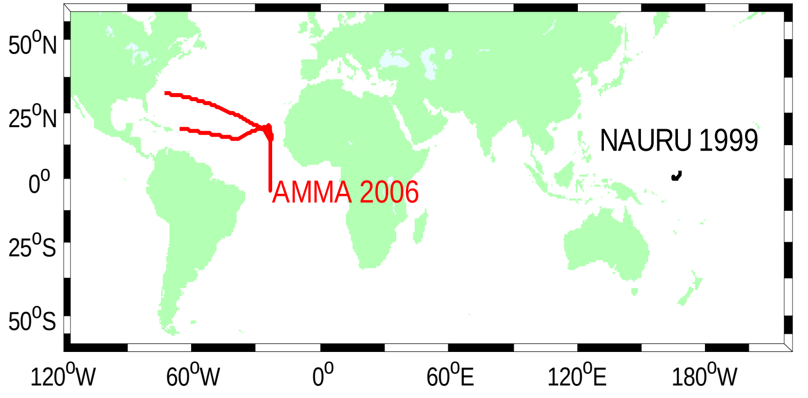
1. Increased levels of infrared radiation from greenhouse gas emission absorbed in e-m skin layer, increasing temperature in the thermal skin layer…
2. But, the radiant energy is not absorbed uniformly with depth, leading to a change of curvature of the temperature profile in the skin layer…
3. Leads to less heat entering skin layer from below, for constant surface heat loss….
4. Means more heat generated from absorption of solar radiation in upper ocean can stay there…
5. Leading to increasing upper ocean heat content…
6. Leading to indirect warming of the ocean by greenhouse gases.

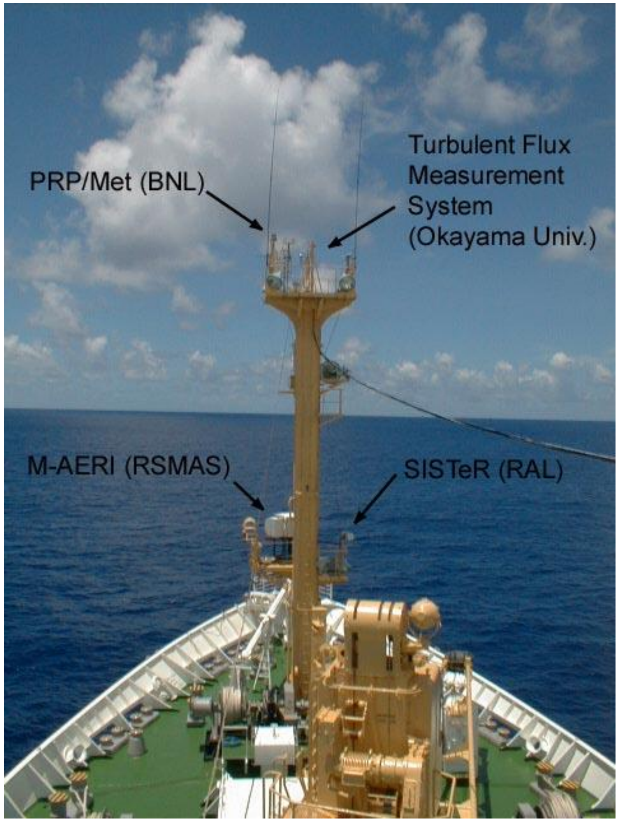
Testing the hypothesis

- Increase in infrared radiation from increasing levels of greenhouse gases is too small a signal….
- So, use much larger increases in surface incident infrared radiation from cloud cover.
- Need:
  - Measurements of incident infrared radiation.
  - Measurements of components of surface heat fluxes (turbulent and radiative).
  - Measurements of temperature gradient in the thermal skin layer.
- Approach:
  - Assess response of surface heat losses to changing infrared radiation from clouds.
  - Assess changes in thermal skin layer to changing infrared radiation from clouds.

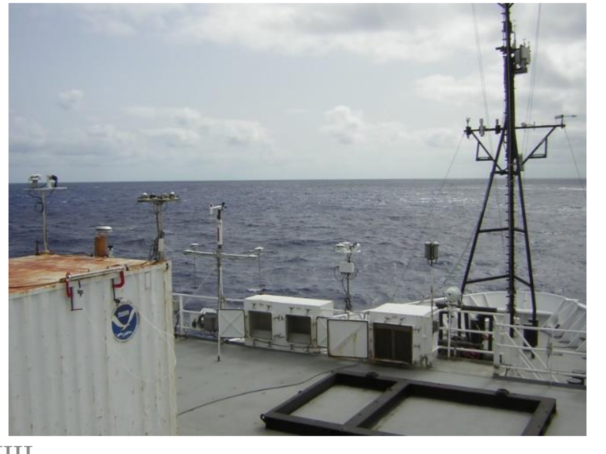
Cruise details

- Two cruises, in Equatorial Pacific and Tropical Atlantic:





  - Nauru 1999 on R/V *Mirai*.
  - AMMA 2006 on NOAAS *Ronald H. Brown*.



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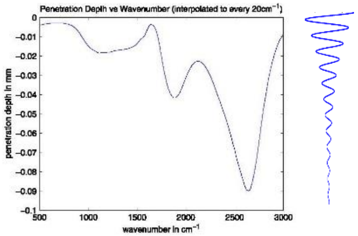
Derivation of TSL profile

$T(z)$ is the vertical temperature profile of interest, and $d(e^{-\alpha z})/dz$ is the weighting function given by Beer's law. The radiation emitted at wavenumber υ from the sea surface is the integral of each attenuated radiance:



$$I_m(\upsilon) = -\int_0^{\infty} B\left(\upsilon, T(z)\right) \frac{d(e^{-\alpha z})}{dz}\, dz$$

where $I_m(\upsilon)$ is the measured radiance at wavenumber υ, $B(\upsilon, T(z))$ represents Planck's function with $T(z)$ being the vertical temperature profile.

This is similar to a nonlinear Fredholm equation of the first kind and is known to be ill-conditioned which means that the errors in the measurements can be amplified resulting in a possibly meaningless solution even if the least-squares-fit solution agrees with the measurements.

Derive $B(\upsilon, T(z))$, given $d(e^{-\alpha z})/dz$ from measurements of $Im(\upsilon)$. Once $B(\upsilon, T(z))$ is found, $T(z)$ follows by inverting Planck's function.

Derivation of TSL profile

- Approximate integral equation by summation over 100 irregularly spaced discrete layers in 0.1mm depth below the surface.
- Use synthetic data from a radiative transfer model to simulate surface emission spectra for a set of realistic temperature profiles in the thermal skin layer.
- Include noise levels in spectra as in M-AERI measurements.
- Experiment using different approaches to retrieving the initial profiles.
- Use truncated singular value decomposition TSVD to regularize the equation, truncated at p=6 singular values.
- But realistic first guess is important….

Derivation of TSL profile

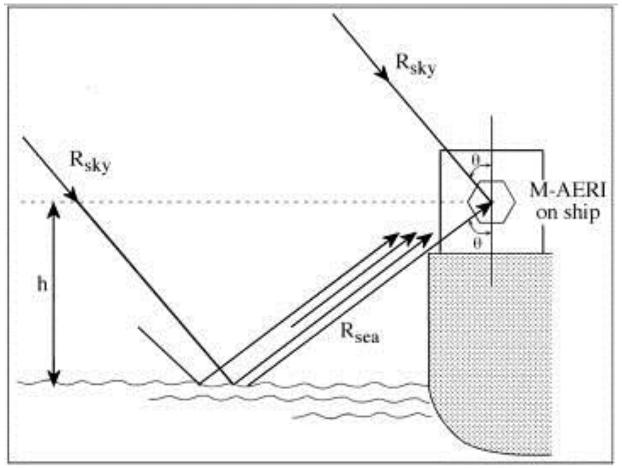
A good first guess profile is a complementary error function:

$$\frac{T - T_b}{T_s - T_b} = \pi^{0.5} 6 i^3 \mathrm{erfc}\left(\frac{2z}{3\pi^{0.5}\delta_c}\right)$$

where $6i^3\mathrm{erfc}(x) = (((1+x^2)e^{-x^2})/\sqrt{\pi}) - (1.5+x^2)x\,\mathrm{erfc}(x)$,
$\mathrm{erfc}(x)$ is a complementary error function defined as $1 - \mathrm{erf}(x)$.

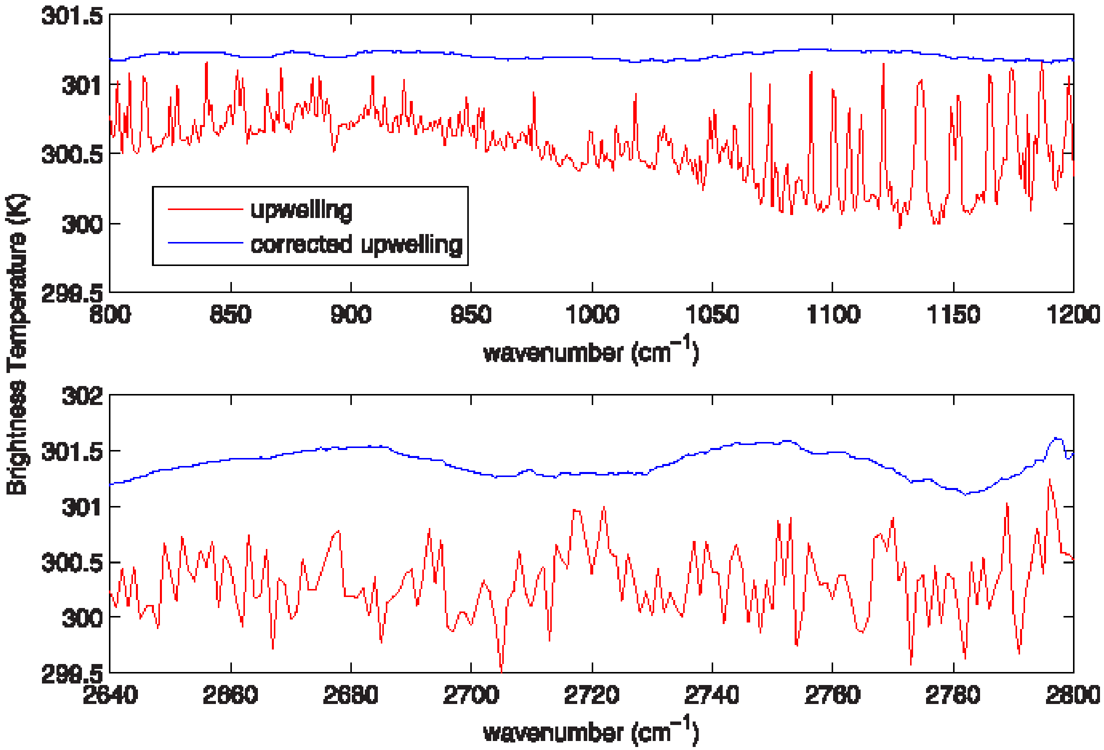
Liu, W.T., & Businger, J.A. (1975). Temperature profile in molecular sublayer near the interface of a fluid in turbulent motion. *Geophys. Res. Lett. 2*, 403-404.

Derivation of TSL profile



$$R_{\text{water}}(\lambda,\ \theta) = \varepsilon(\lambda,\ \theta)B(\lambda,\ T_{\text{skin}}) + (1 - \varepsilon(\lambda,\ \theta))R_{\text{sky}}(\lambda,\ \theta) + R_h(\lambda,\ \theta)$$

Need to correct for surface emissivity not being unity.



Sample brightness temperatures spectrum obtained from the M-AERI during nighttime and cloud-free conditions.
Red - measured upwelling radiance spectrum.
Blue - the corrected upwelling radiance spectrum

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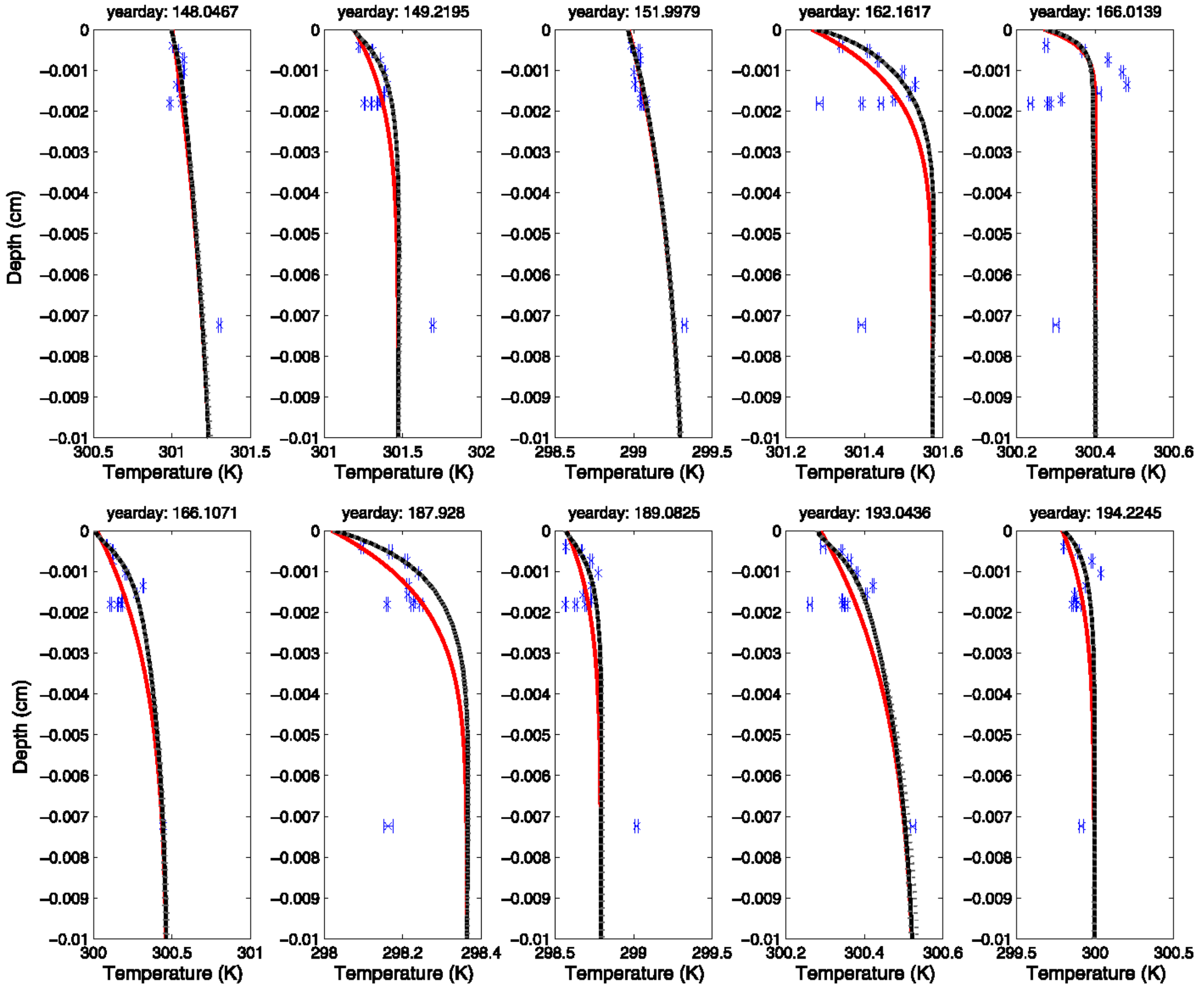
Results

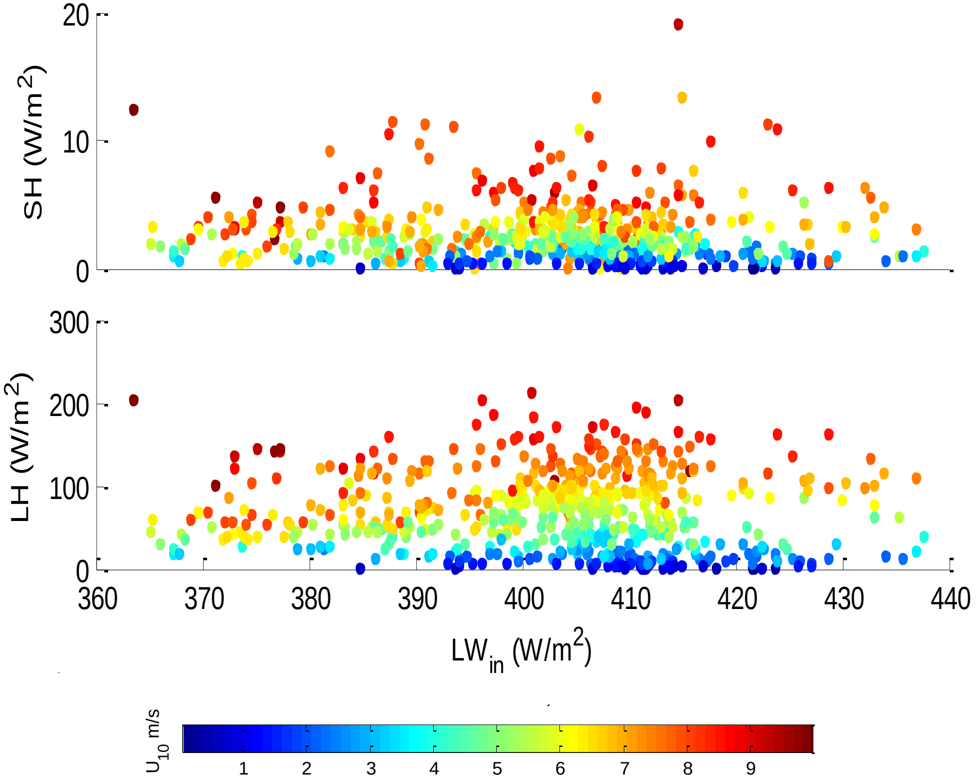
Ten sample profiles derived from spectra taken during the AMMA 2006 cruise.
Blue X's represent the mean BT of the wavenumber intervals with error bars plotted as ±1 standard error. Red solid line denotes first-guess profile; black solid line represents the retrieved profile with respect to the mean BT; gray dotted lines represent the retrieved profile with respect to ±1 standard error. A majority of the gray dotted lines are overlaid on the black solid lines, thereby indicating the similarity between the retrievals to the mean and ±1 standard error in BT.

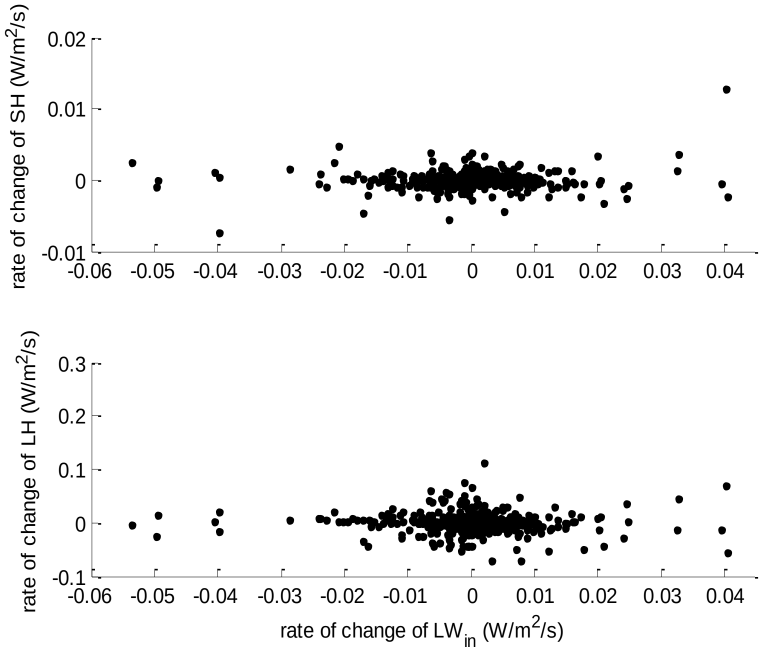


Story so far

- We can derive information about the temperature profile in the thermal skin layer….
  - But, because we need measurements at 2500-2700 cm^{-1}, we will only use night-time data.
- We have cruise data to test our hypothesis….
- So, first step is to test the basis of hypothesis that turbulent heat fluxes do not increase to immediately remove added energy provided by increased LW_{in} from clouds.
- Next step is to check additional heat is not immediately re-radiated by LW_{out} ($\varepsilon\sigma T^4$).

Clouds and turbulent surface fluxes





Conclude – surface turbulent fluxes do not respond to increasing incident infrared radiation.

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LW_{out} ?

- What about LW_{out} increasing?
  - At T=300K, $\varepsilon\sigma T^4 \approx 450\ Wm^{-2}$.
  - For cloudy skies additional ~ 50 Wm^{-2} arrive at the sea surface.
  - For this additional energy to be re-radiated, requires $T \approx 308K$.
  - Not observed….

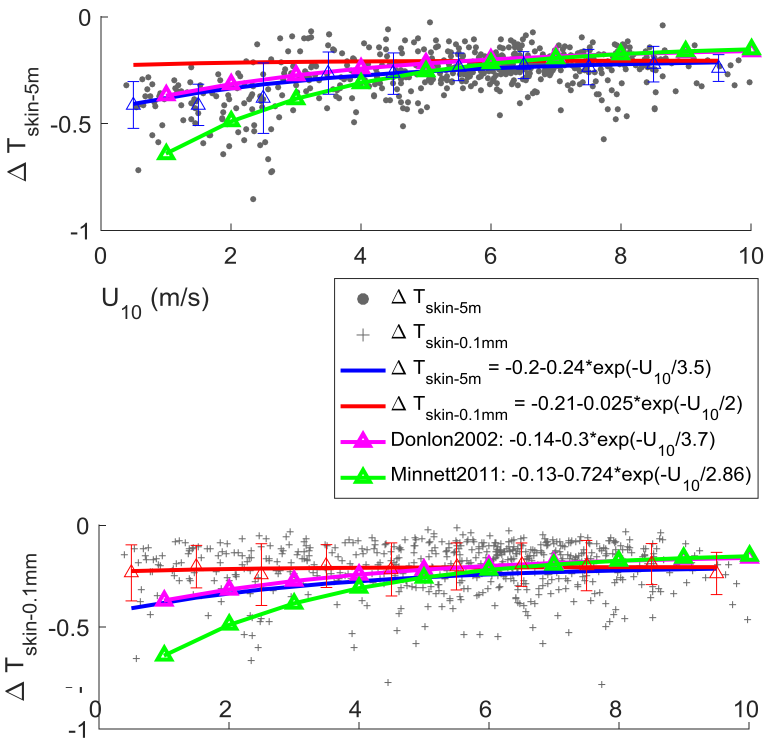
- So what is happening?
- What do we know about the skin layers?

Wind speed dependence

Wind speed dependence of temperature difference between skin SST and T_{5m}.

Wind speed dependence of temperature difference in M-AERI profile.

At low winds, thermal skin layer is thicker, so temperature gradients extend below depth of M-AERI temperature profile, beyond e-m skin layer.



Donlon, C.J., Minnett, P.J., Gentemann, C., Nightingale, T.J., Barton, I.J., Ward, B., & Murray, J. (2002). Toward improved validation of satellite sea surface skin temperature measurements for climate research. *Journal of Climate 15*, 353-369.

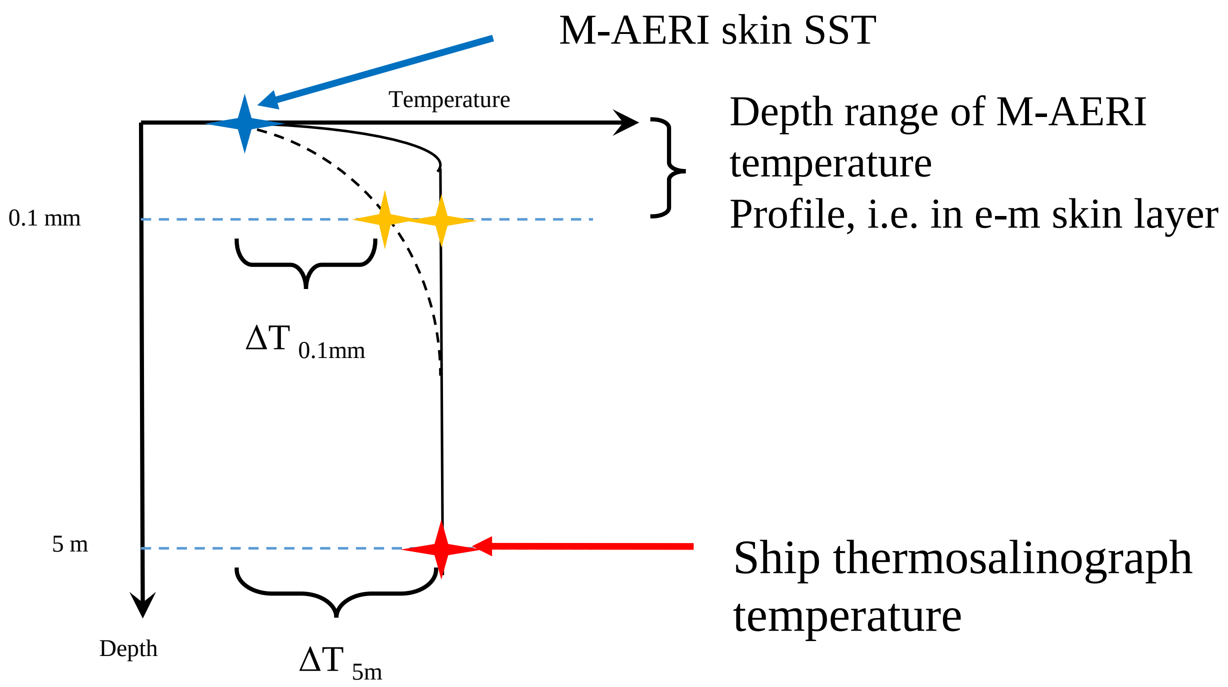
Minnett, P.J., Smith, M., & Ward, B. (2011). Measurements of the oceanic thermal skin effect. Deep Sea Research Part II: Topical Studies in Oceanography 58, 861-868. 10.1016/j.dsr2.2010.10.024

Conceptualization

Ratio

$$\frac{\Delta T_{0.1mm}}{\Delta T_{5m}}$$

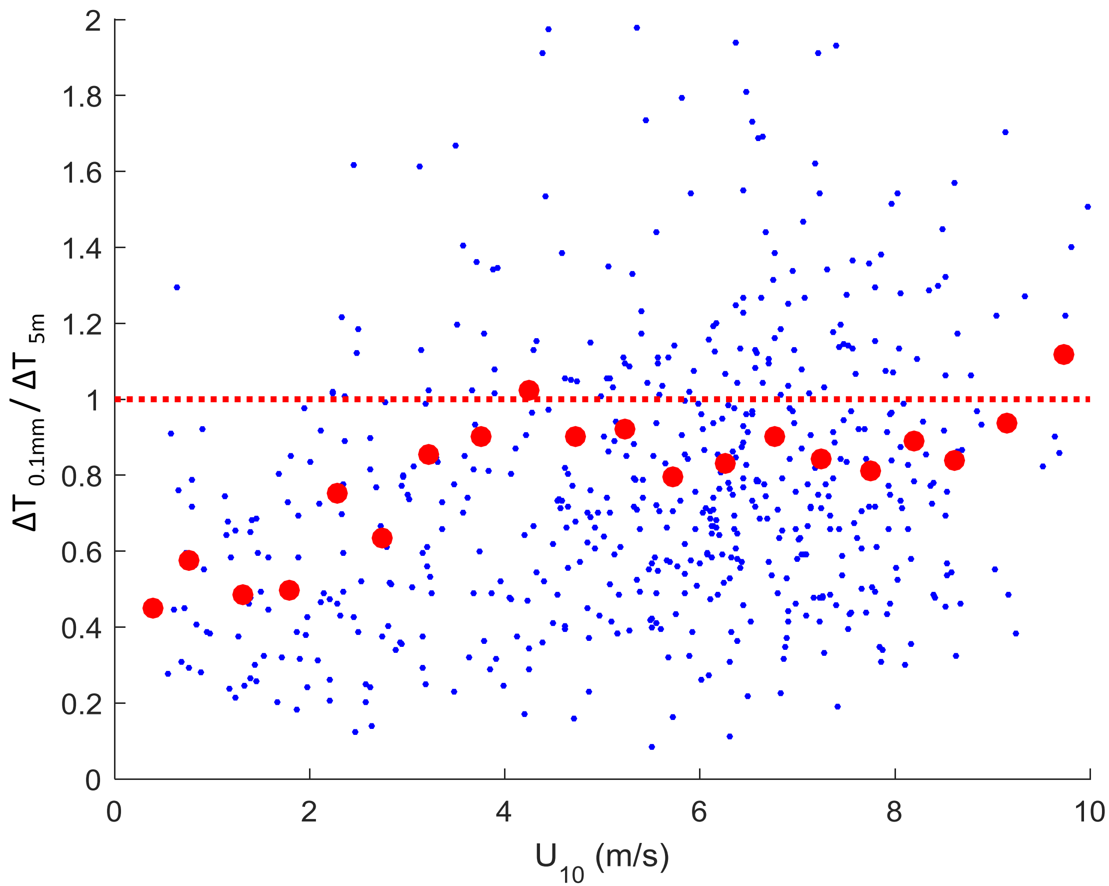
is the fraction of the total temperature change across the thermal skin layer that is sampled by the M-AERI profile retrievals.



Wind speed dependence

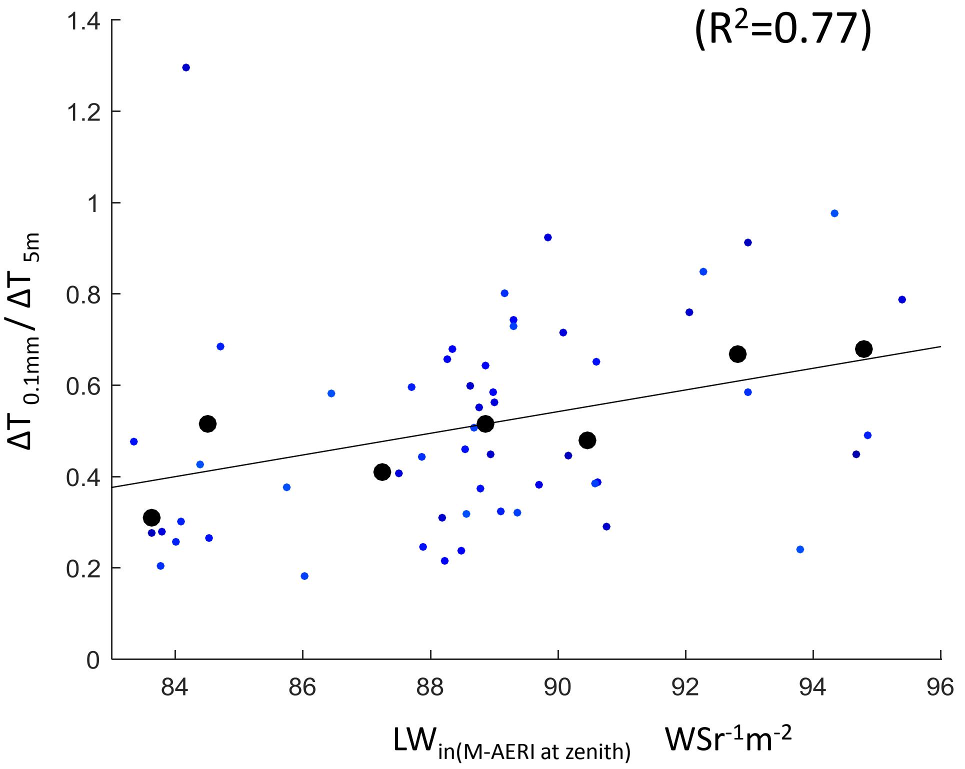
$\Delta T_{0.1mm}/ \Delta T_{5m}$ as $f(U_{10})$. Red dots represent $\Delta T_{0.1mm}/ \Delta T_{5m}$ values binned at every 0.5 ms^{-1}. Red dotted line is $\Delta T_{0.1mm}/ \Delta T_{5m} = 1$.

At $U_{10} < \sim 3ms^{-1}$, thermal skin layer is thicker, and exceeds the depth of the e-m skin layer (at 55^o propagation angle).

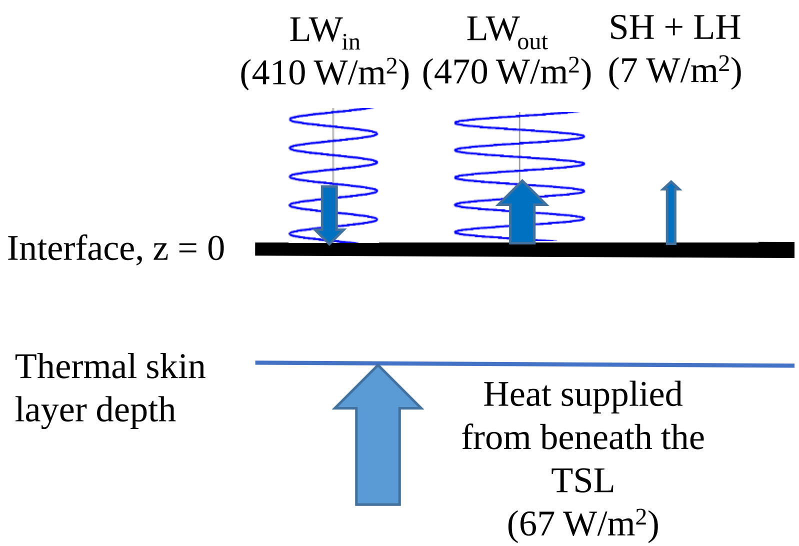


LW_{in} dependence

- Consider $\Delta T_{0.1mm}/\Delta T_{5m}$ as f(LW_{in}); for $U_{10} < 2$ ms^{-1} to reduce U_{10} dependence.
- As LW_{in} increases, more of temperature change across thermal skin layer occurs near the surface, in the e-m skin layer.
- Thus the vertical temperature gradient in the deeper thermal skin layer is reduced – less upward heat conduction from below.



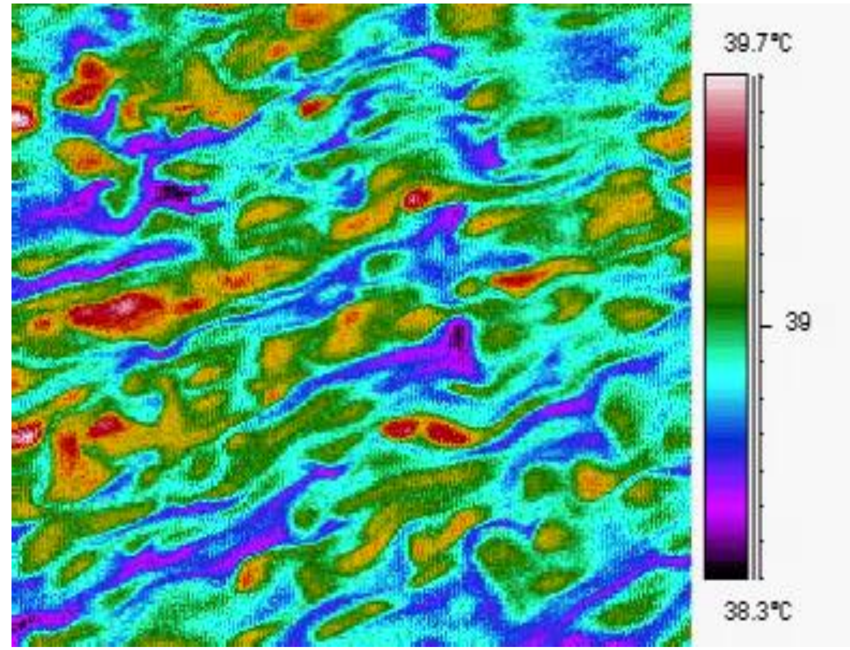
Clear Sky



Flux values are averages from both cruises for U_{10} < 2 ms^{-1}.

Other issues

- What is happening on time and spatial scales in the skin layers not resolved by current instruments?
    - Surface renewal events?
    - But mean quantities still have meaning.
- Are magnitudes of effects sufficient to explain observations?
- Is increase in LW_{in} from clouds a good surrogate for greenhouse gas emission?
- What is happening in the daytime?



Infrared camera images from a wind-wave tank experiment.

Summary and conclusion

- A hypothesis to explain how infrared radiation from the atmosphere can heat the ocean has been posed and tested.
- The hypothesis is for indirect heating of the ocean, with the heat below the skin layers being provided by solar heating; more heat remains beneath the thermal skin layer as a result of the modification of the vertical temperature gradient in the mean thermal skin layer by the absorption of infrared radiation from the atmosphere.
- The hypothesis is upheld by analysis of at-sea measurements.
- Perhaps this is the mechanism for greenhouse gases to heat the ocean…

Supporting references

M-AERI:

Minnett, P.J., Knuteson, R.O., Best, F.A., Osborne, B.J., Hanafin, J.A., & Brown, O.B. (2001). The Marine-Atmospheric Emitted Radiance Interferometer (M-AERI), a high-accuracy, sea-going infrared spectroradiometer. *Journal of Atmospheric and Oceanic Technology, 18*, 994-1013.

Skin-layer profile retrieval:

Wong, E.W., & Minnett, P.J. (2016). Retrieval of the Ocean Skin Temperature Profiles From Measurements of Infrared Hyperspectral Radiometers - Part I: Derivation of an Algorithm. *IEEE Transactions on Geoscience and Remote Sensing*, *54*, 1879-1890.

Wong, E.W., & Minnett, P.J. (2016). Retrieval of the Ocean Skin Temperature Profiles From Measurements of Infrared Hyperspectral Radiometers - Part II: Field Data Analysis. *IEEE Transactions on Geoscience and Remote Sensing*, *54*, 1891-1904.

- Thank you for your attention.