Interdisciplinary Observations of Air-Ocean Energy Fluxes During Arctic Freeze-Up

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1) **Surface energy fluxes** key to understanding melt/freeze processes in new seasonal ice/open water regions of Arctic Ocean
- modulating **processes interdisciplinary** (air-ocean; air-ice; ice-ocean) **& poorly understood**
- improving understanding requires simultaneous measurements of lower atmosphere (incl. clouds), upper ocean, sea ice

2) measurements from recent cruises in MIZ in 2014 & 2015
- SWERUS/ACSE; Jul 5 - Oct 4, 2014; R/V Oden; Laptev, E Siberian Seas
- MR-14-05; Sep 1 - 27, 2014; R/V Mirai; Eastern Chukchi/Western Beaufort Seas
- Sea State; Oct 2 - Nov 5, 2015; R/V Sikuliaq; Chukchi/Beaufort Seas

3) Melt season processes July- mid-Sep; **freeze-up processes mid-Sep - early Nov**

2233 UTC Sep 23 (YD266)
Winds: 12.2 m/s, 208°

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(2) NOAA/ESRL/PSD, Boulder, Colorado, USA

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Atmospheric Surface Energy Flux

$$F_{atm} = SW_{net} + LW_{net} - H_{turb} = SW_d - SW_u + LW_d - LW_u - H_s - H_l$$

Transform to use ship-board measurements:

$$F_{atm} = SW_d(1-\alpha) + \varepsilon(LW_d - \sigma T_s^4) - \rho_a c_p C_H U(\theta_s - \theta_a) - \rho_a L_v C_E U(q_s - q_a)$$

F_{atm} - net atmospheric energy flux at the surface; SW_{net}, LW_{net} - net SW/LW radiative fluxes; SW_d, LW_d - downwelling SW/LW fluxes, α – surface albedo; T_s – skin temperature; H_{turb},H_s, H_l – atmospheric turbulent sensible/latent heat fluxes; ε = 0.985 (snow & ice); ε = 1.0 (ocean); C_H, C_E – turbulent transfer coefficients (function of stability)

Albedo α:

Characterize surface type

1 min webcam images; 5 s KT-15 T_s; 1-min CT-15 T_s ; sea snake T_s

Use previous studies (e.g., Perovich et al 2003)

Sea ice (melting or freezing)

- $\alpha_{sea\ ice}$ ~ 0.35 (w meltponds) - 0.65 (0.55)
- α_{snow} ~ 0.75 - 0.85 (0.80)

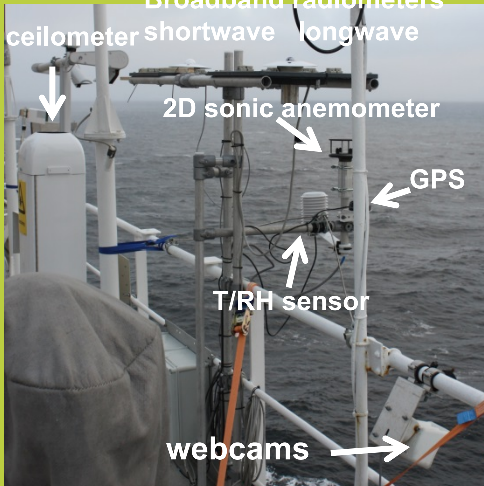
Open water (warming or freezing): α_{water} ~ 0.05 - 0.1 (0.08)

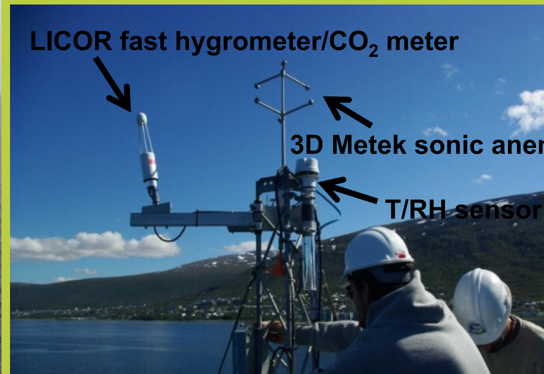
Preliminary study: Bulk rather than covariance turbulent fluxes

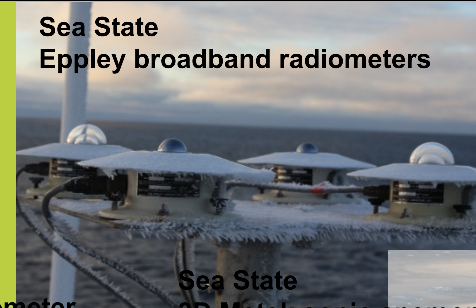
- COARE algorithm (e.g., Fairall et al 2003) modified for sea ice (e.g., Andreas et al 2010)

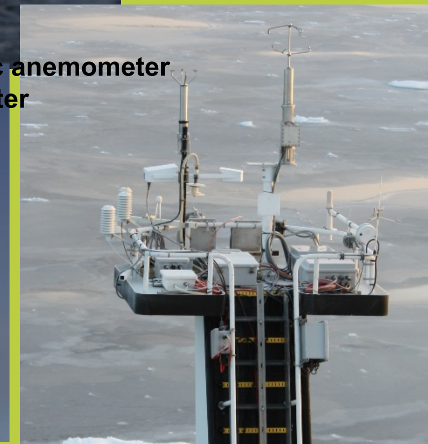
Necessary Measurements - direct

Surface fluxes – turbulent and radiative

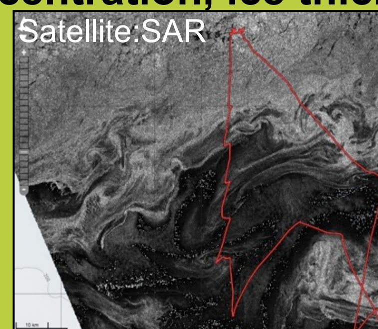


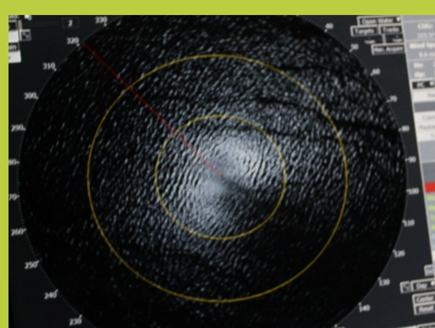




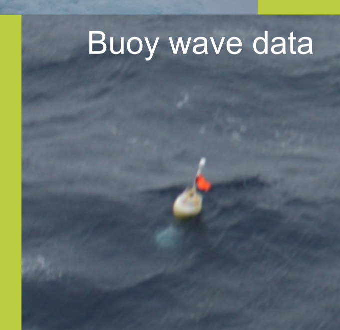


Surface Conditions – temperature, ice concentration, ice thickness, wave height & period



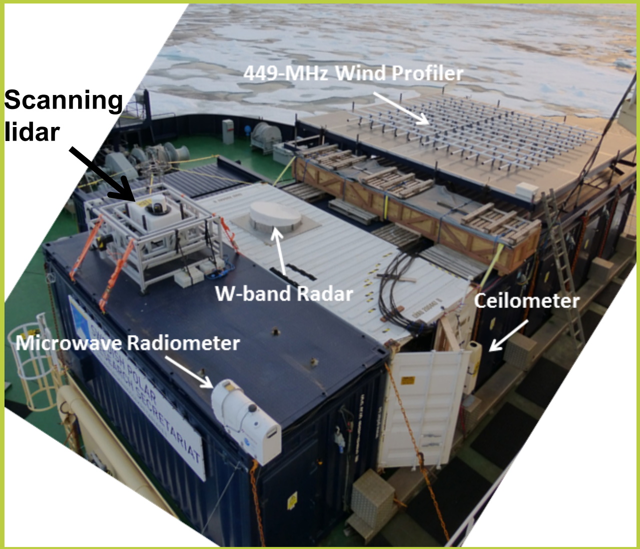


visual ice observations



Measurements for understanding

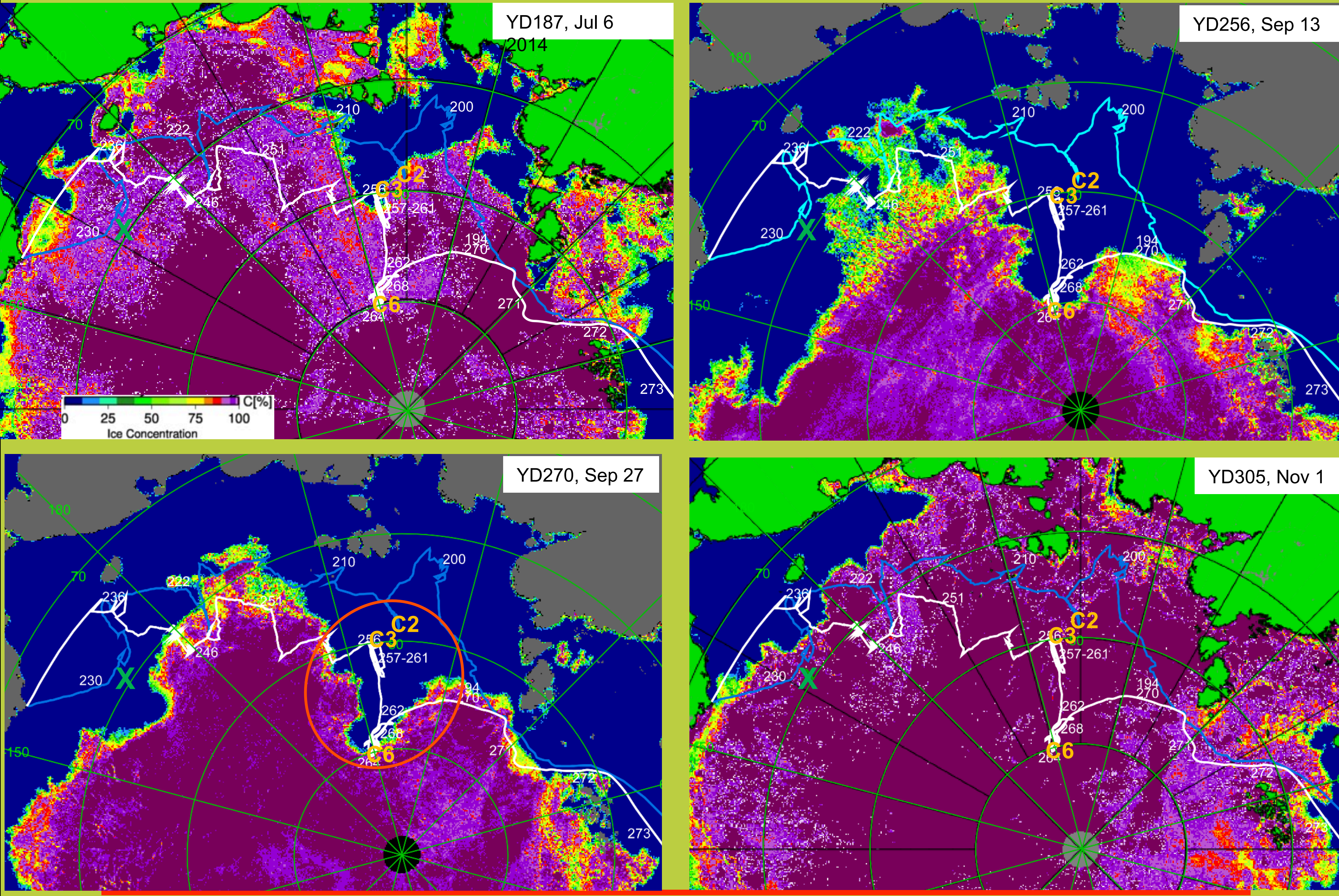
Lower tropospheric wind, temperature, humidity, cloud profiling



Upper ocean temperature, salinity, and turbulence profiling

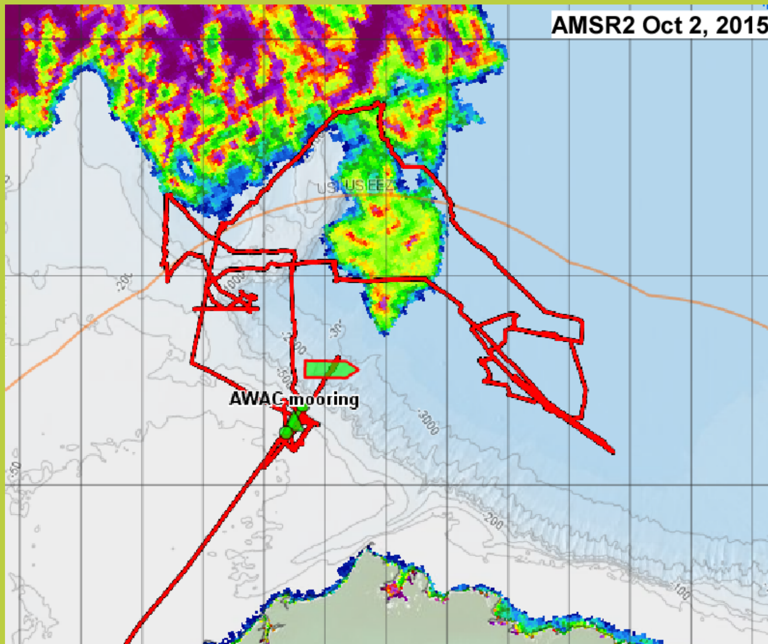
8-m Ocean T, S

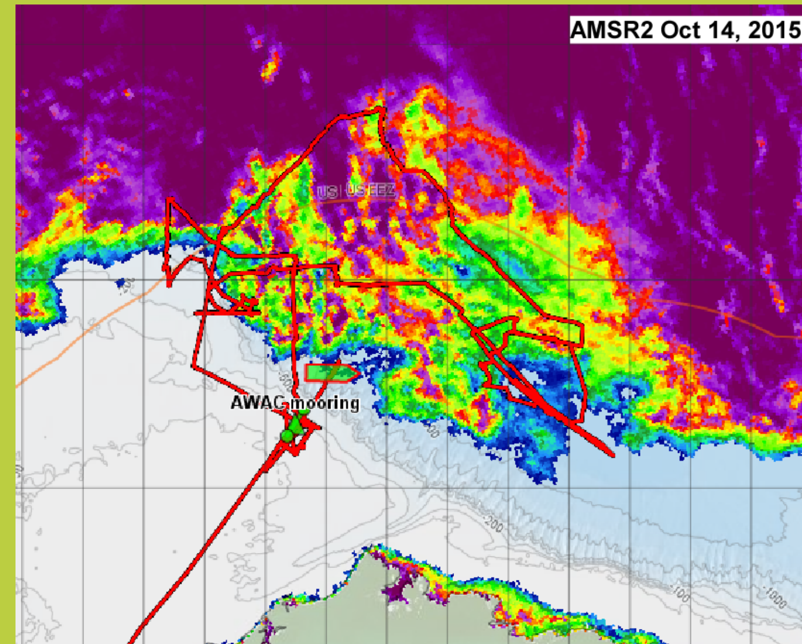
AMSR2 Ice Concentration Evolution 2014; ACSE Leg Tracks

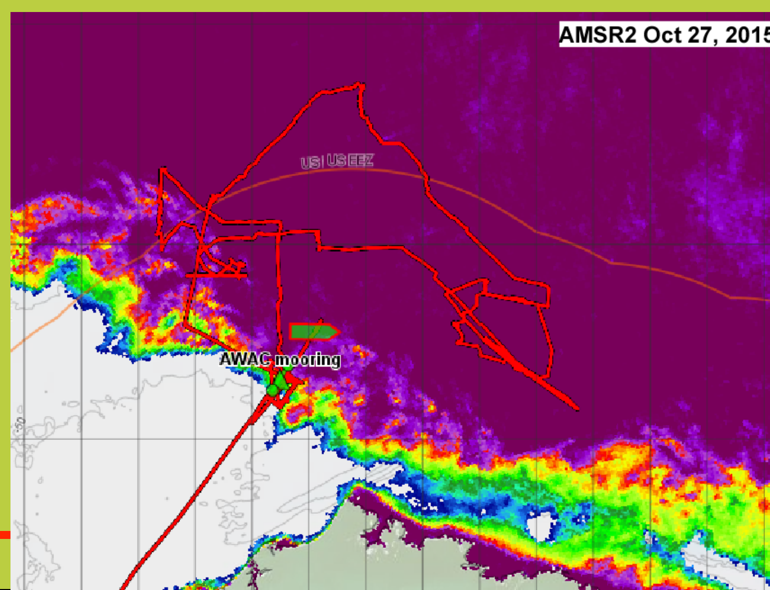


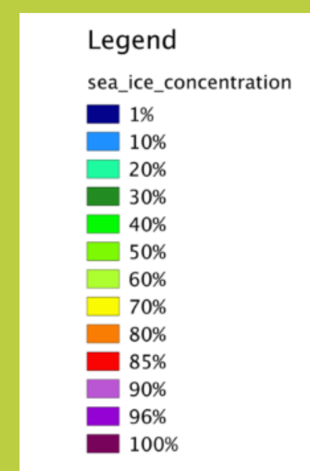
Sea State 2015 Cruise

- Chukchi/Beaufort Sea freeze-up conditions; Oct 2 - Nov 5, 2015
- R/V Sikuliaq



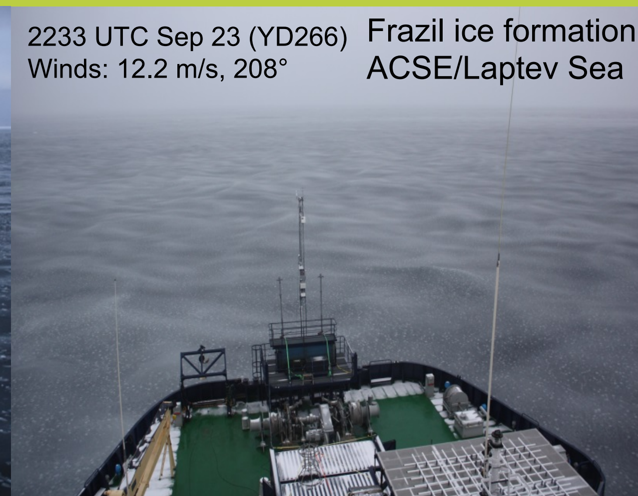






Many States of Arctic Freeze-up


Swell through sparse pancakes
Sea State/ Beaufort Sea


2233 UTC Sep 23 (YD266)
Winds: 12.2 m/s, 208°
Frazil ice formation
ACSE/Laptev Sea


Nilas ice formation
Sea State/ Canada Basin

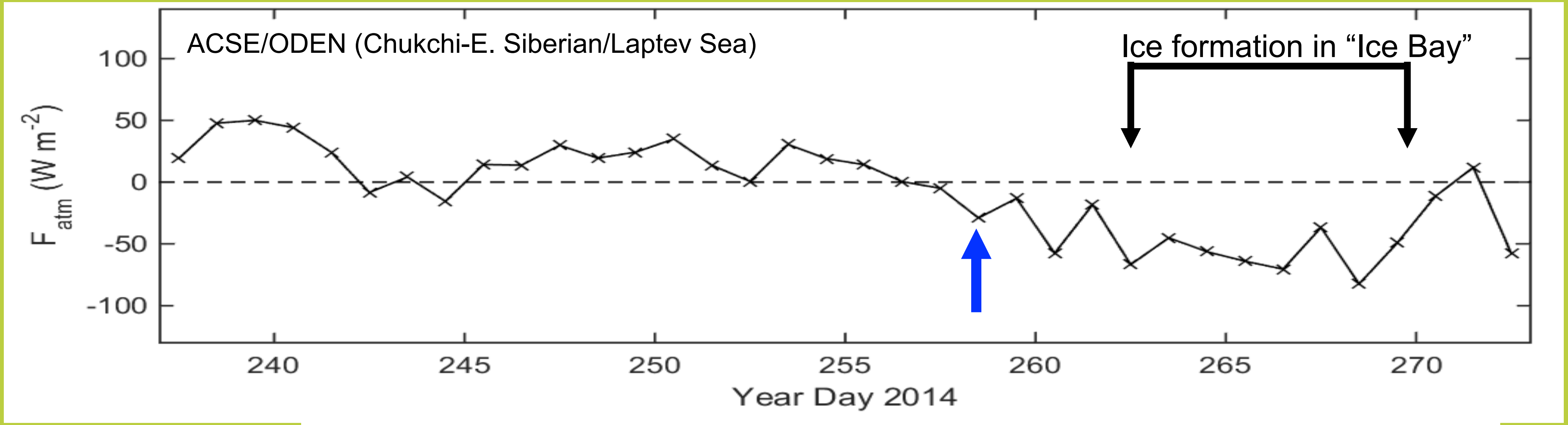

Pancake ice formation
Sea State/ Beaufort Sea

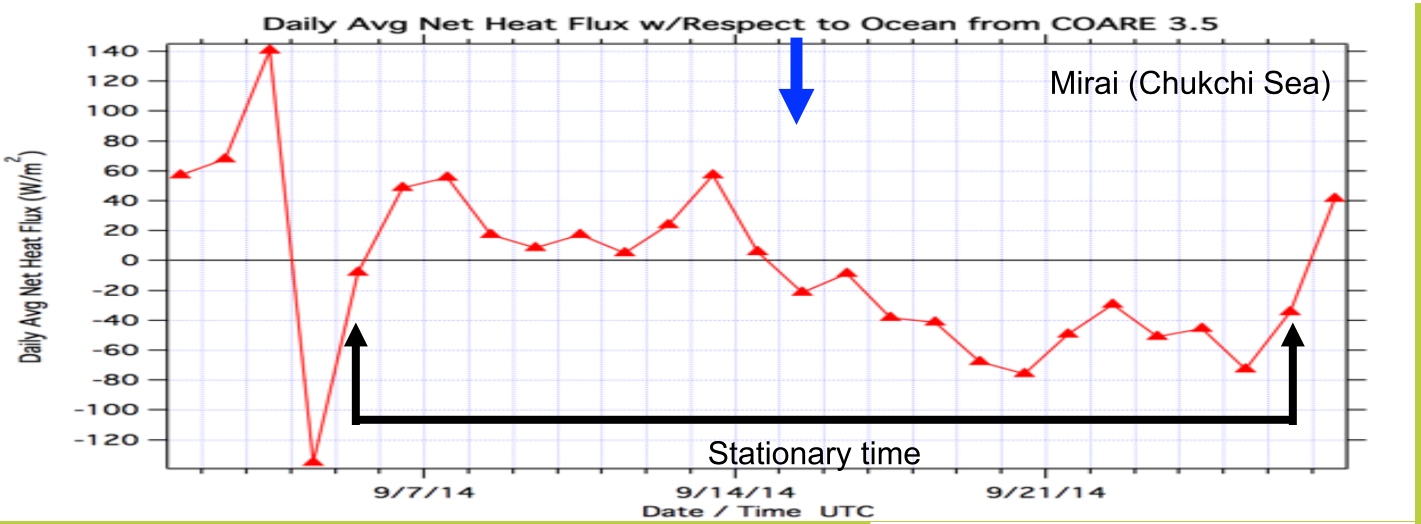

2209 UTC Sep 20 (YD263)
Winds: 2.3 m s^{-1}/ 125°
T_{air} = -3.1° C; T_{sea} = -1.5°C
Rafted pancake ice
ACSE/Laptev Sea


Congealed pancake/nilas
Oct 22; Sea State/ Beaufort Sea

Freeze-up Starts Sep 15

Both ACSE (Oden) and Mirai daily mean F_{atm} become consistently negative Sep 15

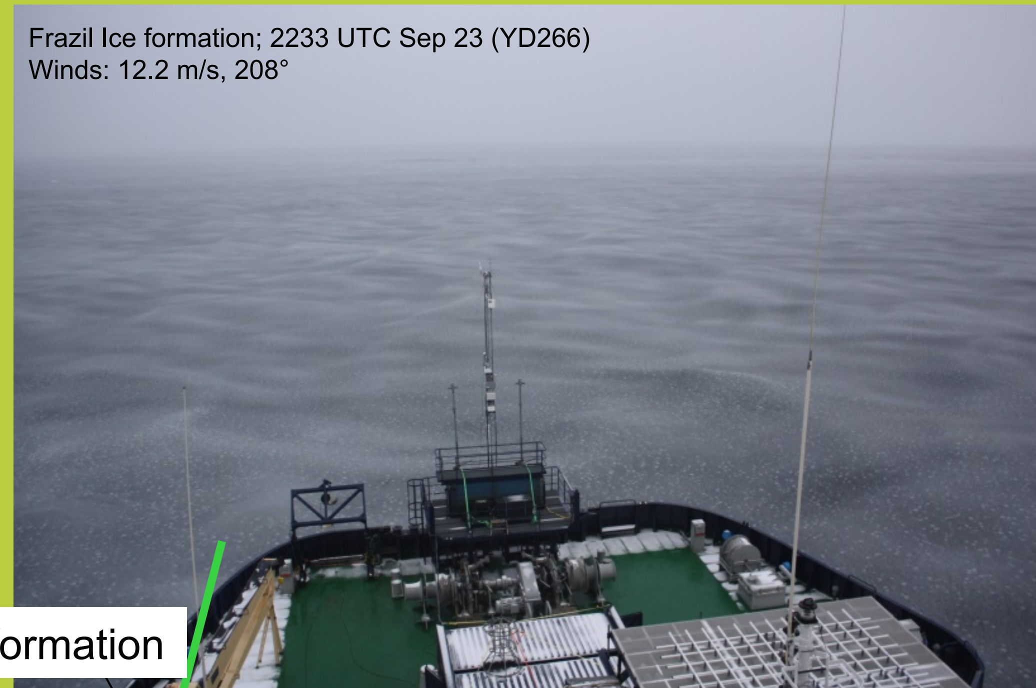


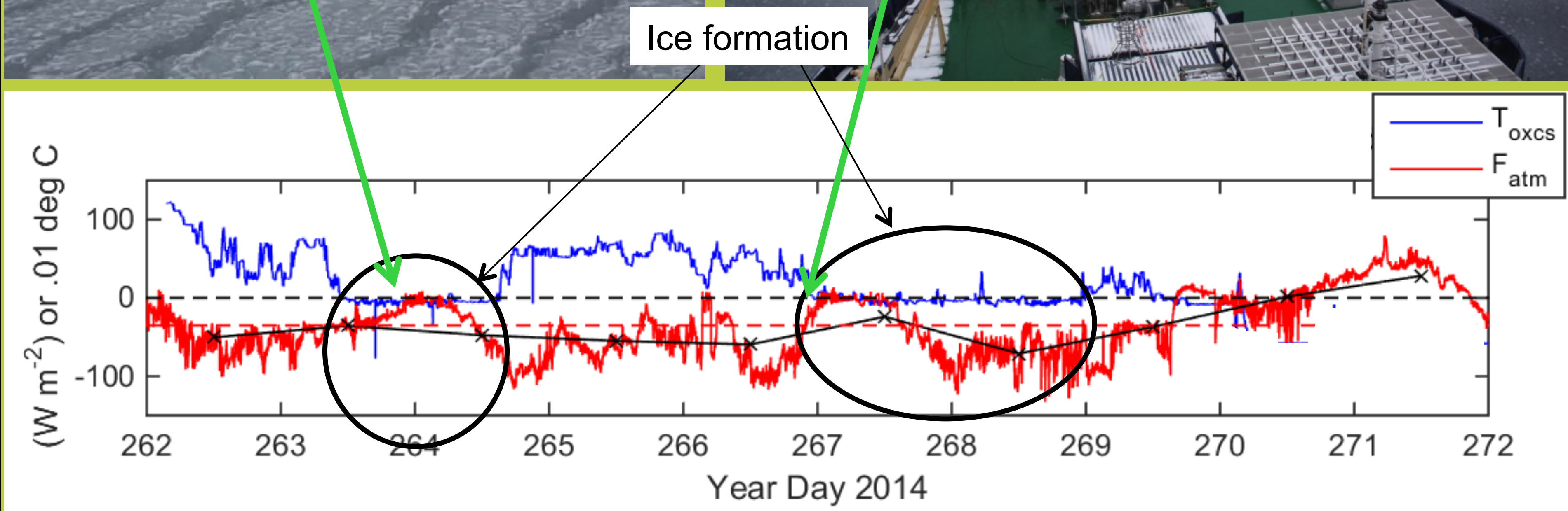


Courtesy B. Blomquist and J. Inoue

ACSE YD262-271 (Sep 19-28)

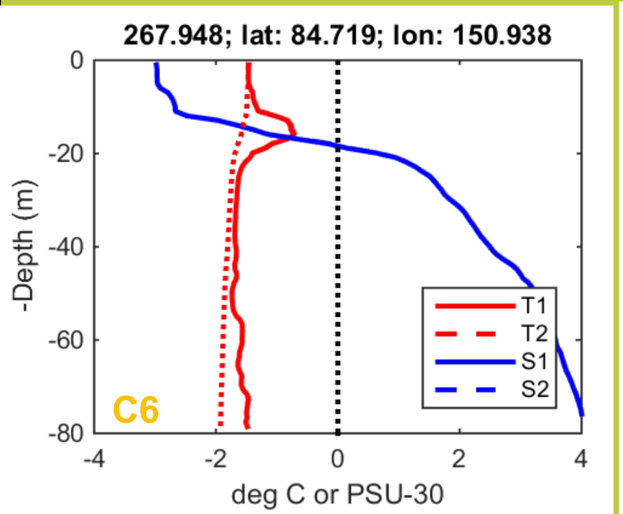
Ocean freezing occurs when T_{oxcs} = 0 AND F_{atm} < 0

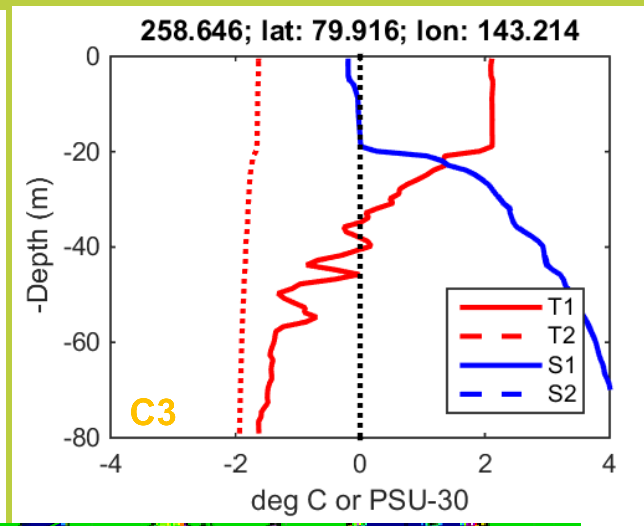


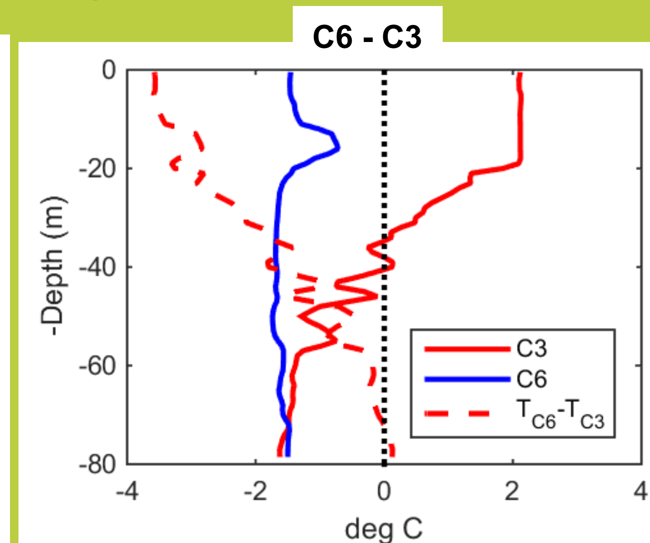


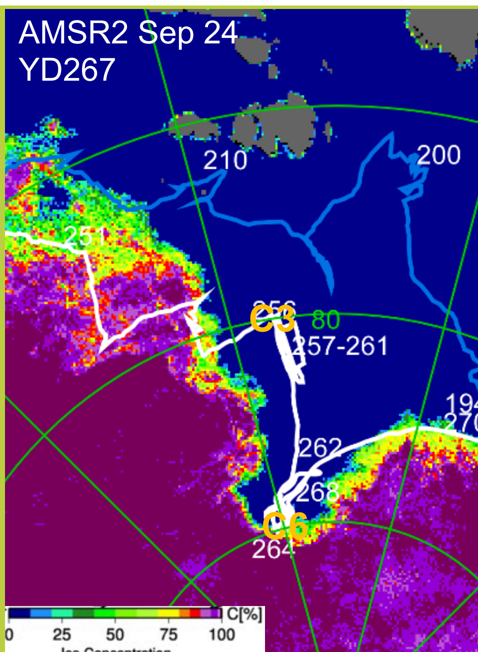
How Much Heat Loss Do We Need for the Observed Ice Advance?

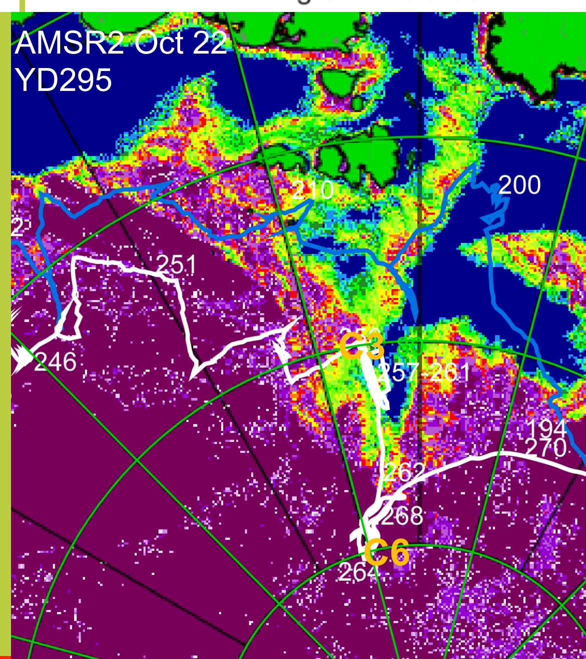
Assume: T-profile at C3 on Oct 22 (in top 20 m) same as observed at C6 on Sep 24
Cooling top 20 m over 37 days (Sep 15 - Oct 22): ~ -84 W m^{-2}

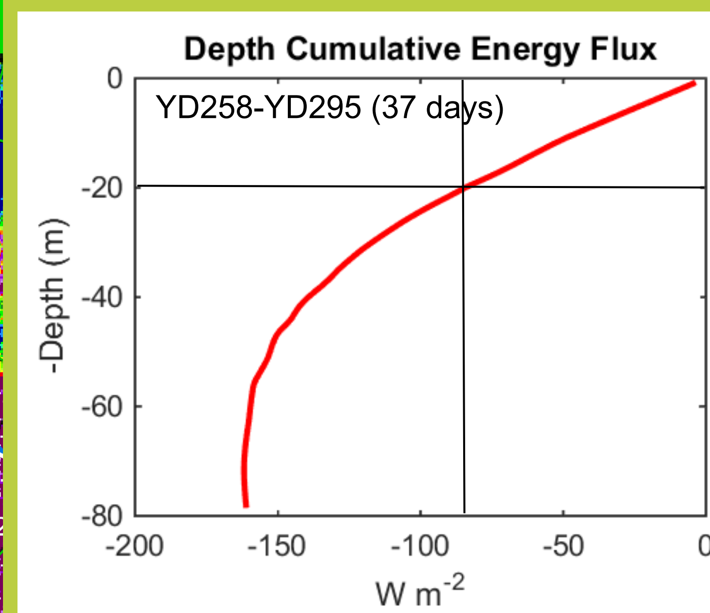










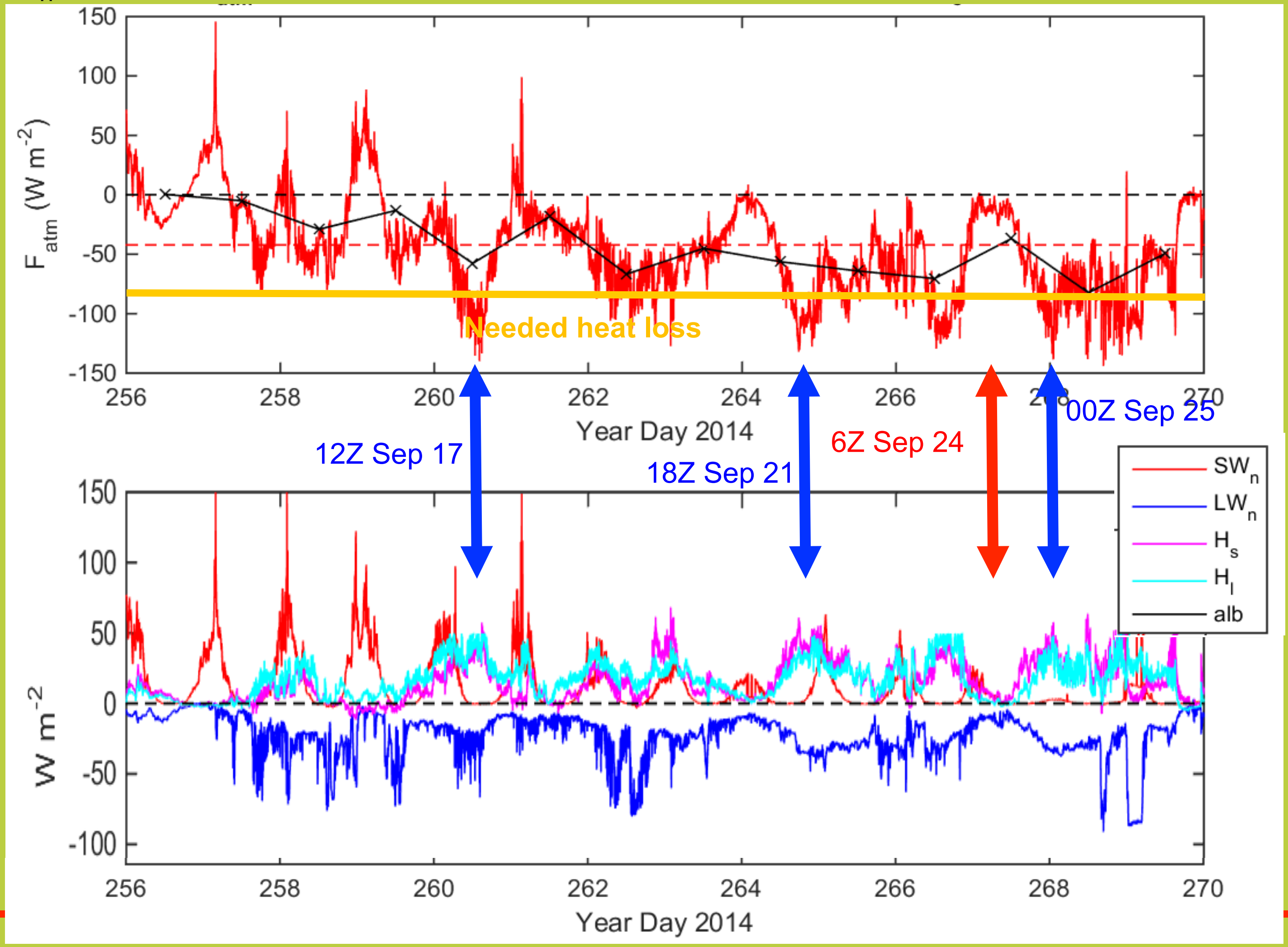


Observed Heat Loss YD258-YD270

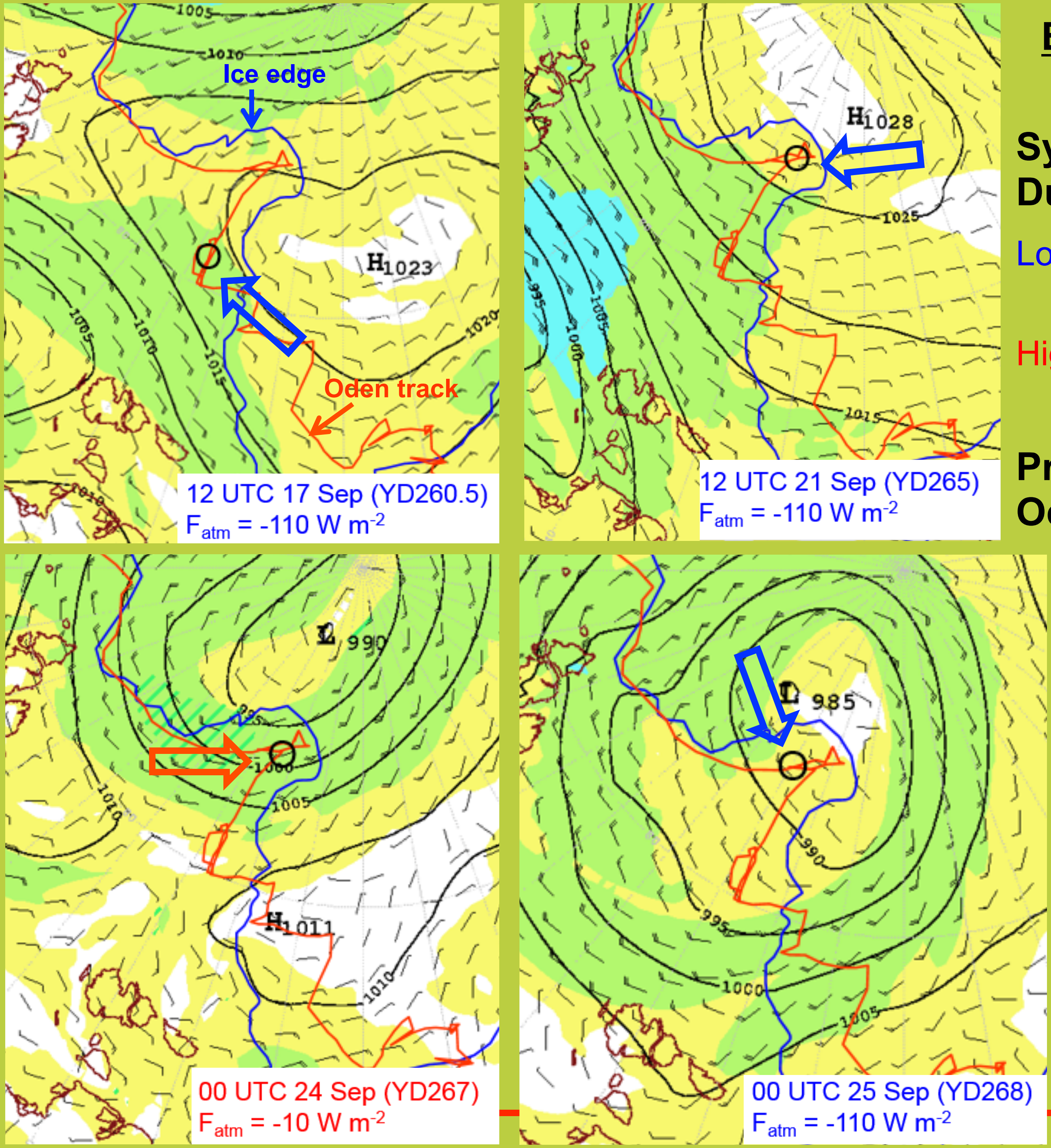
More loss needed to reach -160 - -84 W m^{-2}, but minima sufficient

Minima occur when:

a) enhanced LW_n loss (colder atm)
b) larger H_s & H_l (colder/drier atm)
c) SW_n small



ECMWF SLP, 10 m Winds



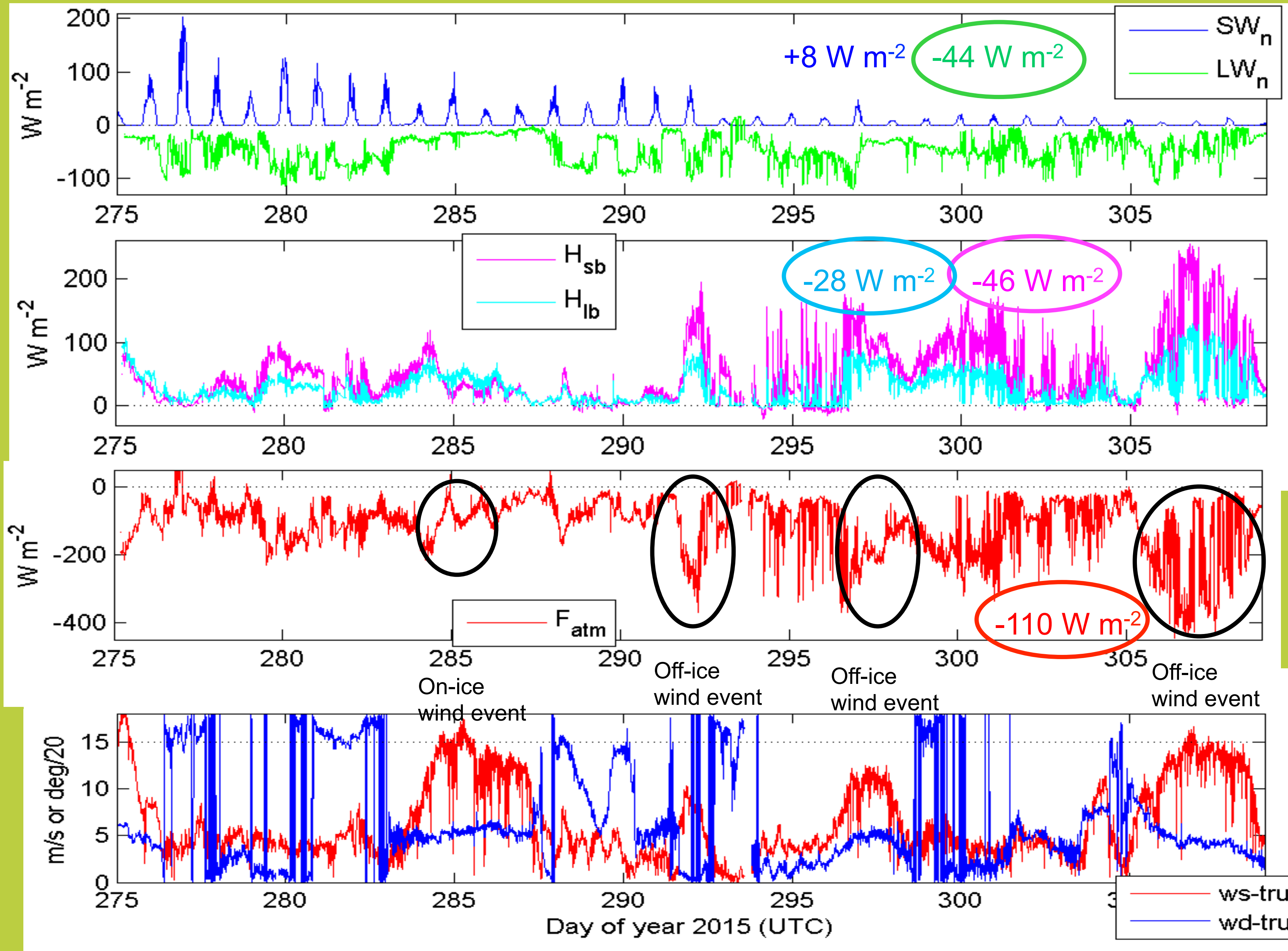
Synoptic Conditions During Freeze-up:

Low F_{atm}: off-ice synoptic flow

High F_{atm}: open-water synoptic flow; prefrontal storm system

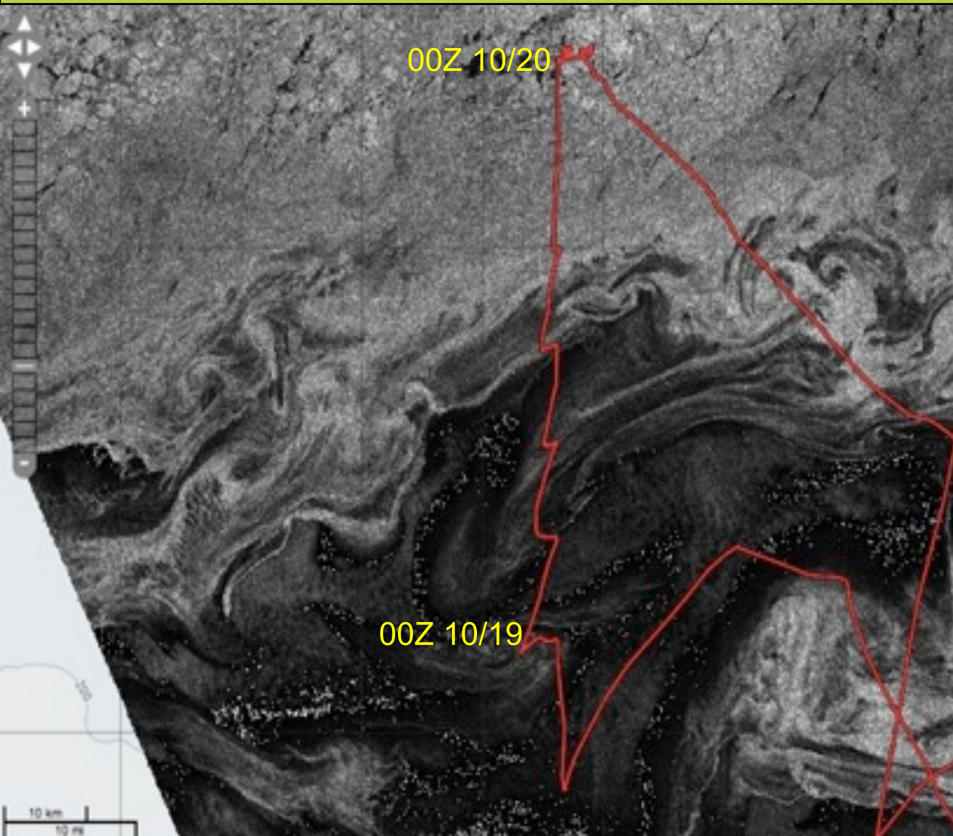
Presence of Ice Accelerates Ocean Heat Loss

Sea State Bulk SEB Oct 2 – Nov 4

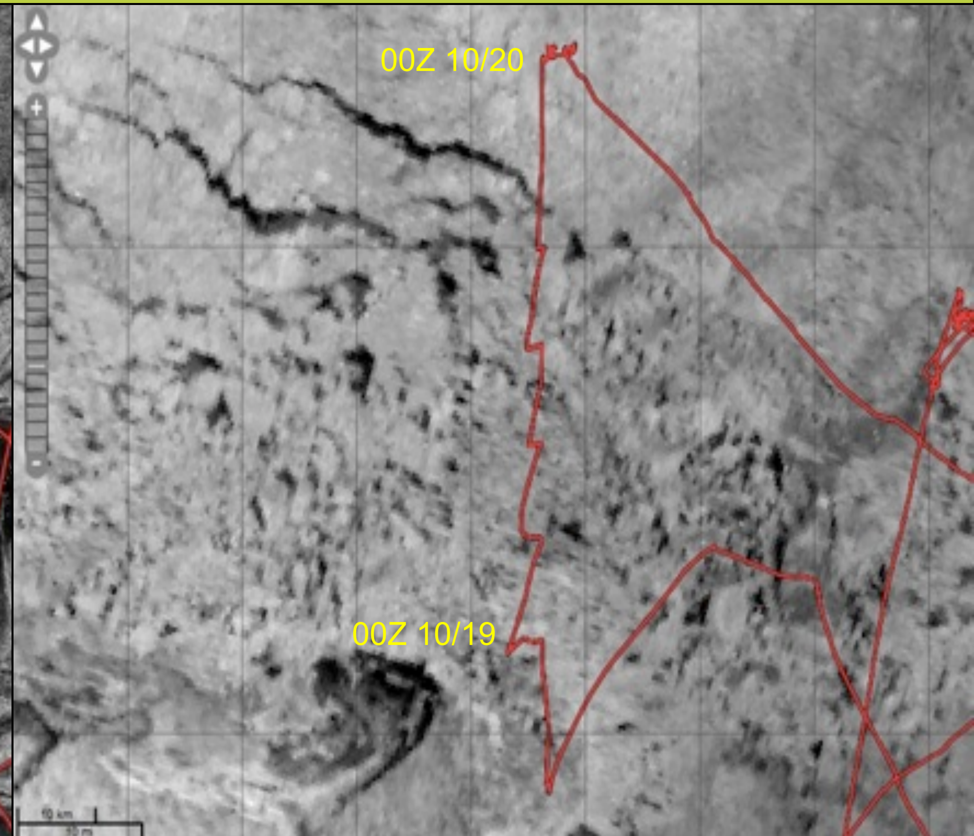


Sea State Modest Off-ice Wind Event, Oct 18-19

Oct 17, 2331 UTC



Oct 19, 0413 UTC



Sea State modest off-ice wind event

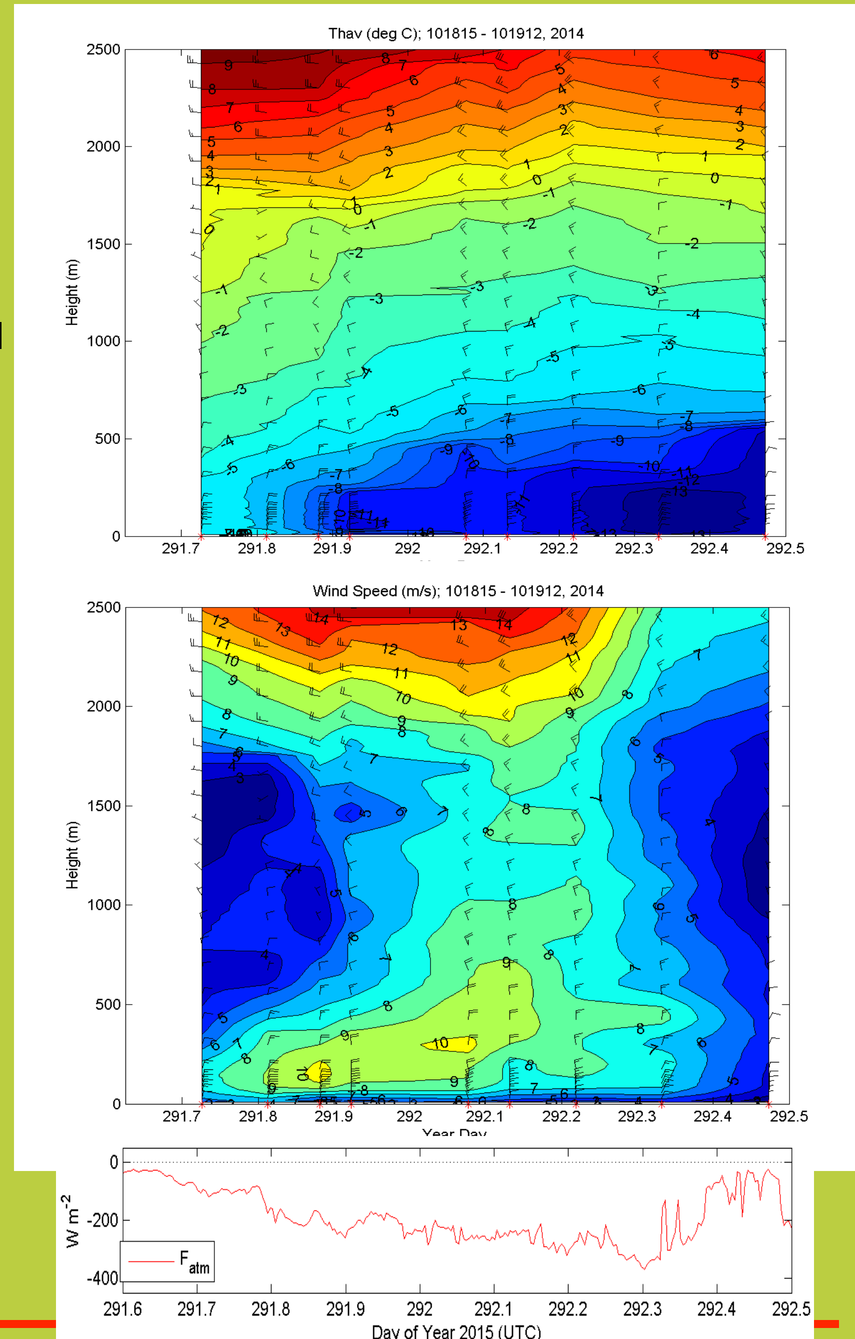
Oct 18-19, 2015

Time-Height Cross-Sections

Virtual Potential Temperature

Off-ice density current with low-level jet

Isotachs



Significant ocean heat loss
(~ - 250 W m^{-2})

Conclusions:

1) Ocean cooling starts ~ Sep 15

2) Observed surface heat fluxes sometimes consistent with necessary upper-ocean heat losses – depends on ocean heat source

3) Understanding fate of sea ice during autumn freeze-up requires surface flux measurements and understanding of interdisciplinary processes

a)History of surface fluxes and upper-ocean heating throughout melt and freeze-up period

b)Understand atmospheric processes that impact radiative and turbulent surface fluxes
- boundary-layer structure, **thermal advection**, low-level winds, cloud characteristics (macro- and microphysics, temperature)

c)Understand ocean processes that impact release of ocean heat
- heat storage vertical profile (e.g., surface energy fluxes, currents), wave characteristics/vertical mixing events